Practical Holography Third Edition

About the author

After a career in photography with the Royal Air Force, including seven years as OC Photographic Science Flight at the RAF Joint School of Photography, Graham Saxby joined what is now the University of Wolverhampton, teaching educational technology to trainee teachers, and, later, modern optics to degree courses in applied sciences. This gave him the opportunity to indulge his enthusiasm for holography, and to build his own laboratory, where he organized projects for students from both arts and science faculties. His work in this area has earned him an international reputation, and his published material has received a number of prestigious awards. Now formally retired, he continues to operate as a freelance editor of technical and scientific literature and as a consultant in holography, photography and applied optics.

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Graham Saxby



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Foreword to first edition

Looking at holograms is exciting. Bobbing our heads around, probing the new visual spaces holography offers, can be a captivating experience. Indeed, most of us vividly recall the first hologram we ever saw, and many more we have seen since. And making holograms is even more exciting! Watching our own entirely new images come 'out of the soup' and light up in the beam brings a real thrill of exploration and discovery. It must be similar to what photography provided in the last century, and amateur radio earlier in this one. No matter how humble the setup, every new hologram is an adventure. And as a holographer's understanding and insights develop, and his or her techniques advance, the holograms become ever more ambitious and intriguing.

For these are still the early days of holography. Despite its emergence more than twenty-five years ago (in its modern laser form), most holographers are largely self-taught, and many fall away when their understanding fails to help them past the various challenges facing this complex new medium. There are books and papers to be found, certainly. Holography has stimulated some of the most profound theoretical work in optics. And there are even a few hobby 'how to' books that show exactly where to put the laser, the mirrors, and so forth. But there are only a handful of educators who have brought their skill to a comprehensive approach to making, understanding, and improving holograms. I find this volume a singularly responsible work along these lines. Saxby clearly describes what to bring together, and how to use it to make high quality holograms. And with an experienced educator's flair, he conveys the insights necessary for the student to take the next steps alone. Especially important is the ability to diagnose flaws in holograms, and to experiment with corrective actions. This can be especially challenging because holography draws together such diverse concepts from optics, photography, chemistry, and mechanical engineering. Further, Saxby's experience proves valuable in guiding the student toward setups and images that will work well enough the first time to provide an encouraging toe-hold in this mysterious territory.

The efforts of scientists, artists, inventors, and advanced amateurs are combining to change the 'look' of holography on a regular basis. Embossing technology has brought white-light transmission 'rainbow' holograms into the direct experience of hundreds of millions of people over the past few years. And with the requirement that they be visible in almost any light, a new genre of 'shallow depth' image design has developed. Pre-exposure swelling is still being refined to expand the palette of reflection holographers. And new materials are offering new options for all kinds of holograms. The scope of holographic imaging is being widened by refinements in pulsed laser holography, especially for portraiture, and in holographic stereography, which promises to make outdoor scenes, computer graphics, medical images, and other traditionally nonholographic content available in ultimate '3-D' form. From a fundamental point of view, these are all simply 'holograms'. But from a practical point of view, they involve different equipment and skills, and habits of thought, requiring a broad ranging concept-based education. Saxby has been tracking these with careful readings of the literature backed up by interviews with the innovators involved, the essences of which are also offered here.

Where the trail of holography will lead next is anybody's guess. Armchair holographers had best stick to the current fare of science fiction, but for fellow 'hands-on' types, I warmly commend the pages. There are real adventures aplenty ahead!

Stephen A. Benton Spatial Imaging Group Massachusetts Institute of Technology Media Laboratory, Cambridge, MA 1988

Preface to third edition

Since the previous edition of this book was published there have been two important developments relevant to display holography. The first was the decision of Agfa-Gevaert to cease production of holographic film and plates. This looked like being a disaster for holography, both scientific and creative. Fortunately, other companies stepped in to fill the gap, with emulsions that were actually an improvement on the older ones. The second has been the proliferation of semiconductor diode lasers suitable for making holograms. Costing no more than a cheap camera and able to run off a cycle lamp battery, such lasers have brought holography within the reach of all amateur image-makers. Although HeNe and ion lasers still have their place in the laboratory, diode lasers are taking over in holography as rapidly as digital imaging in photography.

The aims of this book were set out in the prefaces to the two previous editions. I have therefore included the preface to the second edition unchanged except for the deletion of a few sentences that are no longer appropriate. I have also included extracts from the preface to the first edition that seem to be still relevant, as well as Stephen Benton's original Foreword. This third edition has a new layout that should improve its readability: the numerous asides have been set as marginal notes, along with some of the smaller diagrams. This has produced a better continuity, and has enabled me to do away with the glossary and some of the boxes. There is no longer a list of suppliers, as such lists quickly become out of date, and it is a simple matter these days (with a few exceptions) to obtain the relevant information via the Internet. I have also dispensed with the booklist in its previous form, and included titles of relevant literature within the text. I have retained American spelling, as British readers are less likely to have difficulty with this than American readers might have with British spelling. However, to avoid possible ambiguities I have retained the European spelling of metre (m), micrometre (µm) etc.

Further to the acknowledgments in the preface to the second edition, I should particularly like to thank Steve Benton, Tung Jeong, David Pizzanelli, Hans Bjelkhagen, Nick Phillips and Jeff Blyth for their help in providing information vital to the updating of this edition, as well as my editor Tom Spicer, and the artists at IOP Publishing who produced the many diagrams appearing in this book. And a special thank you to John Brown of Light Impressions Plc, for his company's generous donation of the embossed hologram that embellishes the cover.

G.S.

Preface to second edition

While the Beaver confessed, with affectionate looks More eloquent even than tears,It had learnt in ten minutes far more than all books Would have taught it in seventy years.

Lewis Carroll, The Hunting of the Snark

Many years ago I made my first photographic print. The thrill of seeing, for the first time, the image gradually emerging in the developer had me hooked for life. It was some while before I managed to become a professional photographer, and I had to join the RAF to do it; but that, as they say, is another story.

Years later, I made my first white-light reflection hologram. I had, it is true, made a hologram of sorts some time previously, but you could only see the image by laser light, and even then only with the help of a vivid imagination. Then I heard of a way of making holograms you could view by white light, by a process so simple it made box-camera photography look complicated. I borrowed a small laser, blacked out the bathroom and set about it. At about the fourth attempt I obtained an image. The sight of that image, at first dull red, then gradually turning a bright golden color as the film dried, was every bit as overwhelming as the sight of my first photograph. I was hooked again.

How I got from that ecstatic experience to writing the first edition of *Practical Holography* is another long story. Now, six years after its publication, holographic techniques have advanced so far that a new edition is urgently needed. During the run of the first edition I received a gratifying amount of feedback, and this has helped to make what I hope are improvements in format, content and approach. I have brought some of the material previously in appendices into the main text in boxes. Some of these do contain mathematical material, but nothing beyond simple pocket-calculator operations. I have used SI units and scientific notation throughout, and, in accordance with recommended practice, have adopted negative indices, so that the speed of light is now shown as $3 \times 10^8 \,\mathrm{m \, s^{-1}}$ instead of 3×10^8 m/s. I have found it necessary to retain some anomalous units held by stubborn tradition, such as 4×5 and 8×10 inches for film size, and microjoules per square centimetre (μ J cm⁻²) for radiation energy. I have used metres and centimetres for larger measurements; but as the building and allied industries now use millimetres for all measurements, and this is the way dimensions have to be specified when ordering materials such as timber and metal strip, do-it-yourself measurements are given in millimetres.

The greater part of the book is concerned with practical holography for display purposes, and progresses from very simple single-beam holograms that a child of ten can make to techniques for producing multicolor art holograms and holographic stereograms of any desired complexity. The final part of the book is concerned with applied holography. Here the treatment is confined to broader descriptions, with the emphasis on practical setups. Applied holography is well covered in the literature, so rather than attempting a long-winded rehash of what has been written much better by other people, I have kept to fairly general outlines and have provided references to the more important original papers or books on the various aspects of the subject. As it is now so easy to obtain access to facsimiles of this material, this should not inconvenience anyone whose appetite has been whetted by a brief description of some application.

The early part of the book deals with the principles of holography, and in dealing with image formation I have used the Fourier approach rather than the more commonly used Huyghens wave model. It is true that a rigorous Fourier treatment of image formation involves some neat mathematical footwork; but the difficult part – the computation of a two-dimensional Fourier transform – is no trouble for a modern computer. The Fourier model provides an elegant and deeply satisfying metaphor for the way in which both photographic and holographic images are formed. As the concepts involved can be grasped intuitively as well as logically, the whole model can be understood and applied without the use of mathematics. Furthermore, once the fundamental concept of frequency space has been grasped, it is possible to look at an object and perceive it in a new and enriched way. Appendix 2 sets out the principles of Fourier optics, though necessarily somewhat briefly, so a reading list is included for those who wish to follow up this fascinating approach.

Almost all of the techniques described in the book have been validated by my students. Where this has not been possible I have used the best of the original research reports, and in most cases have visited the labs and discussed the techniques with the originators.

If I were to list everyone who has given help and encouragement during the preparation of this book, it would include almost every holographer with whom I have had the pleasure of conversing or corresponding, as well as many whom I know only through their published papers. In particular, I should like to express my gratitude to Steve Benton, Nick Phillips, Rob Munday and Nigel Abraham for their support and valuable advice during the preparation of this edition. I must also thank (in random order) Jeff Blyth, John Webster, David Jackson, 'Hari' Hariharan, Ric Parker, Rich Rallison, Paul Dunn, John Kaufman, Steve McGrew, Jody Burns, Bill Molteni, Suzanne St Cyr, Hans Bjelkhagen, Peter Waddell, Nils Abramson, Bill Durell and Martin Richardson for supplying valuable information about their specialisms. I am indebted to the authorities of the University of Wolverhampton for providing time and facilities for carrying out essential research work, and, in particular, to the many former students who tried out the setups and showed me where I had gone wrong. I should also like to thank the members of the MIT Spatial Imaging Group for all the information they have given me, as well as for the welcome they have afforded me on my visits.

I owe a special debt of gratitude to Tung Jeong, whose triennial symposia on display holography at Lake Forest, Illinois, have enabled me to make the acquaintance of both Emmett Leith and Yuri Denisyuk, two of the nicest people I have had the privilege of getting to know, and to pick the brains of almost every practising holographer in the world. Any felicities you may find in the text are theirs. Any errors are mine.

G.S. 1994.

From the preface to the first edition

For so youthful a technology, holography seems to have generated a record number of papers. Yet during the same time a mere dozen books have appeared on the subject, none of them covering it in anything like a comprehensive way, especially where practical techniques are concerned.

Even books plainly intended for the scientist and technologist are oddly reticent about practical details. Yet before such people can get down to work they need to know all sorts of practical things, some of them fairly mundane: how to set up a spatial filter; whether optical path matching is necessary (and how to check it); the highest laser power that can be used without damaging aluminized mirrors; what happens if retroreflection occurs in a pulse laser; how to adjust a Fabry–Pérot etalon; even where to find a 400 mm diameter collimating lens for under £1000. Such practical books as do exist (almost all of them out of print at the time of writing) are mostly written at a do-it-yourself level that is unlikely to appeal to either the technologist or the professional. Furthermore, writers on the artistic aspects of holography [tend to avoid] reference to the techniques they use, which is equally frustrating to the holographic artist.

This book attempts to fill that gap. It avoids [unnecessary] mathematical theory, which is already covered by existing books. What it does cover is the *practical* aspect of holography, at all levels. The artist can find out the table geometry that can realize a particular concept; the aspiring professional is taken step by step through simple foolproof setups to the most complex table geometries; and the technologist who wants to use holography as a research tool *can* find out how to set up a spatial filter, as well as why one is necessary, the kind of power that will damage an aluminized mirror (anything over 1 W), how to match optical paths (use a piece of string), what happens when the beam of a pulse laser is retroreflected (it blows the ends off the ruby rod) and so on.

The layout of the book is as logical as possible, given a subject with so many ramifications. Those readers with a pathological aversion to mathematics (i.e. about 90 per cent of the likely readership), will be relieved to discover that it has been quarantined in an appendix, and if they want to glue the pages together to stop the numbers and letters from getting out they may do so, provided they have bought the book and not borrowed it.

There are a good many allusions to and comparisons with photography. In the early days of photography its practitioners were seldom trained photographers; and even now many holographers come from a background of the fine arts. However, professional photographers are beginning to realize that [some] knowledge of holography is becoming a necessary part of their stock-in-trade, and students on visual communications courses are beginning to treat holography as a medium that touches and often overlaps the plastic arts, graphics and photography. This is a healthy sign; the gee-whiz attitude to holography is disappearing as people become familiar with the medium, and images of telephone handsets are no longer exciting. Display holography has come of age, and is fit to take its place alongside photography and other media of visual communication.

G.S. 1987.

Part 1 PRINCIPLES OF HOLOGRAPHY

Chapter 1 What is a hologram?

'I'm afraid I can't put it more clearly,' Alice replied very politely, 'for I can't understand it myself, to begin with...'

Lewis Carroll, Alice in Wonderland

To the physicist, a hologram is a record of the interaction of two mutually coherent light beams, in the form of a microscopic pattern of interference fringes. To the well-informed lay person, it is a photographic film or plate that has been exposed to laser light and processed so that when illuminated appropriately it produces a three-dimensional image. To the less well informed it is just some kind of three-dimensional photograph. Certainly, both photography and holography make use of photographic film or plates, but that's about all they have in common. The image is produced in a totally different way: you can't even describe the way the two types of image are formed in the same terms. You can show how a camera lens produces an optical image using a simple ray diagram and basic geometry; but to explain a holographic image you have to invoke the concepts of diffraction and interference, and these are wave phenomena.

Stereoscopy

When you take a photograph, the image you get is two-dimensional. If you look at it from an angle the only change you see is a foreshortening of the image. If this is a face looking at the camera, the eyes appear to be fixed on you, and they remain fixed on you when you move to one side. People sometimes express surprise at this, although painters understood the reason long before photography was thought of.

In contrast, when you look at a sculptured head the eyes look at you only when you see the head from the front; when you move to the side your viewpoint changes, but the eyes continue to look in the original direction. The image is plainly endowed with depth. Even without your moving, each of your eyes sees a slightly different image by virtue of its differing viewpoint; one of the clues to your perception of depth is your brain's interpretation of these differences. Soon after photography appeared, the idea of presenting two photographic images taken from appropriate viewpoints, one for each eye, led to the invention of the stereoscope by John Herschel and its commercial realization by Charles Wheatstone.

Since then the popularity of stereoscopic presentation has fluctuated; but stereoscopy continues to earn its keep in metrology, photogrammetry, and, most notably, in aerial reconnaissance and survey.

A fair number of people, perhaps as many as one in five, have poor stereoscopic perception. Around one in twenty has none at all. Yet such people have no difficulty in telling whether they are looking at a real object or a flat photographic record. The reason for this lies mainly in the phenomenon of *parallax*, the way that the view you see changes in appearance when you change your viewpoint. Even with your head fixed and one eye closed, the small movements your eye makes in scanning the scene are sufficient to verify the solidity (or absence of solidity) of what you are examining. However, with stereoscopic pairs of photographs there is no live parallax. At the showing of a stereoscopic film, everyone gets the same view

The reason, of course, is that nothing changes in the image when you change your viewpoint, except that it just becomes a little foreshortened (squeezed up).

In a stereoscopic presentation two views of a scene recorded from the positions of the two eyes (i.e. 6–7 cm apart) are presented optically, one to each eye. This may be achieved by an optical device, or by donning colored glasses; the effect is the same. Your brain interprets the discrepancies between the images in terms of depth.

This is analogous to the effect you get when you are listening to a stereo recording on headphones; you can move around the room and the sound stage moves with you. More disturbingly, if you swivel your head the whole sound stage swings round with it. Of these cues only stereopsis, and to some extent convergence, are represented in a stereoscopic pair of photographs. The remainder, with the important exceptions of parallax and accommodation, are present in a single photograph.

The most recent camera of this type to appear was the Nimslo, with four lenses. It was not a commercial success.

For example, if you record the image at 1/10 scale, its depth is reduced by a factor of 100.

Box 1.1

In real life there are seven visual cues involved in the perception of depth:

- *Parallax*: As you change your viewpoint the relative positions of objects appear to change.
- *Relative size*: More distant objects appear smaller in proportion to near objects.
- *Aerial perspective*: Subject contrast decreases with increasing distance, and hues become bluish.
- Obscuration: Nearer objects overlap farther objects.
- *Accommodation*: You need to re-focus your eyes for objects at different distances.
- *Lighting contrast*: Coarse contrast (modeling) and fine contrast (texture) indicate the three-dimensionality of objects.
- *Convergence*: The axes of the eyes need to converge to fuse the images of nearer objects.
- *Stereopsis*: Differences between the two images are recognized and interpreted by the brain as depth in the scene.

as you do. If you move your head sideways when you are examining a stereoscopic illustration in a book using colored glasses, your viewpoint of the scene doesn't change. The eyes of a portrait remain fixed on you, and the perspective stays exactly the same.

One method of overcoming the lack of parallax, and at the same time avoiding the necessity for wearing special glasses, is the parallax stereogram. The technique for producing these involves moving a camera past the subject matter (or moving the subject matter past the camera) while you take photographs at intervals of a few degrees. You then need the resulting negatives to be printed on a single sheet of print material, using a special optical printer that interlaces the images in narrow vertical strips. After processing, the print is mounted under a fine lenticular screen that allows you to see only a single image from any one viewpoint. You can view the result without glasses and see genuine horizontal parallax over a limited range of angles. Such *autostereograms* (i.e. stereoscopic images that you can view without any optical aid) enjoy some success in the picture postcard industry, and from time to time cameras embodying similar principles appear on the amateur market.

The images they produce are not always entirely convincing. Horizontal parallax is certainly present, but the perspective often appears shallow, and figures and backgrounds may appear like cardboard cutouts. One of the reasons for this 'cardboarding' effect (which also occurs in conventional stereoscopic pairs) is that in the optical image formed by a camera lens the longitudinal scale of the image is the square of its lateral scale. Only at 1:1 scale is the depth rendered truthfully. However, provided you keep within certain distance limits (about 2–4 m for an interlens separation of 6.5 cm), you can produce convincing stereoscopic effects with just two photographs (Fig. 1a).

Any simple photograph is, of course, two-dimensional, yet the optical image formed inside the camera was itself three-dimensional (Fig. 1.1b). If you form a full-size image of an object such as a glass animal with a camera lens, and catch this real image on a ground-glass screen, when you move the screen back and forth



Figure 1.1 (a) This is a stereoscopic pair of photographs, showing David Pizzanelli holding the master hologram of the kitten that was the model for the cover hologram of the first edition of *Practical Holography*. To view it in 3-D without a viewing aid, hold the book in front of you at a distance of about 45 cm (18 in), look at a distant object above the book, then bring the book up into your line of sight. After a little practice you should be able to re-focus with your eyes remaining aligned with the two photographs, and see the central image in 3-D. (b) The optical image produced by a lens is three-dimensional; a ground-glass screen placed at any plane within the depth of the image will produce a two-dimensional image with the part intersected by the screen plane appearing sharp.

you will see different parts of the image coming into focus successively. The image has the same depth as the object (provided the scale is 1:1). If you remove the screen you will see the whole image, hanging in the air. It is inverted, but has full vertical and horizontal parallax, though as the diameter of the camera lens is less than the distance between your eyes, you won't be able to see it stereoscopically. It is a fact that inside every camera is a three-dimensional image struggling to get out. This, of course, is not news: Leonardo da Vinci knew it, and so did Galileo. But is there any way of recording this image so that we can see it as it really is, in three dimensions?

In geometric optics, a ray is used to indicate the direction of propagation of a light wave, and in lens design it provides graphical shorthand. This is called 'ray tracing'.

Depth of field is the distance between the nearest and farthest planes that give an image of acceptable sharpness when the lens is focused on a specified distance.

The frequency (strictly, temporal frequency) of a wave is the number of waves passing a given point in a second. I discuss electromagnetic radiation in detail in Chapter 3.

A wavefront is the locus of all points in a light beam that are in the same phase (see margin note, p. 9).

Defining the problem

Stereoscopic photography, as we have seen, provides only a partial answer to the question. Other systems involving arrays of microlenses or vibrating screens have been tried, with varying degrees of success. But the only wholly successful technique so far has been to move away from photography altogether and to look at the problem in a different light – or rather, with a different model for the behavior of light.

The ray model is generally used in photographic optics to describe the formation of an optical image, to calculate such quantities as depth of field and angle of view, and even to design lenses.

But the ray model is limited. It doesn't correctly describe the way fine detail is rendered in the optical image, even by a theoretically ideal lens: for example, it doesn't predict that fine detail in the image progressively disappears as the aperture is closed down. Nor can the ray model tell us anything about polarization (see p. 28), nor describe the special qualities possessed by laser light. For an explanation of these phenomena we need to consider light as electromagnetic radiation, as waves propagated through space in the same manner as radio waves. Indeed, light does possess all the characteristics of radio waves; the only difference is in its much higher frequency.

We can define the problem by analyzing what happens when we 'see' an object, in terms of a wave model. When a previously undisturbed beam of light waves falls on an object, the transmitted or reflected light is modified by it so that the wavefronts, instead of being planes, become complicated (Fig. 1.2).

Now, the only information your eye receives concerning the object you are viewing is contained in the part of the wavefront intercepted by the pupil of your eye. As long as your eye and the object remain stationary the shape of the intercepted wavefront remains unchanged, and the appearance of the object also remains unchanged. But if you change your viewpoint your eye will intercept a different portion of the wavefront: the information carried by this portion is different, and you see a different view. This is the clue to the working of stereoscopic vision in terms of the wave model: your two eyes intercept different portions of the object wavefront, and thus see two different views. Stereoscopic photographs encode part of the information contained in the two portions of the wavefront. Though



Figure 1.2 A plane wave diffracted by a transparent object (a) or an opaque one (b) becomes a highly complicated wave carrying information about the object.

admittedly only a part, the information is sufficient to provide the illusion of depth. But the only way to provide *all* the information is to provide a reconstruction of the entire wavefront. If this can be done, the experience of the viewer will be precisely the same as if the object itself were present. The question is: *how* can this be done?

The problem solved

Holography provides the answer. A hologram is a complete record of the information, and when correctly illuminated it generates a replica of the object wavefront, enabling you to see an image that in every respect replicates the object, with full parallax in all directions.

There is one proviso. The wavefront from the object gives us information not only about the object but also about the illuminating source. In order to record the object information uncontaminated by information about the light source (which could otherwise swamp it) the illuminating beam must contain no information at all; that is, it must consist of plane wavefronts. Such wavefronts are produced only by a monochromatic point light source at infinity.

A filament lamp is out of the question: it is an extended source with a whole spectrum of wavelengths. Laser light, on the other hand, conforms closely to the requirements. Light from a filament lamp and light from a laser can be compared respectively to the longer-wave radiations from an electrical storm and those from a radio beacon. In both cases the former emit radiation (light or radio waves) that is random, traveling in all directions and containing all frequencies, whereas the latter emit disciplined beams that contain only a narrow band of frequencies and can be made highly directional (Fig. 1.3). They also possess an important property called *coherence*, which I discuss in Chapter 3.

Throughout this book, when I use the term 'image', without qualification, I mean the *three-dimensional* representation of the subject matter produced by a hologram or other optical device.

A plane wavefront is the wavefront of a collimated (i.e. parallel) light beam. Monochromatic light is light of a single frequency. This ideal is approached by some lasers, but can't be totally achieved. The degree of monochromaticity is specified by the frequency bandwidth.



Figure 1.3 Ordinary white light (a) contains all wavelengths emitted more or less at random, like the random radiation emitted by an electrical storm (b). The disciplined beam emitted by a laser (c) contains only a very narrow band of wavelengths, which remain in phase for a considerable number of wavelengths, like the beam of radio waves emitted by a broadcasting station (d).

When two or more sets of waves travel through the same space they interact, and if they have the same wavelength the interference pattern, as it is called, is regular and predictable. You may have seen demonstrations of interference patterns using water waves in a ripple tank.

Interference

To understand the way a hologram encodes the object wavefront we have to introduce the concept of *interference*.

If you use a car radio when traveling, you will almost certainly have experienced interference patterns with radio waves. Sometimes when you are passing through a town the sound from your speakers begins to fade up and down in pulses. What is happening is that you are receiving a signal directly from the transmitter, but you are also receiving the signal after it has been reflected from a tall building. At one point the two signals are in phase, i.e., the crests and troughs of voltage from the two sources coincide and you get a strong signal. At another point a few metres farther along the troughs coincide with the crests (the signals are in antiphase), and the signal is cancelled out. Result: silence. This keeps repeating along your route until one of the signals becomes too weak to have an effect. Figure 1.4 illustrates this.



Figure 1.4 Multi-path interference in radio waves.

An experiment with interference fringes

The phenomena I have been discussing are called respectively *constructive* and *destructive interference*.

The first demonstration of interference of light waves was by Thomas Young early in the nineteenth century, using a pair of narrow slits, now known as *Young's slits*, illuminated by sodium light, which contains only a narrow band of wavelengths. Because the slits had to be very narrow and the light source itself needed to be masked down by a further slit, the interference pattern was very weak, and Auguste Fresnel suggested using a device (now known as a *Fresnel biprism*), consisting of a pair of very shallow wedge prisms made back to back from a single piece of glass. The device causes the two halves of a beam of light to overlap. If you use a laser pointer, with a concave lens to expand the beam a little, you can see strong interference bars (usually called *fringes*).

You might like to try this experiment for yourself: it will give you considerable insight into the way a hologram codes the information contained in the object wavefront. Fix the lens to the front of the laser, and place the biprism with its dividing line bisecting the disk of light vertically.

Don't confuse this with the 'interference' you get from other radio stations or from thunderstorms. That is properly called *noise*. (You have probably noticed that whenever I use a precise technical term for the first time I put it in italics. This is because many of these specialized terms also have generalized meanings in everyday speech.)

You can obtain Fresnel biprisms from educational suppliers.

If you can't get hold of a short-focus concave lens (about -5 or -10 mm), you can use a 5 mm diameter ball lens, or, at a pinch, a convex lens of up to 50 mm, or a camera lens (but in this case you may need a good deal more room).



Figure 1.5 Fresnel biprism experiment. (a) When both beams are undisturbed the interference pattern is a row of parallel straight fringes. (b) Where an object is inserted, the fringe pattern becomes distorted. This distortion contains all the information about the shape of the object wavefront.

Position a piece of white card (a postcard will do) about 1.5–2 m away, at a distance where the two D-shaped beams overlap. Now turn the card about a vertical axis until the overlapping patch is well drawn out (Fig. 1.5a).

You should now be able to see a series of vertical dark and light interference fringes. The dark bands correspond to regions where the two waveforms are interfering destructively; the bright bands correspond to regions where they are interfering constructively. The spacing of the bands will be a millimetre or so. Fig. 1.6a is a photograph of these fringes, at about twice actual size. You will notice that they are straight and parallel.

Now comes the crucial demonstration. Take a fine sewing needle, or a straight piece of wire (about 20 gauge), and embed one end in a cork at an oblique angle. Place it in one of the two halves of the beam fairly close to the biprism, and examine the fringe pattern again. You will see that they are still vertical overall, and equally spaced, but are kinked in a regular sort of way (Fig. 1.6b). This effect is a direct result of the disturbance of the wavefront by the object. The amount of disturbance of a fringe at any point is directly proportional to the disturbance, or change in phase, of the wavefront of what I shall from now on be calling the *object beam*, relative to the phase of the wavefront of the undisturbed or *reference beam*.

If you now remove the needle and replace it by a more complicated object such as a small glass animal, which you may need to position closer to the screen (Fig. 1.5b), you will see that the fringe pattern has become much more fragmented (Fig. 1.6c). Nevertheless, it is still displaying the nature of the disturbance in the object beam. What is more, you can record this information if you replace the screen with a photographic film, and, when this has received a sufficient exposure, remove and process it. You now have a record that contains *all* the information about the object wavefront. You have a *hologram*.

If you can't lay your hands on a Fresnel biprism, or, failing that, a 3° wedge prism (see Fig. 1.7a), you can carry out the same experiment by positioning a large sheet of glass in the beam at a very shallow angle, deflecting one half of the beam across the other half (Fig. 1.7b). The system is known as *Lloyd's mirror*, and this configuration is a replica on a small scale of what you experienced with your car radio (cf. Fig. 1.4). You were, in fact, driving through a huge interference pattern.

'Phase' is the relationship between the position of the crest of a wave and a given reference point. It can be specified in degrees or fractions of a cycle, but is most often given in radians (1 cycle = 2π radians). *Object beam* and *reference beam* are standard terms used to describe respectively the beam reflected from (or transmitted by) the object, and the undisturbed beam falling directly on the plate or film.

The term 'hologram' was coined by Denis Gabor, the prefix 'holo' coming from a Greek word meaning 'whole' and the syllable 'gram' from another Greek word signifying a visual representation. The word 'holograph', which he might otherwise have coined by analogy with 'photograph', had already been pre-empted by the literary fraternity to mean a document in an author's handwriting - which was a pity, as the term 'autograph' means the same thing. On the other hand, a photogram is a photographic image made without a lens, so perhaps the analogy isn't altogether lost. Incidentally, it was G L Rogers who subsequently coined the term 'holography'.



Figure 1.6 Fringes formed using the configuration of Fig. 1.5. (a) Both beams undisturbed; (b) the changes in pattern when a sewing needle is placed obliquely in one of the beams; (c) the pattern when a glass animal is placed in one of the beams.

There is also a third emergent beam, which I am leaving discussion of until later.

You have now recorded the information carried by the object wavefront, frozen into the holographic fringe pattern, but can you retrieve it? The answer is yes, and the method is surprisingly simple. You simply develop the exposed film like a photographic negative, and then place it back in its original position, illuminated by the reference beam alone. Both of the original beams will emerge.

So the *reconstruction* (or *replay*) beam re-creates the original object beam, which continues out of the hologram as the *image beam*. An observer looking along it will see what appears to be the object itself, and with full parallax: a shift in viewpoint causes the eye to intercept a different part of the image wavefront. The upper part of the hologram records the view of the upper part of the object, the right hand side of the hologram the right side of the object, and so on. It is like looking through a window at the object itself; and if you reduce the size of the



Figure 1.7 Two alternatives to a Fresnel biprism: (a) a single 3° prism; (b) Lloyd's mirror. The geometry is the same as that of multi-path distortion of a radio signal (Fig. 1.4).

window (for example, by breaking the hologram into small pieces and looking through a single piece) you don't destroy the image, but merely restrict the range of viewpoints.

Now, although the fringe pattern obtained in the biprism experiment is a genuine hologram, it's not a very interesting one, as there is very little parallax, and the direct beam is very close to the image. Increasing the angle between the reference and object beams moves the direct beam well out of the way of the image beam. You can then also use more interesting subject matter. It needn't be transparent, for one thing; you can reflect the object beam off opaque subject matter, and by placing the film close to the object you can record a hologram with a wider parallax angle.

But before we go any further, we need to look at what goes on when we replay a hologram. How does this set of irregular fringes turn one beam into more than one when it passes through them? The optical phenomenon concerned is called *diffraction*, and it plays a key role in the reconstruction of the image.

Diffraction

You will be familiar already with some of the manifestations of diffraction. The iridescent colours of butterfly wings, the flashing hues reflected from the surface of a CD or DVD recording, the tail of a peacock, the rainbow hues of metalized gift wrapping papers, all these produce their colors by diffraction. When light waves (or, for that matter, any waves) pass through a narrow grating, they spread out in well-defined directions. The simplest possible form of grating is called a *cosine grating*, and if you pass a beam of laser light through it, three beams emerge.

One is a continuation of the original beam; the other two, symmetrical on either side, emerge at an angle that depends on the wavelength of the light and the number of light/dark cycles per millimetre, usually called the *spatial frequency*. The spacing, or pitch, of the grating is the reciprocal of the spatial frequency, called the *spatial period* (Fig. 1.8).

A photographic record of the fringes produced by the biprism in the absence of any disturbing object is in fact a cosine grating, and if it is illuminated by a laser beam it behaves in precisely the manner described. (If the light is reflected from the surface of the grating the result is also the same.) Surfaces that show iridescent



Since the aperture of the hologram is reduced, the resolution is somewhat reduced too, just as with a camera lens.

A cosine grating is a one-dimensional grating with a transmittance profile that varies cosinusoidally with distance. It is also called a sinusoidal grating (cosine and sine functions have the same shape, as explained in the margin note on p. 25).

The spectrum produced by a diffraction grating is in the opposite sense to that produced by a prism, in which blue is deviated more than red.

Figure 1.8 (a) A cosine grating. The spatial frequency is 1/s patial period (*d*). (b) When a laser beam passes through a cosine grating, three beams emerge.

Box 1.2 The Fourier model for diffraction

If two cosine gratings of different spatial frequencies are superimposed, each will produce its own independent pair of spots, the spacing of the spots being directly proportional to the spatial frequency of the grating. Most diffraction gratings for teaching or research purposes are replicas of gratings that have had opaque lines ruled mechanically: these are called 'square gratings' (more correctly, rectangular), from their transmittance profile. A square grating illuminated by a laser beam produces a row of spots on a screen, spaced at regular intervals (Fig. 1.9).



Figure 1.9 (a) A square grating. (b) When a laser beam passes through a square grating, a whole series of beams emerges.

The technique of Fourier analysis, a mathematical procedure developed by Joseph Fourier at the beginning of the nineteenth century, shows (among other things) that a square grating is identical with the sum of (i.e., the superposition of) a series of cosine gratings having equal increments of spatial frequency (e.g. 10, 30, 50, 70, etc. cycles per millimetre), and corresponding amplitudes decreasing in the series 1, 1/3, 1/5, 1/7, etc. In fact, any regular grating in one, two or even three dimensions can be constructed from a Fourier series of cosine gratings of differing spatial frequency, amplitude and orientation. Moreover, the grating doesn't even have to be a regularly repeated figure, but can have literally any profile: it can still be described as a spectrum of spatial frequencies. Fourier developed a mathematical technique, now known as Fourier transformation, to perform the operation. Although he evolved the model in connection with thermodynamics, its main application in the first half of the twentieth century was in communications technology. In the 1950s it became clear that the Fourier model could also be applied to the quantitative evaluation of optical images. The Fourier-based concept of the optical transfer function led to a revolution in the understanding of the imaging performance of lenses, and eventually to new insights into lens design.

The advent of the laser in the 1960s made it possible to demonstrate that a lens actually produces in its rear focal plane an optical Fourier transform of an object positioned in its front focal plane, thus confirming the validity of Fourier optics. You will find a fuller treatment of the Fourier model for imaging in Appendix 2.

The optical transfer function (OTF) is a graphical representation, for a given lens system, of the contrast of the optical image of a cosine grating relative to that of the original, plotted against spatial frequency (the modulation transfer function), and the relative shift of the image from geometrical correctness (the phase transfer function). The OTF thus predicts the imaging performance of a lens system with great precision.



Figure 1.10 The diffraction pattern produced when a laser beam passes through a single slit (a *top hat function*).

colors do so because they have regular microscopic patterns of scales or grooves. The reason for the different colors is that the angle of diffraction depends on wavelength: blue light has a shorter wavelength than green light and is diffracted less than green light, which in turn is diffracted less than red light. Thus white light, which contains all visible wavelengths, is dispersed (spread out) into the colors of the spectrum by the pattern of scales. However, as light from a laser has only a single wavelength, diffraction of a laser beam by a cosine grating produces only three narrow beams of light (Plate 1).

In the experiment with the biprism, one of the beams was disturbed by a straight wire. What happened to the interference pattern? Well, the disturbing object was a single opaque bar; an object that mathematicians call (from its transmittance profile) a *top hat* function. This function has a readily calculable spatial frequency content (see Box 1.2), and produces a well-described diffraction pattern of its own (Fig. 1.10), which displays both the amplitude and the phase of the wavefronts in the beam. This shows up in the interference pattern of Fig. 1.6b as kinks and variations in brightness.

It can be shown mathematically that if the disturbed and undisturbed waves are combined, and the result recorded on film, the interference pattern on the film will diffract a laser beam so as to produce a continuation of the same disturbed waveform, propagated onwards from the recorded pattern; and so it proves in practice. This applies to both transmitted and reflected beams: the beam diffracted away from the hologram replicates the original object beam. For the more mathematically minded reader there is a proof of this in Appendix 1.

So far we have been considering the behavior of light when the distance between the object and the hologram is large enough for the various diffracted components of the object beam to have sorted themselves out. This type of 'far-field' diffraction is called *Fraunhöfer diffraction*, and is not difficult to analyze by Fourier methods. In general, however, when we make a hologram we have the recording material close to the subject matter, and the diffracted wavefronts are all mixed together. This is known as *Fresnel diffraction* (it was Fresnel who first described this situation). In a Fresnel hologram the diffraction information is not localized, but is distributed over the whole emulsion surface.

Amplitude and phase gratings

There is just one more item. In the mathematical analysis in Appendix 1, the assumption is that the *transmittance* of the hologram codes the object information. Now, it is an unfortunate fact that if your exposure lies within the linear region of the transmittance/exposure response curve of the emulsion, and you process it

The refractive index of a material is the speed of light in the material divided into the speed of light in empty space. For plate glass and most plastics it is around 1.5. It is higher for shorter wavelengths, and this accounts for the dispersion of white light by a prism, as deviation is approximately proportional to refractive index.

The diffraction efficiency of a hologram is the intensity ratio of image-forming light to incident light, expressed as a percentage. conventionally (i.e., develop and fix), less than 3 per cent of the replay beam will actually go to make up the image beam. However, if the grating that forms the hologram consists of variations in refractive index rather than transmittance, it is possible to make all of each fringe contribute to the diffracted beam.

By converting all the developed silver back into silver bromide (which has a higher refractive index than gelatin, the main constituent of the emulsion), we can raise the diffraction efficiency considerably. Methods of doing this are described in later chapters.

Box 1.3 The information in a hologram

The Fourier model tells us that all the information about the subject matter of a hologram is coded in its diffraction field. By looking at its far-field pattern you can obtain the following information about an object:

- The spatial frequencies of the cosine-grating components present, from the distances of the pairs of spots from the center of the pattern.
- The relative amplitude transmittances or reflectances of the components, from the brightnesses of their spots.
- Their orientation, from the orientation of the pairs of spots.



Figure 1.11 If the function (a) is squared, the function (b) results. It is entirely positive; you can't now be sure whether the original function was like (a) or (c), or, indeed, one of many other functions.

But there is no way of telling *where* the dark and light bars of the gratings are (i.e., their spatial phase), as this depends on the relative phases of the components of the diffracted wavefront. Phase information disappears when a diffraction pattern

The phase of the beam tells us how much farther the object wavefront (at a particular point) has traveled than the corresponding reference wavefront at that point. This is the depth information that is lost in a photograph. is recorded, for one simple but frustrating reason: every light detector, whether photochemical, photoelectronic or biological, records only the time-averaged *intensity* of the field. This is proportional to the square of the amplitude, and is therefore always positive. When you take the square root to get back to the amplitude you have no way of knowing whether the answer is positive or negative (Fig. 1.11). The presence of a reference beam, however, preserves this information, as it gives us something we can measure the phase of the object wavefront against. The phase of the object beam relative to that of the reference beam is encoded in the displacement of the fringes.

So a hologram is, indeed, a total record of the wavefront diffracted by the subject matter; and, as we have seen, its illumination by a replica of the reference beam reconstructs the object wavefront.

Chapter 2 How holography began

'Ahem!' said the Mouse with an important air. 'Are you all ready? This is the driest thing I know. Silence all round, if you please! "William the Conqueror, whose cause was favoured by the pope, was soon submitted to by the English, who wanted leaders, and had been of late much accustomed to usurpation and conquest. Edwin and Morcar, the earls of Mercia and Northumbria – "' 'Ugh!' said the Lory, with a shiver.

Lewis Carroll, Alice in Wonderland

There seems to have been no particular reason why holography should have been such a late developer. Although holograms today are invariably made using a laser as the light source, they can – and have been, with some restrictions – made using other light sources. The theoretical principles underlying holography could have been formulated as early as 1816, the year that Auguste Fresnel clothed Thomas Young's early theory of diffraction and interference with the respectable garment of mathematical rigor. At about the same time Thomas Wedgwood in England and Nicéphore Nièpce in France were carrying out experiments that eventually resulted in photographic images. In 1856 Scott Archer discovered how to produce a light-sensitive material coated on glass.

The monochromatic property of the golden-yellow sodium flame was well known, so that it would at that time have been just possible to make a single-beam reflection hologram of, say, one of the new-fangled postage stamps (Fig. 2.1).

But history makes it plain that inventions appear only when contemporary culture is ready for them. The principles of holography in fact came together only in the late 1940s, and for purposes quite irrelevant to those of today's holograms, namely the improvement of the quality of electron microscope images. The idea came to Denis Gabor, quite suddenly, it seems, while he was waiting for a game of tennis on Easter Day 1947. At that time he was an electrical engineer working for British Thompson-Houston in Rugby. He spent the rest of the year working with his assistant Ivor Williams on his 'new microscopic principle'. As it was not possible at the time to generate beams of electrons that would be sufficiently well behaved for his requirements, Gabor carried out his experiments using visible light from a filtered mercury arc. Because of the limited coherence of his source, his holographic images were restricted to transparencies little larger than a pinhead. His first hologram bore an image containing the names of Huyghens, Young and Fresnel. Gabor's two papers^{1,2}, for which he was subsequently to win a Nobel Prize, were published in 1948 and 1949, but it was to be fifteen years before any further useful developments appeared.

Denis Gabor made his first holograms using a light source that consisted of a mercury arc with a narrow-band green filter. Its coherence length was barely a millimetre. Figure 2.2 shows how he managed to get round this difficulty. The object was a tiny circular transparency of opaque lettering on a clear background (Fig. 2.3a). The light diffracted by the lettering formed the object beam, and the light that passed undeviated through the clear part formed the reference beam. The photographic plate was 60 cm from the object, so the interference fringes were

Archer's wet-collodion process produced an ultrafine-grain material that was slightly sensitive to yellow light. The spectrum of sodium vapor contains a pair of very bright lines at 589 and 589.6 nm, and the *coherence length*, which describes the distance over which the wavefronts remain in phase, is about 0.3 mm – just enough for a contact reflection hologram. There is a fuller explanation of coherence length in Chapter 3.



Figure 2.1 A Denisyuk (single-beam reflection) hologram made using a sodium lamp as source.

Gabor's Nobel Prize was for the discovery of the holographic principle, and his priority is indisputable; but at the time it was argued that his geometry was flawed and that Yuri Denisyuk and Emmett Leith, who had (independently) made the first successful holographic images, should have shared the prize.



Figure 2.2 Gabor's holographic system. 1, reflector; 2, small-source mercury arc; 3, green narrow-band filter; 4, pinhole; 5, collimating lens; 6, object (transparency); 7, plane reference wavefronts; 8, object wavefronts; 9, photographic plate, recording the phase differences between 7 and 8 as an interference pattern. Exactly the same system, with the transparency removed, was used for the reconstruction of the image.

TOUNG, FRESNEL	NUNG, FRESHEL RADAY, MARMELL CHYOPF MANCE INSTEIN, BOMB
FARADAY, MARWELL AIRENHOFF, PLANCK- EINSTEIN, DONR (a)	
KIRCHHOFF, PLANCK-	
EINSTEIN. DOMA (a)	
	(C)
	hanka

Figure 2.3 One of Gabor's first holograms: (a) shows the original object, a tiny transparency; (b) shows the hologram, much magnified; (c) shows the reconstructed image. Photographs courtesy of National Physical Laboratory.
Practical Holography _

Nevertheless, *in-line* or Gabor holograms still find some uses in industrial research, for example in particle counting (see Chapter 26).

Aliasing is the general name for a particular type of information corruption, a familiar example being the staircase effect produced on a sloping line images by rectangular pixels (picture elements). Another example is the incorrect retrieval of a continuous function represented by discrete samples that are too widely spaced.

This arrangement is optically identical with that used in Chapter 1 to illustrate the principle of holographic interference fringes.

Reminiscing informally about those early days, Leith said: 'At the time, we were quite unaware that a holographic image was three-dimensional. When we got a laser we made that hologram of the model engine, and when we saw that the image was threedimensional we were astonished.' broad enough to be resolved by a normal photographic emulsion. Figure 2.3b is a reproduction of the enlarged photograph of an early hologram that appeared in one of Gabor's follow-up papers².

When the same light source was used to illuminate the developed plate, a virtual image appeared in the position of the original object (Fig. 2.3c). Unfortunately, the view of the image was marred by the presence of a spurious real image in line with it.

Gabor's proposed application for holography was to make a hologram using an electron beam, and to view the result by visible light. As the wavelength of light is vastly greater than that of an electron, this would have resulted in enormous magnification of the image. However, the inability of electron microscopes to produce a coherent beam of electrons put his ideas out of court, and before long new insights into optical transfer function theory had enabled the quality of electron microscope images to be improved to such an extent that the holographic principle became irrelevant to them. Only a few physicists continued to work on the subject, notably Hussein El-Sum³ at Stanford University.

But, unknown to Gabor, important things were happening behind closed doors at the University of Michigan. There, Emmett Leith and Juris Upatnieks were working on the development of sophisticated radar imaging systems. Familiar with Gabor's papers, they had recognized that synthetic-aperture radar records had much in common with holograms, and that when recorded in the correct format, radar images of terrain could be reconstructed optically. Furthermore, they had already noted the spurious image problem, recognizing it as an aliasing artifact⁴.

Because of the security classification of their work, Leith's team was unable to pass its findings to Gabor. As Leith said⁵ in 1981: 'As holography actually shrank in one area, it grew in the other... In a manner of speaking, it went underground. Optical holography... gave rise to new data processing systems. What was pertinent to holography... was not available to the optical holographers, because radar research was a classified area.'

So Leith and Upatnieks worked on optical holography themselves, solving the problem of the spurious real image by displacing the reference beam so that the unwanted image was moved out of line. Their arrangement allowed the reference beam to bypass the transparency rather than pass through it, deflecting it by means of a wedge prism to overlap the object beam at the photographic emulsion. When this off-axis beam was used to replay the hologram, the unwanted image was displaced by an angle equal to twice the angle between the reference and object beams (Fig. 2.4).

Because of the very poor coherence of available light sources before 1962, these early holograms, like Gabor's, were of two-dimensional transparencies. It was only with the advent of the first practical laser that the holography of solid objects in three dimensions became possible.

Meanwhile, in the Soviet Union, Yuri Denisyuk was experimenting with an optical configuration that was radically different from Gabor's. In his arrangement the reference and object beams were incident on the emulsion from opposite directions. To achieve this he mounted the photographic emulsion between the light source and the subject matter, so that the portion of the reference beam not absorbed by the emulsion passed through it, and was reflected back from the object. This resulted in interference planes that were parallel to the emulsion surface rather than perpendicular to it as Gabor's and Leith's were, i.e., more like the pages of a book than a venetian blind (Fig. 2.5).



Figure 2.4 The off-axis principle. (a) When part of the incident beam is deflected by the thin prism P to form an off-axis reference beam RB, this interferes at an angle with the object beam OB from the transparency T at the photographic plate H. (b) When the developed plate is returned to its original position, the holographic image beam IB is reconstructed by the reference/replay beam RB, and the virtual image VI appears in the exact position of the original object; the zero-order beam O and the spurious real image RI are moved out of line. The beam geometry is identical with that of Fig. 1.7a. (c) One of the first off-axis transmission holograms.



Figure 2.5 Principle of the Denisyuk (single-beam reflection) hologram. (a) In making this type of hologram the reference beam RB passes through the emulsion and illuminates the object to form the object beam OB, which is incident on the emulsion on the side opposite to the reference beam. (b) The hologram is replayed by a reconstruction beam RB using the same optical path as the original reference beam, incident from the viewing side; the image beam IB is reflected from the hologram. The reconstruction beam can consist of spatially coherent white light. (c) An early reflection hologram.

Denisyuk was unaware of the work of either Gabor or Leith, and drew his inspiration from a process for producing photographs in natural colors invented by Gabriel Lippmann in the 1890s. So he called his holograms *Lippmann holograms*, a name still sometimes used for this type of hologram. By 1962 Denisyuk had succeeded in producing holograms that could be replayed using a point source of white light⁶. This was a considerable advance, as other configurations required a monochromatic replay beam.

The appearance in 1962 of a workable laser gave holography the impetus it needed. Its importance centered on the enormous increase in coherence length the



Figure 2.6 Two of the first 'fine art' holograms, both employing purely holographic phenomena. (a) *Thoughts*, by Ken Dunkley, incorporating the sand that formed his optical table, with several further holographic images in the background; (b) *Equivocal Forks*, by Harriet Casdin-Silver, a pseudoscopic real image. The grainy appearance is laser speckle (these are both laser-lit transmission holograms).

laser beam provided, measured in centimetres or even metres rather than fractions of a millimetre. It now became possible to make holograms of solid objects. In 1963, while Leith and Upatnieks were producing the first laser transmission holograms⁷, Denisyuk was beginning to produce holograms of art objects⁸. After this, holographic techniques developed rapidly. Much of the progress consisted of small improvements in optical components, holographic emulsions and processing methods, alongside a growing mastery of the techniques. Some pioneering artists began to use holograms as a fine-art medium (Fig. 2.6). There were also three

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Powell and Stetson were not the first to notice secondary fringes, but they were the first to produce a rigorous analysis of the effect.

It isn't entirely clear how or where this important concept arose. This seems to be one of the tasks for a future historian of holography. advances so significant as to add a whole new field of applications to the technology.

The first was the discovery that if an object was subjected to stress between two holographic exposures on the same plate, any distortion that had occurred in between the exposures would be contoured in the holographic image by secondary (or moiré) fringes. The first published paper concerning this phenomenon, by Robert Powell and Karl Stetson, appeared in 1965⁸. The importance of this discovery to measurement science and to stress and vibration analysis has been inestimable. Its techniques are dealt with in Chapter 23.

The second had its main impact in the field of creative holography. As long as holography was confined to producing virtual images, i.e., images lying behind the hologram, it could be argued that a hologram offered no more than a vicarious experience of the original subject matter, and behind a window at that. But in the mid-1960s it began to be appreciated that by using appropriate reconstruction geometry the virtual image could be suppressed and a real image reconstructed instead. This image could be used as the object for making a second or *transfer hologram*.

By restricting the vertical parallax, Stephen Benton, building on an idea by De Bitetto¹⁰, produced in 1968¹¹ a transmission hologram that could be replayed by white light, now usually referred to as a *rainbow hologram*. The principle of transfer images was soon extended to reflection holograms; thus both types of hologram could now be produced via an intermediate stage. Just as in photography, it was now feasible to introduce creative effects into a fine-art hologram.

The third advance was in the commercial field. In 1974 Michael Foster¹² introduced a method for duplicating holograms mechanically by an embossing process similar to that used for stamping out compact disk recordings. This had been forecast in a paper by Bartolini *et al.* in 1970^{13} in a proposal for holographically coded motion pictures. The embossing process would make it possible, at very low cost, to mass-produce rainbow holograms which, when converted to reflection holograms by an aluminum foil backing, could be used in textbooks, art publications and publicity handouts, and on credit cards, ID cards and banknotes as a security device.

The past three decades have seen many more advances in holographic technologies, such as live portraiture, images in natural colors, holographic stereograms made from series of photographs or computer graphics, animation, holographic optical elements, and holographic images produced by interference patterns designed and drawn by computers. The seminal papers (including those listed below that are starred) have been gathered in a single volume by Hans Bjelkhagen and John Caulfield¹⁴. I discuss all of these techniques in detail in later chapters.

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* These papers also appear in Reference 14.

** This Society is almost always known simply by its initials (SPIE), and will be so indicated throughout this book.

Chapter 3 Light sources for holography

'I engage with the Snark – every night after dark – In a dreamy delirious fight:
I serve it with greens in those shadowy scenes, And I use it for striking a light; ...'

Lewis Carroll, The Hunting of the Snark

Light as an electromagnetic phenomenon

Over the past two millennia there have been many theories purporting to explain the nature of light. Most have eventually been discarded because they could not provide a fully satisfactory explanation of its behavior. Modern philosophers of science assert that the concept of a *theory* of light (or, indeed, of any physical phenomenon) is logically unsound, and that it makes more sense to consider the 'theories' as models that represent the behavior of light under certain circumstances. These models can then be used within their limits to make useful predictions. It is, of course, good sense to choose the simplest useful model for a given investigation. For most of this book I have therefore chosen the comparatively simple *Huyghens wave model*. This represents light as transverse waves.

If one considers these waves to be the propagation of an electromagnetic disturbance (Maxwell's *electromagnetic model*), then the behavior of light can be described using the same equations as are used to predict the behavior of radio waves, as well as more arcane phenomena such as the propagation of light within single-mode optical fibers. The transverse wave models predict all the phenomena of holography and the optical properties of holograms, but are unwieldy when attempting to describe complicated diffraction patterns, or what happens at the principal focal plane and image plane of a lens. For this I use the powerful and elegant *Fourier model* (see Appendix 2). However, none of these models can satisfactorily describe the way in which light is generated, nor what happens when it is absorbed, say, by a photographic emulsion or a photodiode (these effects are known as *photoelectronic phenomena*). For this we need to use the *quantum model*, which represents light as being generated not continuously, but as large numbers of tiny pulses of electromagnetic energy. Albert Einstein, who first extended the quantum model to include light energy, named them *photons*.

Propagation of electromagnetic waves

The passage of an electric current through an electrical conductor always generates a magnetic field. You can check this by placing a small compass needle close to the conductor with its axis of rotation parallel to it. When you switch on the current the needle deflects, to lie on an imaginary circle drawn round the conductor. If you place a second compass needle, similarly aligned, somewhat farther away, it will also deflect, apparently simultaneously. However, the deflection isn't quite simultaneous: the second needle moves a fraction of a second after the first. This delay occurs because the magnetic field doesn't in fact appear instantaneously

A transverse wave is a wave motion in which the direction of vibration is orthogonal (i.e. at right angles) to the direction of propagation, like a water wave. A longitudinal wave oscillates along the direction of travel, like a sound wave. Huyghens's original model was of longitudinal waves, but this model didn't account for the phenomenon of polarization. Maxwell's electromagnetic model uses the field equations of an electromagnetic disturbance to predict the speed of light, and extends the wave model.

Don't think of these models as mutually incompatible. The Fourier approach is a particular way of looking at the transverse wave model that makes the discussion of the nature of image formation more straightforward. Similarly, the quantum model doesn't contradict the electromagnetic model but subsumes it, so that it can describe not only the propagation of light but also the action of a laser and other photoelectronic effects.

Maxwell predicted the exact speed of light using only electrostatic and magnetic quantities (permittivity and permeability). For brevity, the figure of 300 000 000 is usually written 3×10^8 , where the number 8 represents the number of zeros that come after the 3. This method of writing numbers is known as 'scientific notation', and it is used throughout this book.



Figure 3.1 Propagation of an electromagnetic disturbance. When the current in conductor A is switched on, compass needle B deflects immediately. Needle C, 3×10^8 m away, deflects 1 s later.

throughout space: it propagates outwards from the source at approximately 300 000 000 metres (186 000 miles) per second (Fig. 3.1).

As a magnetic field created in this way always has an electric field associated with it, we call this propagation *electromagnetic radiation*. The electric and magnetic fields are perpendicular to one another, and are propagated in phase.

Now suppose that the conductor is carrying alternating current (a.c.) drawn from the mains. This reverses direction 100 times a second, so that a full cycle occurs 50 times a second (60 in the USA). We say that the frequency (strictly, temporal frequency) of the a.c. is 50 cycles per second, or 50 hertzes (abbreviated Hz). These cycles are being propagated into space at a fixed speed, so that at any instant a single cycle is spread out over a distance (the *wavelength*) that can be calculated. As the frequency becomes higher, the wavelength becomes shorter. You can find a wavelength by dividing 3×10^8 by the frequency: for 50 Hz it works out at 6000 km. The parameters that describe a wave are given in Box 3.1.

Box 3.1 How to describe a wave

The simplest kind of wave has a curved profile that is described as 'sinusoidal', because its equation has the form $y = A \sin Bx$, where A and B are constants. All the electromagnetic waves we shall be considering are sinusoidal (or cosinusoidal – see margin). You will have seen earlier that the frequency, which is the number of complete cycles passing a given point in a second, is related to the wavelength, which is the distance between successive crests. The relationship is

 $Frequency \times wavelength = velocity$

Frequency is given the symbol f for radio waves and ν (nu) for light waves; wavelength has the symbol λ (lambda) for both radio and light waves. The speed of propagation in empty space has the symbol c, and is equal to $3 \times 10^8 \text{ m s}^{-1}$. We also need to know the amplitude (strictly, peak amplitude, if it is necessary to distinguish it from instantaneous amplitude) of the wave, which is the maximum excursion of the curve from zero.

An electromagnetic wave is always described in terms of its electric component (or *electric vector*); the magnetic component (or *magnetic vector*) is in phase with it, and the direction of its field is orthogonal to the electric field, clockwise to it when looking down the direction of propagation.

Two traveling waves are said to be 'in phase' when crests coincide with crests and troughs with troughs. Otherwise they are 'out of phase'. When crests coincide with troughs and vice versa they are said to be 'in antiphase'.

You will encounter sine waves throughout this book. Often they will be called 'cosine waves'. Don't let this confuse you. The equation of a cosine wave is $y = A \cos Bx$, where A and B are constants, and its curve is exactly the same shape as the sine wave $y = A \sin Bx$, but just moved back along the x-axis until its peak is symmetrical about the origin. (The wave shape in Fig. 3.2 is in fact a cosine wave.)

In an electromagnetic wave, the units of amplitude are volts per metre $(V m^{-1})$, though this is not usually important for our purposes.

A vector is a quantity that has both magnitude and direction. Examples of vectors are velocity and force. 'Speed' isn't quite the same as 'velocity', as it doesn't imply a direction, although people often treat the two words as synonymous.



Figure 3.2 Parameters of an electromagnetic wave. A is the (peak) amplitude of the wave; *a* is the instantaneous amplitude; *c* is the velocity of light in empty space, $3 \times 10^8 \,\mathrm{m\,s^{-1}}$; λ is the wavelength, the distance between successive crests; ν is the (temporal) frequency, the number of wavecrests passing a fixed point in 1 s. B represents the magnetic wave, out of the plane of the paper; it is clockwise to the plane of the electric wave by 90°, looking in the direction of propagation, and in phase with it.

Oscillators

By using electronic devices called *oscillators* we can produce electromagnetic waves with frequencies much higher than 50 or 60 Hz, and correspondingly shorter wavelengths. These are called *radio waves*, and those with frequencies between approximately 100 kHz (10^5 Hz) and 100 MHz (10^8 Hz) are used for sound broadcasting.

The conductor that radiates the signal is called a transmitting antenna (or, less formally, 'aerial'), and its dimensions need to match the wavelength being transmitted. The receiver also has an antenna, which picks up the coded signal (i.e., the electromagnetic radiation induces a flow of current in it). The receiver decodes this signal, amplifies it, and turns it back into sound energy via loudspeakers. The much higher information content of television pictures is more readily accommodated by ultrahigh frequency (UHF) waves, so still higher frequencies, of the order of 1 gigahertz (GHz, =10⁹ Hz), carry television broadcasts.

As the frequency rises further, the radiation becomes more directional: the paraboloidal dishes used to relay TV programs to local transmitters and for satellite transmission and reception use these frequencies and resemble optical devices. The wavelengths corresponding to 'radio' frequencies thus go from 3 km for LW radio to a few centimetres for UHF relay stations. These very short waves are called microwaves, and are so directional that they can be beamed to satellites hundreds of kilometres away. Microwaves represent the highest frequencies we can produce using conventional electronic circuitry, though terahertz (THz, 10¹² Hz) waves i.e. the range of wavelengths around 0.3 mm, are now possible. If we could manage to raise the frequency to as much as 5×10^{14} Hz (500 THz), the wavelength would be only about 600 nanometres (5 \times 10⁸ m), which is in the visible spectrum! Of course, we can't produce a conventional oscillator that can do this, but by stimulating atoms to emit at these frequencies we can indeed produce visible radiation as a continuous wave at a single wavelength. The device that achieves this is called a laser, and its name is an acronym of its method of operation: light amplification by stimulated emission of radiation. This is the light source we need for making holograms.

The sound or 'audio signal' is superimposed on the 'carrier wave' in the form of modulations in amplitude (AM) or frequency (FM).

Properties of light beams

If you want to make successful holograms you have to use light that has rather special properties. A few kinds of gas discharge tube possess these, but to so small a degree that we can use them only to display transmission holograms, or, under certain restricted circumstances, to make contact copies of existing holograms. However, the light produced by a laser does possess the required properties, in large measure. These properties are known collectively as *coherence*, and individually as *spatial, temporal* and *phase coherence*.

• *Spatial coherence* Of the three qualities this is the easiest to define. It is the degree to which a beam of light appears to have originated from a single point in space. The spatial coherence of a source is inversely proportional to its angular diameter as seen from a given reference point (in the case of a hologram, from the plane of the emulsion). Sunlight has fairly high spatial coherence, as the Sun subtends only about one-third of a degree at the Earth's surface, but we can manufacture artificial light sources with better spatial coherence than this. The usual source of this type in practice is a compact-filament lamp with the filament focused by a lens to form a small concentrated image, the size of which can be restricted further by an iris diaphragm or pinhole (Fig. 3.3).

Most lasers produce beams with very high spatial coherence and a high degree of collimation, that is, the divergence of the beam is very small: typically less than 1 milliradian or 1 part in 1000. However, some types of laser, in particular diode lasers, produce a divergent beam.

• *Temporal coherence* This is the extent to which all the photons that make up the beam have the same frequency (or wavelength). The spread of frequencies in a beam of electromagnetic radiation is called the *bandwidth*. In communications technology it is the spread of frequencies taken up by a transmission channel, say 98 ± 0.02 MHz for a typical FM sound radio transmission. With light we tend to speak of wavelength rather than frequency, and thus might describe the bandwidth of a typical helium–neon laser as, say, 632.8 ± 0.002 nm.

From these figures you can calculate the distance over which the beam keeps a substantially constant phase, and this distance is called the coherence length. For white light this distance is less than a hundred nanometres; for a filtered mercury arc it is a millimetre or so; but for a laser it may be anything from a centimetre or so to a kilometre or more, depending on the type of laser and the optics used (Fig. 3.4).



Figure 3.3 Optical arrangement for producing a spatially coherent beam of white light. The filament is at the centre of a hemispherical reflector, and a small image of the filament is formed at the pinhole by the lens L_1 . The lens L_2 controls the divergence of the beam.

Formal specifications of lasers usually do in fact give bandwidths in MHz.



Figure 3.4 Comparison of relative coherence lengths for (a) a filament lamp, (b) a gas discharge tube with filter and pinhole, (c) a laser.

It is the coherence length of the light source that determines the available depth of the subject space when you are making a hologram. A (hypothetical) light source that emits light of a single frequency is said to be *monochromatic*, and although this term is not strictly descriptive of laser light (or, indeed, of any practical light source), I shall be using it, for convenience. The more rigorous term 'quasi-monochromatic' is reserved for light sources such as sodium and filtered mercury vapor light, which may have a bandwidth of anything between 0.1 and 15 nm.

- *Phase coherence* Two otherwise mutually coherent sources will not produce a stationary interference pattern unless their outputs have a constant phase relationship. It is possible (with some difficulty) to phase-lock two or more lasers, but it is much simpler to derive all the beams you need from a single laser by means of beamsplitters.
 - *Polarization* A further property a light source should possess for the efficient formation of interference fringes is linear polarization. A source is said to possess linear (or plane) polarization when the electric vector lies in a single plane. The magnetic vector will lie in a plane orthogonal to this. In general the light beam emitted by a laser is linearly polarized, though some lasers have what is called 'random polarization'. The beam is polarized, but the direction of polarization is random, and wanders through a large angle over time.

Without these special properties we won't be able to generate the interference patterns that form a hologram. So let us now look at the way in which lasers generate such very well-behaved beams of light.

Atoms and energy

Filament lamps, gas discharge tubes and lasers all emit photons, and though the light from them differs greatly in its qualities, the photons all originate in a similar manner. They are emitted by the individual atoms that make up the light source in question. An atom emits a photon only when it rearranges its structure, in general when it changes ('flops') from a less stable state to a more stable state. There are many ways an atom can do this, but they are constrained by certain rules that are part of the quantum model for the structure of matter. To show how these rules operate, a good model for atomic structure is Niels Bohr's model in its simplest form.

This model visualizes an atom as being made up of a central nucleus of protons and neutrons surrounded by three-dimensional 'orbitals' in which electrons are to

A beamsplitter is a partial mirror that divides one beam into two, one part being reflected and the other transmitted.

I am using the term 'flops' for a sudden loss of energy, and 'flips' for a sudden gain. These terms may be inelegant, but they do suggest the rapidity of the process. be found. Each orbital represents a fixed energy state, and as no intermediate states are permitted by the model, they are called *quantum energy levels*.

Each orbital is permitted by the quantum laws to contain only a certain fixed number of electrons. The innermost orbital can contain up to two electrons, the next one eight, the third one eight again. When the atom is in its normal or *ground state*, the electrons all occupy the orbitals that represent the lowest energy possible. Thus in the neon atom, which has ten electrons, the two innermost orbitals are completely filled, and in the magnesium atom, which has thirteen electrons, the two innermost orbitals are filled and there are three electrons in the third.

In a filament lamp the electrical energy absorbed by the filament causes the atoms in it to vibrate violently. Some of this energy of vibration becomes converted into electromagnetic energy, which is radiated away as photons. These have a continuous spectrum of frequencies, the energy distribution of which is related to the thermodynamic temperature of the filament. Thus at a temperature of 3400 kelvins (K) a filament radiates mainly infrared and red photons, and looks yellowish-white to the eye (e.g. halogen spotlights). At 6000 K (daylight) the peak radiation is in the yellow-green region, and the light appears white to the eye.

So-called cold light also originates from atoms, but in a somewhat different way. Consider a glass tube filled with hydrogen gas. Hydrogen is the simplest of elements; its atoms consist of a single proton and a single electron. If we put energy into the gas, say by passing an electric discharge through it, we shall flip some of the electrons present into higher quantum energy levels. As these levels are unstable the electrons will quickly flop back to the ground state, each emitting a photon. The energy an electron loses in returning to the ground state determines the wavelength of the photon. The highest possible energy state for hydrogen is where the electron escapes completely; this is known as *ionization* (an atom that has lost an electron is called an *ion*), and an electron that flops from this state to the ground state emits a photon in the ultraviolet region. There are also levels below the ionization level that emit a photon. The electrons can return to the ground state via an intermediate level, too, in which case they emit photons of longer wavelength at a quantum jump. Together the possible transitions, which are limited in number for so simple an atom, give a number of discrete wavelengths. If the light emitted by a hydrogen-filled discharge tube is dispersed by a prism, it appears not as a continuous spectrum but as a series of lines (known as a *line spectrum*, the wavelengths of which can be predicted from the Bohr model). Sources that emit this kind of radiation are called *line sources*. Unfortunately, the lines are not infinitely narrow, as in theory they should be, and as we would like them for holography. While they are emitting the radiation the atoms themselves are moving rapidly, so that the bands of radiation are broadened by the Doppler effect. These bands become even wider if the gas density or temperature is increased.

Doppler broadening also occurs when the atoms in solids are excited so that fluorescence occurs. However, not all the lines in solids are broadened in this manner. With some elements, notably chromium and some lanthanides, a few energy levels are not spread at all. This forms the first clue to laser operation.

Stimulated emission

The second clue to laser operation comes from the work of Einstein, who did more than simply postulate the existence of the photon. In 1917 he showed that if an

Protons (carrying unit positive charge) and neutrons (carrying no charge) form the nucleus of the atom and account for nearly all its mass. Electrons have unit negative charge and very much less mass; however, they collectively take up nearly all the space in an atom.

The close correlation between thermodynamic temperature and perceived color leads to the notion of color temperature, used to describe the spectral power distribution of incandescent light sources and some other sources (such as the xenon arc) that closely match them. The color temperature of a source is the temperature (in kelvins) of a so-called black body (a perfect radiator), the spectral power distribution of which exactly matches the color of the source. The kelvin scale has the same intervals as the celsius scale, but starts at absolute zero (-273 °C), so that $0^{\circ}C = 273 \text{ K}.$

The actual energy is given by the equation $e = h\nu$, where ν is the frequency of the photon, and *h* is a constant knows as *Planck's constant*.

When a source radiating at a constant frequency is moving relative to a receiver, the received frequency is higher when the source is approaching and lower when it is receding. This is called the *Doppler effect*. The increase in bandwidth of spectral lines due to this effect is termed *Doppler broadening*.

The *lanthanides* form a series of elements of ascending atomic masses in the Periodic Table from 58 (cerium) to 71 (lutetium). They all have very similar chemical properties. They were formerly (and often still are) called *rare-earth elements*.



Figure 3.5 Stimulated emission of a photon. If a photon *a* spontaneously emitted by an excited electron A encounters an appropriately excited electron B, it stimulates it to fall (flop) back to the ground state, emitting as photon *b* of the same frequency and phase as the stimulating photon.

electron flopped from a higher to a lower energy state, emitting a photon in the process, then if that photon passed close to another electron in a similarly excited state, the second electron would also flop to its lower energy state, emitting an identical photon. What was more, that second photon would travel in the same direction as the first, and would have the same phase and the same polarization. He called this phenomenon *stimulated emission* (Fig. 3.5).

This is precisely the kind of event we are looking for. If we have a large number of atoms all in the same excited state, and we introduce a photon of the right wavelength traveling in the right direction, it will trigger a chain of emissions of photons from the excited atoms, and build up a beam of photons all of the same wavelength, phase and polarization, and traveling in the same direction: a beam of coherent light. This will be achieved provided the number of excited atoms exceeds the number of ground state atoms; this condition is called *population inversion*. Under these conditions a photon of the right wavelength entering the space will cause a chain reaction. One photon enters the chamber; millions leave it, in a collimated, coherent beam. Forty-three years after Einstein's prediction the first laser light was seen in California, and, within the space of a few weeks, in Russia.

The three-level solid-state laser

The first lasing medium to be tried out – and still going strong today – was chromium. It was chosen because it has a partially stable (or *metastable*) energy level above the ground state, for which the energy difference between it and the ground state corresponds to a photon in the visible region (694.3 nm, in the deep red). In the metastable state the electron remains in the excited state until disturbed by quantum fluctuations or some external disturbance. This time interval is of the order of a millisecond, a comparatively long time in atomic terms. If we make a diagram of the energy levels involved, we can get a picture of the energy spectrum of chromium – at least, the part of it that is relevant (Fig. 3.6).

In order to raise the energy level of an electron from the ground state to the precise level A in Fig. 3.6, we would have to supply it with the exact amount of energy required; otherwise nothing would happen. Fortunately, a little above level A is a group of energy levels B that are so close together that they form what is effectively a continuous band (an *energy band*), and to flip an electron into this band demands a much less determinate amount of energy. Now band B is not stable, and



Figure 3.6 The relevant energy levels of a chromium atom. G represents the ground state (minimum possible energy); A is a metastable energy level somewhat higher than the ground state; B is a group of energy levels sufficiently close together to form an energy band.

electrons in it quickly lose energy through vibrations that appear as heat, and fall to the metastable level A. Here they are targets for stimulated emission.

Of course, it isn't quite as simple as that. If the energy source is a flashtube (as it usually is for this type of laser), it contains an immense range of levels of energy, so very few of the chromium atoms would actually receive the right amount of energy to find themselves in energy band B. So in practice the chromium atoms are embedded in a matrix of aluminum oxide crystal. This absorbs all the energy from the flash and passes it on in the correct quantities to the chromium atoms, whose electrons are thus flipped to the right energy level. The aluminum oxide is called the *pumping medium*, while the chromium is called the *lasing medium*.

So, with the aid of the pumping medium, we have a population inversion. Now, if a stray photon-producing decay occurs, and the emitted photon happens to be traveling in the right direction, stimulated emission will begin. Or will it? If each photon were to gather up another photon every hundredth of a millimetre, we might well imagine a single photon gathering up millions of companions in a transit of a metre or so. But, again, it isn't as simple as that. For one thing, one photon isn't nearly enough to begin the chain reaction, and only a tiny fraction of the spontaneously released photons are traveling in the right direction; and for another, the solid material has to be a perfect crystal, and for practical reasons such a crystal can be only a few centimetres long. What should we do?

The answer again turns out to be straightforward: we simply put a mirror at each end of the rod. Now the photons will traverse the rod many hundreds of times, each time gathering up more photons. If we make one of the mirrors slightly leaky, the laser radiation will emerge from it in a pulse lasting approximately the duration of the flash, about 1 millisecond. This type of laser is called a *three-level laser*, as three energy levels are involved (Fig. 3.7).

Ruby pulse laser As mentioned above, the first, and still useful, pulse laser was the so-called ruby laser. It takes quite a lot of energy to power a ruby laser. The most common source is a xenon flashtube, much like the flashtube used by photographers, but straight. An elliptical cylinder mirror surrounds the rod and flashtube, which are mounted along the lines of the two foci of the cylinder (Fig. 3.8).

Now, a ruby laser of this type can be made to produce holograms without any modification, and was so used in the earliest days of holography. Unfortunately,

The chromium-doped aluminum oxide rod is actually a ruby, in the strictest sense, though by gemstone standards it would be considered decidedly anemic, as there are only a few parts per million of chromium present. The deep color of a natural ruby does in fact come from spontaneous random emissions between these same levels, and represents the same wavelength, 694.3 nm.



Figure 3.7 Action of a three-level laser. An electrical or light energy stimulus (pumping) raises the energy of an electron in the ground state (1) to energy band B (2). From there it loses energy spontaneously and falls to energy level A (3), where it remains until stimulated by a photon of precisely the right energy e. It then flops back to G (4), emitting an identical photon in phase with the first (laser action).



Figure 3.8 (a) In a ruby laser, the laser rod and the flashtube are positioned at the conjugate foci of an elliptical reflecting cylinder. (b) All rays emanating from one focus of an ellipse are reflected to pass through the other focus.



Figure 3.9 A simple ruby laser produces a series of pulses over roughly 1 ms.

the range of its applications was severely limited, largely because its light was squandered in the form of a succession of mini-pulses spread over a millisecond or so. The reason for this was that in a three-level laser, stimulated emission occurs if, and only if, more than half the atoms in the lasing medium are in the appropriate excited state. As soon as the number of excited atoms falls below the number of ground state atoms more energy is absorbed than emitted, and laser action is quenched. This happens repeatedly throughout the flash duration, resulting in a number of spikes of laser action (Fig. 3.9)

Q-switching

The output of a simple ruby laser as described above is low, typically around 0.04 joules (J).

By a process known as *Q*-switching you can confine the laser action to a very short period (around 25 ns) and increase its power dramatically. To do this you can employ either of two systems, called respectively *passive* and *active switching*. For both systems the 'leaky' mirror is separated from the ruby rod, and the switching device is installed in the intermediate space.

The passive system uses a cell of a bleachable dye such as rhodamine. This dye is opaque to light of the laser wavelength, so losses in the optical cavity are so great that no laser pulse can be formed until the population of excited atoms is high enough for the amplification to become greater than the losses (in telecommunications parlance the gain becomes greater than unity), and laser action begins. The dye bleaches virtually instantaneously and the pulse is emitted. As soon as the pulse is over the dye regains its opacity.

The active type of Q-switch employs a Pockels cell. This is basically a crystal (sometimes a liquid) that exhibits birefringence when an electric field is applied to it.

When linearly polarized light is passed through a Pockels cell, the application of a suitable voltage causes a phase difference of one-quarter of a wavelength between the two transmitted components. The result is circular polarization of the beam. To use the Pockels cell as a shutter, it is placed between a linear polarizer and the leaky mirror. When energized, the cell produces a quarter-wave phase shift in one of the transmitted components; when this passes through the cell a second time after reflection it undergoes a further quarter-wave phase shift. This amounts to a half-wave delay altogether, and this means a rotation of the polarization vector through 90° to its original direction. With this polarization the beam cannot pass through the polarizer on its return. If the Pockels cell is switched on as the flashtube first fires, and is switched off towards the end of the flash, the accumulated energy is dissipated in a so-called giant pulse.

Both passive and active switching have their advantages. The former is cheap, and improves the coherence length of the beam. The latter, though comparatively expensive, is more flexible, and permits double and triple pulses. It is universally used for industrial holography, where double pulses are often needed for interferometric work. The coherence length is extended by means of a Fabry–Pérot etalon (see pp. 37–8).

A single ruby rod can manage only about a tenth of a joule, so modern pulse laser designs pass the beam through two further ruby rods of larger dimensions. These are known as amplifiers, and are also excited to the point of laser action. They

The joule (J) is the SI unit of energy or work. $1J = 1 \text{ kg m s}^{-2}$. It is thus the same as a watt second (W s).

The 'Q' comes from an electronics term defining the narrowness of the resonance peak of a tuned circuit. It probably originated as the initial letter of 'quality'.

The optical cavity is the space between the two laser mirrors.

A birefringent substance divides a light beam into two orthogonally polarized beams. In circularly polarized light the polarization vector rotates through 360° with each cycle. This is something like the power consumption of a moderate-sized city!

boost the energy of the emerging beam by a factor of up to 100, giving a maximum output of up to 10 joules, plenty of energy for adequate exposure of a large holographic plate or film. As the pulse duration is only about 25 nanoseconds, this represents an instantaneous power of 400 megawatts.

Plainly this sort of power is not to be treated casually. A ruby laser operates at a wavelength that is close to the visual limit, so the flash looks deceptively weak; but it is emphatically not so. The precautions needed in pulse laser holography are set out in Chapter 16, and you will find recommendations for safety when using lasers at the end of this chapter.

The extremely short duration of the laser pulse makes it possible to produce holograms of subject matter moving at up to 4 m s^{-1} without loss of fringe contrast. The use of a pulse laser in a holographic studio avoids the need for expensive isolation tables, and conditions can resemble those of a conventional photographic studio. However, ruby lasers are expensive, and require a bulky energy storage capacitor bank and a supply of cooled water. They need special safety precautions not only for the operator and any human subjects, but also for the laser itself. It seems likely that their role will eventually be taken over completely by the much more tractable solid-state green pulse laser, described later in this chapter.

Four-level gas lasers

Although pulse lasers are routinely used for making industrial and commercial holograms, they need special optical equipment and a good deal of expertise in their use; and this, along with their cost and the need for regular maintenance, puts them out of reach of most amateur or self-employed holographers. What is needed is a laser that produces a continuous beam, with a power output that is sufficiently low to require neither special optics nor tedious and restricting safety precautions. The problem with a three-level laser is that it takes a great deal of energy to flip



Figure 3.10 Action of a four-level laser. The pumping stimulus X raises the energy of the electron from the ground state G (1) to the energy band B (2). It then loses energy and falls to the metastable energy level A (3). A photon of energy e stimulates the electron to give up the same amount of energy and flop to level C (4), emitting a photon of the same frequency and phase. Level C is unstable, so the electron immediately returns to the ground state, leaving level C empty.

more than half of the atoms in the lasing medium into the energy band at the same time to achieve a population inversion, and this energy reappears as heat. Fortunately, a solution is not hard to find. All we need is a medium with an atomic structure that permits the existence of a lowish energy state that is unstable, and is normally completely empty. For such an element, the raising of even a single atom to a higher level constitutes a population inversion. Provided the low level is unstable, any electron flopping down to it from a higher level will quit it immediately, leaving it empty again (Fig. 3.10).

The energy required to drive a four-level laser system is much less than that required to drive a three-level system, and such a laser can be operated continuously without overheating. The simplest four-level continuous-wave (CW) lasers are gas lasers, that is, the pumping and lasing media are both gaseous. Where the lasing medium is not ionized, such a laser is called a *neutral-gas laser*. These produce only one wavelength at a time. The energy is usually supplied by a d.c. electrical discharge through the tube itself.

Mirrors and windows in CW lasers

The mirrors in a CW laser are not both flat. One or both are made slightly concave, so that the photon transits are kept aligned within the tube.

As the mirrors need to be very efficient they are not metalized, but are coated with a number of layers of alternately high and low refractive index, the thicknesses of which are such that the reflected light waves interfere constructively and the transmitted waves destructively, so that effectively no light is transmitted. Such *dielectric* mirrors, as they are called, apart from being very efficient, are selectively reflective, and reflect only a very narrow band of wavelengths, and over only a narrow angle. Light of other wavelengths, or incident from a non-axial direction, simply passes through. In low-power lasers these mirrors are sealed to the ends of the tube. In medium-power lasers (15–75 mW) they are separate and capable of fine adjustment. In high-power lasers (>100 mW) there is usually room to insert further components into the optical cavity.

Laser light, as I explained earlier, is linearly polarized, a property that is important in the making of a successful hologram. Unfortunately, if the laser windows are perpendicular to the beam there is no way of stabilizing the direction of polarization, and the electric vector wanders over an angle of up to 120°; this is undesirable in holography. The polarization can be stabilized by the use of *Brewster-angle windows*.

The way that these function is ingenious. When light is incident on a glass surface obliquely, some of it is transmitted and some is reflected. Both beams become partially polarized, the reflected beam being *s*-polarized and the transmitted beam *p*-polarized. At a certain angle of incidence (around 56° for optical quality glass) the reflected and transmitted beams are at right angles to one another: at this angle of incidence the degree of polarization is total for the reflected beam and a maximum for the transmitted beam. The angle is called the Brewster angle, after Sir David Brewster, who first described the phenomenon. In a laser with Brewster-angle windows, as the light passes back and forth through the windows it becomes more completely polarized at each transit, so that by the time it finally emerges it is almost totally polarized (Fig. 3.11).

In order to align the beam totally after a few passes, the mirrors should theoretically be slices of the ends of a long ellipsoid. A pair in which the leaky element is flat is equivalent to an ellipsoid twice the cavity length.

Dielectric mirrors operate by Bragg diffraction. The coating operates in exactly the same way as a reflection hologram.

In *p*-polarization the plane of polarization is parallel to the plane containing the incident and reflected rays; in *s*-polarization it is orthogonal to this plane. The *p* and *s* prefixes come from the German *parallel* and *senkrecht* (perpendicular).



Figure 3.11 (a) When unpolarized light is incident on a surface at an angle such that the reflected and transmitted beams are orthogonal (the Brewster angle), the reflected beam is totally s-polarized and the transmitted beam is partially *p*-polarized. (b) A Brewster-angle window has 100% transmittance to the *p*-polarized component of the beam.

Helium–neon laser This type of laser (usually abbreviated HeNe), is still one of the most common types of gas laser, the laser most used in general industrial situations for measurement and alignment purposes, at least until the advent of reliable diode lasers. It has always been the most popular laser with amateur and semi-professional holographers, though diode and solid-state lasers are now seriously challenging its position in both fields. The tube contains helium gas as the pumping medium, at a pressure of about 1 torr, and neon gas as the lasing medium, at a pressure of about 0.1 torr. The helium thus acts as a reservoir of energy (supplied by an electric discharge) for the neon.

The HeNe lasers used for general holography operate at a wavelength of 632.8 nm (usually rounded off to 633), with a power range from 0.5 mW to 100 mW. They can also operate at several other wavelengths including infrared at full power, and at orange, yellow and green wavelengths at somewhat lower power (1-5 mW). They are available with random or fixed polarization, but the former, as mentioned earlier, are of limited use in holography.

Although in a HeNe laser the helium and neon appear to be at a low pressure, they are nevertheless at a much higher pressure than the very small amounts of free helium and neon present in the atmosphere. Neon atoms are comparatively large, but helium atoms are so small that they slowly diffuse out through the glass walls of the tube. Their loss gradually deprives the neon of its energy source. For this reason HeNe lasers are initially overfilled with helium, and their output power rises during the first few thousand hours of use. A HeNe laser rated at 15 mW could well be producing as much as 24 mW in its prime.

Of all the gas lasers HeNe lasers are the most inexpensive, and they are not difficult to find second hand at knockdown prices. They are also among the most reliable; a new tube will usually be guaranteed for a minimum life of 20 000 hours, which amounts to keeping it switched on continuously for more than two years.

Lasers suitable for holography have a beam described as TEM_{00} . This describes the mode pattern of the beam (other modes produce more complicated beam patterns

The torr is a unit of pressure approximately equal to 1 mm of mercury, or 1/760 of an atmosphere. In SI terms it is about 130 pascals $(1Pa = 1 \text{ kg m}^{-2}).$

This is because many holographic set-ups depend on the use of the Brewster angle to eliminate unwanted reflections, and because the diffraction efficiency of the hologram depends on the relative orientation of the polarization vectors of the two beams.

Most of them soldier on for well over 50 000 hours. A 15 mW laser I bought around 1980 is still working perfectly, though its output is now down by about 30 per cent. such as doughnut and double-ellipse shapes). In a HeNe laser the TEM_{00} beam has a diameter of about 1–1.5 mm, and the beam divergence is about 1 milliradian, that is, about 1 mm per metre of throw. The intensity profile of the beam is described as 'Gaussian', which means that you can only use the central portion for exposure, as the outer part falls off in intensity (Fig. 3.12).

The main disadvantage of the HeNe laser for commercial and large-format holography is its low power; also, the coherence length decreases as the power increases, so that anything over 50 mW has too short a coherence length for making holograms of subjects more than a few centimetres deep, unless you design the table geometry very carefully. However, some higher-power HeNe lasers are now available fitted with an etalon, which increases the coherence length of the beam to several metres. The trade-off is that it reduces the power output by up to 50 per cent (but see Box 3.2 below).

Ion lasers

Neutral-gas lasers have energy levels that are usually too close together to produce visible laser radiation (HeNe lasers are a notable exception). However, once a gas becomes ionized, i.e. has one or more electrons completely removed from its parent atoms, a whole new range of energy levels becomes available. A simple example is the difference in energy between the removal of one electron and the removal of two.

The helium–cadmium laser This type of laser (usually abbreviated HeCd), uses helium as the pumping medium and cadmium vapor as the lasing medium. In the

Box 3.2 The Fabry–Pérot etalon

As used in laser optical cavities, this essentially simple device consists of two extremely flat partially reflecting glass plates separated by invar rods that produce a precisely parallel gap.

Alternatively it may consist of a quartz glass rod with accurately parallel, partially reflecting coated ends. A quasi-monochromatic beam of light incident on the etalon will undergo multiple reflections within the cavity. Only light that has a wavelength that is an integral submultiple of twice the cavity width will emerge; light of other wavelengths will interfere destructively.

If you position a narrow optical cavity in a much larger cavity such as a pair of laser mirrors, you will get an exceedingly efficient frequency selector (Fig. 3.13). A long optical cavity will allow through a number of wavelengths, each with a narrow bandwidth; a narrow cavity will let through a single band of wavelengths with a broader bandwidth. Between the two, only a single narrow band emerges. Little energy needs to be lost, as most of the energy in the unwanted frequencies is diverted into the required band, and with careful design and adjustment the inclusion of an etalon in the optical cavity may result in no more than a 25 per cent drop in output (though fine adjustments can be fiddly). In order to tune the etalon to a particular wavelength it is mounted so that you can rotate it about a small angle. This varies the effective spacing between the faces. Etalons can also be fine-tuned by thermal expansion if they are installed in a thermostatically controlled oven.

The Gaussian curve is a bell-shaped curve; it is also known as a normal distribution curve, familiar to students of statistics. Its equation has the general form $y = A e^{(-Bx/2)}$, and it is named after Karl Friedrich Gauss, who discovered its statistical significance. It is particularly interesting in optics, as its shape remains unchanged under Fourier transformation.



Figure 3.12 Gaussian intensity profile of $\ensuremath{\mathsf{TEM}_{00}}$ laser mode.

Invar is a nickel steel that has an extremely low coefficient of thermal expansion. It can thus be used to finetune the gap to within fractions of a wavelength by controlling the temperature surrounding the device. Quartz is another material with a similarly low coefficient of expansion.

You can experience an acoustic equivalent when you walk through a narrow alley. You will hear the echo of your footsteps at a definite musical pitch corresponding to a wavelength of twice the distance between the walls.

Because an etalon is many wavelengths in width it can resonate at more than one wavelength, and can thus allow several frequencies to emerge simultaneously. In theory it is possible to design an etalon that would allow three or even four frequencies to resonate at once, allowing, for example, a Kr^+ laser to produce red, yellow, green and blue coherent light simultaneously. This could have important implications for color holography, at least in theory (see Chapter 17). But as far as I know nobody has yet managed it.





visible spectrum it produces a beam with a wavelength of 442 nm in the blue-violet region. HeCd lasers have a range of output powers similar to that of HeNe lasers, and are suitable for making holograms on a variety of non-silver materials that are sensitive only to short-wave radiation. As a rule, the coherence length is somewhat limited, around 4 cm, although single-isotope HeCd lasers are now available (at a price) that have a metre or more of coherence length.

The tube life of a HeCd laser is less than that of a HeNe laser, in practice not much more than 10 000 hours, because there is a progressive deposition of cadmium metal on the laser windows.

Argon-ion This type of laser (usually abbreviated to Ar^+) also employs ionic transitions. It produces coherent light at a number of wavelengths, the most important for holography being 488 nm (blue) and 514.5 nm (green). You can get much higher powers from an argon laser than from a neutral-gas laser, anything from 0.5 to more than 20 watts. The 5 W Ar^+ laser has up to now been the workhorse of professional display holography, though it now seems likely to be overtaken by solid-state lasers, which are less power-hungry. The high power consumption and low conversion efficiency of Ar^+ lasers represent their main disadvantage, apart from the high initial cost. Any output over about 1 W demands a three-phase power supply and a sophisticated water-cooling system; and as they operate at a comparatively high temperature there is Doppler broadening of the emission lines, which renders the use of an etalon mandatory.

Krypton-ion laser This laser (usually abbreviated to Kr^+) also has applications in holography. Krypton is a heavy gas with many possible states of ionization. It can produce coherent beams at a number of wavelengths throughout the visible spectrum. The most useful line is in the red region at 647 nm, with a typical power of 250–750 mW. As this is close to that of the ruby laser (694 nm), it is useful for

Most elements have atoms that may contain two or more different numbers of neutrons in their nucleus, and thus have different atomic masses although they are chemically identical. These *isotopes* have slightly different spectra, which broaden the spectral lines, reducing the coherence length. producing transfer holograms from pulse-laser master holograms. The high output of the Kr^+ laser makes it a useful alternative to HeNe in professional reflection holography. Kr^+ lasers also have a useful output at 621 nm (green) and 476 (blue); they could thus in theory be used for making color holograms with a single source (see Box 3.2). However, Kr^+ lasers are notoriously temperamental, and many professional holographers, faced with horrendous bills for tube replacements, have come to regret buying them.

Tunable lasers

Many lasers have several strong wavelengths available. Some, like the Ar^+ , produce all their wavelengths simultaneously, and a single frequency has to be sorted out by an etalon. Others, such as the HeNe laser, produce only one at a time, dependent on the tube configuration. There are also several types of laser action that produce an indeterminate wavelength, which has to be fine-tuned by some sort of narrow-acceptance filter or wavelength selection device. The most commonly used of these is called a Littrow prism (see Box 3.3).

Excimer lasers use the high energy levels achieved when noble gases such as xenon and halogens such as chlorine form interatomic bonds when ionized at elevated temperatures, producing a beam of laser radiation in the ultraviolet.

Dye lasers When such a beam is passed into cells of certain dyes such as rhodamine, a large range of visible wavelengths can be produced, any of which can be selected by a dispersing device such as a Littrow prism (see Box 3.3). These dve

Box 3.3 Wavelength selection devices

Littrow prism A Littrow prism is a dispersion device that causes very little light loss, and is suitable for singling out spectral lines where the laser gain is low. The refracting angle of the prism is such that a beam of p-polarized light entering the prism at the Brewster angle (undergoing no surface reflection) strikes the second glass-air surface at normal incidence. This second surface is coated to form a dielectric mirror, and acts as the plane mirror for a halfelliptical laser cavity. Its operation is shown in Fig. 3.14.

Figure 3.14 Wavelength-selective action of a Littrow prism. When a beam containing more than one wavelength enters the prism, shorter wavelengths (1) are refracted more, and longer wavelengths (2) less, than the selected wavelength, which alone is retroreflected. Apart from its wavelength selectivity, the Littrow prism also acts as a combination of Brewster window and laser mirror.

'Excimer' is an abbreviation of 'excited dimer'. A dimer is an association of two identical molecules linked together. This can occur with noble gases (these are the gases helium, argon, neon, krypton and xenon, which have complete outer orbitals and are very unreactive), which under certain circumstances become at high temperatures able to form compounds with reactive elements such as the halogens. (Radon, the heaviest of the noble gases, is unstable, with a halflife of only 3.8 days.)



Elliptically polarized light resembles circularly polarized light in rotating the polarization vector through 360° in each cycle, but the vector changes in magnitude as it rotates.

The optical fibers used in communications systems are what are known as *single-mode fibers*. The core carrying the light beam is only a few wavelengths in diameter, and acts in a similar manner to a microwave waveguide – that is, the beam goes straight down the middle, with no internal reflections, thus remaining phase-coherent.

When red diode lasers emitting at around 630–640 nm first appeared, I obtained some myself and tried them out. A Michelson interferometer test indicated a coherence length of about 4 cm, but I was unable to make holograms of anything deeper than about 2 mm. This turned out to be because of a high sensitivity to temperature differences. More recently, improved production methods have extended the coherence length to compare with that of HeNe lasers, and in many cases to exceed it by an order of magnitude. By rotating the prism through a small angle, any desired wavelength can be selected for retroreflection; thus the device can be used to separate out one of a number of wavelengths. A Littrow prism is one half of a *Brewster prism*. This latter has the same selective effect, but instead of reflecting the appropriate wavelength it transmits it.

Birefringence tuning element This is a disk of birefringent material positioned in the beam at the Brewster angle. Its thickness is such that when polarized light of the correct wavelength passes through it, the polarization vector is rotated by 180°. It will thus pass through the device unattenuated on its return from the cavity mirror. Light of other wavelengths will become elliptically polarized (equivalent to two orthogonally polarized beams of different intensities that are out of phase), and on subsequent passes will be attenuated sufficiently to prevent lasing. Tuning is by rotating the disk about a line normal to the face.

lasers are used primarily for the investigation of chemical reactions, but as the beam can be restricted to single frequencies, it has some promise for color holography. The dye laser is, however, a complicated piece of technology that seems unlikely to leave the laboratory for the studio, at least at present.

Semiconductor (diode) lasers

There are many materials that can be made to produce laser action, and some, such as doped optical fibers, produce radiation that could be suitable for making holograms. But the most important development in recent years has been that of the semiconductor diode laser.

This type of laser bids fair to render almost all other lasers obsolete: in the year 2001, 99.95% of all lasers manufactured were diode lasers. The attraction of these lasers is their small size, low voltage and power consumption, and cheapness. The original incentive for their production came from the communications industry. Optical fibers have very high transmittances in the wavebands around 900 and 1500 nm, and diode lasers can readily be made to operate at wavelengths in these regions.

The semiconductor lasers used in CD players typically operate at 780 nm in the near infrared, though new types of videodisks and CD-ROMs can have even more information crammed on to them if the laser has a shorter wavelength. This has proved an incentive for evolving green and even blue lasers with long working lives. The universal use of laser barcode readers in supermarkets, the advent of optical computers and the growing use of lasers in the printing industry, have also stimulated research into visible-light semiconductor lasers of all wavelengths.

For many years it has been known that the photoelectronic effect, the creation of an electric potential by light energy acting on a suitable medium, could be operated in reverse, that is, electrical stimulation of such a medium could cause it to emit light. Semiconductor technology led to the light-emitting diode (LED). It was later discovered that the light from certain types of LED could be tamed by constructing them so that the boundaries of the active region acted like a Fabry– Pérot etalon, resulting in laser action. These were developed into the infrared and red lasers that are now ubiquitous in barcode scanners and CD players. It was only a short time before holographers began to look into the suitability of these lasers for holography. Although the earliest diode lasers operated in the near infrared region, red-sensitive holographic emulsions have some sensitivity at these wavelengths, and a few experimenters managed to make somewhat dim images with them.

Since then the demand for visible red laser beams has led to the mass production of red diode lasers emitting light at around 630 nm. You can now make tolerable single-beam reflection holograms with an ordinary laser pointer costing less than five pounds. Laboratory quality diode lasers have a vastly improved coherence length, some of them as much as 5 metres. They are still sensitive to both temperature and applied voltage, variations of which can cause abrupt changes of wavelength (*mode hopping*). With properly stabilized temperature and voltage input, however, they can make excellent holograms.

The radiation from a diode laser is different in pattern from that of other types of laser. Instead of a narrow collimated beam, it gives a beam that spreads to an ellipse with a major-minor axis ratio of about 4:1, and an angle of divergence on the major axis of about 20° . This beam is linearly polarized parallel to the short axis, is very clean, and doesn't need a spatial filter (see Chapter 7) for simple Denisyuk holograms. Laboratory-quality diode lasers come with their own focusing optics, and these can be used for diverging the beam, with or without a spatial filter. You can also obtain semiconductor lasers feeding their output into a single-mode fiber-optic 'pigtail', which delivers a clean uniform circular beam with a divergence of around 5°.

Diode-pumped solid-state (DPSS) lasers

As I explained earlier, the very first lasers were ruby lasers, and these are classified as *solid-state lasers*. They are very wasteful of energy, and can't be operated continuously: this is a characteristic of three-level laser operation. Just as aluminum oxide doped with chromium is a ruby, so aluminum silicate doped with manganese, iron or other metals is a garnet. Many types of garnet can produce laser action, in particular yttrium aluminum garnet (YAG). This material is four-level, and can be driven much more efficiently than a ruby laser, by a diode laser operating in the near-IR region. It can be operated continuously, as a single-pulse system, or as a stroboscopic system producing repeated short pulses at high rates.

The output typically has a wavelength of 1064 nm in the IR, which would be unsuitable for holography. But an exciting development in the 1980s gave rise to a completely new piece of technology. It was found that under very high light intensities some substances respond to light in a nonlinear manner: like a poor-quality audio amplifier they produce second harmonic distortion. This means that if you pass a high-intensity beam of wavelength 1064 nm into such a substance, what comes out contains a substantial amount of light of wavelength 532 nm, twice the frequency. One such substance is barium titanate. By passing the beam into a crystal of barium titanate carefully matched to suppress the IR frequency, you can convert the output into green light, near the center of the visible spectrum. And with all the optical controls involved in producing this beam, the spatial and temporal coherence are superior to anything previously achieved. These lasers are called *diode-pumped solid-state lasers*, abbreviated to *DPSS*. With these lasers it is

also possible to separate out the third and fourth harmonics and obtain UV radiation at 355 nm and 266 nm.

By pumping a garnet laser with a flash it is possible to obtain a green pulse of about the same duration as a ruby laser, with an output of around 1.5 joules. This is sufficient for portraiture, and already some studio holographers are taking advantage of the improved skin rendering given by the green lighting. There are many variants of garnet suitable for lasers, giving a wide range of wavelengths; other substances can also be made to produce laser action. Indeed, it seems as if under the right conditions almost any material can be made to lase, even optical fibers, an important development area that is now beginning to bear fruit.

Pseudowhite lasers

Recently it has become possible to use the Raman scattering from certain crystals to produce several wavelengths simultaneously from one laser and produce 'pseudowhite' laser beams that could possibly be used for color holography.

Other types of pseudowhite laser producing red, green and blue beams simultaneously have been developed, usually by introducing other gases into a HeCd system, and these have obvious applications in the printing industry; but at the time of writing none of these lasers has a sufficient coherence length to be used for making color holograms. But it is only a matter of time, and already the company Geola has coupled three lasers via fiber pigtails to produce a three-color beam claimed to be suitable for natural-color holography.

Lasers and safety

'Come back!' the Caterpillar called after her. 'I've something important to say!'

Lewis Carroll, Alice in Wonderland

For the purpose of defining laser safety, there are four general classes of laser. Class I comprises very weak lasers unsuitable for holography. Class II comprises lasers of powers up to 1 mW, including those in which the beam is broad enough for no more than 1 mW to enter the unaided eye. These will not damage your eyesight unless you force yourself to stare into the beam.

As a holographer you will be working mainly with Class III lasers, though uncollimated diode lasers with a diverging beam are likely to fall under the Class II group. Class IV includes large Ar^+ and Kr^+ lasers and pulse lasers. With Class III lasers of powers up to about 25 mW an accidental exposure to the undiverged beam is unlikely to do any permanent damage to your retina, as the blink reflex is rapid enough to prevent a dangerous amount of energy from entering your eye. Above this power there is a risk of permanent damage, particularly if the beam is focused on the fovea. Class IV laser beams can damage the cornea too.

The International Electrotechnical Commission's specification IEC 825 lays down the safe exposures to various types of radiation, and these can be helpful when you

Raman scattering is somewhat akin to Rayleigh scattering, but occurs at specific wavelengths typical of the substance the laser beam is traveling through. Its main application in the past has been spectroscopic analysis; but Raman beams can be tamed into coherence and used in the same way as laser beams.

be looked at through a light-gathering device such as a telescope or a theodolite. Class III comprises lasers up to 500 mW, which is the accepted limit for safe viewing of a diffusely reflected beam. Finally, Class IV comprises all lasers of higher power, where viewing even of a diffuse reflection of the beam can cause eye damage, and the direct beam can cause skin damage.

Class II broad beam lasers must not

The fovea is the central area of the field of vision. In other regions of the retina the focus is less sharp; but even in the peripheral regions a 5 W Ar^+ beam can cause permanent damage through its heating effect.



Figure 3.15 International warning notices for laboratories containing lasers. (a) Minimum warning for any room containing an operational laser; (b) warning for a Class III or IV laser.

are installing a powerful laser for making large holograms. The Laser Institute of America is Secretariat and publisher of the series of ANSI Z136 Safe Use of Laser standards.

However, in practice the circumstances are so varied that published figures don't always reflect the true hazards. The golden rule is to regard anything over 5 mW as potentially dangerous and anything over 0.5 W as actually dangerous. Furthermore, it's not enough to be aware of this yourself; you have a duty to others, too.

Warning notices

When you set up a lab, even in your own home, the first thing to do is to fix a permanent sign on the door. There are international symbols indicating laser radiation (Fig. 3.15). If you are working in an establishment where there are visitors, you should have a notice on the door indicating that the door must be locked whenever the room is not in use. You should also have a sign that lights up when the laser power supply is switched on, saying 'Laser on: Do not enter'.

Avoiding accidents

As a rule, the risk isn't usually from the direct beam; even uninformed people are usually careful to keep out of its way. In any case, if you are determined to look down the bore of a laser you won't find it easy, as both the laser beam and the pupil of your eye are pretty small in diameter. It is the slightly diverging specular reflections from glass surfaces, metal clips, etc., that are dangerous. Many workers have at some time received an eye-watering flash from some piece of unblacked metal equipment, and have been more careful afterwards.

If two of you are working on a setup the one not actually manipulating the beam should wear protective eyewear (see below). As you set up the table, card off all unwanted specular reflections as near to their points of origin as you can, paying particular attention to any beams reflected at an upward angle.

Gas laser power supplies are themselves dangerous, as they operate at several thousand volts. If you have to operate the laser with the cover off (for example on

The Institute's website is at www.laserinstitute.org.

But don't lock yourself in when you are working. If you do, and there is a mishap, nobody will be able to get in to help you.

Specular reflection is directed reflection from a polished surface, as distinct from diffuse reflection from a matt surface. On most modern gas lasers you can do this adjustment without removing the cover.

The capacitor bank for a large ruby pulse laser is particularly dangerous (see Chapter 16).

A density of 6 corresponds to an attenuation of 10^6 , i.e. a million times.

some older large HeNe lasers, when adjusting the mirrors), be extremely careful, and have somebody with you all the time.

With the more powerful ion lasers you need to be particularly careful, as your blink reflex won't be fast enough to prevent serious retinal damage in the event of a direct hit. Set up the table using the lowest possible power, and turn up the intensity only when you are satisfied that all stray beams have been carded off. Check the water-cooling system each time you use the laser: water leaks don't go well with high-voltage power supplies.

Protective eyewear

The present generation of laser protective eyewear is lightweight and easy to wear; it blocks off only a narrow band of wavelengths, having a density of around 6 to the wavelength to which it is tuned, but being almost completely transparent to all other wavelengths.

When you are making adjustments to the end mirrors of your laser it is essential to wear such eyewear. Of course, you can't set up a table successfully while you are wearing protective glasses, because you can't see the beam; but make sure anyone not involved in this operation wears them. And always provide visitors with them, even if there is no danger; some people are nervous in the neighborhood of a laser beam, and you don't want to be blamed for a subsequent headache, even though it couldn't possibly have been caused by the laser. You can obtain protective eyewear matched to any laser wavelength; some glasses give protection from more than one wavelength.

Pulse lasers

Here you are in a different world as far as safety is concerned. To appreciate this you need only fire a pulse laser at a piece of black paper and see what happens to it. The undiverged beam can cause skin burns, and it is risky even to look at a white surface illuminated by it. It is strongly recommended that you isolate the beam inside a metal conduit up to the point where you have to manipulate it. You need to expand a 10 J beam to about 10 cm diameter before passing it through an etched-glass diffuser, or it will damage the diffuser (lower energy pulses will be in proportion). A flashing light on the door should indicate 'Laser armed'. As mentioned above, the storage capacitors themselves can pack a lethal punch, but the makers of these lasers take elaborate safety precautions, and it *should* be impossible to override the safety circuits; but remember Murphy's Law, and treat any power supply with respect.

The laser itself

It is not only users who can be put at risk where high-power CW and pulse lasers are in use. If the beam is retro-reflected down the tube it can damage the laser. With the more powerful HeNe lasers the result is merely an unstable beam; with a larger diode laser it can cause an uncontrolled rise in temperature that at best will cause uncontrollable mode hopping and at worst destroy the diode; with a large ion laser it will damage the laser mirrors and cause the tube to overheat. With a pulse laser it can blow the ends off the ruby rods, causing internal havoc; any optical component in the undiverged beam should be slightly offset to guard against this.

Finally, you need to keep a sense of proportion. Very few workers have actually suffered eye damage from a laser in a laboratory, even in the early days. The risk, indeed, is minuscule compared with those on the average building site, as anyone who has spent a morning's observation in the A&E section of an eye hospital will confirm. Nevertheless, if you intend to employ anyone in your lab, or to teach students on a regular basis, book them for an eye checkup before they first start work. You don't want to find yourself being sued for retinal lesions that may in fact have existed before they ever entered your lab. And perhaps you will be that little bit more careful about their welfare, too.

Further reading

This has necessarily been a sketchy survey. There are many types of laser, such as tunable alexandrite lasers, femtosecond titanium-sapphire laser, and free-electron lasers, which have all yet to be tried out for holography. If you want to know more about lasers in general, a good book to start with is Jeff Hecht's *Laser Guidebook* (McGraw-Hill), or editors C. Breck Hitz, James Ewing and Jeff Hecht in *Introduction to Laser Technology* (3rd Edn) (IEEE). To find out more about specific types of laser, look for them on the Internet on the website of a bookshop such as amazon.co.uk. (amazon.com in the USA) under Lasers. An excellent monthly trade magazine, *Laser Focus World*, published by PennWell, contains many informative articles on recent research and development.

The standard work on laser safety is *Safety with Lasers and Other Optical Sources*, by D. Sliney and M. Wolbarsht, Plenum Press, but only a small part of it is strictly applicable to holography setups. The Laser Institute of America (LIA) has produced a 20-minute video *Mastering Light: An Introduction to Laser Safety and Hazards*, which incorporates the revisions for the year 2000 of the ANSI Standard for Safe Use of Lasers (ANSI Z 136.1)

Chapter 4 The basic types of hologram

Of course, the first thing to do was to make a grand survey of the country she was going to travel through. 'It's something very like learning geography,' thought Alice.

Lewis Carroll, Through the Looking Glass

There are quite a number of different types of hologram, and you will find details of all of them in this chapter; the subsequent chapters will explain how to make them. There are two main categories of hologram: *transmission* and *reflection*. Transmission holograms, as you have seen, are made with the object and reference beams incident on the holographic emulsion from the same side; reflection holograms are made with the object and reference beams incident from opposite sides. For the purpose of displaying holographic images, there are also two broad categories of hologram: those giving images that can be displayed only by light from a laser or some form of quasi-monochromatic light source, and those that can be displayed using white light. The former are usually confined to scientific and technological applications, whereas the latter have their main uses in the world of display holography. However, display holograms have to be made initially from laser-lit originals, so it is appropriate to begin with this type.

Laser transmission holograms

You saw in Chapter 1 how the interaction between a reference beam and a beam disturbed by passing through a transparent object generated an interference pattern that could be recorded in the form of a hologram. There is no essential difference in its nature between the wavefront refracted by a transparent object and that reflected by an opaque one. Both are examples of diffraction by the object; both contain the entire information about the object, and this information is encoded in the hologram in the same way. There are numerous ways of providing the two beams, one of the simplest being that shown in Fig. 4.1a. In this arrangement the mean angle between the object and reference beams is roughly 45°. At this angle the spacing of the interference fringes is about 1.4 times the wavelength, or slightly less than $1 \,\mu m (10^{-6} \,m)$. To record so fine a pattern demands an ultrafine-grain recording material. There is also a need for absolutely stable conditions during the exposure: a lateral displacement of the fringes of as little as one-tenth of the fringe spacing will noticeably affect the contrast of the fringes, and this will result in low diffraction efficiency and a weak image.

Replaying the image

To produce the holographic image, all you have to do is to process the hologram as if it were a photographic negative, then place the processed plate back in the original reference beam.

You have seen that if a hologram is illuminated by a replica of either of the two original beams alone, both of the original beams will emerge: this is proved in

In practice this set-up is suitable only for transparent objects, and the subject matter needs to be close to the plate, though not so close as to cut off any of the reference beam. If you use an opaque object you will just get a rim-lit silhouette – but it *will* be three-dimensional.

I am using the terms *plate*, *film* and *emulsion* throughout this book where each seems most appropriate; but the terms are usually interchangeable: you can use plates all the time, and film mounted on glass most of the time. I am using the term 'emulsion' when it is the recording properties of the material, or the purely geometrical nature of the discussion, that matter.



Figure 4.1 Simple transmission hologram geometry. (a) The beam expander BE produces a broad beam that acts both as reference beam and as a subject-illuminating beam; when deflected onto the hologram this becomes the object beam OB. (b) Illuminating the processed hologram with a replica of the reference beam produces a virtual image VI in the position of the original subject.

Appendix 1. Thus if you position the processed hologram back in its original position in the reference beam, a replica of the object beam will emerge (Fig. 4.1b).

If you look back along the reconstructed object beam (which we may properly call the 'image beam') you will see a virtual image of the object, and as you shift your viewpoint you will be able to see different perspectives of the image. It thus appears three-dimensional; it has full parallax, and is said to be *autostereoscopic*. This type of hologram is called a *laser transmission hologram*.

The real image

An image that the light actually passes through is called a *real image*. Unlike a virtual image, you can catch a real image on a screen placed in its plane.

When you replay a hologram, the virtual image isn't the only image present. Apart from the virtual-image beam and the undiffracted beam (the *zero-order beam*) there is a third beam diffracted towards the other side of the replay beam. You may remember that I mentioned this in Chapter 2, and showed it in Fig. 2.4. This real image is on the viewer's side, and it has some peculiar properties. For a start, its perspective is reversed, so that parts of the image that should be at the rear of the image appear at the front, and vice versa. Thus the image of a ball looks like a cup, and that of a cup looks like a ball. Moreover, parts within the image that appear to be at the rear cast shadows on parts that appear to be at the front. As

Remember, a virtual image is like the image you see in a mirror: the light doesn't actually pass through the mirror, but it does look as though it has come from behind it. 'Autostereoscopic' means that you can see depth in the image without having to use artificial optical means. 'Full parallax' means that you can see the upper and lower sides of the three-dimensional images, as well as the left and right hand sides of it, simply by changing your viewpoint.

The image formed by a camera lens is a real image, as is the image formed by a slide projector or a photographic enlarger.

Practical Holography



Figure 4.2 Virtual and real images. (a) When illuminated by the reconstruction beam RB, the image beam IB is a replica of the original object beam, so that the viewer sees a virtual image VI in the position of the original subject. (b) When the hologram is flipped so that the reconstruction beam becomes its conjugate, a real image is formed. It is inverted and pseudoscopic (i.e. has reversed parallax).

you move your head to the right you see more, not of the right side, but of the left side; and if you lower your viewpoint you see more of the upper side of the subject. Your brain has to cope with this anomalous information, and may do so by perceiving the image as swinging round as the viewpoint is changed.

In most holograms you will find it difficult to see this spurious real image. This is because the emulsion has a finite thickness (at least 10 wavelengths), so rather than being just on the surface of the emulsion, the fringes that form the hologram run through its thickness like the slats of a venetian blind. This affects the diffraction efficiency, as the brightness of the image is largely determined by the *Bragg condition*. This states that when a beam of light passes through a thick grating (i.e. any grating that is several wavelengths thick), light of a given wavelength will emerge if and only if the wavefronts emerging from each spatial cycle of the grating have optical path differences that are a whole number of wavelengths, that is, are all in phase. In a holographic emulsion of finite thickness the Bragg condition is satisfied for the virtual image but not for the real image, which is consequently very dim and may be missing altogether.

However, by a little cheating you can produce a really bright real image. You simply reverse the direction of the replay beam, or flip the hologram through 180°. (This is called using the *conjugate beam*.) The Bragg condition is again satisfied for a similar image beam, but this time it is the real image you see, hovering in front of the hologram (Fig. 4.2). And, like the spurious real image discussed above, it is pseudoscopic. What is more, you can catch it on a screen. You will be able to see the significance of this when we come to discuss transfer holograms later in this chapter.

Reflection holograms

The maximum possible angle of the interference planes in a transmission hologram is a little less than 45° when the subject matter is directly in front of the hologram.

At this angle the Bragg condition exerts sufficient effect to permit viewing by partially filtered white light. The reference beam is at near-grazing incidence. If it is taken even farther around, so that it falls on the emulsion from the side opposite to the object beam, the interference planes resemble the pages of a book rather than a venetian blind, and the Bragg condition becomes so powerful that the image will replay in white light, provided it comes from a small source such as a spotlight.

Such an image is said to be *pseudoscopic*: an image with normal perspective is *orthoscopic*. If the reference beam is at an angle of incidence of more than 45° it won't be there at all, as the geometry makes it impossible for it to be more than 45° round from the reference beam.

The concept of Bragg diffraction is of overwhelming importance in all types of holographic image. Over and over again the Bragg condition comes into discussions of image formation. In practical work an appreciation of its implications, as you will see, is essential to the making of top-quality holograms.

Due to the refractive index of the emulsion (around 1.5) it is in fact less than this within the emulsion, as light entering the emulsion at an angle of incidence close to 90° is refracted at an angle of 42° , forming fringes at 21° to the perpendicular. I am ignoring this for the sake of simplicity. It has no effect on the imaging, and is relevant only as far as the resolution of the emulsion is concerned.



Figure 4.3 Denisyuk (single-beam reflection) hologram. (a) In making the hologram the reference beam RB passes through the emulsion and illuminates the subject to form the object beam OB, which falls on the emulsion from the side opposite to the reference beam. (b) The hologram is replayed by a reconstruction beam RB on the same side as the viewer; the image beam IB is reflected from the hologram.

Such a hologram is called a *white-light reflection hologram*. The simplest form of reflection hologram is the *single-beam* or *Denisyuk hologram*, in which the beam falls on one side of the emulsion, acting as the reference beam, passes through the emulsion and is reflected back by the subject matter on the other side, forming the object beam (Fig. 4.3). The fringe planes are formed by the standing waves generated when two beams of coherent light travelling in opposite directions interact (see Appendix 1). These planes are more or less parallel to the plane of the emulsion, as I explained above. Under these conditions Bragg diffraction is the controlling factor in image formation: the spurious real image is totally suppressed, and the zero-order beam very nearly so.

The diffraction efficiency can be very high, 70% or more. In addition, you can replay the hologram using white light, as explained above. As with a dielectric mirror, a reflection hologram reflects light only within a narrow band of wavelengths, so if you illuminate it with a directed beam of light from a spotlight or a slide projector, the hologram will select the appropriate band of wavelengths to reconstruct the image, the remainder of the light passing straight through (Fig. 4.4).



In this case there will be more than a dozen Bragg planes within the thickness of the emulsion, enough to select out a quite narrow band of wavelengths from the spotlight. The result is as if the hologram were being illuminated by a quasi-monochromatic source.

