Optical materials for near infrared Wollaston prisms

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Abstract. The optical characteristics of birefringent materials transmitting in the near IR (0.9 – 2.5 μm) are analyzed. Wollaston prisms with large beam separation and virtually free from lateral chromatism – e.g. with fields of view > 1 arcmin and image elongation < 0.3″ – could be manufactured using AgGaS₂ or LiYF₄ (YLF). These materials are used for non linear applications and may therefore find another interesting application in IR focal plane instruments. From the optical point of view the best materials are used for non linear applications and may therefore find another interesting application in IR focal plane instruments. From the optical point of view the best material is AgGaS₂ but YLF may be practically more convenient because of its lower refractive index (n ~ 1.45), better thermo–mechanical properties and lower price.

New measurements of the transparency of Calcite at room and cryogenic temperatures are also presented, these show significant absorption (≃ 0.4 cm⁻¹) of the ordinary ray already at λ = 2 μm and very strong bands (absorption coefficient a > 3 cm⁻¹) beyond 2.25 μm. The absorption does not decrease significantly when the crystals is cooled, CaCO₃ should not be therefore used in instruments working beyond 2.0 μm.

Key words: instrumentation: miscellaneous — instrumentation: polarimeters

1. Introduction

Wollaston prisms are extensively used in focal plane astronomical instruments working at visual/ultraviolet wavelengths (e.g. Fosbury et al. 1989). Their main advantage compared to other polarizers/analyzer is that they produce simultaneous images in two perpendicular polarization states, and this minimizes the effect of transparency variations, i.e. the photometric errors propagating into the polarimetric measurement. The use of Wollastons in the IR was so far much more limited though excellent polarization images obtained with this technique can be found in the literature (e.g. Packham et al. 1996). In this paper we present a study of the optical properties of infrared birefringent crystals aimed at defining convenient materials to manufacture Wollaston prisms with large beam separation and small lateral chromatism.

The second aim of this paper is to determine the long wavelength transmission cutoff of Calcite at cryogenic temperatures. Surprisingly, no such information exists in the literature and, to the best of our knowledge, all available data are still based on the room temperature work of Nysander (1909) who found that CaCO₃ becomes opaque to the ordinary ray at λ > 2.2 μm.

In Sect. 2 we briefly review the basic concepts of Wollaston prisms and analyze the optical performances of birefringent crystals, including several materials recently developed for non–linear applications. In Sect. 3 we present and discuss new measurements of the transmittance of Calcite at cryogenic temperatures. In Sect. 4 we draw our conclusions.

2. Wollaston prisms and IR birefringent materials

Figure 1 is a sketch of a Wollaston prism with a schematic ray–tracing. In the first (entrance) prism the “o” light beam vibrating perpendicular to the optic axis has a refractive index nₒ while the e–ray has a refractive index nₑ. At the prisms interface the refraction index of the e–ray changes from nₒ to nₑ and the opposite occurs for the e–ray, and when exiting the second prism the angle between the two rays is increased further.

For most practical applications the deviation δ can be considered symmetric around θ (i.e. δₒ ≃ −δₑ) and the separation between the o and e rays is given by:

δ = |δₒ − δₑ|/2 ≃ Δn tan α

where Δn = nₑ − nₒ is the birefringence index of the crystal. For astronomical instruments the separation δ can be most conveniently expressed in sky–projected angles

δ″ ≃ 2063″Δn tan α (Dₒ/1 cm) (Dₑ/1 m)⁻¹

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with an image blurring of only $≤ 2.1$. AgGaS$_2$ are analyzed in some details in the following subsections.

AgGaS$_2$ crystals are significantly deformed by cooling. The thermal expansion coefficients $||$ and $\perp$ to the optical axis are $+29$ and $-19$ ($10^{-6}$ K$^{-1}$), respectively.

2.2. LiYF$_4$ (YLF)

This material is transparent from below 3000 Å to beyond 4 μm. It displays a very low chromatism from 1 to 2 μm and also has excellent performances from 0.8 to 2.5 μm. The computed beam separation for an $\alpha = 48^\circ$ YLF Wollaston are displayed in Fig. 2 (right hand panel) where one can better visualize the chromatic performances of this material which is comparable to AgGaS$_2$ in all bands but K. The thermo-optics coefficients of YLF are very small, $n_o$ and $n_e$ respectively increase by $1.4 \times 10^{-4}$ and $5.1 \times 10^{-4}$ between room temperature and 77 K (Barnes & Gettemy 1980). Practical advantages of YLF are:
The refractive index of YLF is $\simeq 1.45$ and very close to that of standard optical cements.

YLF crystals are only slightly deformed by cooling because the thermal expansion coefficients $\parallel$ and $\perp$ to the crystal axis differ by only $5 \times 10^{-6}$ $\text{K}^{-1}$.

Presently, YLF is much cheaper than AgGaS$_2$.

