Chapter 5.

Pulse Generators.

In order to gain-modulate the correlating APD it was necessary to modulate its bias voltage with a short pulse. It has been shown earlier, that the greatest increase in gain occurs for large modulation voltages. For the greatest time resolution, it is necessary to generate as short a pulse as possible. Methods will be described for pulse generation.

5.1 Use of a photodiode for pulse generation.

If a fraction of the pulsed laser power is coupled to a photodiode, then it is possible to generate a short pulse of voltage. This method was investigated, but found to be unsuitable. The method of connection is shown in figure 5.1. Note the centre connection to the high voltage input connector is positive - a convention used throughout this thesis, but which is not standard practice. It is standard to use a negative centre, as this is safer when using PMTs, allowing the PMT photocathode to be at ground potential.

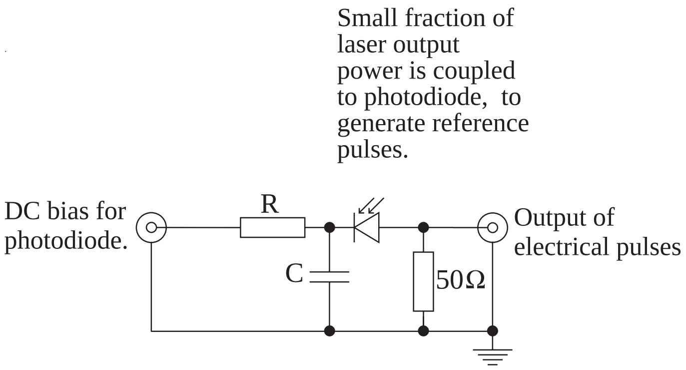


Figure 5.1 Diagram showing the reference APD receiver. The capacitor and 50 Ω resistor are soldered to the APD with negligible lead length.

Unfortunately, the voltages that can be generated by this method are very small. They can of course be amplified, but the bandwidth of the amplifier needs to be considerable to pass the pulse without causing significant broadening.

If the photodiode is replaced by an avalanche photodiode, then the level of the signal can be increased by the carrier multiplication in the APD.

5.1.1 Disadvantages of using an APD as the pulse generator.

There are a number of problems with using the APD as the pulse generator. These include:

1) Some fraction of the laser power must be used for pulse generation, which limits the maximum range and/or signal to noise ratio of the final instrument, due to decreased optical power injected into tissue.

2) It was only possible to achieve a voltage of about 2 V peak, when using 90% of the available laser power to generate the pulse.

3) The pulse width was greater than desirable.

4) The phase delay, must be a mechanical moving mirror, as used by Berndt, since the pulse risetime needs to be very fast (say <100 ps) and the bandwidth of any alternative phase shifting network needs to be at least 3.5 GHz.

5) The chopper used to generate a reference for the lock-in amplifier needs to have a wide bandwidth. Hence this too must be a conventional mechanical chopper or a very expensive high-speed electro-optic device or LCD shutter. There are no cheap wide-bandwidth, non-mechanical choppers available.

5.2 Use of a step recovery diode (SRD) for short pulse generation.

An electrical signal was available on the laser mode-locker, which is synchronised to the laser pulses. This is not a standard waveform (sine, square, triangle etc), but when passed through a low-pass filter with a cutoff frequency of approximately 100 MHz, the output becomes approximately sinusoidal at a frequency of 82 MHz. A pulse generator, that could generate ultra short electrical pulses synchronised to this sine wave drive would offer an ideal solution. The advantages would be:

1) It is no longer necessary to use any of the laser power for pulse generation. All the power could be injected into the tissue. Whilst lack of power is not a problem when using the Ti:sapphire laser, it is expected to be more of a problem when using solid state diode lasers, with their much lower output powers.

2) The time delay necessary for calculating the cross-correlation could be achieved with a phase shifting network operating at a single frequency of 82 MHz, avoiding the need for bandwidths of many GHz. All electronic phase shifters for doing this are readily available.

3) The chopper necessary for the lock-in amplifier reference can consist of a switch which switches on/off the 82 MHz sine wave to the pulse generator. The switch would no longer need a bandwidth of many GHz. Such a switch is again readily available.

A step recovery diode can be used to generate the required short electrical pulses from a sine wave drive. For the device used for this project, there are also other advantages compared to the APD method of pulse generation.

1) The amplitude of the voltage pulse is greater (~7 V compared to 2 V of APD).
2) The pulse is narrower (~130 ps, compared to the 800 ps of APD).