The color of a reflection hologram is not necessarily that of the laser beam you used to make it. The precise final color depends on the processing method, and on the type of emulsion. Processing can remove some of the material originally present in the emulsion, bringing the Bragg planes closer together so that the image replays at a shorter wavelength than the one used to make the hologram. This isn't necessarily a disadvantage. The manipulation of the hue of the image is an important factor in creative holography.

Figure 4.4 The Bragg condition for reflection holograms. (a) Two coherent wavefronts passing through an emulsion in opposite directions create a standing wave; the result is interference fringes one half-wavelength apart. (b) Light of wavelength equal to twice the fringe spacing is reflected from the fringe planes in phase, resulting in constructive interference and a strong reflection; light of other wavelengths suffers destructive interference and is not reflected.

Phase holograms

The earliest reflection holograms were very dim. When you develop and fix a hologram using conventional photographic processing techniques you get what is called an *amplitude hologram*. The fringes are alternately opaque and transparent, and modulate the amplitude of the replay beam. If you examine the developed emulsion through an electron microscope, the developed silver grains look like black mop-heads. They absorb almost all the light that falls on them and scatter the remainder. So what should be reflective layers absorb most of the light that falls on them, and hardly any light reaches the lower layers; consequently, the diffraction efficiency of such a hologram is seldom more than about 3%. However, if the silver layers can be turned into transparent layers having a higher refractive

Box 4.1

Refer to Fig. 4.5. As the 'planes' of alternate high and low refractive index have a finite thickness that we may assume to be the same as their distance apart, they will be one-quarter of a wavelength thick. Now, at the interface between two materials of different refractive index, a wave reflected from the higher-index material back into the lower-index material undergoes a phase reversal (a phase delay of π radians, or one half-wavelength), whereas a wave reflected from the lower-index material into the higher-index material does not. Each successive optical path between layers will be one half-wavelength longer than the previous one, but as alternate layers undergo a phase reversal, effectively adding a half wavelength to alternate optical paths, all the reflected waves will be in phase.



Figure 4.5 Bragg diffraction at layers of alternate high and low refractive index of thickness $\lambda/4$. Alternate layers are reflected with their phase reversed, so that all the reflected wavefronts are in phase.

Dielectric mirrors are fabricated by coating quarter-wave layers of transparent materials of alternately low and high refractive index on a surface; the refractive index variation has a step profile, as in Fig. 4.5. (However, in a reflection hologram the index variation has a sinusoidal profile, so, strictly, a more rigorous analysis might be in order. Nevertheless, the above argument does remain broadly valid.)



Figure 4.6 As a holographic emulsion absorbs much of the incident light, the beam intensity ratio for a Denisyuk hologram is often higher than ideal. If the subject-illuminating beam bypasses the hologram the ratio can be lowered. It can be controlled further by the insertion of a neutral-density filter in the reference beam.

index than the plain gelatin layers, the emulsion will effectively have two sets of interleaved fringes each of which contributes to the holographic image.

As the refractive index of silver bromide is very high, if we turn the dark fringes back into silver bromide we will have alternate layers of higher and lower refractive index. This will give us the kind of interference mirror that is so efficient in a laser. In practice this process is simple. It is called 'bleaching', or, more precisely, *rehalogenation*, and the result is a *phase hologram*. In such a hologram every part of the emulsion earns its keep.

The Denisyuk configuration provides a simple and reliable system for making holograms with wide parallax, but it gives satisfactory images only if the subject matter is light colored, shallow and mounted close to the holographic emulsion. This is partly because the transmitted light is attenuated by the sensitizing dye in the emulsion.

The ideal beam intensity ratio (see Box 4.2) for a reflection hologram is low, somewhere between 1.5:1 and 3:1. This means that the intensity of the object beam needs to be as high as possible, and with subject matter that is deep or not very bright it is difficult to achieve the optimum ratio. To obtain bright reflection holograms of deep or dark objects you need to illuminate the subject independently, and to control the beam intensity ratio (Fig. 4.6).

Image-plane holograms

A hologram that has been made with the object wholly in the plane of the emulsion (called an *image-plane hologram*) will reconstruct with light that is not spatially, or even temporally, coherent. This applies even to transmission holograms. You can make a Denisyuk hologram of a flat object using the light from a low-pressure sodium lamp – even a yellow sodium street lamp – with a coherence length of around 0.3 mm. (Fig. 2.1 was made using a small-source laboratory sodium lamp.)

Such holograms are two-dimensional, and no more interesting than a photographic copy of the same object. But if you use a laser and an object with a small amount

This is something of a simplification, though it does give an idea of what is going on in a bleached hologram. There is a fuller explanation in Box 4.1.

It is also due to the Inverse Square Law: the illumination at the plate from the object falls off as the square of its distance from the plate.

Jeff Blyth and I actually managed to make a hologram under a street lamp in Brighton some years back. The exposure was several minutes, and although the resulting image was pretty feeble it was certainly there. of relief, say a coin or a medal, in contact with the emulsion, you can make a Denisyuk hologram that will reconstruct an image and show the relief in almost any light. That is the way the early hologram medallion pendants were – and still are – made (Plate 15a shows an example). The images are small and shallow, and not entirely sharp under diffuse illumination; but they are undeniably three-dimensional, and that is what the customers have always wanted.

White-light transmission holograms

If one could find a way of placing a fairly shallow object, or its optical image, right into the plane of the emulsion, it would be possible to play back a threedimensional image from a transmission hologram using a white, or at least only partially filtered, light beam. You can't do this with a solid object, of course, but what you can do is to create a real optical image across the emulsion plane using either a lens or another hologram. This real image becomes the object for the hologram. When the image is produced by a lens, the result is called a *focused-image hologram*; when it is produced by another hologram it is known as a *transfer hologram*. Both types of hologram belong to the class of *image holograms*.

Focused-image holograms A hologram is the record of the electromagnetic field in the plane of the emulsion. When you replay a hologram you see what the holographic emulsion saw, no matter how bizarre that may have been. So there is no reason why you shouldn't use the optical image produced by a lens as the subject for a hologram. If you focus a camera on a near object at full aperture, hold the shutter open, and open the camera back, you will be able to see the optical image hovering in the region of the film plane. It is inverted, certainly, but it has full orthoscopic parallax. Of course, a photographic exposure would record as sharp only the region of the image intersecting the plane of the film, the remainder being more or less blurred. But if you use coherent illumination for the subject, and supply a reference beam, you can record all the missing information. Focused-image holograms do just that.

Figure 4.7 shows the general principle. You will be able to learn how to make a focused-image hologram in Chapter 14.



Figure 4.7 Focused-image hologram. The subject, illuminated by laser light, is imaged by the lens L in the plane of the holographic emulsion H, where it forms the object beam.

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Figure 4.8 Full-aperture transfer hologram. (a) A laser transmission hologram H_1 is made first. (b) This is flipped to form a real inverted pseudoscopic image, which forms the object for a second hologram H_2 . (c) After processing, this hologram is itself flipped, so that it is now erect and orthoscopic. As the image is in the plane of the hologram it can be viewed by white light.

Full-aperture transfer holograms The pseudoscopic real image produced by a flipped hologram is inverted, as is the image formed by a lens, but this time it is pseudoptic, or left–right reversed.

To make a hologram of the real image you flip the master hologram (usually designated 'H₁' in layout diagrams) and place a second holographic emulsion in the plane of the real image, with a suitable reference beam. This produces a second (or transfer) hologram (H₂) which, after processing, needs to be flipped again to make it orthoscopic. Provided the image is shallow you can use white light for the replay beam. Fig. 4.8 shows the principle.

Rainbow holograms In a full-aperture transfer hologram the depth of the subject matter is limited to a centimetre or so. Anything deeper than this will show colour smear when you look at the image from slightly to one side. In 1968 Stephen Benton fortuitously found a way of getting over this difficulty.

Since binocular vision operates only in a horizontal plane, the vertical parallax of a holographic image isn't very important, and if it is absent this has only a minimal effect on the realism of the image. Benton therefore eliminated parallax by making a transfer hologram with the master hologram masked down to a narrow horizontal slit. In effect, this replaced the vertical parallax by a holographically generated diffraction grating. When such a hologram is illuminated by white light, any point in the holographic image is thus seen by light of only one wavelength. In a rainbow hologram a vertical change in viewpoint results only in a change in image hue, without any change in perspective. The geometry is usually such that a progressive change in viewpoint from above to below causes the image hue to go from red through the visible spectrum to violet.

I have coined the two words 'orthoptic' and 'pseudoptic' to denote right-left correctness and reversal respectively, analogous to 'orthoscopic' and 'pseudoscopic' for front-rear correctness and reversal. 'Erect' and inverted' are traditional terms for updown correctness and reversal. Not everyone agrees about the pseudoptic reversal of a holographic real image. by the way, because if you flip the hologram about a horizontal axis it will now be orthoptic. But if you rotate it in its own plane it remains pseudoptic. (If you have studied the mathematics of group theory you will appreciate the finer points of this argument.)

He was looking for a path towards achieving holographic video. His paper announcing the birth of the rainbow hologram, as it became called, was titled 'A method of reducing the information content of holograms'. In view of this somewhat oblique title, it is not surprising that research workers in holography, including (by his own admission) Emmett Leith, took little or no notice of it at the time. D.J. De Bitetto had earlier produced a somewhat similarly titled paper discussing restricted-aperture focused-image holograms (see list of references for Chapter 2).


Figure 4.9 Rainbow hologram. Stage (a) is unchanged. (b) The master hologram H_1 is masked down to a narrow slit. On transfer this produces an H_2 in which the vertical information is replaced by a diffraction grating formed by interference between IB and R"B. When H_2 is flipped (c), the image of the slit is projected close to the eye of the viewer, and when this final hologram is illuminated with white light the image of the slit varies in position according to the wavelength. The viewer sees the image in a hue that depends on the height of the viewpoint.

The way this happens is ingenious but simple. The layout is similar to that for a full-aperture transfer hologram, but the aperture of the master hologram H_1 is restricted to a narrow slit.

Thus although the whole width of the master hologram is used, encoding all the horizontal viewpoints in the final transfer hologram, only a single viewpoint is encoded in the vertical sense. When the processed final hologram is flipped to give an orthoscopic image, the image of the slit is flipped too, and if you use laser light for reconstruction you see the image of the object only when your eyes are lined up with the image of the slit. It is like looking through a letterbox: if you move your viewpoint up or down, the image disappears.

However, if you use white light for the replay, there will be a 'letterbox' for every wavelength, and these letterboxes will not coincide. Since red light is diffracted more than green light and green light more than blue light, the red letterbox will be above the green one, and the green one will be above the blue, with the other spectral hues in between (Fig. 4.9).

When you are making the master hologram, the distance between your subject matter and the plane of the holographic emulsion determines the position in space of the real image of the slit. By varying the distance between the master hologram and the transfer emulsion the final image can be made real, virtual or partly real and partly virtual (i.e., intersecting the hologram plane). The purity of the colors and the sharpness of the image in the vertical direction depend on the narrowness of the slit.

The process is very versatile. By varying the angle of the reference beam for the transfer hologram you can control the color of the image as seen at normal

The slit also has an effect analogous to the use of a small aperture in photography for obtaining a large depth of field. A large rainbow hologram can display an image several metres deep with excellent definition throughout, provided the slit used in the transfer process is relatively narrow. viewing height. In addition you can store several images in a single hologram and replay them in different spectral hues either simultaneously at a single viewing height or successively at different viewing heights. A number of workers have brought the technique to a precise craft, and their methods and geometries are described in Chapter 18 and Appendix 3.

Other types of hologram

Several other types of hologram are extensions of those already discussed. They have a role in commercial, fine art and industrial holography, and the methods of making them are described in full in later chapters. To give you some idea of the scope of these techniques, here is a brief descriptive account of them.

- *Edge-lit holograms* In edge-lit holograms the reference beam is introduced into the glass substrate of the holographic plate (or the glass supporting the film) through the edge. It thus travels parallel to the emulsion plane, i.e., it enters the emulsion at an angle of incidence of 90°, giving maximum tilt to the fringe planes. Such holograms, while not easy to make, are in principle much more convenient to display than conventional transmission or reflection holograms, as they can have their illumination built unobtrusively into the base. They are discussed in Chapter 13.
- Achromatic holograms These are a type of white-light replaying transfer hologram that gives a colorless image. You need to make the master hologram with the emulsion plane tilted forward at a steep angle; the reference beam comes from directly below. If you have the geometry exactly right, a full-aperture transfer gives an image with all the spectral hues superposed in register. You can apply the technique to reflection holograms too, with some modification. You can find out about this technique in Chapter 18.
- *Far-field (in-line) holograms* These are single-beam transmission holograms made with the beam in line with the emulsion plane. The layout is similar to Gabor's original concept. For this reason they are also called *Gabor holograms*. The methods and their applications are set out in Chapter 26.
- *Holographic interferograms* These are used mainly in industrial research and development, in the conservation of artworks, and occasionally by artists for special effects. They record small distortions in the subject matter as a kind of contour map with intervals at one half-wavelength or less. They can also contour surfaces at any desired interval, and visualize pressure and shock waves. They are useful in non-destructive testing, fluid flow analysis and quality control. The technique has given rise to a number of other interferometric techniques such as electronic speckle-pattern interferometry (familiarly known as 'TV holography'), holographic schlieren interferometry, and shearography. Interferometric techniques are dealt with in Chapter 23.
- *Fourier-transform holograms* This type of hologram uses a configuration that records the optical Fourier transform of the object wavefront (see Appendix 2). Although not very interesting esthetically, Fourier-transform holograms are important in information processing and pattern recognition. They are (at present) the only type of hologram that readily lends itself to being drawn directly by a computer. Techniques for making them are described in Chapter 14. Their applications are discussed in Chapter 24.

'Multiplex' is an unfortunate coining that has been attributed more than one meaning in both technology and commerce. In this book I am using it as a verb to describe the incorporation of a number of images within a single record. • *Holographic stereograms* A holographic stereogram begins as a set of flat images that represent perspective views of a subject taken at intervals along a straight line or around a circle; alternatively, they may be the cinematic or animated record of some event in time. All the images are multiplexed into a single hologram in such a way that for any viewing position the two eyes of the viewer see only the two images appropriate to that viewpoint.

By moving past the hologram the entire range of viewpoints appears in turn, so that the overall image has full horizontal parallax, or animation, or a share of both. The system is very versatile, as it can be used for naturalistic views, action sequences, computer-generated animations and successions of unrelated images. You can find out all about this technique in Chapter 19.

Color holography

You can make holograms in natural color by using three laser beams, respectively red, green and blue, to make the hologram. The process is not easy. It is less difficult in practice to make full-color stereograms, starting with color separations from transparencies. Three-color holograms and full-color stereograms are tackled in detail in Chapters 17 and 18 respectively.

Pseudocolor holograms are an important branch of creative and fine art holography. They differ from true-color holograms in that the color is under the control of their creator, just as it is in dye-bleach photography. In a rainbow hologram you obtain the various colors by adjusting the reference beam angle in the transfer process. In a reflection hologram you use differential pre-swelling to manipulate the spacing of the Bragg planes. You can find out about the techniques in Chapter 17 and Appendix 3.

Embossed holograms

These are the only type of hologram fabricated mechanically. An embossed hologram begins life as a rainbow hologram, but the final transfer is made onto a material that records the holographic fringes as a relief pattern. A metal replica is made from the relief master, and this is used to stamp out duplicates in hot plastics material in much the same way as CDs and DVDs. A rainbow hologram is a transmission hologram, so it is backed with reflective aluminum foil to act as a mirror. This is the most familiar type of hologram, used as a security measure on credit cards and banknotes as well as for decorating greetings cards and for wrapping paper, book covers and bumper stickers. Chapter 21 discusses the techniques involved.

Chapter 5 Materials, exposure and processing

('That's exactly the method,' the Bellman bold In a hasty parenthesis cried,'That's exactly the way I have always been told That the capture of Snarks should be tried!')

Lewis Carroll, The Hunting of the Snark

Several categories of light-sensitive material can be used for making holograms; the most widely used at present, and for the foreseeable future, is the *silver halide emulsion*. When this is exposed to light a *latent image* is formed. This is rendered visible as a photographic image by the process of *development*.

The final photographic image consists of black metallic silver, and in an ordinary black-and-white photograph this is the negative. *Fixation* removes any undeveloped silver halide, and a final wash removes the remaining chemicals, leaving a stable photographic image. If you are unfamiliar with the photographic process, you can find a fuller description in Box 5.1.

In photography the negative needs to have a wide range of densities, and is not designed to resolve spatial frequencies greater than about 100 cycles per millimetre (i.e. detail finer than 0.01 mm). The silver grains that make up the final photographic image can thus record the required detail provided their mean diameter is no more than 10 μ m. Such grains would arise from silver halide crystals typically 1–2 μ m across, as there is some clumping of grains during development. In fact, crystals go up to tens of micrometres in diameter, the largest crystals being the most sensitive to light.

Now, a hologram is a photographic record of interference fringes that normally have a separation of less than 1.5 wavelengths (i.e., less than 1 μ m). So for a transmission hologram the mean crystal diameter needs to be no more than about 60 nm; for a reflection hologram, with a fringe plane spacing of only 0.5 wavelengths, it needs to be less than 25 nm. The sensitivity of a silver halide crystal falls rapidly as its size decreases: the ISO index (arithmetic) for holographic materials is only 0.01–0.03, as against 200 for an average amateur photographic film. Emulsions available for holography at the time of writing are shown in Table 5.1. This table also shows the availability of non-silver materials, which are described briefly at the end of this chapter, and in detail in Chapter 20.

The silver halide process

Silver chloride, bromide and iodide, known collectively as silver halides, are used in various proportions in photographic emulsions.

In the manufacture of a photographic emulsion the silver halide is formed as a dispersion of microscopic crystals in gelatin. It is, strictly, not an emulsion at all, but a solid suspension (but the term is too deeply entrenched in photographic lore to be changed.) When coated in liquid form on a substrate of glass or film and allowed to dry, it becomes a thin, tough, flexible layer that is very sensitive to light

'Latent' means 'concealed'. The specks that make up the latent image may consist of as few as four or five atoms.

In accordance with common usage I am using the term 'black and white' to refer to a continuous-tone image in shades of gray, and not a binary (allor-nothing) image.

I am distinguishing between crystals, which represent the undeveloped silver halide, and are regular in shape, and the much larger developed grains, which are reduced silver and irregular in shape. Unfortunately, many photographic textbooks don't make this distinction and call both of these forms 'grains', which can be confusing.

Holographic material is thus some 10 000 times slower than amateur photographic film, having a speed similar to that of photographic print paper. Non-silver holographic materials are almost all much slower. Speeds of holographic materials are usually rated in terms of the energy per unit area required to produce a useful set of fringes. The conventional units are millijoules (mJ) or microjoules (µJ) per square centimetre (cm^{2}) . The joule is a unit of energy equal to 1 watt second. The SI unit for energy per unit area is the joule per square metre (Jm^{-2}) , which is 100 times as large as the microjoule per square centimetre (μ J cm⁻²).

Chlorine, bromine and iodine belong to a group of five elements called *halogens*. The other two halogens are fluorine, which is not relevant here as silver fluoride is soluble in water, and astatine, which is an unstable element with a half-life of only eight hours.

Practical Holography _

Material		Thickness (µm)	Spectral sensitivity (nm)	Sensitivity (μ J cm ⁻²) at				Resolving power	Grain size
				442	514	663	694	per mm)	(1111)
SILVER HA	LIDE EMULSION	IS							
Slavich									
Red	PFG-01	7	<700	_	-	80	-	>3000	35–40
Red	PFG-03M	7	<700	-	-	1500	-	>5000	10–20
Green	VRP-M	7	<550	-	80	-	-	>3000	35–40
Pan	PFG-03C	9	400–700	1000	2000	1000	-	>5000	10–20
Colourholo	graphic								
Red	BB-700	7	<700	_	-	50	150	>2500	50–60
Red	BB-640	7	<650	-	-	150	-	>4000	20–25
Green	BB-520	7	<540	150	150	_	-	>4000	20–25
Blue	BB-450	7	<470	150	-	_	-	>4000	20–25
Kodak									
Red	131PX	9	<650	2	_	0.5	-	>1250	70
Red	131CX	9	<650	2	_	0.5	-	>1250	70
Red	120PX	6	<750	60	_	40	40	>2500	58
Red	120CX	6	<750	60	_	40	40	>2500	50
FilmoTec -	ORWO								
Red	HF 65	10	<650	_	_	1500	_	5000	30
Green	HF 53	10	<550	_	700	_	_	5000	30
Ultimate									
Ultimate	15	7	<700	_	150	150	150	>5000	15
Ultimate	08	7	< 650	120	200	200	_	>7000	8
oraniaco	00			120	200	200		>1000	0
DICHROMA Slavich	ATED GELATIN E	MULSIONS							
Blue	PFG-04	16	<515	1×10^{5}	2.5×10^{5}	_	_	10,000	_
FilmoTec -	ORWO		(010	2 / 20	2.0 / 20			10000	
Blue	GF 40	6/20	*	*	_	_	_	_	_
* delivered:	non-sensitized	0/20							
THERMOPL	ASTIC MATERIA	LS							
Tavex Ame	rica								
Pan	TCC-2	-	<800	1	1	1	1	1500	-
PHOTORES	SIST MATERIALS								
Towne Tec	hnologies								
UV-Blue Shipley 1800		1.5–2.4	<450	$1.5 imes 10^{3}$	-	-	-	1000	-
Hoya Corporation Custom orders only									
BACTERIO	RHODOPSIN MA	TERIALS							
MIB GmbH					2				
BR-WT B-ty	pe	30-100	<650	_	80×10^{3}	-	-	5000	
RK-D96N N	vI-type	30-100	<650	30×10^3	-	-	-	5000	-

Table 5.1. Summary of commercially-available holographic recording materials. List compiled by Hans Bjelkhagen and reproduced with permission.

at wavelengths less than about 500 nm. Its sensitivity can be extended to cover the whole of the visible spectrum and the near infrared by the addition of appropriate sensitizing dyes.

When light is allowed to fall on the emulsion its energy is absorbed by the silver halide crystals, causing local disruptions of some of the atomic bonds holding the crystalline structure together and freeing some silver atoms within the body of the crystal. Above a certain critical energy enough silver atoms are released to form a stable speck of metallic silver, or *latent image*. The developer, which is used to turn

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the latent image into a visible photographic image in metallic silver (a process called *reduction*), is a solution containing an agent capable of reducing silver halide crystals that bear a latent image to metallic silver. Crystals lacking a latent image are unaffected by the developer.

There are plenty of reducing agents that will reduce silver halides to metallic silver, but only those classed as developing agents have their reducing ability confined to those crystals that carry a latent image. Most developing agents have molecular structures that are related, as explained in Box 5.1.

Developing solutions have two main constituents, the developing agent and an alkali. The latter is necessary because most developers operate efficiently only at high pH values.

The proportion of crystals that are reduced increases steadily throughout development, and the reaction proceeds sufficiently slowly for it to be halted when the photographic image is judged dark enough. *Fixation* makes the image permanent by removing the unchanged silver halide, using a solution of a salt such as ammonium thiosulfate, with which it readily forms soluble complexes. These are removed by washing in water, after which the emulsion is dried.

Technical requirements for holographic materials

In photography the most important technological pointer to the quality of the photographic image is the H&D curve, named after Ferdinand Hurter and Vero Driffield, who first devised it. It shows the relationship between blackness and light energy for a negative or print processed under given conditions. As visual sensation is approximately proportional to the logarithm of the stimulus, the scales of the H&D curve are logarithmic: photographic density is the log of the reciprocal of the transmittance (or reflectance, in a print), and this is plotted against the log of the exposure (illuminance multiplied by duration). The part of the curve that shows a linear relationship between density and log exposure represents the range of subject luminances (i.e. contrast) that the emulsion can record without distortion of tone values. H&D curves are of considerable value in photographic technology, as many of the qualities of photographic images can be derived from them, but they are of little use in holography.

But one aspect of the H&D curve *is* relevant: the slope of the curve, or gamma, as it is called. In a hologram, this slope should be as steep as possible. Gamma is related to the time and temperature of development, to the developer formula, and to the inherent qualities of the emulsion. These concepts are discussed in greater depth in Appendix 1.

Constituents of a developer

The progress of holography as a display medium was hampered for a number of years by preconceived ideas about processing techniques derived from practices in photography.

It will accordingly be helpful to look at what goes into a commercial developing solution, and to show the way in which an effective holographic developer needs to differ from a photographic developer.

A reducing agent is a donor of electrons. It turns a silver ion (which is an atom with one electron missing) into a silver atom, which has a full complement of electrons and is stable. In dietetics parlance, reducing agents are known as 'antioxidants'.

The pH value denotes the alkalinity of a solution. A pH value of 7 is a neutral solution. Above this value the solution is alkaline; below, it is acid. Most developers operate at pH values of from 8.5 (low-energy) to 10.5 (fierce). Holographic developers mostly need a pH of between 9 and 10.

This is because it is the linear part of the curve obtained when you plot transmittance against exposure that concerns holography, at least in theory. It bears little relationship to the linear portion of the H&D curve, as there are antilogs and a square root involved in converting from one to the other.

Even now, on studying scientific papers where the experimental work has involved holography, you may often notice that the researchers have processed their holograms using commercial photographic developers (such as Kodak D-19) that are unsuitable for holography, resulting in feeble images.

Box 5.1 Developing agents for holography

Of the hundreds of possible developing agents only a handful are useful in holographic processing. A molecule of a developing agent possesses at least one comparatively loosely bound hydrogen atom, which becomes dissociated from the parent molecule as a positive ion when dissolved in water. Nearly all developing agents are derived from the benzene molecule, C_6H_6 . This molecule has a structure that is a flat hexagon or 'ring', and in organic chemistry it is so ubiquitous that in molecular diagrams it is usually represented by a simple hexagon (Fig. 5.1).



Figure 5.1 The benzene molecule. (a) Benzene; (b) shorthand version; (c) hydroxybenzene (phenol); (d) shorthand version. Note that the six electrons that are represented by the double bonds in the representation are not localized, but are distributed uniformly round the ring.

Any of the peripheral hydrogen atoms can be replaced by a radical (i.e. a group of atoms containing an unpaired electron) such as hydroxy (–OH), amino (–NH₂) or methyl (–CH₃). The substitution of a single –OH radical in the benzene ring is so common that this molecule is given its own name, *phenol*. The relative positions of substituted radicals are important: for identification they are numbered clockwise beginning from the top. Positions 2, 3 and 4 are also named: respectively they are *ortho* (*o*), *meta* (*m*) and *para* (*p*) (Fig. 5.2).



Figure 5.3 Holographic developing agents: (a) based on substituted benzene; (b) not based on benzene.

Names of organic chemicals reflect their molecular structure (and are often consequently very long). Modern terminology follows a strict protocol, but in many cases alternative nomenclature survives from an earlier era, and some manufacturers have given their products their own, simpler names. The names and molecular structures of the developing agents commonly used in holographic developers are shown in Fig. 5.3.

The benzene molecule is a ring of six carbon atoms with six hydrogen atoms attached. Any or all of these can be replaced by a radical such as amino (NH_2) , hydroxyl (OH), methyl (CH₃), etc. as explained in Box 5.2.

Ascorbic acid (vitamin C) and phenidone are two rare examples of developing agents that are *not* benzene derivatives. They both appear in holographic developers.

A complex is a compound of a metal with another compound – in this case, silver sodium sulfite.

'Air bell' is the term used for a bubble adhering to the emulsion in the developing solution, as distinct from a bubble in air.

This is because the relative surface area of a crystal increases as its diameter decreases, by the power of 3/2. So if the crystal size of a holographic emulsion is onehundredth of that of a photographic emulsion containing the same amount of silver halide per square centimetre, the crystal surface area of the holographic emulsion will be one thousand times as great. The important constituents of a developer are the developing agent and an alkali. A developing agent, as I pointed out earlier, is a reducing agent that will remove halogen atoms from silver halides if (and only if) there is a latent image present. There are hundreds of developing agents, almost all of them based on a 'substituted' benzene molecule.

These substituted benzene molecules tend to have long chemical names, and are instead often referred to by manufacturers' nomenclatures. (An example is 'metol' for methyl-*p*-aminophenol sulfate.) It is often advantageous to use two developing agents together rather than one, as some combinations, e.g. metol or phenidone with hydroquinone or ascorbic acid, or metol with pyrogallol, form a *superadditive combination* (i.e. their activity together is greater than the aggregate activity of the two separately).

Nearly all developing agents operate efficiently only in alkaline solution (i.e. at a pH greater than 7). The most popular alkali in photographic developers is sodium carbonate, a substance that maintains a large reservoir of OH^- (hydroxyl) ions when in aqueous solution. These neutralize the H^+ (hydrogen) ions produced in the reduction process, which would otherwise lower the pH of the solution to the point where the developing agent(s) would no longer be operative. This action is called *buffering*.

These two components are all that are necessary to develop the photographic image. However, in photographic practice it is common for the developing solution to remain exposed to the air for fairly long periods. Most developing agents in alkaline solution react with atmospheric oxygen and thereby lose their reducing power, so it is advisable to add a further reducing agent that is not a developing agent to protect the solution from oxidizing in the air. This is the *preservative*, usually sodium sulfite, and it is usually added in fairly large quantities. With a typical photographic emulsion, sulfite actually helps the development process by forming complexes with the silver compounds.

Finally, to prevent the developer from attacking unexposed crystals ('chemical fog') it is usual to add a *restrainer*. This may be potassium bromide or an organic antifoggant such as benzotriazole, or both. In proprietary developers there may also be other additives, the most common being a wetting agent to guard against the formation of air bells.

Altogether, a photographic developer is quite a complicated brew, and many hundreds of papers have been written attempting to explain exactly what goes on, chemically speaking, when an emulsion is being developed. One thing is agreed: many of the known developing agents form soluble complexes with silver halides, and sulfite ions play a large part in the complexing. Unfortunately, in holographic emulsions the silver halide crystals are so tiny that a small amount of sulfite, and even the chlorides present in tap water, can have a considerable solvent effect on the developing grains.

An important effect recognized in photography is *physical development*. This term was originally coined to describe a method of development in a bath containing silver nitrate, which deposited silver metal on the latent image specks instead of reducing the silver halides. This process is long obsolete, and the term has more recently come to mean the action of a developer that dissolves the smallest, unexposed silver halide crystals and re-deposits the material on the developing grains, which act as seeding centers. Of these substances the most important is – you've guessed it – sodium sulfite; others include sodium thiosulfate and potassium

thiocyanate. Developers with a strong physical action have their uses in holography, particularly in the making of master transmission holograms, where their tendency to produce smooth rather than whiskered grains improves the signal-to-noise ratio. A range of developers pioneered in Russia for their ownmanufactured emulsions exploits physical development to the extent that the developed fringe planes consist almost entirely of colloidal silver (see p. 64). An example appears in Appendix 5.

But as some of the silver halide is lost from the emulsion during processing, the angle of the fringe planes changes, altering the Bragg condition, so that if the same wavelength is used for reconstruction as for making the hologram the image will be displaced, and distorted by a kind of horizontal–vertical astigmatism. For this reason developers of this type are usually confined to techniques in which a shorter wavelength is used in reconstruction (as in a ruby pulse laser studio, with transfers being made by a HeNe or Kr^+ laser).

In holography it is advisable to use developers that contain nothing but noncomplexing developing agents and alkali, making up the solutions with distilled or de-ionized water, and excluding air from made-up solutions. Some developing agents, in particular pyrogallol, are used in 'tanning' developers, where the developer oxidation products promote cross-linking of the molecules of gelatin, so that it resists shrinking even when material has been lost from the emulsion during processing.

Thus although some of the ingredients may be the same, holographic developers don't in general have the same formulas as photographic developers; and even when they do, the action may be quite different. Holographic developers containing no sulfite (particularly pyrogallol developers) should not be exposed to the atmosphere for any length of time, or the solution will rapidly become oxidized and useless. A good way to minimize atmospheric oxidation is to float a second, empty tray on the developer solution when you are not actually using it, and to keep the developing agent and alkali solutions separate until you are ready to begin processing.

In Appendix 5 there is a selection of developer formulas suitable for the materials available at present.

Bleaches

When a holographic emulsion is developed, all the crystals of silver halide that bear a latent image are converted into grains of opaque silver that replicate (in negative form) the pattern formed by the interference of the object and reference beams. If we can turn this silver into a transparent substance of high refractive index, no light will be absorbed. If we get everything right, all the light – or nearly all of it – will go to form the holographic image, as I explained in Chapter 4. Silver bromide has a high refractive index, nearly as high as diamond, so where it is present the emulsion will have a higher refractive index than where it is absent. (Silver bromide is the main silver halide in a holographic emulsion.) There are several techniques available for obtaining fringes of this type:

• *Rehalogenation after fixation* With this technique, you develop and fix the emulsion as you would a photographic film, then convert the negative fringes back into silver bromide *in situ* with a solution containing potassium bromide and an oxidizing agent such as iron (III) nitrate (ferric nitrate) or potassium dichromate.

Signal-to-noise ratio in this context means the ratio of image-forming light intensity to scattered light intensity.

In holography, the term *astigmatism* refers to an image in which the vertical scale differs from the horizontal scale, making the image appear squashed or stretched in the horizontal plane. The focus may also be different for horizontal and vertical rays, as in astigmatism of the eye. This is a different meaning of the term from that used in photographic optics, and must not be confused with it.

I am using 'negative' here in the photographic sense: these are the black silver fringes. An oxidizing agent is an electron acceptor. In this case it removes an electron from the silver atom, turning it back into a silver ion, which combines with the sulfate radical to form a sulfate of silver that is soluble in water.

Colloidal silver consists of silver particles that are so small they are no more than clusters of molecules a few nanometres in diameter. When colloidal silver appears in photographic negatives (usually through contamination of the developer), the result is called 'dichroic fog'. It appears red by transmitted light and green by This method has fallen out of favor as it removes material from the emulsion and preserves only the larger grains, giving inferior resolution (the small crystals will have been removed at the fixation stage).

• Solvent bleach Also known as 'reversal bleach' by analogy with reversal (direct positive) processing in photography (see Appendix 5). The technique involves removal of the negative fringes (the developed silver) in lieu of fixation, leaving the positive fringes (the undeveloped silver bromide) unchanged. An oxidizing agent such as potassium dichromate is used along with sulfuric acid or with an acid sulfate such as sodium hydrogen sulfate.

The process converts the silver into a soluble complex, which is then washed away with water, leaving the positive fringes. An advantage over the previous method is that the smallest, unexposed crystals are left undeveloped, so the resolution is higher. Like the previous one, this method removes material from the emulsion; in reflection holograms this results in a color shift to shorter wavelengths. You can reduce the extent of this by using a tanning developer such as pyrogallol. The staining effect of pyrogallol's oxidation products also helps to reduce noise.

- *Rehalogenating bleach* This process, also-called diffusion-transfer bleach, uses an oxidizing agent accompanied by a large amount of bromide in acid solution, the emulsion having been very fully developed but not fixed. The effect of the bleach is to remove the silver from the negative fringes and deposit it as silver bromide on the silver halide crystals forming the positive fringes, which act as nuclei for precipitation. Bromine water, which is a saturated solution of liquid bromine in de-ionized water, has the same effect, but it is not often used as the vapor irritates the lungs (and how!). Provided you have used a non-tanning, non-complexing developer, this method results in a hologram in which the fringe planes are undisturbed, giving an image of high diffraction efficiency that is free from astigmatic distortion and reconstructs at the correct position when played back by the original laser. It is therefore the recommended technique for use when making transmission master holograms. A reflection hologram processed using this technique replays at the original laser wavelength, so you can use it as a master for making contact copies. Some types of holographic emulsion contain preservative chemicals, and for such reflection masters you may find it necessary to guard against a small amount of shrinkage by washing and drying the emulsion before exposure in order to remove these chemicals.
- *Total bleach* This process amounts to the complete removal of the positive fringes after rehalogenation. Subsequent dehydration by alcohol or a similar substance leaves fringes in the form of plain gelatin that has had its physical structure, and thus its refractive index, altered. This process has been evolved fairly recently by combining features of the silver halide and dichromated gelatin processes, and is now known as the *silver halide sensitized gelatin* (*SHSG*) process. I discuss this process in detail in Chapter 20, and you will find the processing formulas in Appendix 5. The method is very promising, as it combines the high sensitivity of silver halide emulsions with the high diffraction efficiency and high signal-to-noise ratio of non-silver processes (see below).
- *Colloidal silver processes* Not strictly a bleach process. If you develop a finegrain emulsion in a solution that contains powerful complexing agents such as sodium thiosulfate or potassium thiocyanate, much of the liberated silver is deposited in the emulsion in colloidal form. In a carefully balanced holographic developer the result is a set of fringes made up almost entirely of colloidal silver. It works well with Slavich Russian emulsions.

Other processes

Processes not employing silver chemistry are attractive because the results are virtually grainless, and one at least (DCG) is very cheap. Their universal disadvantage is their low sensitivity to light.

- *Dichromated gelatin (DCG)* Dichromated gelatin holograms use a layer of gelatin sensitized to light by a dichromate, which catalyses cross-linking in the presence of light. DCG holograms are usually of the Denisyuk type, and are very bright. I explain how to make them in Chapter 20.
- *Photoresists* These are substances that become either insoluble (negative photoresists) or soluble (positive photoresists) in certain common solvents after exposure to light. They are used chiefly as the precursors of stampers for producing embossed holograms.
- *Photopolymers* The fringes are formed directly by a change in refractive index when they are exposed, and they don't need any chemical processing as they develop in real time and are fixed by exposure to ultraviolet light. They can be made sensitive to the whole visible spectrum. Unlike photoresists they can be used for reflection holograms, and have high diffraction efficiency and a high signal-to-noise ratio.
- *Photothermoplastic materials* These are made for special applications in industrial holography. They are based on an electrostatic principle.
- Organic dyes Certain substances that are normally highly colored are bleached by light. The two most significant examples to date are methylene blue and bacteriorhodopsin (BR). Both have been subjects of much recent research. BR emulsions are now available commercially.

All these processes are described in more detail in Chapter 20, with references.

If you feel that this chapter has gone through everything at a bit of a gallop, you can stop and admire the scenery in detail, at least as far as silver halide technology is concerned, with Hans Bjelkhagen's book *Silver Halide Recording Materials for Holography and Their Processing* (Springer-Verlag, 1997). Hans Bjelkhagen is also editor of the SPIE Milestones Series Volume MS 130, *Selected Papers on Holographic Recording Materials*.

Part 2 PRACTICAL DISPLAY HOLOGRAPHY

Chapter 6 Making your first hologram

The White Rabbit put on his spectacles. 'Where shall I begin, please your Majesty?' he asked. 'Begin at the beginning,' the King said, very gravely, 'and go on till you come to the end: then stop.'

Lewis Carroll, Alice in Wonderland.

Basic requirements

If you've already made a hologram at some time, or if you have an experienced friend to help, you may find you can skip much of the earlier part of this chapter. But if you are working on your own, with no previous experience, you should follow the instructions carefully, at least until you have acquired some confidence. There's nothing more frustrating than to find, after an hour's work, that you have no image at all. And that's what happens in holography when something goes wrong. You don't get just a blurred or feeble image, as in photography. You don't get an image at all: you have a 'nullogram'. And finding out what went wrong when you have a failed hologram can be a good deal less easy than finding out the cause of a dud photographic negative or print. But don't be deterred.

Box 6.1 Items required for your first hologram

Laser pointer, modified if necessary*, or HeNe laser with beam expander* Support for laser* Piece of black card, to act as a shutter Support for holographic plate and subject^{*} 6×6 cm or 4×5 inch red-sensitive holographic plates (preferable to film at this stage) Blu-tack Black felt marker pen Sink with running water Firm bench at least 1 m long Three 4×5 inch processing trays (at least one should be white) Scales for weighing processing chemicals Thermometer Minutes and seconds timer Green safelight Cellulose sponges Window-cleaning rubber squeegee (new!) Processing solutions and bottles Distilled or deionized water You also need a subject for your holographic image, of course. Choose something small, hard and white, or at least pale colored. Don't pick anything green or blue or floppy. A small statuette, a piece of jewelry, a key ring, a

If you already do your own photographic processing, you probably have many of these items already.

The starred items are discussed below.

seashell or a few coins will do.

Remember, any vibration of more than one-thousandth of a millimetre can turn your hologram into a nullogram.

Amateur photographers generally use a timer for the minutes only: they count seconds by muttering 'a thousand and one ... a thousand and two...' (or some similar phrase).

Blu-tack is a synthetic putty that you can use in small (or large) lumps for positioning blackout paper, fixing reminders to the wall, or (in holography) for stabilizing optical components. It goes under a number of different names outside the UK. Most stationers stock it. No optics lab, amateur or professional, is able to operate efficiently without a supply of this invaluable substance.

Many holographers don't even bother with a safelight, but just work with a bit of stray light to help them to stumble around the processing area. A decent safelight has other uses, though, as I shall explain later, and is well worth installing. The first thing you need is a space to work in. Many amateur photographers have begun their hobby in a darkened bathroom or kitchen, or even a cupboard under the stairs, and you can begin your holography in a similar place. Your basic needs are a table, a sink, and a reasonable blackout (unless you propose to work after dark). If you have access to a photographic darkroom, that is best of all. A few light leaks don't matter, as holographic emulsions are not very sensitive to stray white light, at least no more so than photographic print paper, but it is important that there shouldn't be any heavy vibrations in the vicinity, as they could cause the glass to vibrate, and ruin the holographic image.

You can get 4×5 inch processing trays from any photographic dealer. Later you may need larger ones, but small ones are better to begin with, as they don't use so much of the processing solutions. The same dealer will be able to provide you with a photographic thermometer with a temperature range from 10-50 °C (50-130 °F). The scales can be any kind that will measure down to 1 gram. You can get excellent ones from stores with departments that deal in slimming diets. There are many types of timer on the market, too: the ones in hardware stores are usually cheaper than those specially made for photography, and they are just as good.

Other things amateur photographers always have around the darkroom are paper towels (preferable to cloth ones, as it doesn't matter if they get chemicals on them), push pins, black paper and card, and Blu-tack. Cellulose sponges are useful for mopping up spills. The squeegee has a more specialized use, which I shall be going into later.

The next thing you need is a packet of small holographic plates. These are just glass plates coated with photographic emulsion, but this emulsion has a much finer grain than any ordinary photographic material, and you can't buy the plates from a photographic supplier, at least not at the time of writing. Later on, you will probably prefer to work with film, which is cheaper, but plates have the considerable advantage of being rigid, and once they are in place they stay put. I have listed the principal suppliers in the UK and USA at the end of the chapter, but you may need to resort to the Internet for further information, if you live outside these countries. Holographic emulsions can be red-sensitive, green-sensitive or panchromatic (i.e. sensitive to the whole visible spectrum, like photographic films). As you will be starting with a red laser, you need the red-sensitive type. You also need a support for your plate, and for the subject matter. There are several ways of going about this. You will find two simple set-ups later in this chapter.

To make the exposures you need a laser. At one time buying a laser was quite an undertaking, and costly too; but now you can buy laser pointers off the shelf from educational suppliers, and even in souvenir shops, for a few pounds. I am leaving discussion of the laser until later in this chapter.

A green safelight is a great help. You can obtain safelight material from a supplier of holographic materials and equipment, or at a pinch you can use a dark green stage gel. Wrap it round a fluorescent tube (two thicknesses), or install it in a darkroom safelight housing with a long-life lamp. Don't use an ordinary filament lamp, as these emit infrared radiation, which can fog red-sensitive material, and most safelight material does allow some infrared through. Alternatively, you can use a safelight designed for panchromatic film, with a somewhat brighter long-life tube replacing the usual 15 W bulb, or a Wratten OB printing safelight with two thicknesses of cyan stage gel added. With this latter material it *is* safe to use a filament lamp. But it is best to get the proper material, as you will then have more light to work with.

Finally, you need processing solutions. If you have ever developed your own films or made your own black-and-white prints you should be familiar with the processes, which are only slightly different from those used in photography. One important difference, though, is in making up the solutions: you must never use mains water, as it contains chlorides that will attack your image. Use distilled or deionized water. The water from de-icing the fridge, or from a dehumidifier, is perfectly satisfactory. As I mentioned in the previous chapter, the developing solution is alkaline, and the bleach bath can sometimes cause allergic reactions, so it is a good idea to use protective gloves. The solutions stain, too, so don't wear your best clothes when processing your holograms.

The processing chemicals I recommend are no more hazardous than commonly used photographic chemicals. Indeed, most of them are the same. Nevertheless you wouldn't be advised to drink any of the solutions (even though one of them contains vitamin C). You can get them from any supplier of chemicals for laboratories. There are full instructions for mixing them in Appendix 5, but there is also some basic information later in this chapter.

The laser

In a previous edition of this book, I advised against trying to use a diode laser to make holograms. At that time (1994), diode lasers were not stable optically: they were subject to 'mode-hopping'. This meant that they suffered frequent abrupt and unpredictable changes in wavelength, so that although their nominal coherence length was several centimetres, this was in practice reduced to little more than a couple of millimetres if the exposure needed to exceed a second or so.

Box 6.2 Polarization of the laser beam

As I explained earlier, laser light is linearly polarized, that is, the light waves vibrate in one plane only as they are propagated. If you want to minimize internal reflections in the plate or film holder glass (an important factor in maximizing image brightness), you need to have the plane of polarization such that both the incident and reflected rays lie in it. This condition is called '*p*-polarization'. The simplest way of checking the plane of polarization is to use a pair of Polaroid sunglasses (Fig. 6.1).

Place one of the lenses in the beam, and rotate the sunglasses until the transmitted beam is extinguished. If this occurs when the glasses are horizontal (the way they are when you are wearing them) then the axis of polarization is horizontal too.

In the set-up described in this chapter you need the polarization axis to be vertical (glasses as in Fig. 6.1). To achieve this you may have to rotate the laser. A diode laser will normally have the axis of polarization parallel to the short axis of the elliptical beam, but if it is fitted with corrective optics to give a circular beam you may not be able to find this axis without the help of the sunglasses. If you are using a HeNe laser, and it has what is called 'random polarization' (see Box 6.3), follow the direction of polarization with your glasses as it changes over a period of a minute or so, and finally set the axis midway between the two extremes.

From time to time dealers in holographic materials offer prepacked processing chemicals. The processes for transmission and reflection holograms are different (see Appendix 5), so if you do opt for made-up chemicals, make sure you are buying the right ones.



Figure 6.1 If a pair of Polaroid sunglasses blocks off the beam in this orientation, the polarization is vertical.

Polaroid sunglasses have their axis of polarization vertical, to reduce glare from water and other shiny horizontal surfaces. If you have a polarizing filter for a single-lens reflex camera you can use this instead of the sunglasses, but you must have the front of the filter facing the laser, as there is a second element behind the polarizer that changes the nature of the polarization. *Collimating* is a word you will come across frequently in this book. It means 'making a beam parallel'. *Aspect ratio* is the ratio of horizontal to vertical dimensions.

If you have a HeNe laser, you will find things a little different. HeNe lasers produce a beam that is already collimated. They are more stable than diode lasers in terms of temperature, and in that respect they are easier to use; but they have a number of idiosyncrasies of their own, and I discuss these near the end of this chapter. Advances in production techniques have resulted in much more stable operation, and the more expensive diode lasers have a coherence length of many metres. They are still sensitive to temperature changes, but if you use a stable d.c. voltage source such as a 4.5 V cycle battery (make sure you get the polarity right), and give the laser several minutes to reach a steady temperature, you should be able to obtain a usable image depth of at least 10 cm with even the simplest laser pointer.

Some cheap key-ring laser pointers have fixed collimating optics built in: you may have to saw these off with a junior hacksaw to get a spreading beam.

An uncollimated beam from a diode laser diverges to a longish ellipse, about 4:1 in aspect ratio, which is just what you want. When you allow this to fall on the plate at angle of $45-56^{\circ}$, it spreads out to about 2:1, an economical shape for covering a 'landscape' format. The beam is remarkably clean, too, with none of the puddles and rings you find in a HeNe laser beam. You will, however, notice the 'laser speckle'. This is an inherent property of coherent light.

A beam expander

Diode lasers with a power of 3 mW or more usually have optics that you can adjust to produce either a focused (collimated) beam or a divergent beam. If your laser doesn't have adjustable optics, and you are reluctant to take a hacksaw to it, or if it is a HeNe laser with a beam that is already collimated, you can spread the beam with a *ball lens*. These have a focal length that is somewhat greater then their radius, and to get a spread of around 20° you need a 5 mm diameter ball. You can also use a minus-6 mm focal length concave lens, which has the same effect. If

Box 6.3 Laser safety

With the increasing popularity of laser shows, you will no doubt have become familiar with the sight of powerful laser beams filling the air above you, and you may be disappointed to find that your laser resembles a pen torch rather than a searchlight. Don't be fooled. The energy in a laser beam is very concentrated: even in a 3 mW laser it is intrinsically as bright as the Sun. So don't under any circumstances stare into the undiverged beam. Just to catch a stray reflection of a powerful laser beam off a metal surface can be an eye-watering experience that leaves an after-image lasting several minutes.

Watch out for visitors too. Make sure nobody can walk into the room and look into the beam accidentally or deliberately, and make sure nobody can operate the laser when you are out of the room. If you are working with a HeNe laser, remember that its power supply operates at several thousand volts, so never operate the laser with the cover off either the tube or the power supply. There are both national and international regulations for the operation of lasers; they tend to be more stringent in the United States than in Europe. The main recommendations governing the safe use of lasers as they apply to holographers are at the end of Chapter 3.

you don't have access to either of these, but you can lay your hands on some glass rod about 5 mm in diameter, you can mount two pieces of this in contact and at right angles to each other, using Blu-tack, so that the laser beam passes through the point of contact (Fig. 6.2). With a little manipulation you can get a uniformly diverging beam of roughly circular cross section. In later chapters I suggest that you use a $\times 40$ microscope objective. If you do decide to use one at this point, buy the cheapest you can find.

Support for the laser

The best kind of support is a heavy based burette or retort stand of the kind used in chemistry labs, with its own clamp. This will support a fairly powerful diode laser. With a HeNe laser it is better to employ two stands and clamps, or you can hot-glue the laser base to bricks, as illustrated in Fig. 6.4. But if you are going to work with a simple diode laser pointer, all you need is a coffee mug filled with sand, and a spring clothes peg to hold the laser, as in Fig. 6.3. For a shutter, simply lean a piece of black card against the edge of the mug to block off the beam. Don't lean it against the laser itself, as you may jerk it when you take the card away to make the exposure.



Figure 6.2 A beam expander improvised from glass rod and Blu-tack.



Figure 6.3 Setup for a simple Denisyuk hologram.



Figure 6.4 (a) Alternative layout for a Denisyuk hologram. (b) Detail of plateholder.

Support for the plate

It is worthwhile taking the trouble to arrange the angle to the optimum for subsequent viewing. The best angle is 45° to 56° to the vertical, from "above" the plate.

So in the scheme of Fig. 6.3 your plate and your subject are lying horizontally on a glass plate and the laser beam is directed upwards.

In the arrangement of Fig. 6.4 the laser beam is horizontal, and the plate needs to be tilted forward. For this setup it is worth taking the trouble to make a small



Figure 6.5 Glass sandwich film carrier.

Throughout this book I shall be using double quotes as an indication that the direction is relative to the subject, irrespective of the subject's actual orientation. In the setups of Figs. 6.3 and 6.4 the beam is directed at the subject matter from "above". support frame, and a simple one is shown in Fig. 6.4b. Take a piece of plywood or hardboard about 150×200 mm, and fix two wooden battens about 10 mm square to it with panel pins, so that they project about 150 mm above it. They need to be the right width to support your plate by the edges. Fix a horizontal batten at the top of the plywood, wide enough to support your subject, which will then rest against the plate when the whole frame is tilted 45° forward. Figure 6.4a shows the way it will look when you set it in a firm base such as a washing-up bowl filled with cat litter or gravel.

If you have elected to use film rather than plates, you will need to make a glass sandwich film carrier. You need two pieces of glass at least 10 mm larger all round than the film. Hinge them together using masking tape. Along the edge opposite the hinge, inside the glass sandwich, lay a second and third strip of tape along adjacent sides to act as guides when you are loading the film in the dark. Fig. 6.5 shows the construction.

Setting up for the exposure

Finding the emulsion side You need to be able to identify the emulsion side of your plate or film. For films there is a universal identification code: a notch near one corner of each sheet of film. If you hold the film in 'portrait' format (that is, with the longer sides vertical), then the notch will be in the right hand corner of the upper edge when the emulsion is facing you (Fig. 6.6a).

If you cut up the film for test strips or to make smaller holograms, always keep the cut pieces in the box with the emulsion down. You will then know which is the emulsion side, and will be able to avoid touching it with your fingers (something you must never do with an unexposed emulsion). It is also a good idea to make an identification notch in the top right hand corner of all the smaller pieces with scissors (Fig. 6.6b).

It is a little more difficult to identify the emulsion side of a plate. If you place the extreme corner of the plate between your lips, the emulsion side will feel slightly sticky. Alternatively, tap the corner of the plate between your upper and lower teeth or with a pencil point. The glass side will make a bright click, the emulsion side a duller sound. Plates are normally packed with all the emulsions facing the same way, so once you have identified the emulsion side of the first plate you can mark the container for future reference. Keep any cut pieces facing the same way up.



Figure 6.6 (a) Finding the emulsion side. With the film in 'portrait' orientation, the notch in the top right-hand corner indicates that the emulsion is toward you. (b) When you cut films into halves or quarters, notch the appropriate corner with scissors.

As I explained earlier, 'parallax' means the angle over which you can view the image. Horizontal parallax is usually more important, in terms of threedimensional realism, than vertical parallax.

I generally use a large saucer-shaped seashell I found in a holiday souvenir shop.

Remember, at the Brewster angle, light polarized at right angles to the glass surface (*p*-polarized) isn't reflected at all. Loading the plate or film It is advisable to have the emulsion side of your plate or film next to the subject, i.e. on the 'downstream' side of the laser beam. You will then view the finished hologram from the base side, and the emulsion will be protected from damage. If you are using an oblong rather than a square plate, choose a 'landscape' (horizontal) format for preference: this will give you more horizontal parallax in the final image.

The subject matter If you want a bright image, the lighter the subject matter the better. Put simply, a dark subject implies the absence of light, and if there's no light there can be no image – and, in contrast to photography, you won't be able to improve matters by increasing the exposure. You need a reference beam: object beam intensity ratio that is around 2:1, for a really bright image. It is a good idea to back your subject with metal or acrylic sheet sprayed with matt white paint.

Setup with a small diode laser

A diode laser is small and light, and you can easily position it pointing upwards at an angle. You need two extra props: a bar stool or a kitchen chair with horizontal stays, and a sheet of glass that you can balance across the stays. Ordinary float glass is fine, provided it is absolutely clean. This time you simply lay the plate on the glass, and the subject on top of the plate: gravity does all the work of stabilization for you. (If you are using film, you will have to use a second sheet of glass to hold the film flat.). You will notice from Fig. 6.3 that I have set the angle of incidence steeper than 45° . This is to avoid internal reflections in the glass. If the angle of incidence is close to the Brewster angle (56° for glass) the reflections will be suppressed, because your laser beam in polarized parallel to the short axis of its beam and is thus *p*-polarized with respect to the glass surfaces.

An alternative setup for a larger laser

This setup takes up about a metre of bench space. It is the most satisfactory arrangement if you are using a HeNe laser, which is larger and heavier than a diode laser of equal power, and needs to be mounted horizontally.

Set up the plateholder first. Push it into the bowl with the top tilted towards the laser at an angle of about 45° , or up to 56° if you can manage this without the shadow of the plate edge falling across the subject. Put a white card the size of your plate on to the supporting frame. Now set up the laser at the opposite end of the bench, and switch it on. Turn the laser on its axis until the plane of polarization is vertical, and adjust its distance until the uniform part of the beam covers the card. Try out your subject, making sure it doesn't sit too high or too low, and can't roll: it mustn't shift by even the tiniest fraction during the exposure. Now block off the laser light with a black card, and switch off the lights except for the safelight and the laser itself. Take a holographic plate out of its wrapping and check the emulsion side. Before you position it, run a black felt marker pen along what will be the upper edge of the plate: this will prevent your getting a series of obtrusive internal reflections across the image. (If you are using film, do this with the glass edges of the film holder.) Now position your subject matter again, as near as possible to where you set it up initially. Allow about three minutes for everything to settle. While you are waiting you can organize the processing area.

Processing solutions

In the early days of holography we simply developed and fixed the emulsions in exactly the same way as photographic negatives, using a powerful developer such as Kodak D-19.

This works reasonably well with transmission holograms, but it gives miserable results with reflection holograms, which show feeble dark green images instead of bright red ones, and replay at the wrong angle. Some workers, however, continue to use develop–fix methods for transmission master holograms because the results are more free from noise, and if the image is to be used specifically as a transfer master, the fact that the image is weak is not so important.

Modern processing methods aim at avoiding any removal of material from the emulsion during processing, and employ a developer containing no silver halide solvent, followed by a rehalogenating bleach bath; this produces transparent silver halide fringes that are insensitive to light. If you make up your own solutions, use the ascorbate-metol developer and the EDTA rehalogenating bleach formula given in Appendix 5. Dissolve the chemicals in the order given, use deionized or distilled water, and make sure each component is fully dissolved before you add the next one. You can put out this particular developer and bleach in the processing trays in advance, as they don't deteriorate to any extent in air. If you are using proprietary solutions, follow the manufacturer's instructions. You will need a (white) tray for the developer, one for the bleach and a third one you need to fill with ordinary mains water, for washing.

Exposing

To expose the hologram you simply remove the card shutter with as little disturbance as possible, make the required exposure, and put back the card. The exposure time will usually be 4-6 s for a hologram 6 cm square, or about 30 s for a 4×5 in plate, if you are using a little laser pointer. It isn't possible to be more accurate than this, because the beam from one of these may have a power of anything from 0.5 to 3 mW, and if it is highly elliptical you may have to let it spread well beyond the edges of the plate. All lasers have by law to be marked with a maximum output power, and for safety this marked maximum is usually at least twice their actual output, so don't be misled. A genuine 5 mW laser will probably be marked 'Maximum output 10 mW', or something similar, and will need 10 s or more for a 4×5 in plate. But you can only tell if the exposure was correct when you see the plate darken in the developer. As I mentioned earlier in a marginal note, most people count seconds by mumbling some repetitive phrase. But if you are using a darkroom timer you can listen for the seconds if it is a quartz-regulated timer, or for the ticks if it is mechanical (most mechanical timers do 200 ticks to the minute). It doesn't matter whether the 'seconds' are accurate, as long as they are consistent.

Processing

If you have had some experience of processing prints in a photographic darkroom, this should all be fairly familiar to you. But if you are working with plates you

The Open University for many years included in its *Images and Information* course a project involving making a small transmission hologram, and in order to simplify processing employed a single-solution develop-fix formula. It worked, too, against all the odds.

You can keep the working solutions in glass or polythene bottles more or less indefinitely, provided there isn't too much of an air gap at the top. Photographic stores sell special bottles that concertina down to exclude air. Photographic density, numerically, is the logarithm (base 10) of the reciprocal of the transmittance (sometimes called the *opacitance*) expressed as a decimal. It is used widely in photography because it gives a better impression of the visual blackness than the corresponding figure for transmittance does.

(A density of 3.0 represents a transmittance of 0.001 or 0.1%.)

Now you see why I insisted on at least one white tray.

need to watch out for the sharp edges. Surgical gloves offer some protection, but polythene ones don't, and you shouldn't use these, as if they do get perforated you will get the solution inside them, and it will cross-contaminate the processing baths as well as failing to protect your skin. Even if you are familiar with dish processing, you should read the following instructions:

- 1. Place the plate (or film) in the wash tray, emulsion side up. Agitate the tray vigorously, and brush your fingers very gently across the emulsion to dislodge any airbells. After a minute or so lift the plate out of the tray, holding it by one corner.
- 2. Start the timer and immerse the plate in the developing solution, emulsion side up. Do this in one clean sweep. During the development rock the tray continuously in all directions. At normal room temperature (20 °C) the correct development time for the ascorbic-metol developer will be between 3 and 6 minutes, the exact duration depending on the darkness of the image. It should reach a density of about 3.0. This is very dark but not quite opaque.

The best way to judge the density is to lift the plate out of the developer briefly and look through it, first at the developing tray, then the safelight. If you can see the tray, it is too light; if you can't see the safelight, it is too dark. So when you can see the safelight but not the tray, the density is about right.

- 3. When the development is complete, rinse the plate briefly in ordinary water, then immerse it in the bleach solution, emulsion side up. You can now turn the lights on. Rock the tray until the emulsion has been clear for about a minute. (Check this from the back of the plate, which clears last.)
- 4. Wash the plate for 5–8 minutes in running water. When you first put the plate into the water (emulsion side up), brush your fingers very gently all over the emulsion surface as you did in the first wash. This is because the bleach bath sometimes leaves a deposit on the surface. Empty and refill the tray several times during the wash to get rid of any stagnant water. Don't overdo the washing.
- 5. Lay the plate, emulsion up, on a paper towel, and remove all the surface water with the squeegee. Take care not to leave any streaks on the surface, as this will leave discolored marks on the image. If you are in a hurry to see the result, dry the emulsion with a portable hair drier set to medium heat, holding it not less than a foot or so away. You will see the image begin to appear as the emulsion dries, but you won't be able to see it properly until you get the hologram under a spotlight.

Don't throw away the solutions yet. As little as 100 cm^3 of solution (developer or bleach) should process six or more 4×5 in plates before it is exhausted. When you begin more exacting work you may prefer to use a separate small quantity of developer for each exposure.

Viewing the image

When you are sure the emulsion is dry, you can examine the image under a spotlight. The best way to do this is to hold the plate with the emulsion away from you, with the light falling on it from about 45° (or 56°) "above". If everything has gone well the image should be bright orange–red, with no blemishes. If you flip the hologram top to bottom, looking at the emulsion side, you will see the pseudoscopic real image. It will look hollow, and as you move your head it may seem to swing round in space. This strange image is actually located in front of the hologram, and it has some useful properties, as we shall see later.

A one-step real image

I explained in Chapter 4 that one way of turning a pseudoscopic real image into an orthoscopic real image is to use it as the object for a second 'transfer' hologram, which is flipped a second time for viewing. I shall be showing you how to do this in Chapter 7. However, there is a way of producing a natural-looking real image in one step, with a little cheating. The trick is to start with a 'pseudoscopic' object. If you have a small statuette (Fig. 6.7), you have an excellent model. Get a packet of self-curing mold material (obtainable from educational stationers, model shops and dental suppliers) and make up a mold of the object. When this is fully cured, strip it off and cut it cleanly into front and back halves. Keep the back half: you can use it to make a second hologram of this, and then mount the two holograms back to back to give a 360° image (see Chapter 7). Spray the inside of the mold with white or metallic spray paint, and go round the edges with a black marker pen.

An alternative way of making the mold is to pour the mold material into a small margarine tub and push the statuette into the soft dough to the halfway mark. This has the advantage of being more rigid once it has fully cured, but you will have to do the front and back separately.



Figure 6.7 One of the author's earliest holograms (right). Pluto is actually half of a hollow mould (left); when the image is viewed flipped the perspective becomes normal, and the image appears in front of the film plane.

Set up the pseudoscopic object on the plate in the same way as an ordinary object but upside down, so that the laser light strikes the "lower" side. When you display the hologram flipped, the result will be a natural-looking image standing out in front of the hologram.

Displaying your hologram

You can improve the appearance of your image by spraying the back with black paint; this will also protect the emulsion from damage. But don't on any account use cheap cellulose paint that smells of pear drops or acetone, because it will probably damage the fringes, and may cause the image to be discolored and possibly unsharp too. Use slow-drying gloss black paint. You can also get matt black self-adhesive PVC backing, but you have to apply it carefully (see p. 114). When displaying your hologram, plates have an advantage: you only need a clip frame. If you used film, you need to mount the hologram behind glass or acrylic sheet. Hang it on a wall, with a small-source spotlight at about 45° (or 56°) elevation. The best kind of spotlight is the low-voltage type of halogen lamp that has a built-in reflector, and a transformer in the mains plug. You can get these with various wattages and beam divergence angles: a 12 V, 20 W, 30° lamp will probably prove the most suitable. If you have to use a different kind of light, test it by holding your hand between the lamp and the wall you are going to use, and see how sharp the shadow is. If it gives a sharp shadow at a distance of about 10 cm from the wall, it will do justice to your image.

Box 6.4 Using a HeNe laser

There is still much to be said in favor of HeNe lasers. Although they are initially more expensive than even the most powerful diode lasers, they are very stable, and it is not difficult to pick up a good one secondhand at a fraction of its original cost. They produce a highly collimated beam about 1-2 mm in diameter, with a spread of not more than about 1 milliradian (that is, 1 mm per metre of throw). There is one caveat, however: don't be tempted to buy one with what is described as 'random polarization'. The beam is actually polarized, but the axis of polarization wanders erratically, and can cause problems with beamsplitters, because the beamsplitting ratio may vary unpredictably as the polarization vector wanders. Make sure your laser has fixed polarization, and buy the most powerful one you can afford. 5 mW is the lowest power suitable for serious work, and 35 mW is not too powerful for holograms up to 30×40 cm.

Another problem with HeNe lasers is that the expanded beam isn't at all clean, even in the highest quality lasers. When you spread the beam out with a lens you will notice rings and puddles in the patch of light, apart from the inevitable speckle. I will explain in Chapter 7 how to get rid of these with an optical device called a spatial filter; but this device is quite an expensive item, and until you are sure you want to go ahead and make more advanced holograms, my advice is just to rotate the beam expanding lens until the worst of the swirls are away from the most important parts of the subject matter.

What went wrong?

No matter how careful you are, things can still go wrong. The most frustrating, as well as the most frequent when you are starting out, is a completely blank plate – a nullogram. But the Denisyuk configuration is a robust one, and even with very little experience you should be able to obtain a fairly good image, even if you have been a little careless in some way. Some of the faults that do occur in holograms, such as unsharpness or low contrast, look like those you sometimes get in photographs, but the causes are usually quite different. Rather than give a lengthy verbal analysis at this point, I have drawn up a list of faults and their possible causes in the form of a diagnostic chart (Table 6.1). At the end of Chapter 8 I do give a more thorough analysis, which will be helpful when you have more experience. There are also some examples of the more common faults in Fig. 8.12 (page 117), donated by some of my former students and a few reluctant professional friends.

Suppliers of holographic materials

The two main suppliers of silver halide holographic materials are Geola, who distribute Slavich materials throughout the world, and Colourholographic, who produce the BB materials originally designed by Richard Birenheide and Jeff Blyth and formerly produced in Germany. Geola's address is P.O. Box 343, Vilnius 2006, Lithuania, tel. (370-2) 23-27-37, e-mail sales@geola.com and technical@geola.com, website www.geola.com or www.slavich.com. The UK distributor is HMD at 38 Arlington Road, London N14 5AS, UK, tel. (44) (0) 208 368 6465, e-mail hmd@eivd.globalnet.co.uk. Colourholographic Ltd is at Braxted Park, Great Braxted, Witham CM8 3BX, UK, tel. (44) (0) 1621 890 890, e-mail colourholographics@btinternet.com, website www.colourholographic.com. The main distributor in the USA for both of these holographic materials is Integraf, 745 North Waukegan Road, Lake Forest, IL 60045, USA, tel. (001) (708) 234 3756, e-mail integraf@aol.com, website http://members.aol.com/integraf/catalog/html



Further reading

There are a fair number of introductory books on making holograms, but the area is a minefield. Some of the books appear to have been written by people who have never progressed beyond the key-ring laser stage. Others have been liberally supplied (presumably by their editors) with serious errors in processing formulas, and diagrams of setups that are all but unworkable. Others again have never been brought up to date, and discuss materials and equipment that are no longer obtainable. One practical introduction I can recommend unreservedly is Frank deFreitas's *Shoebox Holography*, obtainable through his website www.holoworld.com. This website is worth a visit for the enormous amount of basic information on amateur holography and diode lasers, as well as a list of other relevant websites. One excellent read is *Holography Handbook* by Fred Unterseher, Jeannine Hanson and Bob Schlesinger (Ross Books). Some of its advice has to be taken with a pinch of salt, but it is well worth having a copy, if only to get the flavor of the authors' enthusiasm (Fred Unterseher is one of the foremost American fine-art holographers, and a charismatic teacher).

One or two other books, while not recommendable in their entirety, contain useful information; they are cited in the text where appropriate.

Chapter 7 Single-beam techniques 1

'The method employed I would gladly explain While I have it so clear in my head.'

Lewis Carroll, The Hunting of the Snark

Once Yuri Denisyuk's single-beam hologram technique had become accepted by the academic authorities, it quickly became a standard research tool in Soviet archaeology. The southern states, in particular the Ukraine, with two thousand years of turbulent history, have always been a rich source of ancient artifacts. Farmers' ploughs have unearthed so many of these in remote districts that it has become necessary to provide traveling exhibitions in order to bring the country's ancient heritage to the people. All the major museums employ full-time holographers to record their treasures in three-dimensional form. These records are nearly always Denisyuk holograms, and are of the highest quality. Figure 7.1 is a photograph of one such example, which I took during a visit of one of these exhibitions to Britain.



Figure 7.1 An image from the National Museum of the Ukraine, Kiev.

Single-beam holograms of unstable subject matter

Of the two configurations described in the previous chapter, the single-beam arrangement with a forward-tilted plate works well for small light-colored rigid objects, and is well suited for many museum specimens. To make the subject matter more stable you can position the plate and subject erect, and have the laser elevated so that the beam illuminates the subject from above. This setup is often the only one you can use for models of stage sets, and flimsy models made from



Figure 7.2 Shooting a Denisyuk hologram with an overhead beam down a flight of steps. The subject is the original architect's model for the Albert Memorial. Photograph by the late Michael Langford.

modeling clay, but there can be problems raising the laser high enough. When a group I was working with had the task of making a hologram of the original architect's model for the Albert Memorial, we used a professional camera tripod and took advantage of a short flight of stairs (Fig. 7.2).

If, as is likely, you lack the space (and the flight of stairs), you can mount the laser horizontally and fold the beam using a mirror large enough to catch the whole beam. This can be an ordinary mirror metalized on the back, but the two surfaces (front and rear) can produce an unwanted artifact. It is preferable to use a front-surface mirror (see Box 7.1).

This is also often called a 'first surface' mirror.

Box 7.1 Front-surface mirrors

Traditional mirrors are metalized on the rear (or second) surface, to protect the reflecting metal from corrosion. If you use this type of mirror you will find that your holographic image is overlaid by a grid of parallel lines about 0.5 mm apart; this is caused by interference between the wavefronts reflected at the front and rear surfaces of the mirror. These don't usually affect the image itself, though they can weaken it, and they are certainly unsightly. Mirrors for optics labs are metalized on the front (or first) surface; the coating is usually of vacuum-evaporated aluminum. As this metal is very soft, it usually has a protective coating to prevent scratching, and this makes the mirrors somewhat expensive in larger sizes.

Laser Beam expander Mirror at 22.5-28° Scooter tube Holographic Subject emulsion

There is a trick, explained later (Box 7.2), that allows you to get away with rear surface mirrors; but eventually you will find a large front surface mirror to be an indispensable part of your equipment.

'Breadboard' is a term used in optics labs to describe a small heavy optical table that is positioned on a main table. It is generally employed for small independent setups that may need to be moved without disturbing the components.

Figure 7.3 'Folded' layout for an erect subject.

Figure 7.3 shows the slab isolated from the table by a partially inflated scooter inner tube, another useful prop to have around. This helps to prevent the transmission of any vibration to the setup. The mirror is held in position by two wooden blocks and a stave, all of which you can fix in position with spots of hot glue, once you have adjusted the mirror to give a downward beam of around 45° to 56° .

Unstable or slippery objects, or subjects such as necklaces that cannot be stood upright, usually have to lie flat, and so need a different arrangement. There are two alternative configurations with a beam incident from overhead; which you prefer will depend on which you find easier. The one illustrated in Fig. 7.4 is the simpler, optically speaking, though it does need a much larger and therefore more expensive mirror. The plate or filmholder is positioned on three blocks (not four, which would allow it to rock), with the emulsion facing the subject. Again, a long stave serves to hold the mirror at the required angle; the subject matter is illuminated from "above". If you are pushed for space, and you possess a heavy-duty camera tripod, you can adapt the latter to carry the overhead mirror system of Fig. 7.5. With this configuration you can arrange the overhead mirror to be at the Brewster angle (even though the angle of incidence at the plate may be less), so that you can get away with a rear-surface mirror. The steering mirror at the laser output should be a proper optical front-surface mirror, though. It will prove well worth the expense.

A third type of horizontal arrangement has the subject matter prone rather than supine.

Most exhibition holograms are designed for replay at 45°, for ease of installation. As I pointed out earlier, a p-polarized beam gives zero reflection at 56° incidence (the Brewster angle). and this is the best way of suppressing the unpleasant 'wood grain' effect that can appear when using film sandwiched between glasses; after experimentation, you may decide to compromise, with an angle of incidence of around 50°.



Set up the table as in Fig. 7.3, using bricks or cement blocks hot-glued to a rigid



Figure 7.4 Setup for a supine subject, using a front-surface mirror.



Figure 7.5 Alternative setup for a supine subject, using a tripod or heavy stand and an elevated horizontal mirror.

It follows the general principle you encountered in the previous chapter (Fig. 6.3a), employing a stool and a horizontal glass plate to support the sensitive material, with the subject matter lying on it, and is the basic layout I recommend as the standard for single-beam holograms, once you decide to begin making images more seriously. As you will see in this chapter and the next, there is a great deal you can do with this configuration. Indeed, many professional holographers have begun their career using this set-up.

The main difference from the arrangement of Fig. 6.3a is that you mount the laser horizontally. This means that you can use a larger and more powerful laser, and it can be farther away from the subject, with a beam that diverges less. Again, you will need a front-surface mirror. This mirror, propped up against the support for the glass plate as in Fig. 7.6a, at an angle of from $17-22.5^{\circ}$ to the vertical, directs the beam upwards, giving an angle of incidence of $45-56^{\circ}$. Figure 7.6b shows an actual 'frame' that I have regularly used in demonstrations

With this setup you can allow some of the beam to bypass the hologram at the sides, and you can add reflectors (which don't need to be front surface) to add light to fill in the shadows. Of course you mustn't allow any of this light to fall directly

It is vital to 'card off' all stray light at any time, and particularly so when you begin to work with more complicated set-ups, as stray light not only lowers the image quality but can lead to unwanted ghost images.



Figure 7.6 Shooting upwards at a prone subject. (a) Geometry of setup; (b) a practical solution.

on the emulsion, so this kind of 'fill-in' assistance is usually feasible only when the subject matter is set back from the film or plate.

Building a single-beam frame

The single-beam frame described here is based on the same geometry as the lab stool configuration, but is a good deal more versatile, as you will see. You can use it to produce first-class holograms of appropriate subject matter, and you will find it worthwhile upgrading your optical equipment to take advantage of its capabilities. To make holograms up to a format of 8×10 in, you need a throw of about 2 metres. You can scale up the frame to take a 30×40 cm format, suitable for making commercial copies of larger holograms. The material I suggest is the slotted L-section strip sold by builders' merchants (in the UK under the name of 'Dexion'). It has slots 25 mm (1 in) long and the same distance apart, which allow you to make adjustments. You will need coach bolts to join the strips together. These will probably be fitted with hexagon nuts, but it is a good idea to use wing nuts on the bolts that are going on the sections of strip that are going to be moved fairly frequently, otherwise you will have to take a spanner or a wrench to them every time you need to make an adjustment. Take with you a list of all the sizes of strip you will need, and ask the supplier to cut the strip to size (they usually have a special guillotine for this). You will need to clean up the rough edges with a file, of course.

This is what you will need for the smaller frame:

Dexion: 8 pieces 300 mm long; 4 pieces 350 mm long 8 triangular gussets 36 coach bolts 8 wing nuts 28 hexagon nuts Two 4 mm float glasses or 6 mm plate glasses, 275 × 300 mm One 300 mm square front surface mirror

Note: For a 30×40 cm frame, scale up all the dimensions by 50%.

Coach bolts are bolts made with square shoulders that fit the slots and prevent the bolts from turning when you tighten the nuts. You can buy these at the same time as the Dexion strip.

Method of assembly

The construction of the frame is shown in Fig. 7.7. Note which components go inside and which go outside; otherwise you may not be able to get the slots lined up. Cut the two slots (X–X on Fig. 7.7) on the two rear legs first, using a hacksaw. They should go right to the outside edge, and they need to be about 12 mm wide. Assemble the frame loosely first, place it on a level surface and adjust it, finger



Figure 7.7 Single-beam frame. The horizontal pieces are 300 mm long and are bolted together first, hand tight, with the nuts on the underside. They are then bolted to the 120 mm legs with the nuts outside. The frame is lined up with a setsquare and the nuts tightened a little at a time. The upper frame A is used only for transfers and can be removed when not required. Concealed corners B, C and D are pinned as at A. Locations at EE and FF are mirror stops for 33° and 22.5° inclinations respectively (nuts uppermost). Four gusset pieces G hold the frame square while adjustments are being made to the upper horizontal pieces. XX are the two sawn slots that allow the glass to be slid onto the lower of the two supports when the upper supports are in use.

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Figure 7.8 Two examples of completed frames of different sizes. In each case the upper shelf pieces can be adjusted over a wide range of spacings.

tight, until it is straight, level and square; then tighten the nuts, first on the lowest part of the frame, making sure everything remains square, then on the upper parts. Now slide one of the glass plates on to the middle frame and adjust the frame until the glass lies flat without rocking. Tighten the wing nuts and repeat the adjustment for the upper frame. Insert the mirror, using tissue to avoid any finger marks, and fit the 30° and 22.5° stops, using a protractor or a goniometer.

Remove the mirror and the supports for the glasses, and spray the frame and supports matt black. Once the paint is dry, refit the mirror and supports and slide the glass plate onto the middle shelf through the slots cut in the vertical members. Place the second glass on the upper frame.

Figure 7.8 shows two examples of completed frames of different sizes. Both of these have seen many years of useful service.

A rear-surface mirror system without double reflections

I explained earlier that you can avoid double reflections from the front and rear surfaces of a glass plate if you have the light *p*-polarized and incident on the glass at the Brewster angle (approximately 56.3° for ordinary float or plate glass). Box 7.2 explains how you can make use of this property to provide a 45° incidence beam for the frame system via rear surface mirrors without the nuisance of double reflections.

The laser

By now you will no doubt have committed yourself to some serious holography, so you need to consider obtaining a laser suitable for larger work. Improved diode lasers appear on the market fairly regularly, many of them with the same wavelength and power as HeNe lasers, and with comparable stability. In general they give a very clean beam. When you decide to buy one, you should first

A goniometer is an engineer's protractor with a long pointer pivoted at its center, to simplify precise alignment.

Float glass is the glass normally used nowadays for windows and other general purposes, and it is optically entirely satisfactory for this frame. The glazier will cut it to size for you, and will also clean up the sharp edges with a stone. Plate glass is heavier gauge material, usually 6 mm or more in thickness. It is ground and polished, and should be completely free from flaws, but it costs about twice as much as float glass. As you may sometimes have to exert quite a lot of pressure on the glass, it is worth the extra cost.

Chapter 8 gives details for checking both stability and coherence length. If you have an option on a laser that lacks a guaranteed specification, you must carry out these tests before you agree to buy it. This applies to all types of laser, not just diode lasers.

Box 7.2 A rear-surface mirror configuration

In order to exploit the full versatility of the frame, with the possibility of varying the reference beam angle of incidence, you need a front-surface mirror, as discussed earlier. However, if you are prepared to work at 45° incidence only, you can get away with rear-surface mirrors, with a little low cunning. They need to be good-quality mirrors, of course. The trick is to exploit the properties of the Brewster angle. You need two such mirrors, and they need to be mounted with some degree of precision. The vertical elements of the frame



Figure 7.9 Geometry of a rear-surface mirror configuration making use of the Brewster condition. The laser beam must be p-polarized.

need to be some 600 mm in length rather than the original 300 mm, to allow for the greater overall height of the mirror system.

In the normal way, if you try to use a rear-surface mirror with an expanded laser beam you will get a grid of fine parallel lines about 0.5 mm apart all across the beam; you can see the effect if you put a white card into the expanded beam. It is caused by interference between the reflections from the first and second surfaces of the glass. However, if the beam is *p*-polarized with respect to the glass surface, and is incident at the Brewster angle, there will be no reflection at the first surface. The Brewster angle is the angle at which the reflected and refracted rays are orthogonal, so that the tangent of the angle of incidence is equal to the refractive index. For glass of refractive index 1.5 this angle is approximately 56.3° .

If you position two mirrors in tandem so that both are at the Brewster angle with respect to the incident beam, the beam will be deviated by $4 \times 56.3^{\circ}$, i.e. 225.2°, which is $180^{\circ} + 45.2^{\circ}$. That is exactly what you need. The mirrors do need to be good ones, by the way, not just something salvaged from an old bathroom cabinet. The geometry is illustrated in Fig. 7.9. The overall height of the frame from the lower end of the first mirror will need to be 480 mm, so your uprights will need to be 500 mm instead of 350 mm, and you will need four extra bolts and nuts to prevent the mirrors from slipping.

This double Brewster configuration has other uses, for example on a much smaller scale when you find you need an extra steering mirror and have run out of front surface mirrors. But keep the *p*-polarization criterion in mind.

ascertain its frequency stability from the manufacturer's data, and check whether the coherence length is adequate. It needs to be a minimum of 25 cm, and preferably more for any image larger than 4×5 in. Incidentally, you will probably be better off to obtain your laser through a specialist supplier rather than direct from the manufacturer.

There are a good many excellent secondhand HeNe lasers around, available at a fraction of the original price, and if you are offered one don't scorn it. HeNe lasers are very reliable, and the tubes (in my experience) are usually good for well over 10 years of constant use. However, if you buy such a laser from a commercial source, insist on a tube replacement warranty. Also make sure the beam is linearly, not randomly, polarized.

Triangular benches

Whatever kind of laser you have, you will still need a good rigid mount for it, as well as for the necessary beam expander. Although you can make do for some time by hot-gluing the laser to bricks, sooner or later you will need a better support. A *triangular bench* is a heavy steel bar, in cross-section an equilateral triangle, with a deep channel milled along both upper sides. It supports mounts called 'saddles', which hold vertical pins on which you can mount optical components. You will need it to be at least 150 mm longer than your laser, and you will need three saddles and mounts, two for the laser and one for the beam expander (Fig. 7.10).

This follows from Snell's Law, which states that the angle of incidence *i* is related to the angle of refraction *r* according to the rule $\sin i/\sin r = \mu$, where μ is the refractive index of the medium (in air).


Figure 7.10 Triangular optical bench and saddles, shown supporting a 5 mW HeNe laser and a spatial filter.

Spatial filtering

I mentioned in Chapter 6 that if your expanded laser beam was marred by swirls and puddles there was a way of getting rid of these. The method is known as *spatial filtering*. The term belongs to the Fourier model for imaging, and you can find out more about this model in Appendix 2. Some modern diode lasers do give an extremely clean beam, so you may not need a spatial filter for your single-beam holograms; but you will need at least one, probably several, once you start splitbeam work; and you will certainly need one if you are working with a HeNe laser. The details are in Box 7.3 below.

Box 7.3 Spatial filtering

A spatial filter consists of a short focus lens (typically, though not necessarily, a microscope objective) with a very small pinhole positioned accurately at its principal focal point. The mounting system is adjustable horizontally, vertically and longitudinally.

You've already learned that a diffracted beam of light contains information about whatever it was that caused the diffraction, coded in terms of the spatial frequencies that describe the wavefront emitted (or reflected) by the object. When a lens focuses a beam of light, the electric field at the principal focal plane is the *optical transform* of the field of the object, and it forms a diffraction pattern in this plane, in which the highest spatial frequencies (representing the finest detail) form spots that are farthest away from the optical center of the pattern. The swirls in an unfiltered beam are caused by the interference of parts of the beam that have been diffracted by dust and by optical imperfections in the laser and components upstream of the focusing

I shall call these movements *x*, *y* and *z* movements respectively. But some published papers label these axes differently, so be careful when you are reading other material. lens, as well as the lens itself. At the focus of the lens the optical transform of the *undiffracted* part of the beam narrows down to a 'waist'; we can calculate the diameter of this. If you position a pinhole of the correct size at the precise focal point, only this clean beam will be transmitted. The minimum pinhole size is given by the following approximate formula:

$$D = 600\lambda/Md$$

where D is the required pinhole diameter in μm , M is the magnification of the objective, λ is the wavelength of the laser light in μm , and d is the diameter of the beam in mm. Where focal length rather than magnification is given you can calculate the magnification from the approximate formula

$$M = 250/f$$

where f is the focal length in mm. For the various magnifications used in holography setups, the figures for a beam diameter of 1.5 mm are as follows:

Objective magnification	10	20	40	60
Focal length (mm)	25	12.5	6.3	4.2
Minimum pinhole diameter (mm)	50	13	7	5
Size commonly used (µm)	50	20-25	10-15	7-10

These figures are for a HeNe laser or a diode laser with a collimated beam diameter of 1-1.5 mm. For an Ar⁺ laser, where the wavelength is less and the beam diameter greater, the corresponding pinhole diameter is reduced by 20-30%.

You can save money by buying pinholes of non-standard sizes (e.g. 9 or $11 \,\mu m$ rather than $10 \,\mu m$). If you find lining up the pinhole difficult you can usually get away with a larger pinhole until you have had more experience at setting up. In practice, as you see from the table above, holographers tend to use pinholes that are rather larger than the minimum. This doesn't affect the cleanliness of the beam provided the dust and other artifacts are very small in size.

Even when you have a high-quality spatial filter made by a precision optics manufacturer, lining it up can be quite tricky. If you are trying to use a homemade spatial filter you may be in for a good deal of frustration and waste of valuable time.

If you are determined to make your own spatial filter, there is a good design in D McNair's *How to Make Holograms* (Tab Books, 1983). However, such devices are no substitute for a properly engineered spatial filter holder, and they still need a pinhole and a lens. And prices have come down somewhat. Fig. 7.11 shows the effect of a spatial filter on a HeNe beam, and a commercial spatial filter.



Figure 7.11 The appearance of an expanded laser beam (a) before and (b) after spatial filtering. (c) shows a commercial spatial filter.

When I made my first holograms in the early 1970s the cheapest purposemade spatial filter cost more than the laser, not including the pinhole or microscope objective. So I made my own pinhole from an aluminum foil milk bottle top using a sharpened needlepoint, glued the pinhole to a steel washer, and mounted it on the microscope objective with a ring of Blu-tack. The first time I tried, I got it aligned inside three minutes. The second time, it took me two hours. The third time I gave up altogether, and thereafter made my holograms with a dirty beam. Incidentally, I still have the pinhole. It has a diameter of 33 µm, and it still works well with a \times 10 objective.

After a beam, no matter how initially clean, has been passed through, or been reflected from, one or more optical surfaces, it will probably need cleaning up if you are to use it as a reference beam. Conditions for subject-illuminating beams are less stringent.

Each time you align a spatial filter you will need to go through this routine. It may look tedious, but with practice you should be able to do it quite quickly, probably in a good deal less time than it takes to read these instructions.

Setting up with a spatial filter

These instructions apply to the undiverged beam from a HeNe laser, or to a collimated beam from a diode or diode-pumped laser that needs cleaning up, and here apply to the laser as set up in the single-beam frame system described in this chapter.

Begin by checking that the laser beam polarization is vertical. Adjust the height of the laser so that the beam reflected from the front-surface mirror passes centrally through the horizontal glass plate on the lower shelf of the single-beam frame. If you don't have a triangular optical bench and supporting clamps, use bricks, and once everything is properly adjusted, fix it all in place using a hot glue gun.

Spatial filter holders usually have x, y and z adjustments (i.e. lateral, vertical and axial movements respectively) on one component holder, and x and y adjustments on the other. It doesn't matter which one you pick for the objective and which for the pinhole, but you will probably find the manipulation easier if you have the z control knob on the downstream side.

Fit the objective into the spatial filter holder and line up the patch of light so that the horizontal glass in the frame is uniformly illuminated. The easiest way to check this is to put a piece of 8×10 in card on the glass with the long side across the line of the beam. To align the microscope objective precisely, examine the laser output port. You will see two small discs of light reflected from optical surfaces in the microscope objective. Adjust the laser and the objective until the two discs are overlapping and central. Now move the beam as necessary to give as uniform a patch of light as possible on the white card, examining it from below.

Aligning a spatial filter

- 1. With the pinhole mount well clear of the objective, fit the pinhole, and adjust the z-axis control until the pinhole is 2–3 mm clear of the objective. Adjust the x and y controls until the pinhole is approximately central. Now bring your eye down to the level of the pinhole and observe it from a distance of 20 cm or so. You should see a fairly weak red point of light. Move the x control to see if you can make the light any brighter. Now do the same with the y control. Repeat this a few times, getting the point of light brighter each time. Then, suddenly, you will see a bright flash. This is what you have been seeking. (This isn't dangerous, as the beam is greatly attenuated. If your laser is fairly powerful, say 35 mW, you won't need this stage: you can begin at stage 2.)
- 2. Now you can begin the alignment proper. Switch off the room lights and pick up a piece of white card. Hold it about 10 cm away from the pinhole. You will see a small disk of red light on the card, surrounded by faint rings; this is the *Airy diffraction pattern*.
- 3. Adjust the x and y controls until the central disk is at maximum brightness. Now carefully operate the z control to bring the pinhole nearer to the objective. The spot will grow larger and brighter; then at some point it will begin to wander off-center and become fainter again.
- 4. Keep repeating step 3 until the patch of light suddenly becomes very bright, large and uniform, and the rings disappear. Your pinhole is now at, or very close to, the focus. At the exact focal point the patch doesn't move to one side or the other when you adjust the *x* control, but spreads out horizontally and disappears, behaving similarly in a vertical direction for the *y* control.

5. Check that the patch of light is still accurately in the center of the frame. If it is slightly off center you can realign it by nudging the front of the laser. Do this very carefully, as a movement of less than a millimetre will usually be sufficient. If the laser is free standing you can lever its base with a pencil. Provided you aligned the objective accurately in the first place the patch won't disappear, though you may need a further small x-y adjustment to bring it back to full intensity. Check the patch of light on the card as you do this, and see that it stays accurately centered.

If you have done everything correctly so far, you should now have a perfect beam. However, two possible hiccups that have nothing to do with your alignment procedure may occur:

- If no adjustment produces a completely even beam, you have probably got one or more large particles of dirt on an optical surface. Clean the laser mirror and/ or the glass surface of the objective with a lens tissue wrapped round a matchstick, or a cotton bud (be very gentle). If this fails, your pinhole is too large: replace it with a smaller one.
- If the patch of light is still faint and surrounded by rings, even at the point of best focus, the pinhole is too small. Try the next size up.

Sometimes it is difficult to tell if you have really reached the correct focus. To check this, try moving the x or y control very slightly. If the patch of light moves in the same direction as the controls, you haven't reached the focal point yet: if the patch moves in the opposite direction to the controls, you have passed it.

Care of pinholes

When you are not actually using it, always keep your spatial filter covered with a plastic bag to keep out the dust. Never put an unmounted pinhole down on a bench top, no matter how clean you think the surface is, and on no account allow any fluid to make contact with the pinhole. If its diameter is correct for the laser beam and objective but still doesn't allow a clean beam through when it is correctly aligned, it is probably dirty. This is uncommon, but it can happen. To check this, set up the pinhole in the unexpanded laser beam and examine the Airy pattern with the room lights out. The central disk and the rings round it should be circular and uniform; if they are not, the pinhole needs cleaning. The only satisfactory way to do this is in an ultrasonic cleaning bath with distilled water or methanol, or a mixture of the two. Failing this you can try a cotton bud moistened with acetone (flammable), carbon tetrachloride or chloroform (both toxic) or audiotape head cleaner (safe, but less powerful). Use a gentle rotary action, a fresh bud for each side, and finish with a dry bud. But don't be too optimistic about the result.

Making an electrically operated shutter

Some holographers don't bother about a shutter, but simply use a black card over the laser output port. Some switch the laser off between exposures, inviting instability in both pointing and wavelength and probably shortening the life of the laser tube into the bargain. The card method is fine for single-beam arrangements, which are very robust; but for large table set-ups with a number of beams it is better for you to be well out of the way when you make an exposure, as your body heat is enough to affect the optical paths. A simple remote control I used for many years was made from an old 10 V d.c. voltmeter, a PP9 battery with press-fastener By the way, if you get mixed up about the sizes of your pinholes you can check their diameters by the same method. The diameter of the Airy disc is inversely proportional to the pinhole diameter. The exact formula is

$d = 2.44\lambda z/D$

where *d* is the pinhole diameter, λ is the wavelength of the laser light, *z* is the distance of the pinhole from the screen and *D* is the diameter of the Airy disk to the center of the first dark ring. (All measurements are in metres.)



Figure 7.12 An electromagnetic shutter from an old voltmeter. A 6 mm diameter hole is drilled in the case immediately behind the zero needle position, and the front glass removed. A disk of black paper is glued to the tip of the needle, which is then balanced with a small piece of Blutack. The battery, of a voltage correct for full-scale deflection, with a variable series resistance if necessary, is in series with a push-on, push-off switch. The laser beam is aligned with the hole, and when the switch is operated the pointer swings out of the way.



Figure 7.13 An alternative shutter employs an electromagnetic relay or solenoid, which moves a black paper flag out of the beam when the switch is operated.

terminals, a connector to fit these, some bell flex and a push-on, push-off switch. If you can find an old meter, you can easily make one yourself. Remove the back and scale from the voltmeter and glue a disk of black paper about 7 mm in diameter to the needle tip in the plane of its movement. Counterbalance its weight with a spot of Blu-tack at the other end of the needle (Fig. 7.12).

Drill a 5 mm diameter hole in the back of the meter casing in such a position that the black disk covers it when no voltage is applied. Connect the voltmeter in series with the battery and switch, and fix it to a block so that the laser beam passes centrally through the hole. When you operate the switch the disk swings out of the way, allowing the laser beam to pass through. Move the whole shutter device out of the way when you are setting up the table, to avoid draining the battery unnecessarily.

You can use a solenoid instead, to make a shutter that takes up less room. Buy a low-voltage solenoid with a current-limiting resistor from an electronics supplier. Don't be tempted to use a mains-voltage solenoid: in darkness it is much safer to use low voltages. A solenoid is a coil containing a plunger made of soft iron: when the current is switched on the plunger is drawn into the coil. Some types of solenoid operate a lever rather than a plunger, but either type is suitable. All you need to do is to fix a black card flag to the plunger or lever and place it so that it interrupts the beam (Fig. 7.13). This type of shutter operates rather more rapidly than the meter type, and is a better choice if you are using very short exposure times.

If you want to time your exposures accurately and automatically, you will need to put an electronic timer into the circuit. Buy one intended for a photographic enlarger: this will give you a series of exposure times ranging from a fraction of a second up to several minutes. As these timers operate at mains voltage you will need to send the output through a small transformer such as a d.c. source of the type made for operating portable transistor radios from the mains.

Safelights

I suggested in Chapter 6 that as holographic emulsions aren't very sensitive to light you could manage without a high-quality safelight. As I mentioned there, you can use a photographic No 3 safelight (panchromatic), with a brighter bulb than the one recommended for photographic film, but there are snags: the heat from the larger bulb will eventually damage the gel; the light still isn't very bright; and the filter lets through some infrared, which may fog a red-sensitive holographic emulsion. Low-consumption long-life tube type lamps don't emit infrared, and you can use any narrow-band material such as Cinemoid 39 (tricolor green) with the 9 W size lamp. Suppliers of holographic materials and equipment can usually supply the correct material for wrapping round fluorescent tubes. With standard 4 or 5 ft tubes you need two thicknesses. If you are working with a green laser and green-sensitive material you can use the standard red safelight for orthochromatic films.

If you go to a theatrical supplier to buy safelight gels, take a diffraction grating with you. Test the gels by looking at a small bright light source, preferably a filament lamp, with the gel over the grating, close to your eyes, and examining the spectrum. You should see only green, no red or blue at all. You may have to combine two gels for success. Back in the lab, take a piece of holographic film or plate, position it about 60 cm from the safelight and place four coins on it. Cover up the section with the first coin after $2\frac{1}{2}$ minutes, the second after 5 minutes, the

third after $7\frac{1}{2}$ minutes, then remove the film completely after 10 minutes. Develop it normally and either fix it or stabilize it in a stopbath of 1% acetic acid solution. Place the processed film on a white surface and examine it for outlines of the coins. If any are visible this will give you a good idea of the limiting time of exposure at that distance. At other distances the safe time will be in proportion to the square of the distance. Thus if the safe time for 60 cm was 5 minutes, then at 120 cm it will be 20 minutes, and at 180 cm it will be 45 minutes. If there is visible fogging at 60 cm within $2\frac{1}{2}$ minutes the safelight won't be adequate for its purpose. You will need either to add a further gel or to reduce the wattage of the lamp.

Index-matching fluid

If you used film rather than plates for your first holograms you may have noticed a closely spaced pattern of irregular lines, something like wood grain, on some or all of them. This is caused by interference between the light waves reflected from the various surfaces. It is possible to get over this problem by using anti-reflection glass, and this is the method used by some commercial labs that turn out large numbers of film holograms for the display market. But anti-reflection glasses are expensive and easily damaged, and they can disturb the polarization characteristics of the beams, weakening the fringes that form the hologram. You can suppress the wood grain effect with ordinary glass, provided you exclude all air between the film and the glass. The easiest way to do this is to fill any air space with a fluid that has the same refractive index (about 1.5) as gelatin and glass. This technique is called index matching. A number of fluids fit this bill: glycerol, liquid paraffin (mineral oil), carbon tetrachloride, xylene and trichloroethylene are a few. The last is probably the best, but all these fluids have disadvantages, and a cheaper and safer alternative is ordinary white spirit (turpentine substitute), which you can buy from any store that sells paint.

If you use index-matching fluid you need only a single sheet of glass, as the surface tension of the fluid will hold the emulsion in close contact with the glass. It won't usually peel off or shift, even if left overnight.

There must be no speck of dirt between the film and the glass. If there is, fluid will flow into the space by capillary action, and this movement will result in a black patch or doughnut (Fig. 8.12c). This can continue even after hours of settling time. So once you have cleaned your glass plate, don't lean over it or allow any of your clothing to pass over it until you have put the film in position.

There are many possible routines for fixing films to glass using index-matching fluid, and no doubt you will eventually develop your own. But for a first few times at least, try the following reliable (if somewhat tedious) method.

Before you start, prepare the workspace with a bed of newspaper to absorb spilt fluid. Keep the fluid in an old liquid soap or shower gel dispenser. Have a good supply of lint-free paper.

For the squeegeeing process you can use an ordinary window-cleaning squeegee (keep it separate from the one you use for wiping down the processed hologram), though some people prefer a roller squeegee for the final stage. If the glass is new, clean it with a proprietary window cleaning fluid, and make sure it is free from smears.

1. Lay the glass on the newspaper, and switch off the main lights. Have the box of film ready. Pick up the blade squeegee, wipe the blade across the palm of your

In the USA white spirit is known as 'paint thinner' and often goes under the name of 'Thin-X', but it mustn't be confused with cellulose thinners, which are totally unsuitable and will ruin your film.

Specks of dandruff are the most common offenders. This makes it doubly important to keep your head well back when applying the fluid to the glass. Even if you have little or no hair you will still have dandruff.

Any kind of lint-free paper or kitchen wipe paper will do, but the best I have come across is P-Tork, by Mölnlycke, used widely in the printing trade. I showed the way to identify the emulsion side of a film earlier (p. 75). If an offcut of film lacks an identification notch, you can still tell the emulsion side, as it is almost always concave. Sometimes if a box has been stored under very humid conditions (not recommended) the emulsion surface becomes convex through absorption of water. If so, dry the emulsion carefully before you use it, with a hair drier set to half heat, until it becomes concave again. hand to get rid of any dust or hairs, and draw it gently across the glass. Without lifting the squeegee, let it fall on the newspaper.

- 2. Pick up the container of fluid and squirt about 5 cm³ on to the center of the glass plate.
- 3. Take a film out of the box, and identify the emulsion side. Tap its edge sharply on the newspaper to knock off any foreign matter. If it has been out of the box before, place it on the newspaper, emulsion up, and draw the squeegee very lightly across it as in step 1.
- 4. Position the film squarely on the plate, emulsion side down. Try to get the center of the film to touch the fluid first.
- 5. With the film now on the glass, take up the blade or roller squeegee and give a rapid light stroke from the center of the film to each corner in turn, to spread the fluid and remove any airbells. Check whether any do remain, by sliding the film around on the surface of the fluid. A remaining airbell will demonstrate its presence by causing the film to stick at that point. Squeegee out any of these.
- 6. Squeegee the film down hard, this time parallel to its edges. After this operation you should still be able to move the film, but with more difficulty. Center the film as necessary.
- 7. Using lintless paper, remove any remaining fluid from all surfaces.
- 8. Hold the sandwich up to the safelight and pass it across the light, looking for any 'lenslets' caused by foreign particles between the film and the glass. You can spot these by the way they cause the edge of the light to wobble as they pass it. If you find any, heave a sigh, remove the film from the glass and lay it, emulsion side up, on lintless paper. Remove the indexing fluid from the glass with a single sweep of the blade squeegee, and repeat the whole procedure, including taking the squeegee over the emulsion surface.



Figure 7.14 Stages 1–8 (see text) in the mounting of an unexposed holographic film using index-matching fluid.

9. Polish both sides of the sandwich with a fresh piece of lintless paper, and stow it in a lightproof box until you are ready to load it.

Stages 1–8 are illustrated in Fig. 7.14.

Exposing and processing

You are now ready to start the exposing sequence. Again, you need to follow a regular routine. I suggest the following sequence:

- 1. *Final alignment check* For the final setup use the upper support flanges; this is easier than using the lower set, as you can simply set the glass bearing the film onto it rather than needing to slide it in through the slots. Before you do this, though, check that the alignment is still correct, by putting the other glass on the upper flanges with a white card the size of your film on it. The illumination should still be substantially uniform over the card. If it has shifted, make a fresh adjustment to it.
- 2. Loading and settling Remove the glass and close the shutter. Switch off the room lights, and bring out the glass with the film. Place it, with the film uppermost, on the upper shelf. Adjust the position of the glass as necessary to align the film correctly. Lay the subject matter on the film, oriented so the light is from "above". Allow 3 minutes for settling, more if the subject is not completely rigid, or if you have been handling it with hot hands.
- 3. *Exposing* You are now ready to make the exposure. If you know the approximate output of your laser, make a first guesstimate of 2 seconds per milliwatt of power, e.g. 10 s for a 5 mW source and a 4 × 5 in film. Make a note of the exposure time you actually gave.
- 4. *Processing* You need four processing trays of a size appropriate to your film size, and a larger tray or a bowl for washing.

The developer and bleach formulas differ, depending on whether you want a red (master) hologram or a yellow or green (final) hologram.

You will find appropriate formulas in Appendix 5. If you are using the 'pyrochrome' process, once you have mixed the two parts of the developer the solution keeps only a few minutes, so take only the minimum amount (for a 4×5 in processing tray some 25 cm^3 , or about one 35 mm film canful, of each solution), and mix the solutions immediately before use. Give the film a short but vigorous rinse in plain water before processing to remove the index matching fluid (which is slightly oily). This will also allow the developing solution to penetrate the emulsion more quickly and uniformly.

Immerse the film in the developer in one clean sweep. The easiest way to do this is to tilt the tray so that the developer is all at one end, place the film in the tray and tilt the tray back so that the solution flows evenly over the film (Fig. 7.15).

Give plenty of agitation, especially in the early stages of development. If the room temperature is low, float the tray in a bath of warm water: this will make agitation easier, too. Agitate irregularly, not uniformly (this could cause bars and streaks). Pyro developer stains skin and fingernails, and is an irritant, so avoid putting your fingers in it: wear protective gloves or use film tweezers, and if you do get any developer on your skin, rinse it thoroughly.

Ascorbate developers, on the other hand, keep for several months, provided you exclude air from the container. You can also leave them in an open tray for several

You will probably remember that I suggested in the previous chapter that it was preferable to have the emulsion facing the subject matter. However, this was for a film sandwiched between two glasses. A small separation of emulsion and subject helps to avoid a possible burnout patch. (There is a marginal note on burnout on p. 100). In this case, because of the natural curvature of the film it is easier to get the emulsion side to stay down on the glass.

Always keep a log of your exposure times, film or plate size, and type of developer used. It will save you a lot of time and test pieces later.

To avoid the possibility of chemical cross-contamination, always use each tray for the same purpose. Label the trays 'developer', 'rehalogenating bleach', 'solvent bleach' and 'final rinse' on the outside with a black waterproof marking pen.

If you are using a green laser, you will want a green master, of course. Use the mastering developer.

This is particularly important with developers containing pyrogallol, as the emulsion begins to stain immediately, and any non-uniform immersion or lack of agitation will result in uneven image color.



Figure 7.15 When immersing a film in a small quantity of solution, tilt the processing tray away from the film so that the solution can flow evenly over it as it is slid into the tray.

A wetting agent is a chemical that reduces surface tension; it helps to prevent the formation of airbells, and allows water to run freely off an emulsion surface when drying. Some wetting agents also have detergent properties, i.e., they allow aqueous and oily solutions to mix. *Printout* is the term used for the darkening of silver halides that have been exposed for some time to bright light. It can sometimes happen unpredictably, and when it does it may affect the diffraction efficiency of a hologram.

Burnout is a local wipe-out of fringes caused by saturation exposure. What you see is a small black patch at the point where the image should be brightest, sometimes with the image peeping out behind it. It is most likely to occur where the highlight is very close to the plane of the hologram. Figure 8.12h shows an example. hours without their deteriorating. One liter of ascorbate developer is sufficient to process about twenty 8×10 in or eighty 4×5 in films, but its activity decreases with repeated use, so you need to increase exposures and development times progressively, up to about twice the initial values for the final film. Many people prefer to use small quantities, as with the pyro developer, and to discard the solution after use.

You can use the bleach baths repeatedly, until the bleach time becomes inconveniently long, provided the solutions don't become contaminated with developer. Their working life is about the same as that of the developing baths, but when a solvent (dichromate) bleach nears the end of its life it tends to deposit scum on the emulsion surface, and it is important to wipe this off in the final wash.

You will also need *wetting agent* for some processes. It is a good idea to add a little to the pre-wash, and you will need it if you have to put a processed film back into any solution after it has been dried. Most manufacturers of photographic solutions market wetting agents; the best known is Kodak Photo-Flo. This has often been recommended in American texts, but if it gets into a developer it can cause fogging with some types of emulsion, and if you use it in the final wash it seems to be a contributor to 'printout'. Ilford Ilfotol, however, seems to have a clean bill of health – at least in my own experience.

Getting the exposure right

There is a great deal of latitude in the exposure that will give you a good image. When I wanted to produce the illustration of under-, correct and overexposure in Chapter 8, I began by giving exposures to the three sections of 4 s, 8 s and 16 s respectively. There was scarcely any difference in brightness between the replayed images, and in order to obtain a really noticeable difference for the illustration I had to space out the exposures to 0.5 s, 8 s and 60 s. Provided the system is stable, the main reason beginners get a feeble image is underexposure. Serious overexposure will also result in a poor and 'noisy' image, often with burnout in the brightest highlights.

The optimum density for a reflection hologram varies somewhat for the different makes of film, but the guidelines I gave earlier apply broadly: dark enough for you not to be able to see the processing tray through the film, but not too dark for you to be able to see the edge of the safelight through it. If this seems too vague, Box 7.4 contains a more precise account of what is meant by density, and how to measure it.

Multi-exposure techniques

You can put several independent images into a hologram. One of the most impressive of these, on a small scale, is a 360° hologram (on a flat film) that shows the front of the subject from one side and the rear from the other. The technique for making this and other 360° holograms is described in Chapter 8.

The simplest multi-exposure technique that you can do with a single-beam setup is the real-image nameplate or logo. This comes out with the name or logo standing out in front of an object that can be an abstract design or a collection of objects. Make up the name in white dry-transfer lettering on a piece of acrylic sheet at least

Box 7.4. Estimating density

If you measure the transmittance of a piece of gray film, then take the reciprocal of this figure and take the logarithm (base 10) of the result, your final figure will be the *photographic density*. This sounds pretty complicated, though it is simple enough if you have a pocket calculator. Densitometers, which are devices used for measurement in professional photographic labs, read density directly. The concept of photographic density may seem somewhat removed from reality, but we do perceive things in a logarithmic way, and tend to rate subjects in terms of darkness rather than lightness; so in fact 'density' represents a fairly close match to what we perceive. Nevertheless, to appreciate what a density of , say, 2.0 looks like, you need first to see a piece of film that has a density of 2.0 in order to be able to recall its appearance.

There are two ways of obtaining a series of calibrated densities:

- Obtain a set of Kodak ND (Neutral Density) gelatin filters. These come in steps of 0.3, 0.6, 0.9 and so on. By putting them together you can obtain higher densities by simple addition. Thus two ND filters of value 0.3 and 0.9 together give a density of 1.2. The important densities in holography are 1.5 for transmission holograms, and 2.5, 3.0 and 3.5 (for various processes) for reflection holograms. Using combinations of ND filters you can get densities of 1.5, 2.1, 2.4, 3.0 and 3.6, which are near enough to work from. Cut the filters into quarters, and stick them with cellulose tape to the safelight along the edge, to use as a comparison with the emulsion you are developing.
- Buy a Kodak Density Step Tablet No 3. This is a strip of film with a set of steps of equal density increments of 0.15 from 0 to 3. Cut the film in half lengthwise and place one strip over the other. All the marked densities will be doubled, so that it now runs in steps of 0.3 from 0 to 6. Again, you can tape this to your safelight; it will allow you to estimate your density accurately.

You can measure density with an ordinary photographic exposure meter, as nearly all meter scales are logarithmic. The way you do it is to aim the meter at a white surface illuminated strongly enough to give a reading near the top of the meter scale. Note the reading; then, without moving the meter, hold the piece of film you wish to measure over the meter cell. Count the number of blocks on the scale that the meter needle has fallen. Each whole block represents a density increment of 0.3, and each one-third of a block represents a density of the film is 0.9. This also works for parts of a block: if the reading falls from 9 to $3\frac{1}{3}$, i.e. a fall of $5\frac{2}{3}$ blocks, the density is 1.7. You simply multiply the number of blocks by 3 and divide by 10.

If you want to measure density accurately you need a densitometer. The ones used in large processing labs are large and very expensive, and (for our purpose) display considerable technical overkill. A simple and much cheaper meter is the X-ograph (Fig. 7.16), which was originally designed for X-ray units. It reads density directly via a fiber-optics probe, from a film placed on a light table. If you want to read the density of a developed hologram before bleaching, remove it from the developer and immerse it briefly in a 1% acetic acid solution, Blot the surface and measure the density, taking care not to scratch the emulsion.

You can obtain ND filters and step tablets from any Kodak agent, though you will probably have to order them specially. ND filters are much cheaper than the step tablet, but the latter is more useful for finding and plotting the response curve of an emulsion, when you need to do this.



Figure 7.16 A simple densitometer (X-ograph) and a density strip.



Figure 7.17 This office nameplate has the name in bright orange letters hanging in the air some 2 cm in front of the green background.

3 mm thick, and place it on two spacer pieces 6–8 mm thick (two pencils will do) on the glass above the film, oriented so that when you look down at the letters they are the right way round and the light is coming from "below". The film should be on the underside of the glass with the emulsion facing up. Now remove the nameplate and flip the glass and film 180° about a "horizontal" axis. For the second exposure, lay your subject matter on the film, oriented so that the light is coming from "above". Make a second exposure, then process the hologram in the usual way. You can use a similar technique for a number of themes, but make sure the image that is to appear in the foreground is brighter than the image that is to appear in the background, which might otherwise swamp it. You can pre-swell the emulsion between exposures so as to have the image in two different colors (see Chapter 18). Fig. 7.17 shows a nameplate that I had on my office door for several years. The background (my old Contax camera) was green, and the name was in bright orange.

Chapter 8 Single-beam techniques 2

'Oh, Kitty, how nice it would be if we could only get through into Looking-glass House! I'm sure it's got, oh! Such beautiful things in it! Let's pretend there's a way of getting through it, somehow, Kitty....'

Lewis Carroll, Through the Looking-Glass

The transfer principle

If you examine a Denisyuk (single-beam reflection) hologram under a spotlight in the usual way, you will see the virtual image behind it, looking exactly as if the subject were sitting in a glass case. If you flip the hologram you will also see the image, but this time it is inverted and pseudoscopic. It is a real image, and is in front of the hologram.

The transfer principle involves the use of this real image as the object for a second hologram, which you can also make using a single-beam frame. The best results are when the final image straddles the plane of the final hologram, i.e. is partly real and partly virtual. Such images replay well even under white light of poor spatial coherence.

Making a reflection master hologram

Master hologram In making a master reflection hologram you need to follow the same rules as you did in Chapter 7. The image has to be as bright as possible, so you will need a bright subject. If it isn't already white, yellow or red (for a red laser), consider spraying it matt or glossy white. As you will no doubt be using the same laser for both the master and transfer holograms, you must use a process that doesn't shrink the emulsion. The master hologram developer formula given in Appendix 5 will accomplish this. But there is another caveat. Some emulsions contain a built-in preservative designed to extend shelf life, and this is likely to have swollen the emulsion by up to 2%. This is enough to shift the optimum angle of reconstruction several degrees towards the normal. If this built-in pre-swelling isn't removed, the final image will be displaced and possibly distorted. So for some emulsions, before you expose them to make a master hologram you may have to wash the film for up to 3 minutes in distilled or deionized water, before squeegeeing and drying the film. In order not to have to do this unnecessarily, though, make tests, one without and one with pre-washing.

Transfer hologram Having made a satisfactory master, set up the frame with two shelves. Place glasses on both of them, and adjust the spacing between the glass surfaces to 12–15 mm, about a finger's breadth (Fig. 8.1a). Remove the glasses, and mount the master hologram with index-matching fluid, emulsion to glass. As the emulsion is now harder, you may have to secure the edges with cellulose tape. Turn the glass over and position it on the top shelf of the frame with the master film now on the underside of the glass, oriented so that the image is illuminated from

Just to remind you about the difference between a virtual and a real image: a real image is focused, and you can catch it on a screen, whereas with a virtual image the light rays only *appear* to have come from the image. As another reminder, 'flipping' means 'turning through 180° about a "horizontal" axis'. I shall be keeping to these conventional descriptions throughout.



Figure 8.1 (a) Frame set up for a reflection transfer hologram. The master hologram is on the upper of the two shelves. (b) Examining the master image from below.

"below". Turn off the room lights. Tilt the mirror in the laser beam while you examine the image from below (Fig. 8.1b), and adjust the tilt until you are sure you have acquired the brightest possible image. Set the mirror in this position.

Now mount your final transfer film on the second glass, emulsion down, and insert it through the slots in the frame uprights onto the lower shelf with the film uppermost (Fig. 8.2). After a little practice you will be able to align it with the correct offset by feeling the edges. But until you have had some practice it is a good idea to use a larger piece of film, so that there is less need for accurate registration.

After three minutes or so settling time, make the exposure, about the same as you made for the master. This time you can process the hologram in solutions that give you a brighter yellow or yellow-green image. It will have its nearest point some 12–15 mm in front of the hologram plane.

If you feel that the image should be further forward of the hologram plane, increase the separation of the glasses a little and make another copy. You might notice a slight



Figure 8.2 When making transfer holograms from reflection masters you may need to use a larger piece of film for H_2 to avoid a shadow of its edge falling on H_1 . Notice that H_1 is on top of the glass plate G_1 and H_2 is underneath G_2 .

This should be close to the original position, unless something has gone wrong with the processing.

steepening of the perspective in the transfer copy. This is because both the reference beam and the reconstruction beam were diverging instead of being true conjugates; but as long as the format is small this effect is unimportant. The hologram in Plate 3a was transferred from a Denisyuk original by this method.