### 2.3. Other materials

YVO$_4$ is an interesting crystal to which attention was already drawn by Bennet & Bennet (1978) and which is now produced by several companies. It has a large birefringence ($\Delta n \simeq 0.20$) and could be therefore useful for manufacturing thin Wollastons when the physical thickness of the prism is limited e.g. by the space available in the filter wheel. Accurate measurement of the refractive indices of YVO$_4$ are not available in the literature and the only information we could find is from the CASIX data sheet which gives the following relationships ($\lambda$ in $\mu$m)

\[
\begin{align*}
\alpha^2 &= 3.77834 + 0.69736/(\lambda^2 - 0.04724) - 0.0108133\lambda^2 \\
\beta^2 &= 4.59905 + 1.10534/(\lambda^2 - 0.04813) - 0.0122676\lambda^2.
\end{align*}
\]

These are probably based on measurements at $\lambda < 1.4$ $\mu$m and are not necessarily accurate at longer wavelengths.

MgF$_2$ is a well known crystal for quasi-achromatic Wollastons from the ultraviolet to 1 $\mu$m but has a very low birefringence ($\Delta n = 0.011$) and becomes quite chromatic at $\lambda > 2$ $\mu$m ($V = 52$ in the $K$ band, cf. Table 1).

CdSe has a very low chromatism in $J$, $H$, $K$ but is not suited for applications below 1.1 $\mu$m. Compared to LiYF$_4$ it has a much higher refractive index ($n \simeq 2.55$) and a slightly lower birefringence ($\Delta n = 0.020$). Both facts make CdSe a not attractive alternative to YLF.

LiNbO$_3$ is a cheap compound extensively used for non linear applications and which is transparent to well beyond 2.5 $\mu$m. It has a quite large birefringence ($|\Delta n| \simeq 0.07$) and may be useful to manufacture low cost prisms whose performances are however limited by the relatively large chromatism of the crystal ($V \leq 40$).

Rutile (TiO$_2$) is another classical material which could be a good though expensive alternative to LiNbO$_3$ whenever high birefringence is required.

Calcite, the most widely used birefringent crystal, has the advantage of low refractive index and high $\Delta n$ but displays a large lateral chromatism and cannot be used beyond 2.0 $\mu$m because of its large opacity to the ordinary ray (cf. Sect. 3).

LiIO$_3$ has interesting optical properties, large $|\Delta n|$ and $|V| \geq 80$ in all bands, but is very hygroscopic and

<table>
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<tr>
<th>Material</th>
<th>$n_\alpha$</th>
<th>$(0.9 - 1.1)$</th>
<th>$J(1.1 - 1.4)$</th>
<th>$H(1.5 - 1.8)$</th>
<th>$K(1.95 - 2.4)$</th>
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<td>2.83</td>
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</table>

(1) The best materials (in bold type) are those with very low lateral chromatism, i.e. $|V| > 100$ in all bands.

(2) Refractive index of ordinary ray at 1 $\mu$m.

(3) Birefringence index $\Delta n = n_\alpha - n_\beta$ at band centers ($\lambda_c = 1.0$, 1.25, 1.65 and 2.2 $\mu$m).

(4) Reference for the refractive index data.

(5) Coefficient of lateral chromatism (Eq. 3), the image elongation is proportional to $1/V$ (Eq. 4).

Table 1. Refraction indices and chromatic characteristics of IR birefringent crystals with $|n_\alpha - n_\beta| > 0.01$ (1)
therefore unlikely to find practical applications in astronomical instruments.

3. Infrared transmittance of Calcite

CaCO$_3$ is a widely used birefringent material but its use in IR astronomical instruments may be limited by the fact that at room temperatures the crystal becomes opaque to the ordinary ray at 2.2 µm. The transmittance of CaCO$_3$ at cryogenic temperatures is not known (cf. the Introduction). To fill this gap we performed measurements of Calcite at 20 °C and 77 K using the FT–IR Perkin–Elmer System 2000 spectrophotometer of the National Optical Institute of Florence (Perkins 1986).

The resulting external transmittance is plotted in Fig. 3 where the absorption bands at 2.0, 2.15, 2.35 and 2.5 µm are narrower and much deeper than in the old measurements of Nysander (1909) which are reported in optical handbooks. This is also evident in Fig. 4 which compares the absorption coefficients derived here and those of Nysander (1909). Cooling the crystals slightly decreases the absorption at some wavelengths but the overall transmittance of our relatively thick (9 mm) specimen remain quite low.

4. Conclusions

Near infrared (0.9 – 2.5 µm) imaging polarimetry of large fields of view (> 1 arcmin) with sub–seeing image elongation can be best performed using Wollaston prisms manufactured with AgGaS$_2$ or LiYF$_4$. From the optical point of view the best material is AgGaS$_2$ because it has larger birefringence and smaller chromatism. However, YLF may be practically more convenient because of its lower refractive index (n ~ 1.45 and similar to optical cements), better thermo–mechanical properties and lower price.

New measurements of the transmittance of Calcite at 77 K indicate that CaCO$_3$ cannot be used for applications at wavelengths λ > 2 µm in astronomical polarimeters.

References

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