A step recovery diode[114,115,116,117,118,119] is a pin junction diode that has a special doping profile, to give it an unusual characteristic curve. The idealised current characteristic of a step recovery diode are shown in figure 5.2, along with the output spike produced by this rapidly changing current. Like a normal pn diode, the SRD conducts when forward biased. Unlike the normal pn diode, it also shows significant conduction when reversed biased. However, this only continues for a short time, after which the diode no longer conducts when reversed biased. The transition from the conducting to non-conducting states of the reversed biased diode occur in a time of typically less than 100 ps. This means the current waveform has a high harmonic content and can be used for generating short pulses.

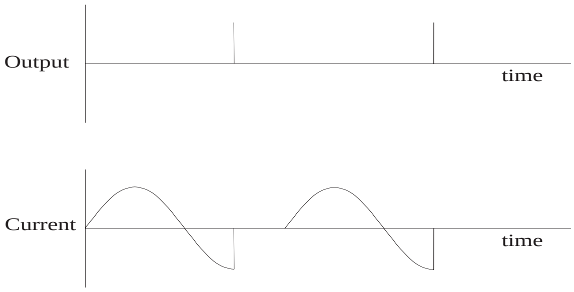


Figure 5.2 Idealised current waveform of an SRD, driven with a sine wave, and the resulting output spike produced.

Step recovery diodes are available as individual diodes, or as a module containing the SRD and a few passive components. SRD’s have 2 main applications - (1) and (2) below and a third (3), less frequently used.

1) A multiplier[114,115,116,117,119]. This multiples an input frequency by a fixed integer. A typical x7 multiplier module, driven at 1 GHz would produce an output at only 7 GHz.
2) Comb generators[114,115,116,117]. These generate a number of harmonics simultaneously, which look like a comb if viewed on a spectrum analyser.
3) Occasionally SRDs are used to sharpen the rise time and reduce the pulse width[120] of pulses generated by other SRDs or other components.

5.2.1 Theory of a step recovery diode.

An SRD is made so that majority carriers[102] (electrons on the n side, holes on the p side) injected across the junction under forward bias create a number of minority carriers (electrons on the p side, holes on the n side). Unlike a normal diode, where these soon recombine, the minority carrier lifetime in an SRD is sufficiently long to ensure that carriers do not immediately recombine, so that charge is stored. When the applied voltage changes to reverse bias the diode, these minority carriers (charge) are withdrawn across the junction due to the applied reverse bias, where they become majority carriers. Hence a current flows in reverse bias, until all the carriers are back to their original side of the junction. In order for this to work, two conditions must be met:

1) The carriers must not recombine before they are withdrawn.

2) The minority carriers must not diffuse too far from the junction, that they can not be withdrawn under reverse bias.

It should be evident, that the minority carrier lifetime of the diode determines the frequency of operation. Silicon can be made to have a minority carrier lifetime of approximately 10^{-6} s to 10^{-8} s, which limits the fundamental frequency of operation of silicon devices from approximately 10 MHz to 1000 MHz. Gallium arsenide, which has a minority carrier lifetime of less than 10^{-10} s, would only be useful if driven at mm-wavelength microwave signals (100 GHz). As such, all SRDs are currently made with silicon, although one can expect GaAs devices to be available in the future.

The SRD is also known as a charge storage diode, since its operation depends on the ability to store charge. Sometimes it is known as a snap diode, for obvious reasons.

5.2.2 Ideal dynamic characteristics.

The charge stored can be easily obtained from the charge continuity equation:

rate of increase of charge=rate of injected charge - rate of recombination

hence

$$i=\frac{q}{\tau_{mc}}+\frac{dq}{dt} \qquad \mathbf{5.1}$$

where i = instantaneous diode current.

q = charge stored at junction.

τ_{mc} = minority carrier lifetime of diode.