Transmission transfer holograms

Master hologram This configuration suits translucent subject matter best. This time you will need to use both shelves for the mastering, the lower one to hold the subject matter, and the upper one for the film. You need the shelves more widely spaced, not less than 100 mm for a 4×5 final hologram. (This is about the largest hologram you can make with this setup.) Reset the mirror to 17° from the vertical, so that the light falls on the emulsion at the Brewster angle (56°). This larger angle of incidence not only suppresses any 'wood grain' effect, but also reduces the chance of the shadow of the subject matter falling on the holographic emulsion. The setup appears in Fig. 8.3.

Mount the film, emulsion down, on the upper glass, and turn it over, to position it above the subject matter with the film on the underside. In order to obtain maximum parallax you need to have the film as wide as possible in the "horizontal" aspect; but its height should be much less. (You can even get away with using 35 mm holographic film.) If you position the subject on clear glass you will have a dark background: if you use a matt glass the background will be bright and the illumination less directional.

Process the film in one of the master developers given in Appendix 5. You don't need to take special precautions against emulsion shrinkage this time, as laser transmission holograms are less selective with respect to wavelength than reflection holograms. Nevertheless, you should be wary of older develop–fix regimes, which will compel you to use unsuitable replay angles and may cause astigmatic distortion. If you give exactly the same exposure and development times as you give for a reflection hologram you will finish with a lower density, about 2.0–2.5, and this is fine for a transmission hologram.





Figure 8.3 Making a master transmission hologram with the single-beam frame. OB is the object beam, RB the reference beam. The subject should preferably be translucent.



Figure 8.4 Setup for a restricted-aperture transmission transfer hologram.

Transfer hologram The setup for a transmission transfer is similar to that for a reflection transfer, except that the position of the master and transfer films are reversed (Fig. 8.4).

You may need to lower the upper shelf a little, if the real image is to straddle the plane of the H_2 hologram. Mount the master in the same way as for a reflection transfer (but positioned, flipped, on the *lower* shelf), and center the beam on it. Put the upper glass in position and look down through it to see the real image. (This time you will probably have to stand on a stool.) To see where the image is situated in the plane, cut off the upper portion of the beam with a piece of card, and place a piece of tissue or tracing paper on the glass. If you raise and lower the glass you will see different parts of the image come into focus in turn. Pick a plane about halfway between the extremes.

Mount the transfer film in the same way as you did for a reflection transfer. Position it on the upper shelf with the film on the underside of the glass, line it up, and, after allowing settling time, make the exposure. Process the film as you did for the master. A good result will show a bright image when you illuminate it from behind at an angle of around 45° .

This technique falls somewhere between that of a full-aperture and a rainbow transfer; it can be called a *restricted-aperture transfer*. There is a small amount of vertical parallax, and the image is less highly colored than that of a rainbow hologram. It should be viewable by transmission using almost any kind of light, including a fluorescent tube (end on). The hologram in Plate 3b (colour) was made using this method.

360° holograms

'You may look in front of you, and on both sides, if you like', said the Sheep, 'but you can't look *all* around you – unless you've got eyes in the back of your head.'

Lewis Carroll, Through the Looking-Glass

There are a number of ways of making holograms with 360° parallax, holograms you can walk right round, seeing an image all the time. Some of these, such as

Remember, the "front" of the subject is farthest from you in the pseudoscopic image.



Figure 8.5 Setup for a coffee-table hologram.

cylindrical stereograms, are holograms made from assemblies of large numbers of photographs, and are quite complicated. These are dealt with in Chapter 19. Others are fairly simple in principle, and you can make them using single-beam techniques.

Coffee-table holograms These are holograms that are displayed flat, illuminated by a spotlight from directly above. They are not visible over a complete hemisphere, because your head gets in the way of the replay beam if you try a vertical viewpoint; but are very nearly so. They are straightforward Denisyuk holograms made with the reference beam perpendicular to the plane of the film. Use as large a piece of film as you can. Shallow subjects such as seashells look as though the objects themselves were let into the table under a glass cover. Fig. 8.5 shows a way of setting up the single-beam frame for this, but you can also employ the configuration of Fig. 8.6, using a circular piece of flat film rather than a cone, mounted on a glass plate with three supports. With either method you can go on to make a transfer, resulting in a spectacular real image floating over the table.

Single-beam conical holograms A conical reflection hologram is an impressive way of producing a full 360° image of a comparatively deep object. You need to choose a subject that matches the conical space fairly closely; and it is a good idea to use a white base in order to soften any dark shadows from the overhead lighting.

The simplest setup is with an overhead beam, as in Fig. 8.6a, which uses a diffusing reflector. This can be any matt white surface, for instance an aspirin or a vitamin C tablet (depending on your preferred type of hypochondria). The diffuse reflection



Figure 8.6 Setup for a conical hologram, (a) with a diffusing reflector, (b) with a quasi-collimating system and a quarter-wave plate.

has the effect of partially destroying the polarization of the laser beam, but it also spreads the beam uniformly without the need for a spatial filter. The down side is that the spatial coherence is lowered so that the final image is rather less sharp than it would be with a true point source for a reference beam. The reason we need to get rid of the polarization is that in one direction the incident beam is *p*polarized, and very little of it is reflected from the surface of the cone; but at right angles to this direction it is *s*-polarized, so that much of the light is reflected off the upper surface of the film and is wasted. Worse, a significant proportion of the light that does pass into the film undergoes internal reflections, generating unwanted wood-grain effects. A matt diffuser minimizes these unsightly artifacts, though it doesn't get rid of them altogether. A better solution is shown in Fig. 8.6b. By using a quarter-wave plate you even out the reflection over the whole surface. The operation of a quarter-wave plate is explained in Box 8.1.

If you buy a quarter-wave plate from a specialist optics manufacturer you will find it quite expensive. You can obtain one much more cheaply from a photographic dealer, who will call it a 'circularly polarizing filter'. It is intended for use with single-lens reflex cameras equipped with automatic exposure control, which is sensitive to linear polarization. In this device the retardation plate is mounted behind a linear polarizer (which you can't remove, and therefore need to align with the existing polarization of the laser beam). The linear polarizer has, of course, to be on the upstream side of the laser beam (i.e., the male screw thread on the flange is downstream). If you fit it the wrong way round it won't work.

Retardation plates operate with full efficiency only at a specific wavelength (usually yellow-green). You will probably need to fine-tune yours to red laser light by skewing it by a few degrees, otherwise it will produce elliptical polarization, which is somewhere between circular and linear polarization – not much use for our purposes. When a quarter-wave plate is correctly set up there will be no change in the intensity of the transmitted beam through a linear polarizer set up downstream of the plate when you rotate the polarizer. You may have to try various orientations of the plate before you find the correct direction in which to tilt it. Once you have found this, mark the flange for reference.

The best type of holder for the optical components is a metal burette stand as used in chemistry labs. These usually have a shaft 12.5 mm in diameter, the same as the standard pins that hold optical components. An ordinary magnifying glass is fine

You can buy retardation plates that are matched to specific wavelengths from optics specialists, if you are prepared to pay the higher cost.

Box 8.1 Retardation plates and circular polarization

So far I have discussed only linear polarization in detail, though I mentioned circular polarization in Chapter 3. Some substances, by virtue of their crystalline structure, possess two different refractive indexes, and light passing through such a substance (which is said to be *birefringent*) is split into two orthogonally polarized beams traveling at different speeds, so that one beam has its phase progressively delayed with respect to the other. When this delay amounts to exactly one quarter of a wavelength (plus an integral number of whole wavelengths) it changes the nature of a linearly polarized beam entering the crystal. What emerges is a beam in which the electric vector rotates through 360° from one wavecrest to the next, remaining constant in amplitude. A *quarter-wave plate* (one of a number of optical devices called *phase* or *retardation plates*) is a thin section of mica or some other birefringent material aligned to produce circular polarized light of a specific wavelength, mounted between two optical flats.

The same types of crystal can produce a second valuable effect. This requires the crystal to delay one of the beams by one half-wavelength (again, plus an integral number of whole wavelengths). The result is called a *half-wave plate*; this is another type of retardation plate regularly used in holography. It rotates the polarization vector of a linearly polarized beam without attenuating it. Rotating the plate in its own plane by x° rotates the plane of polarization in the same direction by $2x^{\circ}$. This property is useful for matching the polarization directions of the object and reference beams and for realigning the axis of polarization of a laser where it is impracticable to turn the laser on its side. The same effect is produced by two quarter-wave plates in series; this property is made use of in the Pockels cell (which was also mentioned in Chapter 3) and the polarizing cube beamsplitter, both of which you will meet again in Chapter 16.

for the focus adjuster. You need this if your spatial filter is less than about one metre above the cone, so that the final spread of the reference beam matches the intended distance of your replay source. Fig. 8.7 shows the shape you need to cut out if you are to get the largest possible cone from a standard 4×5 in film. If you want to make your cone from 8×10 in film, double all these dimensions. Cut a template from heavy card or metal, and use this to draw the outline on the base side of your film, using a broad black marker pen. Cut the shape out with scissors on the inside edge of the line, and make the center hole with a gasket punch or a leather punch. The purpose of this hole is to reduce the risk of the film splitting, so make sure the hole is clean or it will defeat its own purpose.

Sticking the two edges accurately together to make the cone isn't very easy in the dark, but you will find it less difficult if you make a second identical template from heavyweight card and stick it together to make a conical former. You can then wrap your cone on to this before sticking the edges together with cellulose tape. Keep the curved pieces you have cut off the film, and put them away in the film box, emulsion down, to use as test pieces for the next time you need to make a trial exposure.

When you have the beam aligned and expanded, its diameter should be rather less than twice the diameter of the cone at the base. The beam is concentrated, In optics diagrams a quarter-wave plate is usually indicated by the symbol $\lambda/4$ and a half-wave plate by the symbol $\lambda/2$.



(d)

Figure 8.7 (a) Template for a conical hologram for a 4×5 in film; (b, c, d) an example of a conical hologram.

Holographic film base material is cellulose triacetate, which tears easily, unlike the much tougher polyester material used for photographic film. Polyester can't be used for holographic material, as it is optically active, that is, it alters the polarization of light passing through it. (If you have ever looked through a toughened glass pane when wearing Polaroid sunglasses, you will know what I mean.)

You may be surprised (most people are) by the amount of film you need to line a comparatively small cylinder. Remember that the circumference of a circle is more than three times its diameter, and you need a little overlap as well. and the exposure will be comparatively short, so in spite of the flimsiness of the cone you won't need to allow more than the usual three minutes of settling time. Before you process the film you will need to remove the cellulose tape. Take care over this because of the risk of tearing the film. You need to choose the subject matter carefully, of course. The illumination is from directly overhead, so you should choose a subject that doesn't have much in the way of recesses, and is broader at the base than the top. The base or plinth should be matt white, to reflect as much light as possible into the shadows and improve the beam intensity ratio.

An interesting thing about conical holograms is that if after processing you darken the film in a haze-clearing bath (see Appendix 5) instead of using a black backing, the image will appear bright against a dark background, but if you hold the cone up to the light you can see right through it. This often comes as a surprise to people who are not familiar with holograms, and makes an interesting talking point.

Cylindrical single-beam holograms You can increase the parallax of a Denisyuk hologram if you wrap the film round the subject instead of having it flat – even to a full 360° , if you are prepared to make more than one exposure, and to rearrange the layout between exposures.

Here's how you do it. The first thing you need is a glass or acrylic cylinder with an inside diameter a few centimetres more than the width of your subject matter. Don't be too ambitious: an 8×10 in film produces only a slender 75 mm (3 in) diameter cylinder.

You will need to make a blanking plate that is roughly half a cylinder, to fit inside the main cylinder to cut off light from the rear of the film (Fig. 8.8). You can cut a suitable piece from a cylinder of the kind used for mailing rolled-up documents. Spray it on the outside with matt black paint. Now make 120° registration marks



Figure 8.8 Setup for making a cylindrical Denisyuk hologram.

on the main cylinder at its base, as well as on the base and plinth supporting the subject.

Set the laser beam to shoot down towards the cylinder from an angle of about 60° . Close the shutter. Fit the film into the cylinder, emulsion inwards, then place the cylinder over the subject with the join at the back (or opposite some comparatively insignificant part), and allow a full ten minutes of settling time. Make an exposure, then cut off the beam and rotate both cylinder and subject through 120° , but leave the blanking half-cylinder in the same position.

Allow a further settling time of three minutes or so, and then make a second exposure. Rotate the subject and cylinder a further 120° and repeat the process for a third exposure. Process the film as for a final reflection hologram and blacken the back or darken it with haze reducing solution, before reassembling the cylinder.

If you illuminate the hologram with three beams at the original angles it will appear as a complete walk-round image, though the joins may show a little because of the change in the shadows. If you use a single spotlight and rotate the cylinder slowly on its plinth you will see the separate images appearing in turn. There will be some fading between the images, though the continuity will be there (Fig. 8.9).

Double-sided holograms These are walk-round holograms. You can simply mount them between two glasses and place them so that people can pick them up and turn them over, or display them hanging vertically with a replay light on each side. This is a good way of showing off holograms of small *objets d'art* (Fig. 8.10). The technique depends on the fact that you can put more than one set of fringes into a hologram and replay the images independently, provided the reference beams are well separated.

The effect is most realistic if the image is a real image, i.e. stands out in front of the film plane; it works well for the pseudoscopic-object technique described in Chapter 7. Make a mold of your subject as described there, and divide it along the midline between front and rear. Blacken the cut edges with a waterproof marker pen. Expose the front of the pseudoscopic object, illuminated from "below". Now spin the film 180°, and make an exposure of the rear half in the same way, making sure you set up the subject in good registration with the front half (or at least as close as you can get).

If you can't make a mold of your subject because it has re-entrant surfaces (as in the complicated figurine of Fig. 8.10) you can instead make master holograms of the two sides separately, then make image-plane transfers on to both sides of the transfer film (again taking care over the registration).

If you find that the results aren't as bright as you had hoped, you can cheat a little and make separate holograms for the front and rear, mounting them together for display. Do try the single film method, though: it will give you some experience of the multi-image capabilities of the holographic process.

 360° cylindrical transmission holograms This type of hologram has a venerable history, having been described by Tung Jeong as early as 1966; some examples of early work still exist. The modern setup (Fig. 8.11b) resembles the one used for conical holograms. You use a similar illumination system, but instead of having a beam that diverges only slightly you have a strongly diverging reference beam, so that the angle of incidence on the inside of the cylinder isn't too steep. You do this by using a concave lens to spread the spatially filtered beam further (Fig. 8.11a).

The easiest way to do this is to rotate the whole setup, plinth and all, then re-set the blanking half-cylinder.

You may find that the second exposure needs to be somewhat less than the first. This is a characteristic of some types of double exposure technique, but the effect varies from one film to the next, and you will probably need to experiment.

You need much more space in a cylindrical transmission hologram than in a corresponding reflection hologram, as too narrow a cylinder will mean that the upper part of the subject blocks off the reference beam from the lower part of the film. This setup works best with translucent subjects (Fig. 8.11c).

Practical Holography .



Figure 8.9 (a, b, c) Three views of a cylindrical Denisyuk hologram. (d) The same hologram opened flat.

Use an opaque cylinder this time, preferably sprayed matt black on the inside; install the film with the emulsion inwards, as before.

The exposure needs to be generous, as a lot of light is lost by reflection from the surface of the emulsion. You may get some wood-graining, and again a quarter-wave plate will help.

To display the hologram, use a small-filament lamp such as a car tail-lamp bulb suspended over the cylinder. There will be some color dispersion, which may or may not be acceptable (it can be attractive with mineral crystals or coral). You can reduce the color fringing by covering the end of the cylinder with an amber gel.



Figure 8.10 (a) Front and (b) rear views of a double-sided hologram by George Clare.



Figure 8.11 Setup for a cylindrical transmission hologram. ($\lambda/4$ is a quarter-wave plate.) (b) Two views of cylindrical transmission holograms, flanking the original model. (c) The most satisfactory type of subject is translucent, and conical in general shape.

Further applications of single-beam holograms

Single-beam holography has a number of applications in science and technology; these are discussed in later chapters. The technique is also important in the commercial production of display holograms, and Chapter 13 deals with this aspect.

Mounting and finishing holograms

Reflection holograms The general instructions on pp. 79–80 apply. If you spray the back of the hologram black, don't use a quick-drying paint: glossy black is better than matt black. Make sure the back of the hologram is absolutely clean and free from fingerprints, grease, and any scum that may have been deposited by partly exhausted bleach or by hard water.

If by chance you get some paint on the wrong side – or even spray the wrong side by mistake – you can remove the paint with trichloroethylene or xylene. Don't use other fluids (not even methanol) as they may soften both the emulsion and the base.

A better way to back the hologram is to use a self-adhesive black PVC backing material such as that made by MacTac. To apply this successfully you need a very hard-bladed squeegee of the type used in silk-screen printing. Remove the backing from a sheet slightly larger than the hologram and tack the far edge of the sticky sheet down on to a clean glass sheet or melamine surface, using your thumbnail or the end of a ruler so that a strip about 3 mm wide adheres firmly to the surface. Slide the hologram, viewing side down, up to the line of separation. Then, holding the black sheet with one hand taut at about 30° to the surface, pull the sheet hard down on to the hologram with the squeegee held in the other hand. Some people prefer a roller squeegee, but I have always found that the sharp angle of the blade squeegee is more effective in preventing air bubbles from being included between the sheet and the hologram. If you do get a bubble, the only thing you can do at this stage is to lance it with a sewing needle and force the air out with your thumbnail. If you have been unfortunate enough (or careless enough) to have trapped a piece of grit, there is nothing you can do but peel off the black material (a tedious business that can take up to a quarter of an hour), and start again with a fresh sheet.

If you have used the haze removal technique described in Appendix 5, you will probably find that all you need for backing is a piece of plain black card.

A photo frame is as good a display mount as anything. A sunken mount is best, as it keeps the film separated from the glass. If you prefer flush mounting, you can mount the hologram on the type of self-adhesive expanded polystyrene board sold for mounting large photographs and posters, and fix this to glass or acrylic sheet with clips. You can get all these items, as well as MacTac sheets, from photo framing specialists. One of the problems that occur with this type of mount is that in hot or humid atmospheres the film sticks to the glass, resulting in ugly dark patches. The only way to avoid this (apart from using a sunken mount) is to mount the film directly on the glass using optical quality double-sided transparent adhesive material, which is also made by MacTac. You need to squeegee this to the glass first, after removing one side of the release paper. You then remove the other release paper and lay down the hologram using the same squeegee technique as with the black backing.

A final rinse in 1% acetic acid will help; don't wash the film after this, but simply remove the surface liquid with a blade squeegee.

Do this in a well-ventilated room or in the open air. Inhaling the vapor of either of these fluids is not a good idea. Laminating by hand isn't easy when you are working with large holograms. Certainly, if you were envisaging the production of large numbers of holograms for sale you would be well advised to buy a purpose-built laminating machine. A number of these are particularly suitable for holograms, and you should seek advice on this when buying one.

Transmission holograms These need illumination from the rear. There are two ways you can mount them: either between two sheets of transparent material (acrylic or glass), or on a mirror. In both cases the film is in contact with at least one of the surfaces, and may suffer from the 'damp patch' effect referred to earlier. You can avoid this by laminating them as with reflection holograms, using doublesided optical-quality adhesive sheet. You can also buy specially treated glass ('Anti-Newton'). More cheaply, you can use a solution of gelatin. Dissolve 10 grams of cooking gelatin in 100 cm^3 of hot water (not more than $70 \degree \text{C}$) in a beaker, with constant stirring. Pour a large puddle of the solution onto the prewarmed glass plate. Lay the hologram on it, center first, and immediately squeegee the fluid out to the corners, chasing out any bubbles. Remove as much fluid as you can: an old rubber-roller clothes wringer is an ideal adjunct, if you can lay hands on one. Allow the sandwich to cool, and remove any surplus that has oozed over the edges. You don't really need a cover glass, although it may improve the finished appearance of the hologram. If you are going to use a suspension mounting you need holes at the corners. You can hold the glasses together with decorative screws and nuts or with rivets, or with long clips of the type used for holding conference documents together, mitering them at the corners to fit closely together. If you want to hang the hologram on a wall and illuminate it from the front, use an ordinary rear-surface mirror in place of the rear glass.

Transmission holograms are not nearly as easy to display as reflection holograms, even with a mirror backing. You can illuminate white-light transmission holograms with a small-source filament lamp, but it isn't easy to get the alignment exactly right (more about this in Chapter 22). Laser transmission holograms probably produce the most spectacular images of all, but displaying them is decidedly tricky. Indeed, the only really satisfactory way is with a laser, and this usually means the construction of a darkened box.

Troubleshooting

'Bye-the-bye, what became of the baby?' said the Cat. 'I'd nearly forgotten to ask.' 'It turned into a pig,' Alice answered.

Lewis Carroll, Alice in Wonderland

In some respects holography resembles silver halide photography: a light-sensitive material is exposed to light, and a latent image is formed; this is then developed. But there the resemblance ends. This is particularly so with respect to the diagnosis of faults. An experienced photographer can look at a negative and say with certainty, often at a glance, that it has been underexposed or incorrectly processed, or that the camera moved during the exposure. This is seldom the case for a hologram.

Indeed, even experienced holographers may disagree over the cause of some minor defect, such as a noisy image. Nevertheless, there *are* methods of diagnosis that can

At the end of Chapter 6 there was a flowchart showing the elementary faults a beginner is likely to encounter, and how to correct them. identify the causes of the most common faults in holograms, though a photographer might not be familiar with either these effects or their causes. Here are some of the troubles any holographer may encounter on a bad day, with their possible causes:

- No sign of an image (reflection holograms) This, easily explicable in a photographic negative, can be baffling in holography. The answers to the following questions may provide a clue: Did the emulsion go black in the developer? If not, it may not have been exposed at all (it *can* happen!). If it darkened normally, the cause is almost certainly movement of the film or of the entire subject matter. Hold the film up to the light. Is there a faint grayish image? If this was a first-generation hologram (not an image-plane transfer), there was some out-of-plane movement, which destroys a reflection image but leaves a vestige of a transmission image. Unfortunately, this doesn't help with a hologram-plane image, which always produces a kind of photographic negative along with the fringes; but you can try examining it in a laser beam to see if there is a faint transmission holographic image. If the emulsion darkened only very slowly in the developer, the cause is gross underexposure, and what you have is only chemical or (un)safelight fog. If the emulsion turned black very quickly in the developer, either it has been grossly overexposed, or - more likely - the film has been fogged by accidental exposure to white light at some earlier time.
- Only a flicker of image from some viewpoints (Fig. 8.12a) The most likely explanation is that the subject moved during the exposure. The visible bit of the image is the part of the subject matter that remained stationary relative to the emulsion. If the visible part is a long straight bar, there are two possible explanations. If this part of the image changes as you move your viewpoint across at right angles to the bar (as if you were looking at the image through a slot), the subject has rolled slightly during the exposure. If the visible part doesn't change, your laser has mode hopped during the exposure. 'Mode hopping' is an abrupt change of wavelength that severely reduces the effective coherence length over the exposure. If the 'hop' is comparatively large, the image may appear striped with light and dark fringes. Mode hopping is most prevalent in diode lasers having poor voltage or temperature stabilization.
- *Part of the subject matter is missing (Fig. 8.12f)* If your subject is an assembly of objects and one of these becomes displaced during the exposure, the image-forming fringes corresponding to that object will be destroyed, and only a three-dimensional 'black hole' in the shape of the object will appear in the image. The appearance of this artifact is so striking that you will readily recognize it the next time around.
- Dark patches in the plane of the hologram (Fig. 8.12c) These are caused by out-of-plane movement of parts of the emulsion. If the patches have an irregular shape, you haven't squeegeed the film down hard enough, and it has separated from the glass in patches. If the patches are disk or doughnut shaped, you have trapped foreign particles between the film and the glass. This is a common fault, and is a good reason for using plates rather then film.
- Dark patches in the plane of the image (not illustrated) The dark parts represent parts of the subject matter that have moved or vibrated during the exposure. This is similar to missing details above, but the area is less determinate. This tends to occur if your subject matter includes paper or living matter such as flowers.

Single-beam techniques 2



Figure 8.12 Examples of faults in single-beam holograms. (a) Image is only a narrow band. (b) Feeble lowcontrast image. (c) Black doughnut shaped patches. (d) Wood grain effect. (e) Image unsharp. (f) Black hole caused by movement of part of subject matter. (g) Drying marks (also visible on (c)). (h) Burnout (arrowed). (i). The similar effects of gross overexposure (left) and underexposure (right), compared with correct exposure (centre).

- Image is feeble and has low contrast (Fig. 8.12b & i) Did the emulsion turn fully black in the developer within the appropriate time? If not, the cause is underexposure. If it turned black very quickly it was overexposed. Figure 8.12i shows the effect on a single subject where different areas of the emulsion were given gross underexposure, correct exposure and gross overexposure, development being the same for all three. If you know the exposure was correct but the image was still feeble (Fig. 8.12b), the subject was too dark or too far away from the emulsion. Try lowering the beam ratio by bringing the subject nearer and adding a light background.
- Parts of the image are hidden behind small gray or black patches that are also visible by transmitted white light (Fig. 8.12h) This is called burnout. In the areas in question light has been focused on the emulsion and has swamped the fringe structure locally. This effect is common in reflection transfer holograms where a catchlight is inadvertently focused on the H_2 emulsion. Try changing the transfer spacing, or retake the master with the position of the subject adjusted to avoid strong specular reflections.
- There are fine criss-cross lines all over the plane of the hologram (Fig. 8.12d) These are called 'wood grain' from their appearance, and are a form of the optical phenomenon known as *Newton's rings* (or sometimes, more pedantically, as *Fizeau's fringes*). You have probably got the polarization of your laser wrong (s- instead of p-polarization), or you may be using a dry film sandwich, as in the earliest experiments of Chapter 6, or both. This shouldn't happen if you are using anti-reflection glass, whatever the polarization. If it does, return the glass and complain.
- There are fine parallel straight lines about 1 mm apart over the whole area of the hologram Most probably you have set up your front-surface mirror back to front. If not, the trouble must have been caused by internal reflections in the glass film support. Check the polarization of the laser beam, and set the angle of incidence of the beam nearer to 56°.
- *After a while the hologram begins to darken* This is called *printout* and is caused by resensitization of the silver halide to light. Holograms that have been bleached in EDTA rehalogenating solution that hasn't been fully washed out are liable to this trouble: don't expose master holograms to an undiverged laser beam for more than a few seconds at any one point, or a dark brown spot will appear. Residual traces of triethanolamine, and atmospheric pollution, can also aggravate printout effects. The excessive use of Photo-Flo has also been suggested. A final rinse in deionized water acidulated with a few drops of acetic (ethanoic) acid is a good preventative. In bad cases you can try re-bleaching.
- *There is a scummy deposit on the emulsion surface* Insufficient agitation in the bleach bath (especially dichromate bleach that has been used repeatedly). If you notice this before drying the emulsion, give the emulsion a good wipe with a soft cellulose sponge in deionized water. If you have already dried the film, soak it in deionized water to which you have added wetting agent, and wipe it gently from time to time until all the deposit has gone.
- *The background doesn't show* It is probably so far from the film that the total distance there and back is greater than the coherence length of the laser. If it is merely faint, it is probably under-illuminated, and the beam ratio will have been too high for it to create strong fringes.

- Although the beam ratio, exposure, development and everything else were correct, the image was still weak The most common cause of this puzzling problem is instability of the system, i.e., very slight vibrations or creep in the components. In the systems described in this book, every effort has gone into designing stability into all the structures, and the single-beam systems in these two chapters are particularly robust. In most cases you don't even need the isolating inner tube. The most common causes of instability here are insufficient settling time and the presence of warm air currents in the subject space. Double the settling time; turn off all heaters; listen for loud noises; use a remote exposure control. If none of these precautions improves the image, the film may be stale or faulty. Send the film back to the manufacturer in its original box with a specimen hologram and a full description of the symptoms and your methods.
- The image is redder and somewhat unsharp in the deeper parts (reflection holograms) (Fig. 8.12e) The solvents in the spray paint you have used have attacked the fringes. Don't use quick-drying paint sprays that are based on acetone or similar harsh solvents. If you are already using a satisfactory spray, you may not have given the hologram sufficient time to dry out thoroughly before applying the spray.
- The image has patches of different color or density with irregular edges (Fig. 8.12g) This is the result of uneven development. Either you failed to immerse the film in the developer in one sweep (particularly with pyro developer), or it has floated to the surface during development, and not been properly covered with solution. Another common problem, namely streaks and blobs of different colors, is uneven drying, caused by not removing all surface moisture; you can sometimes alleviate this by re-washing.

Chapter 9 Bypass holograms

... there was only one road through the wood, and the two fingerposts both pointed along it.

Lewis Carroll, Through the Looking Glass

Figure 8.3 showed one method of making a laser transmission hologram with part of the laser beam illuminating the object and part going directly past it to form the reference beam, effectively producing two beams without the need for a beamsplitter. This configuration is suitable only for rim-lit or translucent subject matter. This chapter shows how you can get over this limitation, and produce a whole family of holographic setups based on similar geometrical principles. As this family of configurations seems to need a name I have coined the general term *bypass holograms*. Because the geometry is simple, and both parts of the laser beam travel through much the same space, you don't need a rigorous stabilization system. You can make all the types of hologram described in this chapter literally on the kitchen table, provided you have the individual optical components fastened down to a paving slab or an optical breadboard.

Box 9.1 lists the items you need to make all the holograms described in this chapter.

The only limitation on the subject matter (apart from size) is that it has to be mounted on its side; and the subject illumination, as with the Denisyuk configurations, is somewhat basic. The bypass principle in its simplest form was first described by Hans Bjelkhagen as early as 1977,¹ and was subsequently adapted for holographic interferometry by Nils Abramson.²

Box 9.1 Equipment required for a bypass hologram system

Laser, spatial filter and supports as for single-beam frame holograms 600 mm square paving slab or equivalent (inner tube optional but recommended) Three printed circuit board (PCB) holders and supports Three 2 mm float glass film supports, 125×150 mm Mirror, preferably front surface, at least 125×150 mm ND 0.6 optical filter, 50 mm square, and support Cylindrical lens 200 mm focal length, approximately 40 mm square (for rainbow holograms) You can obtain PCB holders from electronics suppliers. They are on standard 12.5 mm pins, which will fit the kind of short three-legged stand you can get from physics educational suppliers. To mount the PCB holders so that they can be turned in any direction you need universal clamps, obtainable from optics suppliers. If you have access to metalworking facilities you can make your own; a suitable design is shown in Fig. 9.1. Neutral-density (ND) filters cut down the

intensity of a light beam without affecting its spectral qualities. Kodak supplies gelatin ND filters with calibrated densities, but they are delicate and expensive. Cheap acrylic filters from your local photographic retailer are equally good for

'Breadboard', as I mentioned in an earlier note, is researchers' jargon for a steel or alloy slab carrying an array of threaded holes – a miniature optical table. Breadboards are useful for small setups that may need to be moved around without disturbing the relative positions of the components fixed to them. the purpose. You need an ND 0.6, which attenuates the light at 0° incidence by a factor of 4. However, as the filter is to be set at an oblique angle of incidence the greater effective thickness gives an attenuation factor nearer to 10.



Transmission master holograms

Figure 9.2 shows perspective and plan views of the basic setup for a master transmission hologram. Mount the subject on its side at 45° to the laser beam, coming from "above". Ensure that it is fastened firmly and cannot vibrate.

Next, install the mirror, also at 45° to the beam, and in the same plane as the midline of the subject. Now position the PCB holder that is going to hold the holographic film, in "landscape" format (relative to the subject, that is).

As a rule of thumb, it is best to start off with the distance between the subject and the film about the same as the diagonal of the film, or about 30% more for a master for a rainbow hologram.

Fit a white card into the hologram PCB holder. Set up the laser beam and spatial filter (without the pinhole) to illuminate the setup. Adjust the three main components (the subject, the mirror and the hologram holder) so that the subject is opposite the hologram and lined up, the mirror illuminates the white card fairly uniformly (examine its reflection in the mirror from the laser end) and none of the components casts a shadow on the subject matter. Adjust the laser beam until the lighting on the subject is also uniform, then fit and align the pinhole.

You now need to match the object and reference beam intensities. Unless your subject matter is very bright indeed, you will need to attenuate the 'reference' part of the beam by a factor of around 8–10. This is where the ND filter comes in. Mount it on a vertical pin in a holder. You can get pins with bulldog clips attached from optical suppliers (or make one yourself); but it is easier just to cut a slot in

Remember, directions enclosed in double quotes refer to the direction of the subject matter, not the environment. For sideways mounting, I have always found hot gluing to a brick painted matt black to be the best method. A hot-glue gun and a spray can of matt black paint are as indispensable to a holography lab as are large lumps of Blu-tack.

For transfers, you should always make your master holograms in landscape format, as this means that the transfer hologram image will have maximum horizontal parallax. Note that, as previously mentioned, the term 'film' doesn't exclude the use of plates; in many situations plates are more convenient to use than film.



Figure 9.2 Setup for a master transmission hologram. ND is a 0.6 neutral density filter set at the Brewster angle, BC is a black card for carding off stray light from the back of the film, H is the filmholder, O the subject matter, M a front-surface mirror. The same symbols are used in subsequent diagrams.

the top of a 12.5 mm pin with a junior hacksaw, and simply mount the filter in the slot, secured with a lump of Blu-tack.

For all bypass configurations the laser beam needs to be horizontally polarized, to avoid multiple reflections at the glass surfaces. This can be awkward if you are using a diode laser without collimating optics, as the polarization axis is the minor axis of the elliptical beam, and the spread of light is in the wrong direction. But if you have a polarizing filter as sold for SLR cameras you can solve this problem neatly. All you have to do is to place the filter in the beam so that the camera side of the filter (the side with the male thread) is upstream (i.e. towards the laser), and rotate the filter until its axis of polarization is along the long axis of the beam. This way you get both the polarization and the spread of light in the right direction, losing little light in the process.

Set the ND filter in a position where it will cover the whole of the reference beam but not the object-illuminating beam. You need to set it at the Brewster angle, which you can judge roughly to begin with. If you turn the filter carefully about a vertical axis, catching the front surface reflection on a piece of white card, you will find a position where the intensity of the reflected patch falls almost to zero. This is the Brewster angle, the setting you need. Without rotating it, adjust the position of the filter in the beam until its shadow precisely covers the reference beam.

You can now compare the two beam intensities at the plane of the hologram, using a photographic exposure meter. Take out the card, and point the meter in turn at the subject and the mirror, while you cut off the unwanted beam with a black card. If the two readings indicate a ratio of between 3:1 and 10:1 ($1\frac{1}{2}-3\frac{1}{2}$ divisions on the meter scale), everything is fine. Card off the edge of the beam so that it doesn't fall on the rear surface of the film.

If you need a reminder about the principles underlying this, have another look at Box 8.1 (p. 109). You will no doubt notice that another way of achieving the same result (with no light loss at all) is to use a half-wave plate.

The edge of the shadow of the filter will consist of a narrow band of diffraction fringes. Ensure these fall between the mirror and the subject.

With transmission holograms it is a good idea to keep a support glass that you have sprayed matt black on the back. This will be an extra guard against fogging light (in case your carding off has been less than conscientious). You also need to prevent light from getting in at the edge of the support glass (or the plate, if you are working with plates). It is a wise precaution to block off an "upper" edge by wiping it with a black felt pen or by sticking a strip of opaque insulating tape along it. *Rear-surface mirrors* You will already have spent a good deal of money on a front surface mirror for your single-beam system, and you may want to use the same mirror for your bypass system. You can do so, of course, but it may be a bit unwieldy for small holograms, and it will be exposed and open to damage. From what has gone before, you will probably have deduced that if you alter the angle of incidence of the mirror to 56° , the Brewster angle, you can get away with a rear surface mirror. And so you can. Set up the mirror using the undiverged laser beam, and adjust its angle until the front surface reflection disappears.

This set-up is very robust. It is capable of producing really bright masters without any isolation from vibration. You can set it up on the concrete floor of a machine shop (not an inner tube in sight) and still get bright holograms.

Reflection master holograms

The setup for a first-generation reflection hologram is shown in Fig. 9.3. As you can see, there is a discrepancy between the optical path lengths of the object and reference beams; but as long as this discrepancy is less than half the useful coherence length of your laser, it is unimportant.

As the light falls on both sides of the emulsion you will have to use plain glass (i.e. not sprayed black) as the support for your film. If you work at an angle of incidence of 56° rather than 45° you will be able to position the subject nearer to the holographic film, resulting in more parallax. You can use some overspill light to fill in the shadows, but (again) make sure none of it falls directly on the emulsion.

The beam intensity ratio needs to be lower than for a transmission hologram. The optimum ratio is between 1.5:1 and 2.5:1. You can check this ratio by positioning your meter cell at the film plane and pointing it first at the subject, then at the laser. The two readings should differ by no more than one block, or at most one-and-a-half blocks. By eye, the reference beam side of a white card in the filmholder should be just noticeably brighter than the brightest part of the object beam side. You can adjust the beam ratio by nudging the front of the laser so that more light falls on the subject and less on the reference side, or vice versa. It doesn't matter if the reference beam isn't absolutely uniform, as long as it is nowhere weaker than the object beam.

As a rule, the bypass technique gives brighter reflection holograms than the Denisyuk set-up, as the beam ratio is under better control. There is, of course, less



This means a "higher" lighting angle for the subject, so make sure it doesn't produce unwanted deep black shadows. If it does, consider adding "side" reflectors as I suggested for the single-beam frame. Use matt white, as a shiny reflector can change the angle of polarization, with the result that instead of adding to the illumination it merely adds fog. Two beams don't produce satisfactory fringes unless their polarization vectors are approximately lined up. If the two polarization vectors are at right angles there will be no fringes at all. Make sure no strav light from any of the side reflectors reaches the emulsion.

Hans Bjelkhagen's pioneering setup was intended for factory-floor holographic images of large machine tools.

The 'useful' coherence length of the beam from a HeNe laser of between 5 and 50 mW is of the order of 30 cm. For a solid-state laser at 532 nm it is likely to be several metres. For a diode laser it may be anything from 4 cm to well over a metre. In cases of doubt you should always carry out an interferometer test as detailed on pp. 153–6.

Figure 9.3 Setup for a master reflection hologram.

This isn't always easy to do. With a little practice you can use a plain glass instead of a ground glass; when you look through this you will see a bright pseudoscopic image. Make a mark on the glass, and when you move your head from side to side you will be able to see which parts of the image are in front of it and which are behind. But don't forget that the image is inside out. In the final image the parts of the image that now appear behind the glass will then be in front.

As mentioned in the previous chapter, 'burnout', which appears as a small black patch in the plane of the film, can ruin the appearance of an image. Moving your viewpoint to one side reveals the detail that caused the burnout. There is an example in Fig. 8.12. parallax. You may need to pre-wash and dry the film before mounting and exposing if you are going to use the hologram as a reflection master, and you need to use the appropriate processing system for a master reflection hologram as detailed in Appendix 5.

Reflection transfer holograms

The layout (Fig. 9.4) is very similar to that of Fig. 9.3, the reflection master hologram (flipped) taking the place of the subject. If you use a card (or, better, a ground glass) in the transfer holder while you are setting up, you will be able to see the image projected on it. You can adjust the separation of the two holders so that any detail you want to appear in the hologram plane is focused sharply, just as you did for single-beam transfers (Chapter 8).

It may not be easy to estimate the beam ratio by eye, as the object beam intensity varies over the image area. If you are using a meter, take a reading at the brightest part of the image, and adjust the reference beam intensity to be just a little brighter. If the reference beam intensity is too low you will risk 'burnout' in the highlight area. Make a test of this area using a small offcut of film, and if it shows burnout, decrease the object beam intensity. Conversely, if the image is feeble overall, increase the object beam intensity.



Figure 9.4 Setup for a reflection transfer hologram. H₁ is the master hologram, H₂ the transfer hologram film.

Full-aperture transmission transfer holograms

The layout for this, as you will see from Fig. 9.5, is similar to the transmission master layout using a single-beam frame (Fig. 8.4). It produces neutral gray images when illuminated with white light. The originals have to be shallow, and the



Figure 9.5 Setup for a full-aperture transmission transfer hologram.



Figure 9.6 Setup for a rainbow transfer hologram. CL is a truncated cylindrical lens.

projected image close to the final hologram plane, or the result will be bordered by unwanted color fringes.

Use glass blackened on the back for the transfer film support. The beam ratio should be around 3:1, lower than that for a master transmission hologram. Measure this for the brightest part of the image. If you are judging by eye, you should just be able to see the highlights on a piece of white card in the filmholder.

Rainbow holograms

The mastering set-up is essentially the same as for full-aperture transfers, except that you need to have the subject somewhat farther away from the film (typically 30% more than the diagonal of the film); you also need an angle of incidence of 56°. You need an extra piece of equipment: a cylindrical convex lens with a focal length of around 200 mm. It needn't be high quality, as its only purpose is to concentrate the object-illuminating beam down to a slit. Only about three-fifths of the width of this lens is used, and, rather than trying to do the necessary reduction yourself, you should get a professional glazier to remove the surplus for you with a diamond saw.

Set up the system as for a full-aperture transfer, then insert the lens into the objectilluminating beam so that it forms a "horizontal" slit about 6 mm wide, aligned roughly down the middle of the master. This time the image on the white card will appear sharper.

Reflection holograms from transmission masters.

In order to produce a reflection transfer hologram from a transmission master you need to illuminate both the master and the transfer film from the outside. To avoid having to sacrifice the center area of the laser beam, its best part, it is worthwhile introducing a wedge prism into the part of the beam that will illuminate the master (Fig. 9.7a).

This arrangement gives a good optical path match. If you don't have access to a wedge prism you can manage equally well by mounting the master hologram on a rear-surface mirror with index-matching fluid (you can use your front-surface mirror, flipped), and using the setup of Fig. 9.7b. The optical path match isn't so good, but it should be within the coherence length of your laser.

The steeper angle is necessary because the usual angle of replay lighting is $45-50^{\circ}$. This will make the image appear in yellow-green rather than red when viewed from the same level, and as the eye is more sensitive to this region of the spectrum, the image will appear brighter. With the geometry described, the color of the image will be uniform when the hologram is viewed from a distance equal to about three times the diagonal of the film.

A wedge prism is a prism with a very small refracting angle, typically 3°. You can obtain these from optical suppliers. You can also use the lower half of a Fresnel biprism (see p. 8).



Figure 9.7 (a) Setup for a reflection transfer from a transmission master. BC is a black card, WP is a wedge prism. (b) Alternative setup. RM is a rear-surface mirror.

You will have noticed that all the setups I have dealt with use diverging beams. There are strong arguments in favor of using collimated (parallel) beams rather than diverging ones, and in later chapters I explain the reasons for this. Most advanced geometries require at least some of the light beams to be collimated, and once you have acquired some collimating optics you will probably want to use a collimated beam in your bypass configurations too.

Transflection holograms

While experimenting with these configurations I tried switching H_1 and H_2 in the arrangement of Fig. 9.7b. (See Fig. 9.8.)

If you examine this set-up, it is plain that it will result in a full-aperture transfer hologram and a coincident reflection hologram in the same emulsion. As the fringe planes of the two holograms are more or less at right angles to one another, both images should be bright. The idea of an image that could be seen equally brightly from either side, with a single spotlight for illumination, was appealing, especially as both images would be orthoscopic, so I investigated it further. To describe the result I coined the term *transflection hologram*.³



Figure 9.8 Setup for a transflection hologram.

When I made a transflection hologram I was surprised to find, not just two, but *eight* equally bright images. First, there were the two primary images already described. Second, when the hologram was flipped there were inverted, orthoptic, pseudoscopic images of the two types. Third, when the hologram was spun there was an erect, pseudoptic, orthoscopic image of each type; and finally, when the hologram was rotated there was an inverted, pseudoptic, pseudoscopic image of each type. (All of these with a single spotlight at 45° above.) It took me a little while to work out where they had all come from. I leave you to work it out for yourself, too.

Other configurations

As I mentioned at the beginning of this chapter, other configurations such as focused-image and Fourier-transform setups are possible, though these don't fit easily on a paving slab. You will find methods for making these holograms in later chapters.

References

- 1. Bjelkhagen, H.I., 'Experiences with large-scale reflection and transmission holography' *Proceedings of the SPIE*, Vol. 120, 1977, pp. 122–6.
- 2. Abramson, N., *The Making and Evaluation of Holograms* Academic Press, 1981, pp. 90–91.
- 3. Saxby, G., 'Bypass holograms: a family of stable optical configurations for holography in unpromising environments' *Proceedings of the SPIE*, Vol. 1732, 1993, pp. 411–22.

To save you having to check back, here are the definitions again. Flipping is turning through 180° about a horizontal axis; spinning is turning about a vertical axis; rotating is turning in its own plane. Orthoscopic and pseudoscopic mean respectively having correct and reversed parallax; orthoptic and pseudoptic mean respectively having correct and reversed right/left orientation. If an image is inverted by simple rotation it retains its "right/left" configuration. This tedious list is necessary because many textbooks get these concepts confused.
Chapter 10 Building a holographic laboratory

'And you'd best be unpacking the things that you need To rig yourselves out for the fight.'

Lewis Carroll, The Hunting of the Snark

All the setups described in the foregoing chapters produce excellent holograms, and you can easily rig any of them up for a practical demonstration in a school or college laboratory. But if you intend to take up holography seriously, as a hobby, as a medium for fine art, or as a research tool, you need a good deal more in the way of equipment than I have suggested in these chapters. This chapter discusses these requirements in detail.

Laboratory space

The first thing you need to think about is the laboratory space. The smallest floor space you can consider is about 40 square metres (400 sq ft). This will take care of the optical table, workbench and processing area, and the necessary shelf and cupboard space.

If you are considering the construction of a full-blown professional setup, you will need a minimum of four times this area in order to include separate transfer and copying tables, possibly a pulse-laser studio (Chapter 16), finishing and office areas, a storeroom for models and cabinets for master holograms, and an area for model building. You will, of course, have to ensure that the accommodation complies with local health and safety regulations. This is an exercise comparable with setting up a professional photography studio, and will cost about the same.

The first thing you need is an adequate power supply, at least three double power sockets. If you are intending to work with a large ion laser you will need a separate three-phase supply. You also need a filtered water supply, and a solid concrete or paved floor, preferably bituminized to reduce dust. You must have an efficient blackout, of course. You will need to install some form of temperature control, and adequate ventilation, particularly in the processing area.

This sounds a formidable list, and an expensive one, too. But you may not need all this at first. Many enthusiasts have begun by converting a garage or outhouse. Don McNair¹ gives a very full description of such a conversion. If you are fortunate enough to live in a house with a stone-floored cellar, you have an ideal site as long as your house is situated well away from heavy traffic, and provided you can isolate the space from sources of convection currents such as freezers and central heating boilers. A heavy curtain will usually do the trick.

Loud noises are not usually a problem, but if they do turn out to be troublesome, you may need some sound insulation. If you can't afford acoustic wall paneling, egg boxes are just as good, and will help to keep the room temperature steady.

I am using the term 'laboratory space' here to include not only the optical table, but also a workbench, an area for loading and processing films, and storage space for unexposed films and for chemicals.

Even if you are setting up a small facility in your own home as a hobby, you need to check that your home insurance will cover it.

You needn't be over-concerned about earth tremors from traffic. My first lab was separated by only a few metres from a bus terminus. John Kaufman has a lab situated right over the San Andreas Fault!

The optical table

All the larger optical companies supply tables suitable for holography. Some companies specialize in this area. Their products are all very expensive. Consequently, many people starting out in holography either use a table originally intended for a different purpose, or build their own from scratch. There seems to be no limit to ingenuity in both cases. Many holographers opt for an engineer's steel marking out table. You can often find one secondhand, going for no more than its scrap value.

But all kinds of material seem to have been adapted for holographic tables, from old snooker or pool tables and laundry presses to stacks of old railway sleepers and even discarded headstones from refurbished churchyards. One of my fellow holographers began his career in professional holography with a table consisting of a large wooden box crammed with plastic containers filled with water. Another, eschewing tables altogether, built from shopfitting equipment a rigid frame that was portable enough to be carried around for demonstrations. Others have simply set up their optics on a stone floor (this is not recommended for enthusiasts with back trouble).

If you anticipate moving the location of your lab at any time, you will need a table you can dismantle. You can build such a table from pre-cast concrete blocks held together with tie-rods, or you can clamp together rectangular beams as sold for door lintels. The sand table described below is one of the most versatile tables. A sand table is simply a large rigid box filled with sand, into which you push the optical components, mounted on posts. The sand is a good damping medium, and its weight provides the inertia needed to prevent vibration. Many holographers would use nothing else, though others view the presence of such quantities of sand with feelings similar to those of the Walrus and the Carpenter. It is true that the compatibility of sand and delicate optical surfaces is questionable; but a sand table is excellent for carrying out experimental setups.

Building a sand table

Various designs of sand table have appeared in the literature, often with comprehensive building instructions. The simplest type of sand table is known as a tension table, a design attributed to Lloyd Cross and described in detail by Unterscher *et al.*² Fig. 10.1a shows the construction. The material is 20 or 25 mm heavy-duty chipboard (particle board). Threaded rod comes in lengths of about 2 m. Five lengths will suffice for a table 1.25×2.5 m in size and 300 mm deep. You don't need to glue the box together, as the tension of the rods holds it rigid (hence its name). But you must take care to mark out and drill the holes accurately, or the tensions won't be at right angles, and the box will collapse while you are building it.

Assemble the sides first, then the top and bottom pieces, with the nuts finger tight, making sure everything is square and true. Go round all the nuts in turn, giving each nut half a turn each time with a spanner or wrench, until they are all tight. Since you are going to mount the box on inner tubes it is a good idea to countersink the nuts and washers on the underside so that there are no projecting heads to damage them.

Moving it into your lab, though, is another matter.

Getting a full-sized table out of a building and into another is no joke. I have seen tables stuck on stairways, door frames and walls having to be demolished, even on one occasion a table in a goods lift jammed between two floors for six weeks while frantic efforts were made to free it.

I used one myself to do the research for my early writings on holography. It is shown in Fig. 10.1b, set up for a focused-image hologram with a liquid-filled lens (see Chapter 15).



Figure 10.1 (a) Tension sand table (after Unterseher *et al.*²). The material is heavy-duty chipboard (particle board). (b) My first experimental sand table, set up for a focused-image hologram. Its dimensions were $1.5 \times 2 \times 0.5$ m.

The simplest form of stand for the table is concrete or breeze blocks, standing on their ends. As you are going to have nearly a ton of sand in the box, you will need six of these, and you will need a second full size piece of board to support the inner tubes. Arrange the supports somewhat inboard of the edges of this, so that the tubes can be centered on the supports. An alternative support is a Dexion frame as shown in Fig. 10.2, described in an earlier book of mine.³

Stand the blocks or frame on squares of carpet: this will avoid any possible trouble from unevenness of the floor. Place more squares on the tops of the blocks before you position the baseboard on them. Next come the inner tubes. Choose mid-size scooter tubes, say $3\frac{1}{2} \times 10$ in. Inflate them so that they are firm but not hard, and set the box on top.

This reference explains the way to build your box using tongued and grooved floorboard timber rather than chipboard.

Samples of discontinued carpet lines from home furnishers are very cheap, and sometimes even free.



Figure 10.2 Concrete-based table (after McNair¹) supported on a frame built from heavy-duty angled strip ('Dexion') (after Saxby³).

But how to re-inflate the tubes when you have to? Well, when I built my original box, I cut holes in the baseboard below where the valves would be, and bought tubes of the kind with long cranked valves so that it would be fairly easy to reach them with a foot pump. In the event this wasn't necessary, as it was easy to lever the box up with a batten of wood sufficiently to be able to slide each tube out in turn, re-inflate it and slide it back into position.

Once everything is in place you can start filling the box with sand, to within about 2 cm from the top.

The sand can be any kind, as long as it is thoroughly dry. Builders' washed river sand is the cheapest, but it becomes dusty after a time, and you are better off to shoulder the extra expense and buy coarse white silica sand. This comes in bags rather than by the truckload, so it won't be dumped in a great heap in your driveway while you are out. For the dimensions I have given you will need approximately 1 cubic metre (about a ton). It may seem too much at first, but when the sand settles down you will need to top it up.

If you have inflated the tubes correctly, you should just be able to get three fingers in between the baseboard and the box, but don't worry if it is a bit high or low. As long as the box rocks just twice and no more when you push it, fine.

The box I have described may be a little bit oblong for your designed layouts; but of course, you can make it with any ratio of sides you like. 3.2 square metres is about the maximum area for this type of table, though: any bigger and the sides may begin to warp.

If you want a larger or more permanent table, you can make one on a concrete base. McNair² gives a detailed account of the building of such a table, explaining how to cast a concrete base. If you can find an old snooker or pool table with a

It is a good idea to line the box with polythene sheet before you fill it with sand, in order to prevent any leakage at the joints.

Keep the bags the sand was delivered in. You will need them if you have to move your lab.



Figure 10.3 Optical component inserted into 38 mm plastic piping.

slate base you are in luck, as you will not need to go to this trouble. You can simply build the sidewalls on to the base, using concrete blocks and ready-mix mortar from the local DIY shop. Figure 10.2 shows such a table, supported on a Dexion frame. The dimensions of the frame are 900×1800 mm, and it is 300 mm high. You will need four pieces 1800 mm long, six pieces 900 mm long, six pieces 300 mm long, 24 gusset plates and 80 bolts and nuts, i.e. one gusset piece and three bolts and nuts for each corner and eight bolts and nuts for the corner stays.

Supporting the optical components

The best support material for small optical components such as steering mirrors and beamsplitters is 38 mm $(1\frac{1}{2} \text{ in})$ PVC piping, which you can get from builders' merchants and DIY stores. Use a junior hacksaw to saw the end that is to stick into the sand at a 45° angle, and clean up the rough edges with a sharp knife. Saw the other end straight across. The more expensive optical components such as steering mirrors are usually supplied on 12.5 mm pins for use with optical bench mountings. For these you should make wooden bungs that are a tight fit in the pipes, and are bored to take the pins. You can mount plain mirrors on wooden posts. To hold homemade components such as diffuse reflectors, screw bulldog clips to lengths of 15×36 mm batten that have had the edges rounded off. You can fit these into the pipes by putting your foot on the pipe and inserting them: when you release the pressure the batten will be held firmly (Fig. 10.3).

Large components such as collimating mirrors need a firmer support. You can fix them to a piece of planking cut to the shape of an outsize plant label (Fig 10.4a). Spatial filters need a very firm base (Fig. 10.4b).

There is a good deal to be said in favor of sand tables. It is easy to set up any of the simpler types of hologram on a sand table. You can make adjustments to



Figure 10.4 Supports for maximum steadiness on a sand table: (a) 'giant plant label' for large flat components such as collimating mirrors; (b) flat wooden base with spikes; (c) Cotton glove filled with sand steadying component on post.

components simply by tapping them with a pencil, and to large components manually, without the need for complicated gimbal mountings. The main disadvantage is the very long settling times. Sometimes changes in humidity or temperature can cause the sand to shift after a period of apparent stability, so that you may come back from lunch to find, for example, that your spatial filter and/or steering mirrors have gone out of alignment, and you have to start again. A useful tip (due to Pascal Gauchet) is to buy some cheap cotton gloves, fill them with sand and tie up the wrists. You can then use them as steadying weights, molding them to the shape of the components (Fig. 10.4c).

Building a concrete table

The great thing about a sand table is its versatility, and a number of distinguished creative holographers still use them, at least for trying out new ideas. But in the end you will probably feel the need for a hard-surface table. And, almost invariably, the cheapest way to get exactly what you want is to construct your own.

If you already have a sand table, you can convert it to a rigid one by laying a sheet of steel on top of the sand. Rake it absolutely level first. Use a plank and a spirit level, but don't obliterate the rake marks, as they will help the sand to settle. The steel sheet must be at least 3 mm thick. Even so, heavy components can distort it when they are moved around, and you may still need long settling times. In the end you may well decide to consign the sand to the children's play area and build a concrete table after all.

If you have ever laid a concrete path or floor, casting a concrete table should present no difficulties.

You need to make a mold first. If you simply want to replace a sand table with a concrete table the same size, all you need is to pour the concrete into the box. You don't even need to remove the sidepieces or the base when the concrete has cured.

If you are starting from scratch, and your floor is smooth and level, you can spread a sheet of heavy-duty polythene on the floor and use four planks for the sides, holding them together with right-angle brackets, or, better, with carpenter's sash cramps (which you can hire from tool hire specialists).

It isn't quite as straightforward as that, though. Concrete is a brittle material, and it needs reinforcing with metal bars or mesh to compensate for its weakness in tension and shear. You can buy proper reinforcement bars or mesh from builders' merchants. One layer should be enough. You can support the mesh in position on long nails driven through the planking from the outside. If you use bars, cut them a little on the long side, and drill holes in the planking to support them. You can use the projecting ends to lift the slab into its final position, then remove them with a hacksaw and file them flush.

If you haven't had much experience working with concrete from basic ingredients, it is best to order it ready mixed. There are many firms who will arrange this, and it is worth shopping around for the best price. You need a mixture that will give the hardest possible result, especially if you are planning to work directly on the concrete surface. Go for a high-granite aggregate. For professional quality holograms up to 30×40 cm or more, your table will need to measure at least $2.25 \times 2.75 \times 0.25$ m deep. For this size table you will need about 1.5 cubic metres,

These look decidedly eerie in the dim light, so forewarn any visitors who may be of a nervous disposition.

But if you are a complete novice, don't rely on a DIY handbook: get an experienced friend to help you.

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If stopping is unavoidable, cover everything with a wet sheet until you are ready to start again.

If you are going to use your components directly on the concrete surface, you must use a pure granite mix; but even this can be scratched by spiked gravity bases.

Given the help of half-a-dozen wellbuilt friends and the use of a lowloader truck, you can do it yourself; but see that your insurance covers you before you start. The promise of a small wine and cheese party held on the newly installed table may swell the ranks of volunteers.

 $\frac{1}{4}$ /20 means 0.25 in diameter, 20 threads to the inch, the same as the old British $\frac{1}{4}$ in Whitworth, or British camera tripod thread.

or around 2 tons. If you don't intend going beyond 8×10 in size, $1.5 \times 2.5 \times 0.2$ m will be large enough, and this will need about half the quantity of mix. If you buy ready-mix in bags rather than having it delivered in bulk, the supplier will usually take back any surplus, provided it is still in sealed bags.

You must pour all the concrete in one go. If you stop for a coffee break, particularly if the weather is hot, a weak line will appear where you stopped, and the table may develop unpredictable resonances.

Tamp the mix down all over several times during the pouring operation, and when you have finished, level the surface off with a length of wooden batten to smooth it. Check with a spirit level. After about an hour, use a wooden float (a square of plywood with a handle nailed to it) to smooth the surface, and to bring the cement to the top. Sprinkle the surface with water from a fine-rose watering can every three or four hours to prevent the cement from drying out and cracking.

After 24 hours you can remove the wooden sides and smooth the surface with a breeze block, using a circular motion like a sander. Now stay out of the area for a week, no matter how tempting it may be to sneak in and have a look. There won't be anything to see in any case, as curing is a slow chemical process invisible from outside.

Most workers opt for a steel top, as this is less prone to damage than bare cement, and enables you to secure your components using magnetic rather than gravity bases.

You can use ordinary 3 mm mild steel plate, which is comparatively cheap, but you have to keep it absolutely dry, otherwise it may begin to rust within hours. It is worthwhile paying extra for ferromagnetic stainless steel plate. (Check with a magnet that the sample really is ferromagnetic.) Fix the steel plate down with mastic adhesive. Consult your local builders' merchant about the most suitable type of adhesive, and how to apply it.

Metal tables

Engineer's tables One of the best kinds of ready-made holography table is an engineer's marking-out table. These are made from cast iron or steel about 40 mm thick, usually with ribs underneath for extra rigidity. They are machined to a highly flat surface, and usually stand on six cast iron legs. The smallest, $0.9 \times 1.8 \text{ m}$ ($3 \times 6 \text{ ft}$), weighs about half a ton. They are very expensive to buy new, but so many have gone out of use during recent times that you can often buy one for no more than its scrap value (if you can get to it before the scrap merchant does). As I said earlier, the expensive part is taking it away and installing it.

Purpose-built tables These are expensive, but they are what you will need if you are involved in scientific research, nondestructive testing or quality control. You may be able to find one secondhand. They are usually constructed of two ferromagnetic stainless steel plates separated by a metal honeycomb structure, bonded with epoxy resin. The upper surface is usually drilled and tapped at 50 mm intervals with a 6 mm thread (2 in and $\frac{1}{4}/20$ in the USA).

If you propose to use only magnetic bases you can order a table without holes, and this will be less expensive. These tables are much lighter than engineer's tables: a 1.5×3 m table weighs about 330 kg (750 lb).

Table supports

Engineers' marking-out tables come with their own legs, usually six of them. To construct isolation supports for these, all you need are four disks of 18 mm plywood (or squares with the corners rounded off), with a 75 mm hole cut off-center so that you can get at the valves of the inner tubes. It isn't particularly difficult to lift the table on to these supports on your own, with the aid of a car jack. Once you have maneuvered the table into position, set up the car jack at one end, on a pile of cement blocks or house bricks, and jack up one end of the table enough for you to be able to position the end tubes and the disks. Release the jack, and move it to the other end of the table. Now jack this end up, and position the remainder of the tubes, including those in the middle. If the floor is uneven, it will pay to set the tubes on carpet squares. Fig. 10.5a shows this support system.

If you have ordered a research-grade table and still have plenty of funds, you can buy stabilized supporting legs that are dedicated to this type of table. These are pneumatic, self-leveling and hydraulically damped, with a price tag to match. For the hobbyist, or even the professional, they are a waste of money. They don't actually give any better isolation than ordinary inner tubes, and they need far more maintenance. Four scooter tubes will easily support a table weighing half a ton, and won't cost more than a restaurant lunch. If your table consists of a simple slab, you may decide simply to jack it up a few centimetres, slide the tubes into place, and work at floor level. There is no real objection to this arrangement. It does make it easier to adjust any overhead components, and it reduces the likelihood of anyone accidentally looking into the laser beam, but, just as with a purely floor-mounted setup, it can be hard on the back. A working surface that is some 80–100 cm above floor level is more comfortable, and has the advantage of giving you useful storage space beneath the table.

For this type of table the best support is four legs made from stoneware pipes filled with ordinary sand and topped with 450 mm square concrete paving slabs. You can obtain 230 mm (9-inch) inside diameter salt-glazed pipes from builders' merchants. In the UK these are 1 m long, and need to be cut down to about 60—70 cm, depending on the depth of your table.

The positioning of the supports is critical for stability. If they are not positioned correctly there will be an uneven stress on the table. For a completely bare table the legs would be centered on the center of gravity of each quarter of the table.





Figure 10.5 Supporting a table: (a) Engineers' table with legs; (b) slab table (see text).

Again, if you can coerce six hefty friends into helping out, this task will be much easier. Don't forget to lay in the wine and cheese.

If you buy these from an engineering supplier rather than an optics specialist you will probably find them cheaper. This positioning will be correct if the table is to be used without any superstructure. However, if you are going to install the gantry system I suggest below, you will need to position the supports about ten per cent farther out towards the corners of the table (Fig. 10.10).

Mark these points on the upper side of the table and measure their distance from the table edges. Then, while the table is still on the floor, mark the position of its edges. Place the pipes, broad end down, on carpet squares. Put a large polythene bag inside each, and fill the bags with sand. Put a further carpet square on each of the pipes, then a paving slab, and finally an inner tube, pumped up fairly hard, but not so hard that it develops a bulge. Now you can begin to jack up the table a little at a time, placing blocks under the corners as you go, until it is high enough to slide the pipes underneath, complete with inner tubes, carpet squares and paving slabs. Once it is high enough, mark the positions for the legs on the floor, and then the underside of the table (use a plumb line). Now, if you sit on the floor, you can push the pipes into position with your feet. Lower the jack, remove the blocks, and repeat at the other end. Figure 10.5b shows this system of support.

Bases for optical components

If your table has a steel surface you will find magnetic bases (Fig. 10.6b) convenient. For any components you have to move about a great deal, choose the kind that have a push-button or lever release.



Figure 10.6 Magnetic bases: (a) limpet magnet; (b) engineers' magnetic base; (c) angled bracket magnet.

They are supplied with a threaded 6 mm hole ($\frac{1}{4}/20$ in the USA), to take a standard 12.5 mm optical pin. If the component doesn't have to be moved much you can use much cheaper 'limpet' magnets (Fig. 10.6a), which are powerful ring magnets built into circular cups. Components on nonmagnetic bases can be wedged in position by small ceramic magnets. Another useful accessory is a pair of ring magnets mounted between angled brackets that will hold steel components at angles of 15°, 30°, 45° and 60° according to the orientation of the bracket (Fig. 10.6c).

Some larger components, for instance burette stands, large mirrors, triangular benches and lab-jacks (Fig. 10.6d), are unsuitable for magnetic fixing, and are kept

Don't automatically go to optics suppliers for these components. You can often find them in army surplus stores, artists' materials and drawing office suppliers, or tool and hardware stores, for a fraction of the price. in position by their own weight, often by heavy iron bases (gravity bases). These are often equipped with three setscrews or spikes, for stability on uneven surfaces. Beware of scraping these across the table: they can do a good deal of damage, especially to a cement surface.

Excluding drafts

One of the most common causes of poor quality results is the existence of stray air currents. Over your table area, a change of local temperature of as little as 1 °C can alter the optical path by several wavelengths, and any such variation during an exposure will destroy a holographic image. The best way to prevent this trouble is to isolate the table area from all drafts. Ordinary black curtains suspended from the ceiling work well enough, but they gather dust, and working inside them is uncomfortable and claustrophobic. Some workers build a complete cover from acrylic sheet, with lifting tackle to hoist it out of the way for setting up. This is a popular method in research labs that are liable to drafts; but it is cumbersome, and acrylic sheet is expensive.

A better solution for small tables is to build a Dexion frame around the table and suspend PVC strip curtaining around it. This material is clear, tough and self-sealing. The best width is 100 mm \times 1.5 mm thick. Punch holes at the top end to match the slots in the Dexion. Fix the strips to the outside of the slots with bolts, washers and nuts (or industrial grade press fasteners), allowing about 25% overlap, alternately over and under. The lower edge of each strip should reach just below the top of the table. An example of their use is shown in Fig. 10.7. This method of draft exclusion is also suitable for use with the gantry system described later. If you have ever looked through a window with a radiator underneath it, you will have noticed a shimmering effect. The refractive index of air reduces as its temperature rises, and as its density is lower too, it rises and causes these optical ripples.

This is used for curtaining factory doors used constantly by forklift trucks. You can get it in 50 m rolls from factory suppliers and some builders' merchants.



Figure 10.7 Dexion frame holding PVC strip curtaining round an engineers' table.

For 8 \times 10 in holograms the beam needs to be about 225 mm above the table surface; about 250 mm for 30 \times 40 cm.

You also need a cover over the top. The best material is heavy-duty polythene sheet, taped over the top of the frame with carpet tape. I recommend the sheets sold in DIY stores to protect furniture during home decoration.

Mounting the laser

The best way to mount the laser is on lab jacks, which work on the lazy tong principle and will allow you to adjust the height of the beam.

Once you have found the correct position for the lab jacks, secure them with a spot of hot glue. As you will need to adjust the laser position slightly when adjusting the beam path, use Blu-tack rather than hot glue to hold the laser itself in position on the lab jacks. The draft excluder needs to hang *inside* the laser, because it becomes fairly warm in operation, creating its own convection currents. When you have decided on a permanent position for the laser, clip back the PVC strip so that



Figure 10.8 Installing the laser outside the table.

the laser beam reaches the table unimpeded. If your table is small, consider fixing the laser on outriggers, which you can make from Dexion strip and fix to the side of the table (Fig. 10.8). You will also need to mount the permanent relay mirror, which directs the beam across the table, on a bracket.

A gantry for overhead equipment

Most industrial and scientific holograms are made with a side reference beam, as they are almost always replayed using a laser. Holograms for display, on the other hand, are usually image-plane transfers, and demand an overhead replay light source. Now, it isn't easy to construct a satisfactory transfer setup when the master has been made with a side reference beam and the final hologram requires an overhead beam.

It is common practice, therefore, especially (as you have seen) with bypass configurations, to mount the subject on its side so that a horizontal reference beam becomes "vertical" with respect to the subject. But both subject matter and lighting are severely limited by such an arrangement. However, if the reference beam comes from overhead the subject matter can be either stood upright or laid flat, so that the geometrical difficulties disappear, and the lighting can be much more versatile.

Now, if you build up your overhead components from the table surface, you are going to need high stands for the lighting optics and a very robust pillar construction for the large collimating mirror you will be using. The optics will be prone to vibration and the mirror mount will distort the table significantly. But there is no need to build the structure up from the table. If you think of the space above the table as a large cuboid of holographic space, and you frame this cuboid with a rigid structure of scaffolding, you can then mount your components on and across that structure. In addition, the superstructure will be able to hold your PVC curtaining. It needs, of course, to be rigid and well damped.

There are numerous kinds of clamps and connectors for builders' scaffolding, but the best for this purpose (although not the cheapest) is KeeKlamp, a system of connectors that are locked in place using large grub screws and a hexagonal key. The components you will need are shown in Fig. 10.9.



Figure 10.9 KeeKlamp components for gantry superstructure.

If you do need to do this, a suitable configuration is shown in Chapter 12.

On the other hand, as you will see in later chapters, transfer holograms are much more convenient to make if set up sideways.

As a bonus, such a superstructure will add greatly to the rigidity of the table itself. These ideas were originally presented in a paper given at the Lake Forest Symposium in 1991.⁴ The vertical members need to be about 1 m long, to allow adequate height for the reference mirror (this is dealt with in Chapter 11), and for you to work on the table in comfort. The horizontal components need to be 100 mm shorter than the dimensions of the table, to allow room for the baseplates to be bolted down. The frame is held together by corner fittings 20-8, and the frame is secured to the table by baseplates 61-8. As the KeeKlamp system is designed to be used on building sites it is rigid and very strong.

Box 10.1 lists the parts you will need to construct a gantry frame suitable for mounting an overhead collimating mirror and three or more light-directing optics.

Box 10.1 Parts required for gantry superstructure

The superstructure is constructed from 48 mm o.d. (outside diameter) steel scaffolding pipe. The connections are made using no 8-size KeeKlamp connectors.

Parts list

Fitting No	Description	No required
99-8	Hexagonal key	1
20-8	3-way, all blind	4
M50-8	1-way with lug, through	4
F50-8	F50-8 1-way with 2 lugs, blind	4
10-8	2-way, 1 through, 1 blind	1
45-8	2-way, both through	2
61-8	1-way, blind, baseplate	4
70-8	1-way, through, baseplate	1
81-8	Clips	8
Other parts required are as follows:		
Galvanized steel tube, 48 mm o.d., VS 1387: 2 pieces length of table less 100 mm; 2 pieces width of table less 100 mm; 5 pieces 1 m; 4 pieces, various lengths from 300 to 700 mm.		
4 bolts and nuts for joining Type 50 fittings		
3 metal plugs and spigots, local manufacture (Fig. 10.11), with grub screws		
12 bolts for securing frame to table.		

Figure 10.10 shows the completed superstructure, with the curtaining in place.

Cantilevers

It is advisable to provide at least four anchorages for cantilevers on the top bars, two on each long side. These are M/F50-8 pairs, with a bolt and nut that can be tightened to make the pivot joint rigid. The pieces of various lengths are for the cantilever beams, and you can change these round as appropriate. Each of the cantilever beams requires the insertion of a cylindrical metal block about 100 mm long, a close fit in the end of the tube, fixed by screws. These need to be bored to



Figure 10.10 Completed slab table, showing draft excluder and support legs.

take a length of standard 12.5 mm steel rod as used for optical pins. This rod should be at least 200 mm long and secured by a grub screw with a hexagonal socket hole matching those used for the KeeKlamp joints, so that you can use the same hexagonal key to adjust them (Fig. 10.11).



Figure 10.11 Cantilever supports for elevated optical components.

Draft excluder

Fix four Dexion slotted L-section strips to the top horizontal tubes using the 81-8 clips (without their protective U-pieces). Cut the PVC strips to length and secure them as described earlier (Fig. 10.12).

Processing area

The minimum space you need for your processing area is about 9 square metres. This space will include a processing sink, a worktable, shelves and cupboard areas.

The most important item is the sink. $McNair^1$ has an excellent design, though it is a little small; if you plan to make 30×40 cm holograms you are going to need a processing sink at least 1×2 m in size. Rather than lining a wooden construction with waterproof material, I recommend that you buy a ready-made fiberglass photographic sink.

You can knock up a frame for the sink from 25×50 mm timber, and complete the plumbing with DIY plastic units and piping. You will probably need the taps (faucets) fitted professionally. You need a minimum of two cold taps, well separated, and a hot tap, all fitted with hose connectors. If you have no hot water supply you will need a dish heater. As you will be using a hair drier, an inspection lamp and scales (probably digital), you will need a double power socket, which must be situated at least 2 m from any water source for safety reasons.

You can make cupboard space under the sink for your processing equipment and glassware. For processing chemicals you need a lockable cupboard. Certain listed chemicals need to be kept in a metal cupboard – the bottom drawer of your filing cabinet is fine. Again for safety reasons, flammable chemicals (except small quantities for immediate use) must be stored outside.

You will need a work surface for squeegeeing, preferably alongside the sink. A small rigid table is advisable, as you are going to exert quite a lot of pressure on it. The other worktable, where you do your preparation of unexposed film, should be well away from the sink, and not too near the safelight. It will need two cupboard or drawer spaces, one to house delicate glassware, thermometer, pH papers and so on, the other for templates, sponges, squeegees, etc. The shelves will hold the weighing scales, pH meter, densitometer, guillotine, glass cutting equipment, processing solutions and spare dishes.

You may also wish to use this area as a conventional photographic darkroom, in which case you will need storage space for an enlarger and a photographic safelight.

One of the most important items in a processing area is an efficient extractor fan. As long as you stick to the formulas in the book, that is all you need. But if you are going to experiment in the processing area with chemicals such as parabenzoquinone or bromine, or organic solvents such as trichloroethylene, you need to have a proper fume hood fitted.

You can construct your processing area in a corner within the lab, but this can be very inconvenient when you want to examine a freshly processed hologram while a film is settling on the table. A black curtain is better than nothing, but it is far better to panel off the processing area. A sliding door saves space.

These are not expensive, and are virtually indestructible: I have been treating mine with all kinds of acids, alkalis and solvents for more than 25 years, and it is still as good as new.

The legal requirements for electrical and chemical safety vary from one country to another, so you should take this only as a general guide.

For health and safety reasons, keep your coffee-making equipment well away from this area.



Figure 10.12 Method of fixing PVC draught excluding strips to frame.

The only other thing you need to consider in the processing room is the lighting. The best system is undoubtedly a double fluorescent fitting with separate pull switches. One of the tubes is wrapped in safelight material; the other is plain. You also need a spotlight for quick examination of test strips or finished holograms.

Storeroom

There are no special requirements for storing unexposed holographic films or plates, as long as the temperature and humidity are not too high. A cool, dry cupboard is fine. Under these conditions a holographic emulsion will keep for at least four years before it begins to fall in sensitivity and increase in fog level. Store boxes of film on edge, as this reduces the risk of pressure marks. The storeroom will also be useful for storing finishing material, seldom-used optical equipment and small models. Don't keep any unsealed chemicals in the storeroom, as the fumes may affect the emulsions.

Display area

If you are a hobbyist, your display area will probably be your living room. But if you are going in for holography professionally you will want an area specifically devoted to displays. Think about hiring a shop window in an arcade, where your display will be seen by passers-by. Even if your work is confined to research and development you should think about a permanent display area, because every visitor to your lab – and there will be plenty of them – will want to see some of your results. The various methods of displaying holograms are described in Chapter 21.

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Chapter 11 Master holograms on a table

'The question is', said Humpty Dumpty, 'which is to be master – that's all.'

Lewis Carroll, Through the Looking-Glass

When you design single-beam and bypass setups, you have very limited control over beam intensity ratios, and even less over the illumination of your subject matter. No studio photographer would be content with a lighting arrangement confined to a single harsh spotlight from 45° above and directly in front of the subject, however dramatic the result might appear.

In studio photography, most subjects need at least two lights, more often three. Holographic subjects deserve no fewer. The way you achieve this is to divide the laser beam into several beams by using partially reflecting mirrors called *beamsplitters*. Box 11.1 shows the optical components you need for this type of lighting.

Box 11.1 Optical components required for table holography

This list represents the least you will need for the production of holograms with the sort of illumination you would expect in a photographic studio.

Laser Lab jacks to support laser Four 20 mm square front-surface mirrors on adjustable mounts Variable beamsplitter and mount^{*} 1:1 beamsplitter and adjustable mount^{*} Two spatial filter assemblies Beam diffuser^{*} 12.5 mm mounting pins, one for each component Half-wave plate^{*} Six magnetic bases (see Fig. 10.6) Two metal burette stands Twelve component securing stands, plateholder and glass plate^{*} Collimating mirror and mount^{*} Plinth for subject matter

Beamsplitters

Metalized beamsplitters The simplest type of beamsplitter is a piece of optically flat glass coated on one side with a thin film of reflective material. You can obtain beamsplitters with fixed ratios between 1:1 and 9:1, the most useful being 1:1. Cheaper beamsplitters are coated on thin material, and the second-surface reflection can be a nuisance when it overlaps the first-surface reflection and causes interference patterns. If you choose a beamsplitter of thicker glass it is easier to

When I started out as a portrait photographer, this was in fact one of my favourite lighting arrangements for close-ups of women's faces; but I came to realize its limitations before long (for starters, your sitter needs an immaculate cheekbone structure).

The starred items are discussed below.

blank off the second-surface reflection with a piece of opaque card. More expensive beamsplitters are made from thick glass, and have their rear surface coated with antireflection material.

The main purpose of fixed-ratio beamsplitters is to separate the beams you will use to illuminate the subject. To obtain the correct beam ratio between the object and reference beams you need a variable beamsplitter. These can be straight or circular. The straight (or linear) type is an oblong glass plate with a coating that varies from full reflection at one end to plain glass at the other, The glass substrate is usually fairly thick (about 10 mm) so that the second-surface beam is well clear of the wanted beam, and is easy to card off. The mount is called a *translation stage*. It usually moves the beamsplitter by means of a lead screw or rack-and-pinion mechanism, providing fine adjustment of the beam ratio. The circular type has a broad ring of metalizing, and you alter the beamsplitting ratio by rotating the disk. The metalizing can be continuous or in calibrated steps. This type of beamsplitter is more expensive than the linear types, but is not necessarily better for the purpose.

Beamsplitters aren't 100% efficient. A metalized variable beamsplitter absorbs as much as 40% of the incident light energy at the high-reflection end; some light is also lost at the second surface (Fresnel reflection). The amount of light reflected at a plain glass surface depends on the angle of incidence and the direction of polarization of the beam. At 45° it is about 10% for an *s*-polarized beam, but only about 1% for a *p*-polarized beam (see Fig. 11.1).

Beamsplitters are usually metalized, with a thin coating of either aluminum or inconel. Inconel is a nickel alloy that is very hard, and has a reflectance that varies very little with wavelength; but at best it reflects only some 60% of the light energy. Aluminum, on the other hand, reflects about 92%, but is soft and liable to abrasion. Silver has a higher reflectance (98%) than any other metal, but is prone to surface oxidation. Both types of metal coating can be damaged by laser beams having a power higher than about 500 mW.

An alternative to metalizing is *dielectric coating*, which is up to 99% efficient. A dielectric beamsplitter is in effect a leaky interference mirror. The wavelength and angle of incidence need to be specified, as otherwise the Bragg condition may not be satisfied. Dielectric beamsplitters are not usually damaged by powerful laser beams, as they absorb little energy; but pulse lasers (which may have peak powers running into megawatts) require special types of beamsplitter that operate on a different principle (see below).

Other types of beamsplitter

The best (albeit the most expensive) type of beamsplitter is the *polarizing cube*. This is one of the few types of beamsplitter that can handle an undiverged pulse laser beam without being damaged. It is described in Chapter 16. Other types of beamsplitter include split cubes, which operate by total internal reflection, and vary the light transmitted by varying the (very small) separation between the oblique faces of two 45° prisms.

In general optics a popular way of avoiding second-surface reflections is to use a pellicular beamsplitter. This is a very thin ($\sim 5 \,\mu$ m) partially reflecting membrane.

'Translation' in the optical sense simply means moving in a straight line.

It was Fresnel who first worked out the formula for the amount of light energy reflected at an interface. For a light beam at normal incidence it is given by $[(n_2 - n_1)/(n_2 + n_1)]^2$, where n_1 and n_2 are the refractive indexes of the two materials, but the formula becomes more complicated for larger angles of incidence.

A dielectric is a substance that does not conduct electricity. The refractive index of a dielectric depends on certain of its electrical properties, so dielectrics can be chosen with both high and low indexes.

The Bragg condition for maximum reflection is that $2d \cos \theta = n\lambda$, where *d* is the thickness of the coating, θ is the angle of incidence, λ the wavelength in the medium and n=1, 2, 3 etc. Dielectric beamsplitters are usually designed to operate most efficiently at 45° incidence. You can make your own dielectric beamsplitter, as it is simply a holographic mirror with lowish diffraction efficiency. Instructions for making one are in Chapter 15.

Such beamsplitters make use of the evanescent wave phenomenon that accompanies total internal reflection. There is an electromagnetic field just outside the glass surface, and this can be picked up by a second glass surface if it is positioned sufficiently close: the spacing determines the proportion of light that leaks across.



Figure 11.1 Fresnel reflection at a glass surface for (a) an s-polarized beam, (b) a p-polarized beam.

Unfortunately, such a membrane picks up the slightest vibration, so cannot normally be employed in holographic setups. A further type is the *dichroic* beamsplitter. This is a dielectric mirror that reflects a broad band of wavelengths in the red region of the spectrum, and transmits green and blue. It has an application in full-color holography (see Chapter 17).

Illuminating the subject

As I mentioned earlier, and as anyone who has indulged in tabletop photography will confirm, lighting of the subject makes an important contribution to the quality of the final image. As in photography, there are several basic types of illumination, depending on the apparent size of the illuminating source. We can place the types of source in four general categories; their equivalents in the photographic studio are given here in parentheses:

- Point-source (spotlight)
- Partly diffuse (floodlight)



Figure 11.2 Small-source subject lighting. (a) A minus-6 mm concave lens produces sharp shadows. (b, c, d) Two lenses of any type can be used to increase beam divergence. (e) A reflecting beam expander, which can be a Christmas tree bauble, an aspirin tablet, a chromed rivet head, etc.

- Fully-diffused (brolly or swimming pool light)
- Dappled or patterned light

Point-source illumination To obtain true point-source illumination you need a spatial filter in the object-illuminating beam, just as you do in the reference beam. If you are engaged in scientific work, or making a holographic optical element, this is mandatory, as both beams need to be coherent in every respect. However, for creative or display holograms the subject illumination doesn't have to be spatially coherent. In fact, the less the spatial coherence the less obtrusive will be the laser speckle.

The simplest method of spreading the light is by a concave lens of focal length about -6 mm. This spreads the light out in a ratio of about 1 in 6, roughly the same as a $\times 40$ microscope objective. A second concave lens a few centimetres nearer the subject will diverge the light further and allow a shorter throw. You can use a convex lens (or a ball lens) and obtain the same effect, but a concave lens seems to give a cleaner beam. Point-source illumination gives a very sharp edge to shadows, comparable with that given by a photographic spotlight. If your unfiltered beam is dirty, you will get unsightly interference 'puddles' (see Box 7.3, p. 92); you can avoid this by reflecting the beam off a white surface such as an aspirin tablet or a piece of chalk, though you will lose some of the light and destroy the polarization.

If you confine your lighting to this type (as you are constrained to, in single-beam holograms) you can expect laser speckle and harsh shadows. You can alleviate the shadows by using stray light to illuminate them, reflecting it on to the subject with white cards or mirrors.

Partly diffuse illumination There are two ways of producing partly diffuse illumination. The first is by passing the undiverged or slightly diverged beam through a ground glass. You will get the best and most uniform beam by using

The best matt reflecting surface is a block of freshly scraped magnesium carbonate, which you can get from educational science suppliers. (It is used as a standard for calibrating reflection densitometers.) Destroying the polarization mostly has little effect, as the subject matter usually does this anyway.



Figure 11.3 Partly diffuse subject lighting. (a) Fine-ground or etched glass gives a soft edge to shadows. (b, c) An aluminum-sprayed can lid will give a slightly diffuse reflected beam, the spread of which is determined by the curvature of the surface.

acid etched glass, which you can obtain from specialist photographic dealers (Fig. 11.3a). You can also use a piece of the glass from a broken pearl lamp bulb, or a piece of draughtsman's tracing paper or Kodatrace mounted on a washer, and this will cost you nothing. At a pinch you can use a well-thumbed piece of cellulose tape stuck to plain glass. The second is to reflect the beam off a small piece of solid material that has been sprayed with aluminum paint. This preserves the polarization of the light beam. If you use a can lid for this you can employ the irregularities of the surface to spread the beam out so as to cover the subject matter in exactly the way you want (Fig. 11.3b and c). The shadow of such a beam will be soft edged, and the speckle less obtrusive than with point source illumination; but the shadows will still be dense, and the lighting dramatic and contrasty.

Fully diffuse illumination This is produced by diverging the laser beam fairly widely before passing it through a ground glass or reflecting it off a diffusing surface. The pattern of light and shade such lighting produces depends on the angle subtended by the light source at the subject. There is an area of full illumination, where the entire light source can be seen from the subject, and areas farther back on the subject where the light source is partially hidden. Finally, from the point where the light is not visible at all, there is a region of total shadow (Fig. 11.4).

Dappled or patterned illumination This provides an unusual but artistically useful effect. You can obtain it in a number of ways. The simplest is to expand the beam using a simple lens, and insert a patterned glass into the expanded beam (Fig. 11.5a). This principle is lifted from studio photography. It can be a simple array of lines (to suggest a venetian blind) or a criss-cross lattice, or letters, symbols or squiggles, drawn on plain glass. Use a fine spirit-based fiber-tip pen of the kind used for overhead projector drawings. The contrast will vary with the color of the pen: blue and black give a high contrast, green somewhat less.

In other words, how large the light source appears when seen from the subject.

In physics jargon this region of partial illumination is known as the *penumbral region*.

This is for a red laser. For a green laser, use orange or blue for a lower contrast and black for high contrast.



Figure 11.4 Fully diffuse subject lighting. The beam is expanded before being diffused. (a) Uniform beam spread by negative lens. (b) Two diffusers give a centre-weighted beam. (c) An aluminum-sprayed reflector can be bent to direct light as required.

Alternatively, you can reflect the expanded beam off a randomized reflector such as a well-crumpled piece of kitchen foil that has been flattened out and mounted on a rigid backing (Fig. 11.5b). You can also obtain striking effects using hammered, reeded or fly's-eye glass or acrylic sheet for a transilluminated background (Fig. 11.5c).



Figure 11.5 Special lighting effects. (a) Expanding the beam through embossed or patterned glass or acrylic material produces irregular (or regular) mottled lighting. (b) Reflection off metal foil that has been crumpled and then smoothed out and mounted on a rigid surface produces random patterns. (c) Irregular glass plate between random diffuser and film yields dancing light patterns.



You can illuminate either the subject or the background alone, or both (to give the impression of swirling water). You can also use a ball bearing to expand the reference beam instead, in which case the mottling will be in the plane of the hologram, and will give a quite different effect (Plate 3a). By the way, never handle a steel ball with your bare fingers. If you do, it will begin to corrode within minutes, and may be visibly pitted within twentyfour hours. Store ball bearings wrapped in tissue in a closed box, preferably with a sachet of desiccant (silica gel).

I don't know the reason for this: it may have something to do with the hardening process.

By using differential swelling and multi-exposure techniques in the transfer process (see Chapter 18) you will be able to extend these dancing images in a variety of hues.

Figure 11.6 Marbled effect of an undiverged beam reflected from the surface of a large ball bearing.

One of the most dramatic lighting effects is obtained by using an ordinary ball bearing as an expanding reflector. A 25 mm diameter ball gives about the same beam spread as a $\times 40$ microscope objective. Smaller balls give correspondingly greater divergences. Interference between wavefronts reflected from adjacent crystalline domains on the surface cause the illumination area to be deeply mottled, with an appearance somewhere between greatly enlarged laser speckle and veined marble (Fig. 11.6). The size of the mottling depends on the distance of the ball from the subject, and you can spread it out in one dimension by interposing a concave cylindrical lens in the expanding beam.

You may occasionally come across a ball bearing that doesn't produce a mottled effect. If you do, keep it for producing an expanded beam of uniform intensity.

If you use these techniques either alone or in combination in transmission (for example, illuminating a transparent background from behind), when you view the result you will see dancing beams of light as you move around, forming abstract three-dimensional patterns.

Component mountings

When you buy components from optical suppliers, the bases are drilled and threaded to take a standard 12.5 mm post. The thread is usually 6 mm in the UK $(\frac{1}{4}/20$ in the USA). You can buy 12.5 mm silver steel rod in lengths of up to 2 m or so. You will need to have it cut into various lengths: 150, 200 and 300 mm make a good selection. Have a thread cut on the end of each post. The shortest pieces go on the component mounts, the longer ones on the magnetic bases. As the spatial filter for the reference beam needs to be critically stable, and is often positioned well above the level of the table, it is advisable to use a 25 mm pillar rather than a 12.5 mm as support for this item. It will need to be at least 300 mm long. You will





Figure 11.7 Vibration-free mount for an elevated spatial filter.

Figure 11.8 Plateholder for sizes over 4×5 in (see text).

need a clamp with an adjustable platform (Fig. 11.7), which you can get from optical suppliers.

The remaining clamps are the universal type with independent grips for the component pin and the post. The clamp illustrated in Fig. 9.1 was specially designed for this purpose, and experience has proved its dependability.

But at a pinch you can usually get away with ordinary burette clamps.

Plateholders

The plateholders supplied by research optical suppliers are intended for scientific work, are usually for 4×5 in plates only, and are very expensive. Some small companies make plateholders specifically for large holograms. Many designs for plateholders have been published, some of them very complicated and not all of them entirely satisfactory. The holder shown in Fig. 11.8 borrows the best points of some of them and avoids the weaker points. It is simple to manufacture and very stable. It will cope with ill-cut plates, and it shades the edges of the glass from stray light.

If possible, you should specify brass or some other nonmagnetic material. If you make the holder from steel bar you will need to separate the holder from the magnetic base with a thick plastic or cardboard spacer; otherwise the crosspiece will complete the magnetic circuit and the base will not grip the table firmly.

The vertical bars are milled with channels on both sides, and are reversible. The U-channels were originally milled to take the U-shaped spacers used to separate Agfa plates from one another in their boxes, so that the plates could be held firmly but could be readily removed. These spacers are no longer used in the post-Agfa era, but you can make substitutes from cardboard to fit the plates you use (the larger Slavich plates, for example, are 2.7 mm thick). The alternative is to use wedges (toothpicks are handy!) or small blobs of Blu-tack, at the top and bottom of the glass side of the plate. My own recommendation is the cardboard U-pieces, which you can make the right width by molding them round a used plate and

Although you need only one of these at the moment, you will be needing a further holder for transfer holograms, and more if you need to support large plane mirrors or matt reflectors. I have found four a sufficient number for even the most complicated setups. I haven't put any dimensions on the drawing, as these will vary according to your needs. In my own set the bars were 320 mm from the rebate to the top, made from 25 mm rod, and the horizontal bars (25 mm square) were 350 mm long, the adjustable slots allowing spacings from 125 mm to 320 mm.

Watch your fingers with this stuff. It will take your skin off if you are not careful. Protective waterproof gloves are *de rigueur*.

This means that it must retrace the path of the original reference beam.

Aberration simply means the production of an image that is not an exact match to the object. The term comes from photographic optics, but the aberrations in a hologram are different from those in photography (and a lot nastier).



Figure 11.9 Collimating mirror mount for use on table.

cutting the sides back to a depth of about 4 mm. The V-channel is for plates of nonstandard thickness. 4×5 in and smaller plates are usually 1.5 mm thick (sometimes 1 mm), and are better supported in a PCB holder, as recommended in Chapter 6.

If you are using film for your holograms you will need a number of pieces of glass to support them. You can use spoiled plates for this (don't imagine you will never have any!), which you can clean off with household bleach, diluted 1:4.

If you do have glass specially cut (and it is a good idea to have it about 12 mm larger than the film all round), have it cut from 2.5 mm float glass, with the edges smoothed off. Spray the back of one piece of each size with black paint. These glasses are to support films for transmission holograms, which are illuminated from one side only.

Collimating mirror

When you are making high-quality master holograms you need to get the geometry exactly right, and the reference beam needs to be collimated (made parallel). This is because when the master is flipped to produce the real image that is to become the object for the final hologram, the reconstruction beam must be its precise conjugate.

Thus if the original reference beam is a diverging beam (as, indeed, it has been so far), the reconstruction beam will need, strictly, to be a converging one. Now, as long as the reference beam has a long throw and the hologram is small and the image is close to the hologram plane, this divergence can be ignored. But in a large hologram where the subject is some distance from the emulsion, inexact conjugation leads to aberrations of the image, in this case some magnification combined with exaggeration of apparent depth, and distortion when the image is viewed off-axis.

A collimating mirror is a concave mirror that is used with the reference source (i.e. the spatial filter pinhole) at its principal focus. Unfortunately, collimating mirrors are expensive. Large ones are very expensive. You will need a mirror that has a diameter no less than the largest dimension of the largest hologram you are likely to make (i.e. its diagonal), with a focal length equal to four times its diameter. Thus a 300 mm diameter mirror (for an 8×10 in plate) will have a focal length of 1200 mm, and a 450 mm diameter mirror (for a 30×40 cm plate) a focal length of 1800 mm.

In an overhead configuration the mirror is fixed to the upper part of the superstructure. However, when you come to make transfer holograms it will need to stand on the table. Optical suppliers offer precision gimbal mounts for large mirrors, but these are not only prodigiously expensive, but are unsuitable for suspension from a gantry, as they are then unbalanced. The mount shown in Fig. 11.9, however, costs very little, and works well in both positions. All you need for this is a square piece of well-seasoned timber some 30–50 mm larger than the diameter of the mirror, a triangular piece for the base, three metal strips to make clips to secure the mirror to its support, and three 75 mm lengths of threaded rod, each with a pair of large washers and wing nuts, for tilt adjustment.

To fix the mirror to the overhead scaffolding support you need a 70-8 KeeKlamp connector screwed to the back (Fig. 11.10). To adjust the mirror angle without



Figure 11.10 Mounting a collimating mirror on the gantry.

altering the optical path length significantly, you need a metal or wooden bar and two triangular sidepieces (e.g. Dexion gussets). Use threaded rod for the side pins. Make the holes a close fit, and smear the ends of the rods with epoxy resin before turning them in.

How stable is your table?

The finest holographic setup in the world is useless if there are any disturbances present. There are three checks for steadiness of both the table and the environment that you must carry out before you can start making holograms on your table. The first is very simple; the other two are subtler.

Saucer test This simple test involves only the laser beam and a saucer of water. Place the saucer in the middle of the table and direct the slightly expanded laser beam on to it at a glancing angle. Examine the reflection of the beam on the wall for any trace of shimmer. This may seem crude, but it is in fact a remarkably sensitive detector of floor instabilities.

Try walking around the table. Tap it. Lean on it. See what you can get away with, and what you can't. The saucer test checks the effect on the table of sudden movements as well as of continuous vibration. But it isn't sensitive to the slow movements you get from variations of temperature or humidity, or from the gradual settling of components. For this you need a more sophisticated test using an optical arrangement called an *interferometer*.

There are quite a few types of interferometer configuration, all with different purposes; the two that are useful for our purpose are called the *Michelson* and *Mach–Zehnder* interferometers.

Michelson interferometer test If you have studied optics in school or college you are likely to have used, or at least seen, a Michelson interferometer. It is a precision instrument and not very large. Our Michelson interferometer, on the other hand, is what research physicists would call a lash-up, and may cover several square metres;

If you have only one collimating mirror you can combine the mountings of Fig. 11.9 and 11.10. by adding the overhead adapter to the table-based mounting. This may not look very elegant when it is in position on the scaffolding, but it will save you the expense of buying a second collimator.

Even cement floors can vibrate, particularly if there is heavy machinery in the vicinity.

An interferometer is a device that splits a light beam into two paths, which are recombined after passing through two different spaces. The interference pattern they form gives information on the difference between the experiences of the two beams.

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Figure 11.11 (a) Setup for a Michelson-type interferometer stability test. The relay mirror M_1 directs the beam onto the beamsplitter BS. The two beams are reflected back to BS (the second by mirror M_2), and combine to form interference fringes on the screen S, the pattern having been expanded by the lens BE. (b) A typical set of fringes. The bars may be skewed rather than vertical; this does not matter.

but it is based on exactly the same principle: a beam of light is divided into two by a beamsplitter, and the two beams are directed at mirrors, which return them along the same paths to be recombined and, after expansion, examined on a screen. The arrangement on your holography table is shown in Fig. 11.11a.

The method of setting up the interferometer configuration is as follows:

- 1. Switch on the laser and adjust the relay mirror so that the beam is directed diagonally across the table.
- 2. Position a mirror at the end of the beam throw so that it sends the beam back along the same path. The two spots on the relay mirror should be close to each other but not quite overlapping.
- 3. Place a beamsplitter vertically in the center of the beam so as to reflect it to the other corner of the table (the beamsplitter ratio is not important).

- 4. Position a second mirror in the reflected beam, the same distance (to within a centimetre or so) from the beamsplitter as the first mirror. Adjust it until the light is reflected along its own path, as with the first mirror.
- 5. You should now see two bright spots on the wall, close together. Adjust the second mirror and the beamsplitter in turn until the spots from the two mirrors exactly coincide both at the relay mirror and the wall. Hang a piece of white paper on the wall with the spots central.
- 6. Place a lens in the two overlapping beams so that they spread into a patch large enough for you to be able to see detail from a couple of metres away.

The detail you will see is a set of light and dark fringes as in Fig. 11.11b. To begin with they will probably be moving around unsteadily, perhaps quite fast, so you may not see them at first. There will probably be some additional stationary fringes caused by double reflections in the beamsplitter: ignore these. The moving fringes are a very sensitive detector of movement, and the way they move can tell you a great deal about the nature of any instability present. If they are skittering about a mean position, there is vibration present. Listen for any noise or infrasonic rumbles that may be the cause. If the fringes move around irregularly, but keep returning to their original position, there are warm air currents (convection currents), and you will need draft-excluding curtaining (but try holding your breath first). If there is a steady movement of the fringes in one direction, this is due to the table and the components settling down, and is normal. Make a note of the time it takes for the fringes to settle down and become stationary to within a quarter of a fringe movement in two minutes: this will then be the minimum settling time for any exposure.

While you are about it, see how much it takes to disturb the fringes, as you did with the saucer test. Lean on the table. Shout at the mirrors. Play a portable radio at full volume. Breathe into one of the beams. Wave a card near a mirror. Jump up and down at various points round the table. Get a friend to walk around outside the room shouting, banging a hammer on the wall and stamping. While you are watching the fringes and making notes, bear in mind that a movement of the fringes of just half the width of a fringe during an exposure will totally destroy the holographic image.

You can use the Michelson configuration to assess the coherence length of your laser beam. Starting with the optical path lengths exactly equal, move one of the mirrors along the beam in either direction until you can no longer see the fringes clearly. You have now moved the mirror through a distance equal to one-quarter of the total (zero-to-zero) coherence length.

The usable depth of object space will be about half the coherence length. For a 25 mW HeNe laser it will be around 30 cm, rather more for a low-power laser (5 mW) and a little less for a high-power one (75 mW) A HeCd laser will have a lower coherence length, more like 15 cm, unless it is the (very expensive) single-isotope kind. A Kr⁺ or Ar⁺ laser equipped with an etalon will typically have a coherence length of a metre or more, and a green DPSS laser operating at a single frequency may well have a higher coherence length than you can measure on your table. Diode lasers are much more of a dark horse: their coherence length may be anything from a few centimetres to many metres, depending on their built-in stability.

Mach–Zehnder interferometer test In order to be quite sure about the stability of your table and its basic optics you should now carry out a further test using the

If you mark the positions of a pair of fringes with a marker pen you will be able to detect slow movements more readily.

Not half the coherence length, as you might think, because the light is reflected from the mirrors and is thus traveling twice the distance you have moved the mirror.

Never buy a diode laser for serious work unless you have a full specification; and even then test its stability and coherence length by the Michelson test before you accept it.



Figure 11.12 Setup for a Mach–Zehnder type interferometer test. The path lengths between beamsplitters BS_1 and BS_2 via the mirrors M_2 and M_3 should be approximately equal.

Mach–Zehnder configuration. Instead of going across the table, the two beams go round its edges, being recombined at the opposite corner (Fig. 11.12). You will see fringes just like those produced by the Michelson interferometer setup. If you line up the beams very precisely you can obtain circular fringes that move in and out with any change in optical path lengths, making the detection of drift easy.

It is a good idea to repeat these three tests at intervals of a few weeks, in case conditions have changed. The Michelson test will probably take a little time to set up at first, but you will soon be able to set it up quite quickly as a preface to any important project, or when you do something that may affect the table, such as reinflating the inner tubes.

Basic configuration for transmission master holograms

Although this book isn't directly concerned with the esthetic side of creating holograms, it is nevertheless helpful to look at the way a photographer (or a practitioner of the plastic arts) goes about lighting a subject. Although a hologram gives a three-dimensional image, parts of the subject may be in such low relief as to be effectively two-dimensional, for example skin textures, wood grain and leather. Lighting that shows up such detail adds considerably to the realism of the image.

The standard illumination for a studio photograph employs four types of lighting:

• *Key or modeling light* This is usually a small-area source giving fairly sharp shadows. It is positioned where the graduation of shades on the subject emphasizes its solidity, the most favorable position usually being about 45° above the subject and about 45° to one side (preferably the 'face' side).



Figure 11.13 Conventional three-light setup as used in photography, with optional background lighting.

- *Fill light* The purpose of this second light is to control the lighting contrast by illuminating the shadows. Because double shadows look unnatural, this light is usually a large diffuse source close to the camera axis.
- *Kicker* This light (which is not appropriate for every subject) is to emphasize surface texture, and perhaps to contribute rim lighting to isolate the subject from the background. It is usually a small spotlight above and slightly behind the subject.
- *Background lighting* This may be necessary to make the subject matter stand out, or to provide a patterned background.

This is shown schematically in Fig. 11.13. An example of an image made with this lighting arrangement appears in Plate 5a.

In a holographic setup one can often only approximate to the ideal. The key light is easy: all you need is an elevated beam at the appropriate angle, with a minimum amount of diffusion. The second beam is more difficult. It can't be directly frontal as the filmholder is in the way, so it has to go as near to the edge of the filmholder as possible, on the side opposite to the key light, with a well-diffused beam. Where you need a kicker, you can often arrange for a bit of overspill from the reference beam to do the job. The background lighting can be covered by the key light, but there may be problems with the coherence length, and it may well need a separate source. The main limitation, if you are using a laser of limited coherence length, is the necessity for all the beam path lengths to be the same within a centimetre or so, as measured from the first beamsplitter in the light path from the laser. Fig. 11.14 shows a plan view of a setup that has proved reliable and comparatively simple.

Even if your laser has a coherence length of a metre or more, when you are going to set up this kind of configuration you still need to go about it logically. For example, if you were to fit the spatial filters before you did the final adjustment to There are numerous solutions to this problem in three-dimensional geometry, but the one shown in Fig. 11.14, which evolved by following the above lighting criteria as far as possible, uses the shortest paths and the fewest optical components, and in my experience has proved the best. But don't follow it slavishly.



Figure 11.14 Basic configuration for transmission master holograms. M_1 , M_2 , M_3 , M_4 are relay mirrors. CM is the reference beam collimating mirror (elevated) with spatial filter SF at its focus. The subject is illuminated by the key light from diffuser D_1 (elevated) and fill light from diffuser D_2 (not elevated). The reference beam RB is incident on the holographic film from 45° above; the lower part of the beam acts as kicker, rim-lighting the subject. All optical paths from VBS to H may need to be matched. For undiffused lighting D_1 and D_2 are replaced by spatial filters or simple beam expanders. Background lighting is not shown.

the main beamsplitter, when you did adjust it all the beams would go out of alignment, and you would then have to focus the spatial filters again. So always start at the upstream components and work downstream in order.

Get the reference beam right first. Begin by positioning the plateholder so that the center of the collimating mirror is at $45-50^{\circ}$ incidence to it. Check that the polarization axis of the laser beam is vertical. Place the variable beamsplitter approximately halfway across the table, and adjust it so that the beam falls on its center of travel. Adjust the beamsplitter angle so that the reflected beam is centered on the collimating mirror, then adjust the collimating mirror so that the beam is reflected on to the center of the plate area.

Now insert the spatial filter, without the pinhole. Check that the beam is spread uniformly over the plateholder area, and that the spatial filter holder is set square to the beam.

Check that the beam is collimated by comparing the horizontal diameter of the light patch at the plateholder with that of the collimating mirror. Adjust the distance of the spatial filter until you have made the beam truly parallel.

The next task is to set up the illuminating lights. Place a relay mirror (M_2 in Fig. 11.14) near the edge of the table to intercept the beam transmitted by the beamsplitter; direct the beam diagonally across the table and upwards. Set up another mirror (M_3) on a spigot fixed to the upper rail of the gantry system to catch the light and direct it onto the subject from above and "in front", so that the spot of light falls near the center of the front surface of the subject.

If your laser has a long coherence length you needn't make any further adjustments; but if your laser is a HeNe, or has a similarly limited coherence

A piece of card in the plateholder will help.

A useful tip for centering the holder is to take two bottle caps that fit the apertures of the holder, punch 2 mm holes through their centers and fit them in the apertures. It is now a simple matter to center the holder so that the undiverged beam goes straight through the middle. This can save a lot of fiddling when you come to focus the pinhole.

The distance from the beam expander to the mirror must equal the mirror's focal length, and if you measure this distance carefully the first time you set up this configuration, you will be able to set it up in exactly the same way on all subsequent occasions.





Figure 11.15 Beam path matching with string for a master hologram with overhead reference beam.

length, you will need to match the optical path lengths to within about a centimetre. Take a length of string at least four metres long, and check that the two paths between the beamsplitter and the center of the plateholder are the same (Fig. 11.15).

If they are not, reposition the two mirrors M_1 and M_2 so that the paths are closely matched. (Don't adjust the variable beamsplitter.) Set up a burette stand and clamp it to the spigot on the cantilever to steady it (Fig. 11.16).

Next, insert the 1:1 beamsplitter and adjust it to direct the light to the 'fill' mirror, which should be at table level and close to the edge of the plateholder. This mirror (M_4) should usually be fitted to a magnetic base. If instead you use another cantilever from the gantry, you will need another burette stand to steady it. Check the distances as before, and adjust the position of M_4 as necessary. Now replace the mirror with a diffuse reflector, or add a transmission diffuser.

Fit a beam expander to your key light; this can be either a diffuser or a spatial filter. Now fit the pinhole to the reference beam expander and adjust the beam until it is again uniform over the plateholder area.

Once you have the lighting correctly adjusted, judge its quality by examining the subject through the plateholder aperture. If you are satisfied with it, check the beam ratio with a meter. It should fall between 3:1 and 8:1, the reference beam being the stronger. The meter readings will also give you an estimate for the required exposure. Use the variable beamsplitter to adjust the beam ratio as necessary.

Finally, examine the subject through a polarizing filter set with its axis vertical. It should either show a minimum when the axis is turned to horizontal, or not vary at all (i.e. the light has been depolarized). If the minimum is at some other angle, you will get the best contrast in the master image if you can rotate the reference beam to match. You can do this by using a half-wave plate in the beam (see pp. 108–9).

Figure 11.16 Spigot clamped to burette stand for extra steadiness.

The easiest way to do this is to tweak the laser relay mirror M_1 or to nudge the front end of the laser itself. Readjust the subject illuminating beams as necessary. The overspill light from the reference beam (the kicker beam) will look after itself.

This is the point where you begin to wish you had spent more money on the beamsplitter's adjustable mount. The best kind of mount, in my experience, is a movement with a rack-and-pinion drive to go with a linear beamsplitter. Circular beamsplitters are hard to keep aligned while you are adjusting the beam ratio. By now you will have been working for the best part of three hours. Take a long lunch break while everything you have pushed and pulled gradually relaxes and settles down (including yourself). Before you go, fit up a piece of test film or plate, put out all the lights and lock the door.

Once you are back, and sure everything has settled and is properly aligned (you may have to do a small further amount of tweaking), expose and process your test. The result will indicate whether the lighting is correct and the exposure appropriate (how quickly did the emulsion turn black in the developer?). When you examine the image in an expanded laser beam it should appear equally bright when viewed through any part of the hologram, and not fade off to any extent at either side. If you flip the hologram in the beam it should project a reasonably bright (if blurred) image onto a piece of white card set up in the correct off-axis position.

What went wrong?

Things don't always go entirely smoothly. Here is a checklist of some things that might have gone wrong; this list is supplementary to the list on pp. 81 and 115–19.

- *No image at all* Oh dear. This should be a rare occurrence if you have followed the instructions exactly. The most common cause, provided your exposure and processing weren't grossly incorrect, is insufficient settling time. Look for a faint backlit image. If you see this, your subject lighting hadn't settled, and what you have is a feeble bypass transmission hologram from the reference beam rim-lighting the subject.
- Only one of the illuminating beams seems to be working Again, not enough settling time. Only one of the two beams has fully settled. Watch for this problem; you may not notice it until you come to the transfer process, and then it will be too late.
- *The image is very weak* This can be difficult to pin down. If the exposure and processing were OK (did you have to push the development?), check the beam ratio. Also check the path lengths if your laser has limited coherence length: do a fresh string check. Check the environment too. Are there radiators on? Check the laser beam. Is the laser fully stable? These problems are more common than they ought to be.) Do a Michelson check on the table (if possible without disturbing the setup). Was the exposure very long? It may have been too long for the limited stability of the setup.
- The image brightness falls off when viewed from above This is a subtle one. If your reference beam is *p*-polarized with respect to the hologram plane, the object and reference beams will be at a larger angle to one another at the top of the hologram than at the bottom, and the fringe contrast (which is inversely proportional to the cosine of the angle between the beams) will be lower at the top. Try moving the subject a little farther away from the plateholder, and raise it a little. Keep the beam ratio down to about 3:1 and give a full development. The final hologram may not be seriously compromised, as the vertical parallax component isn't as important as the horizontal component.
- There are iridescent bars down the holographic image, visible by white light This is a common problem, and can ruin an image. Stray light has entered the glass plate through its edge and is being internally reflected. Block off light from the upper edge of the glass by painting it with a black waterproof marker pen.

It is unwise to attempt exposures of more than about a minute without active fringe stabilization (see Appendix 4).

Backlighting and background illumination

The overspill from the reference beam isn't always sufficient to provide a powerful enough kicker light. You may need to introduce a further beam for this purpose. Fig. 11.17 shows one method of introducing it. The extra beamsplitter should be variable, so that you can match the relative brightness of subject and background.

With this setup you may not be able to match the path lengths exactly.





So far I haven't said much about illumination of the background, and it may have been dark in any image you may have made so far. This can be particularly effective if the subject matter is translucent (Fig. 11.18a). The frontal illumination of the subject may also illuminate the background to some extent, but the extra optical path length may take this light beyond the coherence length of the beam, so that it appears dark. If the subject matter is fully transparent, as in Fig. 11.18b, you can transilluminate the background as light as you like. Fig. 11.19 shows the setup for a translucent background with the subject matter transilluminated.

Silhouettes and black holes

If the subject is opaque and you use backlighting only, you will get a threedimensional silhouette. With some types of subject (e.g. a sculptured head in profile) this can be very effective. Use a strongly lit or transilluminated background. An alternative way is to use the 'black hole' technique. You set up the subject in the usual way, and nudge it during the exposure. This will wipe out the fringes forming the image, and you will be left with a three-dimensional black hole where the subject was.

This technique has been exploited by a number of holographic artists, sometimes in combination with other effects (Plate 3b). You can even make black-hole

You may have achieved this result already without trying, in some of your earlier efforts.



Figure 11.18 (a) Translucent subjects look best directly lit, against a dark background. (b) Fully transparent subjects often look best with diffuse backlighting from a bright background.

holograms of live subject matter such as hands and facial profiles. The sitter should remain still (by photographic standards) during the exposure.

Supine subjects

Often a subject can't be recorded upright: typical examples are jewelry and collages of delicate objects. In such cases you simply lay the subject on a suitable horizontal support. Instead of a plateholder, set up four magnetic-based pillars like a fourposter bed round the subject, and lay the glass plate holding the film on top of them.

You need the reference beam to come from below the plate, in order for it to be from "above" with respect to the image. Direct the collimated beam down at 45° on to a horizontal front-surface mirror laid on the table "above" the subject. If the

If the pillars are not all exactly the same height the glass may rock. If so, remove one of the pillars and just use the remaining three, as in earlier chapters.



Figure 11.19 Providing background illumination. All optical paths are measured from VSB. (Again, the reference beam has been omitted.)

reference beam is sufficiently spread out you will effectively produce a bypass hologram setup, though the beam ratio will be high and the lighting probably unsuitable, so you will need to add auxiliary illumination (Fig. 11.20).

Frontal illumination

In studio photography the fill light is usually positioned close to the camera axis. In a hologram the plateholder gets in the way. As a result the light is a long way off axis, and creates a shadow of its own. Double shadows are unrealistic: worse, you may find that some parts of the subject aren't receiving any light at all. There are two ways of dealing with this problem. One may seem a little surprising: it is to direct the fill beam straight through the plate. The trick is to converge the beam so that its focal point is in the plane of the film. The beam will then fog only a tiny spot, and this will be invisible in the final transfer hologram. You will need a converging lens positioned in the expanded beam, with a focal length appropriate for spreading the light out on the opposite side of the film to cover the subject matter (Fig.11.21a). Place the focal spot well away from the center, on the opposite side to the key light, and either above or below the centerline. The second method is to place a large sheet of glass between the subject and the plate at about 45°, and reflect the expanded fill light off the glass onto the subject (Fig. 11.21b).

The advantage of this method is that you can use a fully diffused beam, though a proportion of the light is wasted by transmission through the glass.

Multiple-exposure techniques

The effects you can obtain by multiple exposures are similar to those you can get in photography, except in one respect, namely the three-dimensional nature of the images. You can produce interpenetrating images if you expose one subject, then, This principle is the basis of front projection backgrounds as used in TV programs, and is known as the Pepper's Ghost principle, a term dating from its use as a stage device in Victorian times.


Figure 11.20 (a) Reference beam arrangement for a supine subject. (Broken line indicates optional bypass illumination.) (b) Delicate collages such as this model by Max Holden need to be set up in this way.



Figure 11.21 Frontal lighting. (a) Directed lighting through peripheral area of film. (b) Diffuse lighting (Pepper's ghost). L = focusing lens, BE = beam expanding lens, D = diffuser.

without changing the lighting, substitute another and make a further exposure on the same emulsion. In this way you can display, for example, an image of a stereo amplifier with and without its cover, simultaneously. The image will show the cover, with the components showing through. You have to balance the two exposures by trial and error: it sometimes makes a difference which image you expose first.

One thing you can't easily do in photography is to make one image disappear and another one appear as you change your viewpoint.

You can do it in a hologram, though, in either of two ways. One is to change the angle of the reference beam between the two exposures, positioning it so that it falls from the left for one exposure and from the right for the other, with an angle of 30–40° between the beams. However, you can't transfer this type of hologram easily. The other way is to cover one half of the film for the exposure of the first master hologram, and the other half for the second. You can do this with more than two images, of course, and with either vertical or horizontal divisions. If you decide to make your multiple exposures in this way, the best way to go about it is to cut out a piece of thick cardboard (preferably black) the size of your plateholder, and make two (or more) doors from it, hinged with tape, so that you can have one open for the first exposure, and the other for the second. For three or more exposures you can have the doors hinged at the bottom and opening downwards. However, it is difficult to ensure that all the images will be equally bright, so most workers prefer to delay the production of multiple images until the transfer stage. The techniques for this are described in Chapter 13.

Masters for rainbow holograms

When you make a rainbow transfer hologram you illuminate only a narrow strip of the master hologram. This means that you don't need to use the full height of the film, but need to expose only a comparatively narrow horizontal strip. In practice it is advisable to make the strip a good 50 mm deep, so that you have the option of choosing a somewhat higher or lower viewpoint, once you have seen the first test.

When you make a master hologram you intend to use for a reflection transfer hologram, it is a good idea to have the subject as close to the film as you can manage, subject to the requirements of the lighting setup. This gives maximum parallax, and helps to keep the exposure short. However, when you are making a master for a rainbow transfer there are two further considerations. The first is that you have to leave room for the transfer reference beam in between the master and the final hologram; the second is that when you flip the final hologram for displaying, you will be looking at the image through the real image of the slit, and this should be in the plane of your eyes.

In practical terms, for an 8×10 in final hologram the subject should be about 40 cm from the film, and for a 30×40 cm hologram the distance should be about 60 cm.

Reflection master holograms

Practicing holographers seldom make first-generation reflection holograms using split-beam techniques, as the stability requirements are an order of magnitude

A lenticular stereogram can do this, of course, but it needs special equipment to interlace the images and mount them in register under the lenticular array.

Nevertheless, I have made a good many masters of this type on 35 mm holographic film, saving a lot of expense in the process.

The geometry of this is explained in detail in Appendix 4.

Under the usual display conditions the image of the slit will be projected out some 30% more than these distances.



Figure 11.22 A sophisticated assisted Denisyuk configuration for high quality first-generation reflection holograms. The fill beam can be close to the edge of the film or can actually pass through it near its edge.

higher than for transmission masters. When they do, the preferred method is usually an assisted Denisyuk configuration. The majority of the holograms made for the museums of the former Soviet Union are made by this method. A typical setup is shown in Fig. 11.22.

You can use first-generation reflection holograms as reflection masters, of course. It is important to use a processing technique that gives a bright reconstruction of the real image when illuminated by the original laser light at the original angle.

Working with plates

Many holographers prefer to work with plates rather than film for master holograms, in spite of their extra cost. Indeed, at the time of writing, film has sometimes been difficult to obtain, though there are indications that this will change.

Plates, at one time universally used in photography, are now employed only by research workers in fields such as particle physics and astronomy, and in the making of masks for microcircuitry, in all of which demand 100% dimensional stability. This quality is also required by some types of holography. Nearly all scientific holography, and much commercial holography, uses plates rather than film, at least for first-generation images. Plates don't need index-matching fluid, and multi-exposure techniques that require removal and later precise repositioning of the hologram are simpler. The extra expense is partly due to the cost of the glass, but also because glass plates need to be coated individually, and there can be a high rejection rate at the factory. They are, of course, less easy to cut up than film for test pieces or rainbow masters.

The method was explained on pp. 103–5 and p. 124.

At one time almost all commercial and press photography was on plates, because they were rigid and easy to retouch; they could be used in an enlarger without pressure glasses or clamps; they could even be printed wet – useful for press photographers in a hurry.

Cutting glass

People unfamiliar with the glazier's profession tend to associate glass cutting with diamonds. Certainly, there are diamond glass cutting tools, but they are expensive, difficult to use and easily damaged.

In fact, professional glaziers seldom use them. They almost always use steel wheel cutters, which are cheap and reliable. You can buy a wheel cutter in any DIY store; and as they are made with six wheels (when one is worn you just move the next one into position) they last for years.

If you are new to glass cutting, try out your wheel cutter first on some pieces of clean scrap glass. Place the glass on several thicknesses of newspaper. Put a thick straight edge or rule on it (a boxwood metre rule, not a carpenter's steel rule), and hold it pointing towards you, firmly, using the thumb and first two fingers of your left hand (right, if you are left-handed). Take the wheel cutter in your other hand, hold it upright with the flat side against the rule, and rest it on the far side of the glass with the wheel just over the edge and touching it. Pull the cutter towards you a little to start the scratch, then draw it steadily and fairly quickly towards you across the glass, making sure you don't wander away from the rule.

Don't press hard, just do it confidently, at a steady speed. You will hear a gentle hiss from the glass as you draw the cutter across it. Put down the cutter, pick up the glass, and place it with the scratch uppermost along the edge of the rule. Put the palms of your hands on the two sides of the scratch and press down gently. The glass will snap like a biscuit. If you find you need to use force there is probably a gap somewhere in the scratch, and when it finally gives way the break will curve away from that point. You will probably be able to break the other part away, and will be left with a shallow cusp. You will have to nibble this off piece by piece using the notch in the glasscutter or a pair of pliers, leaving you with a ragged edge and a feeling of defeat. (You can smooth it off with a carborundum stone afterwards.) Keep trying: you will soon acquire the knack of applying exactly the right amount of pressure, and will hear that satisfying hiss every time.

A useful tip practiced by professional glaziers is to touch the cutter wheel on a drop of oil before using it. You can do this too, but don't use ordinary oil on unexposed holographic plates. Index-matching fluid (white spirit) works just as well.

One of the more difficult skills in this connection is cutting up glass plates in the dark. You may want to make test pieces, or to cut up, for example, 8×10 in plates to make four 4×5 in ones. The simplest guide is the type shown in Fig. 11.23. It is just a square of plywood at least as big as the largest plate you use each way, with an accurate L-piece at the top end, to use as a stop. Cut templates for the sizes you want, allowing for the thickness of the glass cutter (e.g. 3.9×10.5 in and 4.9×10.5 in for the example above), and work against these when you do the cutting.

One final caveat: don't attempt to cut curves. If you need a circular or elliptical plate cutting, mark it out with a chinagraph pencil or a marker pen and take it to a professional glazier.

I used to have one at one time. It scarcely ever cut cleanly, and ruined more square metres of glass sheet than I care to remember. After I changed to a wheel cutter I had no further difficulty.

Each time you cut a piece, remove and bin the top layer of paper. The tiny shards of glass on it can damage both your skin and the next plate you cut up.

Some people make a slotted template, with the cutter an exact fit in the slot, but that shouldn't be necessary, after a bit of practice.

Don't do this with an unexposed plate: even a professional would refuse to cut odd shapes in the dark. Make your hologram first, on a rectangular plate, and have it cut to shape afterwards.



Figure 11.23 Template for cutting glass in the dark. This (right-handed) example is designed for cutting 8×10 in plates down to four 4×5 in plates.

Processing plates

You process plates in exactly the same way as film. With 4×5 in plates, which are not smooth edged, you need to be careful. If you cut your finger and subsequently put it in the developer or bleach bath you will know all about it very quickly (rinse your finger immediately). Even if you use disposable plastic gloves, the sharp edges can cut right through them. Large plates are often (but not always) coated on glass that has had the edges smoothed off.

Optical fiber systems for holography

'I beg your pardon', said Alice very humbly: 'You had got to the fifth bend, I think?'

Lewis Carroll, Alice in Wonderland

Optical fibers are used routinely where it is necessary to convey light from one place to another, and where straight paths, with or without mirrors, are out of the question. A familiar example is their decorative use in lamps, producing points of light at their ends. But optical fibers find more serious uses: in car dashboard illumination, in the lighting of small specimens for photography, in endoscopy and, increasingly, in communications technology.

Multimode fibers

For most of the above purposes the light is confined within the fiber by total internal reflection. This occurs at the interface of a medium with one of lower refractive index, when the angle of incidence is greater than the critical angle and thus cannot escape.

You also need to be careful when squeegeeing glass plates, but for a different reason, namely that gelatin doesn't adhere to glass as firmly as it does to a film base, and if you are over-enthusiastic you can fetch chunks of emulsion off the plate. When the overall diameter of the source is required to be large, a bundle of fibers is employed. For ordinary lighting purposes (as in dashboard lighting) the positions of the fibers at the ends of the bundle are not correlated, and the bundle is said to be 'incoherent'. However, if the bundle is intended to convey an image from one location to another, as in an endoscope, the fibers have to retain their spatial relationships at both ends of the light guide. Such a guide is said to be 'coherent'. The resolution of the image is limited by the diameters of the individual fibers.

Single-mode fibers

In a multimode fiber, which may typically be 0.1 mm to 1 mm or more in diameter, some parts of the beam will have been reflected back and forth many times. Some will have followed a skewed or spiral path, and some will have traveled more or less straight down the middle. The optical paths will be different for all of these rays, and if you tried to send a stream of digital information down the fiber on a laser beam it would become smeared out and useless after only a few metres.

If you reduce the diameter of an optical fiber sufficiently the rules change, forbidding the occurrence of total internal reflection. The beam travels down the middle of the fiber, retaining both its coherence and polarization characteristics.

For red laser light this occurs when the fiber diameter is reduced to about $6 \mu m$. As this is such a small diameter (less than that of a human hair) the fiber is protected by transparent cladding of greater diameter (and lower refractive index), and usually by a plastic protective sheath as well. The central fiber is now called the *core*. On emergence from the fiber the light behaves as if it were emerging from a spatial filter, with a divergence of some 12° , depending on the numerical aperture of the system.

This means that we can use single mode fibers for making holograms, provided we can manage to launch the laser beam into a fiber and then divide it into at least two paths, still within fibers.

Launching the beam

Fiber launchers resemble spatial filters except that the pinhole is replaced by a ferrule that holds the fiber end. As well as x, y and z movements, the ferrule holder can be tilted through a degree or so in all directions to allow the beam to enter the fiber squarely on (fiber cleaving is seldom at exactly 90°). You line the fiber up exactly as you would a pinhole, using a $\times 60$ microscope objective (or a $\times 40$ with the beam slightly expanded by a concave lens situated upstream of the objective). To begin with, most of the light will be passing down the cladding, giving a diffuse speckled patch at the exit. Once the beam is lined up you will see a pool of clean bright light, just as you do with a pinhole.

Cleaving a fiber The usual method of cleaving a fiber is by the scratch-and-pull method.

There is a diamond tool made especially for producing the scratch; but, as in glass cutting, a steel tool (a razor blade) is every bit as good. First, remove the protective plastic sheath with your thumbnail. Then stretch the fiber over a curved surface about 25–30 mm in diameter (e.g. a section of broom handle or plastic pipe). Scratch the fiber with the blade, then take the fiber and pull it apart, firmly but not roughly.

Note that these terms have nothing to do with coherent light.

This follows from waveguide theory, which says (roughly) that there is destructive interference at the periphery of the waveguide when its width is only a few wavelengths, so the wave is propagated down the center of the waveguide without loss.

Numerical aperture (NA), which in lenses is related to *f*-number, is equal to the sine of the semi-angle of the cone of acceptance of the core (the maximum angle at which light can enter the fiber if it is not to escape into the cladding). This is the same as the cone of emergence. In a singlemode fiber it is equal to $\sqrt{n_1^2 - n_2^2}$, where n_1 and n_2 are the refractive indexes of the core and cladding respectively.

You can probably brighten this by carefully adjusting the tilt controls, but this may not make much difference unless the fiber has been very badly cleft.

There are many expensive cleaving devices in the catalogs. Don't waste your money on them. This method is as good as any, and need cost you nothing.

The scratch shouldn't be a deep one: as with glass cutting, it is breaking the surface that counts.



Figure 11.24 Types of single-mode fiber optics direction coupler. (a) Fixed-ratio coupler. A pair of fibers drawn out and twisted together so that light leaks from one to the other via the evanescent wave. (b) Variable coupler. Fibers embedded in grooves in two blocks are ground down until evanescent-wave coupling occurs on contact. Coarse adjustment of beam transfer ratio is by lateral shifting of one block relative to the other, fine adjustment by longitudinal movement.

If you have access to a microscope or a powerful loupe, examine the break. If it is completely clean (which it usually is), you can use it. If not, try again. Alternatively, if you are going to use the fiber in a ferrule, cut the fiber with scissors and mount it in the ferrule nearly flush, then polish it down flat using lapping paste and finally jeweler's rouge. You can also use equipment made for preparing metallurgical or petrological specimens, if it is available.

Beamsplitting devices In fiber-optics technology a beamsplitter is called a *directional coupler*. If two fibers have their core diameters reduced and are brought into close contact, some of the light energy will leak from one to the other via the evanescent wave. Directional couplers exploit this principle. By controlling the reduction in the core diameter the two emergent beams can be made to have any desired intensity ratio. These devices are readily available from suppliers of fiber optics equipment. Variable couplers are also available. These have a micrometer movement that varies the separation of the two cores. Their actual construction is shown in Fig. 11.24.

Making holograms with fiber optics

You can use multimode fibers for illuminating the subject in an otherwise conventional setup, and this not only makes path matching much less of a chore, but also allows you to bring your fill beam right up against the plateholder, and

In a previous edition of this book I explained how to make your own directional coupler. In practice it isn't at all easy; but at that time the technology was in its early days, and directional couplers were very expensive. They are much less so now. even, as suggested above, to feed it through the film itself. You don't need any steering mirrors or pinholes, either.

Where fiber optics really scores is with single-mode fibers. Only the immediate area round the subject and the fiber clamps needs isolating, so you can work on a breadboard with the laser well out of the way. You don't need any steering mirrors, as you can curve the path as much as you like; or pinholes, because the beam emerges from the fiber absolutely clean, and diverging. The only items you are likely to need are small concave lenses to increase the spread of the beams. There is a caveat, though. Although in fairly short runs of fiber (a few metres) polarization is preserved, this is so only if the fiber isn't significantly stressed; and it must not be moved during the exposure. The latter requirement is easy to fulfill given a supply of Blu-tack; the former less so. The answer is to use *polarization-preserving fibers*; these are fabricated with a built-in stress across their diameter, which does not allow the polarization to change in direction. The fiber core has a cross section that may be elliptical or bow tie shaped.

A recent development in fiber optics is the so-called *holey fiber*. This is drawn initially from a bundle of glass tubes, so that it contains a large number of air spaces. These are only a few nanometres in diameter, and therefore by classical theory shouldn't permit any light to travel down them. The reason these fibers do in fact convey light in coherent form is (I am happy to say) well beyond the scope of this text; but don't be surprised if holey fibers crop up in a good many optical applications in the future.

Connecting fiber ends

Various devices are available for connecting lengths of optical fiber so that losses are small. Although they are still expensive, prices are coming down as fiber optics becomes ever more important in the world of communications technology. You will need one if you intend to use a pigtailed diode laser as your source.



This is a diode laser that is supplied with a short length of single-mode optical fiber for its output.

Figure 11.25 Optical connector with included beamsplitter.



Figure 11.26 A fiber optics holography table. Equipment supplied by Durell Laboratories, North Barrington, IL, USA.

For a permanent setup you would need a proper connecting device, but for experimental work you can make a satisfactory connection using two ferrules and a pair of lenses. You can also include a conventional beamsplitter in the system (Fig. 11.25).

Stray light in the cladding can be a nuisance. You can eliminate it by stripping off the sheathing near the ends of the fibers and passing them through a small box of petroleum jelly. The effect is to leak out all the unwanted light in the cladding, leaving the wanted beam confined within the core.

Fig. 11.26 shows a setup for a fiber optics holographic system, using purpose-built equipment to produce the required beams in the right ratios.

Further reading

Fiber optics is a rapidly developing subject in its own right. If you want to know more about it, I suggest you look at a copy of *Optical Fibre Devices* by J-P Goure and I Verrier (Institute of Physics Publishing, 2002). Another good introduction to this now not-so-arcane world is Jeff Hecht's *Understanding Fibre Optics* (Prentice Hall, 2001).

Chapter 12 Transfer reflection holograms

'Would you tell me, please, which way I ought to go from here?' [said Alice.] 'That depends a good deal on where you want to get to,' said the Cat.

Lewis Carroll, Alice in Wonderland

As I explained in Chapter 4, if you make a hologram and illuminate it with the conjugate of the original reference beam, the diffracted beam will form a real image occupying the precise position of the original object. When you view this aerial image you see it, in effect, from behind, so that it is pseudoscopic (i.e. has reversed perspective). In other respects it is the same as the image of an object formed by a convex lens situated at twice its focal length from the object (Fig. 12.1). You can make a hologram using either type of image as the object. When you make it from the image formed by a lens it is called a *focused-image hologram*, and Chapter 14 explains how to make this. A hologram made from a holographic real image is called an *image hologram*, and is the subject of this chapter.





In an image hologram, the beam that forms the pseudoscopic image becomes the object beam for the final (transfer) hologram. As with first-generation holograms, if the object and reference beams are incident on the emulsion from the same side the result is a transmission hologram; if they are incident from opposite sides the result is a reflection hologram. Whether the final image is virtual or real depends on the spacing between the master and transfer plateholders.

If this is less than the distance between the master hologram and the original subject the image will be virtual and behind the final hologram plane; if it is greater it will be real and in front of the final hologram; and if the spacing is the same it will lie across the plane of the hologram. This rather special case is called an *image-plane hologram*, and has a number of desirable properties. Figure 12.2 shows the three situations.

To see why these images come out this way, remember that the transfer image is pseudoscopic, and in order to see it the right way round ('orthoscopic') you need to flip the hologram. The image that was in front of the transfer plane is now



Figure 12.2 Setting up an image hologram. If the transfer emulsion H_2 is in plane A the image will be virtual; if it is in plane B it will be partly real and partly virtual; if it is in plane C it will be wholly real.

I am using the term 'plateholder' throughout, to avoid tedious repetition of the words 'film or plate'. A film will, of course, always be mounted on a plate.

The most desirable property is that you can get away with a display source that has limited spatial and temporal coherence, i.e., a bogstandard spotlight bulb. It follows from this that there will be a good many double quotes in this chapter. These, you will recall, indicate an orientation considered with respect to the image rather than the table.

Virtual-image transfers have the most parallax and real images the least, with hologram-plane images in between. behind it (a virtual image), and the image that was behind the transfer plane is now in front of it (a real image). Table rigs for transfer holograms are almost always horizontal, with the image on its side, as this makes setting up much simpler.

Parallax in transfer holograms

An important consideration in designing an exhibition hologram is the amount of horizontal parallax you are going to have in the final image. You should always aim at having the maximum possible amount. For reasons you will appreciate when we come to look at the transfer geometries, you can't put the master plateholder closer to the subject than its vertical dimension. As it is the horizontal width of the master hologram that dictates the amount of parallax in the final hologram, the master needs to be as wide as possible, which means that you should use landscape (horizontal) format for the master, even if the final image is to be in portrait (vertical) format.

The reason that parallax is limited in the final hologram is that in viewing a transfer image (which has necessarily been flipped) you are viewing it through the real image of the master hologram plate, i.e., through a rectangular hole of the same size and shape as the master. You can see this effect clearly if you stand several metres back from the hologram and move sideways. At a certain point on each side a black shadow will move across the image in the opposite direction, indicating that the edge of the real image of the master hologram plate is passing in front of both the hologram image. If you move up and down you can see the vertical boundaries too. Because of this restriction the amount of parallax in a transfer hologram is always less that that of the original virtual image (Fig. 12.3).

f-number and parallax angle The *f*-number (f/no) of a camera lens is the figure you get when you divide its focal length by its aperture diameter. One of the lens-like characteristics of a hologram is that it also has an f/no. The concept can







Figure 12.4 Parallax angle (α) of a primary holographic image. *I* is the position of the image, f the distance of the image from the plane of the hologram, *d* the width of the hologram, the parallax angle is given by $\alpha = 2 \tan^{-1} (d/2f) \cong d/f$ if α is measured in radians.

be extended to any type of hologram, the distance of the image from the plane of the hologram constituting the 'focal length'.

The angle of parallax is determined by the points (in a horizontal plane) at which the image of the object is cut off by the edges of the hologram – or, in the case of a transfer hologram, by the edges of the real image of the master hologram plate (Fig. 12.4). If D, the parallax distance, is less than the separation of your eyes, you won't be able to see the image with both eyes at the same time, though there will still be a small amount of parallax, as you can confirm by moving your head.

If the transfer beam and/or the replay beam are divergent, the viewing aperture will be larger and farther from the display hologram plane than it was in the making of the hologram. Since the distance of the aperture from the hologram increases faster than its size, the use of divergent rather than collimated beams actually restricts the parallax angle (Fig. 12.5).



The more divergent the beams, the greater the effect. This is the result of the holographic image obeying the Newtonian lens laws.



Figure 12.5 When a transfer hologram is made with a collimated reference beam and replayed using a similar beam, the real image of the master hologram aperture appears in its geometrically correct position. If the hologram is replayed using a diverging beam the master aperture is imaged farther away from the hologram, and the parallax angle is reduced. IS = illumination source, H = hologram, MA = real image of master aperture.

Reflection transfer holograms from transmission masters

Although these are not the easiest configurations to set up, and need plenty of space as well as rock-steady stability, I am dealing with them first as they are the mainstay of most exhibitions of holograms, and are the easiest to display in the home. The configuration of Fig. 12.6 is the one I have used as standard for many years.



Figure 12.6 Layout for a reflection transfer from a transmission master hologram. This is the optical configuration that is the basis for all subsequent transfer geometries discussed in this chapter.

The mirror M_3 isn't strictly necessary, but it makes beam path length matching easier, and it makes M_4 into a good position for a fringe stabilizer mirror (see Appendix 5). The position of the pinhole of the spatial filter must lie on the focal plane of the collimating mirror CM, and be as close to the optic axis of the mirror as feasible, in order to minimize off-axis aberrations.

Before you do anything else, make sure the light is *p*-polarized with respect to the surfaces; you will then be less troubled by internal reflections in the glasses. This means that the polarization vector of the laser beam should be horizontal. If you can turn the laser on its side, do so. If you can't, you will need to insert a half-wave plate in the beam; this will rotate the polarization vector through any angle you wish.

Set up the illumination for the master hologram H_1 first, with the hologram on its side, flipped and illuminated from "below". Set it up initially at the angle of incidence you used when you made it originally. Place the plateholder H_2 approximately in position, with a white card in it. Now steer the (unexpanded) beam to the center of the collimating mirror CM and adjust CM to steer the beam through the middle of H_1 . You will see the image projected on the white card. Adjust the angle of H_1 until the image is brightest, then block off the beam without delay.

The main aberrations that concern us are those that cause the beam to converge vertically and at the same time diverge horizontally (or vice versa). They result in horizontal/ vertical distortion of the image (astigmatism).

If you allow the unexpanded beam to fall on the master hologram for more than a minute or so it is likely to produce an opaque spot ('printout'). Now introduce the spatial filter without its pinhole, and adjust the beam so that it fills the mirror CM uniformly. Move the H_2 plateholder until the part of the image you want to be in the plane of the final hologram appears sharp.

[This may be easier to assess if you use ground glass or tracing paper in the holder and view from the other side. You can also use a plain glass in the holder and locate the image by holding a pointer against the glass or making an ink mark on it. Move your head and note the direction in which the image moves. If it is in the same direction as your head it is behind the glass and will become a real image when you flip the final hologram for display: if it moves in the opposite direction it is in front of the glass and will become a virtual image.]

Now set up the reference beam for H_2 . With the white card in the H_2 holder, examine the two sides of the card. If the brightest part of the image looks about the same brightness as the average reference illumination, the beam ratio is probably close to optimum. If not, adjust the beam ratio by means of the variable beamsplitter. Measure the reference beam intensity with an exposure meter at all four corners and the center of the H_2 plateholder, and adjust it as necessary until it is uniform to within 50%, then measure both the brightest part of the real image and an average part. Adjust the beam intensities until the ratio is about 1.5:1 for the bright part and (if possible) not more than about 4:1 for the average part.

Once you are satisfied with the beam ratios, fit the pinholes and readjust the beams if they have moved. Give the setup plenty of time to settle, and then make a test exposure, making sure you include the critical parts of the image in your test.

Once you have processed the test piece you will be able to establish three things: whether your exposure was correct (did the emulsion reach its full density at full development time, or too soon, or not at all?); whether the beam ratio was correct (is the image bright all over, with no sign of burnout?); and whether the image is in the required plane (were H_1 and H_2 the right distance apart?).

From what I said earlier about diverging beams, it may have occurred to you that if the final hologram is to be viewed under a spotlight (i.e. under a diverging beam) it should have been made using a converging reference beam, not a collimated one. Although this is strictly true, it isn't very important for a hologram-plane image that is not very deep. The main effect is to push the phantom rectangular window of H_1 farther out into the viewing space, and to enlarge it a little.

If you were a little careless with the processing technique, or used the wrong formula, you may find that the H_1 reconstruction angle is greater (more oblique) than the original reference beam angle. If the difference is only a few degrees this is probably of little importance, but if the angle is significantly greater than the original angle the image will be smaller and closer to the master hologram. More seriously, it will be offset, so that the final image is cut off close to eye level instead of well below it (Fig. 12.7). A further effect is an aberration that causes the image to swing in and out of plane as you move your head sideways.

You can in fact deal with this problem. As it is caused by shrinkage of the emulsion resulting in the interference planes being tilted at the wrong angle, you need to swell the emulsion. This is best done by soaking it in a 5-10% solution of sorbitol. (You can buy sorbitol at any health food store.)

After immersion in the solution for about five minutes, squeegee the emulsion and dry it without rinsing. When you have finished with the master, wash it before filing it away, or it may become sticky.



Figure 12.7 If the master hologram shrinks as a result of incorrect processing, the master and transfer holograms will be out of alignment. This may result in the image being cut off at low viewpoints.

If the image is too contrasty you may get a burnt-out patch in a highlight, or very weak shadow areas, or both, in which case your only remedy is to make a new master with softer lighting.

Under certain circumstances it *does* matter, and this topic is discussed at the end of the chapter.

Don't use the pre-swelling agent triethanolamine, as it re-sensitizes the emulsion and leads to printout. With a metalized beamsplitter, once you pass the 1:1 mark, very little extra light is reflected from the front surface: what happens is simply that less light is transmitted, the balance being absorbed.

How to deal with weak master images

The table rig of Fig. 12.6 works well for good-quality masters that give bright images, but sometimes you will be faced with transferring an image that is feeble, perhaps needing the variable beamsplitter ratio to be wound up to as much as 99:1. With a metalized beamsplitter this is very inefficient, as the metal coating will absorb nearly half the light, and this will result in unacceptably long exposures.

In such cases you will do better to switch the roles of the beamsplitter and the steering mirror M_2 so that the master is illuminated by the transmitted beam (Fig. 12.8). In this arrangement the variable beamsplitter is close to the Brewster angle, and a beamsplitter ratio of up to 1000:1 with negligible losses is possible.



Figure 12.8 Table layout for a reflection transfer from a transmission master with a weak image. The variable beamsplitter VBS is set close to the Brewster angle, and beamsplitter ratios of up to 1000:1 are possible.

There are further strategies you can call on. If you mask the master hologram to reduce its "vertical" dimensions to about 125–150 mm, then when you replay the final hologram all the diffracted light will pass through this reduced aperture, and the image will be proportionately brighter. Unfortunately, this procedure reduces the intensity of the object beam, which is the opposite of what you want. The answer is to introduce a convex cylindrical lens of focal length about 200 mm into the master reconstruction beam, a few centimetres downstream of the spatial filter. This will narrow the beam to an elliptical cross-section that will fill the aperture and waste less light.

Side and underneath beam master transfers

There are some subjects where you may find the only feasible direction for the reference beam is from "below". Sometimes a display hologram has to be lit from below because of some special display conditions. In either case you need to modify the transfer setup to resemble Fig. 12.9.



Figure 12.9 Layout for an overhead-lit reflection transfer from an underneath-lit master hologram (or vice versa).

If you need to make a display copy of a scientific or industrial hologram you will almost certainly find that it has been made with a side reference beam. As display holograms require an overhead replay light you will need a special table configuration. The simplest arrangement I have found is that of Fig. 12.10. You shouldn't find it too difficult to modify your mastering rig with the overhead mirror to achieve this.



Figure 12.10 Layout for an overhead-lit reflection transfer from a side-lit master (or vice versa). The collimating mirror CM is elevated to give a beam from 45° above, and the polarization of the beam is controlled by the half-wave plate $\lambda/2$.

The original may have been made with a diverging reference beam, and if so you will have to try to converge the reconstruction beam by putting the source SF as far from the mirror as you can. Position the original hologram on its side and illuminate it with the collimated beam. The reference beam for H_2 comes from the side, i.e. from "below".

You will appreciate that if your polarization is horizontal, the illumination of H_1 will be *s*-polarized. This isn't particularly important, but you may get a better result if you use a half-wave plate immediately after the steering mirror M_1 to turn the polarization vector through 45° clockwise, looking downstream. You may also need to check whether the polarization vectors of the object and reference beams are aligned. The importance of this is explained in Box 12.1. You can align them if necessary with a half-wave plate in one of the two beams.

Box 12.1 The relevance of polarization

Two beams of light will produce an interference pattern if, and only if, they are correlated; in practice that means that they come from the same source and have similar optical path lengths, i.e. are mutually coherent. A beam that is depolarized (such as the object beam from a light-scattering subject) will form an interference pattern with a reference beam that is polarized in any direction, even circularly, as it may be considered as possessing a measure of polarization in every direction (Fig. 12.11a).



Figure 12.11 Effect of angle of incidence and direction of polarization on efficiency (η) of interference. θ is the angle between the incident beams; ϕ is the angle between their polarization vectors. (a) One beam unpolarized, the other linearly polarized, $\eta = 0.5$; (b) both beams s-polarized, $\eta = 1.0$; (c) both beams *p*-polarized, $\eta = \cos \theta$; (d) beams polarized at an angle ϕ , $\eta = \cos \theta \cos \phi$; (e) beams *p*-polarized and orthogonal, $\eta = 0$; (f) beams polarized orthogonally, $\eta = 0$.

Two beams polarized in a direction perpendicular to their common plane (Fig. 12.11b) will interfere fully. Two beams that are polarized in their common

plane (Fig. 12.11c) or at an angle to one another (Fig. 12. 11d, e, f)) will interfere only partially, in proportion to the cosine of the angle between their polarization vectors. When these are orthogonal there will be no interference at all.

In practice there is only a small loss of effectiveness, as once the beams have entered the emulsion they are refracted towards the normal, and the angle between them is considerably reduced. Fig. 12.12 shows the loss that can be expected in an emulsion with a refractive index of 1.5. This assumes that both beams are *p*-polarized.



The role of the Bragg condition

You will have noticed, when you were setting up the master hologram reconstruction, that a small change in the angle of incidence of the illuminating beam results in a large change in the brightness of the real image. When you process a transmission hologram there may be some loss of material from the emulsion, which then, on drying, shrinks to less than its original thickness. This results in a change in the angle of the fringe planes, which lie along the bisector of the object and reference beams.

If the object and reference beams were at equal and opposite angles of incidence this wouldn't matter, as the fringe planes would remain perpendicular to the plane of the emulsion regardless of any shrinkage; but the more usual situation in display holography is for the object beam to be on average normal to the emulsion and the reference beam to be at an angle of 45° or more (Fig. 12.13).





Figure 12.13 When the object beam is normal to the emulsion and the reference beam is at 60° the separation of the Bragg planes is equal to the wavelength λ . If the emulsion shrinks as a result of processing, the optimum angle for reconstruction changes. If the wavelength of the reconstruction beam is reduced the original angle of incidence is restored.

If you transfer such a hologram using a shorter wavelength laser, the distortion and angle discrepancy disappear. It so happens that the required wavelength change with one processing routine is a good match for the difference between a ruby pulse laser (694 nm) and a HeNe laser (633 nm); holographic portrait studios exploit this match. Calculation shows that shrinkage of around 10% in the emulsion will result in the skewing of the fringe planes sufficient to displace the image by some 5°; it will also be reduced in size by about 10 per cent, and will be somewhat nearer to the plane of the hologram. But this applies only parallel to the plane containing the object and reference beams. Along the line of the fringes there will be no effect. The result is vertical/horizontal astigmatism and some "horizontal" squeezing of the image.

Two-channel transfer holograms

The holograms for sale in galleries often contain two or more images, which appear in turn as you move past the hologram. Eggs suddenly appear in eggcups; billiard balls disappear from between the fingers of a hand; a jack-in-the-box pops up; the Cheshire Cat disappears, leaving only the grin (Plate 5), and so on.

There are two methods of achieving this, based on similar principles. In the first method you set up for a master hologram using the cat complete with grin (Fig. 12.14a). You shoot this master; then make a second master in the same way, but using the grin alone (Fig. 12.14b). You now have two masters. Place these in contact, and adjust their relative positions, under a spotlight, until the two images are in register. Tape the two films together at the edges and cut right through both with a guillotine or a sharp knife (Fig.12.14c). Now take the right half of one master and the left half of the other, and sandwich them edge-to-edge between two glass plates (Fig. 12.14d).

Transfer this double hologram exactly as you would a single one (Fig. 12.14e). When you view the final hologram you will see each image separately, depending on whether your viewpoint is within the projected rectangle of the left master or the right (Fig. 12.14f).

With this method you finish up with two choices of final image: either the cat disappears, leaving the grin; or the grin appears first, then the cat, as you move from left to right.

With the second method you make only one master, and this is the method you will have to use if you are making your master on a plate. (I mentioned this method in the previous chapter.) You load the plate as usual, but cover one half with a black card for the first exposure (the cat). You then cover the other side instead, and make the second exposure (the grin alone). The best way of obtaining correct masking is to construct your black card as a pair of double doors hinged with masking tape, so that you have one door open for the first exposure and the other open for the second.

You don't need to be confined to a single horizontal switch of image, of course. You can drop in subsidiary images in various shapes: for example, if you insert a sneaky image as a narrow "vertical" strip near the middle of the hologram, it can be seen only briefly, with one eye at a time, and not at all when you are looking at the image square on. A much-used gimmick that has still not lost its attraction is the 'keyhole' image, where you see only the real image of a door lock, until you align one eye with the keyhole, whereupon you see the contents of the room. An early (and, in my opinion, still unsurpassed) example of this is Walter Spierings's 'Microscope' (Plate 6), where you can look into the eyepiece of the real image of a microscope (about 20 cm in front of the hologram) and see a highly magnified image of a microchip.



Figure 12.14 Making a two-channel transfer hologram: (a) and (b) are the masters of the cat (complete with grin) and the grin alone. (c) The two masters are assembled in register and sliced down the middle. (d) The left half of the cat master and the right half of the grin master are butted between glasses. (e) The pair of images is transferred in one operation. (f) When the final transfer hologram is flipped, the cat is seen from a left viewpoint, through the exit pupils formed by the real images of the two master formats.

When you are planning the table setup for multiple images of this type you need to consider what you expect the final viewing distance to be. If you want the image to change abruptly (as with the billiard balls) the image of the master hologram plate needs to be in a plane close to the viewing distance; if it is to change more gradually (as with the Cheshire Cat) you can have it closer to the final hologram. As a rough guide you can begin by setting the master plateholder a distance from the subject that is about 20% more than the full width of the master hologram. If you want to be more precise you will find the calculations in Appendix 3.

Holograms of stereoscopic pairs of photographs

One of the disadvantages of conventional stereoscopic photography is that you usually need some kind of viewing device in order to be able to see the depth effect.

An autostereogram is a stereogram you can view without any kind of optical aid. There are three main kinds: the side-by side type (Figure 1.1a), which you need some practice to view, the interlaced-image type (ditto), and the lenticular stereogram, which may bear a large number of images, each one divided into a large number of narrow vertical strips, which are interlaced for printing, and viewed through an integral array of cylindrical retroreflecting lenticules that allow you to see only a single image with each eve at a time.

A typical stereoscopic viewer has the two photographs (taken from viewpoints around 6–7 cm apart) mounted side by side, and viewed through two lenses, one for each eye, providing a virtual image at infinity or a little nearer. More modern methods use an anaglyph system in which the left and right images are printed superposed in cyan and red respectively, and are viewed through filters of complementary hue. The eye with the cyan filter sees only the red image, and the eye with the red filter sees only the cyan image. For a color image, the green and blue records are printed together for the right eye image and the red record for the left. When the print is viewed without the filters it looks like an ordinary color print with the colors slightly out of register, but when viewed through the filters it appears sharp and three-dimensional. More sophisticated systems, including those sometimes used for motion pictures, employ two orthogonally polarized images viewed through polarizing spectacles; this system gives the most convincing three-dimensional color images. There are also various systems of autostereograms, which need some practice to view satisfactorily.

The simplest type of holographic stereogram is a two-channel hologram made of the two images of a stereoscopic pair of photographs. The photographs themselves need to be good quality black-and-white prints, illuminated from "above". You make the master in two successive exposures with each photograph central, just as described for the Cheshire Cat, and make a normal transfer. When you stand directly in front of the final hologram your left eye will see only the left image and your right eye only the right image, giving stereoscopic depth. This is effective over a fairly large range of viewing distances.

Multi-channel images

You don't need to confine yourself to just two channels. If you mask your master holograms down to narrow strips you can produce a reflection transfer hologram containing images from nine or more masters. If you make the strips horizontal, you will preserve the full horizontal parallax, with the image changing as the viewpoint moves up or down (Fig. 12.15).

In principle it is no more difficult to make a multi-channel reflection transfer hologram than a single restricted-aperture transfer. The only difference is in the number of master hologram strips you are juxtaposing. You simply set them all butted together between two glasses, and transfer the lot in one go. However, in practice it is more usual to employ the single-plate method. This is how you go about it:

- 1. Decide how many images are to appear in the final hologram, and whether they are to appear as the viewer moves horizontally (left to right, or right to left?) or vertically. Remember that the more images you put in with horizontal switching, the less parallax there will be. You can afford many more images in a vertical direction.
- 2. Construct a slit of the appropriate width from opaque black card, with a means of moving it accurately one slit width at a time.
- 3. Expose the master strips, one at a time, changing the subject as appropriate and moving the slit one step between successive exposures.
- 4. Process the master hologram, set it up for a transfer, and make the transfer hologram. When this is flipped for viewing, the images of the slits will be projected

If the slits are aligned accurately, with no overlap, the scene will change abruptly as the viewpoint is changed. If the original slit positions overlap a little, one view will dissolve into the next.



Figure 12.15 Six of the nine images of a prototype British $\pounds 2$ coin by Nick Hardy. The coin was a rotated 20° about a vertical axis between successive exposures. Hologram courtesy of Op-Graphics.

into the viewing space, and the different images will appear in turn as the viewer's eyes are aligned with the different slit images.

If you use a sufficiently large number of steps you can produce a somewhat jerky animation (Fig. 12.15). The technique is sometimes known as 'multiplexing'. It is only a short step away from a holographic stereogram, the subject of Chapter 19.

Convergent reference beams

The light beams that are used for displaying holograms are almost always divergent. The trouble about this is that deep images become distorted when the replay light is not the precise conjugate of the reference beam (Fig. 12.16). The main effect is the exaggeration of depth, particularly with real images in front of the hologram plane; but there is also some unattractive distortion in the shape of the image when you shift your viewpoint to one side. In order to produce a deep transfer image that doesn't have these aberrations you need a reference beam that converges to a focus at the point where the replay source will be positioned when the hologram is displayed. For an 8×10 in hologram that is to be illuminated from a point 150 cm distant, you can manage this with a 300 mm diameter mirror (or lens) with a focal length of 870 mm. Figure 12.17 shows a way of achieving this using a 300 mm diameter, 1200 mm focal length mirror for illuminating the master.

The mirrors in Fig. 12.17 may seem oversize, but they're not. For a collimated beam the mirror diameter needs to be not less than the width of the diagonal of the projection of the master (approx. 290 mm), and for the converging beam (in

In general, as I mentioned earlier, I don't recommend the use of the term 'multiplex', which has been used loosely for a number of widely differing processes in both optical and electronics technologies. To complicate matters further, several companies have at some time adopted the term as part of their corporate title.

Indeed, the only time a convergent beam is regularly used is when a convex lens is positioned in the transfer space in order to reduce the size of the final image.



Figure 12.16 Holographic self-portrait of the author. In (a) the use of a diverging transfer reference beam has led to exaggeration of the features reminiscent of a close-up photograph taken with a wide-angle lens; in (b) a converging reference beam results in correct perspective.



Figure 12.17 Layout for reflection transfer hologram with converging reference beam.

portrait format), it is also the diagonal, which is $270 \times 205/150$, which is approx. 370 mm. Even then you lose a bit at the corners. When you try to scale things up it gets worse. If you want a converging beam for a 30×40 cm transfer, you will need a mirror with a diameter of at least 500 mm; this will typically have a focal length of 2000 mm. You may be able to fit this on your table, but the display lamp in the showroom will need to be 2 m away from the hologram. If you want to reduce this distance to 1.5 m, you need to increase the distance between the spatial filter and the mirror to 29 m! Plainly, this is out of the question. The solution is to shorten the focal length of your mirror by inserting a converging lens into the reference beam system. The optimum place for this is just upstream of the transfer plateholder.

What focal length will be needed? We can find out by applying the rule of reciprocal focal lengths, which is

$$1/f = 1/f_1 + 1/f_2 + D/f_1f_2$$

where f_1 and f_2 are the focal lengths of the mirror and lens respectively, D is their separation and f is the focal length of the combination. For a combined focal length of 1220 mm this gives a required focal length for the lens of 2424 mm.

Now, it's a fair bet that you won't find a convex lens with a diameter of 500 mm and a focal length of around 2400 mm easily. Even if you do, it will probably cost the earth. You can, however, make one to these specifications according to the instructions in Chapter 15.

But if you can do that, why bother about a collimating mirror at all? Why not use a simple plane mirror, and let the lens do all the necessary converging? All you need to do is to solve the lens equation for a single lens

$$1/u + 1/v = 1/f$$

where u and v are the object and image conjugates (Chapter 14 has the details).

In the layout of Fig. 12.17, with a plane mirror substituted for the reference mirror and the lens at the upstream edge of H₂, the two conjugate distances will be 2000 mm from the spatial filter to H₂, and 1550 mm to the (future) spotlight; substituting these values in the lens equation gives f = 873 mm.

Pellicular collimating mirrors

There is another solution to the problem, due to Peter Waddell, late of Strathclyde University. The principle is delightfully simple; take a frying pan, stretch an aluminized Mylar membrane uniformly over it, and suck out some of the air. You will then have a mirror that is a close approximation to a paraboloid of revolution. Of course, the constructional details are somewhat less simple, but the principle holds good. Figure 12.18 is taken from the patent specification. Note that the roll-off at the rim, both inside and outside, is very important. If you do experiment with a frying pan, use a length of PVC tubing split accurately along its length and matched at the ends so that they fit together exactly.

Such a mirror is light, cheap to produce, and, above all, versatile. You can use it as a collimating or converging mirror, and select any focal length you please. It is, of course, susceptible to changes in temperature and to vibration, but no more than other components.

Chapter 15 shows you how to put together a liquid-filled lens made of acrylic sheet.

Box 14.1, Chapter 14, explains the calculations for a simple lens.

If you refer to Chapter 15 you will find the formulas and method for building a liquid-filled lens to these specifications.

The University holds patent rights, but there is nothing to stop you making your own version – as long as you don't try to market it without a license.



Figure 12.18 Waddell flexible mirror. (a) Front elevation, (b) side elevation. With acknowledgments to Spectrum, London Press Service.

Copying holograms

Making a copy of a hologram, either transmission or reflection, is a simple matter. Superficially, the process seems to have much in common with photographic contact printing. You simply put your holographic material in contact with the original, expose the sandwich to laser light, and process the copy. Nevertheless, a holographic copy is *not* a photographic copy of the interference fringes: it is a true hologram, made with an object beam and a reference beam.

The original (the 'intermediate master') should be as bright as possible, there should have been no emulsion shrinkage, and the illumination must be geometrically correct. The original will usually be a final transfer hologram, and the copy will be identical, except perhaps for its color. Use *p*-polarized illumination to avoid unpleasant wood-grain effects, and if you are working with the frame described in Chapter 7, hold the intermediate master and copy film down with a further glass and a heavy weight.

Reflection copies Fix the intermediate reflection master to a black-backed glass plate, using cellulose tape (you don't need index-matching fluid). Set up the singlebeam frame, with the laser beam polarized vertically, and position the master on the glass. Adjust the mirror until you get a bright image when you look straight up at it through the frame. Cut off the beam, and load an unexposed emulsion underneath the master.

If you are using film, put a heavy weight on the cover glass. Give about the same exposure as you would give for a Denisyuk hologram.

The fringes themselves, of course, are three-dimensional. In a transmission hologram they resemble the slats of a venetian blind, and in a reflection hologram they resemble the pages of a book.

In a reflection copy the light has to pass through the copy emulsion *first*.



Figure 12.19 Geometry of interference patterns in contact copying. (a) Transmission copy, (b) reflection copy, (c) reflection copy from transmission original (see text).

This method will produce good copies from any hologram that reconstructs with a single laser beam – that is, it will work for a multi-channel hologram, but not for a multicolor hologram. For the latter you need a separate master for each image, and appropriate pre-swelling procedures (Chapter 18).

Transmission copies You can make copies of transmission holograms (original master or intermediate transfer master, including rainbow holograms) equally easily. The only difference from reflection copies is that you need to have the master *below* the copy emulsion, i.e., the laser beam goes through the master first. This time you will need to align the beam angle by looking at the master image from directly above while you adjust the mirror angle for the brightest image. From this viewpoint it should appear the right way round.

Reflection copies from transmission masters For these you need a good bright master image. Set up the master as if for a transmission copy, but flipped and illuminated from "below". Instead of the black glass place a mirror over the copy emulsion. This should be a rear-surface mirror; you can use a front-surface mirror turned over. Align the rig with the mirror in position, examining the image from underneath.

The three optical configurations are shown diagrammatically in Fig. 12.19.

Copies by scanning

This is a method of exposure that eliminates the need for settling time, and avoids reciprocity failure effects (see Box 12.2), as every part of the emulsion receives a short high-intensity exposure. Instead of the beam being spread into a disk covering the emulsion more or less evenly (and thereby wasting a great deal of light from overspill) it is expanded only to a comparatively narrow line of light, which is then swept at constant speed across the emulsion. As each point on the emulsion is exposed for a total of only 10 ms or so, there is no need for settling time or for anti-vibration arrangements.

If you have access to a scanner of the type used for laser display shows you can use it for the exposure with the horizontal (x) movement only, spreading the beam out vertically with a cylindrical lens or mirror set up close to the oscillating mirror.

This technique produces a transmission image coincident with the reflection image, i.e. it is a "transflection" hologram (see **pp. 126–7**); but this doesn't seem to affect the image quality. A notorious example of this occurred when llford marketed a holographic emulsion designed originally for pulse laser work. If the calculated exposure came to more than a small fraction of a second, no actual exposure, however long, would produce a useful image.

Make sure you card off any extraneous areas, as an unexpected reflection can easily fog the emulsion.

Box 12.2 Reciprocity failure

The Bunsen–Roscoe law, which photographers usually call 'the law of reciprocity', states that a photochemical effect is proportional to the total incident light energy. Thus in a photographic negative, for a given density the product of the light intensity and the exposure duration is a constant. If you close down the lens aperture by one stop, halving the light intensity at the emulsion, you need to give double the exposure time, and so on. For general-purpose photographic films this rule holds good for exposures between about 50 µs and 1 s. But photographers who work in very dim lighting situations know that under such conditions exposure becomes inefficient, and the rule breaks down ('reciprocity failure'); exposures may need to be considerably extended. This effect also applies to holographic emulsions where the indicated exposure is more than about half a minute.

If the exposure time can be reduced to a few milliseconds, the required exposure energy may well be reduced by a factor of four or more.

Don't use a spot scan, as this may leave a raster pattern. A simple mechanically operated system employs four front-surface mirrors set on a square block and rotated by a slow electric motor, scanning a linear beam across the emulsion in a single pass (Fig. 12.20).

The cylindrical lens CL focuses a line of light on the hologram. The optimum combination of motor and gearbox is roughly one complete revolution in five minutes. At this rate you will scan an 8×10 in area in about 3 s, giving an exposure of some 20–100 ms, depending on the width of the beam. The optimum width is 8–10 mm. If it is any narrower any small juddering will produce bar marks. If it is wider, you begin to lose the benefit of the very short exposure. The interval between exposures (about one minute) is long enough to allow you to remove the film, inspect the glass for any dirt, and load a fresh film.



Figure 12.20 Scanning system for contact copies. SF is a spatial filter; CL is a cylindrical lens controlling the beam width. M is a square metal block on which are mounted four front-surface mirrors, rotated by a slow motor (1 rev per 4 min). The beam is scanned across the single-beam frame SBF.

What went wrong?

If you have your copy system set up correctly, not many things can go wrong. The following are the most common faults:

- Only a single band of image is visible from any one viewpoint The edges of the beam don't satisfy the Bragg condition. Try flipping the master. If this doesn't work you may have to make a new intermediate master using a collimated or even a converging reference beam.
- *There are uneven horizontal streaks (tramlines) in the image* This can happen if you expand the beam with a glass rod instead of a proper cylindrical lens. If the trouble persists, make up a one-dimensional spatial filter to insert at the focus of the lens, using a slit formed by two razor blades mounted on a small flat magnet.
- *There are uneven vertical bands* This is caused by judder or backlash in the motor drive. Apply a small amount of friction to the mirror shaft, and/or widen the slit a little.

Note that you can control the exposure by varying the distance of the frame from the mirror block. Halving the distance quadruples the effective exposure; doubling it divides the exposure by four.

Chapter 13 Transfer transmission holograms

'Why,' said the Dodo, 'the best way to explain it is to do it.'

Lewis Carroll, Alice in Wonderland

Up to this point I have been asserting that you can't produce a viewable image from a transmission hologram using white-light illumination. This is because the emulsion isn't thick enough for the Bragg condition to limit the bandwidth of the image-forming light: the fringe planes, being through the emulsion rather than parallel to its surface, simply aren't broad enough to have the wavelength selectivity that they have in a reflection hologram. The result of white-light illumination is an image that is no more than a somewhat uncouth spectrum in which one can vaguely detect the shape of the subject matter.

But this changes if you can persuade the subject to move into the plane of the hologram. The 'focal length' of the hologram (considered as an optical component) becomes zero, and the temporal and spatial coherence of the replay source become irrelevant. There are two ways of achieving this: you can use the pseudoscopic image generated by flipping a first-generation transmission hologram, or the optical image produced by a lens. It is the former stratagem that is dealt with in this chapter; the latter is the subject of Chapter 14.

Full-aperture transfer holograms

A full-aperture transfer hologram uses the whole area of the master hologram just as a reflection transfer does, and thus has vertical as well as horizontal parallax. In a transmission transfer this carries a number of restrictions.

Like a lens, a hologram suffers from chromatic aberration. The 'focal length' of a hologram is greater for green light than for red light and greater still for blue light. Thus the green and blue images are larger and farther away from the hologram than the red image. This is so for both real and virtual images. Only when the image is wholly in the plane of the hologram will the images coincide for all wavelengths. A full-aperture transfer is thus suitable only for very shallow images that are focused close to the plane of the transfer hologram. The maximum depth allowable before this dispersion becomes obtrusive is about 10 mm before and behind the hologram plane. If the display beam is filtered, say with an amber or green gel, you can get away with a little more depth. If you also make the reference beam as oblique as you can, the Bragg condition, such as it is, will assist the wavelength selectivity. Figure 13.1 shows a typical table setup for a full-aperture transfer.

In making full-aperture transfers, one of the necessary precautions when setting up the table is to prevent spillover from the master reconstruction beam from falling on the transfer emulsion. It is therefore a good idea to make the master with its reference beam at a steeper angle of incidence than 45° , such as 56° (the Brewster angle) or possibly even steeper. You can then make the master hologram with the subject matter closer to it than usual. Then when you come to make the transfer

In a lens, which operates by refraction, dispersion causes the image formed by red light to be farther away from the lens, and larger, than the image formed by blue light. This is called *chromatic aberration*. In a hologram, which operates by diffraction, red light is diffracted more than blue light, so the dispersion is the other way round.

Note that if you do use a near-grazing incidence for the reference beam you will have to use a much higher beam ratio, as most of the reference beam will be lost by surface reflection.



Figure 13.1 Table layout for a full-aperture transmission transfer hologram. The reference angles are set to 56° , which enables H₁ and H₂ to be close together.

you can have the master and transfer plateholders H_1 and H_2 closer together, giving you more parallax.

Full-aperture holograms replay under almost any light, a consequence of the geometry of the system. Although in theory, to obtain a transmission image that will reconstruct with light of any wavelength and coming from any direction the subject must lie wholly in the plane of the hologram, in practice the emulsion does to some extent suppress light rays that don't satisfy the Bragg condition, so you will see a reasonably sharp and colorless image even under such unpromising illumination as office fluorescent lights, provided the subject matter is shallow.

Rainbow holograms

The principles underlying rainbow holograms were explained in Chapter 4. You've already seen that if you flip a master transmission hologram and illuminate it with an undiverged beam, you can place a piece of white card on the side of the hologram away from the source and see the real image projected on it. What you see is a flat image, not three dimensional, and there is no clear plane of focus. It is as though the lens that is the hologram has been stopped down to a pinhole.

But if you steer the laser beam around the hologram you will see the image change as if the viewpoint had changed. This confirms the assertion that each point on a hologram codes the information from a unique viewpoint.

Now move the spot right across the "horizontal" axis of the hologram. The image will appear to rotate as you do this, giving you a full range of views in a horizontal aspect. There will be no change in the vertical aspect, of course. If you now expand the beam to fill the horizontal aspect, the vertical aspect will still be a pinhole image. So a slit transfer hologram is a true hologram from a "horizontal" consideration, whereas from a "vertical" consideration it is a pinhole photograph.

This image is indeed equivalent to a pinhole photograph.

When you look at a rainbow hologram in the usual way the image stands out in three dimensions, but if you tilt your head 90° sideways the image retreats into the plane of the hologram and becomes flat.

When you view a rainbow hologram illuminated by laser light, you can see the image only when your eyes are aligned with the real image of the slit. But since this image is formed in different positions for different wavelengths, if the hologram is illuminated with white light you will see the image from one viewpoint through a 'red' slit, from a higher one through a 'yellow' slit, and so on. In general, we use a geometry that arranges the image seen from an average height to be a yellow-green. This is the range of wavelengths to which the eye is most sensitive, and which thus gives the brightest image.

Why does a hologram transferred from a master masked down to a horizontal slit produce an image that appears sharp all over even when it may be a metre or more deep? The answer is that the basic condition for a deep image that is sharp overall is that it should be viewed by light of a single wavelength. This requirement is met in a rainbow hologram, because the slit geometry replaces the vertical parallax with an optical device that disperses white light into a spectrum, so that from any viewpoint you see the image by light of only one wavelength. It may be a different wavelength for different parts of the image, but it is nevertheless only one wavelength for any part of the image that you are examining.

Geometry of a rainbow hologram

In a first-generation hologram you are usually concerned with getting the maximum amount of parallax in the image. In a reflection transfer hologram this is no less true, and to achieve it you have the master and transfer holograms fairly close together. In a rainbow hologram the priorities are different. You still want as much (horizontal) parallax as you can get, especially as there is no vertical parallax, but you also need the image of the letterbox slit to be in the plane of the eyes of the viewer. This ensures that the whole image appears in the same hue. In practice this means that the real image of the slit needs to be a fair distance out from the plane of the hologram, whereas the image of the subject matter needs to straddle this plane. That may sound a tall order, but in practice it is fairly easy to achieve.

You have seen that in order to reconstruct a geometrically accurate (though pseudoscopic) image, you need to illuminate the flipped master hologram with the precise conjugate of the reference beam. In practice, for simplicity we make both beams collimated. As far as the final image is concerned, we want to maximize the distance between the real image of the slit and the hologram while keeping the image of the subject undisturbed. Here we need to consider the lens laws (pp. 205–6). If we alter the divergence of the beam that is illuminating the hologram, we change the position of the image in accordance with the lens laws.

If we flip a hologram that has been made with a diverging reference beam, and then illuminate it with a further diverging replay beam, anything in the image that is out of the hologram plane will be shifted along its axis by an amount that is related to the change in position of the point of illumination. If the image was close to the hologram plane this will have little effect, but if the image was several centimetres away there will be a considerable shift in its position: it will be pushed out from the plane of the hologram by up to double the distance. Now this is exactly what we want to do with the image of the slit. So it is usual in a rainbow transfer setup to use a diverging beam for the H_2 reference beam (Fig. 13.2).

Remember, although a hologram isn't quite the same thing as a lens, it does nevertheless obey the same laws concerning image distances.



Figure 13.2 When a transfer hologram is made with a diverging reference beam (a), in order to reconstruct a geometrically correct image you should use the precise conjugate of the reference beam (b). However, if the image is in the plane of the hologram (c), it will reconstruct in the correct position with a non-conjugate, diverging beam, and the real image of the slit SI will be formed farther away from the final hologram.

If your subject matter is deep, its depth will also be exaggerated. Parts of the image that are in front of the hologram will be nearer than they should be, geometrically speaking, and they will also be somewhat enlarged.

Stephen Benton¹ has dealt with the geometry of rainbow holograms in detail. Steve McGrew² and Suzanne St Cyr³ have prepared worksheets, and I have included both of these, in edited form, in Appendix 3, with the authors' permission. Using the configurations described here, the 'letterbox' through which you see the image will be at least 100 mm high, so that if this letterbox can be projected to about 450 mm in front of the hologram, you will be able to see a complete image (for a hologram 300 mm high) from as far away as 1 m. If you view the image from a position close to the real image of the slit, it will appear in a single hue. A low viewpoint will show a blue image and a high viewpoint a red one. From farther away, the image will contain all the spectral hues, with blue at the bottom. From a nearer viewpoint blue will be at the top, and a real image may be too close to see clearly.

This may be fine for effect. There is a famous metre-square exhibition hologram of a trombone, which you may have seen. The image projects more than a metre out of the hologram. But of course this distance is exaggerated for dramatic effect. If you want an accurate representation of your subject matter you have to keep to collimated beams, and the real image of the slit will then appear in its true position.

If you get even closer, part of the image may actually be behind you!



Figure 13.3 For white-light replay the images of the slit are formed at different heights and distances from the hologram H₂, lying on a line at the tip angle α to the horizontal. For a replay beam incidence of 45°, $\alpha = 35^{\circ}$, measured from the normal to the hologram. The spacing of the images has been exaggerated for clarity.

In this context, 'achromatic' simply means 'colorless'.

This is a debatable assertion, and I am not sure I go along with it, particularly in respect to holographic portraiture.

Again, since the final hologram has suffered three successive generations of perspective distortion and astigmatism all in the same direction, it may well be suitable only for admirers of the grotesque. You *do* need a collimator, in my experience.

There is also a third way, which is to move the hologram by a very small amount in its own plane, in a "vertical" direction, during the exposure (see pp. 217–18). This is called 'slitless rainbow holography'. The raison d'être of this approach requires Fourier transform theory, and needn't bother us at this point.

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The slit images for the different wavelengths are also formed at different distances from the hologram. As red light is diffracted more than blue light, the 'red' letterbox will be focused nearer to the hologram as well as higher up than the 'blue' letterbox. The spectrum of slit images lies in a plane at an angle to the horizontal known as the *tip angle*. For a replay beam incidence of 45° the tip angle is 35° to the horizontal, and for a beam incidence of 60° it is 41° (Fig. 13.3). The tip angle becomes important when we try to bring the red, green and blue images together to form an achromatic image, or when we want to form multicolor images that have all the colors in register.

Benton¹ comments on the difficulty and expense of obtaining collimators of large aperture, and suggests that if the reference beam throw is ten times as much as the larger dimension of the H_2 plate, perspective distortion is minimal and little further is achieved by collimation. He also shows that, on the other hand, the real image produced by the master may be displaced by as much as 50% when the master is both made and replayed (flipped, of course) with a diverging beam with the source 1500 mm away. (This is the kind of throw associated with a ×40 microscope objective.)

Slit width

There are two ways of producing slit illumination. The first is to illuminate the whole of the master hologram, but to cut off all but a narrow slit by masking the hologram with opaque card. This technique, obviously, wastes a lot of valuable light, and in addition the sharp-edged aperture produces its own diffraction pattern, which adds high spatial frequency information about the slit to the final hologram and uses up valuable bandwidth. The second method, less wasteful of light, is to illuminate the master with a narrow strip of light, masking the hologram only in order to exclude stray light. It is easy to effect this by using a one-dimensional beam expander. The actual width of the slit is important. As with so

many of the variables in holography, it is a compromise. A narrow slit gives a sharper image and purer colors but more speckle; a broad one causes the vertical aspect to become less sharp. The optimum width seems to be 6–7 mm. The speckle size is a function of the diameter of the smallest aperture in the image beam. It seems logical, therefore, to match the slit width to the average diameter of the (dilated) pupil of the eye.

A one-dimensional beam expander

As I showed earlier, the illumination of the master hologram needs to be collimated, otherwise the geometry of the real image will be incorrect. The onedimensional beam expander must be located in the principal focal plane of the collimating mirror, and the intensity of the line of light it produces must be uniform over the diameter of the mirror. To achieve this with the type of beam produced by most lasers, the line needs to extend in length to about twice the mirror diameter.

The simplest type of beam expander is a piece of glass rod, which you can obtain from suppliers of chemistry lab equipment. The focal length of such a rod is somewhat less than its diameter: a 6 mm diameter rod will give about the same divergence as a $\times 40$ microscope objective.

An alternative, and in my view superior, approach is to insert the usual type of spatial filter, and to squeeze the emergent beam to a narrow line using a positive cylindrical lens with a focal length of 100–200 mm a few centimetres downstream from the pinhole. Varying the distance between this lens and the pinhole will vary the width of the 'slit'. The Gaussian intensity profile of the beam doesn't change, of course. You need to card off the optical hash that surrounds the slit, though. It is best to do this with two pieces of black card close to the collimating mirror.

Two well-tried working setups are shown in Figs 13.4 and 13.5. The arrangement of Fig. 13.5 is suitable for master holograms producing weak images. You are less



Figure 13.4 Standard table arrangement for a rainbow hologram using a master that produces a bright image. BE is a spatial filter–cylindrical lens combination. It can sometimes be possible to reflect both beams off the collimating mirror CM, avoiding the need for mirror M_2 .

Strictly, if your laser needs a spatial filter for a normally expanded beam, it should have one for this beam too. You can use the double razor blade setup if you feel it to be necessary, but I haven't found that its absence makes any visible difference.

The term *Gaussian* refers to the intensity profile plotted across the center of the beam. Its bell shaped curve (see Figure 15.16, p. 240) is named after the mathematician Carl Friedrich Gauss, who showed its importance in statistics.



Figure 13.5 Table arrangement for rainbow hologram with a master giving a weak image. BE is the spatial filter-cylindrical lens combination.

likely to need this arrangement than that of Fig. 13.4, however, as much less light is needed in illuminating the transmission master slit than in illuminating the whole area of a master for a reflection transfer.

If you need to make very large transfer holograms, you will find rainbow holograms much easier to make successfully than reflection holograms. Less light is wasted, and you can produce images of very great depth (up to 3 m in some cases). In addition, stability problems are much reduced. Of course, in making very large rainbow holograms you won't be able to produce a fully collimated beam if the diameter of your mirror is less than the "horizontal" width of your master hologram. But if you can manage a total beam throw of 3 m or more, the perspective distortion is likely to be small enough not to matter. Plate 7 shows two examples of large rainbow holograms (>1 m square) with some 2 m of depth and excellent resolution.

To produce a bright yellow-green image when you view a rainbow hologram made according to these diagrams, you need a reference beam angle of incidence of 54.5° and a replay beam angle of 45° .

A convergent reference beam

Although one of the assets of the rainbow transfer technique is the creative exaggeration of perspective that makes it possible to throw a real image several metres in front of the hologram, this attribute can be an embarrassment if you are trying to produce a realistic portrayal, say of an architectural model. Under such circumstances you need a reference beam for the transfer hologram that is the precise conjugate of the beam you are going to use for displaying the hologram. The situation is similar to that concerning reflection transfers, which I discussed in Chapter 12. The solution, too, is similar. Figure 13.6 shows a layout suitable for an 8×10 in rainbow hologram that is to be displayed using a spotlight at 2 m (slant)

Remember, angles of incidence are measured from the perpendicular to the surface, *not* from the surface.



Figure 13.6 Layout for rainbow hologram with converging reference beam.

distance, using a 300 mm diameter collimating mirror with a nominal focal length of 870 mm. All the relevant distances are shown on the diagram.

Multi-channel rainbow holograms

As the image remains the same when your viewpoint moves up or down, it is easy to produce a multi-channel rainbow hologram using horizontal (rather than vertical) strips of each master, in the same way as I suggested for reflection holograms. The result, however, will be somewhat different. As a rule, all the images will be visible simultaneously, though in different colors. You will need to use the setup of Fig. 13.4. You can then make successive exposures of the three strips, shifting the slit between the exposures by adjusting the mirror M_2 . The effect will be of interpenetrating images of different hues (Fig. 13.7).



Figure 13.7 Multicolor unregistered rainbow images. With three transfers at different reference beam angles, each spectrum projects to a different place, so that the viewer sees three images in different colors and in different planes.
You will notice that there is a displacement of the spectra in a horizontal as well as a vertical direction. This is not important where the multiple images are all different; but when we come to more advanced work where errors of registration are important (Chapter 18) we shall need to find ways of compensating for this.

If the separation of the three slits is sufficiently wide (more than about 6° as seen from the center of H_2) the spectra won't overlap, and the images will come into view successively as the viewpoint changes vertically. But most people aren't prepared (or perhaps able) to move up and down through such a large distance, and if you need this effect it is probably better to make the separation more like 3°, and have the images merge into one another more gradually.

You can, of course, make a multi-image rainbow hologram with vertical dividing lines, just like those of a reflection hologram; and in a way this is easier, as you can make the transfer in a single exposure. But remember that you don't have any vertical parallax, and this can limit your result from an esthetic point of view.

What went wrong?

Practical table geometries for transmission transfer holograms are legion. I have stuck to one basic layout (with some variations) because it is robust and seldom fails. But in all rainbow setups you have to get the angles and distances right. The image must reconstruct in a single hue from top to bottom when you view it from an average distance; and the image hue should be the one you want. If it is a multicolor image, you want *all* the colors to reproduce in their intended hue from the optimum viewpoint (Plate 13c). The distances and angles are much more restrictive than they are for reflection transfer holograms. You can obtain a good bright image from a rainbow hologram only over a narrow vertical angle, and the right color combination of a multicolor image is restricted to an even narrower band. In this introductory section I have given a few rules of thumb that should enable you to finish up with an image of the right color, at the right distance and the right viewing height. However, an accumulation of only a few small deviations from what is geometrically correct can result in various kinds of unsatisfactory outcome:

- You can see only a narrow spectrum that doesn't cover the image You may have set up the final hologram the wrong way round. (The trouble is that almost any orientation gives you *some* sort of image) Try turning it through 180° about each axis in turn. If this doesn't improve matters, move in closer and see if there is a point where the whole image appears, bright and all in one hue. If this distance is too close for comfortable viewing, there are various things you can do:
 - 1. Move the display spotlight closer to the hologram without altering the angle of incidence.
 - 2. Reshoot the transfer, increasing the separation between H_1 and H_2 as much as you dare. Use a diverging beam to illuminate the master, and/or bring the H_2 reference source closer to H_2 .
 - 3. Reshoot the master with a greater distance between the subject and the plateholder.
- *The image is very bright but appears grainy in texture* Your slit was too narrow. If you are using a glass rod beam expander, spread the beam a little horizontally with a cylindrical lens. Broaden it to about 7–10 mm. If you are using a spatial filter and a cylindrical lens, focus the line of light a little less tightly.

- The image replays brightly only when the display beam is almost head-on to the hologram You probably processed the master in a developer or bleach that shrank the emulsion. Did the master have to be set at a greater angle of incidence than the original reference beam to get a bright image for transfer? Was the real image displaced? Try post-swelling the master with 5–10% sorbitol solution, and make a fresh transfer hologram.
- *The image appears bright only when viewed from a high viewpoint* The final hologram emulsion has shrunk in the processing. You can try post-swelling of the final hologram, but it would be better to remake it. Wash and dry the emulsion before making the exposure, and use the processing technique recommended for masters.

Edge-lit holograms

Theoretically, you should be able to make a hologram using a reference beam incident at any angle from 0° to 180° . In practice, though, there is a gap between about 80° and 100° , because at these grazing angles hardly any light penetrates the surface of the material. That isn't the whole story, though. Because of the refractive index of the emulsion (about 1.65), the angle between the reference and object beams *within the emulsion* cannot be more than about 37° from the front or less than about 143° from the back. But there is one possible case where the angle between the reference and object beams is close to 90° : that is when the reference beam enters the hologram through the substrate. You will have seen edge-illuminated signs in theaters. The illuminating light itself is invisible, as all the light goes into the glass. The only light that can emerge is the light scattered by the etched design. Edge-lit holograms operate in a similar manner.

The principle of edge illumination has been around at least since the 1960s; the original suggestion probably came from Juris Upatnieks. However, the first published description of the principle seems to have been by Karl Stetson⁴ in 1967, followed by L H Lin⁵ in 1970. In 1990 Stephen Benton *et al.*⁶ produced a practical guide to the use of the edge-lighting principle for display holograms.

To introduce the reference beam into the transfer hologram you need to couple the edge of the plate (it needs to be a plate) with index-matching fluid or optical cement to a glass block with an optically flat edge through which you introduce the reference beam. The reference beam itself isn't exactly parallel to the plane of the glass plate, but a little under 90° incidence, from the front. You can't use the usual method of flipping the hologram to make the image orthoscopic, as the reference beam needs to be highly divergent in order to cover the hologram area. Instead, you make an intermediate hologram. You then flip this and use the (orthoscopic) real image from this hologram to make the edge-lit final transfer hologram, which will now also be orthoscopic (Fig. 13.8). The reference beam will be replaced by the white display beam. The result will be a rainbow hologram that can have its display light built unobtrusively into the base. If you make the intermediate master H₂ tilted at the achromatic angle, about 35°, this will result in a bright image that is not noticeably colored.

The main problem with this system is that between the two glass surfaces there are a number of unwanted internal reflections that may produce colored bands, This assumes that the object is fairly small and is positioned directly in front of the emulsion.

This type of hologram has been variously described in the literature as surface-wave, total internal reflection and waveguide, but I venture to suggest that 'edge-illuminated' is sufficiently descriptive and lucid.

You would normally use the same glass block for mounting the hologram and introducing the display beam, so it should be finally sealed with optical cement.

This particular configuration is discussed in detail in Chapter 18.



Figure 13.8 Benton's method for edge-illuminated holograms. (a) Rainbow master made conventionally. (b) Virtual-image intermediate master made at achromatic angle. (c) Conjugate beam produces a real image in plane of final hologram. Final transfer made with reference beam directed into edge of plate. (d) Edge-illuminated final hologram produces overlapping spectra in a single plane, giving an achromatic image.

degrading the image. The authors recommend avoiding this problem by exposing the edge-lit final hologram in a glass tank filled with index-matching fluid and blacked out except for the necessary aperture.

The second technique, described by Qiang Huang and John Caulfield⁷, uses a reference beam introduced by an input coupler that consists of a long prism index-matched to the hologram substrate on the emulsion side. The light enters at an angle, and is multiply reflected within the substrate; at each reflection it acts as part of an extended reference beam (Fig. 13.9a). The finished hologram is illuminated by a long-filament lamp or a fiber-optics ribbon (Fig. 13.9b). It works only with shallow subjects. Upatnieks⁸ suggests a number of ways of illuminating such holograms, using a diode laser with its long elliptical beam profile.

The third technique has been developed by Nick Phillips *et al.*⁹. It is a much superior system, producing images that are brighter, deeper and sharper than those described above. In this method the beam is spread into a line, collimated, and fed directly into the edge of the plate, which must itself be polished flat (Fig. 13.10a).

I must confess I haven't tried this myself, though plainly it ought to work. What I can confirm is that you do get colored bands if you *don't* adopt this technique.

Upatnieks also recommends β -ionone as the best possible index-matching fluid for glass plates. I haven't tried this either, though it does have the advantage of being much more viscous than white spirit. It also gives off a powerful odor of violets, which makes a pleasant change from many of the chemical substances we use.



Figure 13.9 Upatnieks's method for edge-illuminated holograms. This is for either first-generation holograms or image transfers, and produces two conjugate image beams.



Holographic plates *don't* have polished edges. One solution is to index-match the plate edge to a piece of optically flat glass using a viscous fluid such as microscope immersion oil (or, perhaps, β -ionone?). Alternatively, you can laminate holographic film to a plate of edgepolished glass with the emulsion side inwards.

Figure 13.10 Phillips's method for edge-illuminated holograms. (a) The beam is expanded through a onedimensional collimating system to produce a true grazing-incidence reference beam. (b) Replay, using white light in a self-contained system.

Displaying an edge-lit hologram All the holograms described in this section can be displayed mounted on an acrylic block with a filament lamp set into the base. The optical system of an ordinary miniature focusing torch works fairly well, but may need to be approximately collimated. The design shown in Fig. 13.10b works well. The center of curvature of the acrylic surface is at half the distance between the lamp filament and the uppermost point on the arc.

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Chapter 14 Holograms including focusing optics

'One side will make you grow taller, and the other side will make you grow shorter.' 'One side of *what*? The other side of *what*?' thought Alice to herself.

Lewis Carroll, Alice in Wonderland

This chapter investigates the possibilities offered by including conventional focusing optics in a holographic setup. There are two broadly related situations. The first involves the insertion of lenses into the space where you are making a hologram: it includes the magnification and demagnification of holographic images, as well as the effects of placing lenses in the object space. The second is concerned with holograms of images formed by conventional optics, usually called *focused-image holograms*, and one-step white-light-viewable holographic images.

Demagnifying and magnifying

If you make a first-generation transmission hologram and reconstruct the image using a replica of the original reference beam, the image will be an exact copy of the object – so exact that it can be used for measurements accurate to within a micrometre, and even for real-time interferometry (Chapter 23 deals with this technique in detail). In display holography this kind of reconstruction is rare. Most display rigs involve a white spotlight positioned 1-2 m from the hologram, giving a beam with a divergence of some $10-30^{\circ}$. As a result the image is not an exact copy of the subject: in general it will be exaggerated in depth and somewhat larger in size. This is because a hologram behaves like an optical lens, and obeys the lens laws.

Box 14.1 The lens laws

The lens laws are readily derived geometrically; you can find the derivations in any textbook of photographic optics. The first law is derived from Snell's law of refraction, which states that when a beam of light passes from one optical medium to another its direction is changed so that

$$n_1\sin i = n_2\sin r$$

where *i* and *r* are the angles made by the incident beam and the refracted beam with the normal, and n_1 and n_2 are the refractive indexes of the two media.

If the first medium is air, the refractive index of the second medium is given by the formula

 $\sin i / \sin r = \mu$

For small angles (measured in radians) we can use the approximation $\sin \theta \cong \theta$.

These laws come under the heading of *Newtonian optics* (they were first set out formally by Newton). They are fundamental to the understanding of the relation between the object–image conjugates and the focal length of a simple lens.

n is the symbol used for the refractive index of a substance with respect to empty space. Refractive indexes with respect to air are slightly less (*n* for air is 1.0003), and are denoted by the symbol μ . This convention is that all distances involving real focal points and real images, and the radii of curvature of convex surfaces, are given positive signs, while distances to virtual focal points and virtual images, and the radii of curvature of concave surfaces, are given negative signs. Some textbooks use a convention in which the lens is at the origin of a Cartesian coordinate system. This changes the signs in many of the formulas, and mostly just makes things more complicated, at least for the ordinary photographer. In geometrical optics the conventional symbol for the focal length of a lens is f, for the distance between the lens and the object u, and for the distance between the lens and the image v. Most photographic texts use the 'real is positive' convention (see margin note).

Using this convention, the focal length f of a lens with radii of curvature r_1 and r_2 and refractive index μ is given by the formula

$$1/f = (\mu - 1)(1/r_1 + 1/r_2)$$

This is the formula used for calculating the focal length in liquid-filled lenses.



Figure 14.1 Illustration of the lens laws.

The second of the lens laws, and (at least among photographers) the best known, is the law of image conjugates, which relates the object and image distances and the focal length of a lens (or optical mirror):

$$1/u + 1/v = 1/f$$

where u is the object distance from the lens and v the image distance.

The third law relates to the image scale *m*, usually called *magnification* in photographic optics:

m = v/u

This is the *transverse* magnification (m_{tr}) , i.e. the image scale for a twodimensional image. The holographer is also interested in the *axial* magnification (m_{ax}) , i.e. the scale along the optic axis. This is the square of the transverse magnification:

$$m_{\rm ax} = m_{\rm tr}^2 = (v/u)^2$$

The final law relates the focal length of a combination of two lenses to their focal lengths f_1 and f_2 and their separation d. The formula is:

 $1/f = 1/f_1 + 1/f_2 - d/f_1f_2$

This is the formula that applies to a lens placed in the space between the master and transfer holograms.

All these relationships apply to configurations with the object and image planes normal to the principal axis of the lens. For the relationship where these planes are tilted, see Box 18.3.

When you make a first generation hologram in the usual way, the image will always be virtual. If your reference beam was collimated, the *u*-distance is infinite, and the focal length of the hologram is the distance between the hologram and the subject. As the image is virtual, this distance is negative. However, when the hologram is flipped to produce a real image its focal length becomes positive. So when you illuminate your hologram with a collimated beam $(u = \infty)$, the image is formed at the principal focus (v = f). This is the usual situation for producing a transfer hologram. However, if you illuminate the master hologram with a diverging beam, the u-distance changes from infinity to the reference source (the pinhole) distance, and the image is formed farther away, in accordance with the law of conjugates. At the same time the image is enlarged laterally by a factor v/u.

If you use a collimated beam for both making and reconstructing the image there is nothing to worry about, provided you have your real image across the plane of the transfer hologram, as the effective focal length of the transfer hologram will be zero. If you now make your transfer hologram using a diverging reference beam the only effect will be to push the phantom rectangle of the master hologram farther out into the viewing space.

Image enlargement and reduction

Now, suppose you insert a device that diverges or converges the *object* beam for the transfer hologram, in between the H_1 and H_2 plateholders. What happens? If you put a diverging lens into the image space you effectively extend the image distance and magnify the image, in a similar manner to the effect of the diverging reconstruction beam that I described above. The effect, though, is much more powerful (Fig. 14.2). If you insert a converging lens you demagnify the image (Fig. 14.3).

Image size reduction One of the disadvantages of straightforward hologram making is that the image is the same size as the object. In commercial holography this often results in the need to make very small, highly detailed models, as I have

<image>

Figure 14.2 The effect of positioning a negative lens in the image space between the master and transfer holograms.

This is something you can't do with a lens!

As an example, if you make a master with a collimated beam and a subject distance of 300 mm, and then transfer it using instead a beam diverging from a point 900 mm away, the new image will be formed 450 mm away, and will be 50% larger. The perspective will be exaggerated by a factor of $1.5^2 = 2.25$ times. This can be bad news if your subject matter is an architectural model.

If your subject matter is comparatively deep, though, some of it will be located in front of the final display, and may show some distortion. As I pointed out in Chapter 12, if this matters, you may have to make the reference beam for the transfer hologram collimated or even converging.

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Figure 14.3 The effect of positioning a positive lens in the image space between the master and transfer holograms.

pointed out earlier. Although this can't always be avoided, it is often possible to make a final transfer in which the image is somewhat smaller then the original. This can be useful in the case of formal portraiture: a boardroom size image can be a little overpowering in a small living room. From the rule for transverse and axial magnifications (Box 14.1) it is clear that a reduction in image dimensions results in a flattening of perspective. In general, the biggest reduction ratio you can get away with is about 1.5:1, though there are exceptions.

From the rule of combined focal lengths (Box 14.1 again) it is clear that increasing the separation of the lens from the master hologram decreases the amount of demagnification, and this means that from a single large lens you can get a range of scales. The lens itself needs to be at least 300 mm in diameter and not more than

Portraiture seems to be one of them. If you view a half-scale image of a human face it still seems to have full depth, even though in fact the perspective has been flattened by a factor of 4. 450 mm in focal length, if it is to be capable of reducing a 30×40 cm original to an 8×10 in final display copy. You can buy such lenses from optical suppliers, but they are expensive. You can also make your own liquid-filled lenses (Chapter 15). You can also use a Fresnel lens of the type produced for overhead projectors. These come in various focal lengths, and they are usually at least 300 mm square; but you need to use them with caution as the lands between the grooves can cause unwanted reflections. They usually consist of two Fresnel lenses mounted back to back, much in the fashion of the condenser elements in old-fashioned photographic enlargers and slide projectors. The focal lengths of these two elements are usually different (see below).

The way to set up a demagnifying lens is shown in Fig. 14.4. Adjust the image to the size you need before you set up the H_2 reference beam. To minimize aberrations, set up the lens with its curved side towards the master. (If you are using the double Fresnel lens from an overhead projector, have the side labeled 'top' facing the transfer hologram. This is the side with the greater focal length.) The closer the lens is to the master, the greater will be the reduction in image size.

Image enlargement As it is difficult to obtain large concave lenses, it may be easier to use a strongly diverging reconstruction beam for the master hologram.

You can achieve this by inserting a small negative lens in the beam, between the pinhole and the master (or, better, before the spatial filter itself). If you make the original master with a diverging reference beam the magnification will be further increased, and by sharing the magnification between the two stages your beam will match the Bragg requirement better.

Enlarging the image will increase the depth out of proportion, and the near parts of the image may seem to jut out unnaturally, so you need to take care in setting up the subject matter. You get the least distortion when the nearest part of the image is close to the transfer hologram plane (but remember that the image is inside out).

Local magnification and reduction If you use a small lens in the image space you can achieve some interesting image-within-an-image effects. A short-focus



Figure 14.5 Principle of Fresnel lens. (a) is a positive lens, (b) is a negative lens.

Augustin Fresnel originally designed the lenses that bear his name for lighthouses. They were cut back in concentric steps so that the lens became a series of toroidal prisms that increased in steepness as their radius increased. Modern Fresnel lenses are milled from a single acrylic sheet (Fig. 14.5). They are usually profiled to an aspheric surface to correct for spherical aberration, a fault that causes lenses with spherical surfaces to have focal lengths that vary from the center to the periphery. Fresnel lenses can have an aperture as large as f/0.5, and give a surprisingly good image.

Large negative Fresnel lenses designed to give coach drivers a wideangle view through the rear window are, however, available from appropriate suppliers. They have a focal length of about -300 mm.



Figure 14.4 Inserting a demagnifying lens in the transfer space. To minimize the effect of spherical aberration the convex side of the plano-convex lens should face the master.

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Figure 14.7 Effect of including a negative (demagnifying) lens in the subject space in the master hologram. (Self-portrait of Edwina Orr, courtesy of Richmond Holographic Studios. Photograph by Tim Hawkins.)

The situation is analogous: a hologram, like a lens, has an *f*number, equal to the object distance divided by the horizontal width of the hologram.



Figure 14.6 Effect of including a positive (magnifying) lens in the subject space in the master hologram. This was a hologram I made for the Open University's course *Images and Information*.

cylindrical convex lens, set up carefully, can give a correct-sized image that is either reversed laterally or inverted, depending on which axis you choose.

A trick that always seems to come up fresh is the inclusion of a magnifying glass in the subject matter. If you include one in front of the subject, the image of the lens will magnify the portion of the image that is behind it, just as though it were real (Fig. 14.6). You need to take some care setting things up, as you need to have the magnified image close enough to the plane of the hologram for it to appear sharp. This does restrict the magnification possible. Arrange for the magnifying lens itself to be a real image in the final hologram. You can produce the opposite effect by inserting a small concave lens into the subject space (Fig. 14.7).

Focused-image holograms

In Chapter 1 I suggested, not entirely facetiously, that inside every camera there is a three-dimensional image struggling to get out. This is the optical image formed by the camera lens. It is inverted and orthoscopic, and can be made the subject of a hologram, a *focused-image hologram*. The image can be behind, in front of, or across the plane of the hologram, just as with an image transfer hologram (Fig. 14.8). However, unless the camera lens has a very wide aperture (f/1.5 or larger) you won't be able to see this image stereoscopically, as there will be insufficient parallax for you to be able to see the image with both eyes at the same time.

As I pointed out earlier, if you want the image to have correct depth it has to be at a magnification of 1. This means that the object is at a distance from the lens that is twice its focal length. (See Box 14.1.) For a lens of aperture f/2 at this extension the angle of parallax is approximately 14°, for one of aperture f/1.5, 21°. Now 14°, or for that matter, 21°, isn't much parallax in terms of what we usually expect of a hologram.



Figure 14.8 The optical image formed by a camera lens is inverted but orthoscopic, and has full parallax. However, the image depth is correct only when the subject is at a distance from the lens equal to twice its focal length, and stereoscopic viewing is possible only if the lens has a diameter comparable with a typical interocular separation. By introducing a reference beam it is possible to make a focused-image hologram with the optical image as the subject.

In a first-generation transmission hologram the effective *f*-number is about f/0.5, giving a parallax angle of 90°. If this image is used to make an image-plane transfer hologram, the latter will have about the same parallax, or a little less. If you want the same degree of parallax in a focused-image hologram you are going to need a very large lens (Fig. 14.9).





Perspective in a focused image As has already been noted (Box 14.1), the axial scale of an image is the square of the transverse scale. In an ordinary photograph, with a size reduction of from 1:10 to 1:1000 or more, the image is effectively flat. The effect on the solidity of the image was noted in the early days of stereoscopic photography. It was called 'cardboarding', as objects in the middle and far distance appeared like cardboard cutouts. It is possible to obtain focused-image holograms using a camera lens, but at anything smaller than about one-quarter scale the image is effectively flat. Nevertheless, such images can be attractive, as camera lenses are fully corrected only for their own format area, and outside it there is curvature of field and distortion. So as you move your viewpoint from one side to the other the image swings back and forward and changes its shape (Fig. 14.10).



Figure 14.10 'Mitzi', a small focused-image hologram by Jeff Blyth, made using a camera lens. Although the image is effectively flat (the scale is roughly one fifth) the curvature of field of the lens causes the image to swing away and alter in shape as the viewpoint moves away from a central position.

You may be lucky enough to find one of these in a junkshop (I did). Keep an eye open for shops with old photographic equipment. The biggest condenser lenses can be as much as 250 mm in diameter. They may be scratched: if so, it is worth paying to have the flat surfaces repolished: the curved surfaces will have been protected. A new lens this size could set you back well over £100.

If you use a display beam that is noticeably divergent, this will restore some of the lost depth. Lenses for focused-image holograms Because of the limited parallax you need to choose a subject that is much smaller than the diameter of the lens, and because of the longitudinal magnification anomaly you need to image it at near full size. The lens should be as large as possible and fairly well corrected for spherical aberration. Pairs of plano-convex condenser lenses from big old-fashioned horizontal enlargers, which are mounted in pairs with the convex surfaces inwards, are fairly well corrected, and have large apertures, about f/1.2.

A second type of lens suitable for this work is the double Fresnel lens used in overhead projectors, which I have already mentioned. They operate at about f/1 or less, and you can get them from large educational suppliers. Get the shortest focal length you can. The side labeled 'top' is the longer conjugate, and if you are reducing the size of the image this side should face the subject matter.

The third type of lens is hollow and built from acrylic sheet ('Perspex' or 'Plexiglas') with the space filled with liquid. Acrylic sheet is difficult to mold into an accurate convex shape, but is very easy to bend into a cylinder. By having a vertical axis of curvature on one side and a horizontal axis on the other it can produce a satisfactory (if somewhat astigmatic) image at an effective aperture of about f/3. I have called such a lens *bicylindrical*. The construction of these and other liquid-filled lenses is detailed in Chapter 15.

Focused-image reflection holograms

These correspond to full-aperture holograms, and the conditions for obtaining a good image are similar. The image is already orthoscopic, so doesn't need flipping for viewing. It is, of course, inverted, so requires a reference beam from "above" the optical image. Deep subjects are best reduced in size, as this also reduces the depth of the image and makes dispersion less obvious. A reduction to two-thirds



Figure 14.11 Basic table arrangement for a focused-image reflection hologram. The sizes of subject and lens have been exaggerated for clarity, and only one subject-illuminating beam is shown. Symbols are as in previous diagrams.

full size will result in a flattening factor of about 2.25; this is about as much as you can get away with before the flattening effect becomes obtrusive. A typical layout for a focused-image reflection hologram is shown in Fig. 14.11.

In this type of hologram the image information is strongly localized, and the beam ratio varies greatly across the hologram. For this reason you should avoid subject matter that has a high contrast. In the table layout of Fig. 14.11 only the basic lighting is shown. To keep the subject lighting contrast down you need supplementary lighting.

For a transmission hologram (see below) the beam ratio within the image area should be on average about 4:1, and for a reflection hologram about 1.5:1. Some workers, however, have reversed these ratios, giving an object beam of higher intensity than the reference beam, and are alleged to have obtained excellent results, in the face of all the theory.

One-step rainbow holograms

By bringing the reference beam of Fig. 14.11 round to the front of the hologram, you will produce a full-aperture focused-image transmission hologram. This has all the qualities of its corresponding image in the transfer configuration, namely seriously restricted depth and some color dispersion. You can do better by making a one-step rainbow hologram.

As you saw in Chapter 13, the necessary condition for producing deep white-light transmission holograms is an image of a 'letter-box' slit in the viewing plane. In a focused-image hologram you have to generate this slit image optically by placing a (real) slit just beyond the principal focus of the imaging lens, on the object side. At 1.5 times the focal length of the lens the slit will reconstruct at 3 times its focal length, and at 1.25 times the focal length it will reconstruct at 5 times its focal length, both of these on the viewing side. If the divergence of the reference beam is less than that of the replay beam, the (replayed) image of the slit will be farther from the hologram.

The presence of the slit closes down the lens aperture and reduces some of the lens aberrations, at least in the "vertical" plane; but as it is situated a long way from the lens it doesn't suppress the off-axis aberrations such as astigmatism, curvature of field and distortion in the optical image. It is still advisable, therefore, to keep your subject matter fairly small in comparison with the diameter of the lens.

The layout is shown in Fig. 14.12. Suzanne St Cyr¹ has investigated this configuration exhaustively, and has worked out a full geometry for one-step pseudocolor holograms.

Benton *et al.*² have adopted a somewhat different geometry in order to project the slit into the viewing space. Clearly, if the slit could be positioned in the plane of the lens it would be more effective in reducing the lens aberrations. For this it is necessary to use a highly divergent reference beam, with an apparent source closer to the plateholder than the lens itself. When the finished hologram is illuminated by a beam with much less divergence, the slit forms a real image in the viewing space (Figs.14.13, 14.14).

The geometrical requirements are straightforward. If you are using a lens of focal length, say, 150 mm, the distance of the lens from the subject and the hologram

The optical path lengths through the lens differ enough to make this type of work fully satisfactory only with a laser that has a coherence length of 20 cm or more. If your laser doesn't come up to this requirement, don't be discouraged. You will simply find that the parallax is more restricted.

I must confess that my own experience hasn't borne this out.

Astigmatism, in this context, is radial/ tangential, not horizontal/vertical. Curvature of field means that the image changes its distance as you change your viewpoint; distortion means that it changes its shape. Creative holographers may enjoy exploiting this quirky behavior of the image.

This isn't an easy set-up. I found the results disappointing (you may be luckier). The Bragg condition isn't well satisfied for the outer parts of the hologram on displaying; but the lens aberrations are certainly minimized.



Figure 14.12 Basic table arrangement for a focused-image rainbow hologram. For a full-aperture hologram the slit S is omitted.

will be 300 mm. If you spread the reference beam by means of a supplementary lens so that its effective point of origin is 150 mm from the hologram, you will be creating a holographic optical element of focal length 300 mm. If the replay source is 1200 mm from the hologram, the slit will be imaged 400 mm from the hologram on the viewing side. For a larger hologram, an effective reference source at 200 mm from the hologram, with a replay light source at 1800 mm, will reconstruct the slit image at 900 mm from the hologram. You can calculate all these distances from the formulas in Box 14.1.



Figure 14.13 (a) The slit S and the reference beam source RS form a holographic lens in the film plane H. (b) If RS is sufficiently close to H, reconstruction with a collimated beam forms a real image SI of the slit in the viewing space. The image of the subject remains in the plane of H.



Figure 14.14 Layout for a focused-image hologram by Benton's method, with the slit at the lens plane. The negative lens BE_2 provides the additional divergence of the reference beam so that the effective reference source is at the midpoint between the main lens L and the hologram H.

One-step rainbow holograms using an optical mirror This rig is modified from an original suggested by Hariharan³, who used a wide-aperture concave mirror to produce a real image. His setup produced a one-step pseudoscopic image, which when spun produced a pseudoptic image (Fig. 14.15).

Hariharan produced what was probably the first true-color hologram with this arrangement, using three lasers. It appears in Plate 10b. Because his images were pseudoptic (right–left reversed) he had to use subjects that were symmetrical.



Figure 14.15 One-step slit transfer configuration as used by Hariharan for color holograms. The focusing mirror FM produces a pseudoptic real image I. S is a "horizontal" slit. The use of a focusing mirror rather than a lens eliminates chromatic aberration and simplifies registration.

Hariharan's original mirror had a diameter of 600 mm and a focal length of 275 mm, giving a parallax angle of some 50°. Such mirrors are rare, but by making use of Peter Waddell's pellicular mirror (see pp. 187–8), this type of hologram could be within the reach of the enthusiast.

Astigmatic one-step rainbow holograms If you illuminate a flipped transmission hologram with an undiverged laser beam you will get a real image that is twodimensional and doesn't focus. As I explained earlier, this is the situation as regards the "vertical" aspect of a two-step rainbow hologram. Looked at "horizontally", however, such a hologram is a straightforward image-plane fullaperture transfer hologram. Now, once it had been appreciated that a rainbow hologram contained two separate optical configurations, a number of workers set about improving the slit geometry independently of the "horizontal" geometry. The first step was to broaden the slit, which would reduce the speckle, and to compensate for the resultant color smear by focusing the 'pinhole' image into the transfer hologram plane. As an image-plane hologram doesn't need a spatially coherent reference beam, the "vertical" aspect of the hologram can use a diffuse reference beam, giving a speckle-free achromatic image. Leith et al.⁴ employed a one-dimensional diffuser made by scoring a piece of acrylic sheet in a single direction using a sliding template and abrasive paper. More recently, such directional diffusers have been produced holographically.

It wasn't long before it began to be appreciated that the intermediate hologram could be dispensed with. In 1987 Chen and Pastor⁵ proposed a one-dimensional version of Benton's focused-image geometry in the "vertical" plane combined with a conventional hologram in the "horizontal" plane (Figs. 14.16 and 17). This



Figure 14.16 Chen's hybrid geometry for a one-step rainbow hologram. In the vertical plane the hologram is a focused-image hologram (Benton's configuration); in the horizontal plane it is a conventional hologram. The reference beam is effectively a point source (PS) close to the hologram in the vertical plane, but a line source (LS) at infinity in the horizontal plane.



Figure 14.17 Layout for Chen's astigmatic one-step rainbow hologram. CL_1 and CL_3 are rod lenses in and out of the table plane respectively; CL_2 is a cylindrical mirror out of the table plane, focusing the "vertical" aspect of subject 0 at image I in the plane of the hologram H.

produces a white-light transmission hologram that is almost achromatic. The addition of a cylindrical focusing lens with its axis horizontal converts the system into a focused-image hologram.

Although Chen and Pastor's geometry is astigmatic, this isn't particularly noticeable in the image, provided it is not too deep. You can obtain the cylindrical lenses in various widths and focal lengths from optical suppliers.

Synthetic-slit holograms

An interesting sideline in focused-image rainbow holograms is the so-called slitless rainbow hologram, more correctly called a synthetic-slit hologram.

Early descriptions of this technique were given by Groves *et al.*⁶, and Shan *et al.*⁷. You can find a good theoretical analysis in the work of Bernardo and Soares⁸. There is no actual slit, as the name suggests; instead, the subject is moved uniformly in a "vertical" direction during the exposure. This amounts to a convolution of the object field with a rectangular function. The optical transform in the principal focal plane of the lens is the product of the transforms of the object function and of the rectangular function. The large central lobe of this transform behaves like a slit (Fig. 14.18).

The hologram needs to be viewed by a near-collimated beam. The 'slit' will then be projected forward into the viewing space, as in Benton's one-step rainbow hologram. The actual movement is, as you might expect, very small. To generate a 'slit' of width 8.5 mm, using a lens of focal length 100 mm, the movement is $0.015 \text{ mm} (15 \,\mu\text{m})$, according to Yang and Yang⁹. You need a high-quality micrometer translating stage as a support for the subject, as the movement, though small, has to be spread absolutely uniformly over the exposure period. This

I mentioned this method in passing earlier.

A rectangular (or 'top hat') function is equal to 1 between two *x*-values and zero everywhere else. 'Convolution' means the dealing out of one function to every part of another. Appendix 3 explains the concept of an optical transform.



Figure 14.18 Schematic arrangement for synthetic-slit hologram. In order to generate the Fourier transform that constructs the synthetic slit the object must be moved smoothly through some $15\,\mu m$ in a vertical direction during the exposure.

technique has the advantage over slit configurations that the whole of the lens is illuminated by the object beam, and much less light is wasted.

Fourier-transform holograms

There is nothing esthetically appealing about a Fourier-transform hologram, though such holograms have a number of applications in data processing and storage (see Chapter 24).

They are a rather special kind of focused-image hologram, though what is focused isn't the image of the subject matter but its optical Fourier transform.

When light is reflected from, or passes through, an object, the behavior of the emergent light can be described in terms of diffraction theory. Briefly, the diffracted wavefront can be thought of as the sum of a large number of plane wavefronts of various amplitudes and with various phase relations, traveling in various directions. Those representing the highest spatial frequencies (roughly speaking, the finest detail) are diffracted through the largest angles.

If the object is in the front focal plane of the lens, all these plane wavefronts will be brought to a focus in the rear focal plane. You can see the diffraction pattern in the principal focal plane, provided the illumination is monochromatic; you can, of course, record this pattern on a photographic emulsion, too, but the phase relationships can't be retrieved from such a record. However, this information *can* be recorded and retrieved, by simply adding a reference beam (Fig. 14.19).

The little patterns generated by the various attachments to the key ring laser pointers sold by souvenir shops are generated by tiny Fouriertransform holograms.

The full theory of optical Fourier transforms falls outside the scope of this book, though you can find an intuitive description of their nature and properties in Appendix 2.

This is why, in conventional lens imaging (photography, microscopy etc.) closing down the lens aperture removes the fine detail from the image.



Figure 14.19 (a) The formation of an optical Fourier transform. The optical field at the object is the sum of a series of plane waves that are focused by the lens L at H, where the Fourier transform field appears visually as a diffraction pattern, with the phase information lost. This information can, however, be recorded by the addition of a reference beam RB, producing a Fourier-transform hologram. (b) The reconstruction beam, a replica of the reference beam, provides a reversal of the optics, and produces both the optically correct primary image PI and the pseudoscopic real conjugate image CI. The zero-order beam ZO appears as a bright central spot.

In the retrieval process two images are recovered. You simply illuminate the hologram via a similar optical system, with a lens positioned so that the hologram is at its principal focal plane; the image will appear at the other focal plane. In the retrieval process two images appear, one of them inverted. The layout for this system (Fig. 14.20) does work, though you need a lens of at least 300 mm focal length, and the reference beam needs to be as close as possible to the lens, or the two images will be a long way off-axis and too far apart to see clearly. A somewhat more amenable geometry is shown in Fig. 14.21. This uses the lens itself to produce the collimated reference beam, and needs a small lens to produce a point source in the object plane, a role that a spatial filter can fulfill.

You can get a good result more easily still by adopting an optical system known (not altogether accurately) as a lensless Fourier-transform configuration. The theory behind this is described in Stroke¹⁰. It bears some resemblance to Benton's configuration for focused-image holograms, in that it exploits the lens-like qualities



Figure 14.20 Layout for a Fourier-transform hologram. FFP and RFP are the front and rear focal planes of the lens L. The subject should in theory be flat and in the FFP, and the reference beam should be collimated, strictly speaking. RB should be at as small an angle of incidence as feasible. This diagram is not drawn to scale.

of the hologram itself. Stroke showed that if the lens were to be placed in the reference beam rather than in the object beam, the interference pattern produced would be the same as that produced by the setup of Fig. 14.21.

Figure 14.22 shows a typical layout for a 'lensless' Fourier-transform hologram. The most suitable lens to use is a wide-aperture (f/2 or thereabouts) lens of about 50 mm focal length, for example the prime lens from a 35 mm camera. In order to have the two images sufficiently close together to be visible at the same time when viewing the hologram, the reference source must be close to the object. It must also be in the plane of the object.

To replay the images you illuminate the hologram from directly behind with a laser beam expanded to fill the format. It will produce two images, one inverted and orthoscopic, the other erect and pseudoscopic. If the replay beam is collimated the images will appear at infinity.

Fourier-transform holograms are a kind of far-field hologram. In order to see the images you have to look directly into the expanded laser beam, which appears as a bright spot between the two images (Fig. 14.21b). As they are transmission holograms they do need a quasi-monochromatic viewing source (a sodium lamp masked down will do), but you can make white light viewable copies by standard transfer methods.

Strictly, the orthoscopic image is virtual and at $+\infty$; the pseudoscopic image is virtual and at $-\infty$. If you replay the hologram using a diverging beam both images will be virtual, and if you use a converging beam both will be real.

This isn't dangerous if the laser power is less than about 35 mW, as when expanded, the intensity of the beam is reduced by a factor of at least 10 000.



Figure 14.21 (a) An alternative setup for a Fourier-transform hologram. DR = diffusing reflector. FTI = Fourier-transform image. Other symbols as in previous figure. (b) Reconstructing the image. H = Fourier-transform hologram, PI = primary image, CI = conjugate image, ZO = zero-order spot.

There are some interesting features in Fourier-transform holograms. The first is that you don't need holographic film. This is partly because of the small angle between the reference and object beams (this angle has been exaggerated in the diagrams for clarity), and partly because of the nature of the coding of the information over the area of the hologram: successively finer and finer detail is coded farther and farther out from the optical center of the hologram. The second is that the image doesn't move if the hologram is moved in its own plane. The third is that because of the nature of the coding of the information, the resolution of the hologram is dependent not on the resolution of the emulsion, but on the size of the hologram. This is the opposite situation to that of a focused-image hologram, where positional information is coded locally, and the detail resolution depends on the resolving power of the emulsion. Fresnel holograms (i.e. traditional holograms) are intermediate; and rainbow holograms. as we have seen, are hybrids of Fresnel and focused-image holograms.







Figure 14.23 The image given by a Fourier-transform hologram made using the arrangement of Fig. 14.22. The zero-order beam has been blocked by a piece of opaque material.

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Chapter 15 Homemade optical elements

All this time the Guard was looking at her, first through a telescope, then through a microscope, and then through an opera-glass.

Lewis Carroll, Through the Looking-Glass

If you want to create holograms for display rather than as part of a scientific research project, you don't have to spend large sums on components of high optical quality. As the diameter of a laser beam is so small, it uses only a very small part of any optical device such as a mirror or beamsplitter, and cheap components will produce perfectly satisfactory holograms. Some of the optical devices you need may well be lying in a cupboard full of photographic (or non-photographic) junk. Everything described in this chapter you can make yourself, at very little cost.

There are three main categories of homemade optical component. The first is the almost endless list of what one might call *objets optiques trouvés*: magnifying glasses, spectacle lenses, pieces of old car wing mirror, optical condenser sets from old enlargers and slide projectors, frosted and patterned glass and so on, not to mention the goodies to be found in defunct scanners, printers and the like. The second category is a range of large liquid-filled optical components made from acrylic sheet ('Perspex' in the UK, 'Plexiglas' in the USA). The third category is a series of holographic optical elements that you can make on your own optical table; they use the properties of a hologram to produce beamsplitters, mirrors and lenses, all operating by diffraction. (They are known as *holographic optical elements*, or HOEs for short.) These last two categories are worth considering in detail.

Liquid-filled lenses

In the world of orthodox optics, these lenses would be considered an oddity, not so much because they are liquid-filled (there have been liquid-filled camera lenses and enlarger condenser lenses) or rectangular (you can find these in many enlargers and slide projectors), but because they are all basically one-dimensional. This is because acrylic sheet is difficult to mold into spherical curves without a special oven and a good deal of skill; but when under compression from its ends it bends into a perfect cylindrical arc. There are many uses in holography for cylindrical lenses.

One-dimensional collimators

These are cylindrical lenses that you can use for collimating a 'slit' beam. As the beam expansion is one-dimensional, the collimating lens can be one-dimensional too. It needs to be made about 100 mm wide, to take account of the lateral shift between exposures when making multicolor rainbow holograms. The simplest type of lens, and optically the most effective, is the plano-convex type. For a master





hologram 10 in long (i.e. one cut from an 8×10 in plate or film) it needs to be 300 mm long, with a focal length equal to its distance from the spatial filter. As the focal length of a plano-convex lens of refractive index 1.5 is equal to twice its radius of curvature, a radius of approximately 600 mm is required. The way you do this is to start with an open box like the frame of a honeycomb, using 3 mm acrylic sheet, with a base of the same material. You obtain the curved part by inserting a piece of acrylic sheet that is slightly overlong. This will naturally take up the shape of a cylindrical arc (Fig. 15.1).

To make the box you will require the following pieces of 3 mm acrylic sheet:

 $\begin{array}{rrrr} 25\times106\,\text{mm} & 2\,\,\text{pieces}\\ 25\times300\,\text{mm} & 2\,\,\text{pieces}\\ 100\times300\,\text{mm} & 1\,\,\text{piece} \end{array}$

and for the curved surface (1.5 mm sheet):

 $100 \times 303 \,\mathrm{mm}$ 1 piece

You can obtain the acrylic sheet from shopfitters, who will also cut it to size for you.

You will need a can of cement suitable for acrylic sheet: Tensol No 12 is suitable. You can also make your own cement by dissolving scrap acrylic pieces in dichloromethane or chloroform. To hold the box while the cement is drying you will need a carpenter's vise; also a sash cramp, which you can hire from a tool supplier.

Mark the center point of one of the long sidepieces by drawing two diagonals on the protective paper, and bore a hole at this point using a 9 mm drill. Remove the protective paper and any swarf. Remove the paper from the other sidepiece and the end pieces, and tear off strips about 20 mm wide from the edges of the sheet that will form the 'plano' side of the lens.

Clamp the sheet and the two long sides between two sufficiently long pieces of 25 mm square wood baulk in the vise, with the sidepieces resting on the vise shafts. You need these sidepieces to be 1 mm proud of the surface of the flat sheet.

Don't attempt to cut it yourself. Acrylic sheet demands a saw with teeth set at an unusual angle. If you use an ordinary saw blade the material may splinter, or even soften and seize.

The surface of acrylic sheet is very soft and prone to scratches. Always keep as much of the protective paper on it as you can while you are working on it.

Recessing the sheet in this way will protect the delicate surface when you lay the lens down flat on the table.



Figure 15.2 Holding the completed box together with vise and cramp.

The easiest way to obtain this rebate is to place a piece of cardboard, of the correct thickness and a little smaller than the face, on the vise shafts, then rest the sidepieces on the shafts themselves before tightening the vise on the assembly. Add the end pieces, holding them in position with the sash cramp. Don't over-tighten.

Now apply the cement to the inside edges that are to be joined, using a small watercolor brush. If the cement is thick and syrupy it may not penetrate the space between the pieces (try it first on two scrap pieces), in which case you will have to dilute the first coat with a little dichloromethane; alternatively, you can run neat dichloromethane or chloroform down the cracks before applying the cement. Apply several coats of cement to ensure the joints are liquid tight, allowing half an hour between coats. When the final coat is dry remove the box, turn it over and apply several coats in a similar manner to the outside of the joins. Set the box aside overnight.

The following day, remove the protective paper from the inside of the box and from one side of the sheet that is to form the curved surface. Tear off strips about a centimetre wide from the margins of the other side. Make sure the inner surfaces are completely clean, and insert the upper sheet into the box with the paper side outwards. It should take up a curve that is a perfect arc of a circle. If it doesn't, test it for freedom of movement by pushing it gently, and if it sticks at any point, indicating a high spot, remove it carefully from the box and get rid of the high spot with fine glasspaper or garnet paper, carefully removing any dust before you reinsert the sheet.

Once you are satisfied, apply cement at the edges as you did with the flat sheet. When the cement is thoroughly dry, remove the rest of the protective paper, and clean the outside surfaces. Make sure there is no swarf or dust left on any of the surfaces. Now fill the lens through the hole with glycerol or medicinal liquid paraffin at room temperature, leaving a small bubble to allow for expansion. Plug the hole with a synthetic rubber bung, and the lens is ready for use. If you treat it with the same care as you reserve for your front-surface mirrors it should last indefinitely.

Don't attempt this work in very humid conditions, as the cement can become milky as it dries. Make sure the room is well ventilated, too. The solvents are not recommended for inhalation.

Use soft lint-free paper with a drop of proprietary window-cleaning fluid to clean the surfaces, which will bear marks from the protective paper. Be very careful when handling these surfaces, as the material is soft and easily abraded. After the initial cleaning, use only lens tissue.

A diamond nail file is a useful tool for this delicate task.

Acrylic sheet will hold an electrostatic charge for a long time, and rubbing it unnecessarily with a dry cloth can actually cause it to attract further dust.

I still have the first one I made more than twenty years ago.

What to do in case of leaks

It is one of those annoying facts of life that the two fluids that are optically the most suitable for filling lenses, namely glycerol and liquid paraffin, should have a penchant for finding the tiniest leak. If you do get one it will probably be at a corner, and should be easy to trace. To deal with it, empty out some of the fluid, prop up the lens so that the leak is at the highest point, and thoroughly clean off any fluid that has leaked out, using tissue dampened with water for glycerol, or methylated spirit for liquid paraffin. Allow the area to dry out thoroughly (this may take longer than you expect), and apply three coats of cement, allowing the appropriate drying time. Once the cement is thoroughly dry, mark the position of the leak with a wax pencil in case it recurs, and fill up the lens again. When you are using the lens try to keep the marked corner at the top, at least to begin with.

Other sizes and focal lengths

If you intend working with master holograms of different sizes you may find it worthwhile to have several one-dimensional collimating lenses of different sizes and focal lengths. If so, you can calculate the required dimensions of the various pieces using the formulas given below.

Calculations for designing a liquid-filled lens

To find the length of the curved side you need to be able to find the length of an arc of a circle relative to that of the straight line (the *chord*) that cuts it off. If the length of the chord is c, and the required focal length is f, then the length of the arc a is given by the formula

$$a = f \sin^{-1}(c/f)$$

The construction is shown in Fig. 15.3. Set your calculator to 'radians' before you begin.

The widths of the sidepieces and end pieces needed to incorporate the required rebate are given by one of the following formulas, depending on whether the lens is to be plano- or double-convex (bicylindrical):

For a plano-convex lens,

Width (mm) =
$$f/2\{1 - \cos[\sin^{-1}(c/f)]\} + 6.5$$

or, for a double-convex lens,

Width (mm) = $f\{1 - \cos[\sin^{-1}(c/f)]\} + 5$

The volume of fluid v required for a plano-convex lens of depth x is given by the formula

$$v(\text{liters}) = xf^2/4[\sin^{-1}(c/f) - (c/f)] \times 10^{-6}$$

and for a bicylindrical lens of linear dimension a (mm) the formula is

$$v(\text{liters}) = af^2/4[\sin^{-1}(c/f) - (c/f)] \times 10^{-6}$$

The derivations of these formulae are in Box 15.1 below.

I don't expect you to work through the Box conscientiously – or even at all, if you don't care for trigonometry. I include the derivations only because (as far as I know) you won't find them anywhere else.

On some calculators 'sin⁻¹' appears as 'arcsin', and in order to obtain this function you may have to press the 'inv' key followed by the 'sin' key.



Figure 15.3 Parameters for a liquid-filled cylindrical plano convex lens.

Box 15.1 Derivations of liquid-filled lens formulas

Given a refractive index of 1.5 for both the acrylic material and the liquid, a plano-convex cylindrical lens has a focal length that is approximately equal to twice its radius of curvature. In Fig. 15.3, f = 2r, c is the diameter of the lens and a is the arc length. Then if the diameter of the lens subtends an angle θ (in radians) at its center of curvature

$$c/2 = r\sin(\theta/2) \tag{15.1}$$

and

$$a/2 = r\theta/2 \tag{15.2}$$

From (15.1)

$$\theta/2 = \sin^{-1}(c/2r) = \sin^{-1}(c/f)$$
(15.3)

i.e.

$$a = f \sin^{-1}(c/f) \tag{15.4}$$

To find the width needed for the side and end pieces you need to find the quantity x in Fig. 15.3 and add the thickness of the acrylic sheets and the depth of the protective rebate.

The distance from the chord AMB to the center of curvature O is $r - x = r \cos(\theta/2)$, so that

$$x = r - r\cos(\theta/2)$$

or

 $x = f/2(1 - \cos\theta/2)$

So, substituting (15.3), we have

$$x = f/2\{1 - \cos[\sin^{-1}(c/f)]\}$$
(15.5)

To this must be added the combined thickness of the acrylic sheets (4.5 mm) and 2×1 mm for the rebates at both surfaces, so the final width *w* for a plano-convex cylindrical lens is given by

 $w = f/2\{1 - \cos[\sin^{-1}(c/f)]\} + 6.5 \text{ (mm)}$

For a bicylindrical convex lens the value of x is doubled and the allowance for the acrylic sheets is reduced to 3 mm, so the width of the side and end pieces in this case is given by

$$w = f\{1 - \cos[\sin^{-1}(c/f)]\} + 5 \text{ (mm)}$$

To find the volume of liquid needed we need to find the area of the segment APB.

Now, the area of the sector OAPB is

 $\pi r^2 \times \theta / 2\pi = r^2 \theta / 2$

The area of triangle OAB is

 $c/2 \times r \cos \theta/2$

and we can substitute equation 15.1 to give

$$r^2 \cos \theta / 2 \sin \theta / 2 = \frac{1}{2}r^2 \sin \theta$$

Hence the area of segment APB is

 $r^2\theta/2 - \frac{1}{2}r^2\sin\theta = \frac{1}{2}r^2(\theta - \sin\theta)$

and substituting equation 15.3 gives an area of

 $f^2/4[\sin^{-1}(c/f) - (c/f)]$ mm²

If the depth d is in millimetres, the volume v is given by the formula

 $v = df^2/4[\sin^{-1}(c/f) - (c/f)] \times 10^{-6}$ liters

for a plano-convex lens. For a square bicylindrical lens the quantity is doubled, and the depth is c.

Two-dimensional collimating lenses

So far, the lenses described have been cylindrical, operating as lenses only in a single dimension. However, for reflection and full-aperture transmission transfer holograms you need to be able to collimate the beam in both dimensions. The simplest lens to make is a *bicylindrical* lens. The best way to visualize this is to think of a cylindrical lens collimating light in a vertical direction, and immediately behind it an identical lens rotated through 90° , so that it collimates light in a horizontal direction. You now have what amounts to an ordinary convex lens with spherical surfaces (Fig. 15.4).

The lens itself is constructed along the same lines as the one described above. In principle it consists of two cylindrical plano-convex lenses back to back.

Assuming (as before) a focal length of 1200 mm and dimensions of 300×300 mm, you will require the following pieces of acrylic sheet:

$45\times 306\times 3mm$	2 pieces
$45\times 300\times 3mm$	2 pieces
$300 \times 303 \times 1.5 \text{ mm}$	2 pieces

There is no flat surface this time. You can either build the sides of the box like a honeycomb frame, holding it together with stout rubber bands, sitting on a 300 mm square drawn on paper to ensure it is square; or, better (if you are prepared to take the trouble), make a temporary flat template from stout



Be very careful when you do this not to allow the scriber to wander away from the straightedge (it is very easy to do this). If it does happen you will just have to start again with a new piece.



When you fit the four sides together, the scribed lines for one curved surface must be above the center line, and for the other curved piece below the center line. If you align all the lines you won't get the second curved piece into its grooves.

It is a good idea to have a dummy run for high spots for both curved pieces before you reach for the can of cement. cardboard or plywood, which you can remove once the cement has set. The first thing to do, though, is to mark a deep line all the way along each sidepiece 1.5 mm from the midline, using a scriber or other sharp point. These lines will go on the inside of the box to act as guidelines for the curved sheets, with their edges actually fitting into the grooves you have made. Drill the 9 mm hole as before, with its center 4.5 mm from the scribed line so that it just touches it on the side nearer the center. Now fit the box together, cement it, dig out any surplus cement from the inside corners and leave the box overnight.

Next day, remove the protective paper from what will be the inside of the curved surfaces and clean them as described earlier. Remove a 20 mm wide strip from the sides of the outer surfaces. Insert the first curved piece so that the ends fit into the upper edges of the grooves you have scribed, with the convex side uppermost. Test for high spots as described earlier, and remove them as necessary. Now seal the edges on both sides.