This is easily solved by any standard means - Laplace transforms[121] will be used here.

$$LT\,[i] \equiv LT\left[\frac{q}{\tau_{mc}}\right] + LT\left[\frac{dq}{dt}\right] \tag{5.2}$$

$$\frac{I(s)}{s} = \frac{Q(s)}{\tau_{mc}} + sQ(s) - Q_0 \tag{5.3}$$

where the convention of using upper case characteres to denote parameters in the s domain and lower case characters for the time domian is used (i.e. f(t)↔F(s)). Q_0 is the initial charge.

$$Q(s) = \frac{I}{s\left(s+\dfrac{1}{\tau_{mc}}\right)} + \frac{Q_0}{s+\dfrac{1}{\tau_{mc}}} \tag{5.4}$$

if there is previously no stored charge (Q_0=0) and a constant forward current I_F

$$Q(s) = \frac{I_F}{s(s+\dfrac{1}{\tau_{mc}})} \tag{5.5}$$

taking an inverse Laplace transform of equation 5.5, we get a solution for the stored charge as a function of time.

$$q_F = i_F \tau_{mc}\left[1-\exp\left(-\frac{t_F}{\tau_{mc}}\right)\right] \tag{5.6}$$

where q_F is the charge stored from the forward current i_F and t_F is the length of time for which the forward current i_F is applied.

If we now apply a reverse current i_R to withdraw the charge and switch the diode, the time required to do so is easily found from equation 5.4 with the initial charge Q_0 not equal to zero, but some finite value due to the forward current injection. Taking an inverse Laplace transform of equation 5.4 gives

$$q(t) = -i_R \tau_{mc}\left[1-\exp\left(-\frac{t_R}{\tau_{mc}}\right)\right] + q_0 \exp\left(-\frac{t_R}{\tau_{mc}}\right) \tag{5.7}$$

The negative sign in front of i_R is due to the assumed positive value of the reverse current, even though it flows in the opposite direction to the forward current. When the reverse current has been flowing for some time t_R, such that all the charge is removed, the diode will snap. This time can easily be found by solving equation 5.7 for q(t)=0.

$$t_R=\tau_{mc}\ln\left[\frac{q_0+\tau_{mc}i_r}{\tau_{mc}i_R}\right] \tag{5.8}$$

Substituting for the initial charge q_0 due to forward current injection

$$q_0=i_F\tau_{mc}\left[1-\exp\left(-\frac{t_F}{\tau_{mc}}\right)\right] \tag{5.9}$$

gives

$$t_R=\tau_{mc}\ln\left[1+\frac{i_F\left(1-\exp\left(-\frac{t_F}{\tau_{mc}}\right)\right)}{i_R}\right] \tag{5.10}$$

This is usually called the snap time, t_s. If t_F is long compared to τ_{mc} and $i_F \ll i_R$, then

$$t_R=t_s\approx\frac{\tau_{mc}I_F}{I_R} \tag{5.11}$$

5.2.3 Equivalent circuit of an SRD.

Figure 5.3 is an equivalent circuit for an SRD[120].

where

C_p = Package capacitance

L_p = Package inductance

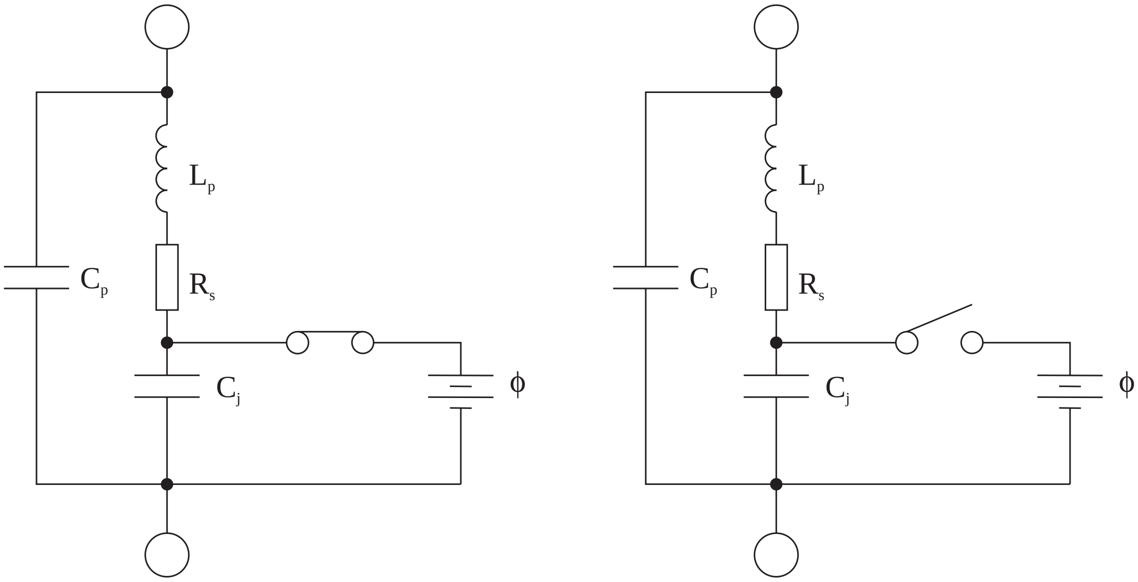
R_s = Dynamic series resistance

C_j = Reverse bias (depleted) junction capacitance

ϕ = Contact potential (0.7 V)

5.2.4 Actual dynamic characteristics.

A number of assumptions have been made in the section 5.2.2, that are not strictly true and so modify the actual device characteristics. These include:



Forward bias
Reverse bias

Figure 5.3 Equivalent circuit of an SRD in both forward and reverse bias.