When you come to put in the second curved sheet you won't be able to seal the inside, so paint cement along the anticipated curved line and the scribed line before you insert the acrylic sheet. Finish off the lens by running cement all round the edges, but don't remove the rubber bands (or other clamps) until 24 hours after you have applied the last coat.

Measurements for a collimating lens

This is a typical lens for collimating a reference beam to cover a 30×40 cm hologram. Its dimensions are 350×450 mm. Applying these dimensions to (15.4) in the formulae of Box 15.1 gives

$$a_1 = 873 \sin^{-1}(350/873) = 360 \text{ mm}$$

 $a_2 = 873 \sin^{-1}(450/873) = 473 \text{ mm}$



Figure 15.5 Reference beam collimating lens for a $30\times40\,\text{cm}$ format.

so that the two face pieces need to be cut to 360×450 mm and 350×473 mm. The spacing x is given by (15.5):

$$x_1 = 873/2\{\cos[\sin^{-1}(350/873)]\} = 36.6 \text{ mm}$$

 $x_2 = 873/2\{\cos[\sin^{-1}(450/873)]\} = 62.5 \text{ mm}$

The width w of the sidepieces is given by the formula

$$w = x_1 + x_2 + 5 = 104 \,\mathrm{mm}$$

Figure 15.5 shows the construction and dimensions. You can use this method for any format and focal length, substituting appropriate dimensions for the ones above.

Focusing lenses

Large lenses for focused-image holograms are very expensive, but liquid-filled lenses work equally well. You use a similar constructional technique, but with a higher degree of curvature on the acrylic sheets, to give a focal length of about 400 mm for a 300 mm square bicylindrical lens. For this you will require the following pieces of acrylic sheet:

$140 \times 306 \times 3 \mathrm{mm}$	2 pieces
$140 \times 300 \times 3 \text{mm}$	2 pieces
$300 \times 340 \times 1.5 \text{ mm}$	2 pieces

Because of the high curvature of the surfaces the pieces may require pre-bending for up to 24 hours before you insert them into the box. Lightly scribe circular arcs marking the correct positions of the outer surfaces on the inside faces of the frame as a guide, so that you can check the correctness of the curve while the cement is drying. If you are dedicated enough you can adjust the curvature so that it approximates to a parabola, which is closer to the ideal curve than a circular arc, but you will first have to make a couple of templates to hold the material steady while the cement is drying.

Such lenses hold a considerable amount of liquid; around 7 liters for the lens described above, so expensive fluids such as glycerol or medicinal liquid paraffin are out. Fortunately, you can obtain technical grade liquid paraffin, usually labeled 'For oil baths', and called 'mineral oil' in the USA. It is yellow or amber in hue, but is fully transparent to red light at 633 nm and almost fully transparent to green at 532 nm. And, most important, it is cheap.

A characteristic common to all bicylindrical lenses is vertical–horizontal astigmatism, because one refracting surface is closer to the object than the other. This can be very noticeable in high-curvature focusing lenses. In a focused-image setup, if the center line of the lens is at the same distance from the object and its optical image, namely twice its focal length, the horizontal and vertical aspects of the subject will be brought to a focus in the same plane, but the scale will be different, so that the image may be stretched out either horizontally or vertically. You can avoid this discrepancy in magnification, in the lens I have described above, by using a piece of acrylic sheet 328 mm long instead of 340 mm, for the side away from the subject. The vertical/horizontal distortion will be corrected. The astigmatism will be exaggerated, but this will not usually be noticeable unless the image is examined closely.

You may want to use such a lens obliquely, in which case you will need to multiply the dimension that has the oblique presentation by 1.5. I would not recommend this, though, as it brings in undesirable off-axis aberrations.

If you are even more dedicated, you may feel it worthwhile to draw a ray diagram using the laws of refraction, to generate an exact curve as suggested by McCormack¹.

After all, this sort of discrepancy is common to all rainbow holograms. Benton² gives a full account of all the difficulties with astigmatic optical components.



Figure 15.6 The author in 1980 with some of his liquid-filled lenses.

All these lenses are simple lenses, of course, and they show the aberrations that are characteristic of simple lenses. When you examine the optical image produced by a wide-aperture liquid-filled lens at a large angle from its axis, the image seems to twist and distort as you move around. But this may well offer opportunities for creative imaging. Furthermore, if you are fortunate enough to have access to acrylic molding facilities and shaping ovens, you can dream up your own weird and wonderful lenses without being confined to one-dimensional curves.

Holographic optical elements (HOEs)

A more sophisticated way of making your own optical elements is to create them holographically. You can make mirrors and beamsplitters as well as lenses. This is because a transmission hologram behaves like a lens in many ways, and a reflection hologram behaves like an optical mirror.

If you make a hologram of an object using a collimated reference beam, and illuminate it (flipped) also using collimated light, the real image is formed at the hologram's principal focus, a distance from the hologram equal to its focal length. Now, the usual holographic image consists of a very large number of points at different distances, and for each of these points the hologram has a separate focal length. So let's simplify the situation. Consider a transmission hologram of a single point of light, made with a collimated reference beam. On replay the virtual image appears where the original point object was. But what happens to the transmitted beam? The hologram is acting in effect in the same way as a concave lens (Fig. 15.7). There are, however, two important differences. The first is that with a hologram the image need not be, and in general isn't, in line with the incident beam. The second is that, unlike a lens, a hologram can be reversed (flipped) in the beam; it will then have a positive focal length and will form a real image of the point source (Fig. 15.8). A reflection hologram, in the same way, behaves like a convex or concave mirror.



Figure 15.7 (a) Negative lens, virtual focus at F. (b) A transmission HOE equivalent. S is the second source or 'point object', which on replay is the virtual focus. (c) Convex mirror and virtual focus F. (d) A reflection HOPE equivalent; again, S is the second source.



Figure 15.8 The HOEs of Fig. 15.11b and d, when illuminated by conjugate beams, behave respectively as a positive lens and a concave mirror, with the same (positive) focal lengths.

A transmission (or reflection) hologram of a point source made in this way shows all the characteristics of a convex lens (or concave mirror). What is more, it obeys the laws of Newtonian optics with regard to conjugate distances, magnification and so on. And you can produce a holographic lens or mirror simply by placing a holographic plate in the interference pattern produced by two diverging laser beams.

Calculation of focal length

A holographic lens or mirror is a type of zone plate that focuses images by constructive interference.

Although a zone plate operates in a different manner from that of a conventional optical system, it obeys the basic laws of optics, notably the basic formula for

The nature of zone plates is discussed in full on pp. 383–5.

image conjugates

1/u + 1/v = 1/f

where u and v are the respective distances of the object and image from the zone plate and f is its focal length. Clearly, if $u = \infty$ (a collimated beam), v = f, and the simplest method of making a holographic lens of a given focal length would be to have a point source (i.e. the spatial filter pinhole) at a distance f from the holographic plate, and a collimated reference beam. However, this is not necessary. You can make a holographic lens using two point sources, and it will have a focal length that you can calculate from the distances d_1 and d_2 using the formula

$$1/f = 1/d_1 - 1/d_2$$

provided d_1 and d_2 are fairly large compared with the diameter of the plate.

For example, if you want to make a zone plate with a focal length of 1000 mm you simply have to arrange the value of d_1 to be 500 mm and d_2 to be such that f = 1000. A little arithmetic shows the correct value of d_2 to be 1000 mm, and you can easily set up the two distances, one with a $\times 20$ microscope objective and the other with a $\times 40$, both beams adequately filling the plate area. There are, of course, many possible combinations of distances that will result in the required focal length. However, it is easy to remember that whenever $d_2 = 2d_1$, the focal length will be equal to d_2 . You can achieve this and fill the hologram area by using two microscope objectives for the two beams, one twice the magnification of the other. This works for both transmission and reflection holograms.

If both distances are the same (or if both beams are collimated) the focal length will be infinite, and your end product will be a plane diffraction grating (transmission) or a plane mirror (reflection).

Holographic diffraction gratings

If you haven't made an HOE before, a diffraction grating is a good place to begin. If you pass a collimated beam of white light through a slit onto a holographically fabricated diffraction grating, the light of the original laser wavelength will be diffracted at the original angle, but shorter wavelengths will be deviated progressively less, and longer wavelengths progressively more, so the light will be spread out into a spectrum. A prism will do much the same job by refraction, but the dispersion is in the other direction (red is refracted less than blue), and is neither as wide nor as linear as the spectrum given by a grating.

All you need to make a holographic grating are two beams of approximately the same intensity, at an angle to one another. There is no need to collimate the beams provided the two sources are equidistant from the center of the plate and not less than a metre away from it. Expose, develop and bleach the emulsion as if for a master transmission hologram, preferably pre-washing and drying before exposure.

You can fabricate the grating in either of two ways. If you set up the two beams symmetrically, when you illuminate the finished grating with collimated white light through a slit (you can use a slide projector with a slit in the slide gate, or an overhead projector with the slit on the platen) you will see the white zero-order beam in the center, and the +1 and -1 order spectra on either side. If the two

The minus sign occurs because on replaying the hologram the reference beam distance d_2 is reversed in direction.

You need to process both types of hologram using a system that will give a geometrically correct reconstruction for the original wavelength. Failure to do so will result in low diffraction efficiency and an astigmatic beam.

It is possible to obtain a diffraction efficiency of more than 90% with a holographic mirror. For a holographic lens the best figure is around 35%. Just to remind you, diffraction efficiency is the ratio of imageforming light intensity to incident light intensity.

The best engine-ruled gratings have only about 600 line pairs per mm (lp mm^{-1}); holographic gratings can be more than twice as fine, and they are much more efficient.



Figure 15.9 Table layout for a holographic diffraction grating. The two sources are equidistant from the centre of the plate and are roughly equal in intensity.

beams you used in the setup were close together you may also see further orders of spectra, farther out from the center. If your beams were set up with each beam at a large angle of incidence, say 45° , the higher order spectra will be suppressed, and the first-order beams will be brighter. However, if you set up the two beams asymmetrically, e.g. with one beam perpendicular to the plate and the other at 45° incidence, the +1 order spectrum will appear to the side of the zero-order beam, very bright, and the -1 order spectrum will be feeble. If you illuminate the grating at 45° incidence, the first-order spectrum will emerge centrally and the zero-order beam will be to the side. Nearly all the diffracted light will be in this spectrum, and it will be so bright that you can afford to use a very narrow slit to illuminate it, resulting in a wavelength resolution high enough for you to be able to see the two sodium lines at 589.0 and 589.6 nm as separate when you examine the spectrum of a sodium lamp.

Figure 15.9 shows a typical rig for producing a holographic diffraction grating.

The reason the asymmetrical setup gives such a comparatively bright spectrum is that the negative diffraction orders are largely suppressed. The grating you have produced is the holographic equivalent of a ruled *blazed grating*, in which the engraving tool is set at an angle in order to produce a sawtooth profile.

Holographic lenses

A holographic lens is only one step away from a holographic grating. As I explained earlier, it requires two beams of differing divergences to fall on the holographic plate. Otherwise the arrangement is exactly the same as for a diffraction grating. Again, you process the hologram as a transmission master, remembering to pre-wash and dry the plate before exposing it. A typical setup is shown in Fig. 15.10.

A glass prism will not achieve this – nor, for that matter, will many student-grade ruled-grating replicas.

When a grating is made holographically in this manner, and reproduced by an embossing process, the surface of the hologram does indeed have a sawtooth profile. This accounts for the dazzling brightness of some types of embossed diffraction-patterned decorative material.


Figure 15.10 Layout for a holographic lens. The length d_2 should be as great as possible, to minimize aberrations when the lens is to be used for collimation. When $d_2 = 2d_1$, the focal length of the HOE will be d_2 .

Making holographic mirrors and beamsplitters

In general, holographic mirrors are more useful than lenses, as their diffraction efficiency can be much higher. They operate on the Bragg principle. Dielectric mirrors and beamsplitters, which operate on a similar principle, are wavelength-sensitive, and the beamsplitters are usually fabricated so as to operate most efficiently at 45° incidence for their chosen wavelength, resulting in the two beams emerging at right angles to one another. However, a holographic beamsplitter doesn't have to be at any special angle: the angle between the two emergent beams will be the same as the angle between the beams you made the HOE with, regardless of the plane of the plate. So it's a good idea to arrange the plate so that when it is set up on the table the main beam enters it at the Brewster angle, avoiding unwanted specular reflections (see margin note) from the surfaces (Fig. 15.11).

The throws of the divergent beams should be as long as you can manage, keeping them equal: use $\times 10$ objectives with 25 µm pinholes if you have them). Set up the plate offset from the center of the beams, so that the diffraction efficiency varies across the final HOE, giving you a wide choice of ratios (Fig 15.12 illustrates this). This type of beamsplitter has negligible losses, and can give you a range of beam ratios from about 10:1 to 1:10.

You can also make holographic plane mirrors by the same method. If you have the two beams directly opposed you will have a mirror that reflects in the same way as a conventional mirror; but mirrors that give their most efficient reflection at other angles from the incident beam may well be more useful. The setup is the same as for a beamsplitter, but the beam intensities must be equal, and uniform over the plate. After processing a 4×5 in plate, you can cut it up to make smaller steering mirrors, but their use is more limited than conventional small mirrors, as they will operate efficiently only over a fairly small range of incidences.

A specular reflection is a direct reflection in which the angles of incidence and reflection are equal, i.e. like an ordinary metalized mirror.

Now for a little secret. When you have to fill the plate area from some specific distance, you don't need objectives with different magnifications for every distance. You can increase the divergence of the emergent beam over a wide range by inserting a minus-50 or 100 mm lens in the unspread laser beam upstream of the spatial filter. Changing the distance between the lens and the filter changes the amount of divergence. You can also reduce the divergence in a similar manner by inserting a positive lens instead, but this isn't generally so useful. This little piece of information can also come in handy when you are lighting a subject for a standard piece of holography, and you need a wider angle of illumination.





Figure 15.12 In making a holographic variable beamsplitter, the expanded laser beams should be decentered with respect to the plate, so that the exposure decreases from one side to the other.

Figure 15.11 Layout for a holographic beamsplitter. One beam is incident on the plate at the Brewster angle; the second beam is at 90° to the first.

Holographic collimating mirrors

These are probably the most useful HOEs, as they provide an excellent substitute for one of the most expensive items on your table.

The easiest way to make a holographic collimating mirror is to use an existing collimating mirror (if you have access to one) to provide the reference beam, and a beam diverging from a point at a distance equal to the required focal length as the object beam (Fig. 15.13).

And not a second-best substitute, either. One of my students made a holographic collimating mirror with a higher reflection coefficient than my aluminized mirror, at less than onehundredth of the cost. In addition, it was only one-twentieth of the weight.



Figure 15.13 Layout for a holographic collimating mirror. d is the final focal length.



Figure 15.14 Layout for a holographic collimating mirror made without a collimated beam. As in Fig. 15.10, to minimize aberrations d_2 should be as large as possible. When $d_2 = 2d_1$, the focal length of the HOE will be d_2 .

In order to obtain the maximum number of fringe planes within the emulsion layer (for high diffraction efficiency) you should set up the two beams to meet nearly head-on. When you use the mirror as a collimator you will obtain the best and most accurately collimated beam if you use it at an offset angle close to the one you used to make it.

If you don't have access to a conventional collimating mirror you can make your HOE using the arrangement of Fig. 15.14. When flipped and illuminated from a distance 2d the mirror will produce a beam that is sufficiently well collimated to use for transfer holograms, though there will be a small amount of horizontal–vertical astigmatism (see below).

Aberrations of HOEs

There are two main aberrations HOEs share with conventional optical components: spherical aberration and astigmatism. We have met these before, but it is worth discussing their effects as they apply here. Spherical aberration is the result of using spherical wavefronts to generate the interference patterns. Although the lens or mirror will give a perfect duplicate of the original object wavefront when illuminated by a replica of the original reference beam, when the conjugate distances are changed the focal point formed by the central zone of the HOE will be at a different distance along the *z*-axis from the focal point formed by its periphery, The effect is fairly small, and is unimportant in a collimating mirror.

Astigmatism is more complicated. If you use the mirror at a distance from the incident source that is different from the distance of the original source you used in fabricating the mirror, you change the angles of incidence on the different parts of the fringe planes in an asymmetrical manner, with the result that the point of focus



Figure 15.15 (a) An astigmatic HOE has a shorter focal length for horizontal lines than for vertical lines (or vice versa, depending on the setup. (b) Adding a negative cylindrical lens to the diverging beam near to the spatial filter will compensate for this.

in the horizontal plane will differ from that in the vertical plane. The beam will converge to a vertical line at one point along the *z*-axis and a horizontal line at another. If you make a holographic mirror according to Fig. 15.14, and illuminate it as suggested, with a beam at a distance 2d, you will obtain a beam that is truly parallel in a vertical direction, but has a positive focus in a horizontal direction, so that the beam tapers to a vertical line several metres from the HOE. Again, this isn't important for most holographic purposes, but if you feel the need to correct it, you can add a weak negative cylindrical lens close to the spatial filter, on the downstream side, to compensate for the horizontal squeezing of the diffracted beam (Fig. 15.15).

Multi-beam HOEs

One of the most striking differences between conventional lenses and mirrors and HOEs is that HOEs can act as multiple lenses and mirrors. If you use two 'object beams' when making a holographic lens or mirror, the emergent beam will follow both paths: you will have two lenses or mirrors, focusing in different directions and (if you want it) at different focal distances, in a single HOE. You needn't stop at two, either. Modern optical processing systems employ diffractive beamsplitters and beam combiners that handle sixteen or more beams, a task well beyond the capabilities of any conventional optical system.

The Gaussian function has the form $y = a \exp(-x^2/b^2)$, where *a* and *b* are constants. Its bell-shape is a familiar one in the field of statistics, where it is known as a *normal distribution curve*. When you perform a Fourier transform on it (see Appendix 2) it stays the same shape. This means that the beam profile doesn't change when you pass it through a pinhole and expand it again.



Figure 15.16 A Gaussian beam intensity profile.

Clearly, you can only use this method with a beam that is already expanded to fill the lens in question. A large number of papers have been published in scientific journals on modifying the intensity profile of a laser beam, one of the most interesting avenues being to design a profile that is immune from expansion due to diffraction. The required profile is called a Bessel beam, from its structure. The Bessel function in question is the Fourier transform of a top hat function, so over a distance the beam is transformed into a top hat profile (i.e. a disc of uniform intensity), and this profile remains the same right out to infinity. Whether this is of any use to the holographer is debatable. Actually producing a Bessel profile (which involves phase as well as amplitude) is tough enough to have already generated a number of PhDs.

A more uniform laser beam

Right from the start, one of the problems with laser light has been the nonuniformity of the laser beam profile. Nearly all lasers used in holography operate in what is called the TEM_{00} mode; this is the mode that gives the highest coherence length. This gives a beam with a Gaussian intensity distribution (Fig. 15.16). This means that only the innermost half of the beam is uniform enough to be used for a reference beam, and this is very wasteful of light.

Some ingenious suggestions for making the beam more uniform have been made. One, due to Han *et al.*³, and developed more recently by Roberts⁴, is to design a pair of holographic filters, the first to redistribute the energy of the beam and the second to re-collimate the light. You can't make these filters holographically, unfortunately; they demand a micro-etching facility.

A ready-made solution is to be found in a radially graded 'bulls-eye' filter, which goes from a density of 1.0 at the center to 0.0 at the edge. It is in fact a pair of lenses, a clear concave one with a gray-dyed convex one of the same curvature cemented to it. Such filters are expensive, and attenuate the light by a factor of at least 10; but if you can afford one, it can be very useful when inserted in the partly expanded beam. Recently, dyed-in-the-mass sunglasses for reading have appeared on the market, and these are necessarily also graduated in density from the center outwards. The most powerful is 4 diopter. In combination with a negative lens of focal length -250 mm (-4 diopters) such a lens will go some way towards evening out the beam.

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Chapter 16 Portraiture and pulse laser holography

He was black in the face, and they scarcely could trace The least likeness to what he had been: While so great was his fright that his waistcoat turned white – A wonderful thing to be seen!

Lewis Carroll, The Hunting of the Snark

The human face and body has always had a fascination for artists: some, like Gainsborough and Reynolds, painted little else. Others, such as Rembrandt and Van Gogh, painted self-portraits obsessively. Sitters were expected to be able to hold a pose, often for hours at a time. With the advent of photography such times came down first to minutes, then to seconds, and eventually to fractions of a second. When the electronic flashtube arrived in the photographic studio, exposure times fell dramatically to a millisecond or less. Quite suddenly it became unnecessary for the sitter to remain even moderately still during the exposure. In a way this simplified the task of portrait photographers, as they were now able to concentrate on the moment when the sitter had just the right expression, though they now had to learn new techniques in the control of this new kind of lighting. At the same time the quality of lenses and films was improving to the point where it was possible to use 6×6 cm and even 35 mm formats for portraiture, and to make a dozen or more exposures in rapid succession, thus increasing the chance of a successful shot.

The earliest studio flash outfits didn't include modeling lamps to show the lighting effect in advance, nor were there Polaroid tests to check all was OK for the allimportant shot. The photographer had to rely on experience to get the lighting balance right. Today flash has become an essential item, and not just in portrait studios. Professional photographers now use flash for the photography of perishables such as food and flowers, and even for cars, audio equipment and furniture. Recently, digital cameras have revolutionized press photography: a photojournalist can take photographs and download them by wire along with the story, straight to the news editor within seconds. Furthermore, photographs taken under almost impossible conditions can be digitally enhanced to produce acceptable images.

The restrictions of the holographic studio are plainly a good deal more limiting than those of photographic imaging. Whereas a photograph of a subject at a distance of ten metres can allow movements of a millimetre or so during the exposure, the corresponding figure for a hologram is about 100 nanometres, some ten thousand times less, at *any* distance. This explains the need for the absolute stability of a heavy optical table equipped with vibration isolation. It is also the reason that many professional holographers, rather than invest in the heavy stabilized tables that limit the range of subject matter to the equivalent of tabletop photography, have turned to flash themselves. The light source that has enabled this is the pulse laser. It can provide a sufficiently brief exposure to produce a holographic record of a subject moving at up to about 8 metres per second (18 mph).

Several types of pulse laser are suitable for holography. At one time the ruby pulse laser (the first type of laser to be invented) ruled, but other types of pulse laser have been developed more recently, and are not only more suitable for portraiture,

Pulse lasers for holography usually operate at a pulse duration of around 25 nanoseconds. During this time a subject moving at 8 m s^{-1} would show a displacement of around one-tenth of a wavelength.

but are easier to operate and maintain. Nevertheless, there are still a great many ruby lasers around, so it is with this light source that I shall begin.

Construction of a ruby laser

The principle of a three-level laser was explained in Chapter 3. The heart of the laser is a single-crystal rod of aluminum oxide doped with chromium, about 150 mm long and 10 mm in diameter. It is pumped (energized) by light from a flashtube.

The primary source has a pulse energy of about 0.1 joule. This beam is fed into a second, larger ruby rod already energized to the point of lasing. This amplifies the energy to around 1 J. The largest lasers have a second amplifier, giving a final energy of around 10 J. A Q-switch limits the pulse duration to a few nanoseconds. The general layout of a ruby laser is shown in Fig. 16.1.



Figure 16.1 Schematic layout of a ruby pulse laser.

Safety considerations

There are two aspects of safety you need to consider: that of the sitter, and that of the equipment. Although the total energy contained in a laser pulse is low, its very short duration means that, during the actual pulse, power is being delivered at up to 400 megawatts (4×10^8 W), roughly the power needed to supply a fairly large city, and along a beam only a few millimetres in diameter. Even a partly expanded beam is hazardous to the eyesight. For safety, it needs to be diffused; and even then it must be expanded so that the diameter of the beam *on the diffuser* is not less than 50 mm for a 1 J pulse or 150 mm for a 10 J pulse. You need to arrange protection (preferably in an opaque tube) for the unexpanded beam so that there is no chance of any part of the body intercepting it, and there must be a safety device ensuring that under no circumstance can the laser be fired accidentally. A set of safety recommendations for lasers was given at the end of Chapter 3.

The most dangerous part of a ruby laser is not in fact the beam but the power supply, a huge bank of capacitors with almost no internal resistance. Anyone making contact with the high-voltage output has roughly the same chance of surviving the experience as of surviving being struck by lightning. However, this part of the system is well shielded by the manufacturer, so it is the light beam that chiefly concerns us; in ruby lasers (as in all pulse lasers) it is the operator, the sitter and the laser itself that need protection.

The main hazard to the equipment comes from the possibility of retroreflection. A beam reflected back along its own path will almost certainly destroy the ruby rod of at least one of the amplifiers.

crystal technically a ruby, though, as I said earlier, a somewhat anemic one. A Q-switch, as you will remember from Chapter 3, is the device that saves up the energy in the laser to deliver it finally as a very short and intense light pulse.

The chromium content makes the

The dangers of lasers, even pulse lasers, are often exaggerated, sometimes resulting in quite ludicrous restrictions on the part of academic authorities. It must be said that even a slackly run holographic studio is a less hazardous place to work in than the average handyman's workshop. Nevertheless, there are certain mandatory precautions when working with lasers, just as when working with power tools; these are especially important when a second person is present.

A ruby rod with both ends blown off is not a pretty sight, either for you or your accountant. This can occur when reflecting surfaces in almost any part of the undiverged beam are positioned carelessly. They should always be set up slightly off axis. Most pulse rigs have a small aiming laser for alignment purposes; and you can easily check with this that all reflections are off axis.

Maintenance of pulse lasers

Ruby lasers need a certain amount of cosseting, if they are to continue to perform to specification. Check the output oscilloscope trace regularly, and investigate any change in the shape of the curve. You need to keep the Pockels cell topped up with fluid, and to flush out the cooling system regularly, checking it for leaks. But above all – and this applies to all types of pulse laser – you must ensure your optical components are absolutely dust-free, as the energy of the undiverged pulse is sufficient to burn any foreign material hard on to the surface. To check that this has not happened, fire the undiverged beam (set to not more than 1 joule) at a piece of fogged and developed photographic print paper. It should evaporate a clean white disk. If there are any black specks, there is dirt on one of the laser rods or an optical flat. Treat all the surfaces with a cleaner suitable for optical surfaces.

Other types of pulse laser

At the time of writing the only other pulse laser fully developed for holographic studio work is the frequency-doubled YAG laser, though others are undoubtedly in the offing.

They seem set fair to take over from ruby lasers, or at least to share the honors (see Chapter 17). YAG pulse lasers oscillate at a fundamental frequency corresponding to a wavelength of 1064 nm, but can be made to produce a strong second harmonic at 532 nm, and this is the wavelength that is selected. They are driven by a flashtube in the same way as a ruby laser, but they are much more tractable. At present they don't reach the power available to a ruby laser: the maximum at present is nearer to 1 joule than 10; but it could be stepped up by amplifiers in a similar way. In fact, 1 joule is sufficient for most holograms, up to and including portraits on 40×50 cm material.

Setting up a pulse laser studio

You must always remember that a pulse of energy as low as 1 J, delivered by a beam less than 10 mm in diameter and time-compressed into 25 ns represents an instantaneous power of some 40 MW. Can you use a spatial filter with this beam? Well, yes, just. The beam is broader than a CW beam, and you may have to use a $\times 5$ objective to catch all of it, with a 40 µm pinhole. But a metal pinhole that is out of alignment can be quickly burnt out, and most authorities recommend a diamond pinhole. All the lenses and mirrors in the path of the undiffused beam need to be antireflection coated for the appropriate wavelength, and mirrors and beamsplitters should be of the dielectric type, also matched to the laser wavelength.

In general you should try to avoid using any focusing optics, as the beam energy may be sufficient to ionize the air at the focal point and render it opaque.

Things happen suddenly and fast in the field of laser research and development, and unfulfilled predictions can on occasion make a technical author look very silly. But so much is going on in the field of diode lasers that it would be surprising if there were not pulse diode lasers of many wavelengths available for holography before long. The YAG pulse laser has been a reality for some years. The initials, by the way, stand for 'yttrium aluminum garnet'. Garnet is a silicon tetroxide (SiO₄) crystal, and is doped with the lasing element in a similar manner to ruby. There are many variants of the YAG formula.

But if your ambitions extend to 1×2 m images of fashion models sitting on Harley-Davidson bikes you are likely to need the full 10J that a twoamplifier ruby laser can provide.

If you are using a red (633 nm) laser for setting up for a YAG pulse laser, the beamsplitter will give an incorrect beam ratio. You must watch this. Incidentally, the use of dielectric components means that their wavelength selectivity suppresses any stray light from the triggering flash, which is good news.

Totally enclosed vacuum spatial filters are available – at a price. Indeed, having costed a number of both photographic and holographic studios, I would suggest that equipping a holographic studio at the level discussed in this chapter costs no more than a professional photographic studio intended to work with equivalent subject matter. There are several kinds of totally reflecting prisms (e.g. Dove prisms) that you can use in place of mirrors. The best type of beamsplitter is a polarizing cube (see Box 16.1), which doesn't absorb any energy.

This may all sound a little off-putting; and indeed, the optical components, which need surfaces of better than $\lambda/10$ accuracy, are expensive. But the components for the fully diverged beam, that is, the collimating mirror and the object illuminating mirrors, can have ordinary aluminized surfaces. You can support them on photographic stands as if they were ordinary lighting components in a photographic studio.

Box 16.1 Polarizing-cube beamsplitters

In this type of beamsplitter a cube is made up of two right-angle prisms separated by a multiple dielectric layer. A beam of unpolarized light incident on one face of the cube emerges as two beams, one from the opposite face and one from the adjacent face. The two beams are equal in intensity and are linearly polarized orthogonally, the transmitted beam being *p*-polarized with respect to the hypotenuse surface. However, if the incident beam is already linearly polarized, the intensity ratio of transmitted to reflected light is determined by the direction of polarization of the incident light, and can be anything between 50:1 and 1:50. There are no losses, and thus no energy absorption. Figure 16.2 shows the principle.



Figure 16.2 Polarizing-cube beamsplitter. Light reflected at the hypotenuse surface is s-polarized; transmitted light is *p*-polarized. Half-wave plates R_2 and R_3 are employed to bring the polarization vectors of the emergent beams into the same plane. The half-wave plate R_1 rotates the plane of polarization of the incident beam in order to vary the beamsplitter ratio. (Rotation of this plate by θ° rotates the polarization vector in the same direction by $2\theta^\circ$.)

The beam ratio is usually controlled by a half-wave plate situated at the entry port. Rotation of this by x° results in rotation of the plane of polarization of the incident beam by $2x^{\circ}$. As the emergent beams are orthogonally polarized, further half-wave plates are needed at the output ports to line up the directions of polarization of the two emergent beams.

Special problems with holographic portraiture

There are three problems associated with holographic portraiture, and until recently these have combined to make the results barely acceptable in esthetic terms. The first is that the need to spend some time in total darkness while the plate is positioned leads to the sitter's pupils being fully dilated, giving a curious staring appearance. You can avoid this by illuminating your sitter with green light (for red-sensitive emulsions) or red light (for green-sensitive emulsions). The most effective way to do this is to use an old 35 mm slide projector with a narrow-band filter in the slide carrier, directed at the sitter's face. This will also help you to see the sitter and judge the moment to fire the laser.

The second problem concerns the nature of the light from ruby lasers. Until comparatively recently this was the only illumination available for holographic portraiture. The problem is somewhat similar to that which faced the pioneers of cinema, where the use of red-blind orthochromatic film forced the use of greenish-blue makeup in order to avoid blotchy complexions and black lips, and to achieve a more natural representation of tones in the photographic image. With the deep red of the ruby laser the problem is that the wavelength of 694 nm is almost in the infrared, and penetrates the outer skin. This makes women's faces look waxen, and men's faces look unshaven. As with the cinema, the answer is to use opaque makeup (Plate 8). There are various proprietary formulas, used today mainly in television work. You need to apply the makeup thinly enough not to disguise the texture of the skin, but there must be no gaps. The problem is receding now that more studios are adopting green pulse lasers for portraiture; these give a result much closer to what the eye actually sees.

The third problem is also related to masters made using ruby lasers. Although the master hologram needs to be made using a pulse laser, it is usually more practical to use a CW laser for the transfer process. This involves a change in wavelength (694 nm to 633 for a HeNe laser or 645 nm for a Kr^+ laser). If you don't take any steps to deal with this discrepancy, your final image will be astigmatic and will show steepened perspective. A choice of developer containing a small amount of sulfite (see Appendix 6) can help to compensate, as can the use of a converging beam for the master hologram during the transfer process. You can minimize the effect of any residual distortion by positioning the transfer plateholder so that the eyes of the sitter are in the plane of the final hologram.

Lighting for portraiture

The first rule is a safety rule. Never allow an undiffused beam, even one that is well diverged, to enter a sitter's eye. This is unlikely to occur with the reference beam, as it is usually set up at an overhead angle of $45-60^{\circ}$ from behind the sitter; but be careful about other beams, which could possibly be reflected from an unexpected direction.

When you first take up holographic portraiture, it is best to begin with the kind of lighting that is usual in formal photographic portraits. The simplest effective lighting is a single key light positioned about 45° round from the direction the sitter is facing, and about 45° above the sitter's face; in a three-quarter view it should be on the side away from the camera.

The rule of thumb for beginners is to arrange the position of the key light so that the shadow of the sitter's nose is just touching the nearside corner of the mouth. A cheaper solution much used by early holographic portraitists was to flash a torch in the sitter's face just before the laser exposure. This, as you might expect, was not often conducive to the adoption of the desired facial expression.

In the early days of pulse lasers there were numerous cases where people were subjected to direct laser illumination in their faces. It is possible that if someone had lost their eyesight as a result of these experiments, holographic portraiture might never have taken off, or at least would have been greatly hindered. Fortunately, eye damage from laser beams has so far been rare – but it *can* happen.

In photography, the main illumination, usually a floodlight, is called the *key light*; the broad frontal illumination that controls the lighting contrast is called the *fill light*; and any small source that picks out edges, and the texture of surfaces, is called a *kicker*.



Figure 16.3 Basic lighting for portraiture. A is the key light, slightly diffused, producing shadows at nose and cheekbone, and highlighting features; it is usually angled forward at 45° above and 45° round from the sitter's face on the same side as the sitter is facing. B is the fill light, more fully diffused, with its axis close to the axis of view. It provides control of lighting contrast. C is a kicker or small spotlight with a concentrated beam, throwing catchlights on the hair and possibly the rim of the face (cf. Fig. 11.13).

For an average face this highlights the features and emphasizes the line of the cheekbone. In a full-face shot, the side from which the key light should come depends on which side of the face needs more emphasis. The primary purpose of the second light, the fill light, is to illuminate the shadows. In photographic portraiture it is a large light (often dubbed a 'swimming pool'), placed close to the axis of the camera so that it doesn't cause a second visible shadow, which would look unnatural. The small 'kicker' is a spotlight, usually behind and above the sitter. Its purpose in this position is to create highlights in the hair, and perhaps to emphasize the cheek structure. Figure 16.3 gives an impression of this basic lighting setup.

In holographic portraiture, although the key light no longer has a special role as the 'modeling' light that creates the impression of depth in a two-dimensional representation, its positioning is still important in bringing out the best in a sitter's features, not to mention subduing those that could do with less emphasis. In a portrait, a small change in the position of a key light can make a considerable difference to the apparent shape of a face. Lowering the beam from 45° to 30° above the sitter's head emphasizes character rather than looks; moving it round from 45° to about 60° horizontally makes a broad face appear narrower; a very low position gives a theatrical appearance and a very high position a mysterious one. Not all effects produce desirable results: a key light on the same side as a hair parting can emphasize a receding hairline, as can an ill-positioned kicker. In holographic portraiture the rules are much the same as in portrait photography. Students of photography are often encouraged to experiment using a dummy head, and the same applies in holographic portraiture.

A fairly unsophisticated lighting setup suitable for a 30×40 cm plate is shown in Fig. 16.4. If your pulse laser isn't equipped with a steering laser, set up your illumination system using a collimated beam of white light (e.g. from a slide projector beam).

Most people have somewhat asymmetrical faces, often with the right side more developed than the left.

But it is more interesting to use a friend as a model, preferably one who has similar aspirations, and can subsequently exchange roles with you.



Figure 16.4 Simple lighting for head-only portraiture. (a) Plan view. The key lighting is the transmitted beam from the beamsplitter BS; the fill lighting is reflected via the diffuse reflector DR from the other side of the sitter. The reference beam is derived from the reflected portion of the beam from the beamsplitter. (b) Side view. A portion of the reference beam acts as kicker. The undiffused light reflected from the hologram surface is directed away from the sitter's face. D is the key light diffuser.

You will probably have realized at this point that you can't put your fill light directly in front of your sitter, because the holographic plate is in the way. There is no easy way of avoiding this problem. The next best position for the fill light is on the opposite side of the plate to the key light, level with the plate. One way to provide this light is to use a large card sprayed with aluminum paint as a diffusing reflector, positioned so as to catch some of the light from the key light, which you can aim slightly off-center for the purpose. A more complicated solution is to employ the Pepper's Ghost principle, which you have already met in Chapter 11. This is illustrated in Fig. 16.5. As the coherence length of pulse lasers is more than a metre, you don't have to match the path lengths exactly, and you can afford to catch the light passing through the 45° glass sheet on the far side, and reflect it back towards the sitter with the large diffusing reflector.

Under no circumstances allow any light from any of these beams to fall directly on the emulsion. If it does it will act as a spurious reference beam, and your image will be marred by one or more unwanted shadowy images alongside the genuine image.



Figure 16.5 Pepper's Ghost setup for portraiture. (a) GP is a large glass sheet at 45°, which provides the fill light from the front of the sitter. Most of the light passes through the sheet and is used to provide side lighting from diffuser D. The key light is not shown. (b) Plan view showing the collimating reference mirror, which also provides the 'kicker' light. BC is a black card preventing light from the diffuser from reaching the emulsion. The key light is not shown.

The lighting balance may be difficult to assess visually from the steering illumination, and there will always be a certain amount of educated guesswork involved. I can't overemphasize the importance of keeping a full record of all your setups and exposures. It can save you from the waste of much valuable time – and material.

Exposure

Until you have sufficient previous exposure details logged, you will need a flash meter to estimate your exposure. Some models of flash meter will do the job, but not all. Don't invest in one until you have had a chance to try it out. It won't give you a direct result in microjoules per square centimetre, as a dedicated energy-density meter would do, but you can easily calibrate it by making measurements in a direct beam for which you can calculate the intensity. You will need to remember that depolarized light is less efficient at forming fringes than polarized light, so it is a good idea to check your relative beam intensities with a polarizing filter over the meter cell.

The most important thing in holographic portraiture, just as in photography, is to choose exactly the right moment for the exposure. With a professional model this is no problem, but with an untrained sitter the onus is very much on you. Watch the sitter from behind the plate, immediately above it. Concentrate on the sitter's face, and when you operate the exposing flash you will be able to hold the image in your mind's eye for perhaps several seconds. If you are making a formal portrait, give a countdown, at a steady speed, so that the sitter won't be blinking at the instant of exposure (this is a serious hazard in group portraits).

Here are some dos and don'ts:

- Don't position an undiffused beam where it can enter a sitter's eye.
- Don't allow the light from any beam other than the reference and object beams to reach the emulsion.
- Do arrange the diffusers, curving them if necessary, so that as much light as possible falls on the sitter.
- Do control the relative illuminances by adjusting the beamsplitter ratios rather than by altering the distances of the illuminating sources as you would with a photographic portrait.

Processing

Processing a pulse laser master is no different from processing any other master, except that if you are working with a ruby laser it is advisable to use a processing regime that produces about 8–10% emulsion shrinkage to allow for the change in wavelength when you make the transfer hologram. You will find suitable developer and bleach formulas in Appendix 5.

Other subject matter

Once you have experienced the freedom of making master holograms with a pulse laser you may be reluctant to go back to the straitjacket of CW laser mastering. A

In photography, of course, you can make a whole series of exposures in rapid succession, but in holography there is no motor drive: you get one chance only. If things didn't look right the first time, you then have to go through the tedious business of loading another plate.

But if you do have any doubts at all about the esthetic quality of the image, don't hesitate to make another exposure. Plates may be expensive, but they are the cheapest item in your setup. pulse laser will 'freeze' anything moving at less than about 16 mph, so you can include live flowers, animals, running water and falling objects in your hologram. You can make 'black hole' holograms of any object that is sharp in photographic terms, even a rifle bullet complete with shock waves, if you are equipped with a suitable triggering mechanism. You can apply many high-speed photographic techniques to holography, using acoustic or infrared triggers: birds in flight, spectacular card shuffles, juggling, water splashes, shattering glass – and all in three dimensions!

Double and multiple pulses

Most pulse lasers can be set to provide double pulses, with a pulse separation interval that can be varied between about 1 and 100 microseconds. This is a useful facility in certain types of holographic interferometry (see Chapter 23). Any movement of the subject in between the pulses is contoured by dark and light fringes. Translational movements during the interval produce long parallel fringes; vibrating objects such as musical instruments show characteristic and often beautiful patterns on their surfaces, and even a supposedly stationary torso shows fringes indicating the movement of blood vessels under the skin (Figs. 16.6 and 16.7).

Some solid-state pulse lasers operate a continuous series of pulses at rates of several kilohertz. You can, at least in principle, obtain stroboscopic holograms



Figure 16.6 An early double-pulse hologram. The dark glasses were necessary because of the undiffused beam. The mysterious viola player is Dr Keith Hodgkinson of the Open University. Photograph courtesy of the OU.

No kidding. All these images *have* been captured, and not only by professionals. Holograms of wildlife (Plate 9) are particularly successful, though you need the presence of the trainer, and lots of patience.



Figure 16.7 'Counting the beats', a double-pulse self-portrait by Margaret Benyon and John Webster, with technical assistance from Chris Mead. The translation fringes on the sitters' faces indicate that John is nodding and Margaret is shaking her head. Notice the strong fringes on Margaret's chest, from breathing and pulse movements.

with these, giving you the opportunity to record golf swings, tennis shots and so on in three dimensions. Little has been done in this field so far, partly because the power per pulse is small; but it offers a tempting field, not least in the area of sports advertising.

Chapter 17 Holography in natural colors

Said the Rose... 'Still, you're the right colour, and that goes a long way.''I don't care about the colour,' the Tiger-lily remarked.

Lewis Carroll, Through the Looking-Glass

It was more than fifty years from the inception of photography before the first photograph in full natural color was made. The theory of color perception and color reproduction had been known for nearly a hundred years, but during its first five or so decades photography in simple black and white was seen as such a marvelous thing that it appears not to have occurred to anyone that there was something inherently unrealistic about it.

Today, such photography is used only for images that carry a message that can be best expressed in stark black and white. More than nine-tenths of today's photographic images are in full color. Indeed, it is now becoming difficult to obtain a black-and-white amateur film except from specialist photographic stores. One may wonder: will holography eventually go the same way, with monochrome the exception rather than the rule?

The answer isn't entirely clear. Although it is certainly possible in theory to obtain a greater range of color on a hologram than in a photograph or a television image, it is difficult to obtain accurate color reproduction in a hologram, especially when the subject matter contains highly saturated colors. The reason for this is that a saturated color reflects only a narrow band of wavelengths, and the wavelengths of the illuminating lasers may not fall within this region. Even when they do, there may be little discrimination in hue. This is logical: under red laser light, red, orange, yellow and white objects all look red; green, blue and violet objects all look black.

There is also a psychological factor. People who attend exhibitions of holography tend to be largely unaware of the presence or absence of color. This is something that has also been noticed with motion pictures: people can seldom remember whether a particular old movie or TV program was in color or black and white. In holography it seems that the three-dimensional nature of the image overrides the other visual stimuli to such an extent that the unsophisticated viewer may not register that the image is overall green or yellow, only that it seems to be suspended in space. However, it may be only a question of time before color holograms become sufficiently commonplace for people to be surprised at seeing a monochrome image. Even now, there are some indications of this, as more and more holographic images depend for their esthetic effect on the use of color in the image (usually false-color). There is plainly a market for color holography in advertising: we may soon be seeing 3-D illustrations of ketchup bottles in what seems to be natural color.

There is more to color imagery than just getting the colors right. In the early days of color negative–positive photography, enthusiasts agonized over the difficulties of achieving really good reproduction of reds and magentas, and of producing greens that didn't look bluish, ignoring the fact that for over a hundred years

Although most early photographs were sepia-toned, I am calling them 'black and white' rather than 'monochrome' because I use the word *monochromatic* specifically to describe light containing only a narrow band of wavelengths.

Saturation is the extent to which a color is pure, that is, it corresponds to a comparatively narrow spectral band. It is a quantitative term in the CIE system of color measurement. In other systems it may be called 'purity' or 'chroma'.

You may have noticed that under one of the older golden-colored lowpressure sodium street lamps a deep red rose looks black. These sodium lamps emit lines at 589 and 589.6 nm only, and a red rose doesn't reflect these wavelengths.

Here I am using 'monochrome' in the sense I have defined it above.

'Seems to be'? Colors may be artificial, or the subject matter may have been specially prepared in offcolor hues in anticipation of the distortions following from laser illumination, just as in early professional color photography. Read on! Consider Tretchikoff's portrait of an Oriental woman: not only is it unfinished, with an area of bare canvas, but the woman's face is green. You may think this picture naff, but a very large number of people have liked it enough to buy a reproduction. Point made?

Light scatter in the emulsion and substrate does reduce the saturation somewhat. To minimize this some workers have used dichromated gelatin for the blue and green record. Modern materials, though, are much less prone to light scatter than earlier emulsions. painters had been using any colors that took their fancy, and getting away with it.

An important characteristic of both transmission and reflection holograms is their ability to produce highly saturated colors. So why not exploit this ability? It is to a large extent a question of esthetics. However, that is a matter for the next chapter. In this one I am going to consider only the production of holograms in natural colors, or at least as natural as the holographic process can make them.

The eye and color perception

The eye, and the parts of the brain that process its information input, make up a remarkable mechanism. Along with all the other extraordinary abilities of the visual system, we are able to perceive and distinguish between something like a million different colors. Yet our eyes are constructed in such a way that much of the color information is lost: in particular, information on the actual wavelengths involved. For example, think of the color yellow. It seems a very positive sensation. Yet there are no cells in the retina of your eye that respond specifically to the wavelength of light associated with yellow. Instead we have light receptor cells that have their maximum sensitivity respectively to orange-red and green. When light having a range of wavelengths centered around 630 nm falls on the retina the red-sensitive or ρ (rho) cells are stimulated, and we perceive 'red'. If the light has a range of wavelengths centered around 550 nm, the green-sensitive or γ (gamma) cells are stimulated, and we perceive 'green'. When the wavelength lies in between, say around 580 nm, both ρ and γ cells are stimulated; but we don't see a mixture of red and green. We see, quite firmly, yellow. A pair of single wavelengths at 630 nm (red) and 550 nm (green) produce exactly the same sensation. We don't see a mixture of red and green, but again, equally firmly, yellow. The same effects apply in conjunction with the blue-sensitive or β (beta) cells, which when stimulated in combination with ρ or γ cells produce the sensation of magenta or cyan respectively.

Our retinas contain two main types of light-sensitive cell, called rods and cones from their shape. The rods operate only in dim light and are not color-sensitive (you may have noticed that you can't see colors by moonlight). The cones respond to bright light, and, as I have explained above, are of three types, responding to specific areas of the visible spectrum.

The ρ -cones respond over a range of some 540–760 nm, with a peak at about 610 nm (orange). The γ -cones respond over a range of about 470–650 nm, with a peak at about 565 nm (green), considerably overlapping the range of the ρ -cones. The blue-sensitive or β -cones, of which there are fewer than the other two types, respond over a range of about 380–540 nm, with a peak at about 470 nm (royal blue) and rather less overlap. There is also a small hump of sensitivity of the ρ -cones centered on 440 nm.

As you can see from Fig. 17.1, there are no cones that respond specifically to yellow, nor to cyan (blue-green) nor magenta (purple-red), though we can see these colors perfectly well. The *sensation* of yellow is, as I said earlier, produced either by a mixture of red and green wavelengths or by a single 'yellow' wavelength, and, looking at Fig. 17.1, you can see why. In a similar manner, a single wavelength of 530 nm produces the sensation of cyan by stimulating the γ and β cones together,



Figure 17.1 Range of sensitivities of the three types of cone cell. The curves have been normalized for clarity.

but so does a pair of wavelengths of 550 and 450 nm. There is no single wavelength that will produce the sensation of magenta: it is produced only by simultaneous stimulation of the ρ and β cones by light of, say, 450 and 650 nm wavelength.

What of all the other colors we can perceive? Well, if we run right through the spectrum starting at the long wave limit of vision (about 760 nm), up to about 650 nm the perceived hue remains the same, though growing brighter as the wavelength decreases, until the γ -cones begin to respond, at which point the perceived hue begins to shift towards orange, then to yellow as the γ and ρ responses become equal. As the wavelength shortens further, the stimulation of the ρ -cones falls and the hue becomes greenish. At about 550 nm the β -cones begin to be stimulated, and as the wavelength continues to shorten the green hue becomes bluish, then passes to blue, becoming slightly reddish (violet) as the little hump of ρ -sensitivity is reached, before darkening to blackness at around 380 nm.

Now, all this is the result of stimulating the retina with single wavelengths. The colors you see are the same as those you see in a spectrum formed by a prism or diffraction grating – or, indeed, in a rainbow hologram. But most light contains a mixture of wavelengths. Early in the nineteenth century Thomas Young showed that you can produce any hue by mixing no more than two colored lights: every color in the spectrum can be replicated by a mixture of just two of the 'primaries', red, green and blue. Later in the century, Hermann Helmholtz quantified the theory, which is now known as the Young–Helmholtz theory of additive color. The isolation in the 20th century of the three types of cone cell confirmed its physiological basis.

The theory also accounts for the many thousands of other colors we can see, but which are not in the spectrum (for example, pink, slate gray and brown). We have seen what happens when we mix lights of just two primary wavelengths. What happens when we add a proportion of a third? Well, the hue stays the same, but the saturation becomes less, that is, the color becomes less intense: red becomes pink; purple becomes lilac; emerald becomes jade. If the three wavelengths are equal in intensity, we perceive the light as colorless (white or neutral gray), and the sensation is indistinguishable from that produced by a full spectrum of wavelengths. If the proportions of the three wavelengths are unequal, the apparent hue is governed by the proportions of the two wavelengths of highest intensity, and the saturation by the amount of the third. Thus a dull brown (a desaturated orange) might contain 50% red, 30% green and 20% blue,

Like the red end, the limit of human vision at the violet end of the spectrum is somewhat indeterminate. It depends to a large extent on the transmittance of the lens of the eye at short wavelengths (see margin note on p. 404). Maxwell was a brilliant theoretical physicist who had had profound insights into the nature of light. But he had a poor grasp of photography and of the limitations of contemporary materials, and he was lucky to have produced any results at all.

Projection television sets actually use Maxwell's setup, with tubes projecting red, green and blue images in register on a screen – a belated redress for the coldness with which his demonstration to the Royal Society was received.

In other systems, 'saturation' becomes 'chroma'; 'lightness' is 'luminosity' or 'value'. The CIE system has a number of other terms to describe various subjective aspects of color, but they are not relevant here. The term 'brightness' is ambiguous, with implications of both lightness and saturation, and I use it in this book only in a colloquial sense, without reference to color, where to talk of 'luminous intensity ' would be unnecessarily pedantic.

This is a crafty method of getting three variables into one graph. It is easily understood if you appreciate that the total color content can never exceed 100%. If, say, the green content were 100% (=1), the red and blue content, by definition, would both have to be zero. It is somewhat surprising that the Committee didn't settle for a graph using trilinear coordinates, the standard practice when measuring color densities in photographic color negatives and transparencies. This would have put the curve inside an equilateral triangle.

all at a low level of lightness, and a bright pink might have 70% red, 15% green and 15% blue, all at a high level of lightness. In order to synthesize *all* the colors we can see, the three bands of wavelengths, red, green and blue, have to be chosen fairly precisely.

In 1862 James Clerk Maxwell made a partially successful attempt to show that if a photographic record were made of a colored object on three negatives through a red, a green and a blue filter respectively, then if the images of black and white transparencies made from these negatives were projected superposed in register, using the original filters, the resulting image on the screen would be in natural colors. The theory was sound; but at the time of his presentation of it to the Royal Society the materials available to Maxwell were almost totally insensitive to wavelengths longer than about 500 nm (as the audience was well aware), and his demonstration was received with some skepticism.

This principle of superposition of primaries is known as *additive color synthesis*, and is the basis of color television, which employs a matrix of dots of red, green and blue phosphor, and of the Polaroid process for instant color transparencies, which uses a raster of fine red, green and blue lines. It is also the principle underlying natural-color holography.

The CIE chromaticity diagram

There are several ways in which a patch of color can be specified quantitatively. The one I have used so far contains three dimensions, namely hue, saturation and lightness. These are the terms quantified by the Commission Internationale de l'Éclairage (CIE). Hue, the 'name' of a color, is described by the dominant wavelength, i.e. the wavelength that has a hue exactly matching that of the patch. Purples and magentas, which are not in the spectrum, are defined in terms of the dominant wavelength that has a hue complementary to that of the patch, that is, would generate neutral gray if mixed with it additively. This wavelength is given a negative sign. Saturation is a measurement of the vividness of the color. Its two extremes are spectrally pure color and neutral gray; the dominant wavelength remains unchanged throughout the scale. An example is the range of blues from royal blue (high saturation) to slate gray (low saturation). Lightness is specified in terms of luminous intensity. If a projector with a filter over the lens produces a patch of light on a screen, and the light intensity is changed without changing anything else, it is the lightness that changes.

As lightness is independent of color quality, two-dimensional diagrams that quantify color usually depict only hue and saturation. Of these, the CIE chromaticity diagram is the most widely used in technology. The original diagram (Fig. 17.2) plotted the spectrum in Cartesian coordinates, the *x*-axis representing red content and the *y*-axis representing green content, both scales running from 0 to 1. The third dimension, blue content, could be obtained by subtracting the sum of red and blue content from 1.

The horseshoe-shaped curve represents the pure spectral colors. (If the eye were a perfect receptor the curve would be a 45° right-angled triangle.) The hues are specified by wavelengths along the curve. The range of perceived hues between blue and red, which cannot be matched by a single wavelength, are represented by a straight line joining the extreme values for red and blue (400 and 700 nm). There is a neutral center, the position of which is determined by the nature of the



Figure 17.2 CIE chromaticity diagram (original form). The large triangle shows the range of colors that can be produced using a Kr^+ laser at 514 nm an Ar^+ laser at 514 nm and a HeCd laser at 442 nm. The broken line shows the possible range using the Ar^+ line at 488 nm instead. The chain line indicates a typical RGB color television display. Neutral gray is at a point corresponding to 0.33R, 0.33G, 0.33B. The numbers round the curve are wavelengths in nanometres, and approximate hues are indicated round the edge.

illuminating light (daylight, tungsten filament, xenon arc, etc.), and the color saturation at any wavelength lies along a line joining the wavelength's coordinate to the neutral point. You can find a full description of the theory underlying this diagram in Hunt¹.

The importance of the diagram is that it can tell you how good any set of colors is at synthesizing the gamut of visible colors. For example, if you make your color hologram using light at 633 nm from a HeNe laser and at 514 and 488 nm from an Ar^+ laser, the color range is somewhat limited. By using the 477 nm line of the Ar^+ laser, at some loss of power, the rendering can be significantly improved. The optimum range you can get at present using readily available lasers is by using a Kr^+ laser at 647 nm, an Ar^+ at 514 nm, and a HeCd laser at 442 nm. This combination can give a range of colors greater than is possible in either color photography or TV. However, this doesn't necessarily mean that any color recorded holographically will appear in its true color when replayed.

It is a pity that this comparatively simple diagram doesn't give a very precise representation of the differences between colors. An ideal diagram would show minimum perceptual differences between colors as equal distances within the enclosed area. The 1976 CIE convention ratified a modification of the diagram that

To see what the gamut of possible colors is, you simply join the coordinates of the colors with straight lines, as in Fig. 17.2.

By the beginning of 2003, with the regular appearance of new diode lasers this set of figures could be altered almost weekly. At the time of writing there is a diode laser operating at 405 nm, another at 514 nm, and several more around 700-760 nm. They are not all suitable for holography, but it is only a question of time before fully stable versions are available with the right kind of power. Geola are offering a pulse laser system delivering lines at 659, 527 and 440 nm, but at present the energy output is low, about 20 mJ. Kaveh Bazargan's early color hologram (Plate 10a) was made using a HeNe and two Ar⁺ wavelengths, and has reproduced the original yellow faces of the Lego figures as pink.



Figure 17.3 CIE chromaticity diagram as revised in 1976. In this diagram equal distances between points represent equal perceived differences in hue and saturation. The two triangles represent 'ideal' laser wavelengths and the best choice of readily available wavelengths.

would achieve this, by a straightforward mathematical transformation. The coordinates x and y, which represent red and green on the original curve, are replaced by new coordinates u', v', according to the relationship

u' = 4x/(-2x + 12y + 3)v' = 9y/(-2x + 12y + 3)

This gives a new diagram (Fig. 17.3), from which it can be seen that the spectral lines chosen don't actually give the best range of colors. For this reason Hubel and Solymar² chose the wavelengths 458, 529 and 633 nm.

Color transmission holograms

It is possible in theory to make a full-color transmission hologram using three laser beams, but a number of difficulties stand in the way. In the early days, the most serious of these was the lack of panchromatic material, but Slavich now produces a holographic emulsion that is more or less uniformly sensitive throughout the whole visible spectrum. However, three difficulties remain. The first is that such a hologram has to be displayed using the same wavelengths that were used in making it; otherwise the images will be out of register. The second is that there is an inevitable loss of fringe contrast in a hologram containing three very similar fringe patterns occupying the same space. The third is *crosstalk*, so-called from an

Laszlo Solymar was Paul Hubel's supervisor for his PhD in color holography. Many research papers involving color reproduction in practice still stick to the old CIE diagram because it gives a direct reading in terms of red, green and blue. For the enquiring, Hubel's thesis is lodged with Oxford University, but the gist of it is in reference 2. electronic analogy. The red laser reconstructs not only a geometrically correct image from the 'red' fringes, but also a smaller, displaced image from the 'green' fringes, and a still smaller, further displaced image from the 'blue' fringes. The green and blue lasers likewise produce two displaced images each. These six spurious images not only waste light: they are right alongside the genuine image and may even overlap it. There is no way to avoid the first difficulty, and the only way to avoid the second and third is to make the three sets of fringes with widely differing reference beam angles; this introduces the further problem of aligning the three lasers in exactly their original positions for reconstruction.

Denisyuk holograms in color

The most practical method of producing color holographic images at present is without doubt the single-beam or Denisyuk configuration. Much of the earlier work was carried out by Hans Bjelkhagen and Dalibor Vukičevič at Louis Pasteur University in Strasbourg. Tung Jeong and Bjelkhagen developed the system further at the Lake Forest College laboratories³, and Bjelkhagen now continues his work at De Montfort University, UK. Using Slavich material, he has been able to obtain some very beautiful images (Plate 11), using a HeCd laser at 442 nm, a DPSS laser at 532 nm and a HeNe laser at 533 nm. As the output of these lasers is not matched, they can be set up to give either an adjustable output (using neutral-density filters) or to be exposed in succession with the exposure times adjusted as appropriate. Figure 17.4 shows arrangements for the two possible methods. It is not necessary to use separate spatial filters: after the undiverged beams have been combined; they can be put through a single spatial filter.



Figure 17.4 Three ways of setting up three lasers for color holography. (a) and (b) can be used for a single exposure. In (a), G and R are dichroic filters reflecting bands in the green and red regions respectively; VND are variable neutral-density filters for relative beam intensity adjustment (unnecessary for successive exposures). In (b) the variable beamsplitters VBS are neutral density. In (c) the mirrors M_2 and M_3 are mounted on translation stages, and are removed in turn for the second and third exposures.

It is, of course, very important to process the emulsion in a way that preserves the separation of the fringes, otherwise all the hues will be shifted when the hologram is displayed using white light. A suitable processing regime is given in Appendix 5.

Yes, it has been done, and it worked (Plate 10a). But it certainly isn't a practical proposition.

You need to use an apochromatic microscope objective, i.e. one corrected for all wavelengths, if you are going to get away with a single spatial filter in the combined beam.

Transfer holograms in color

When the only available holographic emulsions were sensitive to red/blue and green/blue, the only way you could make a color transfer hologram was to make the red transfer on the red-sensitive plate and the green and blue transfers on the green-sensitive plate. This technique does have the advantage of avoiding the loss of contrast caused by having three sets of fringes in one emulsion, but it complicates the exposure procedure. As the final hologram (which may be a rainbow or a reflection hologram) will need to have the two plates emulsion to emulsion, you need to use the principle shown in Fig. 17.5 in order to finish up with the images in correct register. The plain glass plate used for the spacer can be a wasted plate from which you have removed the emulsion with a 1:4 solution of household bleach.





Figure 17.6 In a correctly made naturalcolor rainbow hologram, a spectrum is created for each color. At the correct viewing height the spectra will overlap, projecting the red, green and blue content of the images, each in the correct hue.

Figure 17.5 When making color reflection holograms using more than one emulsion it is necessary to maintain accurate register by the use of a plain glass plate of appropriate thickness. (a) shows the red exposure, (b) the green and blue exposures, and (c) the reconstruction by white light.

You need to make the transfer using the same array of lasers as you used for the master hologram(s). The configurations for reflection and rainbow holograms are exactly the same as for monochrome transfers. Rainbow holograms will show much better color saturation than reflection holograms, because they reflect narrower bands of wavelength. The main snag with rainbow holograms is that the color balance is correct only when they are viewed from a specific height. Above this height everything will appear reddish, and below it everything will appear bluish (Fig. 17.6).

Portraiture in color

Having solved some of the problems inherent in monochrome portraiture (see Chapter 16) we have to ask whether color portraiture is a feasible proposition. There are now satisfactory green pulse lasers, but at the time of writing (2003) no blue candidate with matching power. In portraiture this is not as important as you might think: there is very little blue in a portrait. In a reflection or rainbow transfer hologram made from a red–green combination, the general yellowish cast can be compensated by adjusting the display light to introduce a small amount of bluish overall shift.

The problem of color accuracy

The problem still remains, however, of reproducing hues and saturations that match the original subject. The large wavelength gaps between the three laser wavelengths mean that any subject color that reflects a comparatively narrow band of wavelengths is likely to be rendered in an unconvincing hue. Successful color holograms have invariably been of subjects with either bold primary hues or pastel colors. It appears that in order to produce realistic color reproduction three wavelengths are insufficient, and at least four are likely to be the minimum used in the future (Kubota *et al.*⁴), who found the optimum recording wavelengths to be 439.0, 519.6, 585.3 and 660.1 nm. However, Bjelkhagen and Vukičevič⁵ have successfully introduced a holographic technique for obtaining very lifelike reproductions of paintings, using only the three wavelengths discussed earlier.

The future of color holography

True-color holography is here, and will make its mark. That is as certain as the arrival of color photography was certain once du Hauron had shown the underlying principles. The first worthwhile photographs in color appeared in the 1920s. They were transparencies, produced by an additive process, and although the colors were accurate the images were somewhat dark. Making color prints became possible soon afterwards, but the process was so difficult that few people attempted it at the time.

True-color holography is in much the same position today as color photography was in the 1920s. But there are signs that things are changing. Already there are 'pseudowhite' lasers that emit three or more wavelengths simultaneously: such lasers are already in use in the printing industry. Metal halide lamps that emit three powerful spectral lines in the red, green and blue regions are available, too, for displaying color holograms. At present few pseudowhite lasers have the coherence length needed for making useful holograms, and Geola's RGB pulse laser, which does, is (at the time of writing) a little short on clout. And the problem of color accuracy will remain – as it still does in photography, though for different reasons. So we may still be applying pale green makeup and purple-painting ketchup bottles for a few years yet. In the meantime there is a whole gamut of creative color available in the techniques gathered under the heading of 'pseudocolor', the subject of the next chapter.

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Louis Ducos du Hauron wrote a series of papers in 1869 in which he laid out the principles underlying almost every method since used for producing color photographs.

Chapter 18 Achromatic and pseudocolor holograms

A large rose-tree stood near the entrance of the garden: the roses growing on it were white, but there were three gardeners at it, busily painting them red.

Lewis Carroll, Alice in Wonderland

Achromatic white-light transmission holograms

The word *achromatic* means 'colorless'. An achromatic image is an image that appears in shades of neutral gray instead of being in a single spectral hue ('monochromatic'). For achromatic transmission images I shall be using the term *white-light transmission (WLT) hologram*, as the term 'rainbow hologram' seems inappropriate in this context.

I showed in Chapter 13 that a transmission image that is wholly in the plane of the hologram doesn't alter in shape, size or position when illuminated by light of different wavelengths, because its focal length is zero. This means that any image-plane WLT hologram (full-aperture or focused-image) will give an achromatic image when replayed by white light, provided the original subject matter was sufficiently shallow. This isn't true of rainbow holograms, of course, nor of the usual kind of reflection hologram, as both of these are wavelength-selective.



Figure 18.1 Achromatic viewing of a rainbow hologram. (a) Conventional point-source illumination produces a tilted spectrum providing monochrome viewing. (b) A vertically extended source provides overlapping spectra that add to provide an uncolored image at the central viewing position. For the sake of clarity only the primary green rays are shown.

The term 'achromatic' is usually associated with lens systems, where it means that they have been designed to have the same principal focus for two wavelengths, usually yellow and blue, and are free from primary chromatic aberration (see p. 261). A fully color-corrected lens is called apochromatic. However, you can process dichromated gelatin (DCG) holograms (Chapter 20) to produce near-achromatic images by using a processing technique that results in a fringe spacing that varies throughout the emulsion thickness. This results in a wide-band reconstruction and a very bright image.

You can get an ordinary rainbow hologram to produce an achromatic image if you illuminate it with a vertical line source such as a long-filament lamp or a fluorescent tube. The filament acts as an array of point sources, each producing its own spectrum. From a central viewing point these spectra overlap to form an image in neutral grays (Fig. 18.1).

This works well enough for shallow images. With deeper images the change in image size and position with wavelength produces color fringing at the edges of the image (primary chromatic aberration), and results in parts of the image that are out of the hologram plane appearing unsharp. But it does work for small images, as you can see from your credit card, if you hold it under a fluorescent tube oriented "vertically" with respect to the little security hologram.

Dispersion compensation

It has been asserted more than once that there is no way of looking at the image of a laser transmission hologram by white light, but that is not strictly true. As early as 1966 Dominic DeBitetto¹ proposed a technique he called *dispersion compensation*, which operated in much the same way as the correction of chromatic aberration in camera lenses, by introducing an equal and opposite dispersion.

The technique was further investigated by Kaveh Bazargan and Michael Waller-Bridge², and for a time a device for displaying transmission holograms, based on this principle, was offered on the market.

The principle is simple enough. You make a plain holographic diffraction grating using the exact geometry of your proposed hologram, but with a point source replacing the subject (Fig. 18.2). You take the finished grating, rotate it through 180° , and position it in contact with the hologram. When you illuminate the grating with a white light at the position of the source you used to make the grating, the diffracted light will produce an image that is the same size, and in the same position, for the entire spectrum.



Figure 18.2 To make a dispersion compensation grating you need to make a hologram (H') of a point object (PO) at the centre of the subject matter of the original hologram (H).

This type of fringe spacing is known as a *chirped fringe structure*. The term comes from electronics technology, where a 'chirped' pulse is a short pulse containing a sweep in frequency from low to high.

Security holograms are rainbow holograms that are mounted on a metalized backing that reflects the incident light back through the hologram to form the image.

A convex lens converges red light more than blue light; a concave lens diverges red light more than blue light. By combining a strongly converging lens of low dispersion with a weakly diverging lens of high dispersion, the chromatic aberration can be largely corrected. This is the classic achromatic doublet.

The principle of dispersion compensation was later taken up by the American company Voxel, for displaying volume holographic stereograms of brain and body scans (Chapter 25).



Figure 18.3 Dispersion compensation. By spinning the hologram H' of Fig. 18.2 its optics are reversed, and when it is positioned in contact with the original hologram H the dispersion is precisely compensated for the central portions of the subject. An interposed sheet of $3M 45^{\circ}$ Light Control FilmTM prevents the zero-order (straight-through) beam from emerging. (a) shows the overall effect, (b) shows the detail. Angles and dispersions have been exaggerated for clarity.

Of course, the direct beam from the replay source will then be full in your eyes. However, a remedy is available. 3M produce a material called 'Light Control Film', which is essentially a miniature venetian blind set in a plastic sheet.

You can obtain this in a version that cuts out all directly transmitted light but transmits light incident at around 45° . If you sandwich this material between the diffraction grating and the hologram it blocks off the direct beam (Fig. 18.3).

The achromatic angle for transmission masters

In 1977 Stephen Benton surprised holographers by exhibiting a WLT hologram of a sculptured head of Aphrodite that was completely colorless when illuminated by a small-source white light (Plate 12a). The method was subsequently patented³. He had used a specially produced and very complicated holographic optical element, which he called a diffractor plate. This generated a large number of virtual images of slits, each in its geometrically correct position to produce a final image in which the spectra all overlapped in register. The work has, unsurprisingly, proved difficult to replicate.

As it happened, the research led to a much simpler idea, which is now used universally for making achromatic and full-color holograms with good registration. The concept is known as the *achromatic angle*.

In 1982, Benton outlined the mathematics associated with the production of display WLT holograms⁴. Soon afterwards, Suzanne St Cyr produced a lengthy analysis of the practical applications of Benton's analysis⁵, culminating in a worksheet for producing holograms to meet specific viewing demands. Both papers appear in Appendix 3 (with some abridgement where appropriate), with the authors' permission. The first full derivation of the principle of the achromatic angle is in a paper by Benton⁶ on reflection holographic stereograms; it is discussed more fully in Chapter 19.

When you make a WLT hologram from a master transmission hologram using collimated beams throughout, the real image of the slit is at a distance in front of the (flipped) final transfer hologram that is the same as the spacing between the master and final hologram plateholders (Fig. 18.4).

If the replay beam is also collimated, the image of the 'red' slit will appear in its correct geometrical position, but the rest of the spectrum will be spaced out along

The 'straight through' version of this material is often mounted on video screens in sensitive places such as banks, to frustrate prying eyes.

Benton himself said that if ever the diffractor plate were broken, the team wouldn't be prepared to go through the hassle of re-creating it.

The principle of the achromatic angle is so simple that it seems odd that nobody thought of it before – though that always seems to be the case when somebody has a brilliant intuition. The achromatic angle is the angle that the real image of the spectrum makes with the normal to the plane of a rainbow hologram. It has already appeared under the guise of the 'tip angle'.

Achromatic and pseudocolor holograms



Figure 18.4 Slit transfer principle. (a) Transmission master hologram H_1 . (b) H_1 flipped and masked by horizontal slit. Image beam IB becomes object beam OB to make image-plane transfer hologram H_2 . (c) H_2 flipped and illuminated by laser: image beam IB creates hologram-plane image and real image of slit at original distance. The image I is visible only from position of slit image S.

a sloping curve that is very nearly a straight line. The angle α (alpha) made by this line with the normal to the hologram is given by the relationship

 $\tan\alpha=\sin\theta$

where θ is the angle of incidence of the replay beam. Figure 18.5 shows this relationship graphically. The actual figures are affected slightly by additional factors such as emulsion shrinkage and the distance of the replay source (which, of course, will not usually be collimated).

For the time being let us assume, however, that all the beams are collimated, including the replay beam, and that the angle of incidence of the replay beam is to be 45° , so that the achromatic angle is 35.3° (35° is near enough). You need to set the master hologram at this angle, with the reference beam coming from directly "below" (Fig. 18.6a).

Process the hologram as a transmission master in the usual way, and flip it to produce an image-plane transfer WLT hologram with a reference beam at 45° (Fig. 18.6b). This hologram, when again flipped and illuminated with collimated white light, will give an orthoscopic hologram-plane image, with a real image of the master hologram plate area in the viewing space, tilted at the achromatic angle of 35° . This image is in its geometrically correct position for the original laser wavelength, but is lower and farther away from the image (nearer to the viewer)



Figure 18.5 Graph of α versus θ where $\alpha = \tan^{-1}(\sin \theta)$.



Figure 18.6 (a) The master hologram H₁ is made at the achromatic angle, for final reconstruction at 45°. The reference beam is shown as orthogonal to the object beam, though it need not necessarily be so. (b) The flipped master H₁ is used to make an image-plane transfer hologram H₂. (c) When the transfer hologram H₂ is flipped and illuminated by a white-light point source, the images of the master hologram aperture are superposed in the same plane, but displaced so that the central view contains all wavelengths; thus the final image is achromatic, and possesses some vertical parallax.

for shorter wavelengths. However, this real image is in a single plane for *all* wavelengths, so that at the center point all the wavelengths are present (Fig. 18.6c), and the image is genuinely achromatic and sharp, over a vertical range of about 10° . As you will see in the rest of this chapter and in Chapter 19, the importance of the insight that led to this geometry can scarcely be exaggerated.

It has to be admitted that the registration isn't 100% perfect. The achromatic 'plane' is slightly curved (you can see from Fig. 18.5 that the relationship isn't linear), and the magnification changes somewhat from red (smallest) to violet (largest). But for fairly shallow images such as portraits the registration is good over about 25° each side of center, and there is a small allowable amount of vertical parallax within the achromatic area, allowing the use of a fairly wide slit for the master.

Achromatic reflection holograms

You can use the same general principles to make achromatic reflection holograms. The technique is more complicated because you have to generate two identical images that reconstruct, in accurate register, in two complementary hues.

If you choose red the complementary hue will be cyan. You can obtain a cyan image from a red-light exposure by pre-swelling the emulsion in triethanolamine (TEA) solution at about 18% concentration, i.e. 18 cm³ TEA made up to 100 cm³ with deionized water.

The technique is simple enough: For the 'cyan' exposure, soak the emulsion in the TEA solution for about two minutes, squeegee it carefully without washing, and dry it off before exposing it. I recommend that you make this exposure first, as the TEA treatment increases the emulsion speed for this and the subsequent exposure. However, if you do decide to make the 'red' exposure first, wash the emulsion in

Indeed, the Spatial Imaging Group at MIT was sufficiently proud of the concept to commemorate the discovery with a T-shirt printed with the crucial diagram (Plate 12b), perhaps the most esoteric blazon ever to appear on such a garment.

Complementary hues are defined on the CIE chromaticity diagram as points on the periphery of the curve that are joined by the straight line passing through the neutral (white) point. In color photography they are defined by pairs of primary and secondary hues: red/cyan, green/magenta and blue/ yellow.

This figure is only for starters. Every emulsion batch reacts differently to swelling agents, and after testing you may find you need to alter the dilution. If you are working with a green laser, the news is bad, as you would need to add a red and a blue image. As there is no satisfactory way of pre-shrinking an emulsion you would need to make a separate hologram for the red image and postswell it with sorbitol. deionized water for about five minutes, with several changes of water, then squeegee it and dry it, before making the exposure. Box 18.1 explains the procedure.

Box 18.1 Pre-swelling

You've seen the way you can control image color in a reflection hologram by using different processing regimes. As a rule you can only achieve shorter wavelength reconstructions, which is a good argument in favor of using a red laser. Processing in this way means that for a greener image the emulsion finishes up thinner overall. But if you swell the emulsion before exposure instead, and reduce it to its original thickness afterwards, there will be more fringe planes within the emulsion and a brighter image.

Many substances will swell gelatin. The most popular among holographers is triethanolamine, $(HOCH_2CH_2)_3N$, commonly abbreviated to TEA. It is a powerful hypersensitizing agent, and can lower the required exposure of a holographic emulsion by a factor of 3 or more (which adds to its popularity).

The figures that have sometimes been published for the dilution required to obtain various image hues in reflection holograms are not reliable. Gelatin is an animal product, and doesn't have a consistent chemical makeup; in addition, the various hardening and preserving agents added to the emulsion during manufacture are not consistent in their action. You therefore need to carry out a test with each new emulsion batch you use.

To pre-swell an emulsion, first wash it (in the dark, of course) in deionized water. This will eliminate any preserving agent left in the emulsion by the manufacturer.

Now place the film or plate in the TEA solution for about 2 min, rocking it gently from time to time. At the end of this time lift it out, drain it briefly, place it, emulsion up, on a glass sheet, and squeegee it until it is surface dry.

When you come to the processing, give the emulsion a good pre-wash before you develop it, as the combination of TEA and developer is a powerful foggant. Always put a chip of unexposed emulsion through the whole chemical procedure, as I suggested in an earlier chapter. As soon as this becomes noticeably gray in the developer, it is time to take the hologram out. Nothing will be gained by leaving it in longer.

Unfortunately, although this will produce two images in complementary hues, they won't be in register, as the cyan image will be lower down and larger. To achieve accurate register you have to move the transfer reference beam to a greater angle of incidence (about 10°), and to set the reference source, i.e. the spatial filter, about 40% farther away. As you have probably guessed, the two reference sources need to lie on the achromatic plane with respect to H₂ (Fig. 18.7).

This can take up a lot of room on your table – indeed, you may not be able to fit the setup on it at all. However, if you make the *master* at the achromatic angle, just as I described for a WLT master, there is no need to shift the reference source between exposures. All you need to do is to remove the transfer film or

Triethanolamine, more correctly called tri-(2-hydroxyethyl)amine, in its pure state is a solid that melts at around room temperature. It absorbs water very readily, forming a viscous liquid, and that is its usual form. It is used in the manufacture of high-quality soaps, detergents and cosmetics.

Deionized water is water that is free from dissolved gases and solids. It is the same as distilled water, but is given a different name because it is produced by a different method. It is important to use deionized or distilled water for holographic emulsions because impurities such as chlorides, which are present in tap water, attack the microscopic silver halide crystals. You can obtain perfectly satisfactory distilled water from an air-conditioning plant or house dehumidifier. The water from de-icing a fridge or freezer is OK too.

Use a soft squeegee: I use a window cleaner's blade, but some workers prefer a straight windshield wiper such as the wiper for an old VW Beetle, while others favor a chamois leather. Photographic blotting paper is also effective. Make very sure you haven't left any streaks, as any that remain will result in bands of uneven color. In addition, make quite sure there is no grit on the surface: its presence can lead to ruinous scratches. Once you find a method that works for you, stick to it.



Figure 18.7 Geometry for an achromatic transfer reflection hologram. The 'red' and 'cyan' reference sources lie on the achromatic plane, and are about 10° apart as measured from the centre of H₂. The relative size of the holograms has been exaggerated for clarity.

plate after the exposure, wash out the TEA, place it back and make a second exposure.

Pseudocolor holograms

The term *pseudocolor* has become current in holographic terminology, and means a reconstructed image that is in colors not produced by the methods of Chapter 16. The techniques are also known as 'false-color', but 'pseudocolor' is preferable, as the colors are not necessarily false, but are simply produced by artificial means (as are the colors of toned or tinted black-and-white photographs).

As suggested earlier, the question of what is 'true color' raises a number of esthetic questions. What pseudocolor techniques *can* do is to make any image, or any part of an image, any color you wish.

Pseudocolor holograms are of two types: white-light transmission (WLT) and reflection. The WLT hologram produces its colors by dispersion, and can be dazzlingly bright, with spectrally pure hues, but the hues change with the height of the viewing point, and there is no vertical parallax. In general the colors are somewhat more subdued in reflection holograms, but they do not change substantially with a change of viewpoint, and there is full vertical parallax.

Pseudocolor single-beam reflection holograms

Pseudocolor technique isn't easy, so it makes sense to begin with a fairly simple setup. Pseudocolor holograms that need accurate registration must have their images substantially in the plane of the hologram, and thus demand either a transfer or a focused-image configuration. But if you simply want to produce patterns in color, using abstract matter such as images of brass wire and aluminum

'Synthetic color' would be more accurate still, but is perhaps a bit of a mouthful.

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foil, registration is less important or even irrelevant, and you can use a simple Denisyuk setup. Working with a red laser and three different abstract objects you can produce interpenetrating images in red, green and blue that produce cyan, magenta, yellow and white where they overlap.

The first step is to establish the correct amount of pre-swelling and exposure you need for each of the three images. Set up a plateholder, with a rigid object set on its side behind the film (Fig.18.8), as the single-beam frame is awkward for this technique.

Start with a 33% TEA solution, i.e. one part TEA to two parts deionized water. Treat a test piece with this. Expose the emulsion, giving one-third of your usual exposure as a start. Develop the piece in reflection master color developer, bleach in rehalogenating bleach, wash, and then dry the piece with a hair drier under a spotlight, watching for the appearance of the image and its changes in hue as it dries. On a first attempt it may go right through the spectrum to violet and disappear, in which case you will have to try again with the TEA solution progressively diluted until you get a bright blue image. Take about a third of the TEA solution and dilute it with an equal volume of water, and make a similar test to produce a green image. Take a further test piece, wash and dry it, and make a 'red' test. (This will also help you to find the right angles of incidence for the three exposures.)

Mount the red-image test emulsion in its original position. Substitute a white spotlight for the laser reference source, and adjust the angle of incidence until the image appears brightest. (It should be in the same position as when you exposed it.) Now substitute the green-image emulsion. You will find you have to swing the plane some 8° further round to get a bright image. Note the angle. Repeat the process for the blue image. You will have to swing it a few degrees further. You now have the angles of incidence at which you should set the emulsion surface for each exposure.

You can now begin work on the hologram proper. You need to make sure the emulsion is correctly oriented for all three exposures, so if it is a film, check the position of the corner notch; if you are using an offcut, mark the corner where the notch would be by nicking it with scissors. If you are using plates, mark the corner with a chinagraph pencil or a waterproof marker pen. Prepare the emulsion for the 'blue' exposure in the strongest TEA solution, and dry the film. Mount it in the plateholder and make the exposure. Next, remove the film and immerse it in the diluted TEA solution, agitating it for about 5 min, and dry it. Reset the plateholder for the 'green' exposure, and set up the 'green' subject matter. Remount the film as nearly as possible in correct register, and make the 'green' exposure. Remove the film, wash it in deionized water for about 5 min, and dry it. Now set up the plateholder for the 'red' exposure. Set up the 'red' subject matter, mount the film again, and make the 'red' exposure. Now process the film as for a master hologram.

If you have been frugal and used narrow pieces for the tests, you can mount them side by side for the angle checks, and achieve more precision as well as saving time. Don't be disappointed if your first effort turns out to be less than a masterpiece. It takes a good deal of time and patience to bring all the variables under control. You will probably find that the exposure times need adjusting. You may also find that the images aren't all at their maximum brightness at the same angle, and you need to alter one or more of the reference beam angles to correct this. All in all, it will probably take you an entire day to get your first satisfactory image; but it will have been a day well spent. Don't forget to keep a log of all your dilutions, angles and exposure times. It may seem tedious at the time, but you will certainly find it was worthwhile next time round.

You don't have to expose in the order blue, green, red, of course. About half the people who work in pseudocolor begin with the red exposure. If you do it this way round the exposures will probably vary more. In particular, you will probably have to increase the 'red' exposure quite a lot. The difficulty with all holographic materials is that they are produced in such small quantities compared with photographic films that manufacturers are not able to apply an equivalent level of standardization. If you are going to do a large amount of work in pseudocolor, buy all the film or plates you are likely to need in one go, so that it all comes from the same emulsion batch.

Pseudocolor transfer reflection holograms

Once you have made a few successful single-beam multicolor images you should feel confident enough to tackle the next stage. This time the final hologram will be an image-plane transfer made from three transmission masters.

The first step is to sit down and think about what you intend your final image to look like. This may seem a fairly obvious thing to do, but it helps if you go about it in an organized way. Box 18.2 shows a logical method of pre-visualizing your image. This is where you determine the subject matter, and visualize the way the final image is to look: what colors are to be where, what the lighting should be, and so on. If you are making holograms for display, particularly the complicated ones discussed in this chapter, you need to spend some time thinking about the precise form your image is going to take before you begin to set up your table to achieve that aim. It can be a lengthy process; some of your best creations could be weeks or even months in gestation. John Kaufman⁷ has compiled a checklist intended to help the beginner to reach the desired goal. Kaufman's original paper goes into considerable detail; it is summarized here, with the author's permission.

Lon Moore⁸ has described his method of making a pseudocolor hologram with a minimum overlap of fringe patterns, as applied to his early hologram of an apple, a pear and a pepper, each in its own color (Plate 13a). His method is to illuminate only the object that is to appear in a particular color, for each master. Thus you would make a master of the apple only (to be transferred as red), the pear only (to be transferred as yellow) and the pepper only (to be transferred as bluish-green). The fruit isn't real fruit, of course (that would be too likely to move during the exposures), but artificial fruit sprayed white (gray for the darker pepper). When you make the transfer, swelling in turn for bluish-green, yellow and red, for each transfer you need to restrict the reference beam as far as you can to the area of the color. (If you want to include a crystal bowl, it will have to be included in the masters for both red and bluish-green.) A further tip is to try to position any parts of the image where there is an abrupt change in color as close to the hologram plane as possible, to minimize any small errors in registration.

Store the boxes on end in a cool dry place. They will keep at least five years. You don't need to keep them in the fridge, but if you do so, always allow the boxes to return to room temperature before opening them (this may take several hours).

John Kaufman and Lon Moore are both pioneers of pseudocolor reflection holography and acknowledged experts in the technique. I am much indebted to them for information concerning the details of their methods.

Box 18.2 Previsualization

There are four main steps in the pre-visualization process:

- 1. *What am I trying to say?* At the highest esthetic level, the basic concept may be inspired by a philosophical or political idea, a poem, a painting or a piece of music; or it may arise from purely holographic considerations, in terms of subtle interpenetrating shapes and colors. It may spring from a found object, or from some experience such as a dive on a reef or even a commission for an advertisement that allows a fair amount of creativity.
- 2. *What holographic techniques are appropriate?* Should I use monochrome, achromatic or pseudocolor holography? Reflection or transmission? Direct transfer or focused-image? Real, virtual, hologram-plane or all three? At this stage it is *your* knowledge of the details and limitations of the various processes that enables you to make an appropriate choice. This leads to the next stage:
- 3. *How do I link up concept and technique?* An internalized (or even externalized, as long as nobody is listening!) self-discussion over the way the various technical aspects of your chosen process interact with the details of the concepts, will help to clarify the detail of the concept and identify the most appropriate technique.
- 4. *Finally, how do I realize the concept?* The final stage is the detailed design of the table layout. This is the time for precision. By spending time on getting the geometry absolutely right you will save a great deal of time later. Squared paper is a must for this stage.

This applies to even the simplest layout, for you still need to know the length of throw you need for your reference beam, which stray beams need carding off, and whether you can match the optical paths satisfactorily within the coherence length of your laser, as well as the kind of subject illumination you are going to need for satisfactory image quality.

Accurate color registration by geometry

The change in the angle of incidence of the reference beam between the various exposures isn't critical or even important if you are making a multi-image hologram where registration is irrelevant. However, if you are producing sharp-edged colors as in John Kaufman's 'Silverado' (Plate 13b), you do need to be exact, as otherwise the colored edges will drift apart as the viewpoint shifts in one direction, and overlap as it shifts in the other direction.

Strictly speaking, you should change the distance of the spatial filter from the hologram as well as the beam angle, but you only need to do this if you want very accurate color registration at the extremes of the available parallax.

Benton⁴ gives the mathematics in detail. Steve McGrew⁹ has found a geometrical solution that is not difficult and leads straight to a plan of the table layout. It uses a number of simplifications as compared with Benton's rigorous analysis, and as a result gives slightly less precise registration. Both systems are discussed at length in Appendix 3. For the remainder of this chapter, all distances and angles have been calculated using Benton's method.

The reason for changing the reference source distance between exposures is that is you fail to do this you will find that the red image is formed nearer to the hologram than the green image, and the blue image is formed farther away, so that neither the magnification nor the position of the images is a precise match.

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The bowl, admittedly, receives more than one exposure, but any small lack of register here is scarcely noticeable.

If this seems to be the wrong way round, it's not. Remember, the hologram is flipped for viewing.

How to obtain precise registration

In pieces such as Moore's fruit hologram, exact registration is not essential, as the various items are separated in space and are exposed separately.

However, in a piece with sharply defined colored edges adjacent, such as Kaufman's 'Silverado' any registration errors become irritatingly obvious as soon as the viewpoint moves to either side, or above or below. A hologram acts like a combination of a prism (i.e. deviating the light) and a lens (i.e. focusing the light); it has an angle of deviation and a focal length, both of which vary with wavelength. As the angle of deviation is proportional to the wavelength, the 'red' reference beam needs to be at a smaller angle of incidence than the 'green', and the 'green' than the blue, if the primary rays (the rays passing through the center of the hologram) are to coincide for all colors.

And as the focal length of the hologram is inversely proportional to the wavelength, the 'red' reference source needs to be nearer to the center of the hologram than the 'green' source, and the 'green' source than the 'blue' source. A typical table arrangement using these principles appears in Fig. 18.9.

Draw your plan out on squared paper, or on your computer screen. For an 8×10 in transfer hologram with a final replay beam angle of 45° and a replay source distance of 1.5 m, the angles work out at 45° for red, 51° for green and 57° for blue. The achromatic angle is 35° and the spatial filter pinholes are aligned along the achromatic plane. Set up the 'red' beam first, with the mirror M_R , then the 'green' beam with the mirror M_G , then the 'blue' beam with the mirror M_B . If you then make the 'blue' exposure first, you can then remove mirror M_B to make the 'green' exposure, then mirror M_G to make the 'red' exposure.

 M_3 is a large front-surface plane relay mirror. (In theory it should be a converging mirror.) If you have sufficient room on your table, and a second collimating mirror



Figure 18.9 Table layout (to scale) for a pseudocolor reflection transfer hologram H_2 for a final replay beam of 45° and a master hologram made with its reference beam at the Brewster angle. The 'blue' exposure is made first. M_B is removed for the second exposure ('green'), and M_G for the third exposure ('red'). In this diagram only the 'red' reference beam is shown expanded (broken lines).

(and are a perfectionist) you can put theory into practice; its focal length will have to be a compromise, because of the difference in reference source distances. But as the throw of the reference beams is fairly long, the difference between this and a plane mirror will be minimal.

Pseudocolor white-light transmission holograms

WLT holograms are capable of producing extremely bright images with very pure colors and enormous depth. As they are transmission gratings they are less subject to the Bragg condition than reflection holograms, and there is not usually any need for pre-swelling techniques. However, WLT color holograms lack vertical parallax, and have only a limited range of viewing height within which the color rendering is acceptable.

As with reflection holograms, it is best to begin with a comparatively simple setup. In vertical cross-section a rainbow hologram is just a simple diffraction grating; if you look at people viewing a rainbow hologram you can see the spectrum spread across the region of their eyes. If the viewpoint is fixed while the angle of the replay beam is changed, a different part of the spectrum becomes aligned with the viewer's eyes, and the image appears in a different hue. Thus the hue of the image depends on the angle of incidence of the replay beam with respect to that of the original reference beam.

Whether the viewer sees the image in a pure color, or a desaturated color, or spanned by a spectrum, depends on the geometry of the table (Fig. 18.10). If the viewer's eye is near the real image of the slit, the hologram image will be in a pure saturated color, the hue of which passes through the whole visible spectrum over a vertical range of viewpoint of about 100 mm.

With a reference beam at 51° incidence and a replay beam at 45° , the hue of the image will be green when the image is viewed from a central position coincident with the 'green' image of the slit; from points approximately 6° lower and higher the hues will be blue and red respectively. If, therefore, you make a transfer hologram from several master holograms, using reference beams at slightly different angles for each, the images will appear in different hues, from a central viewpoint.



Figure 18.10 The effect of viewing position on image hue for a rainbow hologram. A viewer at position 1 will see an image that is blue at the top and red at the bottom. At positions 2, 3 and 4 the image will appear overall red, green and blue respectively. At position 5 the image will appear red at the top, green in the middle and blue at the bottom. At positions 6, 7 and 8 respectively only the bottom, middle or top of the image will be visible.

The overall hues are those of rainbow holograms, and change as the viewpoint is changed vertically.


Figure 18.11 (a) and (b) represent two ways of operating a multi-slit exposure. They will give a multicolor image (c) that is in correct angular register, but not fully in register in the *z*-direction, i.e. out of plane.

In practice it is easier to keep the master replay beam and the transfer reference beam fixed, and to move the position of the slit instead. If you move the master hologram in its own plane, slit and all, you can obtain 'echo' images in various hues (Fig. 18.11). This can be very effective in holograms of abstract shapes such as cubes and spheres. To achieve this you lay three slits over a single master hologram. Depending on whether you move the slit or the master hologram, you will obtain three images displaced vertically or coinciding, but out of register axially. If you have made the masters with the subject matter moved between



Figure 18.12 A simple arrangement for multi-image WLT holograms (not drawn to scale). Three slit master holograms S_R , S_G and S_B , to appear respectively red, green and blue in the final image, are taped to a glass plate and exposed in succession. The angles need to be exact. If the separation between H₁ and H₂ is 250 mm, the separation of the centres of S_R and S_G should be 39 mm, and of the centres of S_R and S_B 67 mm. For other separations of H₁ and H₂ the positioning of the masters should be in proportion. Note that this layout doesn't give correct register either in depth or size, and is thus suited only if the three images are mutually independent.

exposures to varying distances, you can make multiple-image final holograms containing real and virtual images together, but in this case you will need to make separate masters. Figure 18.12 shows a setup for making transfers from three slit masters simultaneously, one image being in red, one in green and one in blue.

To set up the rigs for all these you can use the basic rainbow transfer configuration of Fig. 13.4. If you widen the slit reconstruction beam "vertically" to cover all three slits you can make the holograms of Fig. 18.12 in a single exposure.

Obtaining better registration

McGrew⁹ describes a method of setting out the three slit masters that gives better registration. This system works well for a trio of masters made in a single plane perpendicular to the subject matter.

A typical example for an 8×10 in transfer is shown in Fig. 18.13. As the three masters S_1 , S_2 , S_3 are more or less in line with the reconstruction beam, you need to set them up separately between exposures. While you are doing this you will need to remove H_2 and switch on a brighter light. You can then simply move the plateholder to its new position and change the master.

Achieving the correct exposure is again a matter of trial and error. Provided you have pre-washed the emulsion, the best successive exposures seem to be around 100%, 75% and 55%.

You undoubtedly get the best results are when you use a master that has been made at the achromatic angle. The main difficulty with this setup is that the reference beam has to be from "below", which involves some difficulties unless you



This can vary from one emulsion batch to the next, and you may in practice find you have to give the same exposure for all three. Always do a dummy run with simple subject matter when you open a new emulsion batch. Keep an object you know well (it doesn't have to be a figure of a Siamese cat!) and use it for every test.

Figure 18.13 Table layout for multi-image WLT holograms with better registration. S_R, S_G and S_B are the slit master holograms for red, green and blue respectively, and are mounted separately on a triangular bench at the achromatic angle. The exposures are made successively, with a single master holder being set in its position for each exposure. CL is a positive cylindrical lens that squeezes the expanded beam to cover the three slit master positions. H₂ is replayed at 45°.



Figure 18.14 Layout for a master with a subject set sideways and a near-normal reference beam. The master H_1 is at the achromatic angle. (Only one subject illuminating beam is shown.) This layout is suitable for either a reflection or WLT final hologram. For the latter, the masters can be narrow.

are prepared to construct a table specifically for the purpose (see Chapter 19). There are two alternatives: the first uses master slits that are all in one plane, but employ different reference source positions to make the transfer; the second employs masters that lie along the achromatic plane, but have the subject matter on its side (this is the system recommended in Chapter 19 for holographic stereograms). These alternative systems are shown in Figs. 18.14 and 18.15. S_1 , S_2



Figure 18.15 Layout for a pseudocolor WLT hologram with three masters made in the same position. As in Fig. 18.9, mirrors M_R and M_G are removed separately before the second (green) and third (blue) exposures. The three spatial filters SF_R , SF_G and SF_B are set at an average of 35° to the line of the central ray. Note that the collimating mirror CM can be replaced by a combination of a liquid-filled plano cylindrical collimating lens and a plane mirror.



Figure 18.16 Layout for an achromatic WLT transfer. SF₁ has a convex cylindrical lens CL to provide a narrow beam. H₂ is shown at 90° to the H₂ reference beam, but it can be at a different angle depending on the previous mastering conditions. The master slit holograms S_R, S_G and S_B can be exposed successively, using a narrow beam controlled by CL, or simultaneously, using a broader beam covering all three masters.

and S_3 are all exposed in the same position; otherwise they would show different "vertical" perspectives. The transfer table is as in Fig. 18.16.

One-step pseudocolor WLT holograms

In Chapter 14 I discussed one-step rainbow holograms, which typically use a large convex lens and a slit aperture. The same basic layout, with only small modifications, is suitable for pseudocolor WLT holograms. Suzanne St Cyr¹⁰ has written a comprehensive account of the technique, with a discussion of the aberrations of the focused-image configuration (the paper is too lengthy to quote in full here). She points out that the technique minimizes the time need to modify the setup for color changes, and is capable of producing complex images quickly. Her paper gives the form of the calculations necessary for producing pseudocolor WLT focused-image holograms for any desired viewing conditions. The calculations are based on Benton's geometry, which you can find in Appendix 3. The setup of Fig.18.17 is appropriate for a hologram that is to be viewed from a distance equal to twice its diagonal dimension, with a display spotlight at 45° incidence. The layout of Fig. 18.17 is not the same as St Cyr's suggested layout, as it uses fewer mirrors, and is closely related to the basic focused-image rig of Fig. 14.8; but it is fully equivalent to hers. In order to have the plane of the slit image at the achromatic angle, the plane of the slit itself has to be tilted according to the Scheimpflug rule (Box 18.3).

For the layout shown this is approximately 70° to the plane of the lens. In order for the three slit images to overlap in the same plane, the slit needs to be moved along the lens axis by a distance of 0.15f for the 'green' exposure and by 0.35ffor the 'blue' exposure. At the same time, the reference source needs to be moved to a larger angle of incidence and a greater distance, according to Benton's



Figure 18.17 Layout for a multicolor one-step WLT hologram. The aperture of the imaging lens L is restricted "horizontally" by the slit S, which is changed in position between red, green and blue exposures. The reference beam is also changed between exposures by adjusting mirror M_2 and spatial filter SF. Only one subject-illuminating beam is shown, and the intermediate (green) position of the slit S is omitted for clarity.

geometry: about 6° and 12° angular increases and $\times 1.15$ and $\times 1.35$ distance increases.

St Cyr's paper also includes a simpler arrangement, which she calls a 'proofing camera'. Between exposures only the slit moves: as well as being moved away from the lens for the 'green' and then the 'blue' exposures, it is moved slightly towards

Box 18.3 The Scheimpflug rule

In Newtonian (geometrical) optics, the first lens law (Fig. 18.18) states that the sum of the reciprocals of the distances of the object and image from the lens (u and v) is equal to the reciprocal of the focal length (f) of the lens, that is,

$$1/u + 1/v = 1/f$$



Figure 18.18 Newton's lens laws. For a lens of focal length *f*, the relationship between the image–object conjugate distances $(x_1 + f)$ and $(x_2 + f)$ is given by the relationship $x_1x_2 = f^2$. It follows that 1/u + 1/v = 1/f, the familiar form of the lens equation.

Newton himself stated this law somewhat differently: if the object and image distances from the front and rear principal foci F_1 and F_2 are x_1 and x_2 respectively, then

$$x_1 x_2 = f^2$$

which is known as the *Newtonian condition*. This form isn't often seen in photographic optics, where the other form is more useful, but it plays an important part in the geometrical extension known as the *Scheimpflug rule*. This is a lengthy and convoluted piece of geometrical logic; if you are anxious to investigate it you can find a full proof in Jacobson *et al.*¹¹ The condition is that when the object plane is tilted with respect to the axis of the lens, then in order to obtain overall sharp focus the plane of the film has also to be tilted, in such a way that the planes of the object, lens and film all intersect in a common line. All the object and image distances from the lens plane then satisfy the Newtonian condition (Fig. 18.19).



Figure 18.19 Theodor Scheimpflug showed that for Newton's laws to hold for tilted object planes, the object plane (OP), the lens plane (LP) and the image plane (IP) should meet in one straight line.

The Scheimpflug rule is a working rule for studio photographers who operate with large-format cameras, but it is equally important for holographers working in any form of transfer holography where the planes are not parallel, as in some types of focused-image hologram.

the "base" of the subject. This regime results in inferior registration, but is useful for less exacting work, or simply to test color balance. But given the ease of setting up the more accurate rig using triangular benches, it seems hardly worthwhile compromising in this way.

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Chapter 19 Holographic stereograms

She noticed a curious appearance in the air. It puzzled her very much at first, but in a minute or two she made it out to be a grin.... In another minute the whole head appeared.

Lewis Carroll, Alice in Wonderland

Holographic stereograms, in their basic form, are a hybrid of photography and holography. They retain something of the quality of both, but add something very much of their own. They have their own virtues and vices; but their most important advantage over conventional holograms is that they can produce three-dimensional images at any desired scale, even of imaginary subjects – and with movement, too.

The multiplexing principle

As with so many terms current in holographic technology, the term 'multiplexing' was first used in connection with communications theory. It refers to the simultaneous sending of more than one signal down a single channel such as a TV cable (or, more recently, an optical fiber). This can be achieved in two ways: by splitting up the signals on a time-sharing basis; or by sending the signals continuously, but distinguishing them by using different carrier frequencies. The photographic stereogram is analogous to the first type: the images are dissected into interlaced lines, which are separated directionally by a retroreflecting lenticular screen positioned in correct register over the print. The holographic stereogram is analogous to the second: all the image information is encoded into the entire area of the hologram, and the individual images are sorted out by the differing directions of the fringes that code each image, directing the light from each fringe in a specific direction. This is the type of holographic stereogram first described by Dominic DeBitetto¹. A second type of holographic stereogram, developed by Lloyd Cross², has the image information coded locally in narrow strip holograms.

Both of these pioneering designs contributed to Stephen Benton's stereogram principle^{7,8,9}, which has become the accepted format for present-day holographic stereograms.

The highest quality holographic stereograms used in commercial and fine-art imagery are made using sophisticated mechanical and optical systems, in many cases under computer control.

Nevertheless, it is possible to make stereograms of good quality on an ordinary holographic table, using just a few specialized components; but you need plenty of time and patience. There is, however, nothing inherently difficult about making a hologram containing multiplexed images. We have already met the basic technique in Chapter 12.

I have already explained my objections to the loose use of the term 'multiplex', but here I am using it in its strict sense, i.e., 'the simultaneous transmission of several messages along a single line of communication' (OED).

Cross presented his paper verbally to an SPIE seminar, but did not publish it, presumably because of impending patents.

At present such systems are comparatively few in number, and they all differ in detail.

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For this hologram there were actually nine masters, about the minimum that can give any real impression of animation. This geometry is suitable only for small objects, though, owing to the limited amount of bending and stretching the average viewer is prepared to undergo.

Making a multiplexed hologram

In Chapter 12 you saw how to incorporate several images in a single hologram. This is a simple instance of a multiplexing technique. If you put a large number of images into a transfer hologram you can synthesize a kind of animation. Figure 12.5 (p. 185) showed six stages in an animated image of a prototype £2 coin (not the one that was eventually adopted). This was produced by making a number of masters of the coin supported in various positions; these were then cut down to horizontal strips, which were butt joined in the master plateholder, and a reflection transfer made in a single shot. This technique can be very effective, as you have full



Figure 19.1 An animated image by Applied Holographics Plc. This realization of M C Escher's unending staircase has figures that appear to move at different speeds, some rushing, some dawdling, as the viewpoint moves across from one side to the other.

horizontal parallax for each image. The animation is provided by a vertical shift of the viewpoint.

If instead of horizontal strips you have vertical strips, you experience the animation simply by walking past the hologram. And as you have now sacrificed the horizontal parallax, your subject doesn't even need to be a solid object: you can use a series of photographs instead. The simplest possible version of this is a two-channel hologram of a stereo pair of photographs, each visible only to the appropriate eye. From here it is only a short step to a hologram in which nine or more images are multiplexed. Figure 19.1 shows four out of a number of images incorporated into a commercial holographic stereogram. The animation was produced by moving the figures different distances between successive exposures to give the impression of different speeds of movement.

If you want to begin – metaphorically – at the shallow end (and you would be well advised to do so), you can start by shooting nine photographs from points equally spaced along a straight line centered opposite the subject matter, covering a total angle of around 35° . Don't turn the camera to point at the subject; keep it pointing straight ahead. This is easier to do if you have the camera set up on a shelf. You will need a wide-angle lens, as you will have to crop the prints so that the image of the subject stays in the middle of each print.

Now set up a mastering table with the first photograph (the view from the left side) in the 'object' position, sideways. You will need an opaque mask with a vertical slit one-ninth of the width of the master hologram film, and some method of locating the slit precisely, so that there will be no gap between exposures (you can get away with a slight overlap). If you are using 8×10 in material, make the slit 28 mm wide. Mark out the nine positions for the slit. Now make your nine exposures, remembering to move the slit and change the photograph each time. A suitable



Figure 19.2 Table layout for a multi-channel hologram made from flat photographs. The arrangement is essentially the same as for master holograms, but both subject-illuminating beams are point sources at about 60° incidence, this being the angle that gives even illumination distribution and maximum contrast. The usual symbols are used. The masking slit S is shown vertical, but could equally well be horizontal, as in Fig. 19.1. It is moved by its own width between exposures.

The use of a perspective control (PC) or shift lens, as it is often called, is a good idea, if you can get your hands on one. This is a lens that can be shifted in its own plane so that its optical center remains aligned with that of the subject and of the film gate. Some professional 35 mm cine cameras are made with a shift back that serves the same purpose.



Figure 19.3 Holographic stereogram, schematic setup, after DeBitetto¹. The slit is moved by its own width each time the frame is changed in the projector. LB = laser beam (collimated), F = filmstrip, PL = projector lens, DS = diffusing screen.

setup is shown in Fig. 19.2. This is based on the principle developed by McCrickerd and George³ in 1968, in the first published paper on the subject.

DeBitetto went a stage further, and used cine photographs taken from equally spaced positions along a horizontal line on 35 mm material, to produce a much larger number of images. These he projected on a ground-glass screen by laser light to form the object beam for making the master images. This process led directly to the present-day flat stereogram.

Cylindrical stereograms

Another way of making the original photographs for mastering is to take the camera round the subject at a constant distance; or, more simply, to place the subject on a rotating plinth. The photographs are combined in the same way, but this time the finished hologram is part of a cylinder, with the image of the subject at its center. Cylindrical stereograms are a kind of one-step rainbow hologram. The two principles are compared in Fig. 19.4.

The only commercially successful cylindrical hologram was developed by Lloyd Cross, and was called variously an integral hologram, an integram or a Multiplex hologram.

A Cross hologram usually takes the form of a 60° section of a cylinder, illuminated from below by a small-source filament lamp in its base. It can also be a complete cylinder, designed to rotate slowly. In the 1970s the Multiplex Corporation marketed its products extensively, and a number of studios were set up for shooting cine originals to be made subsequently into stereograms at the Multiplex laboratories. The astigmatic optics needed for the printing process meant that aberrations in the image were unavoidable, and in spite of a good deal of research into methods of eliminating them, the esthetic problems remained largely unsolved, with the result that the cylindrical stereogram is now a rarity except in museums. Nevertheless, the process is of considerable interest if only for its curious optics, not least because these include a large 'acylindrical' liquid-filled lens.

DeBitetto seems to have got there first, but his paper wasn't published until the year following McCrickerd and George's. As you can see from Fig. 19.3, his setup used a backprojection configuration, whereas that of McCrickerd and George worked directly with photographic transparencies. Figure 19.2 shows their setup modified for photographic prints.

'Multiplex' in this case was the name of Cross's company, and had nothing to do with the meaning of the word as used in communications technology.



Figure 19.4 (a) Cylindrical and (b) flat stereograms compared. In (a) the subject is photographed on a rotating stage. Narrow one-step WLT holograms are made adjacent on the master film, one for each exposure, which is viewed flipped, illuminated by a divergent white light source from below. In (b) the camera is moved past the subject in a straight line. The master holograms are made in a broadly similar way to (a), but are subsequently transferred to give a hologram-plane image.

At 16 frames per second, a complete revolution takes 67.5 seconds, so the usual 60° arc takes just over 20 seconds.

Making a Cross hologram

The original photographs are in the form of black-and-white positive transparencies on 16 mm or 35 mm cine film. During the shooting the subject is rotated on a plinth at one-third of a degree per frame.

A small amount of very slow movement is allowed during the shooting, as for example in Cross's well known image of his assistant Pam Brazier blowing a kiss (Fig. 19.5).



Figure 19.5 Two views of the image 'Kiss II', an early cylindrical stereogram by Lloyd Cross and Pam Brazier. The vertical distortion is a consequence of the astigmatic optics.

A Cross hologram is a series of narrow astigmatic focused-image holograms of the cine images, set side by side with some overlap. Each hologram is effectively a slit hologram in both directions, and individual images have no parallax. In the horizontal plane they are simple focused-image holograms; in the vertical direction they are one-step rainbow holograms focused at what finally becomes the center of the cylinder. This somewhat bewildering combination is achieved by a series of cylindrical lenses. The optical system is shown diagrammatically in Fig.19.6.



Figure 19.6 Optical principle of the Cross stereogram (updated version). The cylindrical lens pair CL₁ forms a vertically focused image hologram at F_1 and a slit image at F_2 , the viewing slit. The reference beam RB is routed via the beamsplitter BS, the mirrors M_1 and M_2 and the one-dimensional beam expander BE₂. M_3 and M_4 are relay mirrors, and BE₁ is a beam expander/collimator.

A collimated laser beam passes through the cine frame, after which it is focused astigmatically in two orthogonal planes by cylindrical lenses. Vertical image rays are focused in the plane of the holographic emulsion; horizontal rays are focused some distance behind it. The hologram thus satisfies the conditions for a one-step rainbow hologram, and when flipped forms a virtual image roughly in the position of the astigmatic pair of cylindrical lenses. Before each exposure the film is advanced by the appropriate distance. To make any movements of the sitter appear smoother, each frame is actually exposed twice, so that for each exposure the movement of the film corresponds to a rotation of one-sixth of a degree, about 0.4 mm for a display diameter of 400 mm.

The second cylindrical lens needs to be well corrected for spherical aberration, as otherwise the focused line would be too wide, and the diffraction efficiency would suffer because of the excessive overlap. In addition the overlapping wavefronts would cause secondary interference patterns, resulting in moiré fringes and ghost images. The usual solution has been to construct the lens surfaces from acrylic sheet with the space between them filled with liquid paraffin (mineral oil) as described in Chapter 15. The required curvature is established by ray tracing. In practice the building of such a lens is not easy. Sharon McCormack⁴ gives a full set of instructions.

Improving the image If you have looked carefully at a Cross hologram, you will no doubt have noticed its shortcomings, especially with earlier examples. Apart from the gaunt appearance of the sitters and a marked lack of sharpness in the vertical aspect, faces are a sickly green, and the whole image is overlaid with vertical lines, usually described as a 'picket-fence' effect. In addition, there can be a good deal of distortion towards the edges of the image, particularly if it is large. This is due to what is called 'time-smear': when you look at the outside edges of the image area you are seeing an image made earlier or later than the one in the center, and therefore taken from a different viewpoint, This distortion is compounded by any movement the sitter may have been making during the photography.

A number of workers, notably Huff and Fusek⁵, and Okada *et al.*⁶, have devoted research time to reducing the various distortions to enable the image to be larger, for the introduction of dispersion compensation to produce a more neutral-colored image, and for simplifying the optics by replacing the awkward liquid-filled lenses with holographic optical elements.

There are sound reasons for continuing to take the Cross format seriously. It is capable of providing 360° horizontal parallax, and lends itself to medical and scientific applications such as tomographic images, electron micrographs in the round, and, on the artistic side, holographic images of sculptures and buildings.

Flat image-plane stereograms

Perhaps feeling that Multiplex's stereograms (which in any case were protected by patents) represented a dead end, Benton's research team at MIT returned to DeBitetto's original ideas, and concentrated on the development of flat stereograms^{7,8}. They moved the camera past the subject on a straight rail, using a 'shift' lens to keep the image of the subject matter central. They set up the plate for

This distance is calculated such that when the hologram is flipped and illuminated by a white point source from below, the image of the slit (i.e. the spectrum) will be projected outwards to rather more than a metre.

As mentioned earlier, spherical aberration causes the image formed by the outer parts of a lens to be focused nearer to it than the image formed by the central parts.

Such criticisms have led to the disparagement of cylindrical stereograms. As many of these visual quirks have since been successfully tackled, it seems a pity that Cross holograms were launched on the market at a time when so many of these optical problems were still unsolved. the master hologram at the achromatic angle, and this enabled them to produce achromatic images, and, later, images in full color⁹.

Since then, the introduction of computer processing has made it possible to precorrect images and to interpolate further images where there would otherwise be too few to avoid jerkiness. The advent of high-definition liquid crystal displays (LCDs) has simplified the production of primary images for mastering, and made it possible to generate images synthetically direct from a personal computer, without any photographic element being involved.

The scope of modern stereographic imagery

The stereogram offers an almost unlimited field for creativity. To appreciate the extent of this freedom, consider the limitations of a conventional hologram. To begin with, the image is necessarily the same size as the subject; changing the scale by optical means leads to various kinds of distortion. Equally restrictive, during the recording of the hologram everything has to remain stable to within one-tenth of a wavelength. You are also more or less confined to 'table-top' subjects. Buildings, aircraft, landscapes, all have to be models. Even with a pulse laser the images, however inherently exciting, are effectively 'frozen'; in portraits this can be unsettling. In addition, it is difficult to obtain images in natural color, as I explained in Chapter 17.

In contrast, stereographic images take you right out of the studio. Anything you can photograph you can use as a primary image. Subjects ranging from the head of a mite to Mount Everest – even the Earth itself from space – have been used as subject matter. Historic motion images, from Muybridge's sequences of athletes to film clips of Marilyn Monroe, have been made into holographic stereograms. All you need is a set of adjacent horizontal perspective views or a section of movie film. What is more, you can produce realistic full-color holographic images from photographic color transparencies. By sacrificing some depth information you can have animation; if you have the appropriate software you can generate your own animations. The quality of the result depends on your input material, of course, but it depends equally on your equipment and technique.

Geometries for photographic originations

Although a good personal computer system can take care of most inadequacies in the original material, things will always be easier and more straightforward if you can start with top-quality originals.

Ideally, you should have a 35 mm camera with pin registration. At present no such camera is generally available, and adaptation is a costly business; but if you are associated with a graphics department you may have access to one. However, the sprocket registration of high-quality cameras such as the Nikon F100 is well up to the standard needed; and digital cameras, of course, don't have registration problems.

There are two methods for obtaining the sequence of views you need: to rotate the subject matter (or to take the camera round it at a constant distance); and to move the subject matter past the camera (or the camera past the subject matter) in a

Pin registration is a method of ensuring accurate positioning of the film in the camera gate by means of protruding pins that fit into matching punched holes in the material. Some professional films have these holes pre-punched, in addition to the usual sprocket holes.



Figure 19.7 Three ways of shooting originals for a stereogram. In (a) the camera remains at a constant distance from the subject. In (b) it always points at the subject, but moves along a straight line with equal angles between exposures. In (c) it moves along a straight line, but its optic axis remains orthogonal to the subject plane, with equal distance between exposures.

straight line. The former alternative is suitable for cylindrical holograms only. For the latter system you again have two alternatives. You can either have the camera pointing towards the center of the subject throughout its travel, or you can keep it facing perpendicular to the direction of movement. These are all illustrated in Fig. 19.7.

In the configuration of Fig. 19.7b, the *angles* between successive exposures must be constant, otherwise the parallax will be reduced towards the side views of the final image, and the subject will appear somewhat flattened. In addition, the image becomes smaller as the viewpoint moves outwards. Although this may appear normal in the virtual-image master hologram, it looks anything but natural in an image-plane transfer. A further problem is keystoning, which makes the image appear to swing round. The preferred system is therefore that shown in Fig. 19.7c.

Perspective and distortion

You may have noticed on TV news and feature programs that in shots taken with a long-focus lens the perspective appears cramped. This is particularly so in nearfrontal views of races, where horses or cars seem to be piled up together, even though a side shot shows them to be well separated. On the other hand, close-up shots with a wide-angle lens, e.g. inside vehicles, have grossly steepened perspective: faces looking at the camera have large noses and bulging cheeks. These unnatural perspectives are simply due to the relative distances between the various parts of the subject and the camera lens. As an example of the way perspective works, consider three photographs of a rectangular building with the visible portion 10 metres deep. Suppose you photograph this building from three distances, 200 m, 50 m and 10 m from the front of the building, using a zoom lens so that the building fills the frame for each shot. Figure 19.8 gives an impression of the way the three images will look. For the proportions to look right in Keystoning is the perspective effect seen when something is viewed obliquely: rectangles become trapezium shaped, like the keystone of an arch.



Figure 19.8 The effect of subject distance on perspective.



Figure 19.9 Angle of view required by a moving camera with a fixed lens.

architecture and other large subjects, the optimum ratio of near to far distance is about 5:6. In most cases this calls for a horizontal angle of view of around 50° . For a 35 mm camera format this represents a focal length of a little over 38 mm, which is indeed the norm for compact cameras with fixed-focus lenses.

However, if you are going to get a reasonable amount of parallax into the final stereogram you will need at least 30° of parallax in the series of images, and this has to be added to the existing angle of view, because as you move the camera across from the center point to the end of its travel the image will move across the frame too (Fig. 19.9).

The angle of view required in the camera frame is thus $30^{\circ} + 50^{\circ} = 80^{\circ}$. This dictates a 21 mm lens. This is the shortest focal length you can get for most 35 mm cameras if you want rectilinear perspective.

Wide-angle distortion

There are two distinct types of wide-angle distortion. The first is the steepened perspective described above. The second is the apparent broadening of objects towards the periphery of the field of view. Figure 19.10 shows the way this happens. Because the images are projected obliquely onto the film plane they appear stretched out progressively towards the edges when you view the photograph from a distance (i.e. subtending a much smaller angle than that of the camera lens). This apparent distortion doesn't apply to a stereogram where you are looking obliquely at the image: it will be foreshortened by exactly the right amount.

Now, a 21 mm lens will achieve only some 30° of parallax if you keep it parallel to the rail, and that is probably less than you would wish to have. If you want more parallax you will simply have to include some toeing-in of the camera axis. The effect isn't usually noticeable provided you don't overdo it. The alternative is to use a shift lens (Fig. 19.11). Shift lenses usually operate in one direction only, so that you have to stop the operation at the midpoint and turn the whole lens barrel



Figure 19.10 Apparent stretching of image toward edges of wide-angle field.

Formal portraits are an exception. They are almost always made using a longish focal length lens, with a ratio of near to far distance of around 9:10.

There is, though, a new generation of rectilinear lenses going down to 15 mm focal length, representing a horizontal angle of view of just over 100° ; they cost about the same as a shift lens.



Figure 19.12 Image centering ability of a PC-Nikkor 28 mm lens.

To obtain an estimate of the angle of view relative to that of a 35 mm camera, you need to multiply the focal length of your lens by 1.5. Thus a 14 mm lens on a digital camera would be equivalent to a 21 mm lens on a 35 mm camera.

You can buy ready-made equipment of this type. It is suitable for photographic as well as holographic stereograms, but (as with all professional equipment) you need to carry out a cost-effectiveness survey first.



Figure 19.11 Use of perspective-control (PC) or 'shift' lens.

through 180°. The PC-Nikkor lens for the Nikon camera range has a focal length of 28 mm and a sideways shift of 11 mm, giving a total parallax angle of 41° with a fully centered frame (Fig. 19.12). Similar lenses are obtainable for several other makes of SLR camera. Shift lenses are fine for still-life images, but are too slow and fiddly for live subjects. (They are very expensive, too.)

There are advantages to using a digital camera for this work, especially if you are going to store the images in your computer. At present, almost all digital cameras operate with a CCD array that is smaller than the standard 35 mm format.

For the rest of this discussion I am assuming that you will be using a 35 mm film camera with a fixed 21 mm lens.

Alignment and spacing of the photographs

For a subject that is about 60 cm square and 30 cm deep (e.g. a human portrait) you will need a shooting distance of about 3 metres and a camera travel of about 2 metres. This will give you a parallax angle of about 33°. If you make one shot every 50 mm this will give you 40 shots, which is ample for a smooth image. If you load your own cassette from bulk film you should easily be able to get at least 40 exposures into it. For most purposes this is more than you will need: 24 shots, with spacings between shots of 80 mm, are usually enough. As a platform for your camera, use a beam with a batten nailed to the front and marked off in steps. If you have access to workshop facilities you can mount the camera on a length of extruded aluminum rail, with a stepper motor.

Steve Smith¹⁰ uses a bank of 12 Nikon cameras mounted on a single rail with their axes parallel, programmed to make either simultaneous exposures, or successive exposures over a total period of up to several seconds (to include some movement). The exposing mechanism is under computer control, and each camera has its own flash unit. This arrangement is particularly suitable for large groups such as wedding parties. But you need a sound business basis to get an enterprise of this kind under way.

Long base stereograms

If you keep the spacing correct (or have the computer power to interpolate images) you can make photographic originals of large objects such as buildings, aircraft and even mountain ranges.

With outdoor subjects you need a good deal of initial planning. If you are going to make 24 exposures over 33° as seen from the subject, this represents 2 exposures every 3° , or approximately 25 milliradians per exposure.



Figure 19.13 View of the Mount Everest range taken from the series used by a team sponsored by Ilford to produce a holographic stereogram of the range.

This means that for every metre of distance from the subject, the camera needs to be moved 25 mm between exposures. A series of photographs of a large building, which you may need to shoot from 100 m distance, calls for a spacing of 2.5 m per exposure, over a total distance of 60 m. You will have to mark out the camera positions beforehand. If you are going to be able to keep the camera level and pointing in the same direction throughout you need a spirit level and a compass. You also need stable weather conditions, with no variation in lighting throughout the exposing period. Moving clouds will impose their own bizarre stereo perspective on the image, so try to choose a day when there is no wind (or no clouds). Unless you propose to work from prints, you will have to reversal-process the film. (Instructions for this process are in Appendix 5.) Failing this, you can use color slide film, or have black-and-white transparencies made from your negatives by a printing lab.

Registration

In your pre-visualization you will have decided on the part of the subject that is to appear in the plane of the final hologram. You must now pick a salient point in

A party sponsored by llford once made a set of photographic originals of the Mount Everest range from a (comparatively) level glacier surface, making an exposure every 200 metres. The resulting hologram was spectacular (Fig. 19.13).

A milliradian (mrad) is the angle subtended by 1 mm at a distance of 1 m. It is a very rough indication of the resolution of the average human eye.

Black-and white film usually gives a better tonal rendering than color film with laser light. Be warned that some types of film base are optically active, and your transparencies may show irregular patches in transmitted laser light. Try out some of the film you propose to use in an expanded laser beam, before you commit yourself. this plane as your registration point. This point must be in exactly the same position in every one of your projected images. If the camera may have been tilted between shots (it can easily happen with hand held or aerial shots) you will need two registration points, one above the other. The more accurate your original photography was, the less work you will have to do. If both the camera and projector are pin-registered and you were working in a studio with a stationary subject, registration may involve only a small sideways adjustment. At the other end of the scale, a set of shots taken at irregular intervals from a bucking microlight aircraft can prove a nightmare to manipulate into register.

Computer control of imagery

This is where the computer comes in. Given the right software, a personal computer can digitize photographic images and manipulate them in many different ways. Historically, the first use of computers in holographic imagery (apart from actually drawing interference patterns, a subject dealt with in Chapter 24), was to fill the gaps between discrete drawings for animation purposes (the modern sophisticated version of which is known as 'morphing'). This routine is of two kinds: one, familiar from TV titles, shows one image changing into another; another kind has one perspective view rotating into another, or may fill in the action between two positions of, say, the legs and arms of an athlete. Both systems were used to produce imagery for early stereograms, initially by photographing the image on the computer screen (Molteni¹¹), later by printout or direct display on an LCD.

More recently, the demands of the printing industry and of editorial photography have resulted in the development of powerful software such as Photoshop, capable of producing considerable modifications to a photographic image. The photograph is scanned, and the image altered in any way the operator desires. You can make color separations, tilt or distort the picture, correct the perspective, re-register the salient points, even make wayward clouds stationary and unchanging. You can thus organize the tedious business of registration with originals that are far from being perfect, and you can provide as many views – in correct perspective – as you need, from a small number of shots, even from snapshots taken while walking past the subject. And, most important of all, the output can be downloaded directly to a high-definition LCD display (a so-called light valve, or *spatial light modulator* (SLM)), to act as a transmission object for making the master hologram.

Basic considerations for a stereographic holoprinter

Whether you decide to work exclusively with photography, or with computergenerated imagery, or with both, you will still need to construct a printer system to produce your masters. The requirements for this equipment, as far as stability is concerned, are among the most stringent in holography.

You can set up a basic holoprinter configuration on an ordinary holography table with only a small amount of extra equipment, and this should suffice for your early experimental work. A setup that allows you to try out your initial ideas is illustrated in Fig. 19.14. As usual with transfer configurations, the setup is on its side.

You need to distinguish between morphing that is straight 'inbetweening' without considerations of correct perspective, and true parallax morphing, which retains correct perspective, and is not usually to be found on the simpler versions of manipulative software.

The term 'holoprinter' may not have an unimpeachable lexical pedigree, but it is at least clear and succinct.



Figure 19.14 (a) Parallax angle and screen distance. (b) Basic table layout for a flat stereogram master. PS is a projection system (filmstrip projector optics). GG is a ground glass screen bearing the focused optical image I of the object transparency O. When the slit S (broken line) is fixed, BX is a one-dimensional beam expander and CL a one-dimensional collimating lens. If the slit is to move, BX needs to be an ordinary spatial filter, and CL an ordinary collimating lens. (b) Distance between H_1 and screen for given angles of parallax.

This arrangement works for both cylindrical and flat stereograms. For the former the slit remains stationary while the film moves under it; for the latter, it is usually (and preferably) the slit that moves, while the film remains stationary.

For stationary slit mastering you can squeeze the expanded beam with a cylindrical lens, as described for scanned contact copies in Chapter 12. You can also position a field-brightening cylindrical lens on the downstream side of the ground glass. If the slit moves between exposures you will need a reference beam that illuminates

You may need to make adjustments to the condenser system so that the beam remains focused inside the lens at this large extension.

If you took your original photographs using a wide-angle lens with no shift and no toeing in, you can make your transfers with a fixed slit and moving film. This time, *don't* center the subject matter, as its progress across the viewing areas provides the correct registration. In general, I wouldn't recommend this approach, though.

More than one worker has used parts of an old typewriter carriage. If you want to try this, it may be helpful to remember that 'pica' spacing is 10 to the inch and 'elite' is 12. the whole film area, unless you rig up a translating device such as a rotating glass cube or relay mirror to alter location of the slit illumination. The reference beam falls on the slit from "above" with reference to the image on the ground glass screen GG. The projection system can be from an old slide/filmstrip projector, which you should strip down to the bare optics. A filmstrip holder usually has two optically flat glasses that hold the film flat, and a winder that allows you to align the image accurately. The ground glass screen needs to be the best quality you can obtain: a focusing screen for a large studio camera is ideal. The standard lens for a 35 mm projector has a focal length of 85 mm, and if you want an image as small as 4×5 in, you will need an extension of about 106 mm, or a close-up supplementary lens.

The distance of the screen from the lens will be about 425 mm. For an 8×10 in format, the corresponding distances are 96 mm and 935 mm. The distance between the screen and the holographic emulsion is shown graphically for various parallax angles in Fig. 19.14b. For correct perspective this parallax angle should be the same as that used by the originating system. If it is less, the perspective will be steepened and the image may appear to roll as the viewpoint is changed. (This may be desirable in, for example, aerial shots, and in synthesized images where you want to squeeze 180° or even 360° of parallax into a 45° angle of viewing.) If the parallax angle is more than that of the originating system, the perspective will be flattened. This is seldom desirable except perhaps in dynamic portraiture, where the subject carries out some rapid action during the photography, such as smiling, waving or hitting a baseball.

If you have gone so far as to obtain an LCD screen that fits a 35 mm projector, you can use this instead of the filmstrip holder. If you have a full-size LCD screen (yes, they do exist up to 8×10 in) you can do away with the projection system altogether and substitute a full-width collimated beam.

The slit You can make the slit from black rubberized fabric (blackout material), like the focal-plane shutters of old press cameras, or from developed-out lith film or even heavyweight black paper, and wind the slit between two rollers. This is the most compact method, but it isn't easy to wind it on by the exact slit width between exposures, and the last thing you want to do is to leave a gap. You will probably find the operation of the slit simpler if you make it from 18-gauge sheet metal, blackened (Fig. 19.15). The full width of the sheet needs to be twice the "horizontal" width of the hologram, and the width of the slit must be equal to the "horizontal" width of the hologram divided by the number of exposures. Thus if you are working on 8×10 in film with 36 exposures the slit must be 10/36 (=0.28 in, or 7 mm) wide. You need to have it properly machined, of course. If you are going to move it by hand you will need to make locating notches at the side, with a spring catch (Fig. 19.15, inset).

Ideally, the slit mask would be moved by a stepper motor, and this what you will eventually need if you are going to set up a permanent holoprinting device, particularly if you are going to work with different numbers of exposures and/or different film sizes. Another method, suggested by Rob Munday of Spatial Imaging, is to pull down the slit mask using a computer printer, which can be controlled very accurately using the appropriate codes.

The reference beam needs to be collimated for precise work, and you need to cover the whole moving slit area as uniformly as possible, so if you don't possess a suitable collimating lens, have the largest distance you can manage between the



Figure 19.15 Notional drawing of a movable slit. The dimensions shown are for 24 exposures on 8×10 in film, which needs to be mounted as close as possible to the slit. For a different number of exposures or a different film size the slit width should be the film width divided by the number of exposures.

reference source and the film. You might also consider employing a bulls-eye filter (see p. 240) to even up the beam intensity profile.

Exposing

Select one of your images from near the middle of the set, focus it on the ground glass screen, and center the subject matter. Note the exact position of two salient points, one above the other, near the center of the part of the image you want to appear in the plane of the final hologram (e.g. one of the eyes and the corner of the mouth, in a portrait). These must be aligned for every frame. The easiest way to check this is to take a piece of card and hinge it to the lower edge of the screen with sticky tape, on the upstream side of the screen. Lift it up and mark the positions of the points you have chosen. As you change each frame, you should lift the card into position and check that both the marks coincide with the corresponding points in the image.

You will need the film to be spooled, of course, preferably in a cassette. Reloadable cassettes are uncommon these days, but some 35 mm films are still sold in cassettes that you can dismantle without damaging them. Now, with the slit in the topmost position (the "left" side of the hologram), set up the frame corresponding to the leftmost view of the subject. Align the two reference points on the image with those on the card. Now everything is set up. Put a large black card between the screen and the plateholder to block off any laser light while you are changing frames and moving the slit. Load the plate or film, and give the necessary settling time before you make the first exposure. As soon as you have made the first exposure, block off the light from the slit, move the slit down one notch, lift the white card into position, align the second frame and prepare for the second exposure. Keep repeating the process until you have made all the exposures.

Before you start in earnest, do a few dummy runs without film until you feel confident that you can carry the process through smoothly. With practice you could be making several exposures per minute, provided your exposure times don't exceed a few seconds. Nevertheless, allowing for settling time as well, it is likely to take up to half an hour to expose a 24-frame hologram. After you have done this a few times you may become eager to find a way of automating the exposing. With a stepper motor it isn't difficult to rig up a rack-and-pinion system to control the slit movement. Winding the film on by the exact amount is less easy, but if you have made the photographic exposures using a good-quality SLR camera on a rail with the image centered throughout, you can adapt the camera itself as the projector. Fit a macro lens if you have one, and use an electric remote cable release connected to the same timer as the slit stepper motor. With the camera back open you will need to hold the film flat against the film aperture with a piece of optically flat glass or a metal frame held in place by clips.

You can go further than this. With rapid resetting of the slit and frames there should be no need for a shutter, but it is simple enough to fix one up at the laser port, to operate during the changeovers. The next step is the installation of an electronic timer, to produce a set of identical exposure times. The final step, if your programming abilities are up to it, is to put the whole operation under computer control. Once you have this, there is no need for film: you can simply scan all your images into the computer (aligning and modifying them as necessary), and use an LCD instead of transparencies. The final step, of course, would be to build your own dedicated holoprinter.

Stereogram masters from photographic prints

If you have made your originals with a wide-angle fixed lens, with the camera moving in a straight line past the subject, the image will have progressed across the frame from one edge to the other over what may be as many as 40 shots. If your setup has only slit movement and no film movement facility, you will have to center the subject matter in each frame before you can expose it in the mastering process. As you can make the original images in the form of photographic negatives, the simplest way of avoiding this time-consuming chore is to use a photographic enlarger to make prints that you can crop appropriately, and use prints instead of transparencies as originals.

You can do the cropping in the enlarger, if you insert a template marked with your reference points in the paper holder before aligning the projected image. Making a set of 24 or more matched prints with the subject accurately registered in each can be tedious, but if you have had some experience of printing photographs you

You can also use drawn animations in the same system.



Figure 19.16 Table layout for screen projection. MS is a matt screen. The projection optics PS is offset to avoid keystoning. (They are not shown to scale, as is the rest of the layout.) This configuration is based on the holographic facility of the Royal College of Art.

shouldn't find it difficult. It is worth taking some trouble to get the first print right. It needs to be on glossy paper, and to have a complete range of tones from full black to pure white, the kind of quality required for halftone reproduction in magazines. Choose an image from the middle of the series, and give the print the full development time. Once you are satisfied with the image quality, keep the print in front of you and match all the others to it. Blot or squeegee the excess water from the print surfaces after washing them, and allow them to dry naturally in air, so that they don't buckle.

The mastering setup for prints couldn't be simpler: a bypass transmission master configuration as in Fig. 9.2 (p. 122). The only extra item you require is the slit, which needs to be moved stepwise downwards between exposures. The prints should preferably be clamped behind a register glass carrying an L-shaped guide, but if they are sufficiently flat you can use the paper holder from the enlarger and do away with glass.

A somewhat better configuration employs a collimated reference beam, as shown in Fig. 19.16. This design is intended for transparencies projected on a small matt screen rather than a ground glass (the projection lens and film plane need to be offset about 10 mm so that they are parallel with the screen, to avoid keystoning). Using photographic prints you can dispense with the projection system, or use it simply as a source of illumination.

Preventing dropouts

A problem that seems to plague everybody who makes stereograms is dropouts, i.e. missing frames in the final image. This causes flickering of the image as your viewpoint moves across the hologram. Weak frames and dropouts are caused by instability during one or more exposures. If there is a slight movement of the

It is important to number all your prints on the back – and to make sure the numbering doesn't come off in the wash. Give all the prints identical exposures, avoid any dodging or shading, and if you have experience of doing so, develop the prints in batches. This is not to denigrate fringe lockers. In setups where it is impossible to obtain completely stable conditions they can be a blessing. But the transducer mechanism works best on relay mirrors that reflect a beam almost directly back; and you need to be able to generate greatly enlarged fringes somewhere in the system for the detector to operate efficiently. Fringe lockers are discussed in Appendix 4.

They can even be used as diffractive optical elements, with some restrictions (see Chapter 24). fringes during an exposure, the contrast of the fringe pattern will be lowered and the diffraction efficiency affected, and consequently the brightness and contrast will fall. In the worst case the fringes will be destroyed and you will have a dropout. Dropouts are bad news because of the length of time it takes to re-shoot a stereogram master. Don't discard a master, though, just because it has one or two, unless they are right in the middle, or adjacent to one another. With the best optical equipment in the world you can't avoid the effects of tiny fluctuations in temperature, laser wavelength and pointing stability, even variations in barometric pressure. A quarter of a wavelength shift in a fringe pattern can seriously affect the image, and just moving about the lab can be enough to cause a shift of this order. One possible answer is a fringe stabilizer (fringe locker), a device based on servo principles, which detects any movement in the primary fringes and immediately adjusts the optical path length to bring them back to their original position. Unfortunately, with the table geometries described in this chapter it is by no means easy to install a fringe locker, and several workers who have acquired them have eventually abandoned them in favor of concentrating on better stability of equipment.

If you are fortunate enough to have access to a pulse laser your worries are over as far as this fault is concerned. Otherwise, if you are going to take up stereogram production seriously, you will need to build a rigid framework for the optics using heavy-duty Dexion or similar material, to take steps to control the ambient temperature and humidity and to eliminate drafts.

Computer image processing

A somewhat different problem easily confused with partial dropouts is jumping of the image as the viewpoint changes. This is caused by imperfect registration of original images. Either your alignments were less than meticulous, or, if the originals were hand held photographs, the spacing or elevation varied between exposures. For this the cure is computer processing of the images, which, as mentioned earlier, you can carry out on any up-to-date personal computer. The simpler corrections are usually possible without buying extra software, but after trying them out and finding their limits you will probably decide to acquire the facilities for perspective morphing, and maybe go on to do your own creative work. Plate 14a shows a stereogram of New York originated on a helicopter flight and corrected for registration by computer; Plate 14b was originated in three colors entirely by computer, and Plate 15 is a computer animation (the knotted figure writhes as you move past it).

The use of a liquid-crystal display as the object for a hologram was proposed as early as 1988 by Dalsgaard and Ibsen¹², though at that time the resolution of even the best LCDs was very low. With the arrival of pocket television sets and palmtop computers higher resolution became a commercial necessity, and the most recently developed LCD arrays can have a resolution as good as that of a 35 mm film.

There are two possible ways of employing LCDs in holographic stereograms: with a small LCD installed in a projector in the same way as a slide; and with a large transilluminated LCD forming a full-size object (Fig. 19.17).

LCD projectors are rapidly replacing slide projectors for presentations, as they can be coupled directly to a computer program (and produce effects that would



Figure 19.17 (a) Table layout for system with LCD object. (Abbreviations as previously.) In this configuration the combination of CL and M_3 can be replaced by a holographic collimating lens turning the beam through 33.7° . (b) The simplest layout of all. As the beam is not collimated, the throw should be as long as the table will permit.

otherwise need a whole battery of slide projectors to achieve). In fact, if you can manage to introduce a laser beam into one of these, replacing the filament lamp, you will have an excellent source of primary images.

Transmission LCDs intended for viewing by normal white light contain two crossed polarizing filters, and without stimulation are opaque. Application of a local electric field causes the liquid crystal material to rotate the plane of polarization wherever the field exists, so that light is transmitted at that point. If you use an LCD with polarized laser light you can remove the polarizing screen on the laser side, and the transmittance will be improved. You have to have the laser's axis of polarization the same as that of the screen you remove, of course.

To summarize, the importance of LCDs doesn't lie simply in their convenience. An LCD can be the visible output of a computer. There are problems involved in the alignment of a series of images taken under less than ideal conditions, even in a series taken with a fixed lens along a rail; but there are programs that will correct, and even redraw, images that are out of true, fit them into scenes of continuously changing perspective, and fill in missing viewpoints. Given this facility, it is no longer necessary to be meticulous when taking the initial pictures, or to shoot a full complement of frames. What is more, your computer can adjust the contrast and luminance of each frame to a predetermined optimum. And with a little ingenuity you can program the computer to look after the stepping-on process and make the correct exposures, so that once you have everything set up you can start the program running and go off for a coffee.

You can also persuade your computer to construct your own realistic (or surrealistic) images. It can look after the masking for pseudocolor images, and it can make color separations from color transparencies for full-color stereograms. But for these you need a different geometry, one that uses a master hologram that has been made at the achromatic angle.

Achromatic and color stereograms

Chapter 18 showed the way to make an achromatic WLT hologram. The important part of the setup is the inclination of the master hologram at the achromatic angle, with a reference beam that is at right angles to the object beam (Fig. 19.18). The layout for making the final transfer (Fig. 19.19) is very similar.



Figure 19.18 Layout for an achromatic-angle master. The solid lines show the geometry for a reference beam at right angles to the plane of the master hologram; the broken line is for a reference beam at right angles to the object beam. The former arrangement shows a lower discrepancy between the two optical paths.



Figure 19.19 Layout for transfer table for an achromatic WLT stereogram. The solid white lines show the geometry for a reference/replay beam orthogonal to the master, the broken lines for a beam orthogonal to the object/image beam. The paths are matched by adjusting the position of the variable beamsplitter VBS. The combination of CL/M_3 can be replaced by an off-axis paraboloidal mirror (which could be fabricated holographically).

As you can see, this configuration is somewhat trickier to set up than the straightforward arrangements of Figs. 19.13 and 19.16. In order for the (projected) height of H_1 to be sufficient, the slit needs to be twice as long as it would be if it were normal to the object beam. Rod Murray, who was largely responsible for the design and construction of the holoprinter at the Royal College of Art holographic facility (sadly, now closed) has constructed a new version for his personal laboratory, and this is shown in Fig. 19.20.

Transferring achromatic stereograms

The transfer table geometries for achromatic stereograms are similar to those used for achromatic WLT and reflection holograms (Figs. 18.6 and 18.7). The table layout in Fig. 19.21 is an achromatic WLT transfer table. The large relay mirror M_3 is a plane mirror, provided you use a lens for collimating (CL in the figure); otherwise it needs to be an off-axis paraboloid. The two positions are alternatives: the position that gives a beam orthogonal to the object beam provides better achromatism, but has a large optical path difference across the hologram, about 25 cm for an 8×10 in master. This is near the limit for a 35 mW HeNe laser, though well within the coherence length of an argon or DPSS laser, or some diode lasers.

This arrangement will give you an achromatic WLT hologram, neutral in color over a vertical angle of about 10°, shifting towards yellow at the upper limit and towards cyan at the lower. This is the easiest way to make a really bright stereogram: If you want to display it as a reflection hologram you simply mount it

Practical Holography



Figure 19.20 Dual purpose (master and transfer) table designed by Rod Murray. Solid lines = object beam; broken line = H_1 (master hologram) reference beam and H_1 replay beam; chain line = reference beam for H_2 (transfer hologram). For clarity the beams are shown unexpanded.

on an ordinary mirror and illuminate it from the front. Making an achromatic reflection transfer is more difficult, as you need two images, cyan and yellow, in register. The technique is a slightly simplified version of the full-color reflection process (p. 264–6).



Figure 19.21 Spectral sensitivities of the three emulsions of a color film.

Full-color stereograms

The theoretical basis of these was first described by Benton⁹, and re-stated in practical terms by Bill Molteni¹³. Full-color stereograms are at present the only sure way of obtaining a perfect color match with the original subject matter. Before describing the method, an explanation of the principles involved in the correct reproduction of color may be helpful.

In Chapter 17 I discussed the difficulties of recording colors accurately using just three single wavelengths. Color holography with three lasers works only because most subjects reflect a broad band of wavelengths, with some reflectivity over the whole visible spectrum. Even so, there may be shifts in hue and loss of saturation in the image. With color stereograms this doesn't happen: color rendering can be exact. The reason is that the original is a set of color photographs, and color photographs *do* record the entire spectral reflectance of the subject, because they work on a different principle, known as *subtractive color synthesis* (see Box 19.1).

Although color is recorded and reproduced by a computer in a somewhat different manner, the broad principles still apply: the entire spectrum is recorded, and the color separations contain the entire spectral information about the light reflected from any point on the subject.

Box 19.1 Subtractive color synthesis

The principle of subtractive color synthesis, which underlies every commercial color process in photography, was first conceived in 1868 by Louis Ducos du Hauron¹⁵.

Whereas additive synthesis – what we have been considering up till now – is based on the principle that you can obtain any color by mixing red, green and blue light, subtractive synthesis achieves the same end by *removing* red, green and blue light in suitable proportions from white light. In a color slide film there are, basically, three layers of emulsion, sensitive respectively to red, green and blue light, and overlapping so that their aggregate sensitivity is uniform throughout the spectrum (Fig. 19.21).

Any colored object, no matter what its spectral reflectance may be, is recorded in the correct proportions by one or more of the emulsions. Thus a yellow object is recorded in equal proportions on the green and red records, whereas an orange object is recorded more on the red and somewhat less on the green record. (Not quite every process. Polaroid 35 mm color slide material is additive, with a raster of red, green and blue lines.) D. A. Spencer dedicated his monumental survey *Colour Photography in Practice* to du Hauron, saying of him 'There is scarcely a process which du Hauron did not foreshadow... Rarely has any inventor shown such imaginative foresight, or received so little encouragement. He died... in abject poverty in 1920.'

This principle mimics the function of the human retina.

A color negative works in the same way, but tones and hues are reversed: for example, a lightish green object is rendered as a darkish magenta. When the negative is printed, the tones and hues are reversed a second time, so that the colors are correct in the final print.

There is usually a fourth, gray, printer, as these colors alone don't produce a good black using standard printers' inks.

A 35 mm scanner can also make positive separations from color negatives.

If you simply want to make an achromatic WLT hologram, you need only one master with two slits, one in the 'red' position and the other halfway between the 'green' and 'blue' positions, making angles of $\pm 8^\circ$ with the normal to the transfer film.

The emulsion is processed to give a positive, not a negative, and the final image is in colored dyes (the silver is removed in the final stages of processing). The red record layer has its image in the form of a cyan dye, which transmits blue and green but not red; thus an object that reflects no red appears cyan, as it should. The green record layer forms its image in magenta, which transmits blue and red light but not green; and the blue record layer forms its image in yellow, which transmits red and green but not blue. Thus an object that is pure red will have no cyan image, but it will have a magenta and a yellow image, which remove respectively green and blue light from white, leaving red, which is again correct. All other hues and saturations can be accounted for in the same way, including black, which is white light with red, green and blue removed, and white, which (rather obviously) is white light with nothing removed.

To produce a halftone print, as in the color plates in this book, it is necessary to produce three separate printing plates, one each for cyan, magenta and yellow.

This is done traditionally by photographing the transparency through red, green and blue filters onto three separate black-and-white films. Today this process is mostly carried out by computer. These *color separations* are the raw material for a color stereogram. The final holograms, of course, operate by additive synthesis.

The first stage in making a natural-color stereogram is to make a set of colorseparation positives in black and white from the original color transparencies. You can have this done professionally, or you may have scanning facilities that can carry out this task.

The method of mastering is the same for both transmission and reflection holograms.

The general principle is shown in Fig. 19.22. You expose the transfer emulsion to the real image projected by the conjugate beam for each master in turn, the original positive separation being positioned in the achromatic plane in the appropriate place to eventually produce an image in its correct hue. For a WLT hologram the reference beam is from the same side as the object beam; for a reflection hologram it is from the opposite side. In the case of the WLT hologram, as this configuration uses narrow slits for the masters, you can expose the three positives simultaneously, each in its appropriate position.

Full-color WLT transfer stereograms

The setup for mastering is exactly the same as in Fig. 19.18. You need to make three separate masters for a reflection hologram, one for each separation positive, but only one for a WLT hologram. For a WLT hologram, in order to balance the colors correctly, you may need to lower the beam ratio and increase the exposure for the 'red' slit, as the red image is farther away and thus weaker, and to a lesser extent for the 'green' slit. You can do this with ND filters in the unexpanded reference beam, or by reducing the widths of the 'blue' and 'green' slits in proportion.



Figure 19.22 Locations of master hologram strips on the achromatic plane.

Full-color reflection transfer stereograms

The master setup is the same as that shown for WLT holograms except that you need to illuminate a band covering two-fifths to one-half of the "vertical" dimension of the master hologram. The reference beam falls on H_2 from the side opposite to the object beam, at 45° and from "below" (Fig. 19.23).



Figure 19.23 Layout for full-color WLT stereogram transfer with accurate registration. The three beams represent "horizontal" slit illumination of the master. The 'green' slit S_G is at 0° incidence to the transfer hologram (H₂) plane. The 'red' and 'blue' slits S_R and S_B are at $\pm 8^\circ$ as seen from the centre of H₂. Note that as S_B is farther from H₂ than S_G and S_G than S_B , a variable beam attenuator VBA is included in the reference beam to match up the beam ratios; it is included because the variable beamsplitter VBS is usually too touchy for carrying out this exercise.

Making a full-color reflection transfer hologram is much more complicated and somewhat less reliable than making a WLT transfer, as it is by no means easy to produce the exact required primary hues by pre-swelling.

In addition, you not only need to change the master and move the beam for each exposure, but also to remove and pre-treat the transfer emulsion each time. As



Figure 19.24 Layout for full-color reflection stereogram transfer with accurate registration. The 'red' beam is shown shaded and bounded by solid lines.

The saturation is usually lower, too, as the three reconstructions each reflect a comparatively wide band of wavelengths. with pseudocolor reflection holograms, it is probably best to begin with the 'blue' pre-swelling and exposure. Mark the top right hand corner of your film or plate before you begin, and make sure you reposition it in accurate register each time (better than 0.5 mm for an 8×10 in format and 0.25 mm for a 4×5 in). A suitable table layout for reflection transfers is shown in Fig. 19.24.

Achromatic reflection transfers are easier, as you need only one master and two exposures. Pre-swell for cyan first, and position the master reconstruction beam halfway between the 'green' and 'blue' positions. After exposing for the cyan image, wash and dry the transfer emulsion, adjust the beam to the 'red' position, remount the film or plate, and make the second exposure.

As in all pre-swelling situations, color streaks are an ever-present problem. Walker and Benton¹⁶ describe a system in which the swelling was achieved by immersion of the emulsion in a glass tank filled with a mixture of alcohol and water, the hologram being exposed *in situ*. But this system raises further practical complications.

Color balance

In order to achieve a correct color balance you need to have all the holographic images equally bright. This can be difficult, as the diffraction efficiency in a color reflection transfer hologram is likely to be lower for the green image than for the red, and lower still for the blue (the reverse is true for WLTs). When you display a color reflection hologram you may find the color balance improves if you angle the viewing light so as to give the maximum brightness to the blue image.

You may also find that you need to tweak the exposing geometry by turning the plateholder a degree or two between exposures, but don't overdo this, as it risks de-registering the images.

Color accuracy: WLT or reflection?

For exhibition purposes, a color reflection hologram is easier to display than a color WLT. It is less exacting in lighting, as there is much less color change with angle of illumination. In addition, it offers some vertical parallax, and the colors don't change noticeably when the hologram is viewed from a higher or lower viewpoint. It is certainly much more difficult to make, but is it better, when compared with its equivalent, a WLT hologram backed with a mirror?

The WLT hologram with a mirror has two disadvantages not possessed by the reflection equivalent: the hue of the image changes considerably with only a small change in vertical viewpoint; and because of the mirror you see your own reflection and that of the room and any other holograms in the exhibition, in the mirror, unless the setup has been very carefully arranged. By contrast, a reflection hologram is little more difficult to illuminate than an exhibition photograph; the main problem is to get enough blue light out of a tungsten filament lamp, and a bluish 'daylight' filter over the spotlight, or, better, a car headlamp xenon bulb with a reflector, will help to take care of that. But there is a more subtle difference, and it lies in the theory of color reproduction.

As Box 19.1 explains, in order to record the whole spectrum you have to use bands of wavelength that between them cover the whole spectrum. That is the way films

This is because tungsten filament lamps produce less blue light than red.
record color (and this is what three-laser color holograms cannot faithfully record, as I have explained in Chapter 17). But when it comes to reproducing what is in the color film, you need the narrowest bands of wavelength possible, so that there is no cross talk, (i.e. the 'red' projection doesn't include any of the 'green' signal, the 'green' doesn't include any of the 'blue', and so on). So, ideally, the reproducing signal should consist of just three single wavelengths centered on the middle of each of the pass-bands of the filters used in the original recording material. The nature of a WLT hologram is such that it achieves this perfectly. So a WLT full-color hologram gives the most accurate color reproduction it is possible to obtain. Indeed, a color WLT holographic image can be more faithful to the original than the best possible color photographic print.

There is one possible transfer technique I haven't mentioned, mainly because nobody seems to have tried it yet. It is to use panchromatic plates, and to expose the color separations each with a laser beam of the appropriate wavelength. At present this would demand the employment of three lasers, respectively red, green and blue. If the near future brings a suitable pseudowhite laser (see Chapter 17), it will be possible to work directly from the color transparencies without the necessity of making separations or setting up plates at curious angles or messing about with triethanolamine. Perhaps by the time the next edition of this book comes out that goal will have been achieved, and the design of the equipment for making naturalcolor holographic stereograms will have become greatly simplified.

Calculating distances

In order to get the distances between the reference beam sources and the holograms right, you have to start with the display conditions as you envisage them, and work backwards. For this you need Benton's formulas in Appendix 3. Suzanne St Cyr has produced a worksheet for this, and this is also reproduced (with permission) in Appendix 3. All you have to do is put the figures in. The worksheet is easily adapted into a personal computer program. Some professional workers, in particular Walter Spierings¹⁷, have designed fully integrated holoprinters that can be set up to operate directly from the output of a dedicated computer, and will then perform all the necessary operations automatically.

Stereograms with full parallax

The stereograms discussed so far have had only vertical slits. This needn't necessarily be so. To obtain both horizontal and vertical parallax in a stereogram you need to make a number of passes of the subject, changing the height each time by an amount equal to the separation between horizontal frames. You don't need as many passes as there are exposures in a horizontal pass, as you would not normally need more than about 20° of parallax vertically. Six to nine passes are sufficient.

If you thought mastering from a single pass was tedious, you will no doubt be dismayed by the idea of mastering up to nine complete passes. The making of the originals can be tedious, too, and a live subject is out of the question unless you use a vertical bank of cameras (it has been done). In making the transfer you need to add a "horizontal" slit in front of the "vertical" slit, and move this one notch

And this chapter, at present much the longest in the book, could be a great deal shorter!

In order to avoid having to align the subject vertically as well as horizontally, you may tilt the camera axis up or down between passes in order to center the subject matter, as over this small angle the small amount of distortion won't be noticeable. after each series of exposures. You need absolute stability throughout, of course; but you have the consolation that if one of your pixels is a dud, its absence won't be as noticeable as if you had lost a whole vertical slit image.

Michael Klug has been working with the MIT Spatial Imaging team for a number of years on the problem of constructing full-parallax holographic stereograms via a computer. The main problem has been the enormous amount of information that appeared to be necessary (around 10 gigabytes), and the team's main aim has been to reduce this to an acceptable level, using new fast-rendering hardware. A similar setup to the horizontal-parallax configuration is used, but scanning single lines of pixels in the "vertical" sense to record the vertical information. This research is written up in Klug *et al.*¹⁸.

Perspective correction by pre-distortion

This is a big subject, and its implementation is outside the capabilities of all but the most sophisticated facilities, so I will describe only the principles. If you want to know the nuts and bolts of the techniques you should refer to the papers originating from work done by the MIT Spatial Imaging Group^{18–24}.

Using the methods of transfer described in this chapter, when you view the final hologram, in order to see an extended image in correct perspective you need to have your eyes close to the plane of the real image of the master hologram (the slit plane). This restricts the angle of viewing: the image blacks out if you move more than about 20° to either side. In addition, if you move in nearer to the hologram than the plane of the real image of the slit, the image becomes distorted at the edges, as you are looking at the edges of the image through inappropriate images of the slit.

If the image is being put through computer control, or is computer-generated, and is being displayed on an LCD screen, this can be rectified by a technique that the group has dubbed *perspective slicing*. The setup for mastering has the slit plane much closer than usual to the plane of the projected image. In the normal way each camera position would correspond to an imaginary slit in the plane of the lens, so that each camera position would see the whole field of view (Fig. 19.25a). But if the imaginary slits were moved away from the camera position for any one slit, the view would be seen in its correct perspective only by taking sections from



Figure 19.25 (a) Each camera lens aperture represents an imaginary slit, and the view through the viewfinder of each gives an image in correct perspective. (b) If the slits are moved away from the cameras, each slit requires a strip of each picture to obtain a view with correct perspective. For clarity only two are shown here.



Figure 19.26 Artist's impression of a full-size alcove stereogram.

each picture, e.g. the extreme left of the picture from the extreme right camera (Fig. 19.25b). Each picture must therefore be sliced up into as many equal vertical strips as there are camera positions. Suppose there are 99 camera positions. The pictures for each camera position would be divided into 99 vertical strips. The central position (no 50) has the extreme right hand strip (99) from camera 1, the next to the left from camera position 2, and so on; camera position 50 will have strip 50, and camera position 99 will have the extreme left strip (1). For the picture next to the right, camera position 50 will have strip 51; camera position 1 will be off edge, and camera position 2 will have strip 99. Camera position 99 will have strip 2. And so on.

In practice it isn't necessary to use as many dissections as there are photographs: about one for each six positions is enough. The master hologram is made with the slit plane twice as close as would be calculated for the expected viewing distance. The transfer, however, is made at the normal distance, so that when it is flipped for viewing, the real image of the slits is halfway between the viewer and the hologram image. At this distance the perspective appears correct. The system has the advantage of giving almost double the viewing angle (though no increase in parallax, of course), and a much more robust perspective. The image can be viewed over a fairly large range of distances without serious distortion. Using perspectiveslicing techniques it is even possible to put the image of the slits behind the image and use an illuminating beam that is a replica of the reference beam. The authors of the relevant papers call the system an Ultragram, and have even designed a compact one-step printer for the system.

Lessons learnt during the development of the Ultragram led to a revival of interest in full-parallax stereograms, and the Spatial Imaging Group devoted much time during the late 1990s to its investigation, finally emerging with a successful method involving the storage of entire full-parallax stereogram images on disc. Progress was reported in a number of papers, the most complete being Klug *et al.*²⁵ Michael

A more complicated slicing program led to the generation of a real image within a half-cylinder space, which the Spatial Imaging Group called an *alcove hologram*. This reached its final version as a reflection hologram illuminated by a white-light source above the cylinder and on its central line (Fig. 19.26). This is arguably the most complicated hologram ever made. The project reached the demonstration stage, but was not followed up further. Klug subsequently went on to found his own company Zebra for further research and marketing of large full-parallax stereograms.

Conical stereograms

These are a simple variant of cylindrical stereograms, first described by Okada *et al.*²⁶ The subject is photographed in the same way as for a cylindrical stereogram, but with the camera directed downwards towards the subject at 45° (Fig. 19.27). The distance of the camera from the subject must be equal to the distance from the image to the viewer's eye multiplied by the magnification of the projected image (which will usually be less than unity).

To make a WLT conical stereogram from the photographs you project the photographic images on to a one-dimensional diffusing screen (such as a lenticular screen of no more than 0.3 mm pitch) oriented vertically, mounted on a plano-convex field lens to converge the light to the normal viewing position. The film is cut to a fan shape as described in Chapter 8 (the cut-out angle should be 105° for a 45° slope), and masked by a tapered slit of width such that the 360° of camera movement is just accommodated within the fan, which is rotated by one slit width for each successive frame. The schematic arrangement is shown in Fig. 19.28.



Figure 19.27 Photographic setup for a conical stereogram.



Figure 19.28 Schematic setup for printing a conical transmission stereogram.



Figure 19.29 Conical stereograms: (a) virtual image; (b) real image.

The angle of the cut-out should be 0.7 of the angle through which the turntable is turned between exposures. This system will produce a virtual image when the hologram is set up like a lampshade, with the replay light from below (Fig. 19.29a). To produce a real image the film should pass through the projector with the image erect, so that the image is inverted, and the field lens removed. The cone is finally mounted apex down, with a beam from below (Fig. 19.29b).

By having a reference beam from behind and below when making the hologram, a reflection hologram results. The orientation for display is the same except that the light is above the hologram. The film is processed for a narrow-band reconstruction, with a filtered replay beam, as the image will be floating some 10 cm in front of the hologram, and may otherwise be blurred by dispersion.

Volume multiplexed holograms

These operate on a different principle. They assemble a three-dimensional model from a series of cross-sections of the subject material. The main application is in computerized tomography scans.

These scans are sequentially exposed at the appropriate positions on a single holographic plate or film. The resultant images are stacked one behind the other like glass plates on a plate rack, and the details of the rear slices are visible through the images of the front slices. The result is like a transparent model of the subject matter. There is an early description of the process by Higgins²⁷, who with colleagues developed a basic system for visualizing brain scans. This was further developed by Drinkwater and Hart²⁸.

The originals can be photographic transparencies, computer printouts or LCD displays. The last method is clearly preferable, as it avoids the need for a

There are four types of tomography. Computerized axial tomography (CAT) scans the body with a beam of X-rays, and shows tissue in terms of density. The related technique positron emission tomography (PET) records organs that have taken up radioactive material. Ultrasonic scanning shows up interfaces of differing types of tissue. Nuclear magnetic resonance imaging (NMRI) shows up watery and fatty tissue.

Stephen Hart subsequently went to the USA, where he helped to develop a commercial version with the California company Voxel (a *voxel* is a three-dimensional or volume pixel).



Figure 19.30 Layout for volume multiplexing. PS is a projection system or an illuminated LCD display. The system is moved in steps towards the holographic film for successive exposures.

projection system if the display is full-size. Figure 19.30 shows one possible mastering setup.

The object imaging system can be an adapted 35 mm projector for 35 mm slides or a small LCD device, or suitable diffuse illumination for a full-size transparency or LCD. It is mounted on a translation stage equipped with a stepper motor capable of giving steps of a few millimetres over a range of about 300 mm. The slices are displayed and recorded in turn in steps corresponding to their actual position, using a low beam ratio (1.5:1 or less). The exposure should be the minimum that will produce a reasonable image, and the originals will probably need to be enhanced in order to emphasize the organs that are to be depicted.

The master hologram inevitably has low diffraction efficiency owing to the large number of images occupying the fringe spaces (Voxel has reported an ability to support more than 200). However, when the master is used to make a transfer hologram the image can be much brighter. Drinkwater and Hart describe a full aperture transfer system similar to that of Fig. 13.1, giving full parallax, with a dispersion compensation device (see Chapter 18).

Tsujiuchi²⁹ has tackled the problems of low diffraction efficiency and dispersion in a different way. He suggests setting the emulsion at the achromatic angle, masked by a horizontally oriented slit that is moved downwards by one step for each exposure (Fig. 19.31). An image-plane transfer is made as in Fig. 18.16 with full aperture. When the final hologram is illuminated by white light the image appears with full horizontal parallax. The vertical parallax, however, is limited to the width of the (projected) slit. The position in depth of the reconstructed image is represented by a change in color, from blue at the front to red at the back. The reconstruction is bright and sharp, and, as there is no superposition of fringes in the master, any number of fringes may be recorded without loss of quality. There is some exaggeration of depth, which can be pre-corrected by decreasing the With multiple exposures of this type, exposure requirements can vary from start to finish. With some earlier materials it was necessary to increase the exposure time progressively up to 50% extra, but with recent improvements in emulsions this may no longer be so.

'Full parallax' doesn't mean 'wide parallax'. The amount of parallax in Voxel's holograms is barely 15°.





distance between the exposures to approximately 90% of the actual distance between slices.

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Chapter 20 Non-silver processes for holography

'You boil it in sawdust: you salt it in glue: You condense it with locusts and tape: Still keeping one principal object in view – To preserve its symmetrical shape.'

Lewis Carroll, The Hunting of the Snark

In spite of all the advances in emulsion technology, there is still no grainless silver halide emulsion – nor, from its nature, can there ever be. All silver halide emulsions scatter light to some extent after processing, because of reflections from the grain surfaces. In black-and-white photographic negatives this doesn't matter, and in color transparencies the scatter is reduced by the removal of the silver, leaving the image entirely in the form of transparent dye. In holographic emulsions the scattering phenomenon has a different cause, as the developed grains are mostly smaller than the wavelength of light. There are two types, *Mie scattering* and *Rayleigh scattering*. The former is independent of wavelength and occurs chiefly with larger particles, so is of little importance in holograms. The latter is inversely proportional to the fourth power of the wavelength, and causes a bluish haze that can be a nuisance in display holograms.

The reason for the extraordinary sensitivity of silver halides to light lies largely in their crystalline structure. A very small number of photons striking a crystal at random is enough to produce a stable area of weakness (a latent image) that can be attacked by a developing agent. But the silver halides are not the only chemical substances that are sensitive to light energy. Iron complexes are also broken down by light. If you are over fifty years old you will remember blueprints, which were copies of ink drawings in negative white-on-blue. Made using an iron compound as sensitizer; they were exposed to sunlight or mercury vapor light and 'developed' by washing in water.

The process was rendered obsolete by the *diazo* process, which employs a variety of chemically related substances (called diazoniums) that react with ammonia vapor to give intensely colored dyes and are destroyed by short-wave radiation. The diazo process thus gives direct positives. It operates at the molecular level, and is effectively grainless. Apart from its use in making large copies of drawings, it is employed mainly for microfiches and slides of graphics; but it may have some potential in holography because of its extremely high resolving power.

Another light-sensitive element is chromium, in the form of the dichromate ion $Cr_2O_7^{2-}$. This has the property of rendering colloids such as albumen, gum arabic and, most notably, gelatin, insoluble when exposed to short-wave radiation.

All three of these substances have been used in photography. Of these it is dichromated gelatin (DCG) that has proved useful in holography, especially as it can be sensitized to red light.

Three other categories of photosensitive substances have found use in holography, namely *photoresists*, *photothermoplastics* and *photopolymers*. Photoresists have been with us for a long time; they are substances that become insoluble (negative) or

Both forms of scattering can be seen in atmospheric effects: Mie scattering in mist and fog; Rayleigh scattering in bluish haze and the blue color of the sky.

The name of this process is cyanotype. Many early photograms of flowers and leaves were made by this process. It was invented (and named) by Sir John Herschel, and actually predated silver halide photography by several years.

Colloids are systems in which a substance in the form of particles or droplets, typically less than 1μ m in diameter, are dispersed in another substance, forming a viscous liquid or a gel. Dichromated gum arabic mixed with pigments was a favorite print medium among early photographers.

soluble (positive) when exposed to short-wave radiation. Their main application in industry is for making masks for printed-circuit boards and microchips. Although they are binary recording media (i.e. all-or-nothing), they are suitable for making masters for embossed holograms (Chapter 21), and this is their main use in holography. Photothermoplastics materials become conductive to electricity when irradiated with visible light, and this property can be made use of in the production of real-time holograms. These materials can be used over and over again. Photopolymers change their chemical and physical structure, and consequently their refractive index, on exposure to light and subsequent (dry) processing, and can be made sensitive to the whole visible spectrum. They can be used to make any type of hologram (unlike photoresists and photothermoplastics, which produce a surface grating and are thus suitable only for transmission holograms), and the development of new types of photopolymer is a subject of continuing research. A number of companies produce photopolymer materials for holography, though not necessarily for general distribution. Photopolymers are valued for their ability to produce very bright images.

A recent addition to the list is *bacteriorhodopsin* (BR), which belongs to the class of reversible photochromic media. It is related to human visual pigment, and is much more sensitive to light than the materials discussed above, which are all 100–1000 times less sensitive than silver halide. BR emulsions are available commercially.

A somewhat different class of materials, called *photorefractive crystals*, has the property of being able to phase-conjugate light, that is, to send a pulse of light directly back along its original path. This enables them to be used to make highly directional holographic images. These substances have for some years been the subject of intensive research because of their potentialities for information storage and retrieval (Chapter 24).

Dichromated gelatin (DCG)

In photography, dichromated colloids have a long and honorable history. For over a century the medium for making photolithographic plates was dichromated albumen. Many classic photographs were printed by the so-called gum-bichromate process, and the permanence of the medium has ensured that they have survived in pristine condition.

Gelatin treated with dichromate solution at a low pH becomes insoluble in warm water when exposed to light or to certain chemical solutions. It was the basis of the carbon and carbro processes: the former produced photographic prints of extreme permanence and supreme richness of tone; the latter was until the 1950s almost the only way of producing high-quality color prints.

There are still groups of enthusiasts working with carbro and gum-bichromate (and obtaining beautiful images, too). But it is in holography that the principle of dichromated colloids has been most successfully reincarnated.

Gelatin is an animal substance, a derivative of collagen, the stuff of cartilage and sinews. Put crudely, it is manufactured from the inedible parts of cattle and pigs. If you take all the leftover hides, gristle, hoofs and bone, and boil them for a long time, the liquid you are left with is glue, of the kind formerly used by cabinet-makers. Refining this product produces gelatin. Gelatin has a number of

'Dichromate' was formerly called 'bichromate'. Today's stricter nomenclature would reserve this name for potassium hydrogen chromate, KHCrO₄. Potassium dichromate, K₂Cr₂O₇, also known as potassium chromate (VI), is a powerful oxidizing agent that bleaches silver in acid solution, and coagulates colloids in the presence of light energy.

And what a messy, unreliable, expensive and incredibly timeconsuming process it was!

It was reported that when the late Linda McCartney, photographer and dedicated vegan, discovered this she was horrified, and seriously considered giving up photography.

Practical Holography .

A table jelly is roughly 98% water and only 2% gelatin.

In the early days of DCG there were many published papers containing practical advice. Most of them were pretty unreliable.

Kodak 649F plates had just sufficiently fine grain to allow them to be used for holograms, but the images they gave were very noisy. Among modern manufacturers of holographic material, Geola produces a plain gelatin-coated plate at a reasonable price. remarkable properties, one of which is that it can absorb a very large amount of water and still remain more or less rigid.

The molecular structure of gelatin can be changed by a phenomenon called *cross-linking*, making it extremely tough; in this state it not only resists penetration by water, but also retains any water that it has previously absorbed. Collagen molecules consist mainly of long spirals, and under appropriate stimuli these become interlocked, like very stiff knitting. If the water in the interstices is removed the structure remains rigid. This is what happens in a DCG hologram.

The principle is simple: in the presence of dichromate ions, light energy stimulates cross-linking. Cross-linked gelatin becomes rigid, and has a refractive index that differs from that of unlinked gelatin when both are dried out forcibly. That is all that is needed for the formation of a phase reflection hologram. A glass plate coated with gelatin sensitized with dichromate is given a holographic exposure, and the fringe pattern is then 'developed' in a plain water bath. This causes differential swelling of the exposed and unexposed areas. The plate is then dehydrated in an alcohol bath and dried rapidly. The fringe pattern is now 'frozen' into the gelatin structure, which has become a phase hologram, with high diffraction efficiency and almost no scattering, being, literally, grainless.

In practice the method isn't particularly easy. The trouble is that gelatin, being a biological product, doesn't have a fixed molecular structure, and differs from batch to batch. Even if you buy the purest laboratory-standard gelatin, you will find enough variation to compel you to begin from scratch each time you start a new batch.

Much of the early literature on DCG holography refers to the use of fixed-out Kodak 649F plates. Although this was certainly a good method of obtaining a uniformly coated plate, it was a very expensive way of obtaining plain gelatin. In addition, the plates showed considerable variation from batch to batch.

Steve McGrew¹ gives a list of the variables that affect the quality and reconstruction characteristics of DCG holograms:

- Initial thickness of the gelatin layer
- Initial hardness of the gelatin
- Concentration of the sensitizing dichromate bath
- Drying conditions: temperature, atmospheric humidity and speed of drying
- · Exposure waveband, duration and total energy
- · Time delay between exposure and processing
- Composition, pH and temperature of the processing baths
- Time spent in the processing baths
- Recording geometry

The characteristics affected by these variables include fog, scatter, peak reconstruction wavelength, bandwidth and diffraction efficiency. McGrew notes that the initial hardness, the concentration of the sensitizing bath, the pre-exposure drying time and the total energy of the exposure all affect the peak reconstruction wavelength; the initial thickness of the emulsion affects the fog level; and both the pre- and post-exposure maturing time (as well as the concentration of the sensitizing bath) affect the sensitivity of the material to light. Don't take my caveats too much to heart. The gelatin used for photographic films today differs little from batch to batch, and one fairly large order of gelatin from an accredited supplier will be consistent within itself and will last you a long time, as long as you keep it dry until you are ready to use it.

DCG holograms have been extensively used for producing head-up displays (HUDs) for military aircraft; as a result much otherwise valuable research information has been withheld from the public for security reasons. However, a good deal of know-how has been acquired independently, and DCG techniques have become popular with a large number of private enthusiasts, not least because of the cheapness of the raw materials.

Rendering DCG sensitive to red light

DCG normally responds only to short-wave radiation, and has its peak sensitivity in the near UV. The best laser for DCG holograms is a HeCd laser operating at 442 nm (violet), though suitable diode lasers emitting at 405–415 nm are now coming on line.

The required energy for adequate exposure is of the order of 30 mJ cm^{-2} , which is about three hundred times that needed for a silver halide emulsion. The sensitivity is lower for blue light and lower still for green light (40–80 and $200-400 \text{ mJ cm}^{-2}$ respectively). This is nevertheless well within the capabilities of a 5 W argon laser, and that is the chosen tool for making the two-color medallions you can find in souvenir shops (Plate 15a). But such lasers are out of reach for the amateur or semi-professional holographer. So how about sensitizing DCG to red light?

As I mentioned earlier, early experimenters often used fixed-out 649F plates. These contained a greenish dye that sensitized the silver halide crystals to red light, and this sensitivity remained after fixation, conferring some sensitivity to red in the dichromate-treated gelatin. This led to several suggestions for dyes to enhance this effect. Graube is frequently quoted as an early authority: in his paper² he suggested methylene blue or green, but muttered darkly about exposures of several hours. More recently, Jeff Blyth³ has achieved a notable success with methylene blue by employing tetramethylguanidine as an electron donor. He has produced bright holograms using a HeNe laser with exposures of around 50 mJ cm⁻² – still three orders of magnitude more than that needed for silver halide, but a big advance on previous efforts. Blyth also reported that the substitution of eosin for methylene blue would confer a similar photosensitivity to green light at 514 nm. The success of this technique has been widely confirmed, and DCG holography with red lasers is now well established. Appendix 6 includes instructions for the preparation and coating of red-sensitive DCG emulsions.

Coating plates

There are almost as many ways of coating plates as there are DCG enthusiasts, but the method given below does work well, and isn't at all difficult. To acquire the skill you need it is best to start with small plates, certainly no larger than 4×5 in. You can use old holographic plates from which you have cleaned the emulsion with household bleach diluted 1:4, or fresh pieces of 1–1.5 mm float glass cut to size. The glass plates must be absolutely clean. Photographic gelatin is 'doped' with precisely calculated traces of substances such as phosphorus to increase the sensitivity of the silver halide crystals. For this reason the raw gelatin intended for photographic emulsions is highly refined. It isn't inert, though. It can deteriorate with time; and in a warm humid climate bacteria and other microorganisms, insects and even mice can attack photographic gelatin, as anyone who works in the tropics eventually discovers.

Blyth recommends supermarket gelatin as the most suitable type to use. It is, after all, highly refined, so perhaps this is not all that surprising.

A good way of cleaning new glass is to use an ordinary dishwasher, with Calgon in the water. Calgon is the trade name for a mixture of forms of poly(sodium metaphosphate) (NaPO₃)_n, where $n \ge 6$. It inactivates the calcium and magnesium salts in mains water that could otherwise be precipitated on the glass. A Meyer bar is a piece of stainless steel rod about 12 mm in diameter, wound tightly with stainless steel wire. You can obtain Meyer bars from suppliers of materials to drawing offices and the printing trade. You can also wind your own if you have plenty of patience. A long steel spring with a tightly-fitting metal or plastic bar pushed into it works equally well.

Wear protective clothing, including headwear, and preferably work inside a protective container such as a glovebox. Make up the dichromated gelatin solution according to the instructions given in Appendix 5. When it is ready for use, warm the solution to 40–45°C in a beaker by standing it in hot water. You don't need total darkness, of course: a fairly bright green light will not have any effect on the emulsion. When it is completely fluid and only slightly viscous take a warmed glass plate, stand it almost upright in a small tray (a polystyrene food tray will do) and pour a steady stream of fluid over the glass, moving the beaker steadily along the plate just below the upper edge. Allow the plate to drain for a minute or so, then remove the thick bead of gelatin from the lower edge of the glass with a matchstick or toothpick and return the surplus fluid to the beaker. Then stand the plate to dry in a dark dust-free cupboard for at least three hours. 100 cm³ of solution will coat about twenty 4×5 in plates. After drying out, the plates can be stored for a further 24 hours before use.

Plates in sizes larger than 4×5 in should be cut from 2 mm glass; it is a good idea to take off the sharp edges with a fine carborundum stone or waterproof abrasive paper (use it wet). Larger plates are difficult to coat evenly by the pouring method: probably the simplest way of obtaining a uniform coating is to use a Meyer bar. You need a 24 SWG (standard wire gauge) winding; this will provide a coating thickness (when dry) of 7 μ m.

Lay the plate on a soft flat surface (several thicknesses of clean newspaper or print blotting paper), take up a dropper bottle of warm gelatin, and pour a thickish line of it just within one edge of the plate; then, as quickly as you can, grab the Meyer bar and pull it across the plate, using both hands for a steady movement. The plate must now remain perfectly level while the gelatin sets. At this stage it is very important not to allow any speck of dust to fall on the emulsion surface; if one does so it will suck up the gelatin and form a sort of fish-eye.

Another popular method is spin coating, using a whirler. This is basically a centrifuge, and some ingenious workers have built these from parts of salad spinners, modified to hold the plate centrally and firmly. Take it up to about six revolutions a second, then pour the fluid from the center to the edge. Keep spinning for 20–30 seconds.

If you intend to take your DCG work seriously, you need to establish a controlled environment. Room temperature should be $24-26^{\circ}$ C and relative humidity 35-40%. Air should be supplied by a laminar-flow air filter at slight overpressure, and you also need a fume extractor for some of the baths you will be using for processing. The processing area should have a mixer control for providing a supply of water at a constant temperature.

Once the plates are dry, store them at about 60% relative humidity, and in fairly cool conditions, though not refrigerated. Under these conditions the emulsion will continue to mature for 24 hours or so. If the atmosphere is very dry the emulsion will begin to lose much of its sensitivity.

Exposing

A 5 mW red laser will make a bright Denisyuk hologram of a small object such as a coin with an exposure of about a minute, provided the beam just covers the object. A 5 cm diameter beam requires about 5 minutes exposure. The required exposure duration is directly proportional to the (circular) area covered, and inversely proportional to the power of the laser, so in order to cover a 4×5 in

plate (16 cm diagonal) right to the corners with a 5-minute exposure, you need a 50 mW laser. In practice, though, you can usually allow some fall-off at the corners so that you can manage with around 25 mW. With such a laser an 8×10 in plate will demand at least 20 minutes exposure.

Processing

After making the exposure, leave the plate for about five minutes, then immerse it in a 1% solution of sodium dithionate $(Na_2S_2O_2)$ at about 20°C for about 2 min. This removes the dye and the unwanted residual chromates.

Then rinse the plate briefly under the cold tap, and transfer it to a bath of plain water at about 25° C. This temperature must not exceed the yield point (see Box 20.1), or the image will be noisy.

After 1 minute remove the plate and immerse it in a mixture of 90% propan-2-ol (isopropanol or isopropyl alcohol), 10% water at 20°C, for 2 minutes, with agitation.

Finally, transfer the plate to a bath of 100% propan-2-ol at 20°C for 5–10 min, with occasional agitation.

Now blow-dry the plate with a hair-drier set to 'medium'. To harden and stabilize the emulsion, leave the dried hologram in a warm oven at about 70° for several hours. This treatment also reduces the noise level.

Box 20.1 Yield point

Gelatin that has taken up water has an elastic limit, or *yield point*. If stretched beyond this point, it won't return to its original condition. Increasing the temperature of the water bath lowers this limit; increasing the maturing time raises it. If you process a DCG hologram in water that is at too high a temperature (even 25°C may be too high) the unexposed regions may become stretched, so that the fringes are permanently distorted, resulting in a high level of scatter (noise). In order to produce the brightest possible hologram you need to process it in water at a temperature varies for different parts of the image, being highest for the most heavily exposed areas. It is these that you should judge when you assess the image. The shadow areas will inevitably look a little milky, but this is normal. Should the shadow areas be completely clear, the temperature of the water was too low, and you should repeat the processing at a slightly higher temperature.

Sealing the hologram

The image is rapidly degraded in the presence of moisture, and a humid atmosphere can cause it to disappear irretrievably in days or even hours, so it is necessary to seal it by cementing a cover glass over it. Use optical-quality UVcuring cement. Pour the cement onto the cover glass in a dog-bone shape, place the glass on top and squeeze out any bubbles. Cure the cement by exposure to sunlight or to a UV lamp.

Do this with the extractor full on, because dithionate solution smells abominable.

Don't touch the surface of the gelatin with your fingers or breathe on the hologram before the cover glass is in place.

Color control

Steve McGrew¹ discovered that it was possible to obtain either a broad-band or a narrow-band image reconstruction by varying the alcohol-bath treatment routine. If you pass the hologram through a number of baths with the alcohol concentration rising from the first to the last, the image will be almost monochromatic. If, on the other hand, you immerse the holograms directly in 100% alcohol, the image will be almost colorless. This appears to be the result of the sudden dehydration of the surface layer, which seals water in the innermost layers, so that the fringe layer spacings vary from the surface to the interior (a chirped fringe structure). McGrew also reports that the image is more likely to be narrow-band when the reference beam is incident on the glass side, and broadband when it is incident on the emulsion side, but I don't have any confirmation of this.

Silver halide sensitized gelatin (SHSG)

This technique seems to have been discovered serendipitously, probably when some unknown experimenter removed all the silver bromide as well as the developed silver from a processed hologram and found that there was still a visible image (probably owing to the gelatin round the developing silver grains having become hardened by the developer reaction products).

The first serious investigations of the principle appear to have been by Chang and Winick⁴, who found that if a dichromate solvent bleach was followed by fixation and washing, subsequent dehydration in propan-2-ol (as in DCG processing) would result in a hologram with characteristics similar to those of DCG. This was an important discovery, as it meant that in effect the qualities of a DCG image could be combined with the sensitivity of silver halide. This technique has since been followed up, notably by A. Fimia and the research team at Alicante University 5-8. The process requires a non-tanning developer such as metolascorbate, and a tanning dichromate-halide bleach of the Kodak R-10 type. The Alicante method was to develop, fix, bleach, wash and then immerse in successive baths of propan-2-ol at concentrations rising from 50% to 100% before drying. Nick Phillips's team at De Montfort University⁹ has taken a fresh look at the underlying principles, and has suggested variants of the processing sequence, one based on a bleach-fix regime, the other using a second, fogging development followed by total removal of the silver with a solvent bleach. More recent work by the team (Phillips et al.¹⁰) has produced results of very high diffraction efficiency, with the lowest noise level yet achieved from a silver halide material. Details of formulas and methods are in Appendix 5.

Photopolymers

Photopolymers are substances that polymerize when irradiated with light. Examples of photopolymers in everyday use are cyanoacrylate cement ('superglue'), glass bonding cement, and the UV-curing sealant mentioned earlier in connection with the sealing of DCG holograms.

The important property of a photopolymer is that on exposure to light it changes its chemical and physical structure, and consequently its refractive index. The ideal

This does happen, particularly with tanning developers, but the image is usually very weak.

Polymerization is a process whereby small molecules of a simple organic compound (the *monomer*) link up end to end, forming long chain molecules. (Polythene is a familiar example, being made up of long chains formed from ethene, C_2H_{4-}) The physical properties of a polymer depend on the configuration of these chains: whether they are straight or coiled, whether they fit together to form crystals, the amount of cross-linking, and so on. photopolymer would be transparent, flexible, sensitive to all visible wavelengths and completely stable after processing. Photopolymers have been the subject of much intensive research, and both Polaroid and Dupont have produced commercially viable photopolymer emulsions, though the availability of these on the open market has varied according to changes in policy within the companies in question. As Dupont's material was freely available for several years, its nature and processing are well known, and it is described here as a typical example of photopolymers applied to holography.

The material comprises a vinyl monomer and photoinitiation system in a film-forming polymer matrix.

The exposure energy required for a transmission hologram is about 5 mJ cm^{-2} , and for a reflection hologram about 30 mJ cm^{-2} . The material is fully panchromatic, and can be used for true-color holography, given three sufficiently powerful lasers. After exposure the material is given a 'curing' exposure to UV or white light (5 mW cm^{-2}) for a minute or so, then baked in a forced-air convection oven (e.g. a film-drying cabinet at full heat) at $100-120^{\circ}$ C for 1–2 hours. There is a color tuning film which, when laminated to the photopolymer in place of the cover sheet immediately before the baking stage, will increase the replay wavelength band from a green Ar⁺ or DPSS wavelength to a gold color.

An early description of photopolymers is to be found in a Dupont patent of 1969¹¹, which covers the broad principles, and lists possible applications in the printing industry. In 1985 Ingwall and Fielding of Polaroid¹² suggested a role in holography. Since then Polaroid and Dupont have been the chief manufacturers of the materials. Zager and Weber¹³ describe the Dupont material in detail. Development of the material continues elsewhere. Smirnova and Sakhno¹⁴ describe the characteristics of material now being produced in the Ukraine, with 28 references to other papers.

Photothermoplastics

Holographic thermoplastics devices consist of a thin transparent layer of an electrical conductor such as indium oxide doped with tin on a quartz substrate, overlaid by a thin $(1.2 \,\mu\text{m})$ layer of organic photoconductive material such as polyvinylcarbazole sensitized with trinitrofluoronone, and a topmost layer of thermoplastic material with a low softening temperature (70°C), around 0.7 m thick (Umstatter *et al.*¹⁵).

Initially, the device is charged electrostatically; when it is exposed to light the charge leaks away in the exposed areas. The free surface of the thermoplastic material is recharged to an equipotential, and the fringes are 'developed' by passing an electric current through the indium oxide layer, which heats the plastic so that the surface forms corrugations in accordance with the electrostatic charge pattern. The hologram is erased by passing a further current of high intensity (or longer duration) through the conductive layer. Honeywell have developed a holographic camera based on this principle, described by Lee *et al.*¹⁶. Such a camera has obvious applications in industrial research. The plates are small (3 cm square) and produce laser-viewable holograms. Figure 20.1 is a schematic showing the construction of the plates.

A *photoinitiator* is a kind of catalyst that becomes active when stimulated by light energy.



Figure 20.1 Construction and operation of photothermoplastics material. (a) shows the construction. 1 is the thermoplastic layer, $0.3 \,\mu$ m thick; 2 is the photoconductive layer, $2 \,\mu$ m thick; 3 are copper contacts; 4 is a transparent indium oxide conductor layer; 5 is the glass substrate. (b) to (e) show the cycle of operations: (b) the material is given a surface positive charge; (c) exposure causes a redistribution of charges at the thermoplastic photoconductor interface; this is followed by charging of the thermoplastic surface to equipotential; (d) the thermoplastic material is heated by passing a current through the conductor; the softened material forms corrugation patterns in accordance with the electrostatic charge pattern; (e) a further heat pulse destroys the resistance of the thermoplastic material; the charge equalizes and surface tension restores flatness. The material is now ready for another cycle.

Photoresists

These are proprietary substances that become either insoluble (negative) or soluble (positive) in an organic solvent after exposure to short wavelength light. A photoresist coating is typically 1 μ m thick. The required exposure (to blue or violet light) is of the order of 100 mJ cm⁻². Negative photoresists are normally exposed through the base, to avoid parts of the image washing off in the solvent. The method of using photoresist material for masters for embossed holograms is discussed in Chapter 21.

Photochromic materials

Photochromic materials darken (negative) or lighten (positive) on exposure to light. The photochromic material most familiar to the general public is silver

chloride dispersed in glass ('Reactolite'), which darkens on exposure to UV radiation and is used in sunglasses. Alyatina *et al.*¹⁷ have succeeded in making holograms with this material using the UV wavelength of a nitrogen laser, but as it is insensitive to the visible spectrum it doesn't look promising for more general holography. Methylene blue in a substrate of polyvinyl alcohol is a positive photochromic material that is red-sensitive and holds more promise.

Vorob'ev *et al.*¹⁸ have achieved a similar result with green light, using a solution of eosin in gelatin. Photochromic processes have not yet become the subject of much research work, which is a pity, as they operate in real time and are reversible over a large number of cycles: a period in the dark restores the dye to its original form.

Bacteriorhodopsin

One photochromic substance that has not been neglected is bacteriorhodopsin (BR). This material has appeared only fairly recently, but is already making a bid for stardom. BR is a close relative of the purple pigment of the rod cells of the human retina, which enables us to see in dim light. It is generated in a membrane that is formed when *Halobacterium halobium* is cultured in an oxygen-poor atmosphere.

BR has a peak sensitivity at around 590 nm, in the yellow region of the spectrum. When stimulated by visible radiation, particularly between 500 and 610 nm, its molecular structure alters to an intermediate form 'M', which has its absorption peak at 410 nm in the deep violet, and it loses its sensitivity to longer-wave radiation. If the light source is removed, the material reverts to its original form. Illumination with blue light normally has a similar effect, but this can be prevented by a voltage applied across the membrane.

The resolving power of a BR membrane is about 5000 cycles per millimetre, better than silver halide, and its response is almost instant. The sensitivity of the material is around $500 \,\mu\text{J}\,\text{cm}^{-2}$, close to that of the slower silver halide emulsions. In addition, it can be recycled almost indefinitely, and it can be used in real-time holography and all types of holographic interferometry. There are a great many research papers on BR; unfortunately, most of them are intelligible only to biochemists specializing in this area. One of the clearest is by Colleen Fitzpatrick¹⁹. Renner and Hampp²⁰ discuss the performance of 'wild' BR and a mutated form BR_{D96N} that allows adjustment of the M-lifetime between 10 ms and 1 s by adjusting the pH, thus rendering it more flexible for real-time interferometry. BR is certainly one of the most promising non-silver materials yet, not least because of its high sensitivity to visible light.

Photorefractive crystals

Photorefractive substances are (at present) all single-crystal materials, with a lightsensitive volume that may be several millimetres thick; they are therefore capable of recording and storing a very large number of holograms because of their high directionality.

One form of photorefractive material is typified by lithium niobate (LiNbO₃), which is sometimes doped with iron to increase its range of sensitivity to longer wavelengths. Exposure to light frees trapped electrons, which then move through

I have used this material a number of times in demonstrations of real-time interferometry (Chapter 23).

A photorefractive material changes its refractive index under illumination, retaining this change after the illumination is turned off. It can thus form phase holograms.

Photorefractive images can be erased and the material reused indefinitely.

A *photoconductive* material will carry an electric current only when illuminated, the current being directly proportional to the light intensity.

Regrettably, an equal number seem to have been written for no reason other than to swell the number of papers published by any particular research group. the lattice until they are again trapped in an unilluminated region. This produces a spatially varying electrical charge that affects the refractive index. The material can thus be used to record interference fringes. This record is erased by a replay beam of the same wavelength (which would, of course, be necessary if it were to satisfy the Bragg condition). However, this type of crystal is birefringent, i.e. it exhibits a second, different refractive index; so the image can in fact be replayed using a longer wavelength that matches the second refractive index, and to which the material is insensitive. The sensitivity of these materials is very low, typically between $100-500 \text{ mJ cm}^{-2}$, four orders of magnitude slower than silver halide.

The second class of photorefractive materials is a group of photoconductive crystals typified by gallium arsenide (GaAs), materials often used in the photocells of photographic exposure meters.

Such materials can store an electrical field; when they are illuminated the stored field in the illuminated area decays, resulting in a variation of refractive index with illumination. They have a similar range of possible applications in holographic data storage and retrieval (Chapter 24).

Photorefractive crystals and their possible applications have generated an enormous number of papers, many of them (alas) comprehensible only to those equipped with a thorough grounding in electromagnetic theory, and sometimes vector calculus too.

Possibly the best general account of photorefractive optics to date is by Das and Singh²¹. If you wish to refer to other papers, this one contains more than 300 references – and that was in 1991! There doesn't seem to have been a thorough overview since then: most of the more worthwhile papers deal with small improvements in writing and readout capabilities, and with dopant additions to the mainline materials such as lithium niobate. One successful attempt to overcome the readout problem is by Kratzig²², who sensitized photorefractive crystals with white or UV light before exposure to red or near-IR radiation, subsequently reading out with a weak red or IR beam, and erasing with bright green light.

In the same way as it seems that almost any substance can be made to produce laser light, so it seems that almost any substance can be used to record a hologram. Even poly(methyl methacrylate) (Perspex or Plexiglas) has been used, though admittedly with electron beams rather than visible light. Nevertheless, with the exception of BR, none of these substances has come within two orders of magnitude of the light sensitivity of silver halide, and there are sound theoretical reasons for supposing that none ever will. The only device that can surpass silver halide for sensitivity (apart from the human eye) is the charge-coupled device (CCD), which (like the human eye) can detect photons in single numbers. Already the resolution of CCD arrays has reached that of 35 mm film, and it is possible (with some restrictions) to make certain types of hologram on them. There are theoretical limits even to these, of course. But digital holography is already a reality.

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Chapter 21 Embossed holograms

The thing can be done,' said the Butcher, 'I think. The thing must be done, I am sure. The thing shall be done! Bring me paper and ink, The best there is time to procure.'

Lewis Carroll, The Hunting of the Snark

In the early days of photography, a question constantly asked was: 'When are we going to see a photograph printed in a book by ordinary printing methods?' Eventually a method of combining photography with engraving was found, and photogravure was born, to be followed soon afterwards by the halftone screen process. A similar question was asked of holography in its early days; and, sure enough, a method was eventually found, this time combining holography with techniques borrowed from the electronics and sound recording industries. Using these methods it became possible to produce a hologram with its fringes in relief, and to replicate this pattern by a mechanical embossing process.

The initial artwork

Although it is true that you can make a hologram of anything you can see (and a good many things you *can't* see!), there are some types of subject that are not really suitable for embossed holograms. Among these is any subject matter that won't fit into a 150×150 mm format, as this is the limit for most commercially available photoresist master plates, though dot-matrix images of metre (and more) dimensions can be and have been made. Also excluded are any subjects more than about 30 mm deep. This is because embossed holograms are usually viewed under indifferent lighting conditions, and anything other than a shallow image will be blurred or even unidentifiable. So let us look at the categories that *are* suitable.

- *Three-dimensional objects* These have to be the right size for the image required, perfect in detail, and painted in shades of gray. They should be shallow: if they would normally be deep it may be necessary to scale down the depth. Oddly enough, this is seldom noticeable in the final image.
- *Computer-generated models* These can be any three-dimensional digital image possessing parallax.
- *Stereograms* These can be of any subject matter, including drawings, and would normally be in the form of a series of anything up to forty or so 35 mm frames (but typically 20–30), forming a continuous series of perspective views or animations. For objects that can be taken into the studio (including live sitters) a mastering camera setup is needed, as described in Chapter 19. Digital recording has largely replaced film, as information in this form can be fed directly into a computer for processing.
- *Flat artwork* Line drawings, block drawings, photographic prints and screen prints are all suitable. Artwork in two dimensions only will be scanned and turned into a dot master (the holographic equivalent of a halftone).

There is an even closer parallel. One of the earliest photomechanical processes was Woodburytype, in which a photographic negative was developed in a tanning developer that produced a low relief image; this was pressed into a soft metal sheet to form a printing plate. Early experiments in holographic embossing also used a tanning developer and fabricated the embossing master directly from the relief fringes.

In fact, few modern embossed holograms have an image more than about 15 mm deep, though some of the earliest of the genre had a depth of as much as 250 mm.

Existing holograms are hardly ever suitable. The conditions they were made under, particularly the reference beam angle, are unlikely to match the requirements of the embossing laboratories.

'Classical' 2D–3D artwork doesn't always need to be turned into halftone. Artwork in more than one plane (for 2D–3D images) must be drawn out in full, even those parts that are likely to be concealed, and needs to be 5–8% larger than the foreground material to take account of the increased distance and the parallax. The term '2D–3D image' is used to describe a shallow hologram derived from line artwork or color transparencies, and appears at the surface level and at one or two discrete levels of shallow depth.

If you are a customer commissioning a run of embossed holograms from a manufacturer, you will probably find that the company is able to do all this work for you on a computer, and modify the artwork continuously until you are both happy with the result.

Holographic recording

Classical holography If your original is a model, a set of drawings or the (analogue) originals for a stereogram, it may be necessary to produce a standard master hologram, and this will be made using conventional holographic methods, with a geometry appropriate to the viewing of the final image(s).

Digital imagery If, on the other hand, your original is a digital photograph, it can be fed directly into the computer and a color-separation set prepared. If it is a digital clip or a computer model, it will be used to derive a computer-controlled dot matrix master. Each dot is a single exposure from two tightly focused laser beams angled to produce a particular hue on reconstruction. It isn't a hologram in the strict sense of the term: each dot is a tiny diffraction grating that will reflect the correct color back into your eye when illuminated by a spotlight. Alternatively, the fringes of the grating can be written directly, line by line, using an ion or electron beam, for exact control of the grating profile.

Making the photoresist master

Most photoresist holograms are recorded on Shipley S 1800 series resists, which consist of a phenol–formaldehyde base, a photosensitive diazoquinone and an organic solvent. The coating needs to be absolutely uniform and $1.0-1.5 \,\mu$ m thick. The only satisfactory way of producing this is by spin coating. A number of companies supply ready-coated plates, and you would be well advised to buy these rather than attempt to make your own. If you do have access to an industrial spin coater, and wish to make your own, after coating you need to bake the plate for 30 minutes at 90°C to dry off the solvent and improve the adhesion to the glass surface.

The S 1800 series are positive photoresists: exposed areas become soluble in a sodium hydroxide solution, while the unexposed areas remain insoluble. They are insensitive to long wavelengths. Most commercial labs use argon lasers, and operate at either 488 or 458 nm in the blue region. A HeCd laser operating at 442 nm will do the same job, and requires only an ordinary single-phase mains connection. Violet diode lasers are now becoming available, operating at wavelengths around 405–415 nm, and are probably the workhorses of the future.

The table configuration is the one used for rainbow holograms (Fig. 13.4). Photoresist material has a very low light-sensitivity, and your exposure, even with

The artwork and masks can be printed out as hard copy for mastering, though today it is more usual to keep them as computer files and send the suggested image to the customer's (i.e. your own) computer. This is much easier than trying to do it all yourself and perhaps getting it wrong after a great deal of work. Unless you have had a lot of experience in both graphic design and holography, simply take your sketches along and let the specialists deal with the project.

I am using the term 'classical holography' to distinguish the purely holographic approach to embossing masters from the digital approach, which doesn't need to use a conventional hologram at any stage up to, and usually including, producing the master.

The details of the work entailed here are in the province of fairly advanced computer programming, and are beyond the scope of this text.

You may have tried spin coating with home made equipment for DCG holograms, but coating for embossing masters is in a different league: you need professional equipment. The process requires carefully controlled spin rates and absolute cleanliness, and the resist itself must be filtered down to 1μ m particle size.

Although the 458 nm line is much weaker than the 488 nm line it is much more actinic, and exposures are shorter than for the longer wavelength. Iwata and Ohnuma's figure of 10:1 is very high: 3:1 seems more appropriate for a shallow image such as a 2D–3D graphic. For hues in the magenta region, you need to make two exposure of the same mask, one with the slit positioned for 'red' and the second positioned for 'blue'. For masters made by the digital route the image can be either traced out as a dot matrix, using tightly focused laser beams, or written directly on a suitable substrate using ion or electron beam etching techniques.

A buffered solution contains a substance that stabilizes the pH. A reducing agent, as was explained in Chapter 5, is an electron donor. an argon laser, may be as much as 25 minutes. It is worth investigating the use of a fringe locker in the reference beam at M_3 in Fig. 13.4. Your steering mirrors and beamsplitter should be of the dielectric type, tuned to the wavelength you are using. Any unspread beam of over 500 mW will damage a metalized surface.

Masters of three-dimensional originals (including 2D–3D) made by classical techniques are produced by a regular rainbow technique, positioning the slits so that the final hologram will replay in the appropriate color. To make twodimensional graphics you substitute a diffusing screen for the master hologram, and position the (positive) mask directly over the photoresist plate. For a multicolor result you simply repeat the process with your second (and any further) masks in position, adjusting the slit position as necessary. According to Iwata and Ohnuma¹, the beam intensity ratio should be about 10:1.

The developer is Shipley AZ 1400J. At the recommended dilution the development time is only a few seconds at 20° C. You must immerse the plate quickly, and agitate it vigorously during the development, which you follow with a 10-20 min wash. After drying in a dust-free cabinet the manufacturers recommend that the plate should again be baked in a convector oven at 90° C for 30 min, but most workers haven't found this necessary.

Depositing the conductive layer

The first stage is to make the surface of the photoresist master electrically conductive, by coating it with a thin layer of metallic silver. There must be no pinholes, and the thickness must vary by no more than a few nanometres. One of the pioneers of the embossing technique was Jody Burns, who set out the basic requirements in a seminal paper in 1985², and the information in it is still valid, though McNulty³ has given a very thorough account of some more up-to-date methods.

There are three main methods of depositing the silver layer: vacuum deposition, silver spray, and electroless deposition. In the first system the master hologram is supported directly over a filament coated with silver metal in an evacuated bell jar. Equipment for aluminizing mirrors and beamsplitters can be adapted for this purpose, but in order to acquire an absolutely even coating it may be necessary to use baffles and an electrostatic charge to direct the metal vapor uniformly onto the substrate.

The second method, silver spraying, is more suitable for simple setups. It uses a special spray gun with a double solution-mixing nozzle. One of the reservoirs contains a buffered silver nitrate solution, the other a reducing agent.

When the gun is operated the solutions mix and deposit pure silver on the master. The photoresist needs to be prepared with a solution of tin (II) chloride (stannous chloride), which should not be allowed to dry before the spraying begins. McNulty recommends beginning at the bottom and working in horizontal sweeps to the top, repeating the process until the initial bluish translucent coat becomes a uniform bright silver. The plate is then rinsed in deionized water and transferred straight to the plating bath without drying. To check whether the silver layer is thick enough, the electrical resistance of the layer should be measured with an ohmmeter. If the resistance between any two opposite points is below 2 kilohms the coating is thick enough.

The third method is the so-called electroless nickel deposition system. This uses

electroformed metal. It does not require any special equipment, though both McNulty and Burns warn that fluctuations in immersion time, agitation and temperature may result in incomplete coating, necessitating a complete fresh start with a new photoresist master. In practice the difficulty of obtaining a uniform coating has resulted in its abandonment by commercial operators. I have included it because it is a simple method that can be useful to beginners lacking professional

The formulas for both the silver spray solution and the electroless nickel method are taken from A K Graham's monumental work on electroplating⁴. You can find

This master (the *mother*) is electroformed directly on the plated photoresist master.

The plating bath is a nickel sulfamate bath (Appendix 5), which should be held at

The mother forms the cathode (negative electrode) of the electrical circuit. It needs

to be mounted on a jig made of acrylic sheet at least 25% larger all round than the

mother, which is secured by four copper bolts, one at the center of each side. These

are connected to copper hooks that hang on an insulated bar connected to the negative terminal of the plating current source. The plate should be secured with

a pH of between 3.5 and 4.0 by means of a boric acid buffer if the initial pH is

The mother is a negative of the photoresist master, and if used for stamping it

nickel-to-nickel bond between the conductive layer and the subsequent

equipment but anxious to experiment.

The first-generation master

would produce a pseudoptic (laterally reversed) image.

high, or diluted with deionized water if it is low.

them in Appendix 5.

titanium basket.

nickel instead of silver as the initial coating, with the advantage that there will be a

The cleanliness, temperature, agitation and pH of the plating bath, as well as the cathode current, need careful control. Typical figures are pH 4.0, temperature 50° C, cathode current (initially low) increased after 5 min to 30 Am^{-2} . You will require a 12 V 100 A d.c. rectifier for this. It should have no more than 3% ripple. Languedoc⁵ gives a very full account of the plating details, and there is further information in DiBari⁶.

Electroforming of final shims

The final stamping masters, usually called 'shims', can be made at once. The nickel mother is carefully separated from the photoresist master and its edges de-burred. It needs rinsing in 2% sulfuric acid solution to remove any material adhering to it from the master, which must now be discarded. It is then immersed in a 2.5% potassium dichromate solution for up to 10 minutes ('passivating') to prevent subsequent generations of shims from sticking to it, and rinsed in deionized water before being mounted on a fresh jig. As the mother is fully conductive there is no need for the metalized strip this time. Although the overall size will have been

Electroforming is the technique of producing negative replicas in metal from a master by electrodeposition. It differs from electroplating in that the electroformed replica is removed from the master. It is generally much thicker (up to 0.5 mm), and must be detachable from the master.

That is, any text in the image would read backwards. However, the image is still orthoscopic.

Note that McNulty's paper has these instructions switched, in error.

If you are going to use this method, it is a good idea to have the foresight to make more than one photoresist master. As these will be pseudoptic an extra nickel generation must be made to reverse the image.

This is a cut that goes through the hologram but stops short of the backing paper.

reduced by trimming off the edges there needs to be plenty of spare space round it, as the electroformed copy is thicker towards the edges, and these thicker edges must be cropped away.

It is possible to make as many as ten shims from a single mother before the surface begins to deteriorate. For very long runs one is likely to need a third generation of shims, allowing a maximum of about 100 stampers.

The embossing process

Embossing is carried out using purpose-built rotary presses (*roll embossing*). The material is usually polyester, sometimes PVC. There are two main methods, 'soft' and 'hard' embossing. The shims are mounted on heated rollers and the holograms are hot-rolled in a continuous process. After pressing (soft embossing) or before (hard embossing), the embossed side is metalized, converting the WLT hologram into a reflected-light hologram and protecting the surface. This is the method used for the production of self-adhesive hologram labels. It is usual to add a self-adhesive backing and release paper. The borders of the holograms are finally kiss-cut.

Holograms that are to be flush mounted onto the substrate, as on credit cards and banknotes, are produced by a process called *hot-foil blocking*. This is convenient for the graphics industry, as it provides a system whereby a hologram can be printed directly on to paper or card using hot-foil equipment as used for adding metalized lettering on book covers etc. The hologram foil is rotary embossed in the same way as for self-adhesive holograms, but instead of being coated with a self-adhesive layer, the film is coated with a size coat of hot melt adhesive. In most cases the foil is coated after embossing rather than before, usually with either aluminum or a layer of high refractive index material. In the blocking process a heated plate melts the hot-melt adhesive and the wax release layer, so that the hologram adheres to the substrate and is released from the carrier web. The pressure applied is sufficient to force the surface of the hologram flush with the substrate surface, and to cut the foil to the shape of the blocking die.

Figure 21.1 summarizes the basic steps for the two pathways for making a master.



Figure 21.1 Basic steps for producing an embossed hologram.

Further reading

Reconnaissance Holographics is an international organization devoted to the promotion of commercial holography. It produces *Holography News*, a regular newsletter devoted to the business, runs annual conferences under the name of *Holo-pack Holo-print*, and issues a glossy guidebook and business directory under the same name. The conference, and the associated literature, are your best way of keeping up with progress in embossing technology.

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Chapter 22 Display techniques

The shop seemed to be full of all manner of curious things – but the oddest part of it all was that, wherever she looked hard at any shelf, to make out exactly what it had on it, that particular shelf was always quite empty, though the others round it were crowded as full as they could hold.

Lewis Carroll, Through the Looking-Glass

Most holographers carry a small hologram around with them all the time. They don't want to be caught out by someone asking them: 'What *is* a hologram? What does a hologram look like?'

Of course, merely carrying a hologram isn't enough. In these days of universal shadowless lighting you need a pocket torch too, and an appropriate line of patter as well, because the next two questions will inevitably be 'How do they work?' and 'How do you make them?'

The sort of hologram to carry around with you is a reflection hologram with a bright but shallow image – say, a Denisyuk hologram of a small trinket – that will give a tolerable reconstruction under almost any lighting conditions (but keep a small torch available).



Figure 22.1 How to show a hologram with an overhead projector. (a) Reflection hologram; (b) rainbow hologram, with mirror. (Line up the spectrum with audience's eyes.)

It is a sad fact that although display holography has been around for some twenty-five years, the general public has even less idea of what a hologram is than they have of what a charmed quark is, although every one of them is almost certainly carrying at least one hologram on a credit card or a banknote.

I was once commissioned to write an explanation of holography in not more than fifty words, to go on the box of a small holographic toy. It took a whole night to write, but it prepared me for answering this type of question. (There are fifty words in this note.)

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If you are booked to give a talk to a photographic society or similar gathering, you need something much better, of course. A slide projector or overhead projector provides an excellent light source for showing reflection holograms, provided you hold them as high as the beam will allow, and at the correct angle. If you have a mirror you can show rainbow holograms in the same way, though this is more difficult (Fig. 22.1). You can assess the correct angle by watching for the spectrum, and directing it to the audience's eye level.

Basic types of hologram and their display

There are five principal types of hologram for display purposes.

• Laser transmission holograms The image appears in a single hue, and shows laser speckle (Fig. 2.6, Plate 9a). The illumination is usually from the side, and always from behind the hologram. In this type of hologram the image can be deep and the resolution is high: in addition, a transfer laser hologram can put a real image a metre or more in front of the plate, if it is large enough. The down side is that to get the full benefit of these properties you have to use a laser to illuminate the hologram. If it is a large image you will need a powerful laser, and apart from the initial hire fee you will need to pay someone to look after it. In some countries you may find it difficult or even impossible to get permission to use such a laser in a public place. If this is the case you will have to resort to a filtered mercury arc source, which will sacrifice some of the depth and definition. Better news is that the speckle will also be largely suppressed.

Because of the difficulties of adequate presentation, laser transmission holograms have now virtually disappeared from public exhibitions, except for a few images that are of historic interest. The advent of comparatively cheap and reliable diode laser light sources may possibly bring about a rebirth of this genre.

- White-light transmission (WLT) holograms The most commonly displayed white-light transmission holograms are rainbow holograms, which normally produce an image in pure spectral colors. Some use a geometry that gives an achromatic image; but as a rule, creative WLT holograms exploit the ability of this technique to produce bright, saturated spectral colors. These holograms can be difficult to display, as their effect depends on critical positioning of the illuminating light. The vertical latitude is very small indeed. When correctly hung, a WLT hologram produces an image bright enough to hurt the eyes: only a low-power source is necessary even for a metre-square example. The image depth can be almost as great as that of a laser transmission hologram. A WLT hologram is illuminated from behind, which means that it may need to be suspended in the room space.
- *Reflection holograms* These are the most amenable type of hologram for display purposes. Provided the image depth is no more than about 10 cm, an ordinary commercial low-voltage spotlight is adequate. The hologram hangs on the wall like a photograph, and the angle of the replay beam, although important, isn't critical in the way it is for a WLT display. There is normally vertical as well as horizontal parallax, though in image-plane transfer holograms some of the vertical parallax may have been sacrificed in order to increase the image brightness.
- *Holographic stereograms* In the early days of holography exhibitions, stereograms were simply Cross holograms made on 250 mm film wrapped round

With the proliferation of sound-andlight shows, authorities in most countries are becoming more familiar with the principles of safe use of lasers in display situations, so this problem is to some extent receding.



Figure 22.2 Hanging a reflection hologram. Dimensions and angles should be optimized by trial and error.

If the hologram is a plate, you don't need a cover glass, of course.

These days you can buy low-voltage spotlight bulbs with a variety of beam angles from 15° up to 60° , so this is less of a problem than it once was.

The angle that gives you the maximum contrast isn't necessarily the angle that gives you the maximum brightness. Go for maximum contrast.

Don't fix it for posterity: you may want to change things at a later date. It is also conceivable that you might get tired of the image and decide to hang a fresh one. a Perspex cylinder in a 120° arc or 360° cylinder with a radius of curvature of 400 mm. Occasionally these were wholly or partly unwrapped, the altered perspective providing a surrealistic effect. These stereograms have become rare in modern exhibitions, though they often appear in retrospectives. They usually have their own illumination from a small filament lamp in the base. Flat stereograms are now much more common, and some exhibitions contain little else. They may be of either the WLT or reflection type, with the same illumination as for the standard type of hologram.

• *Edge-lit holograms* These have still not come into their own, though they are perhaps the most promising method for home display. Owing to their stringent illumination requirements they are necessarily supplied with a built-in light source, and thus should be capable of being displayed anywhere.

Displaying holograms at home

• *Reflection holograms* In domestic surroundings you simply hang the hologram on the wall and illuminate it with a ceiling spotlight. If your hologram has a plastic backing (which may be self-adhesive), mount it flush on a piece of hardboard or styrofoam, behind glass or acrylic sheet, with a ring at the back about two-thirds of the way up, to hang on a hook or a masonry nail.

As this will leave it pointing slightly downwards, you should position it a little above eye level. This also has the advantage over flush mounting that short people and children will be able to see the image by standing farther away, and tall people by approaching closer.

You can't put the spotlight just anywhere, of course: it has to be directly in front of the hologram and at the correct angle. It should also cover the hologram without wasting light, so the throw distance has to be right, too.

The usual distance for a replay source is about 1.5 m, at an angle of incidence of either 45° or 56° (though there are still plenty of rogue geometries even in commercial holograms). You will need help from a couple of friends when you are hanging the hologram and spotlight. Get one of them to hold the hologram on the wall while the other moves the light around at ceiling height, until the contrast looks highest when you are square on to the hologram (Fig. 22.2).

Mark this position on the ceiling and fix the lamp. You can now make adjustments to the tilt of the hologram with a wooden spacer, if it needs them. Once you are satisfied that you have obtained the best image the hologram can give, fix the spacer in place.

Spotlights vary in their quality. The most important characteristic in displaying a reflection hologram is high spatial coherence, i.e. as near to a point source as you can get. Avoid spotlamps with crinkled reflectors. Choose the type that has its filament capped, if you can. Test your choice by shining it on a light-colored surface and putting your hand in the beam, some 20 cm from the surface you are going to illuminate. If the shadow of your hand is sharp, the lamp is OK. You can sometimes achieve a more dramatic effect by using a filter of the same color as the basic hue of the holographic image. This doesn't lead to any loss of brightness in the image, and may well sharpen it up by reducing color dispersion.

Reflection holograms are sometimes intended for display on a horizontal surface as part of a coffee-table arrangement, or freely suspended as a mobile. As a visit to

any up-to-date exhibition of holograms will show, there are a number of ingenious ways of displaying reflection holograms. Many of the holograms shown at exhibitions and in gift shops are now fitted with their own spotlight, which may or may not be adjusted correctly. If you buy a hologram equipped with its own light source, make sure it is correctly adjusted, and that you can readjust it yourself if necessary.

• White-light transmission (WLT) holograms These are more difficult to hang satisfactorily. They usually need a clear metre or so of space behind them, with no illuminated objects visible on the far side. It is best to mount them in an alcove, if there is one, or in a corner of the exhibition space. The range of satisfactory viewing distances is rather small, as the spectrum they produce is fairly sharply focused. If there is plenty of room, hang the hologram somewhat above average eye level, tilted forward; if there is little room, set it up below eye level, tilted back (Fig. 22.3). The area behind the hologram should if possible be matt black. Figures 22.4 and 22,5 show alternative methods of displaying WLT images where space is restricted.

Where there is little or no space to spare, you can back a WLT hologram with a mirror (it needn't be a front-surface mirror) and illuminate it from the front. This

It is unfortunate that many rainbow holograms are so large that they have to be hung in the middle of the exhibition space, with people walking behind them and sundry reflections from other holograms. Large WLTs should if possible be hung in their own hallowed space, well away from optical distractions.





Figure 22.4 Use of lens or Fresnel lens sheet to shorten replay beam throw.



Figure 22.3 Displaying a WLT hologram. (a) Where there is plenty of room, hang the hologram facing slightly downwards; (b) where space is restricted, mount below eye level, tilted back, and use a folded replay beam. SI is the real image of the slit.

Figure 22.5 Alternative methods of folding the replay beam for WLT display.

This is one of the perennial bugbears with embossed holograms, giving as it does a degraded image that can mislead naïve viewers about holographic images in general. lighting geometry is equally critical, but now anything *in front of* the hologram, notably the viewer's own reflection, will appear along with the image. Stephen Benton¹ has designed a mirror system that avoids this problem by eliminating all direct shadows (Box 22.1).

Box 22.1 An anti-reflection mount for transmission holograms

The standard configuration for a mirror-backed transmission hologram is shown in Fig. 22.6: it has the disadvantage that the room behind is also reflected in the mirror.

Benton's principle is based on an angled mirror. The general principle is shown in Fig. 22.7. It takes up little room, and it certainly works.





Figure 22.6 When a WLT hologram is backed with a mirror the illuminating light IL produces an image beam IB that is reflected towards the viewer and a zero-order beam ZB that is reflected towards the floor. Unwanted room light RL is reflected straight back, degrading the image. Figure 22.7 If the hologram is mounted with a 45° mirror M behind it, ZB is reflected straight back towards the ceiling and IB towards the viewer; stray room light RL is reflected up onto the black baffle B. Note that the reconstruction beam has to come from below in this configuration.







Figure 22.9 A horizontal mirror permits ceiling illumination without reflections in a WLT hologram made with conventional overhead reference beam. Benton suggests fabricating a Fresnel prism with alternate mirrored facets and blackened lands (Fig. 22.8).

This arrangement requires the transfer reference/replay beam to be from below. By inverting the geometry the system would work for existing WLTs with an overhead reference beam, but this would require a floor-level replay light, which doesn't seem a good idea. Figure 22.9 shows a way of overcoming this problem.

Window displays

Holograms are becoming increasingly popular in large window displays, especially around Christmastime, when in northern latitudes it is dark by late afternoon. Such holograms are almost always large rainbow holograms with deep real images, and for the greatest impact they need to be mounted close to the display window.

In spite of their size, such holograms don't need a powerful illuminating source: a 24 V 100 W halogen lamp with a built-in reflector is usually sufficient. The light should be limited to the hologram area and not visible outside it.

Displays to accompany lectures and presentations

Anyone who needs to give a talk about holography has to be able to show some holograms in order to be convincing. In a brief talk during a conference on more general matters it may be sufficient to hold up a hologram in the beam of a slide projector or overhead projector, as in Fig. 22.1. But if you are giving an extended lecture you need a more positive demonstration. You can buy exhibition stands to assemble in various combinations for vertical displays. One type has display boards with a plain plastic surface, on which you can mount your holograms with Blu-tack or double-sided adhesive patches; other types have baize surfaces that require Velcro patches; or pegboard, which is less easy to use if your holograms are on film and unmounted, or are an unusual size or shape. The illumination source needs to be clamped to the top of the display board. The best sources are low-voltage spotlamps in extensible mounts with clamps designed to fit the edges of shelves; these are stocked by large furniture stores. A 12 V 50 W spot with a 60° beam angle will cover a 1 m square display board at a distance of a little over 1 m from its center; but at this distance the light towards the edges will not be at 45° , and you may not be able to use the board right to the edges. Two lamps with 30° beams will give a better, more uniform coverage. Their mounts should be one-quarter of the way in from the edges; you will need to shield them at the side so that the beams don't overlap in the middle.

The simplest way to show WLT holograms is to put a mirror behind them, and illuminate them from the front. It may not show them off to the best advantage, but any alternative will be cumbersome and time-consuming to set up. You don't need a front-surface mirror; an ordinary bathroom-type mirror will do.

If you are not in a position to carry an exhibition stand around, you can simply lay the holograms on a table, with your lighting above and behind it at 45° . Most domestic spotlights, even floor standing ones, don't usually extend very high. The collapsible lamp stands sold by photographic dealers are more suitable; you simply fix the spotlights to the top. If you are giving a talk to a local photographic club The Polaroid Corporation actually manufactured one of these for Benton, and it worked well; but the idea wasn't taken up commercially.

Though not so close as to force passers-by into the roadway in order to see the image properly.

Whether you allow this depends on the nature of your audience. In some venues, a heavy sheet of glass over the lot may be the only way to guarantee that you are going to have any holograms left when the audience has gone.

The result may not be what you would have wished, and you won't be popular with the organizers, who already have enough to do without finishing off your work for you.

If the acrylic sheet is scuffed, clean it up with ordinary metal polish.

It is a good idea to wrap rolled-up newspaper all round the edges first.

you will probably be permitted to use one of their 500 W spotlights. You may find that some of the holograms are not at the correct angle for viewing when they are lying flat, so keep a selection of small pieces of plywood or thick cardboard to place under the edges of holograms that need a bit of extra tilt.

Bring a laser with you: your audience will be expecting to see one, and will be disappointed if they don't. You will probably need to show an image produced by a laser transmission hologram, too. To do so, and to show the principles of slit masters and of Fourier-transform holograms, you need at least 5 mW of power, and a fairly dark corner. If you lock all the components on a triangular bench, including the plateholder, you can swing the whole setup during your demonstration so that everyone gets to see the image.

If your demonstration holograms are on a table rather than mounted on a vertical board, and you want the audience to come and look at them after your presentation, tell them you don't mind their picking up the holograms to examine them more closely (that is, if you really don't mind), but ask them to put them back in their original position.

Submitting holograms for exhibitions

If you are entering holograms for an exhibition, be kind to the organizers: find the optimum lighting geometry for each hologram and make a detailed sketch of it, with angles and distances, to accompany your entry. This applies especially to rainbow holograms, and will save the organizers a lot of time and trouble. Have the holograms adequately mounted and framed first, otherwise the exhibition organizers will have to do this.

Frame your reflection holograms in the same way as you would an exhibition photograph, preferably using a sunken mount. If you have to have a glass cover, use glass with an antireflection coating on the outside. You can laminate a film hologram to glass or acrylic sheet and avoid unwanted double reflections. Warm the cover glass, clean it, and place it on a layer of several sheets of newspaper. Take about 25 grams of plain cooking gelatin and add 250 cm³ of cold water. Warm this gently until the gelatin has dissolved, then pour an extended puddle of it onto the cover glass. Lay the film on the glass and squeegee it down from the center outwards, to get rid of any air bubbles. Wipe off the surplus at once, before it sets. For a more permanent mount you can use UV-curing cement, as described for DCG holograms in Chapter 20. You can also obtain optically clear doublesided adhesive sheets, which you can apply by hand to mount small transmission holograms; for anything larger than 8×10 in you need a laminating machine. For rainbow holograms that are going to be hung on cables, you will also need to drill out four holes at the corners of the sheet. If instead of glass you sandwich the hologram between two acrylic sheets, you can use hollow pop rivets in the holes. These will hold the sandwich together and provide support points.

Packing a hologram for forwarding to an exhibition

If you can, send your holograms in the form of films rather than plates. Where plates are unavoidable, tape styrofoam sheets on both sides. Cover each corner of this package with cardboard. Now wrap the whole parcel in bubble sheet, with the bubbles inside.

Then place the package in a hard case such as a suitcase lined with styrofoam, and label it with 'Fragile' and 'Glass' notices (you can get these from post offices). Finally (and most importantly), insure the holograms with a reputable company for the full amount you would expect to get for them if they were sold.

Organizing an exhibition of holograms

If you yourself are organizing a full-scale public exhibition of holography you are in a different situation altogether. You have the task of illuminating from thirty to two hundred heterogeneous holograms correctly, arranged so that a visitor can walk around and view each individual piece without the constant need to move closer or farther away, or to duck and weave (or, at worst, to bang heads with a neighbor). Posy Jackson-Smith, sometime Director of the Museum of Holography, New York, has written a paper (as Rosemary Jackson²), which deals in detail with these matters. It also gives examples of forms appropriate for exhibitors (loan forms, installation data etc.). The paper is too long to quote in full, but the points relevant to this chapter are summarized below, with the author's permission.

Lighting arrangements

The fixing of the lighting will vary according to the nature of the exhibition area. The easiest method for the spotlights, at least as far as adjustment is concerned, is track lighting, which allows you to position as many lights as you need in almost any location. Many galleries already have tracks installed. If you are unlucky in this respect, you may have to build a timber scaffolding system, screw the lamp holders to the cross members and run the cables along the top.

Light sources

- *Lasers* Use the lowest power you can, preferably 5 mW or less (in the USA the maximum permitted is 5 mW). To get the most out of the illumination, position the display in a darkened area, and expand the beam to fill only the area of the plate. If your source needs a spatial filter, fix it to the laser output port so that it can't become misaligned. Invite an official from your local health and safety authority to inspect your setup. This will cover you against any complaint from some member of the public who has misapprehensions about lasers.
- *Arc lamps* For large laser holograms you will need a 200–500 W arc lamp equipped with a narrow-band interference ('notch') filter. Compact-source xenon (CSX) and iodine (CSI) lamps are the only really satisfactory sources. The radiation from these sources generates ozone gas, and you may find that safety regulations require you to install extraction equipment. Notch filters usually have a bandwidth of about 5 nm, which is small enough to provide a good reconstruction of all but the deepest images. For small transmission holograms made using red or green laser light you can use a sodium lamp, with a small condenser lens and a 3 mm diameter aperture at its focus to improve the spatial coherence of the source. A filtered mercury-vapor lamp is suitable for both green and blue illumination.

A visit to a shopfitting equipment supplier may help to avoid a lot of work with saw and screwdriver.

In the USA you need to file details of your display system with the Department of Health, Education and Welfare well in advance. You can obtain details of laser display regulations from the Department.

CSX lamps have a source area of about 6 mm², CSI lamps somewhat less.

If a reflection hologram with a deep image shows blur from color dispersion, you can try an amber filter over the source (but bear in mind the exhibitor's wishes when you do this).

I know I have recommended a slight downward tilt, but in an exhibition open to the public it is safer to mount the holograms flush to the wall. The height needs to be a little less, about 1.6 metres.

If 2 m seems wider than necessary, remember that, in most cases, to view a hologram you need to be at least a metre away from it.

In small semi-permanent exhibitions it is a good idea to mount a number of appropriate holograms at waist level so that small children can see them without having to climb a step or be lifted up. One also needs to consider wheelchair users. • White light illumination Low-voltage straight-filament lamps are best for reflection or WLT holograms. The best illumination for reflection holograms is a purpose-built low-voltage spotlight. This produces a narrow hard-edged beam suitable for illumination of a single hologram or a small group. A much cheaper alternative is a small-source tungsten-halogen bulb of the type used for window displays. You can get these to cover angles as small as 15°. Very large holograms or arrays of holograms may need a 2 kW photographic spotlight. Rainbow holograms should have a less powerful source than reflection holograms, if they are not to dazzle the viewer. The beam geometry needs to be the same as was allowed for when the hologram was made. A straight-filament car bulb is usually adequate. The filament should lie along the axis of the beam, never horizontally across it. A vertical filament is suitable for Cross and flat stereograms.

Installing the exhibits

Structurally, the soundest method of hanging holograms for display is to mount them flush on the wall. Beware of hanging them on nails or hooks: at best they will be knocked awry; at worst they will be stolen. There are several types of fixing screw that will allow you to adjust the angle of the hologram if some 'tweaking' is needed.

Transmission holograms of all types look best when they are mounted in a corner. If this isn't possible, you may have to build alcoves for them instead. If they have to be mounted in the middle of the room because of lighting limitations, they are best suspended freely on 22 SWG pre-stretched brass wires. Don't use monofilament nylon, which is easily severed; and think hard before you decide to use floor-to-ceiling cables, except for the biggest WLT holograms. Spectators can trip over them and injure themselves, to say nothing of the possible damage to both the hologram and the fabric of the building. Mark any such fixings with brightly colored poles to keep stray feet away. You can also use heavy-duty camera tripods to support the holograms, provided you have the feet firmly fixed to the floor (Plate 3a).

From time to time there is a vogue for horizontally oriented holograms on coffee tables or the floor. If you have to show these, put a rope barrier round them, otherwise things may fall out of people's top pockets and damage the exhibits.

Floor plan

When you design the floor plan, bear in mind that it is the narrowest section of the gallery that will limit the traffic flow. If it is less the two metres wide it will prove a bottleneck. Also, exits have to comply with local and national safety regulations.

Establish a consistent eye level for all the exhibits, at a constant distance. This is important: people shouldn't have to expect to bob up and down in order to see images properly. Jackson suggests that exhibits should be mounted flush to the wall at a height of 1.85 m. She also suggests that plastic drinks bottle cases should be provided for children to stand on. However, in my own experience drinks containers are not very safe. Kick-step platforms as used in public libraries are less hazardous and are an esthetic improvement.



Figure 22.10 Typical plan views of viewing areas for display arrangements. (a) Laser transmission hologram; (b) reflection hologram; (c) WLT hologram; (d) cylindrical 120° stereogram.

Jackson summarizes: 'A good floor plan takes into account the traffic flow of the gallery, the installation requirements of the holograms on exhibition, the "feel" of the work, and the esthetics and intellectual flow of images round the room.' In drawing up a plan for an exhibition, each exhibit needs to be given a diagram showing the plan view complete with viewing distance, viewing angle and position of illuminating lamp (Fig. 22.10). Draw these to scale on card for each hologram, cut out the areas, and arrange them on a plan of the exhibition area drawn to the same scale. There should be no viewing overlap and no possibility of stray reflections.

Try to have a metre or so of free space between viewing areas. Restrict each light to the area of a single hologram or panel of holograms; otherwise you will produce ghost images in neighboring holograms.

Relevant information

In general it isn't necessary to provide a display of graphics showing the principles of holography, any more than it is necessary in an exhibition of photography to provide an illustration of how a camera works. Those who know already don't need to be told, and those who don't know probably don't want to know. What is much more

If you are used to juggling drawings on a computer screen you may prefer to do things that way. (Personally, I prefer pieces of card.)
important is to have a label beside each exhibit indicating the name of the artist, the type of hologram, the date it was made, sponsorship, production credits, and ownership (if relevant). Print these credits in a minimum size of 16 point and in a legible font such as Arial Black – not blown-up ordinary typescript such as pica, which is all but illegible from a metre away, and ugly into the bargain.

Environment

The ambient lighting, decoration, plants, furniture, etc., must support the exhibition and not distract from it. This particularly applies also to music. To my knowledge nobody has ever complained at an exhibition that the music was too quiet. If you simply must have music, keep it neutral, and don't keep repeating the same music, or the visitors (many of whom may later revisit the exhibition) will conclude that you can afford only one tape.

Make sure safety regulations are observed, that staff have an unobstructed view of the public, and that there is supervised space for leaving such potentially hazardous items as backpacks, umbrellas and large briefcases. See that small children are properly supervised, and discourage smoking. Make sure all the exhibits are kept clean and free from finger marks.

Keep a good stock of replacement lamps, and delegate someone to check the lights at least once an hour. Failure to replace a dud lamp promptly guarantees that within the hour the artist who made the hologram will be along to see how his or her piece is looking.

Finally, when the exhibition is over, take down all the holograms before you do anything else. As you do so, check each one, wrap it up carefully, make sure it is identified, and put it in a safe place. Only then should you begin dismantling the setup.

Photographing holograms

If you are organizing the exhibition you will no doubt need photographs of some of the holograms for your exhibition catalogue. If you are exhibiting, you will certainly need photographs of your own images. But don't attempt to take your own photographs unless you are an experienced photographer. Making successful photographs of holograms is not at all easy. Black-and-white (b&w) prints show up the laser speckle, present even in white-light holograms, as a graininess, unless you are careful about lens apertures. Color may be an important contributor to the esthetic effect, so you usually need to use color slide film rather than b&w; but some color films do less than justice to certain colors, notoriously the red of a HeNe laser beam. On the other hand, perhaps paradoxically, a good projected slide can sometimes show the qualities of a hologram better than a view of the hologram itself, especially if the original is small, shallow and dim (as was often the case in the early days of display holography).

One of the difficulties associated with the photography of straightforward holographic images of objects is that they tend to turn out looking like grainy, not quite sharp photographs of the original subject matter, so that one might as well have simply photographed the subject rather than its holographic image. You can see this in the two reproductions on Fig. 22.11.

In the early days of holographic exhibitions the accompanying music was invariably loud and weird. Holography has long outgrown its space-fantasy image, and deserves better.

Use a proprietary window cleaning fluid sprayed on the cloth, not the hologram, and always give your last wipe downwards.

Indeed, when examining photographs of representational images I have sometimes had suspicions that this may have actually been the case. However, you are assured that the photographs of Fig. 22.11 were indeed made from the holographic images and not the originals, which I never saw.



Figure 22.11 In a black-and white photograph of a representational hologram such as the Stations of the Cross in Coventry Cathedral, it is impossible to tell whether the photographs are of the holographic images or of the original subject matter. Sculptures by Malcolm Woodward; holograms by Advanced Holographics Plc; photographs by the author.

Although these superb sculptures were made with the medium of holography in mind, and although the three-dimensional holographic image, straddling the glass plate, itself produces an other-worldly impression that subsumes any *trompe-l'æil* effect, in a photograph the glass plate simply disappears along with the third dimension, and we are left with what appears to be merely a photograph of a sculpture, and a grainy one at that. Nevertheless, photographs of holograms are often needed (this book, for example, would be a great deal less attractive without them), and it is surprising that even professional photographers are often unaware of the special problems associated with the photography of holographic images.

Equipment

You can, of course, take photographs of holograms with any camera, just as you can make a hologram of anything you can see (including the image formed by a camera lens). But there are some difficulties. For a start, not every camera is really suitable. Compact cameras with built-in automatic flash are undoubtedly the most unsuitable of all. Two types of camera *are* eminently suitable, though: a single-lens reflex (SLR) camera, and a small studio camera. The former will normally be equipped with through-the-lens metering and optional manual focusing; the latter will possess lens and back movements.