1) Zero voltage drop under forward bias.
2) Infinitely fast transition time.
3) Zero package inductance.

The effects of these will now be considered in turn.

5.2.5 Forward bias voltage drop of an SRD.

When forward biased, a voltage drop V_F will occur given by:

$$V_F = \phi + i_F R_s \qquad \textbf{5.12}$$

Most practical circuits employing an SRD use capacitive coupling, so this does not appear at the load.

5.2.6 Transition time of an SRD multiplier.

In practice, the SRD does not instantaneously change from being in a conducting to a non-conducting state. There is always a transition time, usually called the snap time and denoted T_s, defined as the time the current waveform takes to change from 80% to 20%, as shown below. Some manufacturers call it the transition time t_t. The diode snap time T_s should be less than the output period of the highest frequency component in the output of an SRD multiplier.

$$T_s < \frac{1}{f_{\max}} \qquad \textbf{5.13}$$

For this project, where a pulse of as short as duration as possible is required, one might expect that a diode be selected with as short a snap time as possible. Unfortunately, diodes with short snap times, always have short minority carriers lifetimes, as the following table giving characteristics[122] for a number of SRD's formerly made by Hewlett-Packard, who were one of the largest manufacturers of SRD's, but have now stopped production completely.

Table 5.1 Characteristics of some Hewlett-Packard Step Recovery Diodes

Part number	Junction capacitance C_j (pF)	Reverse breakdown voltage V_B (V)	Minority carrier lifetime τ_{mc} (ns)	Snap time T_s (ps).
5082-0032	4.00	65	150	250
5082-0112	1.4	35	50	175
5082-0151	0.5	15	10	100
5082-0835	0.4	15	10	75
5082-0018	0.5	25	20	70
5082-0008	0.38	15	10	60

It was shown earlier, that the minority carrier lifetime needs to be adequately long, as otherwise there will be significant recombination before the diode will snap, resulting in a much reduced amplitude for the pulse. This means that SRD's driven at high frequencies will be able to produce higher harmonics (faster pulses) than those driven at lower frequencies.

In practice, the output current of an SRD does not change as fast as the transition time, due to package capacitance and load resistance. The risetime from 10% to 90% of the current waveform t_r is given by[120]

$$t_r = \sqrt{T_s^2 + (2.2 R_{eq} C_j)^2} \qquad \textbf{5.14}$$

where R_{eq} is the equivalent resistance consisting of the parallel combination of the source and load resistance.

5.2.7 SRD Package inductance.

The package inductance L_p causes a voltage spike, V_L due to the rapid change of current i_d through the diode.

$$V_L(\max) = L_p\left[\frac{di_d}{dt}\right] \quad \textbf{5.15}$$

When used for fast pulse generation, this can be a significant voltage spike. For this reason, the package inductance is generally kept as small as possible.

5.2.8 Reducing risetime of pulses with an SRD.

SRDs can be used to reduce the rise time of a pulse generated by other means. This is discussed fully in the HP application note[120], where equations are given for designing practical circuits. It is said that a 10 ns risetime pulse can be sharpened to <300 ps with one SRD, or even less if two or three circuits are coupled together. The application note also discusses how to reduce the pulsewidth of a pulse, using an SRD.

5.2.9 High order frequency multiplier.

This circuit takes a sine wave at one frequency, say 1 GHz and produces another at some high multiple, for example 20 GHz. It is of no use for this project, but is discussed here as the comb generator, which is a minor modification of the multiplier, is important.

5.2.10 Input matching circuit.

The function of this is to match the output of the sine wave drive, which is conventionally 50 Ω to the SRD. Unfortunately, the SRD has two impedance states, one during forward drive, which is about 1-20 Ω and the other in reverse bias which is 50-500 Ω, so the match is never very good.