It's almost impossible to obtain a good photograph of a hologram in an ordinary room, no matter how well illuminated it may be; you need a proper studio. That doesn't mean it has to be anything pretentious: a broom cupboard will do. It needs a shelf about 1.5 m from the floor, and a place to hang a good spotlight.

If the ceiling is too low, you can position the hologram lower, of course, or fix the hologram to the wall upside down and point the spotlight up from the floor, or

The best spotlight for this purpose is an old single-slide projector with clean optics. turn the whole setup on its side. It makes no difference as far as the photograph is concerned (though it may be bad for your back). For most purposes a 35 mm SLR camera with an 80–150 mm zoom lens is ideal. Automatic exposure control is useful, but automatic focus can be a problem, as it tends to home in on the nearest part of the image, sometimes even on the glass. (Set the focus to 'manual'.) The rest of your equipment will comprise a good solid tripod with a central pillar, extending to at least 1.5 m in height, a cable release, a piece of black velvet not less than 1 m square, and a bamboo cane a metre or more long. The make of color slide film you choose is a matter of taste. I use medium-speed Ektachrome for preference, but other films such as Fujichrome Velvia give higher color saturation. As a rule, avoid color print film: it can barely cope with the very high contrast of some holographic images. For b&w photographs use a medium-speed film such as Ilford FP4.

When you are setting up the camera, make sure the hologram fills the film frame as far as possible. Most cameras have viewfinders that show some 5% all round less than you actually get in the picture, so you can afford to crowd the image a little. The aspect ratio (ratio of width to height) of a 35 mm format is 1.5:1, but that of most holograms is lower, around 1.25:1. This doesn't matter with a b&w negative, as you can mask it down when you are making the print, but with a color slide you should arrange it in the viewfinder to fill three sides. When the slides come back from being processed, mask off the odd edge with blocking-out medium or black gummed strip.

Reflection holograms

When you set up the hologram, look for the highest contrast. Don't simply go for the brightest image; this will probably be at a slightly different angle, and is apt to be noisy and lacking in subtle tonal gradation. Use your piece of black velvet to cut out stray reflections. It needs a large hem (you can make this with a stapler) so that you can push your bamboo cane through it, to hold it up with one hand. Cut a cross in the center, big enough to go over the lens barrel. When you are about to take the photograph, hold the cloth up to cut out reflections from behind, with the lens poking through the slot. Check through the viewfinder that the cloth doesn't cast any shadow on the hologram (Fig. 22.12).

The main problem with the photography of reflection holograms – indeed, almost any hologram – is depth of field. To achieve maximum sharpness throughout the depth of the holographic image you need a small aperture, but this makes for an inordinately long exposure time (which may affect the contrast and color balance), and aggravates any speckle effect (Fig. 22.13).

The solution is to use the longest focal length lens you can, and the largest aperture that will give you the depth of field you require. The way to check depth of field at close range is as follows:

- 1. Focus on the nearest point of your holographic image. Note the point on your focusing scale.
- 2. Focus on the farthest point of the image that is visible. Note the point on your focusing scale.
- 3. Adjust the focus by moving the focusing ring on the lens until the 'focus' mark on the lens barrel is equidistant from the two marks (Fig. 22.14).

A four-foot bamboo cane is an awkward object to carry in a bus or train. When I regularly took publicity photographs at holography exhibitions I used the telescopic leg from an old camera tripod. A telescopic radio aerial would do equally well.



Figure 22.12 A black cloth (BC) with a hole for the lens eliminates reflections from stray light (SL).

4. Set the lens aperture to that indicated by the limits (i.e., read off the *f*-number indicated on the lens barrel opposite these two points), and make your exposure.

In restricted spaces a zoom lens simplifies the photography, as you are able to frame the hologram in the viewfinder without the necessity of moving the camera



Figure 22.13 The effect of varying the lens aperture. (a) At the largest aperture (f/5.6) there is little laser speckle evident, but the depth of field is barely sufficient; (b) a medium aperture (f/11) represents a compromise; (c) at the smallest aperture (f/22) depth of field is a maximum but the speckle is obtrusive.



Figure 22.14 Setting the focus and lens aperture. In this example the nearest part of the image was at about 1.3 m and the farthest part was at about 1.65 m. These two distances are bracketed across the focus mark and the optimum aperture is indicated (in this case f/5.6).

and tripod back and forward. A macro (close-up) facility is also useful, for the occasional small hologram. With the zoom lens you should try to avoid the extremes of focal length, as there is usually a measure of distortion at both the maximum and minimum settings.

For most holograms the exposure indicated by your meter will be correct. However, if the image is on a dark background you should give only half the indicated exposure. Conversely, if it is on a bright background, you should give double the indicated exposure. If your camera has exposure control overrides, use the ' $\times \frac{1}{2}$ ' and ' $\times 2$ ' settings: if it doesn't have this control, reset the film speed indicator to twice and to half the ISO film speeds respectively. If you have plenty of film, bracket the exposures a further notch up and down as well.

If you bracket your exposures in this manner you may find with some rather highcontrast images that one of your transparencies shows a correct exposure in one part of the image and underexposure in another part, whereas another shows a correct exposure in this part but overexposure in the first. In this case you will get a much better result (if you are able to go back and re-shoot) by using the 'dodging' techniques that skilled photographic printers use when making topquality prints. As applied to holograms the technique is simple: you hold your hands, or a piece of paper torn roughly to the shape you want, in the illuminating beam for part of the exposure, to hold back the overexposed area. If you are used to doing this in a photographic darkroom, you will find it easy enough.

One characteristic of reflection holograms that is more obvious in a color photograph than in ordinary viewing is dispersion, which causes out-of-plane parts of the image to appear color-fringed and unsharp. If the hologram is monochrome you can improve the image quality by using a narrow-band filter of the same color as the main color of the image on the camera lens. This applies to both b&w and color films.

Although color transparencies are the most generally useful type of photograph, you may want to use b&w or color negative film to make prints. You can then do the dodging in the darkroom, and your main concern in the photography will be to obtain adequate exposure in the shadows. You can usually rely on your automatic exposure control, as with negative films there is much more exposure latitude; but you still need to give extra exposure to subjects with bright backgrounds.

If you have a computer with facilities for image manipulation, you can often improve an image by altering its shadow and/or highlight quality, to match what

At the shortest focal length the image bulges at the edges (barrel distortion); at the longest it sticks out at the corners (pincushion distortion).

You will also find it easy if you are good at making rabbit shadows on the wall at children's parties. Remember, though, that with color slide film, *more* exposure means a *lighter* result.

This is because exposure meters are calibrated for an average gray, and when confronted by a subject that is unusually bright they simply reduce the exposure. you saw in the holographic image more closely. This becomes even easier if you are working with a digital camera, as you can download the image directly into the computer without the trouble of scanning. You don't need a sophisticated program such as Photoshop: the 'paintbox' facilities that come with word processor programs are adequate.

Transmission holograms

If you need to photograph holograms made for scientific purposes you have a different set of problems. The image produced by a laser transmission hologram can be of great depth and very high definition, with a wide angle of view and high contrast. Use a medium speed b&w film, and if you process the negatives yourself give a generous exposure and develop the film to a lowish contrast. In order to get the whole image in, you may need to fit a 28 mm lens (or a 21 mm lens with a small-format digital camera). A short-focus lens will also help to give the depth of field you need without your having to close the lens aperture down more than one or two stops. This is important, as a small aperture aggravates laser speckle (Fig. 22.13).

A further possible complication is that red laser light may fool your exposure meter, which is balanced for white light, another good reason for bracketing your exposures. This problem is less likely to occur with green laser light. If your photographs are to show the red (or other color) of the image on a printed page, don't use color material, but arrange with your editor to have your b&w print reproduced in the appropriate color, along with a gray printer. If you have your own printer, you can do this yourself, of course, and send your copy in as you wish it to appear.

Rainbow images are less subject to speckle effects than laser-lit images, which is just as well, as they often possess considerable depth, and you may have to use a small aperture to obtain sufficient depth of field. Again, you can use b&w film and have the result colored appropriately, but in my own experience color slide film gives a greater subtlety of tone, and in any case many of today's rainbow holograms are in more than one color.

With rainbow holograms, it's not sufficient just to park your camera in front of the hologram, adjust the zoom to fill the frame, and shoot. Start with the camera about three times the width of the hologram away, and study the image through the viewfinder. If you are the correct distance away, and at the correct height, the image should be all in a single hue (for a single-color image), bright, and yellow-green. If you are too close the image will be red at the bottom and blue at the top. If you are too far away, the image will be blue at the bottom and red at the top, and the upper and lower edges of the image may not be visible at all. In a multicolor image the hues will be wrong, too. Once you have found the correct distance the basic hue will be uniform over the whole image. Now you need to adjust the height of the camera until the colors are right. (See Fig. 18.10.)

All rainbow holograms are astigmatic, with the vertical aspect of the image being in the plane of the plate regardless of where the horizontal aspect of the image may be. Unless your camera is at the correct distance from the hologram, you may get some vertical-horizontal distortion in the photographic image. There is a small discrepancy between the point of zero distortion and the point of uniform hue. The uniform-hue plane is at the vertical focus, whereas the zero-distortion plane is at You are likely to need the full height of your tripod, if you are working at an exhibition. This is where the SLR camera comes into its own: what you see through the viewfinder is what you will get in the transparency.

You can test this by turning your head sideways while viewing a rainbow hologram: the image will suddenly flatten itself onto the surface of the plate. the horizontal focus, and these planes may not coincide. In practice, the most satisfactory result in a photograph seems to be to go for uniform hue. A visual inspection through a narrow-band yellow-green filter makes it easy to find this plane.

Transmission holographic stereograms have a reconstruction geometry that is very similar to that of a straightforward rainbow hologram, and the same rules apply to the photography of these images. However, it is very difficult to obtain a satisfactory photograph of a Cross hologram, as you can see from Fig. 19.5. This is partly because the vertical aspect of the image is some 150 mm nearer to the viewer than the horizontal aspect, and partly because of a mismatch between the printing and viewing optics, which add a further helping of vertical–horizontal astigmatism. The only way to get anything like a satisfactory photograph of a Cross hologram is to use a long-focus lens and set up the camera as far as possible from the hologram. Even so, the image will probably look as though El Greco had a hand in its production.

Transmission holograms are in general much brighter than reflection holograms, and if you have to photograph them *in situ* they are often bright enough to permit a hand held exposure (1/15-1/30 s), whereas reflection holograms usually demand several seconds. But beware of taking casual photographs without a black cloth: you will find a self-portrait superimposed on every image. For a rainbow hologram you will find it helpful to have an assistant holding a second black cloth behind the hologram. In the end, the only way to be totally fair to the artist concerned, as well as to yourself, is to photograph transmission holograms in your own studio, where you can take your time, and experiment with distances and angles until you are satisfied that you have caught the best possible image.

Viewpoint and parallax

Although they operate on different principles, a photograph and a hologram have much in common, visually speaking. The important difference, of course, is the three-dimensional nature of the holographic image, and a single photograph can't show this. Although holographic reproductions do sometimes appear in books, there is as yet no satisfactory way of printing them on paper. In addition, printers' inks fall short of the requirements for accurate reproduction of the vivid colors of a multicolor hologram. Good as the plates in this book may be, they don't stand comparison with the original transparencies, let alone the holographic images from which they were made.

One partial way round the problem of depicting three-dimensional imagery on a printed page is to make photographs in stereoscopic pairs. When these are examined via a stereoscopic viewing device the impression of depth can be very strong. If you have a portfolio of large holograms that you are unwilling to carry around to potential clients, or if you want to send sample transparencies to the organizers of a forthcoming exhibition of holography, stereo pairs of photographs represent the next best thing. All you need to do is to make two exposures with the camera moved horizontally through 6–7 cm between the exposures. Keep the film plane parallel to the hologram surface if you can, rather than toeing in. If you want the images to be in the correct order for viewing, take the left view first.

If you do need to toe in the camera, you may find the images show 'keystone distortion', i.e., the hologram frame appears trapezoidal rather than rectangular.

This is for cameras that wind the film from left to right, as almost all 35 mm cameras do. Keystoning can sometimes cause problems with stereoscopic viewing. This is where the studio camera, with its lens and back movements, comes in. It is of no importance if the viewpoint is off center, as long as the camera lens and back are parallel to the hologram plane: the image will still be rectangular. You simply center the image by adjusting the camera back. A 35 mm camera with a perspective-control ('shift') lens will achieve the same result, though the short focal length of this type of lens may raise other problems.

Unusual holograms

To record the image qualities of multi-image holograms that have a number of different images appearing as you change your viewpoint, you will need to take as many shots as will cover all the variants. Holographic stereograms with animation will usually need at least three; complex multi-image holograms may need twelve or more to do justice to the creative powers of the artist. Mixed-media pieces are perhaps the most difficult to photograph (Plate 16); in some cases the only way to obtain a satisfactory result is to photograph the holographic and non-holographic material separately, and combine the images via a computer program such as Photoshop. This problem can also occur where the frame of the hologram forms an integral part of the overall composition. If you have an assignment to photograph a piece of this kind, forget about getting everything into one shot. You will simply have to put things together on your computer, or find someone with the know-how to do it for you.

Photographing holograms at exhibitions

Often your only opportunity to get a photograph of a display hologram may be at an exhibition. Sometimes you may find it necessary, for example if you have been asked to write a review of the exhibition. There is a protocol about this. For a start, unless you have an official invitation to a press viewing, you *must* obtain permission from the management to photograph the exhibits. The next thing to do is to try to contact the artists and ask them if they already have photographs of their work.

Once you have the go-ahead, make sure the holograms are clean and free from fingermarks. Use the black cloth (don't be embarrassed, any bystanders will admire your professionalism), and bracket the exposures. If you are short of film, keep the exposure low for color slide film and high for b&w.

Using flash

Every exhibition seems to have its quota of visitors who take photographs of the exhibits using a compact camera with built-in flash, with results that are likely to be about as successful as trying to photograph a cinema screen with a flash. But it is possible to use flash in a sensible and fruitful manner. You need a dedicated flash (that is, one that is connected to the camera exposure control), and an extension lead. Hold the flash head in the illumination beam, as far up the beam as you can reach. Align the flash head: its shadow should be a clean rectangle, not a hexagon. Center the image in the finder, and shoot. The flash will swamp any stray

In my experience this can sometimes lead to some embarrassment: not all holographers are expert photographers. reflections. You don't need a tripod, but you do still need to control the exposure for dark or light images.

You can use a flash for rainbow holograms, too, but you need a much longer extension, and an assistant to hold the flash head in the correct position. In order to minimize stray reflections, use maximum flash power and minimum exposure time.

Presenting slides of holograms

Every lecture seems to have at least one slide either the wrong way round or upside down.

It shouldn't be difficult. In all standard projectors the slide goes into the projector gate upside down but right way round when you are looking through the slide at the screen. There is an international standard for marking slides so that they can be inserted without reference to their content: it is to have a spot at the bottom left corner of the slide when it is viewed correctly on a viewing table. In the slide magazine the spot goes at the top right of the slide away from the screen.

Copyright

All works of art are automatically copyright in all countries, and if you make a replica of someone else's work without permission (except in some narrowly defined circumstances) you are breaking the law. You are certainly breaking it if you make a contact copy or a transfer of someone else's hologram without authorization. Even photographing someone else's hologram without permission may be illegal, as well as making a hologram of somebody else's photograph.

In fact, making a photograph or a photocopy of *any* copyright material is illegal in the strict sense of the word, though people often do so innocently for private or educational purposes. However, if you take a photograph of someone else's hologram at a public exhibition you are likely to become unpopular with the public, whose view you obstruct, with the management, who are concerned with safety, and not least with the artist, who may already have a supply of excellent photographs.

It hardly remains to be added that if you are the holographer yourself, it is a good idea to learn how to take your own photographs, be your own publicity agent, and protect your work at the same time. After all, you are the best person to judge whether a particular photograph (or stereo pair) does justice to your work. What is more, the practice of photography, which has so much visually in common with holography, will give you fresh insight into the creative side of holography itself.

References

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- 2. Jackson, R., 'Exhibition techniques and materials for holography', *International Symposium on Display Holography, Lake Forest*, Vol. 1. 1982, pp. 215–38.

In many years of attending such lectures, I have yet to hear the presenter express surprise, much less apologize for the error. It seems to be universally regarded as inevitable. Those who are familiar with Murphy's Law point out that there are eight ways of loading a slide into a slide tray, and seven of them are wrong.

If you fail to mark your slides in this manner, Murphy's dice will be heavily loaded against you.

This is because the word 'photograph' has been replaced by 'image' in a recent legal definition of copyright.

You may find that the artist would be happy to enter into an agreement over royalties for photographs, to your mutual benefit.

Part 3 APPLIED HOLOGRAPHY

Chapter 23 Holography and measurement

'While you're refreshing yourself,' said the Queen, 'I'll just take the measurements.' And she took a ribbon out of her pocket, marked in inches, and began measuring the ground and sticking little pegs in here and there.

Lewis Carroll, Through the Looking-Glass

The potential of holography in measurement science was appreciated early in its history. A branch of applied photography known as 'photogrammetry' had existed since the First World War, where it had had its origins in aerial photographic reconnaissance, and had soon become an important tool in map-making.

An early discovery in photogrammetry was the ability to estimate the heights of surface features by examining the images in adjacent overlapping photographs with a stereoscopic viewing device. These techniques soon became applied to other measurements, including the human body. The arrival of holography, with its potential for direct measurements on a three-dimensional image, seemed almost too good to be true, though its application to metrology in this respect proved to be less immediately useful than anticipated.

However, the fortuitous discovery of a different holographic technique, now known as *holographic interferometry*, proved to be more fruitful. It quickly became clear that it could provide a method for precise measurement of very small distortions and displacements. Two somewhat different approaches have also developed from the same principles, both using laser light (but not holography as such). These are *speckle interferometry* and *shearography*. Though a full description of these two techniques is outside the scope of this text, they complement holography in many ways, so I have included a short discussion of the principles involved.

Direct measurements using holography

Nils Abramson¹ describes a laser transmission hologram as 'a window with a memory', and points out that all the measurements that can be made through an ordinary window can also be made through a holographic plate of the same size. Provided that (a) the glass plate is of high optical quality, (b) there is no distortion of the emulsion during or after processing, and (c) the reconstruction geometry is identical with the exposing geometry, the precision of measurement that is theoretically possible is equal to the diffraction-limited resolution, which depends only on the wavelength of the laser and the dimensions of the holographic plate.

For measurement purposes the hologram is usually reversed in its holder in the collimated reconstruction beam, to produce a real image that is suitable for direct measurement. Tozer and Webster² show that a holographic image formed by a one-metre square plate at a distance of 1 m from the plate can have a resolution of 1 μ m. (For an 8 × 10 in plate the resolution is less, around 6–10 μ m.)

Kilpatrick and Watson³ discuss the problems of underwater holography in the context of structural examinations of oilrigs, in particular the aberrations resulting

Photogrammetry is the use of photography for measurement purposes. By analogy, the use of holography in measurement is termed hologrammetry.

Metrology is the science of measurement.

The replay beam must have exactly the same wavelength as that of the exposing laser, of course. Where a ruby pulse laser has been employed for the exposure, a tunable dye laser or an appropriately tuned diode laser is used. from the need to shoot the hologram under water but display it in air. They show that if the dimensions of the holographic camera faceplate and the air cell in front of the faceplate are correctly chosen, a change from the 694 nm of the ruby exposing laser to the 514 nm of the argon viewing laser provides almost exact compensation.

Further applications in direct measurement by holography include microscopy and particle analysis. These are discussed in Chapter 26, along with several other potential and actual uses of holography in direct measurement.

The principle of holographic interferometry

A hologram is a photographic record of the stationary interference pattern generated by an object beam and a reference beam. In interferometry, this interference pattern is said to be made up of *primary fringes*. Much larger patterns, known as *secondary fringes*, appear on the holographic image if the object or the plate has been moved by a small distance while being exposed. They are a moiré pattern generated by two sets of primary fringes that have been slightly displaced relative to one another.

The phenomenon of secondary interference was noticed in the early days of holography, but the first analysis of it appeared only in 1965, when Powell and Stetson⁴ showed the potential value of secondary fringes in the analysis of vibration. Since then, holographic interferometry has become an important technique in the analysis of stress, vibration and fluid flow, and in quality control and non-destructive testing.

Real-time interferometry

If you make a laser transmission hologram of a rigid object, and leave the object in position while you process the plate, you can return the processed plate to its holder and, provided nothing has moved, the object will coincide precisely with its image. But if you then distort the object slightly, by squeezing it between your thumb and forefinger, or warm it a little with a hairdrier, you will see a pattern of secondary fringes sweeping across it as you apply the stress (Fig. 23.1). The greater the applied stress, the closer together will be the fringes. Because they are produced in real time they are called *live fringes*.

Each whole secondary fringe represents one wavelength of optical path difference between the wavefront from the 'undistorted' image and the wavefront from the 'distorted' object. This represents one half-wavelength of distortion, because the light is reflected, and one half-wavelength out plus one half-wavelength back equals one whole wavelength. This optical path difference is along the line of sight.

In practice, when you place the processed plate back in its holder, a few fringes do usually appear. You can usually reduce their number to one or two by gently tapping the plate. A fringe field with only one fringe is said to be 'fluffed out'. If you don't see any fringes at all, there is probably a large repositioning error. (You may even be able to see a double outline.) As you adjust the outlines to coincide the fringes will appear, and you can then begin to minimize their number.

In practice live fringes are generally used as a run-up to more permanent forms of interferometric record, such as those described below. By making a few test loads

Moiré patterns appear whenever a regular grid pattern is superimposed on a similar pattern with a slightly different pitch (or orientation), The closer the two pitches are, the larger will be the pitch of the moiré pattern. An acoustic analogy is the beat that occurs when two notes of slightly different frequencies are sounded together; the frequency of the beat is the difference between the two generating frequencies.

What is happening is that the wavefront from the object itself is interfering with the wavefront from the object as it originally was, re-created by the hologram. By the way, the words 'stress' and 'strain' may seem synonymous to the layman, but to engineers they mean different things. *Strain* is the measured distortion of a component resulting from the *stress* (force) that causes it. I use these terms in their strict sense throughout this chapter.

Interferometry has long been used in checking the accuracy of lenses and optical mirrors, using the partially coherent light of a mercury lamp, but this technique works only at close quarters, and with optically polished surfaces. Holographic interferometry works at any distance with any type of surface, which gives it a considerable advantage. you can see the amount of stress needed to generate fringes that are wide enough to count and evaluate.

Real-time holography originally seemed promising for the quality control of very accurately machined components. It would only be necessary to make a hologram of the pattern, then to introduce production components into the image space, one at a time and look for fringes, which would contour any discrepancies. However, simpler techniques based on speckle interferometry (which uses television rather than wet processing) have taken over this area of technology.

Double-exposure interferometry

To obtain a more permanent record of interference patterns produce in this way, you need to use the method of *double exposure*. With this technique you don't process the hologram directly after the first exposure, but leave it in its holder while you apply the load. You then make a second exposure. On processing you will have a permanent interferogram, from which you can obtain information on the strain by counting the fringes. This method is called the *frozen-fringe technique*. A typical setup for interferometry is shown in Fig. 23.2. This is based on the bypass configuration, with the object and reference beams at a fairly small angle to each other, and symmetrical to the plane of the plate.

Use of a CW laser, with exposures of several seconds, demands a fully stable optical system; but this kind of setup is unsuitable in many situations. Using a pulse laser, with a pulse duration of a few nanoseconds, you can make



Figure 23.1 An example of live fringes. If the subject remains in position while the hologram is displayed in its original holder, any distortion (here produced by a bulldog clip at the top of the cup) results in the generation of secondary fringes that contour the distortion. This hologram was made using the plateholder of Fig. 23.12.

Every test will probably demand its own geometry: Fig. 23.2 is just one possibility, which I have used regularly for demonstrations.

Figure 23.2 Table layout for an interferogram, using a bypass configuration. The subject and mirror lie on the surface of a paraboloid with its focus at the centre of the hologram H and its axis along the collimated beam. The object and reference beams are at equal angles of incidence to the hologram so that the secondary fringes will indicate displacements perpendicular to the hologram plane.



Figure 23.3 Holographic interferograms of a turbofan. (a) Stationary fan in stable vibrational mode. (b) Shear interferogram of the same fan rotating at high speed. Holograms by P A Storey and R J Parker. Photographs courtesy of Rolls-Royce Plc.

interferograms of moving objects. The laser is set to produce double pulses, typically separated by a few microseconds; the result is an interferogram that shows the amount of movement that has occurred in the interval between the pulses. This technique is known as *holographic shear interferometry*. If the component has a large lateral movement it may be necessary to use some form of motion compensation. This is easy to achieve in the case of rapidly rotating components such as turbofans by employing an optical de-rotator (Box 23.1). An example of the use of this technique is shown in Fig. 23.3.

Unfortunately, as light travels only $30 \,\mu\text{m}$ in 100 fs, and this distance defines the coherence length of the pulse, holographic interferometry with such a light source is out of the question.



Figure 23.4 Abbe derotating prism configuration with optical path in air, mounted in a hollow shaft.

Box 23.1 Principle of de-rotation

A pulse laser with a typical pulse duration of 25 ns can produce a good-quality hologram of an object that is moving at around 8 m s^{-1} . Picosecond (ps, 10^{-12} s) and even femtosecond (fs, 10^{-15} s) lasers exist that could in principle 'freeze' a high-speed projectile sufficiently for a hologram.

However, if you try to make a shear interferogram of a rapidly moving object using a double pulse, the translational displacement of the subject between the two exposures is too great for any useful information about vibrations, etc., to be derived from the holographic image. As many engineering problems are associated with the vibrations of high-speed fans, compressors and other rapidly rotating components, it is necessary to find some way of stabilizing the image. A practical solution is to use an *optical de-rotator*. This is a prismatic device that inverts the image by multiple reflections; the one most used is the *Abbe prism* (Fig. 23.4). When this prism is rotated about its optical axis the image also rotates in the same direction, but at twice the speed. If such a prism is positioned in the optical path of an image-forming device such as a camera lens and rotated in the direction opposite to that of the rotating object and at half its rotational speed, the image will remain stationary in the focal plane.

There are several types of inverting prism that will do this job, but the Abbe prism is chosen because it can be built with mirrors instead of solid glass, making a much lighter structure. The hologram itself is a focused-image hologram, made using a modified 35 mm camera.

Time-average interferometry

One of the simpler holographic interferograms to make is of an object that is vibrating in a stable manner. This technique, which can often be employed using a simple Denisyuk configuration, is called *time-average interferometry*. Although a vibrating object appears to be in continuous motion, it is instantaneously stationary at the two extremes of its movement. You can see this if you clamp a metal rule in a vise and watch it from the side as you twang it with your finger. You can clearly see the extremes of movement; it looks like two separate blades, while the rest of the movement is blurred out. Although the time spent at the extremes is infinitesimal, the time spent in the immediate neighborhood of the extremes, say within one-tenth of a wavelength of them, can be a substantial portion of each cycle (Fig. 23.5).



Figure 23.5 Time-average interferometry. (a) Wide excursion, (b) narrow excursion. The apparent position of the fringe is near the midpoint of the 0.1λ width at the ends of the excursion *A* and is slightly less than *A*. The relative length of time spent within the 0.1λ width (*b*/*B*) is a function of *A*, and is greater at lower amplitudes.

So if you want to investigate the modes of vibration of a loudspeaker, the belly of a violin or guitar, or even a car silencer, you set it in steady vibration using a suitable transducer, and make a hologram of it using a CW laser (Fig. 23.6).

Successive fringes denote an out-of-plane movement of approximately one-quarter of a wavelength per fringe.



Figure 23.6 Time-average interferograms of a microwave transceiver dish, showing the vibration modes at three different frequencies. The nodes are the brightest parts. Holograms by Jonathan Davies.

Not one-half as you might think. The fringes are measuring peak-to-peak displacement, not zero-to-peak. This is the same function as defines the position of the zeros in the Airy diffraction pattern.

A chopper is a disk containing a number of apertures, set up so as to interrupt a laser beam, and rotated rapidly to produce repeated pulses for stroboscopic illumination.

360

In practice, an excursion of only a few wavelengths produces quite a loud sound, but you need to increase the input as the pitch rises: in order to obtain good fringes at 9 kHz you need a fairly powerful squeal.

Although time-average interferometry is comparatively easy to set up, there are difficulties associated with the quantitative analysis of the fringes. First, the contrast of the fringes falls off rapidly as the fringe number increases; secondly, the fringe spacing does not follow a linear rule, but the zeros of a Bessel function.

However, it is easy to spot the parts of the object that are stationary (the nodes of vibration), as they are the brightest parts of the image. This type of hologram is best used for visual judgments. For analytical purposes it is preferable to use shear interferograms.

Strobed interferometry

Another of the limitations of time-average interferometry is that it records only a comparison between the two extremes of the vibrating object. It isn't suitable for unstable vibrations or transient movements and doesn't show the relative phases of the various modes of vibration. It would be helpful to be able to compare the extreme positions of the vibrating surface with the position of the surface at rest. It would be even better to be able to compare *any* position with the rest position. Shear interferometry does this: you can compare any two positions by varying the interval and timing of the pulses. Alternatively, you can make a first exposure with the surface at rest, followed by a second one while it is vibrating, at a point triggered by the voltage input to the transducer. One of the most rewarding methods for investigating vibrations in real time is a strobed live-fringe technique. For this you begin with the surface at rest coinciding with its holographic image, illuminated by a CW laser with a chopper in the beam. The chopper is synchronized to the transducer frequency. By adjusting the chopper frequency to be slightly less than that of the transducer you can see the fringes moving in and out, and make a visual assessment. (This was the method we used for initial assessment of the resonances of the component illustrated in Fig. 23.6.)

Visualization of fluid flows

In aerodynamics and ballistics research an important requirement is the visualization and analysis of shockwaves and vortex phenomena. The traditional way of doing this is by schlieren photography. This is a technique that involves a beam of collimated light passed through a transparent-sided workspace in a flow tunnel and focused on a knife-edge before being expanded again to be recorded on film. As any density gradient in the fluid in the workspace implies a gradient in the refractive index, any such region causes light passing through it to be refracted upwards or downwards, clearing or fouling the knife edge and resulting in a light or dark area in the image. A more sophisticated version employs narrow strips of color filter material instead of the knife-edge. Mathematical analysis of a schlieren image is difficult, as it records density gradient rather then actual densities, and holographic double-exposure interferometry is both more elegant and more readily analyzable. The principle used is related to that of the Mach–Zehnder interferometer (Fig. 23.7), though in holography only one chamber is required as a rule.





Using a pulse laser, a holographic exposure is made of the chamber alone, filled with air or some other gas as appropriate, followed by a second exposure recording the event itself. Any variation in density will alter the optical path length, generating secondary interference fringes that record the changes in density directly. The result not only shows internal detail that does not appear in schlieren photographs, but does so in three dimensions. Real-time techniques are possible: thermal convection can be observed directly, and phenomena such as vortex streets can be examined by still photography or video recording. Figure 23.8 shows an



Figure 23.8 Visualization of fluid flow patterns in a labyrinth seal. Hologram by R J Parker. Photograph courtesy of Rolls-Royce Plc.



Figure 23.9 Two interferograms made with the reference beam turned through a right angle between the exposures can have their information correlated to yield data on both in-plane and out-of-plane deformation of the test object. The exposure may be made on two separate holograms, or on a single hologram in one exposure.

The camera used in the de-rotation setup described earlier operates on similar principles.

example by Ric Parker⁵, who was responsible for the development of holographic non-destructive testing at Rolls-Royce Aero Engines.

One of the important uses of holographic interferometry has been to confirm predictions made by finite-element computations. In this respect it has had a marked success (Parker and Jones⁶).

Doubled illuminating beams

The fringes in a double-exposure interferogram show the amount of displacement in a direction that bisects the directions of the object and reference beams. Although the fringes are located in the object plane when the hologram is viewed from the front, they move when the position of the viewer is changed, hindering analysis. One way of overcoming this problem is to set up the table with two alternative reference beams at right angles to one another. Two holograms are made, one with each beam. The results can be correlated to show true in-plane and out-of-plane movement, by a method that has been described by Nils Abramson⁷. The arrangement is shown schematically in Fig. 23.9.

A camera for holographic interferometry

In order to carry out preliminary investigations, and for teaching purposes, it is helpful to have a device that can produce interferograms under ordinary laboratory or workshop conditions. David Rowley⁸ has modified a 35 mm camera to produce focused-image double-exposure interferograms. Owing to the reduction in scale the images are effectively two-dimensional. By fitting a narrow-band or 'notch' filter on the lens the camera can be operated under more or less normal room lighting conditions, using a 5 or 10 mW laser. Figure 23.10 shows the optical arrangement for a camera modified to produce reflection holograms; Fig. 23.11b shows a later version by the same team in which the reference beam is led in via an



Figure 23.10 A 35 mm camera adapted for focused-image holography by David Rowley. The optical image of the subject 0 is focused on the film in the usual way. The camera lens also focuses the reference beam from the mirror M_1 , which passes through the edge of the frame and is reflected onto the back of the film by the built-in mirror M_2 . Another version of the camera, shown in Fig. 23.11, leads the reference beam to the front of the film via an optical fiber.



Figure 23.11 (a) Double-exposure interferometry of a stressed plate; (b) the modified 35 mm holographic camera. The optical fiber carrying the reference beam is visible in the centre of the photograph. A deep red filter enables work to be carried out in dim room lighting. Photographs by Ken Topley, courtesy of Department of Engineering, Loughborough University.

optical fiber; this is a much simpler adaptation that produces focused-image transmission holograms (Fig 23.11a).

Sandwich holography

In ordinary double-exposure interferograms there is no way of telling for certain whether any out-of-plane movement was towards or away from the viewer, because the plate has no way of recording which of the exposures was made first. In live-fringe holography it is easy to find out simply by pushing the object with a finger and seeing whether the number of fringes increases or decreases; but this method works only as long as the holographic setup remains in place.

A technique known as *sandwich holography* provides a solution, and adds versatility to the double-exposure configuration. The principle of sandwich holography, which has been developed and refined largely by Nils Abramson, is that the two exposures are made on separate plates, which are then combined in an accurately alignable plateholder. The system allows you to make as many plates as you need with the object under various loading conditions; when they have been processed, you can view them in any combination of pairs. One important advantage it that you can compensate for any rigid body motions of the object between the exposures, so that the fringes caused by deformation can be isolated from those resulting from translational movements.

There is one very important requirement, though. You have to be able to reposition the plates with absolute accuracy, and to do this you need a plateholder that has this capability. Fortunately, it isn't too difficult to make one. The most effective plateholder is one that holds the plate in position by gravity alone, with a slight tilt back and to one side, using locating pins as supports (Fig. 23.12).

As there are always two plates in a sandwich hologram there must be two plates in position for each exposure. In all cases the emulsion faces the object. The front plate from the second exposure is placed in front of the back plate from the first exposure. Abramson⁹ recommends using two unexposed plates for this rather than one unexposed plate and a plain glass plate, as there will then be the possibility of combining any pair of holographic records.

If your labeling system breaks down and you mix up the plates from a single exposure, you can sort out the correct order by simply fitting them to the plateholder. If they are in the right order there will be only one or two fluffed-out fringes, but if they are in the wrong order there will be a set of concentric circular fringes.



Figure 23.12 (a) Gravity plateholder (after Abramson⁹). 1, 2 and 3 are ball bearings; 4, 5 and 6 are metal pins. The plate is thus constrained in all six degrees of freedom. (b) A plateholder constructed to these specifications for the author's lab.

You can make any combination permanent by bonding with cyanoacrylate cement ('superglue'), using a tiny drop at two opposite corners and pressing the center of the front plate gently on to the rear plate for a few seconds.

It is a good idea to include a reference surface in the hologram area, for example a piece of metal block that doesn't undergo any distortion between exposures, as a check. (It should not show any fringes, other than perhaps a single fluffed-out one.) To see whether a specimen became distorted towards or away from the hologram plane, tilt the sandwich until the fringes disappear from the surface, or at least become much fewer. The sandwich plane will then have been tilted in the same direction as the distortion of the object, but with a magnification of about 2000 times, making it easy to see. With a little practice you will be able to do this handheld, and to scan the surface for more complex distortions.

Evaluation of fringe patterns for both out-of-plane and in-plane movements is a much less tricky business than with conventional double-exposure or time-average holography. A complete account of the technique appears in Abramson⁹. Figure 23.13 shows examples of the operation of sandwich holography with a simple test object made of L-shaped strips of metal.



Figure 23.13 The sandwich principle. (a) 1-gram weights have been placed on the two L-shaped central strips, which face forward and backward respectively. The outside strips are unstressed, and when the hologram is tilted the fringe pattern is approximately the same on both. (b) When the sandwich is tilted away from the viewer the number of fringes in the strip bent towards the viewer decreases; (c) when the sandwich is tilted away the reverse occurs. The fringes in the reference strips can be used to assess the degree of tilt.

When you evaluate a sandwich pair, they must be in a beam with exactly the same divergence as the original reference beam. If you are working with this technique, keep the original rig until you have finished all the evaluation.

Reference mirror rotation

This is an alternative method of resolving the direction of movement of the specimen under test. It is described in a paper by Boxler *et al.*¹⁰ Between exposures in an otherwise conventional double-exposure interferogram, a mirror in the reference beam path is rotated by a very small angle (a few microradians) in a direction that increases the angle of incidence of the beam. The secondary fringe structure is not affected, except that it leaves the surface of the object slightly; the result is that, for a reference beam coming from the right, when you move your viewpoint to the right the fringe pattern moves towards you for motion towards the plane of the hologram and away from you for motion away from it.

Fringe measurement

For many purposes a simple count of fringes, or often just an examination of their shape and distribution, is sufficient. You can estimate by eye to about one-fifth of a fringe if necessary. The image can be scanned and cleaned up, removing the noise to allow more accurate estimates. However, to obtain the highest accuracy you need to be able to measure the phase of a fringe at any point in the pattern. The first attempts at this were made in the early 1970s by a team led by R. Dändliker in Baden, Switzerland, who evolved a method known as *heterodyne holographic interferometry*.

The method eventually adopted (Dändliker *et al.*¹¹) is to make the first holographic exposure with the reference beam at one angle, and the second exposure with the reference beam at a different angle. The image, when played back using both beams would show normal secondary fringes; but in practice the frequencies of the two beams are shifted very slightly, one up and one down, by means of acousto-optic modulators.

Two detectors are set up behind the hologram. One is stationary; the other can move round the hologram and build up a picture of phase differences at all points. The sensitivity can be as much as one-hundredth of a fringe.

There have been further developments of heterodyne phase-shift interferometry, but these have been largely superseded by computer-controlled enhancements known as *phase wrapping* and *unwrapping*. These are carried out by operating on scanned images with algorithms based on, for example, fast Fourier transforms. Phase unwrapping consists of turning the sinusoidal variations of the fringes into sawtooth forms that can be more readily analyzed; phase wrapping combines fringes into sawtooth forms that cover many fringes for each cycle, and can provide a more visual picture of, for example, fluid flow in gas streams.

Speckle interferometry

Whenever a diffusely reflecting surface is illuminated by a laser beam the surface appears to be covered in a random pattern of bright and dark speckles. This is called laser speckle, and occurs because adjacent small elements making up the surface have optical paths from the surface to the eye that differ by tiny amounts, and therefore interfere. At any point, therefore, diffracted waves are arriving from many of these elements simultaneously, and as they are all highly correlated their The heterodyne effect is the creation of a low frequency by mixing two high frequencies that are slightly different. The result contains a much lower frequency, equal to the difference between the two high frequencies.

An acousto-optic modulator is a crystal of a substance that changes its refractive index when stressed. The Fourier-transform plane is the principal focal plane of the lens. (Fourier transforms are dealt with in Appendix 2.) One effect of this phenomenon is that if you focus your eyes behind a laser-illuminated surface and move your head sideways the speckles move in the same direction, whereas if you focus in front of the surface they move in the opposite direction (try this with and without reading glasses). instantaneous amplitudes add algebraically. However, as the phases are random, they may at any point be interfering constructively or destructively. In an unfocused beam all spatial frequencies are present, but when the light is imaged by a lens, a video screen or a hologram, the spatial frequencies are limited by the aperture, and the size of the speckles is determined by the f-number of the imaging device. The speckle size becomes larger as the aperture becomes smaller, as you saw in Fig. 22.13.

If you photograph an object illuminated by laser light, the speckles will appear on the negative. If you make a double exposure, with the object subjected to stress after the first exposure, the speckles will have become displaced in the second exposure, and fringes will appear in the image, indicating the in-plane distortion. The resolution is not as high as in holography, but the process is simpler and doesn't need special emulsions. By defocusing the object (usually by setting the lens to infinity, so that the emulsion is in the Fourier-transform plane) you can observe fringes due to out-of-plane motion, because the speckles move when the object is rotated out of plane.

A variant of speckle photography is called *shearography*. The principle here is that two images of the object are generated, one slightly displaced from the other, as in a Michelson interferometer that is slightly misaligned. In an unstressed object this system will generate straight fringes. If the object is now stressed, producing outof-plane movement, the fringes will become distorted.

Because the resolution of speckle imaging is lower than that of holography, it is possible to use closed-circuit television recording, and this is called *electronic* speckle-pattern interferometry (ESPI), though it is more often (and less accurately) known as 'TV holography'. This allows you to see the speckle-pattern correlation fringes on a monitor screen. In double-exposure recording the first image is stored and the second subtracted from it. The areas that have not moved will give a zero signal (dark), and the areas that have moved will be uncorrelated and will give a signal that may be positive or negative. The signal is processed by rectifying, so that both the negative- and positive-going signals show as bright fringes; high-pass filtering removes any low-frequency noise, and improves the clarity of the fringes. In time-average and double-pulse exposures, the slow fading of the camera tube image necessitates addition of the signals instead of subtraction. In this case, areas of maximum correlation have maximum contrast and areas of minimum correlation have minimum contrast. For this technique a storage tube is not strictly necessary. Shearograms are produced in a similar manner, where photography is not required.

All the images produced in speckle interferometry can be treated by image enhancement processes. ESPI is a rapidly expanding technique, and has been employed in the solution of complex problems concerning displacement, and the measurement of shape. Its techniques are inherently simpler than those of holography, and are mostly either real-time, or close to it. The standard work on the subject is by Jones and Wykes¹²; other more recent papers^{13–16} are worth consulting.

Holographic contouring

One of the main virtues of holographic interferometry is its extreme sensitivity: it is possible to make measurements of strain and wear down to one-hundredth of a



Figure 23.14 Optical system for two-wavelength contouring, after Zelenka and Varner¹⁷. A is a circular aperture. The object illumination and the reference beam are at equal angles of incidence.

wavelength, just a few nanometres. Unfortunately, we can't use it for comparatively large displacements, as the fringes become too close together to be counted. This is a particular problem with vibrating surfaces.

The techniques used in speckle interferometry help with this problem, as the fringe contour interval is determined by the geometry of the system. However, there are also holographic techniques that can extend the scope of holography by increasing the contour interval. These depend on the use of two wavelengths. The most important use of the technique measures static contours rather than movement. A system for this, described in detail by Zelenka and Varner¹⁷ uses a telecentric lens system.

A first exposure is made using one wavelength, then a second using a slightly different wavelength. After processing, the hologram is illuminated using just one of the wavelengths. Because of the confocal setup there is no lateral displacement of the image, but because of the changed wavelength there is axial (out-of-plane) displacement of one image relative to the other, and contour fringes will appear, the contour interval being inversely proportional to the difference between the two wavelengths. For example, an Ar^+ laser operated at 514 and 477 nm will give contour fringes at intervals of roughly 10 µm.

The technique has been further developed by these and other workers¹⁸⁻²⁰. Now that many tunable solid-state and diode lasers have become available, some of the techniques for altering the wavelength of the exposing beam, such as immersing the object in sugar solutions of different refractive indices, have (happily) become obsolete.

Summary of applications

This summary isn't intended to be exhaustive. In some cases rival nonholographic interferometric techniques have taken over from holography, operating in real time. Several methods now exist for optical contouring, and speckle interferometry has much to offer. However, in many cases holographic and non-holographic methods offer complementary advantages, each having its own special merits. The cones of subwoofer speakers as used in hi-fi audio equipment, for example, may have an out-of-plane excursion of up to a centimetre when reproducing loud sounds.

A telecentric lens is a system of two lenses in which the object is at the front principal focus of the first lens and the image is formed at the rear principal focus of the second, the lenses being spaced two focal lengths apart (Fig. 23.14). The aperture, which is in effect a field stop, is positioned at the common focus of the lenses. The important optical quality of a telecentric combination is that the magnification is constant at all depths of the image. The system is also known as *confocal*.

Direct measurement

- *Measurement of deformation* Comparison of measurements of components over a long period, e.g. measurements designed to detect creep and fatigue on the servicing of components subjected to prolonged heat or stress, such as parts of a nuclear reactor, or re-usable parts of spacecraft.
- *Measurement of components in a hostile environment* For example *in situ* examination of fuel pins in a nuclear reactor, or underwater, as in offshore oilrigs.
- *Medical and pathological data in three dimensions* Records of dental casts, computerized tomograms (Chapter 25).
- *Microscopy* Usually for living objects such as bacteria (Chapter 26) or petrological specimens.
- *Particle counting* Either by off-axis holography (e.g. for fuel-injection systems) or in-line holography (for particle counting and analysis).
- *Contouring* Measuring the accuracy of, for example, shallow stampings or optical components.

Interferometric measurement

- *Real-time* Pre-testing of components, before using frozen-fringe methods; quality control of components produced within very narrow tolerances where speckle methods are not appropriate.
- *Double-exposure (CW)* Measurement of distortion in statically stressed components. Longitudinal studies of creep and wear on repetitively stressed components such as springs and tappets. Routine non-destructive testing on remold tires. Investigations in connection with the conservation and restoration of works of art.
- *Time-average* Investigation of the modes of vibration of objects such as loudspeaker cones, turbine blades in isolation, car door panels and musical instruments.
- *Shearing (pulse)* This is a subset of double-exposure interferometry appropriate to moving objects, with or without image motion compensation. Measurements on rotating fan blades, human muscular action, fluid flow patterns.
- *Stroboscopic* For deeper investigations into areas covered above, or (real-time) to establish conditions for establishment of resonances.
- *Sandwich* Useful for canceling translational movement of the subject, for example in large machines, where several components have translational movements or distortions in different directions. Allows each part to be examined individually.

Further reading

Holographic interferometry was so thoroughly researched in its earlier days that little has been published on the subject since the early 1980s. Abramson's book *The*

Making and Evaluation of Holograms (Academic Press), already referred to several times, is a classic, as is Jones and Wykes's *Holographic and Speckle Interferometry* (Cambridge University Press). Hariharan's *Basics of Interferometry* (Academic Press) covers the full range of interferometric techniques, including speckle interferometry and shearography, at a level comprehensible to the average school leaver. The standard work on shearography is *Digital Shearography*, by Wolfgang Steinchen (SPIE), and if you want to know more about the detailed analysis of interferograms, go to *Phase Unwrapping, Theory, Algorithms and Software*, by Dennis C. Ghiglia (John Wiley).

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Chapter 24 Data storage and diffractive elements

'I'm afraid I am, Sir,' said Alice. 'I can't remember things as I used – and I don't keep the same size for ten minutes together!'

'Can't remember *what* things?' said the Caterpillar. 'Well, I've tried to say "How Doth the Little Busy Bee," but it all came different!'

Lewis Carroll, Alice in Wonderland

Judging by the number of papers published on the subject, one might imagine that the processing, storage and retrieval of data constituted the most important area in holography. Perhaps this is because many other important applications of holography have been researched more or less to finality, so that less remains to be done in these areas. But a study of the numerous papers on data storage published in the past five or so years reveals a great deal of duplication of work, and often a shortage of worthwhile content camouflaged in a thicket of mathematics and jargon. The first part of this chapter attempts to cut through some of the arcane language and describe the background, aims, and practical applications of techniques for data storage and retrieval by holographic methods. The remainder of the chapter goes into more detail concerning methods and applications.

Why holographic data storage?

As it is already possible to store more than 60 megabytes of information on a single CD-ROM, with current developments forecasting gigabytes, it may seem pointless to attempt to store information in what seems in this world of computerized data storage to be an alien medium.

But a hologram *is* a data store, just as is a photograph, or a microfiche, or even a typescript. It has some special aspects, too. For one thing, its storage capacity is very high indeed. A holographic emulsion can store many times as much alphanumerical data as a microfiche of the same size; and although the information held in the hologram is to some extent localized, in that a page of information can be displayed by directing a narrow laser beam at a chosen area, within that area the information is not localized. This means that a small scratch or dust speck that would wipe out a sizeable amount of information from a microfiche has little effect on the holographic image. Weiban Yuan¹ describes a holographic 'ultrafiche' that can display and print out information stored at a density 25 times that of a conventional microfiche, and at one-tenth of the materials cost. Virdee *et al.*² describe a system for producing two-dimensional holographic tags, which they claim offer considerable advantages over barcode readers. But this is small change compared with the inherent possibilities for holographic data storage.

There has long been discussion over the merits of storing information in holographic formats. In theory it should be possible to store vast amounts of information in a single crystal of a substance such as lithium niobate, which when

* I wrote this sentence in much the same words more than nine years ago in the previous edition of this book. and little has changed apart from the number of papers published. I don't want to seem dismissive of this work: it does have a real potential in the hugely promising field of optical computing, where it is almost certainly relevant. But electronic data storage, which may well remain dominant for the foreseeable future, already uses devices that can handle the same amount of information more conveniently and cheaply, if less dramatically.

Although simple, this process is remarkably efficient: it has led to spectacular images of objects in outer space, and to spectroscopic and other analyses that have enormously increased our knowledge of celestial objects, not to mention more mundane matters such as the nature of chemical reactions. Commercial computer programs such as Photoshop have eagerly copied these methods.

A crude example of this kind of processing is a graphic equalizer in an audio system.

The Fourier approach to image formation is dealt with in more detail in Appendix 2, and if you are uncertain about the concepts underlying this approach, it might be a good idea to break off at this point and study Appendix 2 before tackling the rest of this chapter. illuminated alters its electronic structure and refractive index. Plainly, this sort of substance could be used for making phase holograms; indeed, a crystal only 1 mm thick could contain more than 2000 Bragg planes, and would be so sensitive to direction that a reconstruction beam would have to be directed into it at better than 1° accuracy to retrieve a particular image. In theory, more than 10 000 images could be stored independently, using a range of reference beam angles over a cone of 120°. Again, in theory a 10 mm cube of such a crystal could store some 10 megabytes of information per channel. Thus a single crystal the size of a fingernail could contain the whole of the *Encyclopedia Britannica* many times over, with any page instantly retrievable simply by illuminating the crystal in a particular way. Glenn Sincerbox³ analyses the possibilities of holographic storage in meeting the challenges. Robert Shelby⁴ gives an exhaustive account of all the materials that are suitable for holographic storage, with no fewer than 79 references.

A major problem with photorefractive crystals is that because they are photochromic, that is, they form their fringes directly under the stimulus of light, they are erased by the act of reading, which by definition has to be with the wavelength that was used to record the data. (I have already mentioned this problem in a previous chapter.) There has been much work carried out to overcome this problem; but there is undoubtedly a great deal more to do before we reach the stage of a totally practicable device^{*}. Nevertheless, much has already been achieved^{5,6,7}.

Data processing

This is another area where holography seems to be promising, and which has again spawned a great deal of research. In photography, data processing consists mainly of techniques such as contrast control, tone separation and enhancement of fine detail by unsharp masking. These, and other sophisticated processing techniques, are at present carried out in a one-dimensional manner. To take an obvious case, the data transmitted by a satellite arrives as a signal that is built up as a picture on a monitor from a linear sequence of signals. This is the traditional way a computer works – one instruction at a time.

Most of these data processing tools depend on the signal being subjected to frequency analysis, a process that stores the frequency content of the signal rather than the analogue signal itself, and operates on the frequencies, amplitudes and phases of the component frequencies in the signal.

The most recent generation of computers is being designed to perform a large number of operations simultaneously; this is known as *parallel processing*. As holography operates in two and even three dimensions, holographic information processing represents parallel processing in an optical form. It also depends on the Fourier principle, but in a more subtle way.

Spatial filtering with Fourier-transform holograms

As a comparatively simple example we can consider the concept of spatial filtering. You have already met the principle, in the cleaning up of a laser beam using a spatial filter consisting of a simple pinhole, but the use of a Fourier-transform (FT) hologram for the purpose is a more refined method. The central thesis of the Fourier approach is that any source of light waves (i.e. any object illuminated by a beam of light) produces a complex wavefront that can also be synthesized directly by a large number of cosine diffraction gratings of various spatial frequencies and at various angles to one another. The gratings with the highest spatial frequencies carry the information relating to the finest detail of the object, and these wavefronts diverge from the optic axis at the greatest angles.

If a large lens is inserted in the path of these wavefronts at a distance from the object equal to its focal length, the plane wavefronts diffracted by the component diffraction gratings will converge to pairs of points at its rear focal plane. These pairs of points are symmetrically placed with respect to the center of the field, and their position and intensity provide unique information about the object. The electromagnetic field at the rear focal plane is the FT of the field in the front focal plane (i.e. at the object), and if a further lens is positioned so that the FT plane of the first lens is in its front focal plane, a real inverted image will appear in its rear focal plane. This follows from the mathematical fact that if you take the FT of a function, then take the FT of the FT, you get back to the original function. The relevant optical setup is shown in Fig. 24.1.

The ray-trace diagram of Fig. 24.1a may appear fairly trivial to anyone with a basic knowledge of photographic optics. What is much less trivial is the secret it



Figure 24.1 Forming an image with two lenses. (a) Ray model; (b) Fourier model. Examples of patterns observed in the FT plane can be seen in Fig. A2.23.

This is why closing down the aperture of a camera lens reduces its ability to record fine detail. The size of the pattern is inversely proportional to the size of the object. If you want the diffraction pattern to be large enough to see, you need an object that is no more than 1 mm across, and a lens of at least 200 mm focal length.

When some kind of function (say an Airy diffraction pattern) is convolved with a series of points (say a star field), one function is 'dealt out' to the other function. Thus the Airy pattern of an astronomical telescope is convolved with the field of stars: each star is imaged as an Airy pattern.

The only difficulty here is that if the reciprocal becomes higher than unity, its effective value has to remain at 1, because you can't have a transmittance greater then 1. This does limit to some extent the improvement you can obtain photographically. Incidentally, a photographic technique known as 'unsharp masking' was used to clean up woolly images long before anyone had heard of optical FTs. conceals. This is indicated in Fig. 24.1b. If you illuminate the object with the coherent light of a laser, when you position a screen at the common focal plane you will see a pattern indicating the existence of a field that is the optical FT of the object field. For a simple one-dimensional object such as a ruled grating the pattern is simply a row of spots aligned perpendicular to the direction of the grating bars. For a two-dimensional object such as a piece of copper mesh it is a more intricate (though still predictable) two-dimensional array of spots. For a complicated object such as a photographic transparency it resembles a star cluster; but if you examine the pattern closely you will see that each point is one of a pair situated symmetrically across the center of the pattern. The whole pattern is made up of such pairs of points, each carrying all the information about a particular spatial frequency present in the object wavefront.

If this wavefront has been further disturbed, say by being passed through an uneven piece of glass, the information about this second disturbance is also present in the pattern, and in a form that can be disentangled from the information about the object. To see how this happens you need to be aware of the *Fourier-transform convolution theorem*. This states that when two functions are multiplied together in *x*-space (the space of the object), their FTs in frequency space (the space of the FT) are convolved, and vice versa.

In the frequency space of an optical FT setup, as in Fig. 24.1b, forms that were convolved in *x*-space have their FTs multiplied together (the 'vice versa' above). Thus if we were to insert into the common focal plane of the system a filter that divided the product of the two FTs by the FT of the unwanted function, we would retrieve the wanted function. This might not seem important for images of stars (astronomers have found other ways of dealing with this), but it can be very important in other situations, for example, when a vital photograph has been blurred through camera shake or loss of focus. It is important in electron microscopy, where aberrations of the magnetic lenses introduce artifacts rendering the structure of the subject matter difficult to interpret.

Provided you know the exact nature of the 'blur' function, it is (in principle) easy to deconvolve it. The first part, finding the blur function, can be fairly simple. For example, the camera shake function is usually a short straight line, and you can identify it by looking at the image of what should be a point. All points making up the image will be convolved with this function, that is, they will all be straight lines of the same length angled in the same direction. Another common example, the out-of-focus function, is a small disk, and all points on the image are convolved with this disk. The imaging errors in an electron microscope are more complicated, but they are still calculable, as their nature is known with some precision. Other image artifacts such as raster lines and halftone dots, and even quasi-random noise, can also be specified with little difficulty.

Having identified the 'unwanted' function, the next step is to find its twodimensional FT. The FT of the combined function must be divided by this (which amounts to the same thing as multiplying it by the reciprocal of the transform of the 'unwanted' function). You can often achieve this by photographic methods.

It is easy to correct for amplitude errors, which involve only the contrast of fine detail. Errors that involve a shift in the image (phase errors) can't be corrected using ordinary light detectors such as photographic emulsions, because these don't

record phase – the very problem this book began with. But as you have seen, holography *can* do this.

Fourier-transform holograms: the principles

If the history of photographic optics had been a little different, the first hologram might well have been a Fourier-transform hologram, for such a hologram can be made with amateur b&w film and partially coherent light. Denis Gabor's dramatic insight that resulted in the concept of the hologram was in the late 1940s. Around the same time, also in the UK, an equally sudden and radical insight by a research team at the Royal Aircraft Establishment pointed the way to the concept of the optical transfer function, which has revolutionized the design of optical devices. But just as Gabor's work had to await the arrival of the laser to be fully realized, so the implementation of the optical transfer function principle had to await the arrival of the digital computer. Even after Duffieux⁸ had shown the Fourier relationship between the point spread function and the optical transfer function (a fundamental factor in modern lens design), the principle that a camera lens produces its image via a double optical Fourier transform was not appreciated, and could in any case not be physically demonstrated until the mid-1960s, after the arrival of the laser.

None of the existing light-sensitive devices can directly record the amplitude and phase of a light wavefront, since they record only the light energy, which is proportional to the square of the amplitude, and is time-averaged and always positive. This is where holography comes in. As long as a wavefront can be compared with a well-behaved reference wavefront, both amplitude and phase can be saved and recorded. So if we can supply a suitable reference beam we can record a hologram in the FT plane of a lens as well as anywhere. What is more, we can relaunch the wavefront by illuminating the processed hologram with a replica of the original reference beam (Fig. 24.2). There are several geometries equivalent to one another, the simplest practical one having been evolved by George Stroke⁹, and called by him a 'lensless' FT hologram. In Stroke's configuration the hologram itself acts as a lens, and if it is illuminated by a beam of collimated laser light both the real and virtual images are formed at infinity, and can be focused by a lens on the opposite side of the hologram to the reference beam.

This type of hologram is easy enough to make. Although for a true FT hologram the object should be flat, in practice this isn't important provided its distance from the hologram is large compared with its depth. The reference source needs to be close to the object and in the same plane. Holograms made by this technique don't need ultrafine-grain emulsions, as the primary fringes have a low spatial frequency; and the manner in which the information is coded in the emulsion means that the resolution of the image is determined by the size of the hologram, not by its photographic resolution.

Figure 24.2 shows the optical principle of both conventional and lensless FT holograms.

To replay an FT hologram you simply place it in an expanded laser beam (or any quasi-monochromatic light) and look straight through the hologram at the light source. You will see two images in the same plane, one each side of the central spot, one erect and pseudoscopic, the other inverted and orthoscopic. If the light beam is collimated, the images will be at infinity. If you rotate the hologram the

There are practical setups for FT holograms, including the 'lensless' configuration, near the end of Chapter 14, and there is more information about them in Appendix 2.

Haddad et al.¹⁰ have exploited the large fringe spacing of FT holograms in a pioneering holographic microscope, using a tiny drop of glycerol on the slide as the reference source and a CCD array with a pixel width of $9 \mu m$ as detector.



Figure 24.2 (a) Making an FT hologram. (b) Reconstructing the two images. (c) A 'lensless' FT hologram. See also Figs. 14.19–22.

images rotate with it, but if you move the hologram in its own plane the images remain fixed in space.

Image de-blurring

FT holograms have some useful applications in image processing. This implies a modification of the spatial frequency spectrum revealed in the FT plane, in terms of amplitude (which governs the contrast of various sizes of detail) and phase (which governs their position). In the image de-blurring process both are modified. Hariharan¹¹ explains how a de-blurring filter can be made by first making a negative of the diffraction pattern of the blur function, developed to a gamma of 2; this is then positioned in register with an FT hologram of the same blur function. These are now set up in the rear focal plane of a lens, with the original transparency in the front focal plane. The combination takes care of both amplitude and phase, removing the blur by deconvolution.

Correlation filtering

A further use for FT holograms that has (perhaps temporarily) been overtaken by digital methods is as a matched filter for identifying specific features in photographs.

This property has led to experiments with FT holograms as the basis of holographic movies.

Stroke *et al.*¹² discuss the effectiveness of optical versus digital scanning processes, and conclude, somewhat optimistically, that the capacity of the hologram for parallel processing puts holography well ahead. (Mind you, that was in 1969.)



Figure 24.3. Matched filtering. (a) In the FT recording system of Fig. 24.2a, the lens L1 produces an optical FT of the object O_1 (the pattern to be identified). (b) The reconstruction is by the object beam, not the reference beam, and the new object O_2 contains O_1 in various positions. The hologram H reconstructs a separate 'reference beam' for each of these. The second lens L_2 focuses these to the appropriate points C_1 , C_2 , etc., in the inverse FT plane FT₂. Z is the zero-order beam.

When an ordinary hologram is illuminated by a duplicate of the original reference beam it reconstructs the object beam. From the symmetry of the mathematical expressions involved (see Appendix 1) it is clear that if we were to illuminate the hologram with a replica of the object beam it would reconstruct the reference beam. This is the principle behind the *correlation filter*. Suppose, for example, you have a page of a text on optics, and you want to identify the word 'mirror' wherever it occurs. Using the configuration of Fig. 24.2a, you first make an FT hologram of the word 'mirror' on its own, and after processing set it back in its FT plane (Fig. 24.3a). You now add a second lens in line with the original reference beam with its front focus at the hologram and a screen in its rear focal plane.

If you now install a transparency of your page in the original subject plane and cut off the original reference beam, each replica of the correlation filter original (the word 'mirror') will reconstruct a replica of the reference beam, which will be focused on the screen at a position that corresponds to the location of the word on the page (Fig. 24.3b). The system will also show, in the form of weaker spots, the positions of similar but not identical images, for example a word such as 'arrow'. This once appeared a promising method for revealing partly hidden detail in aerial reconnaissance photographs, such as camouflaged missile sites, but in practice the human visual perceptive process proved more efficient and faster. Another suggested use was to prepare short-lists of fingerprints from the huge banks of them held by police departments. Again, the promise was real enough, but the sheer speed of digital correlation methods rendered further development pointless. However, the technique does have real possibilities in 'negative' correlation situations, as for example, in the detection of flaws in microcircuits. Such pictures were originally created on teleprinter keyboards by operators during the Second World War. The tradition continued up to the 1960s, by which time the teleprinter was on the way out.

A Fresnel hologram is a hologram made with the object close to the plate. The diffracted wavefronts are only partly sorted out, and the interference pattern is much more complicated than that of an FT or farfield hologram. Writing the interference pattern for a Fresnel hologram is of the same order of difficulty as the writing of a composition by a modern composer onto a CD by hand – but today's computers can carry out such tasks before breakfast.

This isn't a true computer-written hologram, but it is computer generated in the broadest sense.

Computer-generated holograms (CGHs)

You may have seen pictures created using only typescript letters. Nowadays it is fairly easy to construct these if you have a computer with a word processing facility.

The method of designing such pictures was to consider them as made up of letter-sized rectangles, which would then have one or more letters typed into them to achieve the required level of blackness. Computer-generated holograms (CGHs) have a number of characteristics in common with typewriter pictures. They, too, simulate the structure of an image (in this case the fringe structure of a hologram) by breaking it down into rectangular elements called pixels (short for 'picture elements'), and they have similar limits as to their structure and tonal grading. The rules for designing a CGH are, of course, more complicated than the teleprinter operator's rule of thumb. They use quite difficult mathematical rules that require a large database to store the result of their application to a particular case. The calculations involved in designing a three-dimensional Fresnel hologram are so complicated that only the most recent generation of computers has become able to handle the construction of, for example, the shape of an apple complete with shadow detail. But there are many situations where comparatively simple computer-generated FT holograms can be very useful.

Applications of Fourier-transform CGHs

Because of their comparative simplicity, FT holograms were the subject of intensive research in the earlier days of CGHs, and much of the technology for their production and possible uses was worked out by 1980. In 1978 (updated in 1980) Lee^{14,16} itemized five areas where CGHs are of demonstrable use:

- *Three-dimensional displays* Although the near-field wavefront of an object beam is very complicated, it can nevertheless be computed if the object is considered as consisting of an array of point sources of varying intensity and distance. The wavefronts each of these produces at the hologram plane can be summed and the result plotted in terms of intensity. A more practical approach starts with a description of the three-dimensional object, from which the computer calculates the two-dimensional aspect from a large number of viewing angles. These are recorded in cine film as stereogram masters. Yatagai¹⁵ describes a method of converting the projection images into FT holograms; these are plotted by a printer, reduced photographically and arranged in the same order as the projected images. Each eye sees a holographically reconstructed image from a different direction, giving a stereoscopic image from any viewpoint. The system could operate in real time.
- *Optical data processing* The insertion of a mask in the FT plane of a lens can modify the image of a transparency, as described above, removing artifacts, blur, noise and so on. Although in the preceding description the masks were made photographically, it is comparatively easy to generate CGHs including both amplitude and phase modification, restoring detail invisible in the original.
- *Matched filtering* This has been extensively applied to data obtained from synthetic-aperture radar. Lee¹⁴ discusses it in detail. A technique nearer home is the testing of optical components. The traditional technique is to place a pattern



Figure 24.4 Twyman–Green interferometer set up to test a lens TL. Except for the layout of the test arm with its retroreflective mirror M_2 , the principle is similar to that of the Michelson interferometer. The interference pattern at S contours any optical inadequacies in the lens under test.

directly on the surface of the component, to examine the Newton's fringes, and by repeated working of the surface to reduce their number to an acceptable minimum. There are devices that simplify the testing, such as the *Twyman–Green interferometer* (Fig. 24.4).

The reference waves in these interferometers are usually just plane waves with a very small amount of skew in one of the mirrors to produce broad shearing fringes. In the case of spherical optical components the reference wavefronts are spherical. But in the testing of aspherical components the residual aberrations are so large that the interference pattern doesn't yield any useful data on fabrication errors. If a CGH is used to set up a special reference wavefront matched to the surface in question, the fringe pattern will be reduced to parallel bars showing only the errors in figuring. There are several variations of the system, discussed in detail by Lee¹⁴.

- Optical data storage and random phase coding Information, usually initially in one-dimensional form, can be collected and stored as a series of FT holograms, which may be partially or completely digitized. This area is the subject of active research, and Lee¹⁴ discusses the limitations of the process. It holds much promise in the field of numerical process control.
- *Laser scanning* Holographically recorded gratings can scan at high speed, and with low mechanical tolerances compared with conventional optics; in addition they don't need a focusing lens.

Lee¹⁶ has updated his earlier publication, presenting some new methods for making CGHs and discussing their applications at non-optical wavelengths. Loomis¹⁷ has contributed a useful paper on the design and writing of CGHs for optical testing purposes.

But where CGHs have really taken over is in the fabrication of diffractive optical elements (DOEs). As all DOEs are basically zone plates of one type or another, and as binary DOEs are almost as efficient as the sinusoidal ones made by holography, it has become a fairly simple matter to design components dedicated to specific jobs, at the same time avoiding some of the disadvantages of HOEs such as unwanted zero- and negative-order diffracted beams. Most DOEs are therefore CGHs.

Strategies for making CGHs

At present there are three well-tried techniques for making CGHs:

• *Detour-phase holograms* These were first described by Brown and Lohmann¹⁷ in 1966, and are the oldest type of CGH. In order to simplify the generation of the hologram its transmittance is binary, i.e. at every point it is either transparent or opaque. It is capable of recording both amplitude and phase.

The desired wavefront, denoted by its two-dimensional wave equation, is first sampled at equally spaced intervals using standard sampling theory. The paper base on which the hologram is to be plotted is divided into square cells in which the transmittance is coded by the height and width of a black rectangle within the cell. On making a reduced photographic negative of the final pattern the rectangles become transparent on an opaque ground (Fig. 24.5).



Figure 24.5 Typical cell in a binary detour-phase hologram, after Brown and Lohmann¹⁶. The symbols represent the various coordinates defining the size and position of the components. (b) A typical cell in a generalized detour-phase hologram, after Haskell and Culver¹⁷. This method produces finer levels of amplitude and phase, and reduces noise.

Several versions of the technique have been introduced to reduce noise, and the authors also describe these. Later workers such as Haskell¹⁹, Lee^{14,16} and Burckhardt² describe methods that further subdivide the cells, resulting in better control of transmittance and phase. Piestun *et al.*²¹ were among the first to show how to generate CGHs that operated on-axis without the disturbing optical artifacts usually associated with this configuration.
- *Modified off-axis reference beam holograms* In 1967 Burch²² demonstrated a way of simplifying the amplitude-transmittance equation for a CGH, writing directly on film with ultrahigh-resolution optics to produce a spot only 20 μ m in diameter. Huang and Prasada²³ and Lee describe alternative methods of achieving a similar result.
- *Kinoforms* These were first described by Lesem *et al.*²⁴. They are purely phase holograms and are therefore theoretically capable of very high diffraction efficiency. They were originally produced on silver halide emulsion using bleach techniques that left a relief pattern on the film. Later versions employed photopolymers or dichromated gelatin. Chu *et al.*²⁵ found an interesting method of combining kinoform and amplitude modulation using Kodachrome film, the developed image of which shows a marked relief effect. They recorded the amplitude information in the cyan layer and the phase information in the yellow and magenta layers. Newer fabrication techniques using ion or electron beams have made photographic methods more or less obsolete, and improved programs for on-axis CGHs have given rise to a whole new generation of diffractive optical elements (DOEs), which are discussed below.

CGHs with a personal computer

Over the past decade the power of personal computers has increased and their size decreased to such an extent that today a typical laptop computer has as much power as did a mainframe computer only ten years ago. An enthusiast equipped with a modest personal computer, fast Fourier transform (FFT) software (readily obtainable), a scanner and a good-quality printer can make CGHs of simple figures with ease^{26,27}. Zhang and Joy²⁸ show the way to compute a binary CGH using a personal computer.

Diffractive optical elements

The class of diffractive optical elements (DOEs) subsumes holographic optical elements (HOEs), which you have already met in Chapter 15. Simple DOEs may use holographic methods and silver halide, DCG or photopolymer emulsions, but they can also be designed by computer – even, in the simplest cases, by ray tracing with ruler and compasses. We have seen some of the applications of DOEs in substituting for mirrors, lenses and beamsplitters. However, they have far wider applications in industry and for military purposes such as head-up displays for aircraft cockpits, and they are increasingly important in the new technologies of optical communications and optical computer design. Until fairly recently they were mostly manufactured holographically, using DCG material for preference because of its low noise and high diffraction efficiency. More recently, other materials that are less sensitive to humidity, such as photopolymers, and hybrid techniques such as silver halide sensitized gelatin (SHSG) have come to the fore, particularly for reflective elements. However, for transmissive elements direct methods of fabricating computer designed DOEs under computer control are now in ascendancy. One application that has become important with the rise of laser-driven technologies is beam shaping. Laser beams are notoriously uneven in profile, the most usual being Gaussian for a singlemode beam. Ye et al.²⁹ have derived an algorithm for generating DOEs for producing other profiles, including a uniform (top hat) profile, and a zero-order Bessel function profile, which by definition is self-limiting and does not spread by diffraction.

One can visualize a technologically enlightened artist of the future creating directly from imagination the holographic equivalent of the pictures of those wartime teleprinter operators. DOEs have a number of advantages over conventional optics:

- They need be only as thick as the diffractive layer plus the substrate. This means that a DOE can be used where there is insufficient room for conventional optics.
- The surface of a DOE doesn't need to be at an angle that obeys the laws of ray optics; it doesn't even have to be flat. It is the orientation of the diffracting planes, and their spacing, that determines the nature and direction of the emerging light. There is no difficulty, for example, in producing a mirror that is positioned at 45° to the incident light but reflects it straight back along its path, or a lens that not only focuses a beam of light but also turns it 60° off-axis.
- DOEs don't necessarily require a reference beam to form them. They can be designed by a computer program and fabricated with a profile that gives nearly 100% diffraction efficiency, with the zero-order beam completely suppressed. In this way it is possible to produce corrector plates for lens aberrations of almost any type simply by feeding the appropriate instructions into a computer programmed to design DOEs.
- They are comparatively cheap to produce. Although the original program for a particular element may take many hours to write, the resulting DOEs cost far less and weigh far less than conventional optical components.
- Several different optical elements can occupy the same space on a single DOE, an impossible feat for a conventional optical system.
- DOEs are wavelength-selective. Where they are required to substitute for conventional optical components in white light, this can be a drawback. However, this selectivity can be turned to advantage. For example, in head-up displays (HUDs) used in combat aircraft (and increasingly in other vehicles) the display needs to be bright, but the optics should not obscure the pilot's view ahead. Originally, HUDs used partly silvered mirrors that impeded the view noticeably; their replacement by DOEs tuned to the green color of the display now provides 99% transmittance of the view and 99% reflectance of the display.
- Although DOEs suffer from dispersion to a greater extent than refractive optical elements, the dispersion is in the opposite sense. This means that the chromatic aberration of a glass lens can be corrected by adding a low power DOE, which can in some cases be engraved on the lens surface by diamond turning or electron beam etching.

DOEs are finding an increasing number of uses in commercial and domestic situations, one of the most widespread being in barcode readers Fig. 24.6). For this purpose the laser beam needs to be split up into some twelve beams moving in different directions so that for any orientation of the barcode at least one beam will be scanning it correctly. With conventional optics this would require a complicated series of mirrors, heavy, fragile and expensive to produce, whereas the DOE can be fabricated by stamping from plastics material, in a similar manner to a CD.

Basic types of DOE

All DOEs are basically zone plates. The simplest kind of zone plate is called a *Fresnel zone plate*, and behaves very much like a simple lens. The principle is illustrated in Box 24.1.



Figure 24.6 Bar-code scanner by IBM at a supermarket checkout. The complicated optics needed to produce five or more direction of scanning simultaneously are produced holographically. Photograph by Richard Turpin.

Box 24.1 Zone plates

A Fresnel zone plate is a transparent plate on which are drawn concentric annular opaque zones alternated with clear zones. The radius r of successive zone edges in the same sense (i.e. clear-to-opaque boundaries) is in the proportion of the square roots of the integer series, beginning at 1. The result is that at a certain point on the plate axis (the central line perpendicular to the plate) the optical path lengths of the diffracted beams differ by an integral number of wavelengths, and interfere constructively. Fig. 24.7 shows how this happens. Using the geometry of similar triangles, and provided θ is small, so that $\sin \theta \cong \tan \theta$, the focal length f is given by the relation

. .)

$$f/r = r/n\lambda \qquad (n = 1, 2, 3, \dots$$

Hence

ł

$$^{2} = fn\lambda$$
, i.e., $r = \sqrt{n} \times \text{constant}$

For each point across the innermost transparent radius there is a corresponding point in each of the other transparent zones for which constructive interference occurs, so the zone plate acts like a lens of focal length r^2/λ , where *r* is the outside diameter of the innermost disk (it doesn't matter whether this is clear or opaque).

Because of its rectangular transmittance profile, a Fresnel zone plate possesses several other focal lengths corresponding to higher-order diffractions, but in practice these are weak. If you make a zone plate holographically, which you can do with a point object and a collimated reference beam, you will produce a zone plate with a sinusoidal transmittance profile and a spatial frequency that increases in the same ratio as a Fresnel zone plate. This hologram is called a *Gabor zone plate*, and has only one real focus.



Figure 24.7 Freshel zone plate. The outer radii of the dark concentric zones are proportional to the square roots of 1, 2, 3... and alternate zones are opaque and clear. The focal length of the zone plate is r^2/λ , where *r* is the radius of the innermost ring.

Because a hologram of a point object is a Gabor zone plate, it is possible to consider a hologram of an extended three-dimensional object as consisting of a very large number of Gabor zone plates each corresponding to a point on the object. This is a sound model, and can be helpful in giving an intuitive feeling for the principles underlying holography to those who find the Fourier approach alienating. However, a rigorous analysis of holographic imagery is more complicated with the zone plate model than with the Huyghens–Fourier approach I have adopted in this book. It is useful, though, when considering DOEs, particularly in computer programming situations.

If the opaque zones of a Fresnel zone plate are replaced by transparent zones of different thickness or refractive index, the result is a binary-phase zone plate with greatly increased diffraction efficiency.

In this type of zone plate a proportion of the light is diffracted outwards (from the virtual focus on the other side of the plate), and some is diffracted into higher order foci. In a mechanically produced zone plate the existence of these spurious images, and the resultant waste of light, can be avoided by etching the zone pattern in a sawtooth rather than a rectangular or sinusoidal profile. This type of asymmetrical-sided grating is called a blazed grating. A blazed zone grating resembles a Fresnel lens with very fine grooves. It doesn't operate like a Fresnel lens, of course; the grooves are too close together for that. It operates by Bragg diffraction. If the profile is correct the zero and -1 orders will be suppressed, resulting in a diffraction efficiency for the +1 (and only) order of around 90%. For a transmission grating the angle of the prism bounded by the facets and the rear surface of the substrate needs to be such that the angle of deviation is equal to the angle of diffraction for the first order; that is, the profile is in fact the same as it would be for a conventional Fresnel lens, with a step height of $\lambda/(\mu - 1)$ where μ is the refractive index of the material with respect to air (Fig. 24.8a).

If you have a feeling of *déjà vu*, you are right. A Gabor zone plate is just a holographic lens, and you saw how to make one in Chapter 15. Incidentally, both Fresnel and Gabor zone plates work equally well as reflection gratings.

You can make a Gabor phase zone plate holographically by bleach processing, or using DCG.

As you might expect, for a reflection zone plate the step angle should be half the angle of diffraction, so that the angles for diffraction and reflection are the same. The step height is one half-wavelength (Fig. 24.8b).



Figure 24.8 (a) Transmission and (b) reflection blazed zone plates. The geometry is identical with that of Fresnel lenses and mirrors, except for the scale.

Strictly, the profile of the steps should be parabolic, but the difference between this and a straight slope is negligible. In their analysis of zone plate theory, Smith and West²⁹ give theoretical figures for diffraction efficiency of 10% for a binary amplitude zone plate (i.e. the ruled type) and 90% for a blazed phase plate.

Fabrication of DOEs

- *Photographic emulsions* Using the methods described in Chapter 15, you can achieve more than 90% diffraction efficiency in reflection HOEs and 35% in transmission HOEs. The main advantage HOEs have over ruled and surface-relief DOEs is that they are volume gratings operating by Bragg diffraction. They are thus particularly suitable for reflective elements, and are capable of very high diffraction efficiencies. This efficiency is, of course, confined to the narrow band of wavelengths that satisfies the Bragg condition. Reflection elements can be made very sensitive to wavelength.
- *Dichromated gelatin* Until recently almost all of the research into the fabrication of DOEs was concerned with HOEs in dichromated gelatin. DCG is totally grainless and fully transparent, can produce diffraction efficiencies of around 90% with negligible scatter, and can be made to play back at any desired wavelength with either a broad or a narrow bandwidth. The medium requires careful control of humidity, temperature and pH at all stages, as well as clean room conditions, but provided the final HOE is sealed to prevent any ingress of moisture it will withstand extreme environments. For the experienced holographer with plenty of time and patience, DCG is the best medium for making HOEs, especially as it can be sensitized to red light. Many papers have been published on DCG techniques for making HOEs, but some reliable methods (such as those used in making HUDs) remain unpublished for security reasons.
- *Silver-halide sensitized gelatin (SHSG)* This is a process that has been around for some time, but has been taken seriously only comparatively recently. SHSG

You might be surprised at this, as DCG is notoriously variable in its behavior: it is, after all, an animal product, and its sensitivity to light is low and its sensitivity to humidity high. But it is cheap, and easy to coat; also, any failures can be cleaned off and the substrate used again.

Much that was written about DCG techniques in the early days is unreliable. Don't trust any paper published earlier than about 1985. combines the sensitivity of silver halide with the optical properties of DCG, and as it starts with a commercial holographic emulsion there is no messy coating process for the holographer. Using this technique you expose and develop the emulsion in the usual way for silver halide, but after a tanning bleach the silver is totally removed. Thereafter you complete the processing as for DCG. There is a complete account of the process in Chapter 20.

- *Photopolymers* These are materials that undergo a permanent change in refractive index when exposed to light. Satisfactory emulsions are usually based on polyvinylcarbazole and were at one time difficult to produce, but several international companies now manufacture them successfully (though they are not universally available). Photopolymer materials can be made sensitive to the whole visible spectrum. Processing is dry, and the image color is controllable. As the material is insensitive to damp it seems likely to replace DCG in the long term. It is discussed in detail in Chapter 20.
- *Photoresists* You can use positive-working photoresists for surface-relief HOEs and non-holographic DOEs (transmission elements only). As these materials don't have a linear response they are mainly employed in making binary (all-or-nothing) reliefs. For CGH use they are exposed under a binary mask. Series of masks can be used to build up blazed gratings with staircase slopes; these are nearly as efficient as those with linear slopes.
- *Electron beam (e-beam) etching* In this technique for transmission elements the material is bombarded through a mask by an energetic electron beam. Logue and McHugh³¹ discuss the very high resolution possible, and Bonisch *et al.*³² describe the actual production of DOEs by this method.

Applications of DOEs

I have already given a number of applications of DOEs, e.g. in HUDs, laser scanners and focusing optics. They are beginning to appear in camera viewfinders and focusing screens, corrector plates in Schmidt type astronomical cameras, solar energy collectors, laser beam profile modulators, laser safety eyewear, multi-lens arrays, and in contact lenses and other ophthalmic prostheses. But by far the most important future for DOEs seems to be in optical interconnects such as fan-outs, where a single laser beam may be split into a hundred or more individual beams, and fan-ins that gather as many individual beams into one beam, usually for transmission down an optical fiber.

Further reading

The principle of phase conjugation is a difficult one to assimilate when you have been brought up on the ray principle of reflection. If a light ray passes through an aberrated system and is subsequently reflected back through the same system, you expect the aberrations to be doubled. However, when a *phase-conjugated* beam passes back through the system, all the aberrations are, as it were, unwound, and the beam emerges in its pristine form (see margin note, p. 396). The best account of this I have found is in *Progress in Quantum Electronics* (UK), Vol. 26 (2002), No 3, pp. 131–91, which contains 211 further references in case your curiosity is still unsatisfied.

This type of DOE is indispensable in optical computing, and as this technology matures DOEs will undoubtedly see a big expansion.

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Chapter 25 Holography in biology and medicine

'If I did fall', he went on, 'the King has promised me – with his very own mouth – to – to –'

To send all his horses and all his men,' Alice interrupted, rather unwisely.

'Lewis Carroll, Through the Looking-Glass

As recently as 1988 it was possible for the late Pal Greguss, a distinguished researcher, to suggest in a published paper¹ that although holography had potential in medical education, there was little future for it in biomedical research, and next to none in clinical practice. To be fair, Greguss was defining holography in a very narrow way, and his paper in fact lists many obviously important applications that were at the time the subject of active research. For example, teams such as Wedendal and Bjelkhagen², and Hök *et al.*³, had already carried out valuable work in general physiology; Dermaut and Boone⁴ had reported the possible uses of holographic interferometry in pathology, and Zhou⁵ had pioneered the holographic visualization of CT scans in three dimensions.

Dental holography

Some of the earliest work in medical holography was in the area of dental records, so this seems an appropriate place to begin. One of the biggest clerical problems in Britain's National Health Service has been the keeping of full dental records. Often the only means of identifying a cadaver is by the teeth, which is a sound reason for keeping records of dentitions. These have traditionally taken the form of dental casts. For legal reasons they need to be kept for a minimum of 12 years, and this presents a serious storage problem. The Royal Sussex County Hospital, custodian of some 12 million records, began to tackle this problem by making Denisyuk holograms of all its dental casts, a task which, when completed, would reduce the required storage space from the equivalent of a large aircraft hangar to a few filing cabinets. As a bonus it would be possible to make measurements directly on the holographic image with dividers. Such holograms can serve as either cast or impression simply by flipping the hologram, as pointed out by Keating *et al.*⁶.

Records systems are not the only beneficiaries. Orthodontists can watch the progress of their patients by superposing then-and-now holograms. Ryder and Mårtensson⁷ describe a system for production and measurement of dental holograms using a vertical setup. Holographic dental records can have forensic applications other than identifying dead bodies, too.

Holography also has its uses in dentistry training. Figure 25.1 shows the images in a hologram designed as a teaching aid for dental students.

Histology and pathology

There are holographic techniques that will enable you to obtain a threedimensional image of almost any histological specimen, *in vivo* or *in vitro*. The My lab was once called in to help in matching tooth marks on a plastic object to a dental cast. It was a simple matter to make a Denisyuk hologram of both and to fit the image of the tooth marks to the image of the teeth. There were three exact fits that had not been apparent on a simple visual examination.



Figure 25.1 A two-channel hologram designed as a training aid for a dental school. (a) Left-hand view shows the teeth prepared for crowns, bridges and fillings. (b) Right-hand view shows the prostheses in place.

simplest subject to deal with is bony material, recent or fossil; you can deal with this in a simple Denisyuk setup (Fig. 25.2).

Soft tissues, even when not living, are as a rule insufficiently stable for holography with a CW laser, and need a pulse laser to produce a satisfactory image. However, Hans Bjelkhagen⁸ has demonstrated that endoscopic holography with a CW laser is feasible, using a Denisyuk arrangement with the film in contact with the tissue and illumination from a single-mode fiber. Using 8 mm diameter disks of film and a laser power of 25 mW at the fiber tip, an exposure of 25 ms was adequate, and short enough to provide a satisfactory image. Replay by filtered white light gave a speckle-free image with high resolution. More recent work by Bjelkhagen et al.⁹ established that it was possible to achieve a resolution of better than 5 µm. Von Bally¹⁰ discusses the relative merits of holography at the tip and at the evepiece of the endoscope, and describes the adaptation of an otoscope for making both single-exposure holograms and holographic interferograms of the eardrum. Brown *et al.*¹¹ describe an investigation into the human cardiac cycle using double-pulse interferograms of the chest and neck region, a fairly complicated operation. As the interval between pulses is much shorter than a single cardiac cycle, a large number of double pulses were necessary, triggered by the R-wave peak on the

This is a shearing method that generates static fringes, which are distorted by displacements within the subject matter. (See pp. 357–8.)



Figure 25.2 Two of a set of three-dimensional views of a monkey's skull. These are Denisyuk holograms made with a collimated beam, and allow measurements to be made with calipers in any direction.

electrocardiogram, with delays of various fractions of a complete cycle. The ambiguity of direction of movement was resolved by rotating the reference mirror approximately 6 microradians between exposures (see p. 365).

Holographic interferometry has the potential to play an important part in orthopedics, primarily in the design of joint replacement prostheses. Bones are not totally rigid structures, and need regular stressing and small flexures if bone material is not to be lost. A prosthesis that is completely rigid may thus be selfdefeating. Furthermore, in highly stressed joints such as hip joints the stress must be distributed evenly. The techniques can also be used comparatively, for example to show the difference in reaction to stress of bones weakened by osteoporosis. Much of the testing can be carried out on fresh cadaveric material, and as the flexures are very small, holographic interferometry provides an excellent investigative tool. Shelton and Katz¹² provide a thorough analysis of the whole process, comparing the respective merits of holography and ESPI. More recently, Matsumoto et al.¹³ have carried out deformation analyses on the human femur in the course of an investigation into the effects of osteoporosis. De Caluwé and Boone¹⁴ are among workers who have investigated displacements of the human body subject to sudden stresses, in particular of the head during an impact on a safety helmet, on the hand when firing a gun and on the forearm during a tennis stroke.

Emmett Leith and his team have been working for some time on the possibilities of imaging internal structures through highly diffusing media such as human flesh, a technique that has obvious possibilities for the non-invasive examination of suspected tumours. An early paper¹⁵ reported the making of a hologram through a diffusing medium, followed by the use of a conjugate beam to reconstruct an undistorted real image, an early example of the use of phase conjugation. Later work used a spatial filtering method which they dubbed 'incoherent superresolution'¹⁶. A more recent paper¹⁷ reports the use of ultrashort pulses of laser light, also beams of low coherence length, to record only the directly transmitted beam.

Ophthalmic holography

Because of the large diameter and small aperture of the eye, and its own optical activity, photography of the eye in full depth isn't easy. With a fully distended pupil it is possible with a fundus camera to obtain stereoscopic pairs of photographs of the retina, but the technique is difficult and the results usually mediocre. Xe Shuxian *et al.*¹⁸ describe a method of making a hologram of the eye using a collimated beam incident on the cornea and a beam focused on the sclera near to the cornea to provide diffuse illumination of the interior of the eye. The exposure with a 35 mW HeNe laser was about 0.5 s.

A more fruitful and less dramatic line of research has led to the development of diffractive optics for the correction of refractive errors such as short sight. One of the successes in this area has been the fabrication of bifocal contact lenses for older people or those who have had lens implants for cataract. By combining a contact lens focused for infinity with a DOE with a diffraction efficiency of 50%, focused for near objects, both near and far focus can be accommodated over the whole visual field. In each case the brain appears to ignore the less sharp image. Cohen¹⁹ has designed purely diffractive elements as contact lenses, using a modified surface

The ultrashort pulse method works because the scattered beam takes longer to reach the hologram than the direct beam. By the time the scattered light reaches the hologram the reference beam has been cut off. In the low-coherence beam method the scattered light, having farther to travel, is outside the coherence length when it arrives at the emulsion, and is no longer correlated with the reference beam. The technique is discussed further in Chapter 27.

It goes without saying that this operation could not be carried out on a live human eye without a good deal of modification. fringe profile that is flat topped so that it lies more comfortably on the cornea than a sinusoidal profile, and is less prone to picking up detritus.

Multiplexed holograms

The images normally seen in diagnostic situations, X-rays, brain and body scans, ultrasonic images, are all fundamentally two-dimensional. They can usually be called up in two-dimensional slices, or in views from different angles, by digitizing them and presenting them on a display screen. Recent advances in computer technology have made it possible to view successive slices in animation, giving something like the impression of three-dimensionality. But each individual image remains two-dimensional. If all the slices could be displayed simultaneously in their correct planes, there would be a fully three-dimensional image to work from. It is possible to achieve this holographically by assembling all the images of the slices, each slice in its correct position within the total holographic image. The assemblage of images is from front to rear, and is thus different in principle from a holographic stereogram, where the assemblage is from side to side.

A technique for achieving this was pioneered at the Royal Sussex County Hospital²⁰. It was further developed at Imperial College, London, between 1985 and 1989. The most comprehensive description of the technique at this time was by Hart and Dutton²¹, whose paper also describes the use of stereograms and computer-image holograms. The techniques were described in Chapter 19. Stephen Hart subsequently joined Voxel, a company formed initially in California to exploit the idea. The company now operates from Utah.

There are four main techniques for visualizing tissues by scanning: computerized axial tomography (CAT), positron emission tomography (PET), nuclear magnetic resonance imaging (NMRI) and ultrasonic scanning. CAT scanning uses X-rays, and shows up dense structures such a teeth and bone; PET separates out tissues with various biochemical functions; NMRI shows up different kinds of soft tissue, and ultrasonics shows up organs of differing water content (and, as it operates in real time, movement). All of these techniques produce images containing a good deal of visual noise, and computer processing of the raw input is necessary to clean up the images. This procedure can be as selective as desired: it is possible, for example, to select out a brain tumor, which in the volume multiplexed image can appear like a table tennis ball suspended in a transparent cranium. Equally dramatic is the image of a shattered pelvis, with bone fragments seemingly suspended in air. The real merit of this imagery is that a lesion can be seen in the round, and its position in space can be judged by direct viewing. At present the usefulness of the process is somewhat limited by the time taken to produce the hologram by conventional means, but no doubt as holographic video develops (see Chapter 26), it will eventually be possible to obtain images in real time.

Holographic stereograms have their applications, too, but they are of less value in the operating theatre because of the lack of vertical parallax. They are more useful in the study of orthopedics, where an all-round view before, during and after treatment can be a valuable record, or for synthesizing a full-parallax image from a few X-ray shots taken from different angles. Stereograms also have considerable possibilities for teaching purposes, where an animated image can show, for example, a developing fetus or a progressively sectioned molar tooth. Such images are as useful as a video recording of the same thing, and, unlike a computer image,

This type of hologram is perhaps best named a volume-multiplexed hologram.

Of course, computer software can do more than a hologram can with this type of display, no matter how sophisticated the latter may be. The point I am making here is that the hologram, once made, needs no special technology to view it. don't need anything more than a light bulb to display them. They can even be produced in embossed form, to go into a textbook.

Holograms and diagnostics

An exciting development in diagnostic technology has come from the Institute of Biotechnology of Cambridge University. A team led by Chris Lowe²² has introduced the idea of color changes in trivial reflection holograms (i.e. Denisyuk holograms of mirrors) to detect the presence of pathogens through color changes in the reflected light. Various types of hydrogel that can be silver-halide-sensitized can be used to rapidly detect and identify levels of blood gases, electrolytes and metabolites and changes in pH. With these methods physicians can monitor various pathological conditions in the surgery, thus adding another powerful weapon to the GP's armory.

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Chapter 26 Holographic motion pictures and video

For instance, the pictures on the wall next the fire seemed to be all alive... The chessmen were walking about, two by two!

Lewis Carroll, Through the Looking-Glass

Making the image move

The simplest kind of 'movie' is a holographic stereogram in which the horizontal parallax has been wholly or partly taken over by movement. In the earlier examples the subject would make some simple movement or gesture during the shooting of the originating photography. An early example of this was Lloyd Cross's 120° cylindrical stereogram 'Kiss' in which the image of Pam Brazier blows a kiss and winks as the viewpoint moves from left to right (Fig. 19.5). In these stereograms, shot initially with a cine camera, only a simple brief gesture was possible, and this had to be carried out with exaggerated slowness (most viewers move past a 120° stereogram in about 3 seconds, but the image would have taken 15 seconds to shoot). A large number of stereograms have been made directly from movie sequences shot using a stationary camera. Some of these were made into 360° cylinders that were set up to rotate slowly; others were wound slowly between two spools. Andrews and Rainsdon¹ placed their time dimension in the vertical plane, by masking the temporally separated masters into horizontal strips, so that changing the viewing height animated the image. With this system it is possible to use vertical slit images to add horizontal parallax, but this demands a minimum of some 1000 images per hologram. Yamaguchi et al.² suggest a broadly similar system but with the film scrolled vertically during viewing. A strobed shutter on the playback source would eliminate jumping of the image.

Real-time holography

Real-time holography can by its nature be holography of moving objects, but is not a recording in the same sense as a photographic motion picture or videotape. It has more in common with live TV, in that it is 'here and gone'.

• *Electroholography* This term encompasses the most important techniques for real-time holography. *Dynamic holography* refers to the real-time holographic recording of moving objects. The only sensor that can operate fast enough to record moving objects in conditions of low light is the charge-coupled device (CCD), the heart of digital and TV cameras. The main difficulty with electroholography is the low resolution of the recording material. The amount of information in a conventional hologram is huge: St Hilaire *et al.*³ rate the information content of a hologram only 100 mm square as 25 gigabytes. If transmitted by TV with its normal bandwidth, such a hologram would require some 25 minutes to transmit. Stephen Benton was one of the first persons to attempt to reduce the information content of a hologram without losing its

Electroholography is holography in which both the acquisition and display of the image is achieved electronically. And, as a spin-off, stumbled on the concept of the rainbow hologram, one of the many serendipitous discoveries in the history of holography.

A phase-conjugated beam is not just a reflected beam. A suitable metaphor for the difference is a railway train making a return trip. In the 'reflected' case it negotiates a loop line and rejoins the track facing forwards: in the 'phase-conjugated' case it runs up to the buffers, reverses, and retraces its path. essential qualities. By eliminating vertical parallax, he succeeded in lowering the information content by a factor of about 100. This was still not nearly enough. Although pixel sizes are now down to a few micrometres in width, they will still only resolve the fringe patterns produced by a very simple object in a basic holographic setup such as an in-line or Fourier transform configuration.

• *Four-wave mixing* One device that does record a hologram in real time without the resolution constraints above is a photorefractive crystal with four-wave mixing. Two suitable types of photorefractive crystal are bismuth silicon oxide (BSO) or bismuth germanium oxide (BGO). Of the four waves, two are simply pumping beams that are counter-propagating into the crystal and providing energy to amplify the imaging beam. The third beam is the object beam, and the fourth beam is its phase conjugate, a wavefront propagated back along exactly the same path; this is, strictly, the image beam.

If left to its own devices this wavefront would progress back to the object and simply wrap itself round it, but a beamsplitter sends it on a different route, where it produces a real-time image field identical with the object field (Fig. 26.1).

In holographic terms, beam no 2 can be thought of as the reference beam and beam no 3 the reconstruction beam. The real image can either be viewed directly or captured on a CCD array. It can also be relayed, for example, to a head-up display system. This system requires information reduction only at this stage, where the information is being transferred electronically.

Photorefractive crystals are not easy devices to set up, and as the final readout usually has to be presented electronically, it makes more sense to have an entirely electronic regime, at least as things stand today. The holographic fringes must be large enough to be within the resolving power of a CCD array; but as modern technology progresses, and the size of the pixels shrinks with each new generation



Figure 26.1 Phase conjugation by four-wave mixing (see text).

of devices, this requirement is becoming less restrictive with time. The hologram can be digitized, filtered to remove the conjugate image and the zero-order beam, contrast- or edge-enhanced and reconstructed, all in near-real time.

The next question is: how do we present the data at the output? Bill Parker⁴ gives a comprehensive answer. He lists a number of devices that satisfy the requirement, including non-holographic optical storage, reusable holographic media such as photothermoplastics, and spatial light modulating devices such as LCDs, which, like CCD arrays, are becoming higher in resolution with each succeeding generation, and will probably soon be able to cope with the fringe pattern of a Fresnel hologram. Hashimoto *et al.*⁵, in an overview, cover the situation as it existed in 1992.

Holographic movies

The general public has been conditioned by space fantasy epics, virtual reality experiences and science fiction to expect from holographic movies much more than can be delivered, no matter how sophisticated the system. If tomorrow it were to become possible to screen holographic movies as public entertainment, it would probably prove to be of very limited interest. Stereoscopic movies have never really caught on, in spite of the advantages of a big screen and full color. The limitations of holography differ from those of stereoscopic photography, but they are no less restrictive. The viewing screen can be little larger than the original hologram, and once outside the exit pupil (the real image of the master hologram) a viewer can see nothing at all. This severely limits the size of the audience. Within these limitations, holographic movies are certainly feasible, and a number of intrepid souls have made them: at least one was more than 15 minutes in duration.

One of the first successful attempts to make a holographic motion picture was by Hefliger *et al.*⁶ Using 35 mm holographic film in a Debrie high-speed camera operating at up to 200 frames per second, and a pulsed xenon laser for illumination, they made focused-image holograms at 1:1 scale of tiny marine creatures in a glass tank. Soon afterwards, Hentschel *et al.*⁷, using a pulsed argon laser, succeeded in producing holograms at the rate of 19 000 per second to record short-lived cavitation phenomena, using first a rotating holographic plate, then a modified drum camera. In a later paper⁸ they reported having increased this rate by a factor of four, by introducing an acousto-optic modulator that could switch rapidly between four frequencies, giving four rows of images on the rotating drum. The team later reported⁹ improving the illumination by using a copper vapor laser to drive a dye laser with a 15 ns pulse duration.

There have been a number of attempts to make holographic movies for entertainment, the main problem being the difficulty of achieving a large enough viewing space to accommodate several viewers. Komar¹⁰ devised a complicated system based on a projection technique. He recorded the subject as a series of image holograms on 70 mm holographic film, using a very large diameter lens. He projected the reconstructed image back through the system onto an HOE that was the equivalent of several superposed concave mirrors, each of which formed a real image of the large projection lens in a separate location, so that a number of people could watch at the same time, each through their own exit pupil. The artist Alexander¹², who had conceived much of his work in holographic form and had assisted Smigielski's team, later made holographic films lasting up to five minutes with a full stage, but was restricted to shooting on ordinary film in binocular stereo, later converted into two-channel holograms – not much of a forward step. (Some of this work is not reported fully in the reference.)

An acousto-optic modulator is a crystal that changes its refractive index when it is stressed. Under stimulation by an ultrasonic transducer it behaves like a transmission diffraction grating. Smigielski *et al.*¹¹ describe an improved technique using 126 mm wide film to make holographic movies with a frame size of 100 mm wide \times 10 mm high. Using a pulsed green solid-state laser, with exposure times of 15 ns and between 30 and 50 mJ per pulse, they have been able to obtain takes lasting more than a minute.

However, Albê and Smigielski¹³ suggest recording full-parallax holographic stereograms for each frame. This could be achieved by a battery of cameras arrayed along a horizontal bar. The skeptic might note, however, that a similar result could equally well be accomplished by purely photographic means, using lenticular screen techniques.

It may be too early to suggest that holographic cinema is a dead end, but it certainly looks as if holographic video represents a more promising avenue for further research.

Holographic video and television

The field of holographic video has been dominated for some years by the work of the Spatial Imaging Group at MIT, led by Stephen Benton. The team has succeeded in producing convincing holographic video images in color in something approaching real time. As yet the images are small, and the process is complicated, requiring the back-up of a sophisticated computer program and state-of-the-art optics, The evolution of this achievement is chronicled in Kollin *et al.*¹⁴, Benton *et al.*^{15,16}, and St Hilaire *et al.*^{17,18}.

The broad principle is that the original image is digitized and operated on to produce an image-plane hologram with a reference source alongside the master. It is thus a kind of hybrid of a rainbow and a Fourier-transform hologram. The elimination of vertical parallax reduces the information content, and means that the interference pattern for a single point on the object appears on only a single line of the raster generating the hologram. In addition, the positioning of the reference source in the master plane means that the fringe spacing corresponding to any single object point is constant all along the line. The parallax angle is reduced to 15° , and the highest spatial frequencies recorded correspond to the diffraction limitation of a 2 mm aperture (the average diameter of the pupil of the eve). These restrictions amount to a reduction of information content by a factor of about 50 000, just what is needed. Unfortunately, although the display system can cope with this in real time, existing computer power has so far been insufficient to handle the information at this speed, so the images have to be put into a temporary store (each image takes around one second). No doubt this problem will solve itself as computers become more powerful with each succeeding generation.

The display is built up like a TV display, with (at present) 192 horizontal lines, each of 32 768 points, scanned 40 times a second. If it were possible to have a stationary dynamic diffraction grating it could be scanned by a conventional expanded beam; but the only kind of grating that can be updated at the required rate is the one-dimensional acousto-optic modulator.

This consists of a single large crystal of tellurium dioxide with an ultrasonic piezoelectric transducer at one end. When this is activated at several hundred megahertzes, waves of altered refractive index chase down its length, in the form of a sinusoidal grating moving at 617 m s^{-1} . This is used to diffract a narrow laser beam to form the hologram image line by line; a galvanometer mirror



Figure 26.2 (a) Diagrammatic view of the Scophony display system; (b) schematic representation. After Benton⁵⁶.

accomplishes the vertical transits. In order to compensate for the rapid horizontal movement of the fringes, the diffracted beam is reflected off a polygonal mirror rotating in the opposite direction at compensating speed. A one-dimensional vertical diffuser broadens the viewing aperture vertically, and a demagnification lens corrects size and perspective. Figure 26.1 shows the arrangement.

All that was now missing was color. As the original display used three channels across the acousto-optic modulator, it was fairly easy to use these for red, green and blue signals. St Hilaire¹⁶ gives full details.

As you will appreciate from this account, the success of this work is still somewhat limited (Plate 16b). The image area and parallax are small, the presentation is not yet in real time, and so far only computer imagery has been tried. But as Benton¹⁷ said: 'The first step is to convince people with limited imaginations that it might be possible, and that is what these small, flickering, tumbling [images] have done. The rest ought to be easy!' After all, the necessary theory is in place, and the techniques involved are all improving. Already there are higher computing rates; an updated

Baird's pre-war TV transmission system you are not far wrong. In fact it resembles more closely a later version by L M Myers, called the Scophony system¹⁹, so the MIT team has called its system the Scophony holographic display system. Figure 26.2 shows the layout as a box diagram.

If you think this is reminiscent of

model has replaced the polygonal mirror with an array of galvanometer mirrors, and more acousto-optic modulators have been added (Benton *et al.*²⁰). Perhaps soon, with large high-resolution spatial light modulators (LCDs) and multi-pupil outlets, holographic television may become a commercial possibility. Even in its present form it is capable of useful applications in teaching and exhibitions, and in a number of scientific research areas.

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Chapter 27 Other applications of holography

Alice laughed. 'There's no use trying,' she said: 'one can't believe impossible things.' 'I daresay you haven't had much practice,' said the Queen. 'When I was your age, I always did it for half-an-hour a day. Why, sometimes I've believed as many as six impossible things before breakfast....'

Lewis Carroll, Through the Looking-Glass

This chapter contains a number of applications of holography that are too limited in scope to merit a chapter on their own, or are still in a comparatively early stage of development. There are three main groups of topics: far-field holography and holomicrography, holography at non-optical wavelengths (including acoustic holography), and holography underwater and through scattering media. There is also an outline of research into such rapidly developing areas as polarization and electron holography.

Far-field holography

Far-field or *Fraunhöfer* holography is basically an in-line holographic system using a single beam.

As the setup resembles that of Gabor's original experiment, the result is also called a *Gabor hologram*. It is nowadays mainly used for particle and droplet counting, where the subject matter is so tiny that its diffraction pattern is large, and the spurious image originally encountered by Gabor does not occur: in effect it simply adds a constant to the genuine image term.

The particle chamber is illuminated by a collimated beam of pulse laser light. The particles in the chamber form a characteristic diffraction wavefront, interfering with the undisturbed background that provides a collinear reference beam. For each near-point object the interference pattern forms a Gabor zone plate which, when replayed, forms a virtual image of the object at its original position. A relay lens is generally positioned to produce a real image; this can if necessary be magnified. Because the angles between parts of the object beam and the collimated reference beam are very small, the fringe pattern is coarse enough to be recorded by video or digital recording, and is thus suitable for real-time studies. (See 'Digital Holography' below.)

Thompson and Dunn^{1,2} discuss the use of far-field holography in the measurement of atmospheric fog particles, studies of cloud chambers, aerosol particles, flow diagnostics (with double-pulse illumination) and fiber sizes. Important applications of in-line holography to drop-size measurements in dense fuel sprays are given by Jones *et al.*³ and Webster *et al.*⁴, with particular reference to combustion systems. The technique has also proved useful in studies of cavitation.

The usual configuration for in-line holograms is shown in Fig. 27.2. The image can be analyzed visually or by an automatic readout system, with the focus of a TV

Fraunhöfer diffraction is defined by the diffraction source and screen being effectively an infinite distance (in terms of number of wavelengths) apart.

The principle also holds for somewhat larger particles, but for these the shadows of the objects hide the innermost parts of their diffraction pattern, and they appear black, surrounded by higher-order fringes (Fig. 27.1).





Figure 27.2 Schematic representation of setup for in-line Fraunhöfer holograms. (a) Setup for making the hologram, with two alternative positions for the plate; (b) setup for replay.

camera moving through the depth of the image. If a double pulse is used, the movement of the particles can be traced individually either directly or by Fourier-transform (FT) methods. Thompson⁵ provides a survey that discusses improvements in technique up to 1989, explains the analysis of the FT image, and gives an extensive bibliography. An important advance has been the introduction of high pulse-repetition rate solid-state lasers for high-speed cine-holography (Nyga *et al.*⁶).

Figure 27.1 In-line hologram of ragweed pollen. Although convolved with their own diffraction pattern, the images of these grains reconstruct in three dimensions, and many useful measurements are possible. Hologram and photograph by Paul Dunn.

Holomicrography

When you use an ordinary camera to record the optical image produced by a microscope, the very limited depth of field means that only one plane can be in focus at a time. Confocal systems enable microscopists to build up an image by focusing in turn on different planes, as the magnification remains constant at all distances, but this works for stationary objects only. If the subject matter is, for example, a drop of water containing living microorganisms, owing to their movements there is no possibility of producing a three-dimensional image in slices. A hologram made using a pulse laser can record the whole drop and its contents in one instant. The microscopist can then position the hologram on the microscope stage, illuminated by the original reference beam, and examine any plane within the original drop.

In practice it can be difficult to get a reference beam (or even a holographic plate) on to the microscope stage, but the hologram can in fact be recorded anywhere between the stage and the eye, with identical results. One method of reconstruction is to generate a real image at unit magnification by placing two objectives back-to-back, as suggested by Hefliger *et al.*⁷. These systems are shown schematically in Fig. 27.3.

In Position A the holograms is being made directly, and the microscope itself is redundant, except for the convenience of the optical condenser and the stage. Position B is at or near the prime focus of the objective, and in playback the hologram can be moved in and out relative to the eyepiece. Position C catches a real image and forms a focused-image hologram. This can't be viewed directly as the axial magnification, being the square of the lateral magnification, is enormous.



Figure 27.3 Recording a holomicrogram. (a) A, B and C are possible recording positions. For positions A and B the reconstruction can be viewed through the microscope; for position C the image is projected back through the microscope stage, where (b) it can be viewed by means of a second microscope focused on the other side.



Figure 27.4 Holomicrography, after Wuerker and Hill⁸. A focused-image pulse laser hologram is made using three relay lenses RL to produce a 1:1 real image at H, with a separately routed reference beam. The hologram is examined by conventional microscopy, using a CW laser light source. Cineholography is possible.

Wuerker and Hill⁸ have designed a holographic microscope using a pulse laser as illuminant. The imaging system does not magnify the image. It consists of three lens assemblies, each of the same focal length, spaced two focal lengths apart, the light falling on the first lens (through the stage) being collimated. The middle (field) lens is at the focus for the object on the stage, and this is again focused by the third lens on to the emulsion, giving a 1:1 image. The reference beam is routed to the emulsion separately. The holographic image is played back through the system, and the image (in the plane of the original stage) can be examined by CW laser light using a conventional microscope (Fig. 27.4). Holomicrographic technology, after being fairly static for some years, is now progressing rapidly as the result of the introduction of digital methods (see Digital Holography below).

Microwave holography

Historically, this represents the first application of holography, though this wasn't appreciated until Emmett Leith and Juris Upatnieks came across Denis Gabor's original papers while working on synthetic aperture radar (SAR) in 1955.

As Leith⁹ pointed out, the practitioners of SAR didn't connect it with holography to begin with, as the origins of SAR technology lay in pulse Doppler radar, which resembles echolocation, and pre-dated holography (it was a development of Second World War technology). Nevertheless, an SAR record *is* a hologram, and Leith and Upatnieks were the first to recognize this. The wavelength of the coherent radar beam is a few centimetres. To generate an SAR image the aircraft flies along a straight path, emitting radar pulses, the returns from which are stored on a continuously moving strip of recording material. Every point in the scene generates a linear zone plate, so that the final data amount to a Fourier-transform hologram, which can even be replayed optically to produce an image of the scene. Cutrona *et al.*¹⁰ explain the principle in detail.

As a scaled-up version of optical holography, microwave holography can be useful for demonstrating the principles to students. Using a 3 cm microwave kit you can set up a kind of holographic table, and use the detector to plot the fringes. You can then cut the fringe pattern from aluminum foil, set it up, and play back the diffracted beam.

Synthetic aperture radar is a sidelooking airborne radar system that builds up a highly detailed twodimensional view of the terrain being surveyed from a one-dimensional record of radar echoes over a long horizontal base (the aperture). The principle is closely related to that of holography, and the record is indeed a type of hologram.

You can only do this with simple objects such as discs or gratings. Try making a simple zone plate first. Microwave holography at centimetre wavelengths does have a number of valuable applications. One application is the measurement of the profiles of large reflector antennas, using as reference beams the powerful coherent microwave signals from geostationary satellites. A number of recording media have been used, including mechanical scanning, thermosensitive films and semiconductor arrays. Once the hologram has been plotted, the image can be photographically demagnified and illuminated by laser light to produce an optical image, though owing to the scale factor the image will be effectively flat. Methods of discrete sampling and recording of the field, particularly with direct recording of phase, enable the use of electronic data processing. Microwave holography has proved its value in the diagnosis of surface errors and misalignments in large dishes (Anderson¹¹, Rochblatt and Seidel¹²).

Another application is the holographic mapping of underground cables and other utilities. Natural features such as groundwater can mislead traditional means of location. Microwaves can penetrate the ground to some depth, and don't distinguish water from earth. Anderson¹¹ presents an overview of the technique. Recent advances are mainly in the realm of improvements in image quality by digital enhancement.

Infrared holography

Industrial carbon dioxide (CO₂) lasers used for machining operate typically at 10.6 μ m in the far infrared. Only a small number of materials are transparent to this wavelength, and these are difficult to work with.

Reflection HOEs are suitable for focusing the beam to a small spot or to a predetermined pattern. Sweeney *et al.*¹³ describe methods of fabricating such elements. They fall into three main groups.

- Indirect recording, where the hologram is recorded in visible light for replay in infrared;
- Computer generation, which involves direct fabrication from a computer program containing any required pre-distortion; binary patterns are large enough to permit either microlithography or direct engraving;
- Direct recording by high-resolution thermal detectors, involving recording on thermosensitive substances such as thermochromic copper mercury iodide, which is then used as a pattern for making a metal copy.

Ultraviolet holography

Up to the early 1990s there was little interest in ultraviolet holography, although even then there were plenty of lasers emitting UV radiation. One of the workhorses of coherent UV radiation is the frequency-tripled solid-state laser emitting radiation at 355 nm. Most light-sensitive non-silver materials have their peak sensitivity in this region, and it would seem to be promising source for making holograms on these materials, in view of the shorter exposures and higher resolutions that would be available. Photochromic glass of the type used in ReactoliteTM and similar classes also has a peak sensitivity in this region and could be useful as an erasable medium: its natural decay time is several minutes.

Notably arsenic trisulfide (As₂S₃), silicon and germanium.

Of course, it's difficult to work with a beam you can't see. The lens of the human eye is opaque to radiation of wavelength shorter than about 380 nm. But people who have had a cataract operation involving a synthetic lens implant (myself included) can see the 355 nm beam clearly. So we aging researchers may still have some unique uses in the optics lab!

X-ray holography

At wavelengths of 10 nm and below we enter the field of X-radiation. X-rays are routinely used in crystallography: as the spacing of the atoms in crystals is of the same order of magnitude as the wavelength of X-rays, holography should be able to give us direct three-dimensional images of crystal structures without the spot counting and tedious computation necessary at present. It would also be very useful in medicine to be able to obtain a direct three-dimensional image of, say, a fractured hip joint with a single exposure. But the image would have to be played back by X-rays too, so some kind of three-dimensional fluorescent screen technique would be needed. Robinson¹⁴, writing in 1982, was optimistic about X-ray holomicrography, but doubtful about finding a manageable source of coherent X-radiation. He suggests in his paper that a transmission electron microscope could produce a magnified replica of the interference pattern in the hologram, which could be viewed by visible laser light without the exaggerated depth.

Howells *et al.*¹⁵, in 1985, were more optimistic. They had succeeded in making holograms using soft X-rays at about 3.2 nm, using synchrotron radiation from the 750 MeV storage ring at Brookhaven. All their holograms were of the in-line type, using standard commercial holographic film. Their paper discusses the construction of X-ray beamsplitters and lenses, using gratings at grazing incidences. Progress in X-ray holography has been limited by the difficulty in obtaining beams of coherent X-rays, but these are now becoming available (if scarce), and successful off-axis holograms have been obtained using a Lloyd's mirror system to obtain the reference beam. The recording medium also presents a difficulty, and the most promising medium so far appears to be a photorefractive material pre-exposed to a trivial reflection image by visible light (i.e. a holographic mirror), which is destroyed in a regular manner by the X-ray interference pattern.

Electron holography

In modern physics an electron can be shown to be associated with a wavelength, and a beam of electrons traveling in the same direction and at the same speed acts as a coherent beam of radiation, the associated wavelength being of the order of a picometre (10^{-12} m) . In theory, any such beam can be used to make a hologram, given a suitable recording medium. Tonomura¹⁶ describes how his team at Hitachi used a field-emission electron microscope to produce a collimated beam of electrons, which was overlapped onto itself by an electronic biprism.

One of the applications of electron beam holography sees the discipline coming full circle: Harada *et al.*¹⁷ have used electron holography to produce a HOE to correct spherical aberration in an electron microscopes.

Other possibilities for electron holography include visualization of magnetic fields, measurement of atomic dimensions, and, perhaps, the answers to some of the fundamental questions of quantum physics.

Acoustic holography

This is an odd one out among holographic techniques, as it uses ultrasonic, not electromagnetic, energy. Sound waves are longitudinal waves, that is, the field

Because X-radiation is not reflected or refracted in the way visible light is, ordinary mirrors and beamsplitters are out of the question. Radiation can be reflected only at grazing incidence (less than 1°). Bragg reflection is possible, but the layers need to be only a few molecules thick. The recent boom in X-ray astronomy has led to some spectacular successes in this field.

Gabor's original intention in inventing holography was to use it in improving the resolution of the electron microscope.

There is nothing inherently strange about forming holograms with ultrasound. Dolphins and bats have been using their own brand of sonar for millions of years, and both animals interpret their received pattern of signals by a neural network that closely resembles a real-time hologram. variations are along the axis of propagation, as opposed to transverse waves, where the field variations are at right angles to the direction of propagation. Longitudinal waves cannot be polarized, but they are diffracted, and they interfere in the same way as transverse waves.

Glen Wade¹⁸ describes the function of ultrasonic spectacles for the blind that operate in a similar way to that of the bat's system and can locate small objects several at a time. Poohsan Tamura¹⁹ shows how a real image of an orchestra, originally behind an array of microphones, can be imaged in the reproduction in front of the speakers by methods analogous to those used in transfer holography – even to the extent of creating an intermediate 'pseudophonic' aural image by playing the recording backwards and re-recording the signal on a second array of microphones, finally replaying in the original direction. Fushimi *et al.*²⁰ have used acoustic holography to investigate the vibrations of the belly and back of a violin.

Ultrasound at around one megahertz, a much higher frequency than bats and dolphins use, requires a liquid medium, as the signal is rapidly attenuated in air. In such media, although the wavelength is more than ten times that in air, it is still short enough for all the usual phenomena of interference and diffraction to occur in the same way as with light wayes. You can use ultrasonics to make all the usual types of hologram, including focused-image holograms. All you need are two synchronized ultrasonic transducers, one to illuminate (more correctly, to 'insonate') the subject, the other to provide the reference beam. Much of the early work in acoustic holography is associated with the late Pal Greguss, who from 1965 produced a steady stream of papers on the subject, some of which even speculate on the possible role of holographic models in unraveling some of the mysteries of perception^{21,22}. Greguss initially used ultrasound-sensitive plates to record acoustic holograms. These were photographic plates that had been fogged by exposure to light but not developed. The liquid medium was a dilute solution of photographic fixer. The energy released at the antinodes of the fringe pattern agitated the solution and dissolved away the silver halide, while the nodes left the solution stagnant, so that when the plate was removed, washed and developed, it bore a replica of the interference pattern in the form of a transmission grating. An alternative approach was to use the surface of the fluid as the holographic plane, and to reconstruct the image from this, using a schlieren technique to turn the phase object (the ripples) into an amplitude image of the grating that could be optically demagnified so as to be addressable by visible light or viewed through suitable optics.

Taylor *et al.*²³ describe a method that is simpler in principle and is now standard; it employs an in-line configuration, scanning the pattern with an ultrasonic hydrophone.

Hildebrand²⁴, in a comprehensive survey, gives the theoretical background to all the types of detector mechanism, including a backward-wave propagation system in which a transducer operates in short bursts and measures the time for the echo to return from the various parts of the subject, scanning in a two-dimensional pattern. The authors of these papers also note the resemblance between acoustic holography and synthetic aperture radar, and discuss practical setups for non-destructive testing, showing, for example, the way to eliminate ghost images by the use of more than one frequency. There is a thorough analysis of the whole field of acoustic holography by Sarkissian²⁵ in a recent book on acoustic interactions with submerged structures.

The schlieren principle involves focusing the image on a knife edge, so that disturbances are either blocked or cleared by it, thus turning phase variations into luminance variations.

A hydrophone is a transducer that converts underwater vibrations into an electrical signal.

Light-in-flight holography

The idea of recording the flight of a pulse of light as it speeds through the air at almost three hundred thousand kilometres a second is mind-boggling. But Nils Abramson^{26,27} suggested that with the development of picosecond laser pulses such a feat might be possible. Staselko *et al.*²⁸ had also anticipated this. Soon afterwards Abramson succeeded, subsequently presenting a report²⁹ containing a full description of his method. The technique he used is described below.

If a beam of light exists only very briefly, so that its coherence length is only a few millimetres, there will be an interference pattern, and thus the possibility of making a hologram, only where the object beam and reference beam arrive at the emulsion simultaneously, i.e. the two optical paths from the beamsplitter to that point on the emulsion surface are exactly equal in length. If they are not, the beam with the longer distance to travel will arrive at the emulsion too late; the other beam will have come and gone. The 'object' in Abramson's experiment is a long flat white rigid sheet, set at a small grazing angle to the laser beam; a gently diverging wavefront from the laser will travel along it in the form of a circular arc centered at the source. The holographic emulsion needs to be approximately parallel to the object plane, and the reference beam path modified so that the path lengths match for each pair of points that are opposite one another on the object and hologram planes. Figure 27.5 shows a simple version of the layout.



Figure 27.5 Table layout for light-in-flight holography. PL is a short-pulse laser (less than 5 ps). M_1 and M_2 are reflecting prisms or other suitable reflectors. BE is a negative lens, OIB is the illuminating beam for the object O (a flat white surface). The holographic emulsion H is parallel to O and is illuminated similarly.

This is not difficult to set up. If you measure the initial and final positions carefully, equal path lengths will always exist at each point in the hologram plane. In setting up with a HeNe or diode steering laser, the reference beam should be made much weaker than the object beam, about one-tenth of its intensity. In his first successful demonstrations Abramson made a number of exposures with lenses,



Figure 27.6 Light in flight. This multiple photograph shows a light pulse at five stages as it passes through a lens and is brought to a focus. Photograph courtesy of Nils Abramson, Royal Institute of Technology, Stockholm.

mirrors, etc., mounted on the object plane. In his hologram reconstructions you can see the pulse of light moving along the white screen as your viewpoint progresses along the beam axis, being reflected or refracted by the optical component – a dramatic demonstration. Figure 27.6 shows a set of superimposed still photographs of a series of light-in-flight images with a lens in the optical path.

If you don't have access to a picosecond laser (and not many people do!) you can obtain an identical result with a CW laser that has a very short coherence length, such as an argon laser with the etalon removed. As a pulse of short duration has a coherence length that is proportional to its coherence time, so a beam of short coherence length has a coherence time that is equal to the time it takes to travel a distance equal to its coherence length. It follows that the important thing in deciding whether interference takes place or not is the coherence time, so the two situations are identical. Abramson³⁰ has noted this, and his paper shows that a CW laser of short coherence length produces the same effect as a picosecond laser.

Don't imagine that light-in-flight holography is merely an interesting educational demonstration. Abramson³¹ outlines a practical application in holographic contouring. He has also examined the kinds of distortion that would occur when studying objects moving at relativistic speeds³², and in a recent book³³ he has developed the whole conceptual system into a philosophy involving special relativity.

Leith *et al.*^{34,35} have used the principle of low coherence length in their research into imaging opaque objects embedded in organic tissue (see p. 391). Although nearly all the light is scattered, the first light to arrive is the part of the light that has *not* been scattered, and if the reference beam path is matched to this distance a clear image should result. In a conventional setup the fringe pattern will be seriously underexposed, as it is buried in the general fog caused by the scattered

I discovered this effect for myself some time ago, when experimenting with early diode lasers that had a very poor coherence length, but at the time I didn't have the wit to appreciate what was going on. light. To get round this problem the team adopted an in-line geometry, with recording by a digital camera. The image from a single hologram proved exceedingly noisy, a problem overcome by making a large number of exposures and averaging the result. The realization that resolution depended on the shortness of coherence length led Leith's team to use a laser producing two wavelengths close together, giving an effective coherence time of 0.15 picosecond, corresponding to a coherence length of 0.05 mm. There are considerable possibilities for applications in medical imaging.

Polarization holography

I began this book by saying that, in contrast to photography, holography recorded all the information about the subject that was contained in the wavefronts. That isn't entirely true. A hologram doesn't record the state of polarization of the light reaching it. A hologram will play back equally well by light that is linearly polarized in any direction, or circularly polarized, or not polarized at all. Kakichashvili³⁶ has succeeded in recording polarization in light-sensitive dyes in a polymer matrix, but there is much room for development. Hariharan³⁷ describes two established methods of recording polarization. The first uses successive exposures with separate reference beams polarized orthogonally, the polarization of the object illumination being rotated 90° by a half-wave plate between exposures (Fig. 27.7).

For reconstruction the hologram is relocated in its exact original position and replayed by the two beams simultaneously, with the object beam blocked.



Figure 27.7 Layout for a polarization hologram. The half-wave plate $(\lambda/2)_1$ gives 90° rotation of polarization. The second half-wave plate $(\lambda/2)_2$ is rotated to change the polarization of the object wavefront by 90° between exposures.

The second method uses a single depolarized and diffused reference beam. The half-wave plate is again used in the object-illuminating beam, and the polarization vector rotated between exposures. Again, the hologram must be relocated precisely after processing. Because of the randomness of the reference beam there is no correlation between the two orthogonally polarized components, so the object wavefront is in effect encoded by two discrete reference wavefronts. In both cases the polarization state of the image beam is established by viewing the image through a polarizing filter.

Conoscopic holography

Conoscopic figures are the interference patterns seen on a screen when a beam of light passes through a birefringent crystal set between a pair of crossed polarizers. If such a crystal is set up with its optical axis perpendicular to the polarizers and a monochromatic point source is positioned on the axis, the conoscopic figure that appears on a screen on the other side will be a Gabor zone plate centered on the axis. The focal length of the zone plate is proportional to the distance between the point source and the screen. The zone plate itself (if recorded photographically) is a true hologram, as it has recorded the position of the source in all three dimensions. The interference fringes are formed by the two refracted wavefronts. As the paths of these two wavefronts are the same, there is no need for spatial coherence. Also, as an extended object is simply a large number of point objects at varying locations, each forming its own zone plate, the conoscopic record is a true hologram of the object (Fig. 27.8).

If the hologram is illuminated by collimated monochromatic light, each zone plate forms its own point image in the original position and the complete image is reconstructed. A so-called bias term appears as a flare patch, and this can be moved to one side by tilting the laser slightly; it can be removed if necessary by a spatial filtering technique. If the hologram is recorded by a CCD array, a computer program can filter out the effects of having only partial coherence in the light source, as well as removing the unwanted conjugate image. Sirat and Psaltis³⁸ describe the process, and Mugnier and Sirat³⁹ discuss various methods of optically eliminating the conjugate image. As this technique is effectively real-time, it can produce images under unstable conditions, and even record moving objects.



Figure 27.8 Principle of the conoscopic hologram. The two quarter-wave plates $\lambda/4$ produce circular polarization in opposite senses. BRC is a birefringent crystal.

Hariharan remarks that as the diffraction efficiency is lower for a *p*polarized reference beam at a large angle of incidence, in both methods the angle between the reference and object beams should be kept small. But this doesn't apply if the two directions of polarization are $\pm 45^{\circ}$ rather than 0° and 90°. If necessary the object can be set up rotated 45°, so that the beams are effectively "vertical" and "horizontal". Very thick holographic emulsions produce Bragg planes so numerous that they can store a great many images each coded by the reference beam angle; in transmission mode they will reconstruct a satisfactory image with light of limited coherence.

Pseudodeep holograms

Pseudodeep (perhaps better translated as 'pseudothick') holograms have been a particular interest of Yuri Denisyuk since the late 1980s. The starting point of the research was the desirability of replacing very thick emulsions with a more tractable medium.

The difficulty with thick emulsions is that they are difficult to prepare and to process. Denisyuk has tackled this problem by tilting a conventional holographic emulsion so that it is almost edge on to both the object and reference beams. The first experiments used one-dimensional objects similar to barcodes⁴⁰. Schematics for recording and replaying are shown in Fig. 27.9.



Figure 27.9 Schematic diagram of configuration for a pseudodeep hologram. (a) Line object O exposed to holographic emulsion H at a grazing angle. RS = reference source, close to object. (b) Side view. (c) Reconstruction: IB is the image reconstruction beam (spatially incoherent). The lens L selects light from area A and focuses it on slit S (all other light misses S). The observer views the image from close to S.

The viewing slit restricts the image to one dimension, so by varying the angle of the emulsion it is possible to store a large number of one-dimensional images. As a natural extension of the properties of the hologram, it is also possible to record objects moving towards or away from the hologram (Doppler holography). In a later paper, Denisyuk and Ganzherli⁴¹ show that by including a slit with a one-dimensional diffuser between the object and the hologram, three-dimensional objects can be recorded and replayed by light of limited spatial and temporal coherence. Indeed, it is suggested that this system could form the basis for recording holograms in ordinary daylight. Denisyuk has called this version of the



Figure 27.10 A selectogram. (a) Recording. A diffuser GG is positioned over the right side of the slit S_1 . The reference point source RS provides illuminating light for the object O and the diffuser. (b) Reconstruction. An incoherent beam IB illuminates H, which disperses the light vertically. Horizontally, with the help of transform lens L, it forms the inverted real image RI, which is viewed through slit S_2 .

pseudodeep hologram a *selectogram*. He deals with the topic in some detail in a recent paper⁴² in which the clarity of his exposition belies the obscurity of its title.

Digital holography

Digital holography is basically holography using digital recording of the holographic interference pattern rather than photochemical methods. At present it is limited by the resolution of recording devices to far-field and Fourier-transform formats, though this situation is likely to improve as resolution approaches the wavelength of light. One of the advantages of digital holography is that the information in the holographic record can be analyzed directly by a computer without having to be optically reconstructed, and the spurious imagery associated with far-field holography eliminated. Various forms of the technique have been around for some three decades, but it is only recently that the resolution has been adequate for something like standard Fresnel holography to be carried out using CCD arrays instead of silver halide and other photochemical layers to record the interference patterns. Yaroslavsky⁴³ has made a survey of the past 30 years. Schnars and Juptner⁴⁴ describe the underlying principles and some new applications in a further survey.

Warning: Some of this material is tough going if your maths is shaky.

Allan Evans of De Montfort University, Leicester, UK, has been working with the application of the technique to microscopy, and has already made some significant advances⁴⁵. Digital holography has become a hot topic at conferences, and it is worthwhile following journals such as *Applied Optics* and the *Proceedings of the SPIE* to keep up with what is going on.

Michael Klug's work, which was also discussed in Chapter 19, has taken digital holography to a large scale with his full-parallax stereograms. A recent paper of his⁴⁶ discusses the unique capabilities of digital holograms in this context.

Conclusion

We are now seeing holography being applied throughout a large part of the electromagnetic spectrum, from radar and microwave images at centimetre wavelengths, through the visible and ultraviolet spectrum, to X-rays and even electron beams. Acoustic holography has taken its place alongside sonar and ultrasonic scanning, and holographic techniques are making their mark in medicine. The holographic portrait studio is already with us. Holograms appear in souvenir shops, in books, in museums of fine art, on gift-wrappings, greetings cards and postage stamps. Security holograms are big business: credit cards alone account for several billion holograms a year, and banknotes even more. Conferences on holography and related topics are held several times every year. Techniques are still developing, and though some of the research demands expensive equipment and lavish facilities, by no means all of it does. What is most encouraging about holography is that, just as in photography a hundred years ago and in astronomy today, many exciting discoveries are still being made by amateurs. And remember, 'amateur' doesn't mean 'beginner' but 'enthusiast'.

Now let's make some more holograms.

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Appendix 1 The mathematical background to holography

Let me see: four times five is twelve, and four times six is thirteen, and four times seven is - oh dear! I shall never get to twenty at that rate!

Lewis Carroll, Alice in Wonderland

Formation of a hologram

There are several ways of writing down the equation that represents a traveling wave. Some are more precise than others, but you need to know a little mathematics to be able to understand them. On the principle that if you have to explain something you should always use the simplest explanation that doesn't involve cheating, I have chosen one that has nothing more complicated than cosines. If you have done a little trigonometry, and can remember that

$$\cos X \cos Y = \frac{1}{2}\cos(X+Y) + \frac{1}{2}\cos(X-Y)$$

that is all you need.

Any traveling wave that varies in a cosinusoidal manner when viewed as it passes a fixed point can be described by an equation of the form

 $a = A\cos(\omega t)$

In this equation a and t are variables: a is the instantaneous amplitude at a time t. A and ω (omega) are constants. A is the peak or maximum amplitude; and ω is called the angular frequency, which is related to the wavelength λ by the relationship

$$\omega = \frac{2\pi}{\lambda}$$

and is measured in radians.

At t = 0, a = A (since $\cos 0 = 1$); at $t = \lambda/4$, a = 0 (since $\cos(\pi/2) = 0$); at $t = \lambda/2$, a = -A (since $\cos \pi = -1$);

and at $t = \lambda$, a = A again. The cycle repeats indefinitely in both directions: a = -A at $t = \pm \lambda/2, \pm 3\lambda/2, \pm 5\lambda/2$, etc., and a = A at $t = 0, \pm \lambda, \pm 2\lambda, \pm 3\lambda$, etc. (Fig. A1.1). You will notice that the wavefront is symmetrical about the vertical axis. However, the waveform in question may not have its point of symmetry directly above the origin. If it does not, we have to put a term into the equation to tell us how the waveform relates to a similar waveform that *is* centered on the origin. This comparison term is called the phase, and is denoted by ϕ (phi). The more general equation is written

$$a = A\cos(\omega t + \phi)$$

(see Fig. 1.1b).



Figure A1.1 A cosine wave of amplitude *a* and wavelength $\lambda = 2\pi/\omega$. The equation of the wave is of the form $a = A \cos(\omega t)$. (b) A second wave of the same wavelength referred to the first in terms of its phase difference ϕ . (In this figure, $\phi = \pi/2$.)

Thus the general equation of a traveling wave with respect to time from a fixed point (x, y) is

$$U = A\cos(\omega t + \phi_{[x,y]})$$

where U represents the position of the wavefront at a given time t.

If we represent the reference and object wavefronts by U_1 and U_2 , respectively, remembering that ϕ_1 and ϕ_2 are for some given reference point x, y of the recording medium, their intensities I_1 and I_2 are given by $\langle \frac{1}{2}U_1^2 \rangle$ and $\langle \frac{1}{2}U_2^2 \rangle$, where the angle brackets mean that the values are time-averaged. Now, if U_1 and U_2 are mutually incoherent (uncorrelated) their combined intensity is simply $\frac{1}{2}(U_1^2 + U_2^2)$. But if the beams *are* correlated, their combined intensity I is $\frac{1}{2}(U_1 + U_2)^2$, i.e.,

$$I = \frac{1}{2}(U_1^2 + U_2^2 + 2U_1U_2)$$

Writing out the equations in full gives

$$I = \frac{1}{2} \{ A_1^2 \cos^2(\omega t + \phi_1) + A_2^2 \cos^2(\omega t + \phi_2) + 2A_1 A_2 \cos(\omega t + \phi_1) \cos(\omega t + \phi_2) \}$$



Figure A1.2 Cos and cos² functions.

Using the identity $\cos X \cos Y \equiv \frac{1}{2}\cos(X + Y) + \frac{1}{2}\cos(X - Y)$ for the third term gives

$$I = \frac{1}{2} \{ A_1^2 \cos^2(\omega t + \phi_1) + A_2^2 \cos^2(\omega t + \phi_2) + A_1 A_2 \cos(2\omega t + \phi_1 + \phi_2) + A_1 A_2 \cos(\phi_1 - \phi_2) \}$$

The final term, as you can see, contains information on both A_2 , the object wave amplitude, and ϕ_2 , the object wave phase, in an expression that does not contain t, and is therefore not time-dependent.

This expression is now to be time-averaged. Now, the time-average of $\cos^2 X$ is simply $\frac{1}{2}$, and the time-average of $\cos X$ is 0 (Fig. A1.2). We are thus left with

$$\langle I \rangle \propto \frac{1}{2} \{ \frac{1}{2} (A_1^2 + A_2^2) + A_1 A_2 \cos(\phi_1 - \phi_2) \}$$

Removing the fractional constants leaves

$$\langle I \rangle \propto \{A_1^2 + A_2^2 + 2A_1A_2\cos(\phi_1 - \phi_2)\}$$

This expression does not vary with time, as there is no *t*-term present, so it must represent a constant value of intensity.

How does the intensity vary in space? So far we have considered only one point in space (x, y). If we consider the whole plane in which the point (x, y) lies, then if U_1 is traveling perpendicular to the plane (i.e. if the beam is at 0° incidence), its phase ϕ_1 will be the same all over the plane, and if it is at some other angle of incidence, ϕ_1 will vary linearly across the plane. In contrast, ϕ_2 represents the phase of a highly complicated wavefront which has been reflected off the object. Nevertheless, all the values of ϕ_2 at every point of the plane remain constant with respect to ϕ_1 (this is why we call U_1 the reference beam). The phase relationships are coded in the distortions of the positions of the interference fringes in the plane, and the amplitude variations are coded in the intensity variations of the fringes. We can place a photographic emulsion in the plane, and record this stationary fringe pattern. This record is the hologram.

Reconstruction of the image

To show how the hologram reconstructs the object beam we need to examine what happens when U_1 is incident on the transmission grating we have produced. At any point the emergent wave U_3 can be obtained by multiplying U_1 for that point by the grating transmittance function for that point. Since this is proportional to I, the emergent wave U_3 will be proportional to $U_1 \times I$. Hence

$$U_{3} = U_{1} \times I(\times \text{ some constant})$$

= $U_{1} \{ A_{1}^{2} + A_{2}^{2} + 2A_{1}A_{2}\cos(\phi_{1} - \phi_{2}) \}$
= $U_{1} (A_{1}^{2} + A_{2}^{2}) + 2U_{1}A_{1}A_{2}\cos(\phi_{1} - \phi_{2}) \}$

Replacing U_1 by its value $A_1 \cos(\omega t + \phi_1)$ in the final term gives

$$U_{3} = U_{1}(A_{1}^{2} + A_{2}^{2}) + 2A_{1}^{2}A_{2}\cos(\omega t + \phi_{1})\cos(\phi_{1} - \phi_{2})$$

Expanding the last term by the relationship

$$\cos X \cos Y = \frac{1}{2}\cos(X+Y) + \frac{1}{2}\cos(X-Y)$$

we have

$$U_{3} = U_{1}(A_{1}^{2} + A_{2}^{2}) = \text{constant} \times U_{1}$$
$$+ A_{1}^{2}A_{2}\cos(\omega t + \phi_{2}) = \text{constant} \times U_{2}$$
$$+ A_{1}^{2}A_{2}\cos(\omega t + 2\phi_{1} - \phi_{2}) = \text{constant} \times (\text{modified})U$$

The first term is identical with the reference beam/replay beam, attenuated. The second term is identical with the object beam, also attenuated. The third term is an oddity: it is certainly in the correct form for a traveling wave, but emerges on the other side of the reference beam (turned through an angle 2ϕ), and reversed in phase (i.e. pseudoscopic).

Traveling and standing waves

The previous section dealt with wavefronts at specific points in space, and so I have used a simplified wave equation in which the instantaneous amplitudes fluctuated only in terms of time up to this point. In a full description of a traveling wave we must also think of the way in which the amplitude fluctuates with *distance* at a specific point in time. In the first case (variation in time) we would have an equation of the form

$$a = A \cos\left(\frac{2\pi}{\lambda}t\right)$$

where λ is the wavelength, and in the second case (variation in space) an equation of the form

$$a = A\cos\left(\frac{2\pi}{T}x\right)$$

where T is the wave period. We can combine these into a single equation by writing

$$a = A\cos(\omega t - kx)$$

where $\omega = 2\pi/\lambda$ and $k = 2\pi/T$ (ω and k are both measured in radians) and this is the trigonometrical form for describing a traveling wave, in this case traveling from left to right. For a wave traveling from right to left the sign of kx is changed.

Cosine equations have been used throughout for consistency. Textbooks commonly use the form

 $a = A \sin(kx - \omega t)$, and in this case the

final equation becomes $a = A \sin(kx) \cos(\omega t)$; this puts a node at the origin, which is more convenient for the analysis of the vibration of plucked strings, organ pipes, etc., an important application of standing-wave theory.



Figure A1.3 Two waves of the same period traveling in opposite directions combine to produce a standing wave.

If two traveling waves moving in opposite directions occupy the same space their instantaneous amplitudes add algebraically, and we have

 $a(\text{resultant}) = A\{\cos(\omega t - kx) + A\cos(\omega t + kx)\}$ $L \to \mathbb{R} \qquad \mathbb{R} \leftarrow \mathbb{L}$ Using the identity $2\cos X \cos Y = \cos(X + Y) + \cos(X - Y)$ gives $a = 2A\cos(\omega t)\cos(kx)$

Distance and time are now interlinked, and A and a vary with distance (Fig. A1.3). The result is a waveform with a cosinusoidal profile that has an amplitude varying from +2A to -2A with time. The nodes, or regions of no excursion in amplitude, are one half-wavelength apart, as are the antinodes or regions of maximum excursion, and their positions are fixed in space. Hence this wave is described as a *standing* (or *stationary*) wave.

Bragg diffraction

She puzzled over this for some time, but at last a bright thought struck her. 'Why, it's a looking-glass book, of course!'

Lewis Carroll, Through the Looking-Glass

Bragg diffraction, named after Sir William Bragg and his son, Sir Lawrence Bragg, who first described the phenomenon, occurs when light passes into a medium made up of uniformly spaced layers of partially reflecting material, or of alternate high

Bragg diffraction is utilized in dielectric mirrors and beamsplitters; the principle also underlies the antireflection coating of camera lenses, binocular objectives, etc. Bragg diffraction is of immense importance in the reconstruction of a holographic image. The previous analysis made this assumption.

In fact, they bisect the angle between the *refracted* object and reference beams. The change of direction of a wavefront crossing the interface of two optical media is given by Snell's law

 $n_{1}\sin\theta_{1}=n_{2}\sin\theta_{2}$

where n_1 and n_2 are the refractive indices of the two media and θ_1 and θ_2 are the corresponding angles made with the normal. On emergence the situation is reversed and the effect is canceled out, so for our present purpose this complication can be ignored. In fact, its only important consequence is that because the fringe planes are closer together inside the emulsion than they are in air, the resolving power of the emulsion has to be some 50% higher than would appear to be necessary from the formula used here.

Most optics textbooks use θ_1 and θ_2 as the angles of incidence of the two beams, so that the angle between them is $\theta_1 + \theta_2$. In holography θ_2 is almost always zero, on average, so we can simplify the equation by using θ throughout. and low refractive index with a spacing that is of the same order as the wavelength of light.

In theoretical texts on holography, transmission holograms are often treated as though they are of infinitesimal thickness; their diffractive behavior is accounted for by invoking the grating condition. If this were so, the two diffracted beams would be of equal intensity, and the real and virtual images would be equally bright. Plainly this is not the case: in practice the real image is very dim. Indeed, in order to be able to see a real image at all, we usually have to flip the hologram, which reverses the geometry. This effect is due to the Bragg condition. The reason the grating condition leads us to the wrong answer is simply that the emulsion is *not* infinitely thin. As a rule its thickness is at least six wavelengths. The interference fringes that make a transmission hologram are not just on the surface of the emulsion but go right through its thickness like the slats of a venetian blind. The fringe planes lie parallel to a line bisecting the angle between the object and reference beams (Fig. A1.4a). If the object beam is perpendicular to the emulsion, and the reference beam is at an angle of incidence θ , then the fringe planes will be at an angle $\theta/2$ to the perpendicular. (They also lie along the bisector of the angle between the two beams when neither of them is perpendicular to the emulsion.) The spacing d of the fringes parallel to the emulsion surface is given by the grating condition as

 $\lambda = d\sin\theta$

At this point the Bragg condition enters. For the intensity of the diffracted beam to be a maximum, the wavefronts diffracted by successive fringes must all be in phase or, to be more precise, any phase difference between the wavefronts must be an integral number of wavelengths. If we think of the fringes as acting like simple plane mirrors we can see the conditions necessary for this to occur (Fig. A1.4b). If the grating spacing is appropriate to the wavelength of the reconstruction beam, a bright image will result.

The geometry determining the spacing of the fringes (which we will call the Bragg planes) is shown in Fig. A1.4c. If we call the separation of the Bragg planes w, we can find the angle of incidence of the replay beam that gives maximum intensity in the diffracted beam. The Bragg condition requires that the optical path difference for light diffracted at each successive plane is $n\lambda$, where n is an integer (for a cosine grating n = 1 only). Now, we already know the grating condition

 $\lambda = d\sin\theta$

where d is the grating spacing parallel to the emulsion surface and θ is the angle between the beams, but we are more interested in the Bragg condition, and we need to know the spacing w of the Bragg planes. From Fig. A1.4c we can see that this is given by

$$w = d\cos\frac{\theta}{2}$$

By using the trigonometric relationship $\sin A = 2\sin(A/2)\cos(A/2)$, we can rewrite this grating equation

$$\lambda = 2d\sin\frac{\theta}{2}\cos\frac{\theta}{2}$$

so that

$$\frac{\lambda}{2} = w \sin \frac{\theta}{2}$$

and this is the Bragg condition for reconstruction.



Figure A1.4 (a) In a transmission hologram the fringes are like a venetian blind, and their planes are parallel to the bisectors of the reference and object beams. (b) On reconstruction, rays emerging in the direction of the original object beam differ in optical path length by an amount equal to exactly one wavelength. (c) The relationship between grating spacing and fringe plane spacing. (d) When the reference beam and object beam are incident on the emulsion from opposite sides, the fringe planes are more nearly parallel to the emulsion surface. (e) Reconstruction in a reflection hologram. (f) When $\theta = 180^{\circ}$ the fringe spacing is one half-wavelength. Note that in these diagrams, for clarity the effect of the refractive index of the material has been ignored and the Bragg planes are treated as of infinitesimal thickness.

The real-image beam satisfies the grating condition, but does not satisfy the Bragg condition, as it is at an angle of 2θ , and the mismatch increases as θ increases. The zero-order beam also becomes increasingly mismatched to the Bragg condition (Fig. A1.4d). As θ approaches 90° the angle of the Bragg planes approaches 45°, and their length increases to 1.4 times the thickness of the emulsion. Now, it is clear from the Bragg equation that if θ is fixed then λ is also fixed. The hologram is

thus wavelength-sensitive; and the more extended the Bragg planes are, and the more of them there are within the thickness of the emulsion, the more wavelength-sensitive is the hologram. For a grazing incidence, such as is typical of a cylindrical hologram (see Chapter 8), such a hologram will reconstruct a passable image when illuminated with white (or preferably amber) light. When θ exceeds 90°, so that the reference and object beams are incident on the emulsion from opposite sides, the lengths of the Bragg planes and the number of planes through the thickness of the emulsion are increased so that they resemble the pages of a book rather than a venetian blind (Fig. A1.4d). This, of course, is the geometry for making a reflection hologram (Fig. A1.4f). There are 12 or more Bragg planes within the thickness of the emulsion, and the zero-order and real-image beams are totally suppressed, as are all inappropriate wavelengths. Of course, for practical reasons we make reflection holograms with $\theta \cong 135^{\circ}$ rather than 180° , but we can still achieve very high diffraction efficiencies and narrow bandwidths.

If the angle of incidence of the (white) replay beam is increased to a more glancing angle, the image hue shifts towards blue. This is because the optical path difference for a given Bragg plane spacing becomes less as the angle of incidence increases. Conversely if the angle of incidence is decreased the image becomes redder. The property is sometimes used to tune reflection master holograms to give a bright reconstruction by laser light.

If material is lost from the emulsion during processing, the Bragg planes will in general become closer together. This means that a master hologram cannot be set up using the original geometry and employ the same laser to give a bright reconstruction for transfer purposes. With transmission master holograms the fringe planes may become S-shaped as a result of shrinkage, resulting in a lowered diffraction efficiency and loss of image sharpness. In a white-light transmission hologram the hue will be changed towards shorter wavelengths.

If a reflection hologram is processed in a tanning developer, the cross-linking effect of the developer products will to some extent preserve the spacing of the Bragg planes. However, under certain processing conditions (depending to some extent on the emulsion batch) the tanning effect may not be constant throughout the thickness of the emulsion, with the result that the spacing of the Bragg planes may vary from the outer surface to the inner surface of the emulsion. This condition, sometimes referred to as chirped fringes, results in a broad-band reconstruction which may produce an almost achromatic image. The trade-off is a loss of sharpness that is progressive out of the plane of the hologram.

Effects of shrinkage during processing

The fringe planes that form the hologram bisect the angle between the object and reference beams, the minor angle in the case of a transmission hologram and the major angle in the case of a reflection hologram. (The refractive index of the emulsion causes a change in the fringe angle owing to refraction of the beams, but as the effect is cancelled on emergence it is ignored here.) If material is lost from the emulsion during processing the angle of the fringes will change. If we suppose the object beam to be perpendicular to the emulsion and the reference beam to be at an angle of incidence θ_1 , then the angle the fringes make with the normal to the emulsion will be $\theta_1/2$. If we represent the total displacement from top to bottom of

Unfortunately, the change in angle also causes some image distortion.

For shallow objects this can result in exceedingly bright images, and the phenomenon is exploited in commercial DCG holograms.



Figure A1.5 (a) Transmission, (b) reflection geometry for the formation of fringes in the emulsion. *F* indicates the fringe plane in each case. Note that the refractive index of the emulsion causes a change in the fringe angle owing to refraction of the beams, but as the effect is cancelled out on emergence it is ignored here.

the emulsion by d, and the initial thickness of the emulsion is t_1 , then $d = t_1 \tan(\theta_1/2)$ (Fig. A1.5).

If, after processing, the new thickness is t_2 , the new value of θ , θ_2 , will be given by

$$d = t_2 \tan \frac{\theta_2}{2}$$

As d remains constant,

$$t_1 \tan \frac{\theta_1}{2} = t_2 \tan \frac{\theta_2}{2}$$

i.e. the shrinkage factor is given by

$$\frac{t_2}{t_1} = \frac{\tan(\theta_1/2)}{\tan(\theta_2/2)} \cong \frac{\theta_1}{\theta_2}$$

Thus the proportionate change in the replay beam angle needed to satisfy the Bragg condition is equal to the proportionate change in the thickness of the emulsion (the grating condition depends on d and is unchanged).

The proportionate change in the fringe spacing in a reflection hologram is roughly equal to t_2/t_1 and this also gives the proportionate change in the wavelength reflected, if the replay beam angle remains the same as the reference beam angle. In order to reconstruct an image at the same wavelength as was used to make the hologram, the replay beam will have to be moved nearer to the normal by an angle α , where $\cos \alpha = \lambda_2/\lambda_1 \cong t_2/t_1$.

Modulation and contrast

As used by the layperson (and, in a different way, by the photographer) 'contrast' is an ambiguous word. To the photographer, contrast refers variously to the subject matter, to the photographic image, and to the relationship between the two. For measurement purposes a logarithmic scale is invariably used: for the subject matter the contrast is the common logarithm of the ratio of the maximum to the minimum luminance. For the photographic image, the contrast is the difference between the maximum and minimum densities in the photographic



Figure A1.6 (a) H & D curve for a typical general-purpose photographic emulsion. The inherent contrast of the emulsion is indicated by the slope of the line joining the maximum and minimum useful densities. This is somewhat less than the steepest slope of the curve (the gamma). Both scales are logarithmic. The H & D curve provides a good prediction of the response of the emulsion in a photographic situation, but is not very helpful in holography. (b) A curve of amplitude transmittance τ_a versus exposure *H*. The linear region is short, and in the diagram is centred on $\tau_a = 0.7$, corresponding to a photographic density of 0.4 and a modulation of about 0.35.

image; photographic density is defined as the (negative) logarithm of the transmittance. The inherent contrast of the photographic emulsion is the ratio of the contrast of the image to the contrast of the subject and is equal to the slope of the H & D curve of density versus log-exposure (Fig. A1.6a).

When the useful part of the H & D curve is slightly S-shaped, as in most amateur films, the average gradient is obtained by joining the maximum and minimum useful values by a straight line. In some specialized emulsions, of which holographic emulsions are an example, the useful portion is substantially straight, and its slope is called *gamma* (γ), usually spelt out. However, these methods of specifying contrast are satisfactory only for coarse imagery; they break down when fine detail is being considered and are useless for measuring the contrast of either

 τ is the Greek symbol tau; it is the standard symbol for transmittance.

the fringes (subject contrast), the photographic record of the fringes (contrast of photographic image) or their ratio (relative contrast). There are a number of reasons for this:

- Although we are concerned with time-averaged intensity in the subject contrast, we are concerned instead with amplitude transmittance in the image contrast, and it is the relationship between these two quantities that has to be linear.
- The possible range of densities goes up to infinity, and the range of logluminances goes down to minus infinity. This is plainly inappropriate, as a density of only 4 looks totally black. It would seem sensible to have a range which in the case of both density and luminance went from 0 to 1, especially if such a system could represent contrast much as we actually perceive it.
- With all photographic emulsions the relative contrast (gamma) decreases as detail in the image becomes finer. To say that a holographic emulsion has a gamma of 5 or 6 may be true, but the measurement of gamma is carried out by the comparison of the densities produced by different exposures on comparatively large areas of emulsion, typically about 4×10 mm. This tells us nothing about the relative contrast of a set of fringes with a spatial frequency of more than 1000 cycles per millimetre.



Figure A1.7 Modulation transfer function (MTF) curve for a typical holographic emulsion. It represents the contrast of the developed fringes relative to that of the primary fringes being recorded. Although the emulsion has a high gamma (greater than 4) at low spatial frequencies, the contrast at the spatial frequencies relevant to holography (x) is much lower. The curve corresponds roughly to a plot of gamma against fineness of detail.

The first difficulty can be overcome by measuring the intensity transmittances corresponding to a range of exposures and plotting the square roots of the values obtained against exposure (Fig. A1.6b). The linear region will remain linear for all spatial frequencies, regardless of the fall in relative contrast.

The second difficulty can be taken care of by measuring relative contrast in terms of *modulation*. This is a quantity that is already in use in communications technology. Its value is given by the expression

$$M_{\tau} = \frac{\tau_{\max} - \tau_{\min}}{\tau_{\max} + \tau_{\min}}$$

where M is the modulation and τ (tau) is the transmittance. Modulation can take any value between 0 and 1.

We are now in a position to overcome the third difficulty. Using modulation as the definition of contrast, the relative contrast is simply $M_{\tau}/M_{\rm I}$, where $M_{\rm I}$ is the image (i.e. the fringe) modulation. If we plot the value of this term, which is called the *modulation transfer factor*, against the spatial frequency of the fringes, we shall have a *modulation transfer function*, which will give us the relative contrast for any spatial frequency, no matter how high (Fig. A1.7).

Appendix 2 The Fourier approach to image formation

'I think I should understand that better,' Alice said very politely, 'If I had it written down; but I can't quite follow it as you say it'

Lewis Carroll, Alice in Wonderland

Until comparatively recently, the discussion of image formation has relied on one of three models for the behavior of light. The so-called *ray model* uses a geometrical approach, and is satisfactory for describing the basic geometry of the formation of an image by an optical device, but it doesn't describe the nature of the fine structure of an optical image, nor does it predict the phenomenon of diffraction. The Huyghens *wave model* does describe diffraction fairly well, but is difficult to use with gratings that are other than binary, i.e. 'square', in transmittance profile. The Maxwell *electromagnetic model* is capable of describing all optical phenomena except photochemical and photoelectronic effects, but the precision of its descriptions demands a level of mathematical ability well beyond the reach of most people.

A fourth approach to the formation of optical images is much younger than the others. It is known as the *Fourier model*; it first appeared in the 1940s, but was not at that time taken seriously, and no book on Fourier optics was published before 1960. Unlike the other models, Fourier optics has never been a *theory* of light. The great advantage of the Fourier model over the other three models is not so much that it subsumes them (it doesn't altogether do so), but that is predicts *all* the phenomena of image formation, including the existence of an optical Fourier transform in the rear focal plane of a lens (a phenomenon that could not have been demonstrated before the advent of the laser), and the interference pattern the recording of which results in a hologram. And though Fourier optics has a rigorous mathematical background, its principles are not beyond the grasp of anyone who knows a little trigonometry. If you have been trained in electronics, you will already have mastered it. But the model is equally rewarding at the intuitive level once the underlying concepts have been grasped.

Let us begin with the simplest possible object, and see how and why it diffracts light. Now, you might guess that the simplest possible object is a circular aperture, but you would be wrong: its diffraction pattern is in fact quite difficult to analyze. Let us try a simpler, one-dimensional object. A grating of equally spaced apertures (usually called a *square* grating) is one such object, and if you guessed this you would be nearly right. There is nevertheless an even simpler object, a grating in which the transmittance varies cosinusoidally with distance. We say 'cosinusoidal' rather than 'sinusoidal' because a cosine function is symmetrical about the vertical axis ($\cos \theta \equiv \cos(-\theta)$) (Fig. A2.1).

How does a cosine grating diffract light? We can reach the answer by finding an assemblage of light beams that would produce the same pattern of amplitudes at the plane of the grating. The first thing to notice is that transmittance has to be positive (it can never be less than zero), and therefore the function shown in Fig. A2.1 must contain a component that is uniform and positive. It is simply a constant value of 0.5, which raises the cosinusoidal curve so that it sits on the

I.e. some sort of pattern that varies in one direction only, and is uniform in the other.



Figure A2.1 An impression of a cosine grating, with its transmittance profile.

horizontal axis. This leaves a second component that is positive and negative in a cosinusoidal manner, but fixed in space. Now, it is a fundamental property of all models of the propagation of light that if the direction of travel of the light energy is reversed the result will be geometrically the same. So if we could find two traveling waves that would interfere with one another to form our pattern we would have solved the problem. We can. Two waves traveling in opposite directions create a stationary or standing wave (see Appendix 1) that has troughs and peaks of energy (nodes and antinodes) at intervals of exactly one halfwavelength. However, if the grating period (i.e. the spacing of the maxima) is greater than this, the two traveling waves that interfere to produce that precise pattern will be at some angle to one another that is less than 180°. We can calculate this angle fairly easily. In order to produce constructive interference (i.e. bright fringes) the path difference between the waves must be 0, λ , 2λ , 3λ , 4λ , etc. In order to produce destructive interference (dark fringes) the path difference must be $\lambda/2$, $3\lambda/2$, $5\lambda/2$, etc. If the grating period is d, the angle θ made by the direction of the beams with the normal is given by the formula

 $d\sin\theta = \lambda$

This formula turns up repeatedly in diffraction theory; it is known as the *grating condition* or simply the *diffraction condition* (Fig. A2.2).

From it we can calculate θ , as we already know λ and d. As noted above, it is a fundamental property of light that its direction can be reversed without altering the geometry of the system. If, therefore, a beam of light is incident normally on a cosine grating, half of the total amplitude is transmitted unaltered in direction (the zero-order beam) and the remaining amplitude will be divided into two equal beams in directions $\pm \theta$, exactly as it was for the beams that would produce such a pattern. The value of θ can be calculated from the formula

$$\theta = \frac{\lambda}{d}$$

where $\theta \cong \sin \theta$. We usually describe a cosine grating in terms of its spatial frequency q, which is related to the period d by the formula

$$\theta = q\lambda = \frac{\lambda}{d}$$

This is true for angles up to about 20° provided θ is measured in radians (2 π radians = 360°).



Figure A2.2 Derivation of the grating condition. For constructive interference the optical path difference between wavefronts emerging from adjacent spatial periods of the grating must be one wavelength (λ). If the grating period is *d*, the angle of diffraction θ is given by the equation $d \sin \theta = \lambda$, or $\theta = \lambda/d$, provided θ is small and measured in radians.

As half the total amplitude is present in the undiffracted beam, the two diffracted beams must each possess $\frac{1}{4}$ of the total amplitude of the incident beam (Fig. A2.3).

As the time-averaged intensity $I = \langle \frac{1}{2}A^2 \rangle$, where the symbols ' $\langle \rangle$ ' mean 'timeaveraged' you can see that the maximum diffraction efficiency for either diffracted beam is only $(\frac{1}{4})^2$ or 6.25%. In practice it is usually less than this, as the modulation of the grating is in general less than unity, i.e. the grating is nowhere fully transparent or opaque, so that the undiffracted beam carries more than half the total amplitude.

Fourier series

To return to the main line of the argument: let us suppose that the value of q is increased, i.e. the spatial period (grating spacing) is reduced, then from the formula it is clear that θ is increased; the two beams are thus emitted at a greater angle of emergence. So what happens if we superpose two gratings of different spatial frequencies, say with one having three times the spatial frequency and one-third the amplitude? (Fig. A2.4a). Well, the resultant amplitude transmittance is a more



Figure A2.3 This is Fig. A2.2 redrawn to show wavefronts rather than rays. You can see that the interference pattern of the two diffracted waves matches the period of the grating. It can be shown that for a fully modulated cosine grating (i.e. opaque to clear) the emerging beams will have amplitudes in the proportions $\frac{1}{2}:\frac{1}{4},\frac{1}{4}$ for an incident amplitude of 1. The intensities are proportional to the squares of the amplitudes, and in the diagram are shown in parentheses.



Figure A2.4 If two cosine gratings of differing spatial frequencies are superposed, a more complicated pattern results. If the frequencies are simply related, as here, the result is still a periodic waveform.



Figure A2.5 Each of the cosine gratings from Fig. A2.4 produces its own diffracted beam independently.

complicated transmittance pattern (Fig. A2.4b) which is no longer cosinusoidal, though it does have the same fundamental period.

What happens when we pass a beam of light through this grating is predicted by the Fourier model: the two gratings produce their sets of plane waves independently, each as if the other did not exist (Fig. A2.5).

We can add further gratings and produce a more complicated waveform, but the light is still diffracted as if the component gratings were acting completely independently. If we choose the frequencies and amplitude transmittances of the gratings carefully they can be made to add up to some familiar profiles. For example, if we choose gratings with spatial frequencies of q, 3q, 5q, 7q, etc., with amplitudes respectively of A, $\frac{1}{3}A$, $\frac{1}{5}A$, $\frac{1}{7}A$, etc. in the correct phase relationships (see Fig. A2.9 below), we shall finish with a square wave. We can choose other combinations of gratings that produce triangular, sawtooth and many other transmittance profiles. In fact, *any* periodic function can be shown to be made up of nothing but sinusoidal and cosinusoidal components.

We have now accounted for two diffraction phenomena. The first is that when we illuminate a cosine grating with a laser beam we get just two diffracted spots (Fig. A2.6). We can insert a lens to bring the plane waves into focus, and provided θ is fairly small and measured in radians, we can use the approximation $\sin \theta \cong \tan \theta \cong D/f$, where *D* is the distance of the spots from the optical center.

$$D = f\theta = fq\lambda$$

Thus D is proportional to q, the spatial frequency of any component of the grating.

The second is the converse of the synthesis of gratings. We can say with confidence that any repeated waveform, of any shape, behaves as though it is the sum of a



Figure A2.6 If the diffracted beams are focused by a lens of focal length *f*, a cosine grating will produce three spots separated by a distance *D* such that $D = f \sin \theta - fq\lambda$, where *q* is the spatial frequency of the grating (=1/spatial period). In general, *D* will be much larger than *d*.

large (usually infinite) sequence of sinusoidal and cosinusoidal components of frequencies that are integral multiples of the fundamental frequency (Fig. A2.7).

All the waveforms of Fig. A2.7 – indeed, any repetitive waveform – can be synthesized in a similar manner to our square wave, and if gratings are made with these transmittance profiles, the positions and intensities of the diffracted spots will be as predicted. Notice that the 'sawtooth' profile (Fig. A2.7a) is not symmetrical, and is in fact synthesized from sine terms, which are antisymmetrical $(\sin(-\theta) \equiv -\sin \theta)$: the spots that add up on one side of the zero-order beam cancel on the other side. A so-called *blazed grating* with this profile has a high diffraction efficiency for the beams an one side of the zero-order beam and a low diffraction efficiency on the other side.



Figure A2.7 (a) shows a sawtooth wave, (b) a triangular wave and (c) a rectified cosine wave. All these waveforms (and, indeed, any other periodic function) can be analyzed using Fourier methods into pure sinusoidal and cosinusoidal components.

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The examples of Fig. A2.7 should give you some idea of the principles of Fourier series. The general relationships which have emerged (and which are capable of mathematical proof) are:

- Any regularly-repeated one-dimensional function such as a grating transmittance function will behave as though it were the sum of a number of sinusoidal functions; if the pattern is symmetrical about any point these will all be cosinusoidal functions. The spacing of any pair of spots in the diffraction pattern is proportional to the spatial frequency of the grating component producing them.
- The intensity of the spots is directly related to the modulation of the spatial-frequency component causing them to appear.
- The orientation of the pairs of spots is at right angles to the orientation of the (cosine) bars of the grating responsible for them.

Fourier transform

The Fourier spectrum of a regularly repeated waveform can be plotted on a graph in terms of amplitude and (spatial) frequency. The Fourier spectrum of a plain cosine grating is the simplest (Fig. A2.8a).

In practice, for reasons connected with the mathematical analysis of the Fourier spectrum, we remember that $\cos \theta \equiv \cos(-\theta)$ and split the non-zero spatial frequencies into two, one half positive and the other half negative. This also has the merit of providing a better model for the world of diffraction spots (which always come in pairs) and their amplitudes. Thus the plot of Fig. A2.8a becomes as in Fig. A2.8b.



Figure A2.8 The Fourier spectrum of a cosine wave. It contains only one frequency. (b) shows a way of making the spectrum symmetrical, by remembering that $\cos \theta$ is the same as $\cos (-\theta)$ and dividing the energy equally either side of zero.

The relative intensities of the spots are obtained by squaring these values. A square grating is made up of a zero-order term equal to $2/\pi$ of the incident beam amplitude, and an infinite series of odd multiples of the basic spatial frequency with their amplitudes decreasing in proportion to their order. One way of representing the sum of these components is as in Fig. A2.9.

A second, neater way is shown in Fig. A2.10. This is called the Fourier transform (FT) of the square grating, and corresponds to the spatial frequencies and



Figure A2.9 The cosinusoidal components of a square wave up to the fifteenth harmonic. Only odd harmonics are present, with amplitudes in inverse proportion to their frequency; alternate harmonics are in opposite phase.

amplitudes of its components. Each component spatial frequency q produces a pair of spots at a distance $d = fq\lambda$ from the axis, and the intensities of the spots are proportional to the squares of their amplitudes. Note, however, that some of the waves are in antiphase with respect to others; if the spots of the diffraction pattern are recorded photographically, the information about phase is irretrievably lost, as if you take the square root of the intensities you get back to the magnitude of the amplitude but you lose the information as to whether it is positive or negative. If you get the sign wrong for any of the components you will get a wave of a quite different profile. For example, if you guessed that *all* the components had a positive amplitude together, you would be describing something like a triangular wave, not a square wave (Fig. A2.11).



Figure A2.10 An alternative way of depicting the components of a square wave as a Fourier (frequency) spectrum. Alternate harmonics have positive and negative values.

This is one of the problems that FT holography helps us to solve.



Figure A2.11 If all the frequency components that go to make up a square wave were positive going, the shape of the final periodic function would be quite different.

It is clear from the formula above that the higher the spatial frequency in the original grating, the larger the separation of the spots in the rear focal plane of the lens – which we may now call the Fourier-transform plane. There is a reciprocal relationship between the period of the grating and the spacing of the spots.

Let us now consider a 'square' grating in which the squares are gradually moved farther apart. As the fundamental spatial frequency decreases, the separation of the spots also decreases (Fig. A2.12). As the adjacent square pulses move away from each other towards infinity, the number of spatial frequencies present in the Fourier transform increases; in the limit they completely fill the space of the envelope which has contained them, so that there is a continuous spectrum of spatial frequencies, and this will give rise to a diffraction pattern of which the intensity is proportional to the square of the envelope of the curve.

The same reasoning can be used to develop any repeated function into an isolated pulse of the basic shape. The situation becomes slightly more complicated when the single pulse is asymmetrical, but in the vast majority of cases that concern holography it *is* symmetrical.

The associated mathematics shows the amplitude function to be of the form $(\sin x)/x$, an expression which is called a sinc function, and is written 'sinc x'; the intensity pattern is of the form sinc² x (Fig. A2.13).



Mathematically, what happens is that a Σ (sigma or repeated addition operation) turns into a \int (integration operation).

Figure A2.12 (a) If the rectangular pulses that make up a square wave have their spacing doubled, the number of frequency components doubles, too. (b–d) As the spacing between the pulses increases towards infinity, the component frequencies become ever closer together, until they merge into a continuous spectrum.

Reciprocal relationship of *x***-space and frequency space**

The width of the sinc function that is the FT of the square pulse (or *top hat function*) is inversely proportional to the width of the pulse, as you might expect. As the slit becomes narrower and narrower, its FT becomes broader and flatter until in the limit, as the slit shrinks to infinitesimal width, its FT becomes a uniform straight line. You can actually see this happen if you put a variable slit in front of a laser output port. You can see the sinc² pattern gradually broadening as you make the slit narrower, until just before it vanishes it becomes very wide



Figure A2.13 The Fourier spectrum of a single rectangular pulse (a top hat function) is a sinc function. In the Fourier-transform plane of a lens the diffraction pattern of a single slit (the optical equivalent of a top hat function) appears as a sinc² function, as intensity is proportional to the square of amplitude. The width of the central lobe of the diffraction pattern is inversely proportional to the width of the slit. An example of the pattern appears in Fig. 1.10.

indeed. It also becomes very faint, as the total amount of light energy is being steadily reduced as the slit is made narrower. In order to keep the energy constant we would have to increase the amplitude of the pulse to match, until we reached a pulse of infinitesimal width, when it would have to be of infinite amplitude. This would be mathematically meaningless. However, an ingenious dodge devised by Paul Dirac and called the *delta function* takes care of the difficulty (Fig. A2.14). A pulse of infinitesimal width contains all frequencies in equal amount.



The Dirac delta function (δ) is a pulse of infinite amplitude and infinitesimal width that is considered to have unit area.

Figure A2.14 If a rectangular pulse is made narrower, its FT becomes broader, until, in the limit, when the pulse becomes an infinitely narrow delta function, its FT becomes a straight line.



Figure A2.15 Conversely, if the pulse is broadened indefinitely, its FT becomes progressively narrower. In the limit, as the pulse becomes indefinitely wider, its FT shrinks to a delta function.

What happens if we go the other way, and make one single square pulse indefinitely wider? The width of the sinc function becomes progressively less and less, until in the limit, as the square pulse becomes of infinite width, its FT shrinks to a delta function (Fig. A2.15).

This is an example that shows the reciprocal relationship between x-space and frequency space. The FT of a delta function is a constant: the FT of a constant is a delta function. Another example is that of a cosine function, which, of course, has a single (spatial) frequency (Fig. A2.16).

Figure A2.16a is the example of the cosine grating producing two spots (the center spot is not diffracted and can be ignored), and Fig. A2.16b is the well-known example of Young's fringes produced by a pair of narrow slits. These are Fourier pairs; each transforms to the other, and illustrates a fundamental property of Fourier transforms:

$$FT(FT(f)) \equiv f$$

or if

 $\mathrm{FT}(f\,)=F,$



Figure A2.16 A cosine function and a pair of delta functions form a Fourier pair: each is the FT of the other. This can be shown optically by (a) the pair of spots produced by a cosine grating, and (b) the cosine pattern produced by two slits.

then

$$FT(F) = f$$
,

give or take the odd mathematical constant. There are several variations of the formula for mathematically deriving a Fourier transform, each involving a constant.

All of this is beautifully illustrated in practice. If you pass a laser beam through a cosine grating you will get the two spots, and if you send it through a pair of narrow slits you will get a cosine pattern. If you pass the beam through a variable slit you will see the diffraction pattern become broader and broader as you narrow the slit. By the way, you don't really need the lens. You see, if you use a throw of several metres you need a lens with a focal length of several metres – but this is very little different from having no lens at all; so if your throw is more than about a metre or so you can forget the lens, and use the distance of the screen from the object in the equation instead of the focal length.

The Fourier convolution theorem

So far we have considered only what happens when two functions are *added* in *x*-space: in frequency space the FTs are also added. However, when two functions are *multiplied* in *x*-space, something quite different happens in frequency space. The principle of this is fundamental to image processing and to many other techniques, including imagery from satellite and spacecraft photography and radar.

If you set up a regular line of point apertures (i.e. delta functions) in a laser beam, you would expect to get a similar line of points of light on the screen, with a spacing inversely proportional to that of the original delta functions (Fig. A2.17). Thus an array of delta functions, known as a *comb function*, produces a FT that is also an array of delta functions, with a spatial frequency that is inversely proportional to that of the generating function. But if we limit the comb to only a

Reluctant mathematicians (including the author) are constantly irritated by finding an unwanted $2/\pi$, or something equally unattractive, hanging about at the end of calculations and destroying their symmetry.

cos² in fact, because intensity varies as the square of the amplitude.

This has not been proved here, but it is true.



Figure A2.17 The FT of an infinitely long array of delta functions (a comb function) is a similar array, the spacing being in inverse proportion to that of the original functions.



Figure A2.18 A 'short comb' is an infinite comb multiplied by a top hat function. In frequency space the FT of the top hat (sinc function) is dealt out to each spike of the FT of the (infinite) comb function.

small number of spikes the pattern of the FT changes: each spike turns into a narrow sinc function. Now, the sinc function is the FT of a single square pulse (a top hat), and, if you think about it, you will appreciate that a 'short comb' is in fact an infinite comb multiplied by a top hat (Fig. A2.18). What is happening in frequency space is that each delta function has been dealt the FT of a top hat, i.e. a sinc function. We say that two functions are 'convolved' (Fig. A2.19), and use the symbol (). Convolution follows similar laws to multiplication, in that $A () B \equiv B () A$, and $A () (B () C) \equiv (A () B) () C$. (Read 'A () B' as 'A convolved with B'.) When two functions are multiplied in *x*-space their FTs are convolved in frequency space, i.e.

 $FT(f) \circledast FT(g) \equiv FT(f \times g)$

This is known as the convolution theorem.

The converse is also true. If you take a series of narrow (but not infinitely narrow) slits and illuminate this object with a laser beam, you will get a series of narrow lines which fade off in a manner reminiscent of the diffraction pattern of a single slit (Fig. A2.20).



Figure A2.19 When one function is dealt out to another they are said to be *convolved*. The process is called *convolution*.



Figure A2.20 When functions are convolved in x-space, their FTs are multiplied in Fourier space. In this case a comb function is convolved with a top hat, so in Fourier space the FT of the comb (another comb function) is multiplied by the sinc function.

This time the convolution is in the object: the comb function is convolved with a narrow top hat function. In frequency space the FTs of the comb and top hat are multiplied, so that the row of delta functions is limited by a broad sinc function. This is an example of the converse of the convolution theorem: when two functions are convolved in *x*-space, their FTs are multiplied in frequency space.

$$\operatorname{FT}(f) \times \operatorname{FT}(g) \equiv \operatorname{FT}(f \circledast g)$$

Two-dimensional objects

As soon as we begin working in two dimensions the implications of the convolution theorem become important. For example, when two slits are placed at right angles, they produce a rectangle. This is the product (i.e. the multiplication) of the two slits. Their FT is the convolution of two sinc functions at right angles (Fig. A2.21).

A motif (such as the rectangle above) dealt out to (convolved with) a twodimensional array of delta functions (called a *bed-of-nails function*) will appear in frequency space as another bed-of-nails function with its aspect ratio reversed, masked by (i.e. multiplied by) the FT of the rectangle (Fig. A2.22).

We have considered the smallest item (the motif) in an array (the lattice) which is limited by the overall shape (the mask). Many images can be broken down in this way, from microscopic crystals to views of great buildings. In the FT plane the motif becomes the mask, as we have seen: the lattice retains its general pattern but reverses its orientation. The FT of the original mask becomes the motif in frequency space (remember that the largest item in x-space is always the smallest in frequency space). Now, even though the field in the FT plane is recorded only as a time-averaged intensity and relative phases are lost, most of the information about the nature of the original object in x-space can still be retrieved, and by intelligent use of the addition and convolution theorems it is possible to make an informed guess as to the type of object that produced the diffraction pattern. Indeed, this is the basis of techniques of X-ray crystallography. You can see how much of the information about the object appears in its diffraction pattern from Fig. A2.23. It is not possible as a rule to be certain of the exact position of any detail, as this information is contained in the phase relationships, and the phase information is lost. This information is what FT holography is able to retrieve, and is why it is so useful in information processing. For example, in a photograph blurred through movement the blur function is a short straight line. Its FT is a sinc function, in which the negative-going lobes cause spurious reversal of certain fine details; this

Students studying a Fourier optics module are expected to be able to match diffraction patterns of this type to a selection of two-dimensional objects.



Figure A2.21 In two dimensions a rectangular aperture is the product of two slits at right angles. The FTs of the two slits are convolved in two dimensions.

gives rise to double edges and other image artifacts. A hologram of the FT of the blur function, including the appropriate phase reversals, placed in the FT plane of an imaging lens, can retrieve most of this corrupted information and save the imagery. This technique is discussed in Chapter 24.

The Fourier model is equally powerful in incoherent optics. A camera lens operating in incoherent light does produce an FT in its rear focal plane, but this FT is convolved (by the rules) with every point on the surface of the light source, and with every wavelength of the spectrum, all diffracted to different points on the plane. Hence the FTs and their associated diffraction patterns are totally smeared out; but that they do indeed exist is indicated by the fact that an inverted image (the double FT) is formed at the image focal plane. It has needed only the coming of the laser to show what was really going behind the scenes.

PS Just in case you are wondering what the FT of a circular aperture *is*, it is a zero-order Bessel function. Its profile looks something like a sinc function, but the spacing of the zeros is different – and, of course, it is circularly symmetrical. The associated diffraction pattern is our old friend the Airy pattern.



Figure A2.22 Convolution and multiplication in a single figure. The rectangular 'motif' is convolved with a two-dimensional comb (a 'bed-of-nails' function), and this is multiplied by a large rectangle. In Fourier space the FT of the rectangle is convolved with the FT of the bed-of-nails function, and the whole is multiplied by the FT of the motif, which is a large version of Fig. A2.21. Thus what was the mask in x-space becomes the motif in Fourier space, and vice versa. Notice that the largest item has the smallest FT and the smallest item has the largest FT. (Note: The final motif at the bottom right has been magnified. It resembles the top left pattern in Fig. A2.23 but is much smaller.)



Figure A2.23 Far-field diffraction patterns. In each case the original object is inset. The nature of each pattern can be predicted from the nature of the corresponding object by following the rules given above, and many features of the object can be deduced from an examination of the pattern (for example, in the diffraction pattern of the little face at the bottom left, the hairline can be deduced from the strong series of horizontally oriented spots – though this set of lines could equally well have been a moustache). Photographs of diffraction patterns by the author.

Further reading

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- Harburn, G., Taylor, C.A. and Welberry, T.R., Atlas of Optical Transforms, Bell & Sons, London, 1975.
- Taylor, C.A., Images, Wykeham Publications, London, 1978.

Appendix 3 Geometries for creative holography

Humpty Dumpty took the book, and looked at it carefully.'That seems to be done right' – he began.'You're holding it upside down!' Alice interrupted.'To be sure I was!' Humpty Dumpty said gaily, as she turned it round for him. 'I thought it looked a little queer.'

Lewis Carroll, Through the Looking-Glass

If you are going to make successful multicolor holograms you need to know how to obtain correct color registration. All diffraction systems are sensitive to wavelength. The angle of diffraction of a beam is, to a first approximation, directly proportional to its wavelength. This means that if you want to have red, green and blue images (or red and cyan in an achromatic hologram) that coincide in both position and magnification, you need to do some geometry and trigonometry. If you are a reluctant mathematician (as are the vast majority of people) you shouldn't be discouraged, as there is nothing involved that you can't solve by pushing a few buttons on a pocket calculator. For this small effort the rewards are immense.

Two systems are tackled in this appendix. The first is based on Stephen Benton's analysis¹ of the mathematics involved in designing a setup to make white-light transmission holograms, accompanied by a worksheet designed by Suzanne St Cyr². The second is due to Steve McGrew³. It is an approximate method which gives the most accurate results when the beams used in transferring are conjugates, i.e. the master reference and transfer beams are both collimated. Much of McGrew's original paper has been subsumed by Benton's achromatic-angle transfer geometry, so I have omitted the parts that are no longer appropriate.

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Designing a setup for a white-light transmission hologram

White-light transmission (WLT) holograms, in Stephen Benton's words, 'direct their images to very well-defined viewing locations... They must be carefully designed to make sure the diffracted light does indeed reach the intended viewer.' Let us see what is involved. Benton suggests that we should treat a real-image hologram as a combination of a prism and a lens (Fig. A3.1).

The angle of deviation of the 'prism' depends on the angle of incidence of the H_2 reference beam. The focal length of the 'lens' (which fixes the distance between H_1 and H_2 on the transfer table) depends on the distance between the subject and H_1 on the mastering table. All these values will be modified if there is any emulsion shrinkage in processing and/or any changes in wavelength or divergence of the illuminating beams.



Figure A3.1 (a) A holographic optical element (HOE). (b) Its conventional optics equivalent.

The relationship for focusing is the lens law

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$
(A3.1)

and, for deviation, the grating equation

$$d(\sin\theta_1 + \sin\theta_2) = \lambda \tag{A3.2}$$

(Fig. A3.2).

We need to start at the *end* requirement. This is because if we guess the initial conditions for mastering and get them wrong, it will be difficult or even impossible to correct the error in the transfer operation, and the viewer of the final hologram may then only be able to see the image from the top of a stepladder, or from two inches away – or not at all.



Figure A3.2 The lens law for a diffraction grating. (b) The grating rule.



Figure A3.3 Spread of hues in a typical rainbow hologram.

Most people look at a hologram on display from a distance of about twice its diagonal dimension, and from a point at the level of its center. Let us start from here, taking as an example a 8×10 in hologram viewed from a distance of 60 cm. Let us also suppose that the illuminating (replay) light source is at an angle of 45° and at a (slant) distance of 1.5 m from the center of the hologram, and that we want the middle of the spectrum (550 nm) to be directed at the viewer.

From (A3.2) we have

 $d(\sin 45^\circ + \sin 0^\circ) = 0.55\,\mu\mathrm{m}$ $d = 0.78\,\mu\mathrm{m}$

Now, this grating has been made by red light at 633 nm. What was the angle of incidence of the reference beam? Let us first see where the other colors go. Substituting d = 0.78 and $\lambda = 0.633$ in (A3.2) gives

$$0.78(\sin 45^\circ + \sin \theta_2) = 0.633$$
$$0.707 + \sin \theta_2 = 0.633/0.78$$
$$\theta_2 = \sin^{-1}(0.633/0.78 - 0.707) = 5.8^\circ$$

For blue light of 0.47 µm we have

$$0.78(\sin 45^\circ + \sin \theta_2) = 0.47$$
$$0.707 + \sin \theta_2 = 0.47/0.78$$
$$\theta_2 = \sin^{-1}(0.47/0.78 - 0.707) = -6.0^\circ$$

So the spread of light will be as in Fig. A3.3. Now, in order to achieve a grating spacing of $0.78 \,\mu\text{m}$, what was the angle of incidence of the H₂ reference beam for HeNe light at 633 nm?

Applying (A3.2) again gives

$$0.78(\sin \theta_1 + \sin 0^\circ) = 0.633$$
$$\theta_1 = \sin^{-1}(0.633/0.78) = 54.2^\circ$$

Now we need to find the distances of the red and blue images. We chose 60 cm for the green image, so what is the true focal length of H_2 in terms of the light it was made with (633 nm)? Well, this needs a small modification of (A3.1) to allow for



Figure A3.4 Position of slit images for RGB wavelengths for a typical rainbow hologram. The dispersion angles have been exaggerated for clarity.

the change in wavelength:

$$\frac{1}{u} + \frac{1}{v} = \frac{\lambda'}{\lambda} \times \frac{1}{f}$$
(A3.3)

where λ is the shooting wavelength and λ' is the illuminating wavelength.

Substituting in (A3.3) gives

$$\frac{1}{150} + \frac{1}{60} = \frac{0.55}{0.633 f_{\rm R}}$$
$$f_{\rm R} \cong 37.2 \,\rm cm$$

For red at 633 nm,

$$\frac{1}{150} + \frac{1}{v_{\rm R}} = \frac{0.633}{0.633 \times 37.2}$$
$$\frac{1}{v_{\rm R}} = \frac{1}{37.2} - \frac{1}{150}$$
$$v_{\rm R} \cong 50 \,\rm cm$$

For blue at 470 nm,

$$\frac{1}{150} + \frac{1}{v_{\rm B}} = \frac{0.47}{0.633 \times 37.2}$$
$$\frac{1}{v_{\rm B}} = \frac{0.47}{0.633 \times 37.2} - \frac{1}{150}$$
$$v_{\rm B} \cong 75 \,\rm cm$$

The arrangement will be approximately as in Fig. A3.4. The angle is easy enough to plot geometrically, but it can also be calculated simply. It turns out that the achromatic angle α (alpha) is given by the equation

$$\alpha = \tan^{-1}(\sin\theta) \tag{A3.4}$$

When $\theta = 45^{\circ}$, $\alpha = \tan^{-1} 0.707 = 35.3^{\circ}$.

Next, what should be the distance of the transfer reference source from H_2 ? Here you have a choice. For a completely distortion-free image the reference beam should be the precise conjugate of the final illuminating beam, i.e. it should converge to a point 150 cm behind the hologram (a *u*-distance of -150 cm). However, this is not often feasible, and for a fairly shallow image-plane hologram it doesn't matter too much if it isn't an exact conjugate. You will still need as long a throw as possible given the constraints of your table. Let us suppose you set the reference source (the spatial filter pinhole) 150 cm from the center of the hologram. This is the *u*-distance. We found that the 'red' viewing distance was 50 cm, so that is the *v*-distance. Then, from (A3.1) we have

$$\frac{1}{150} + \frac{1}{60} = \frac{1}{f_{\rm R}}$$

 $f_{\rm R} = 37.5 \,\rm cm$

This is the distance at which the light would be focused if the final hologram were to be illuminated with collimated light. You can probably see now that as the master was made using collimated light and is being replayed by collimated light (which means that the real image is focused at the same distance as the original subject), then the master will have to be made 37.5 cm from the subject (i.e. the eventual separation of H_1 and H_2 on the transfer table). The angle of incidence of the reference beam for making the master is not relevant to any of the calculations.

But what if you don't have a collimating mirror? Well, now you have to recalculate the subject distance. Let us suppose that the longest throw your table will allow is 150 cm. You want to finish up (after flipping the hologram) with a real image 37.5 cm from H₁. So u = 150 cm, v = 37.5 cm. Substituting these values in (A3.1) gives

$$\frac{1}{150} + \frac{1}{37.5} = \frac{1}{f}$$

i.e., $f = 30 \text{ cm}$

 $\frac{1}{150} + \frac{1}{v} = -\frac{1}{30}$

 $v = -25 \,\mathrm{cm}$

What will the subject distance be? We apply (A3.1) again to find the new v-distance:

i.e.,

i.e..

v and f have a negative sign because we have flipped the hologram, and v and f are now in the opposite direction.

You use exactly the same methods for a larger or a smaller hologram; the only difference will be in the figures you choose for the viewing distance and the distance of the illuminating source. If you wish to illuminate the final hologram from some angle other than 45° you will need to put the new value in for θ , too.

Worksheet for multicolor WLT holograms

Suzanne St Cyr² has provided a comprehensive and detailed worksheet for calculating the geometry of a multicolor WLT hologram. The original worksheet is



Figure A3.5 Parameters for multicolor white-light transmission worksheet. (a) Making the master. $SH_1 = \text{shrinkage factor for master}$, $RD_1 = \text{reference source distance (positive or negative)}$, $OD_1 = \text{object}$ distance (negative), $\theta_{R1} = \text{angle of incidence of reference beam}$, $\theta_{obj} = \text{angle of incidence of object beam}$, $\phi_1 = \text{angle between fringes and normal}$, $\lambda_L = \text{laser wavelength}$. (b) Making the transfer. $PD_1 = \text{slit}$ illumination distance, $\theta_{PD1} = \text{angle of incidence of slit illumination beam}$, $\theta_{S1} = \text{angle of emergence of image}$ beam, $\theta_{R2} = \text{angle of incidence of transfer illumination beam}$, $SD_2 = \text{separation of slit S}_1$ and H_2 , $RD_2 = \text{reference source distance (negative)}$. (c) Viewing the hologram. $SH_2 = \text{shrinkage factor for H}_2$, ID = illumination distance, $\theta_I = \text{angle of incidence of illuminating beam}$, VD = viewing distance, $\theta_V = \text{angle of}$ emergence of viewing beam, $\lambda_V = \text{viewing wavelength}$.

very long, and by making a few assumptions and approximations she has been able to produce an abridged worksheet which is much more manageable. As in Benton's formulas, all wavelengths are in micrometres and all measured distances are in centimetres. In order to be consistent with St Cyr's other papers, I have retained her selection of symbols and suffixes, which differ from mine, as does her sign convention. Figure A3.5 shows these. You should be able to see fairly easily the terms that correspond with u, v, f and θ . The object beam angle θ_{obj} is new (in the Benton calculations I have assumed it to be 0° , so that $\sin \theta_{obj}$ vanishes). St Cyr has also included a shrinkage factor for the emulsion, which again vanishes if you use a nonshrink processing system.

The sign convention for all of St Cyr's papers is that the direction of light travel and distance measurement are from left to right; distances measured along converging beams are positive (e.g. hologram to real image). The convention for angles is that angles of illumination are measured with respect to the normal to the

To find the shrinkage factor SH, illuminate the hologram with a laser beam and adjust the angle for maximum image brightness. Then $SH = \sin \theta_{ref} / \sin \theta_{ill}$.
hologram. If the light source is above the hologram the angle is positive; if it is below, the angle is negative. Figure A3.5 shows the various parameters.

Worksheet for multicolor WLT	holograms
Project title Da	ate
Enter display parameters	
$\lambda_{\rm V} = __\mu {\rm m}; \theta_{\rm V} (= 0^\circ); \theta_{\rm I} = __^\circ; VI$	$D = \underline{\qquad} \operatorname{cm}; ID = \underline{\qquad} \operatorname{cm}$
Enter transfer parameters	
$\lambda_{\rm L} = \underline{\qquad} \mu {\rm m}; SH_2 = \underline{\qquad} {\rm cm}; RD_2 = \underline{\qquad}$	_cm
Transfer geometry	
$1 \theta_{\mathbf{R}_2} = \sin^{-1} \left(\frac{\lambda_{\mathbf{L}}}{\lambda_{\mathbf{V}}} [SH_2 \sin \theta_{\mathbf{I}}] \right)$	=°
$2 SD_2 = \frac{1}{\frac{1}{RD_2} - \left(\frac{\lambda_{\rm L}}{\lambda_{\rm V}} \left[\frac{1}{VD} - \frac{1}{ID}\right]\right)}$	= cm
Note: This value will be negative.	
Enter master parameters	
$SH_1 = \underline{\qquad} cm; RD = \underline{\qquad} cm; PD = \underline{\qquad}$	$\underline{\ \ } cm; \theta_{R_1} = \underline{\ \ }^{\circ}; \theta_{obj} = \underline{\ \ }^{\circ}$
Master geometry	
3 $OD_1 = \frac{1}{\frac{1}{RD_1} + \frac{1}{PD_1} + \frac{1}{SD_2}}$	=cm
$4 \phi_{\rm I} = \frac{\theta_{\rm R_1} - \theta_{\rm obj}}{2}$	=°
5 $\theta_{PD_1} = \sin^{-1} \left(\frac{\sin \theta_{R_1} + \sin \theta_{obj}}{2SH_1 \cos \phi_1} \right)$	=°
$6 \theta_{S_1} = \sin^{-1} \left(\frac{\sin \theta_{R_1} + \sin \theta_{obj}}{2SH_1 \cos \phi_1} \right)$	=c°
Note: If $\theta_{R_1} = \theta_{obj}$ then $\theta_{PD_1} = \sin^{-1} \left(\frac{\sin \theta_{R_1}}{SH_1} \right)$	<u> </u>

Multicolor layouts designed by geometry

The geometrical method for table design was originally worked out by Steve McGrew³, and it generates a scale diagram of the table geometry for color holograms. It enables you to see at once whether a given configuration will fit on your table, and if not, how to modify it so that it will. It does require that you should use collimated beams for recording and transferring the master, but not for the final hologram reference beam. The approach is based on two principles: the

properties of diffraction gratings, and the existence in every holographic configuration of a *hinge point*. Figure A3.6 shows the first of these principles. The geometry depends on ray-tracing procedures.



Figure A3.6 Geometry of diffraction.

When any arbitrary ray is incident on a grating, and the zero-order and first-order diffracted rays are intersected by a circle, the sum of their intercepts on the normal (D in Fig. A3.6) is always the same (the *angle* between the rays is not the same). For a circle of given diameter, D depends only on the grating period and on the wavelength of the diffracted light.

For a transmission hologram, the hinge point is the point at which a straight line passing through the reference source and the object intersects the plane of the hologram. For a reflection hologram the mirror image of the reference source reflected in the hologram plane is used instead (Fig. A3.7).

The hinge point corresponds to a point where, if the recording emulsion were large enough to include it, the spatial frequency of the fringes perpendicular to the emulsion would be zero. This happens when the reference beam and the object beam are aligned: in a reflection hologram at this point the fringes are parallel to the plane of the plate, whereas for a transmission hologram at the same point there are no fringes at all.

Considered from a horizontal viewpoint a rainbow hologram behaves like a holographic lens, with the replay source and the real image of the slit as conjugate foci. However, the position of the slit image varies with the wavelength of the replay beam; if a white-light point source is used, the image of the slit is spread into a spectrum lying along a line passing through the source. For *all* wavelengths the hinge point, which is the point where this line cuts the plane of the hologram, is the point at which no fringes would exist in the hologram (Fig. A3.8).

For a reflection hologram the equivalent rainbow configuration can be used to locate the hinge point. A virtual light source, the reflection in the hologram plane



Figure A3.7 Location of the hinge point.



Figure A3.8 Chromatic behavior of a holographic lens or mirror.

of the real light source, is used, the geometrical construction being otherwise the same. In the reflection configuration the ray from the hinge point to the spectrum corresponds uniquely to a ray from the source reflected specularly; for this to occur the fringes at the hinge point would have to lie parallel to the emulsion surface. In a reflection hologram, all but a narrow band of wavelengths fail to satisfy the Bragg requirement and are suppressed; nevertheless, the rule is obeyed in principle.

Locating the hinge point and illumination axis

First decide the position of the replay source and the optimum viewing distance. Draw a diagram to scale on squared paper, with lines passing through the replay source and center of the display hologram H_2 , and through the replay beam and the optimum viewing point. The plane of the hologram is the *y*-axis and the center of the hologram is the origin. The hinge point is located at the intersection of the second of these lines with the *y*-axis, and the first of these lines, the illumination



Figure A3.9 Location of the hinge point and illumination axis.

axis, is also the axis on which the reference beam source will lie when the hologram is made (Fig. A3.9).

Multicolor WLT hologram geometry

Let us suppose that you have decided that the central wavelength will be green at 550 nm as in Benton's method, and that the red will be 633 nm and the blue 470 nm. The initial diagram (Fig. A3.10) shows the basic construction for green replay. To find the positions of the 'blue' and 'red' reference sources, proceed thus:

1. Draw an arc of a circle centered at the origin (the center of H_2), passing through the 'green' reference source, as in Fig. A3.11.



Figure A3.10 Multiple-beam configuration (rainbow hologram).



Figure A3.11 Finding the position of $R_{\rm B}$ and $R_{\rm R}$ (rainbow hologram).

- 2. Measure the *y*-intercept of $R_{\rm G}$ and multiply it by 550/470.
- 3. Measure downwards to a point $-y \times 550/470$ below it, and draw a horizontal line from this point until it intersects the circle.
- 4. Join this point of intersection to the origin, and continue the line until it intersects the recording axis. This new point of intersection $R_{\rm B}$ is the correct location for the 'blue' reference source.
- 5. Divide the *y*-intercept of $R_{\rm G}$ internally in the ratio 550/633. Draw a horizontal line from the division point to intersect the circle, and join the point of intersection to the origin. The new point of intersection with the recording axis $R_{\rm R}$ is the correct location for the 'red' reference beam.

Multicolor reflection hologram geometry

The only change in the diagram from that for a WLT transfer hologram is that when you have completed the diagram for a WLT transfer hologram you construct the reflection of the illumination source in the H_2 plane and join it to the hinge point and the origin (Fig. A3.11, broken lines).

There are many possible variations of these setups, all of which can be analyzed in terms of the hinge point, and the angles and distances found by methods similar to those described above.

References

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Appendix 4 Fringe stabilization

'How puzzling all these changes are! I'm never sure what I'm going to be from one minute to another!'

Lewis Carroll, Alice in Wonderland

The most common cause of failure of a hologram is movement of the primary fringes during exposure. The problem of fringe stability is particularly serious when one is working with low-power lasers, or with very large holograms, or with nonsilver materials such as photoresist, where exposures even with large ion lasers may be tens of minutes.

The answer is an active fringe stabilizer. This works on the principle of the *servomechanism* (servo for short). The elements of a servo system are an error detector, an amplifier and an output which corrects the error. In the case of the fringe stabilizer the error detector detects movement of the fringes and sends an 'error' signal to the amplifier; the output of the amplifier is fed to a device which moves the fringes back into their original position. There are many methods of dealing with this type of situation, and the one that is most appropriate depends on the nature of the error. In the case of holographic fringes, the main difficulty is their small size. They are typically only about one micrometre apart, a far smaller distance than the size of any detector, and they are usually of low intensity.

Let us look at the general principle first, then see what special techniques we need for providing the stability that is necessary for good holograms. Figure A4.1 shows the basic elements of a servo control system. In our particular case the 'device' is the optical system that generates the fringes. The 'error detector' is a light-sensitive device that detects any movement of the fringes, coupled to a difference amplifier. The



Figure A4.1 (a) Basic components of a servo control system. (b) Schematic of error detector circuit.



Figure A4.2 Idealized positioning of fringe detector elements.

output of the error detector is amplified and a corresponding signal fed to a device changes the length of the optical path in such a way as to restore the fringe positions.

Error detector

Let us consider the error detector first. This must contain some kind of light sensor that will change in output if the fringes move. The most obvious way to do this is to have two detectors located one each side of a single fringe, with their outputs being fed into a comparator. The difficulty is the very small separation of the fringes, much smaller than the diameter of any sufficiently sensitive photodetector. We therefore need to consider ways of expanding the fringes. For the moment; however, let us suppose they are large enough to span a pair of photodiodes. We can place a pair of these, one on each side of a fringe; as they are on opposite sides of a slope, any fringe movement will result in an out-of-balance signal being sent out (Fig. A4.2).

Expanding the fringes

Many ways have been tried of expanding the fringes to the 2–3 mm spacing needed, from magnifying them with a microscope objective to making a preliminary hologram and setting this in the interference field to generate large moiré fringes. All these methods have their drawbacks. In the end, it is best to go back to first principles, and consider the optical systems that generate really large fringes. We have already met these in Chapter 11: the Michelson and Mach–Zehnder interferometer configurations. All we have to do is to take a portion of the overspill beams from the reference and object-illumination beams and redirect them along the same path. We can then make the interference fringes as large as we like. Figures A4.3 and A4.4 show examples for a transmission and a reflection transfer hologram, respectively. Other formats can be set up in a similar manner.



Figure A4.3 Other possible positions for detector elements.



Figure A4.4 (a) Use of moiré principle to produce greatly enlarged secondary fringes. (b) Fringe detection for reflection holograms. Part of the object-illuminating beam is deflected by mirror M to overlap the reference beam at a very small angle, generating broad live fringes in the region of overlap.



Figure A4.5 Fringe detection while making a reflection transfer hologram from a transmission master hologram, using a beamsplitter BS. It is immaterial whether the light has bypassed or been transmitted by the film.

This is the type of detector that is recommended for the commercially available fringe locker. There have been other ingenious suggestions for moiré fringe generators. One of these uses a real-time hologram. Methylene-blue-sensitized polyvinyl alcohol forms long-lasting fringes with an exposure of a few minutes, and is worth trying. Photochromic glass is suitable if you are working with violet laser light (it is not sensitive to red). These are particularly simple to set up, as you need only to put the material alongside the hologram with the detector element behind it, and wait for the fringes to build up. Photorefractive crystals have also been used, and these will build up fringes for both transmission and reflection configurations. Probably the best material is bacteriorhodopsin (BR), which is available commercially (see Chapter 4, Table 1). However, all these systems are insensitive to very slow drifts, and it is these that are the real bugbear.

If you are working with a single-mode fiber-optics system, there is an ingenious way of obtaining fringe stabilization. As mentioned in Chapter 11, when a directional coupler is made, there is a fourth stub, which is not used in illumination. At the ends of the 'object' and 'reference' fibers, about 2% of the light is reflected back by Fresnel reflection along the fiber, so that a Michelson interferometer is formed with the fourth fiber. The output from this fiber will be



Figure A4.6 Fringe detector in a single-mode optical fiber system. BL is the beam launcher, DC is a directional coupler. Light output 3 receives the beams reflected back from the ends of fibers 1 and 2, acting as a Michelson interferometer. The output is compared with part of the original laser beam divided off by the beamsplitter BS (a plain glass).

either bright or dark depending on whether the object and reference wavefronts are in or out of phase. If this output is monitored by one photodetector and the output at the laser itself is monitored by another detector, a difference signal will be obtained. This system monitors only the light within the fibers, of course (Fig. A4.6).

Comparator and amplifier

The comparator is a difference amplifier based on the long-tailed pair principle. This is a balanced-input amplifier which gives an output (positive or negative) that depends on the voltage difference between the inputs. It can be built round a cheap operational amplifier (Fig. A4.7).

Transducer

A *transducer* is a device that converts one form of energy into another. In this case it converts electrical energy into mechanical displacement. An everyday example of a transducer is a loudspeaker, which converts an electrical input into vibrations that produce sound waves. If the speaker has a mirror attached to its cone, and the mirror is set up as one arm of a Michelson interferometer, then any current passing through the voice coil will displace the mirror and thus shift the fringe pattern (Fig. A4.8).

If a negative feedback path is established between the fringe detectors and the speaker, any fringe movement will set up a movement of the voice coil, which will move the mirror M to such a position as to restore the fringes to their original position. Ordinary cone speakers are not satisfactory as transducers, as they are current-operated and are not thermally stable. Piezoelectric speakers are made by Motorola, among other manufacturers, and these are suitable as transducer elements. These do not consume current as they are voltage-operated. You can use the piezo transducer from any 'beeper' in a piece of junked electronic equipment. Fix a small mirror to the face with epoxy or contact adhesive, and mount the





Figure A4.8 Principle of fringe-shifting phototransducer (PZT). The transducer is shown operating in one arm of a Michelson interferometer.

Appendix 5 Processing formulas

'Beautiful soup, so rich and green, Waiting in a hot tureen! Who for such dainties would not stoop? Soup of the evening, beautiful soup!...'

Lewis Carroll, Alice in Wonderland

Developers for silver halide emulsions

In the early days of holography its practitioners generally processed their holograms as though they were ordinary black-and-white films, using proprietary developing and fixing solutions. One of the favorite developers was the metol-hydroquinone developer Kodak D-19b.

On the face of it this choice seems odd, as the D-19 formulas were designed for use with X-ray, infrared and aerial films, all of which at that time were characterized by low contrast, high fog level and a broad spectrum of grain sizes. Because the developing solution was mostly held in large open-topped tanks and used over long periods it needed to contain large amounts of sulphite to slow the effects of atmospheric oxidation, also sodium carbonate (a self-buffering solution) to maintain a fairly constant pH value, and bromide to lessen the relative effects of the accumulation of further bromide as a by-product of development. During the Second World War D-19b was used in large quantities in the processing of aerial reconnaissance films, and after the war vast surplus stocks became available cheaply. This no doubt contributed to its widespread use in university photographic laboratories in the 1950s and 60s.

The big disadvantage of the D-19 formulas when used with holographic emulsions is that the large quantity of sulphite present in the solution attacks the developing grains, sacrificing some emulsion speed (though it does lead to clean, noise-free images). Unfortunately, the removal of material from the emulsion during processing, aggravated by further losses in fixation, shrinks the emulsion and distorts the interference planes, resulting in low resolution, poor diffraction efficiency and vertical-horizontal astigmatism in the image when used as a transfer master. The only way to avoid this last is to direct the object and reference beams onto the emulsion at equal angles of incidence, so that the fringes run perpendicular to the plane of the emulsion; but this leads to further lowering of the diffraction efficiency as the Bragg condition is then less effective.

If this nevertheless fails to put you off using old-fashioned commercial developers, I have included the formula for D-19b, along with a couple of amendments that render it more suitable for processing transmission holograms.

Developers for transmission holograms

You can still buy D-19b developer from photographic retailers, but in its original form it is less than satisfactory for use with the ultrafine-grain emulsions employed in holography. A few emendations to the recipe provide a more suitable brew. The

D-19b was a revised version of the original D-19 formula with slightly lowered concentrations of alkali, sulphite and bromide.

After its introduction in the late 1940s, phenidone quickly replaced metol in almost all commercial developers. It is effective in much smaller amounts than metol, and is free from many of metol's disadvantages such as inhibition by bromide, susceptibility to atmospheric oxidation, allergenic tendencies and a readiness to precipitate out of solution in cold weather. In addition, the combination of phenidone with hydroquinone was found to increase effective emulsion speed beyond that achieved by the combination of metol and hydroquinone.

original formula is given below, along with a modification of the D-19b formula developed by Nick Phillips for the Royal College of Art pulse laser facility¹.

D-19b developer

	Original recipe	RCA recipe
metol	2.2 g	_
sodium sulphite, anhydrous	72 g	30 g
hydroquinone	8.8 g	8 g
sodium carbonate anhydrous	42 g	60 g
potassium bromide	4 g	_
phenidone	_	2 g
water to make	$1000 {\rm cm}^3$	$1000{\rm cm}^3$
Developing time at 20–23° C	4–5 min	2–5 min

When used with the object beam at 0° incidence and the reference beam at 45° , the RCA formulation gives exactly the right amount of emulsion shrinkage to compensate for the wavelength discrepancy between a ruby pulse laser (694 nm) used for making the master hologram and a Kr⁺ CW laser (647 nm) used for the transfer.

A modification by Hans Bjelkhagen¹ consists simply of adding 2 g phenidone to the standard formula. This ingredient must be dissolved last. The development time is unaltered, but the emulsion speed is approximately doubled. Fred Unterseher recommends adding 10 g ascorbic acid and 2 g disodium EDTA to the RCA formula to improve diffraction efficiency and reduce shrinkage¹. His formula is suitable for reflection holograms, but not reflection masters.

These formulas were originally designed for use with Agfa-Gevaert and Kodak emulsions, which were noisy and contained numerous coarse grains. With modern finer grained low noise materials the sulfite content isn't usually acceptable. A developer evolved by my own lab from some older formulas gives maximum emulsion speed combined with zero shrinkage, and is suitable for both transmission and reflection masters.

Developer for transmission and reflection masters

ascorbic acid	20 g
metol	5 g
sodium carbonate anhydrous	20 g
sodium hydroxide	6.5 g
potassium bromide	1 g
water to make	$1000\mathrm{cm}^3$

Development time is $6-12 \min$ at 20° C, depending on density and fog level.

Use a large beaker, as the solution will froth when you add the sodium carbonate. Weigh out the sodium hydroxide as quickly as you can, because it absorbs atmospheric moisture very rapidly. It also sticks to the bottom of the beaker unless you keep stirring the solution vigorously while it is dissolving. Potassium hydroxide doesn't absorb water so quickly; you can use 9 grams of this instead of the 6.5 grams of sodium hydroxide.

You can use this developer repeatedly; one liter will develop twenty 8×10 in films, but you need to keep increasing the exposure and development time by about 5 per cent per film. It is preferable to use only about 50 cm^3 at a time, and to throw it away afterwards, so that development is always consistent.

When you are weighing out the components for any of the formulas in this appendix, use a spatula, and keep a sheet of paper on the scale pan to protect it from contamination. When preparing solutions, always dissolve the components in the order given, stirring vigorously, and add each component only when the previous one has completely dissolved. Always start off with about three-quarters of the total volume of water, and make up the total volume after all the components have dissolved. Always use distilled or de-ionized water (water from a dehumidifier or from defrosting the fridge is OK).

EDTA stands for ethylenediaminetetraacetic acid (phew!). Its main use outside photography is in horticulture, as a sequestering agent for acidloving shrubs such as azaleas.

A 35 mm film canister holds roughly 30 cm^3 when full to the brim.

If you use this method, always pre-soak the emulsion in plain water (mains water will do) to which you have added a drop of wetting agent. Ilford Ilfotol is a good proprietary wetting agent, but any washing-up liquid is just as good. Avoid using Kodak Photo-Flo before development, as it has unpredictable effects on holographic developers.

If you prefer to use the developer repeatedly, you can substitute 0.5 g phenidone for the metol (add it to the solution last). Although slightly less active than the original, this developer will maintain its activity throughout its working life, and is suitable for use in processing machines.

Developer for true-color holograms

At the time of writing the only available panchromatic emulsion for true-color holography is Slavich PFG–O3C. The most satisfactory developer is one evolved by Cooke and Ward². With Slavich material it is essential to preharden the emulsion, as the urea in the developer softens gelatin.

CW–C2 developer

Prehardening solution

sodium carbonate anhydrous	5 g
formaldehyde (37.5% solution)	$10\mathrm{cm}^3$
water to make	$1000 {\rm cm}^3$

Soak for 3 min, then wash in changes of distilled water for 1 min.

Developer

Solution A

catechol	20 g
ascorbic acid	10 g
sodium sulfite anhydrous	10 g
urea (carbamide, $(NH_2)_2C=O$)	100 g
water to make	$1000\mathrm{cm}^3$
Solution B	
sodium carbonate anhydrous	60 g
water to make	$1000{\rm cm}^3$

For use, take equal parts A and B. Development time 2 min at 20°C.

Alternatively, keep solutions A and B separate. Immerse film in Solution A for 2 min, then develop out in Solution B.

The pyrochrome process

This process, introduced by Ruud van Renesse, and described by Walter Spierings³, came as a blessing to the early professional holographers, who up till then had had to be contented with somewhat feeble reflection images using proprietary photographic developers and a highly toxic mercuric chloride bleach. The 'pyrochrome' process is a robust system that will tolerate large errors in exposure and processing time and temperature. With a red laser it gives images

Note that this is now the standard developer for the Lippmann process, a photographic technique for color photography that also depends on interference.

A very similar formula is used in conventional photography to rescue images that have been accidentally underexposed by up to three stops. that can be adjusted from orange to green, depending on the amount of sulfite in the developer. The developing agent is pyrogallol (1,2,3-trihydroxybenzene), in this version with metol, in a highly alkaline solution.

This combination of developing agents produces maximum emulsion speed, and gives a powerful stain image that suppresses Rayleigh scattering and hardens the emulsion, limiting shrinkage. The dichromate bleach is a solvent bleach that removes all the developed silver, leaving the unexposed silver halide to form the fringes.

Pyro-metol developer

Solution A	
pyrogallol metol potassium bromide water to make	15 g $5 g$ $2 g$ $1000 cm3$
Solution B	
sodium hydroxide (or potassium hydroxide water to make	6.5 g 9 g) 1000 cm ³
Solution C	
sodium sulfite, anhydrous water to make	$\frac{100 \text{ g}}{1000 \text{ cm}^3}$
Solvent bleach	
potassium dichromate sodium hydrogen sulfate, crystals water to make	5 g $15 g$ $1000 cm3$

Keep the solutions separately in containers with all air excluded (concertina bottles, which you can get from photographic suppliers, are ideal). For use take equal parts of solutions A and B and mix immediately before use (the mixture oxidizes and becomes useless after 10 minutes or less). Development time at 20° C is a minimum of 2 min for a very generously exposed emulsion to about 8 min for a low exposure. Aim at a density of 3.0-3.5. It is important to immerse the whole emulsion in one clean sweep; otherwise there will be a variation in color across the image.

After development rinse the emulsion briefly in mains water, and immerse in the bleach solution, again in one sweep. Agitate continuously until the emulsion has been clear for about 1 minute. In the early stages of bleaching, brush the surface of the emulsion gently with your fingers or a soft brush to remove any scummy deposit. You may need to repeat this in the early stages of the final wash, which should be in running water for 2 minutes, not more.

Image color control

The chrome solvent bleach used in the pyrochrome process will produce an orange image. To produce yellow or yellow–green images add up to 1 part of Solution C to the developer. If you use a rehalogenating bleach (the EDTA bleach given below) with the pyro-metol developer (without sulfite), you will finish with an image that replays at some 30 nm longer wavelength than that of the laser you used

to make the exposure. This can be useful if you are working with a green laser and want a yellow or yellow–green image. Conversely, if you use the ascorbate master developer followed by the chrome solvent bleach, you will finish with an image that replays at some 90–100 nm shorter wavelength, giving a green or blue–green image with a red laser, or a blue or blue–violet image with a green laser. The image will usually be somewhat less bright than if you use a pre-swelling system.

Solution-physical developers

One of the problems associated with bleached holograms is what is called *printout*, the darkening of a bleached hologram exposed to light for long periods. It is caused by the light energy acting directly on the silver bromide and releasing bromine atoms, leaving metallic silver behind. Leaving the emulsion in a slightly acid state (i.e. putting a few drops of acetic acid into the final rinse) helps to combat this effect, but in bad cases the only action to take is to re-bleach.

Colloidal silver is a very finely divided form of silver that is totally unaffected by light. It transmits light, but somewhat preferentially, tending to reflect green wavelengths. A process that forms the fringes in colloidal silver rather than more massive grains can produce very high diffraction efficiency, given the right kind of emulsion. Slavich emulsions are particularly suitable. There are a number of formula given³, all of which work fairly well. The one that has found most favor for modern emulsions is GP-2.

GP-2 Solution-physical developer

Stock solution:

hydroquinone	5 g
sodium sulfite anhydrous	100 g
potassium hydroxide	5 g
ammonium thiocyanate (NH ₄ CNS)	12 g
methylphenidone	0.2 g
water to make	$1000{\rm cm}^3$

For use take 15 cm^3 of the stock solution and add 400 cm^3 distilled or de-ionized water. Development time at 20°C 12 min *without any agitation*.

Fixing bath for GP-2 process

sodium thiosulphate anhydrous	120 g
(or crystals (hypo)	200 g)
water to make	$1000 {\rm cm}^3$

Immerse the developed emulsion for between 30 and 60 s. Don't exceed this time, and don't be tempted to use ordinary rapid fixer: it will remove most of the image.

Wash in running water for not more than 3 minutes.

Rehalogenating bleaches

This type of bleach oxidizes the metallic silver (the negative image, in photographic terms) and deposits it on the undeveloped silver halide (the positive fringes), thus reinforcing them. Because of this action, no material leaves the emulsion, and the Bragg planes are undisturbed. This means that master

If you have difficulty in obtaining methylphenidone, (also-called phenidone-B), you can use ordinary phenidone (properly called phenidone-A).

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holograms used for transfer will replay a bright image when illuminated at the same angle as was used to make the master, and that there are no aberrations, provided you use collimated beams for both making and replaying the image. There are several good formulas, all containing an oxidizing agent and bromide. The standard formula is as follows:

Bleach bath for master holograms

EDTA (disodium salt)	30 g
ferric sulfate, crystals	30 g
potassium bromide	30 g
water to make	$1000{\rm cm}^3$

After development, rinse the emulsion briefly in ordinary mains water and immerse in the bleach solution. You can put on the white light immediately. Keep the film moving until all trace of dark silver has disappeared from the back of the film; this may take up to ten minutes. Give another minute after bleaching appears complete. Wash the film for not more than two or three minutes in running water, finishing with a short immersion in distilled water to which you have added a drop of acetic (ethanoic) acid.

Haze removal

Occasionally this bleach leaves a bluish haze caused by microscopic silver bromide crystals (Rayleigh scattering). This is unimportant when the hologram is illuminated by laser light, but if you intend to exhibit the hologram you can give it an extra treatment to remove the haze.

After bleaching and washing, immerse the emulsion in a 1 per cent solution of ascorbic acid, under a powerful light (a 12 V 20 W halogen bulb is the minimum). Rock the dish gently until the emulsion has turned a light orange. Remove the film and squeegee it surface dry without further washing.

Oxidized developing agents as bleaches

A developing agent is normally an electron donor. However, if it has been fully oxidized it becomes an electron acceptor, i.e. an oxidizing agent. When hydroquinone is fully oxidized it becomes *p*-benzoquinone (PBQ), which has been employed as a very efficient bleaching agent since comparatively early days; but it is toxic and carcinogenic, and has a fearsomely pungent choking smell. Nick Phillips's team investigated oxidized developing agents further⁵, and came up with three other developing agents that could be oxidized to give the same effect as PBQ without its disagreeable side effects, namely metol, ascorbic acid and amidol (4-aminophenol). Of these, amidol is perhaps the best. Once mixed, the solutions keep for only about 48 hours.

Bleaches based on oxidized developing agents

copper (II) sulfate, crystals	2 g
potassium persulfate ($K_2S_2O_7$)	10 g
sodium hydrogen sulfate, crystals	15 g
potassium bromide	20 g
water to make	$1000 {\rm cm}^3$

Ferric sulfate is properly called 'iron (III) sulfate'. The chemically correct name for EDTA is even longer and more complicated than the one given in the margin above, and it is seldom if ever seen outside chemistry textbooks.

Agfa-Gevaert and Kodak holographic emulsions have always been prone to this effect. Amidol is a gray powder that stains anything it touches an indelible blueblack, so be careful with it. You can also use PBQ (1 g) if you must, but give the solution 6 hours to become stable before use, and carry out all operations in a properly ventilated fume cupboard. You can dissolve these ingredients in any order, or all together. When they are all dissolved, add

amidol	1 g
or metol	1 g
or ascorbic acid	5 g

Do not use until 30 min have elapsed. The ascorbic acid bleach will be colorless, but the metol bleach will be pale green and the amidol a port wine color. The ascorbic acid bleach gives an emulsion shrinkage of about 5 per cent.

Pre- and post-swelling

The advantage of pre-swelling over solvent developers for color changes towards shorter wavelengths in reflection holograms lies in the diffraction efficiency, one of the controlling factors being the number of Bragg planes within the emulsion. In the usual type of reflection hologram, the number of fringe planes is equal to three times the number of micrometres thickness of the emulsion, e.g. 18 for a 6 µm emulsion. For an emulsion that is shrunk after processing, this number remains the same. However, if the emulsion is pre-swollen by 22 per cent (for a green image from a red laser), the number of fringe planes goes up to 22, a substantial improvement. If it is swollen by 46 per cent (for a blue image) the number of fringes goes up to 26, a further improvement. The usual medium for pre-swelling is triethanolamine (TEA), a viscous liquid that solidifies a few degrees below room temperature, and mixes in all proportions with water. It also hypersensitizes the emulsion to some extent. The exact concentrations needed vary greatly from one emulsion batch to another, the usual range being from around 5% for orange to 22% for a full royal blue (with a red laser). Without pre-washing, soak the emulsion in the solution for 2–3 minutes, then squeegee it (or use print blotting paper) until it is superficially dry, with no streaks; then dry it thoroughly with a hair drier set to low heat.

Pre-swelling is for the purpose of shortening the dominant reconstruction wavelength of the image; post-swelling is to lengthen it. The usual postswelling medium is sorbitol, which you can obtain from health stores. The range of suitable concentrations is the same as with TEA, about 5–20% to produce an orange to red image from a green laser. As the number of Bragg planes doesn't change in this process, don't expect any improvement in diffraction efficiency. After the final wash, soak the emulsion in the sorbitol solution for about 3 minutes, with agitation. Sorbitol remaining on the surface tends to make the emulsion sticky, so give the film a quick dip in plain water before squeegeeing.

Silver halide sensitized gelatin processing

The present system is the result of exhaustive testing of various techniques by a number of collaborating universities, in particular Alicante University in Spain and De Montfort in the UK (Phillips⁵). It gives exceptionally bright noise-free images.

First developer

<i>o</i> -chloro- <i>p</i> -aminophenol sodium sulfite, anhydrous sodium carbonate, anhydrous urea water to make	2 g 10 g 30 g 50 g $1000 cm^{3}$
Rehalogenating bleach	
Solution A iron (III) nitrate potassium persulfate water to make	50 g 20 g 1000 cm^3
<i>Solution B</i> potassium bromide water to make	17 g 1000 cm ³
For use take 1 part each of A and B a	and 2 parts water.
Reactivator	
sodium sulfite anhydrous sodium hexametaphosphate (Calgon) water to make	50 g $0.5 g$ $1000 cm3$
Second developer	
Agfa G284 lithographic developer, un	diluted
Solvent bleach	
potassium dichromate acetic acid (ethanoic acid) sodium hydrogen sulfate, crystals water to make	8 g $40 cm^{3}$ 1 g $1000 cm^{3}$
Clearing bath	
sodium metasilicate sodium sulfite, anhydrous water to make	10 g 50 g 1000 cm^3

For use, dilute 1 to 4 with distilled water.

The procedure is as follows. (All baths should be at 20° C.)

- 1. Develop in first developer for 5–6 min to a density of 2.5–3.0 (transmission holograms), 3.0–3.5 (reflection holograms).
- 2. Wash briefly.
- 3. Bleach in rehalogenating bleach for approximately 5 min. Stop when the smell of bromine becomes noticeable. (Discard solution.)
- 4. Wash for 3 min.
- 5. Reactivate for approximately 2 min.
- 6. Wash for 3 min.
- 7. Immerse in second developer and illuminate with a powerful light.

- 8. Wash for 1 min.
- 9. Immerse in solvent bleach, and keep agitating vigorously until film is clear (about 5 min).
- 10. Wash for 5 min.
- 11. Clear for 2 min in clearing bath.
- 12. Wash for 5 min.
- 13. Immerse in undiluted methanol for not more than 30 s. (Longer immersions can damage the film base.)
- 14. Immerse in undiluted ethyl methyl ketone (EMK) for 2 min.
- 15. Dry.

Preparation of red-sensitive DCG emulsion

This formulation is due to Jeff Blyth⁶. There have been some improvements since the original paper was published, so this updated worksheet is taken from the author's website, with permission.

3

Stock solution A (TMG)

1,1,3,3-tetramethylguanidine (1MG)	25 cm
water to make	$100\mathrm{cm}^3$

Stock solution B (TMG acetate)

TMG	$50\mathrm{cm}^3$
water to make	$100{\rm cm}^3$

Add, very slowly, stirring continuously:

acetic (ethanoic) acid 16 cm³ (approx) until pH is between 7 and 8.

Prepare this solution in a well-ventilated area (TMG has a foul smell).

Stock solution C (potassium chromate)

potassium chromate $(K_2Cr_2O_4)$ water to make	5 g 100 g
Stock solution D (methylene blue)	
methylene blue water to make	$\begin{array}{c} 0.4\mathrm{g}\\ 100\mathrm{cm}^3 \end{array}$
Stock solution E (gelatin)	
gelatin water at 50°C	75 g 500 cm ³

Preferably use photographic gelatin (limed ossein, Bloom strength 260 is ideal, though supermarket cooking gelatin is satisfactory).

Heat the mixture in a water bath with regular stirring until 50° C is reached. Do not exceed this temperature. The gelatin may take as much as 30 min to dissolve completely. When it is completely dissolved, add the sensitizer as follows:

The reason you need to keep Solution A separate is that you may need some of this very alkaline solution in case you overdo the acetic acid so that the pH falls below 7; you can then add a little more TMG.

Bloom strength is a measure of the resilience of a given specimen of gelatin.

gelatin stock solution $80 \, \mathrm{cm}^3$ stock solution B $10 \, \mathrm{cm}^3$ stock solution C $1 \, \mathrm{cm}^3$

keeping the temperature at a constant 50° C.

Now add stock solution A (TMG) drop by drop until the pH has risen to between 9.0 and 9.5. If the pH goes above 9.5 add a drop of acetic acid to bring it back within the limits.

Now, in dim green light, add:

stock solution D (methylene blue) 6 cm^3

Store in a dark container. The prepared material will keep for several weeks in a cool place (not a refrigerator), and you can prepare it for use by immersing the container in a hot water bath until it liquefies.

Instructions for coating and use are given in Chapter 20.

Making your own holographic emulsion

This process is also due to Jeff Blyth⁷. This updated worksheet was also taken from the author's website, with permission.

The general procedure is that, having coated a plate with pure gelatin, you treat it with silver nitrate. You follow this with a bromide solution containing red- (or green-) sensitizing dye. You need to use distilled water throughout.

Material required

(Minimum quantities and required solution strengths)

- Pre-subbed glass plates (or old plates with the emulsion cleaned off with household bleach). New plates will require treatment with a solution of 3-amino-propyltriethoxysilane in acetone (2% solution).
- 2. Pure photographic gelatin, Bloom strength 250–300, or plain cooking gelatin (30 g).
- 3. Ascorbic acid (vitamin C), culinary grade (5 g) (1% aqueous solution, adjusted to pH 5 with a small addition of sodium hydroxide solution).
- 4. Silver nitrate (1 g) (6% aqueous solution).
- 5. Lithium bromide (10 g) (3% w/v in a mixture of 2 parts water to 3 parts methanol).
- 6. Chromium (III) acetate, or chrome alum (5 g) (1% or 2% aqueous solution respectively).
- 7. Dye: For red sensitization, pinacyanol chloride, for green sensitization, 1,1-diethyl-2,2-cyanine iodide (0.1 g) (0.1% and 0.2% solution in methanol, respectively).
- 8. Sodium hydroxide or carbonate (10 g) (1% aqueous solution).
- 9. Methanol (200 cm^3) .
- 10. Distilled water (as required).

A pH meter is preferable to pH paper, but if you don't have access to one, use narrow-range pH paper, type pH 8.5–9.5.

I have edited this section and the one above a little.

Preparation of plates

New glass plates need pre-treatment with a subbing; otherwise the emulsion will become detached during processing. Old holographic plates need the emulsion removing by a 10-minute soak in ordinary domestic bleach solution (not the viscous type) diluted 1:3, followed by rubbing under warm mains water, but won't require further subbing. New plates should have an overnight soak in the bleach solution.

Rinse the plates in distilled water and allow them to dry naturally. Now rub new plates over with a tissue soaked in a 2% solution of 3-amino-propyltriethoxysilane in acetone until it has evaporated, and leave them to cure for at least two hours. (Old holographic plates don't need this treatment).

Preparation of sufficient coating solution for an 8×10 in plate

Add 30 g gelatin to 170 cm^3 cold distilled water (or a 26-gram packet to 150 cm^3). Mark the liquid level on the beaker. Place the beaker in a water bath and heat while stirring constantly, until temperature reaches 60° C. *Under no circumstances allow the temperature to go above* 70° C. When all the granules have dissolved, top the solution up to the mark as necessary with distilled water. To remove any scum, filter the solution through a piece of old nylon tights into a preheated beaker with a good pouring lip.

Coating (smaller plates)

Hold the beaker in one hand, and with the other hold the (pre-warmed) plate by the edges, inclined at about 30° to the vertical in a clean plastic tray. Pour the gelatin steadily along a horizontal line about 1 cm from the top edge of the plate.

Prop the plate up *in situ* for a minute or two, while the coating cools and gels, then run a blade along the bottom edge to separate the plate from the tray. (You can re-use any overflow left in the tray.) Place the plate in the (cold) chromium acetate or alum solution for one minute, then remove it, drain it and dry it with a hair drier set to 'cool'. Leave the plate for several hours (preferably overnight) in a clean, warm (60°C) cupboard. Once the hardening is complete, rinse the plate in distilled water, and dry it with warm air. You can now cut up the plate if you need to, scoring the back with a glass cutter. Don't separate the pieces without first running a scalpel blade along the gelatin side.

Coating (8 \times 10 in and A4 size plates)

For larger plates it is preferable to use a Meyer bar. This is a bar wound with stainless steel wire. The one you require will have about 7 turns per cm. If you decide to make your own, use 18 gauge wire. You can also use a long spring, provided it has the right pitch and is reasonably rigid. Keep it in a measuring cylinder filled with water at 70°C. Place the (warmed) plate flat on an old magazine a little larger than the plate, pour a line of gelatin solution along the far edge, and draw the Meyer bar smoothly across the plate once only, right to the edge and over it. Now leave the plate face up until the coating has cooled to a gel.

Preparing the silver bromide emulsion

A 4×5 in plate will require approximately 3 cm^3 of 6% silver nitrate solution; other sizes in proportion to their area. In subdued light, pour the silver nitrate

You may find that you haven't poured a thick enough stream for the gelatin to reach the bottom edge. If this is important you will just have to clean the gelatin off and start again.

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solution onto the center of the plate, and immediately place a clean flat glass or acrylic plate on top, and squeeze it down to expel all airbells. Leave it in position for 3 minutes. Then remove the cover and gently squeegee the surplus solution off the surface of the plate. Blow-dry the plate with cool air.

Now, under safelight conditions, add 2.5 cm^3 of the dye solution per 100 cm^3 of the lithium bromide solution, then add about 0.5 cm^3 of the 1% ascorbic acid solution. Stir well and plunge the plate in, continuing to agitate the solution briskly. Keep this up for 1–2 min (the shorter time for softer gelatin). You can use the solution repeatedly until the dye shows sign of separating out (the green-sensitizing bath is more prone to this than the red-sensitizing bath).

Rinse the plate well with running mains water, and stroke the surface gently with an ungloved finger or a soft brush to remove any precipitated silver bromide on the surface. The plate should now appear beautifully clear under the safelight.

Final sensitizing step

Adjust the ascorbic acid solution to pH 5 with a little of the sodium hydroxide or carbonate solution, and immerse the plate for 1 min. Remove, squeegee and dry in warm air. The plate is now ready to expose. If you wish, you can hypersensitize the emulsion with a 10% solution of triethanolamine (TEA).

Electroplating formulas

Silver spray

This is a method of coating a surface with a thin film of pure metallic silver before electroplating. The two solutions are mixed by a special gun so that the silver nitrate is reduced to metallic silver as it falls on the surface to be plated. Use distilled water for making up all solutions in both formulas.

Solution A

silver nitrate	10 g
ammonia, 28% solution	$3.7 \mathrm{cm}^3$
water to make	$1000 {\rm cm}^3$

Solution B

hydrazine sulfate (or hydrate)	16 g
sodium hydroxide	4 g
water to make	$1000\mathrm{cm}^3$

It is advisable to prepare the master with the stannous chloride solution as described in Chapter 21 for both of these processes described here. You can obtain more detailed information in Graham⁸.

Electroless nickel

This method deposits a layer of pure nickel on the surface of plastics materials. The first step is to sensitize the surface by immersing the master in the following solutions:

Sensitizing solution

tin (I) (stannous) chloride	70 g
hydrochloric acid, concentrated	$90\mathrm{cm}^3$
water to make	$1000 {\rm cm}^3$

If you want to avoid the pre-swelling action of TEA you can wash it out before drying the plate without affecting the hypersensitizing. Soak for 3 min, then, without washing, immerse in:

Electroless plating solution

nickel chloride	30 g
sodium hypophosphite	10 g
sodium hydroxyacetate	20 g
water to make	$1000 {\rm cm}^3$

This solution should be kept at 90° C. Plating is at the rate of around 10 m per hour.

Electroforming bath (McNulty⁹)

20.0 g
2.4 g
1.0 g
$1000 {\rm cm}^3$

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