5.2.11 Impulse circuit.

This functions as a voltage pulse generator. This produces the voltage spikes from the rapid change in current when the diode snaps. The impulse voltage is given by

$$V = L_i \frac{di_d}{dt} \qquad \textbf{5.16}$$

The impulse circuit will be most efficient in pulse generation if:

1) The snap time of the diode is less than the time period of the output frequency.
2) The impulse circuit resonates at or just above the output frequency required.
3) The diode cutoff frequency f_c, given by

$$f_c = \frac{1}{2\pi RC} \qquad \textbf{5.17}$$

is at least 10 times the output frequency required.

5.2.12 Output matching circuit.

The purpose of this is to match the diode to the 50 Ω transmission line. A band-pass filter is included in the output matching circuit to select the required harmonic.

5.2.13 Comb generators.

By far the most common application of SRDs is in making comb generators. These are harmonic generators, used to produce simultaneously a large number of harmonics from a single frequency source. A harmonic generator, driven at say 1 GHz, will produce outputs at 1 GHz, 2 GHz, 3 GHz ... to some maximum value, determined by the SRDs capacitance, transition time and the output circuit of the comb generator.

SRD comb generators consist of an input matching circuit, as with the harmonic generator. The impulse circuit containing the SRD must not resonate at or below the maximum frequency required for the comb generator. The output matching circuit, must match the SRD to 50 Ω over a wide band. The match is inevitably poorer than for a harmonic generator, where match is required only at one frequency. As such, the output circuit should be as simple as possible, to

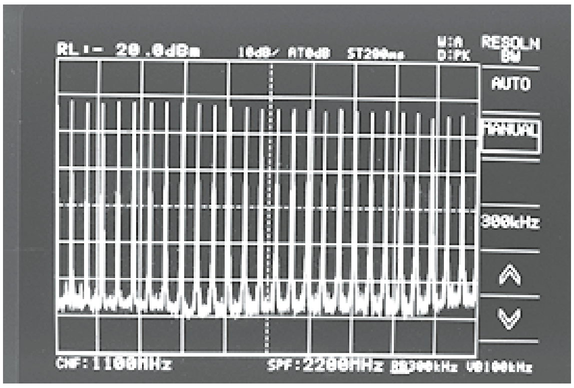


Figure 5.4 Spectrum analyser display showing the output from DC to 2200 MHz of a Herotek GC082-112 SRD comb generator driven at 82 MHz. This is the SRD module used in this project.

prevent unwanted resonances.

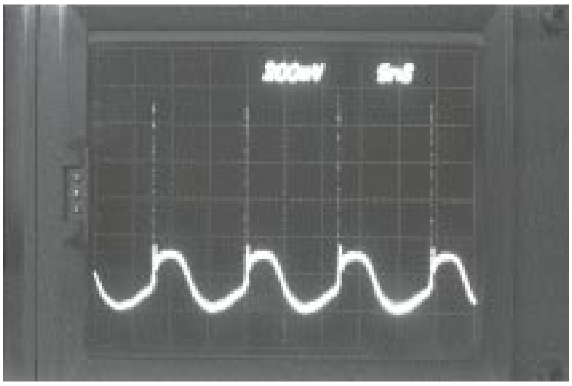


Figure 5.5 Diagram showing the output of the Herotek GC082-112 SRD comb generator as measured on a fast sampling oscilloscope. A 20 dB attenuator is fitted between the SRD and the oscilloscope.

Considered in the time domain, comb generators produce a series of narrow pulses, each separated by a time equal to the time period of the fundamental drive voltage. Figure 5.5 shows the output of a Herotek GC082-142 SRD comb generator module as measured on a fast sampling oscilloscope described on page 138. The output is seen to consist a series of pulses, which if shown on an expanded scale, are around 130 ps FWHM with a repetition time of 12.2 ns. These pulses can be used for changing the gain of the APD. However, the residual sine wave with an amplitude of approximately 2 V peak is undesirable. It is shown later that this caused problems in the cross-correlator and steps were taken to remove the residual sine wave, whilst leaving the pulses intact.

5.2.14 Temperature dependence of SRDs.

The minority carrier lifetime of a semiconductor is strongly temperature dependent. The rate of change is from approximately +0.5% to + 0.7%/°C[123]. This can be a problem when diodes are used for generating harmonics for microwave signal generation, as the optimum bias level is dependent on the minority carrier lifetime.

Unfortunately, the problem is more serious when, as in this application, we are interested in the position in time of the pulses. As can be seen from equation 5.11, a change of minority carrier lifetime, causes a change in snap time t_s, which is a change in the position in time of the pulses relative to the driving waveform. Since the driving waveform is synchronised to the laser pules, a change of temperature causes a timing drift. If the minority carrier lifetime increases due to an increase in temperature, without a change in bias level, we would expect the following to happen:

1) The charge injected at the end of the forward bias cycle will be increased, as indicated by equation 5.6.

2) This will increase the duration of the reverse cycle until the diode snaps, as indicated in equation 5.10. Hence an increase of temperature and therefore minority carrier lifetime will cause

the pulses to occur at a later stage of the RF cycle.

3) If the assumption that $I_F \ll I_R$ is valid, the simplified equation 5.11 can be used. This indicates a linear relationship between the snap time t_s and τ. Clearly by altering the forward and reverse currents, it is in principle possible to temperature compensate.

Some liberties will now be taken in equating results obtained for a square wave earlier, with a sine wave, so the results of this analysis can only be approximate. If we assume that the snap time t_s is a quarter of the fundamental AC cycle, then the snap time will be given by:

$$t_s = \frac{1}{4f} \qquad \textbf{5.18}$$

From equation 5.11, we know that for a constant forward and reverse currents, the snap time is directly proportional to the minority carrier recombination time τ_{mc}. Assuming a +0.6%/°C change in τ with temperature, t_s will also change at +0.6%/°C. If the drive signal is 82 MHz, the snap time t_s should be approximately 3 ns, so a 1°C increase in temperature, will cause a shift of the pulses of approximately 0.6% of 3 ns, or 18.3 ps/°C. This would suggest that temperature changes can not be ignored for this application, but are not likely to prevent the technique from working, if simple precautions are taken.

5.2.15 Radio frequency drive levels for SRD diodes.

The bias currents, are frequently generated by the diode alone. The comb generator modules require no DC supplies at all. The bias currents are generated by the RF waveform, and so depend on the drive level. The snap time and hence the accuracy of synchronisation to the laser pulses, depends too on the drive level.

5.2.16 Practical aspects of pulse generation by SRD.

The step recovery diode module used for this project required a drive of +27 dBm (500 mW) at 82 MHz. The power output from the laser mode-locker after filtering to remove harmonics was -12.6 dBm. Two amplifiers connected in series were needed to increase the -12.6 dBm to +27 dBm. The first stage, providing up to 30 dB of gain, used a commercial wide band amplifier, to which an AGC voltage could be applied. The final stage, which increased the power level to +27 dBm, was used to directly drive the SRD comb generator.

5.2.17 Specification and measurement of SRD parameters.

Apart from specifications which are common to all diode types, such as junction capacitance, series resistance, reverse breakdown voltage, maximum current, maximum junction temperature etc, the SRD has a number of specifications which are unique to it. It should be noted that not all manufacturers define these in the same way, so care is needed in comparing specifications.

Transition time t_r

HP define this as the time between the 20% band 80% amplitude points of the overall step amplitude of the SRD. Since it is measured in a test fixture, the true time of the diodes t_r is less than the measured value, due to the diode junction capacitance. It is typically 60 ps to 400 ps.

Carrier lifetime τ

This is the minority carrier lifetime of the semiconductor. This parameter is particularly important, as it determines what frequency the SRD can be used at. It is typically 10 ns to 150 ns.

5.2.18 Conclusions about the SRD method of reference pulse generation.

The step recovery diode does in principle offer an ideal way of generating the reference pulses needed for this project. It provides large amplitude, short pulses, with a phase that is easily controllable by a simple, fairly inexpensive, rugged, all electronic phase shifter. This has been implemented by purchase of an SRD comb generator, model GC82RC from Herotek Inc, Sunnyvale, CA 94086, USA.

It has been shown that by the use of a number of step-recovery diodes, it is possible to further reduce the risetime of pulses and probably reach a pulse width of 50 ps (risetime approximately 20 ps). Unfortunately, such methods require a custom designed pulse sharpening circuit, since the component values depend on the amplitude, repetition rate, risetime, pulsewidth and falltime of the original pulse as well as the risetime, pulsewidth and falltime of the required pulse. Suitable pulse sharpening circuits are not available commercially - there are too many combinations for any manufacturer to make. Although such circuits can be designed, this has not been done here, since the problems of making a wide band circuit, that show no unwanted resonances to a frequency of approximately 10 GHz is very considerable.

The approach which was taken here was to use the Herotek GC082-142 SRD harmonic generator, as it offers a method of generating very short pulses, of large amplitude, with a phase that is controllable by altering the phase of the RF drive signal.