Research on refractive index of optical cement used in Glan-Thompson prisms

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The influence of the refractive index n_2 of optical cement on the structure angle, field angle, and transmission of Glan-Thompson prism has been studied in detail. The results show that the structure angle will increase with the decrease of n_2 under the condition of the largest field angle. Thus, the ratio of length to width (L/A) of the prism will decrease, which means more materials can be saved. When the value of L/A is 3.0 or 2.5 in the routine design, the field angle will firstly increase and then decrease with the increment of n_2. Two routine designs with the n_2 values of 1.47 and 1.45 have the optimal field angle. In addition, n_2 also has great influence on light intensity transmittance of the prism. Considering all these factors, it will be the best choice with $L/A = 2.5$ and $n_2 = 1.45 - 1.46$.

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For the fabrication of polarization devices, optical cement is necessary. There are many parameters to characterize the performances[1] of optical cement. Among them, wavelength range, transmission, operating temperature, shearing strength, linear expansibility, refractive index, and dispersion are often used. For polarization prisms made in natural birefringent calcite crystal[2−5], the forms include air-gap style and optical cement style. A typical former case is Glan-Taylor prism, with the advantage of high anti-optical-damage threshold and the shortcoming of small field angle (generally no more than 6°); and the latter is the frequently used Glan-Thompson prism, with the virtues of higher transmission and larger field angle. At present, Canada balsam (also called neutral resin adhesive) and fir gum are often used in the fabrication of Glan-Thompson prisms. Generally, the length-width ratio (L/A) of the prism is 3, the field angle ranges from 11° to 13°[1,6], and the transmission can reach 90%. Among the factors determining the prism properties, the refractive index n_2 of optical cement plays a significant role. Here, we take Glan-Thompson prism as an example to analyze how the index n_2 affects the structure angle, field angle, and transmission of the prism. The principle can also be applied to other types of prisms.

The structure and beam path of Glan-Thompson prism are shown in Fig. 1, where θ is the structure angle of the prism, n_1 and n_2 are the refractive indices of incidence region and optical cement, respectively. Optical axis of the crystal is perpendicular to paper surface. For the prisms made from birefringence crystal, its structure angle determines straightly its field angle. So, before investigating how the refractive index affects the field angle, we investigate how it affects the structure angle of the prism. Here we analyze this influence under the condition of the field angle kept maximum.

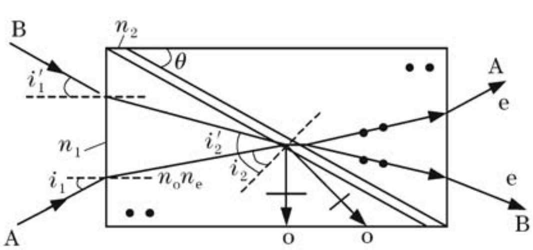

Fig. 1. Determination of field angle in Glan-Thompson prism.

For the Glan-Thompson polarizer made from calcite, the extraordinary ray (e-ray) is the output ray and the ordinary ray (o-ray) is totally reflected on the cutting surface. Usually, angles of arrival (AOAs) on the prism are not equivalent, such as i_1 and i_1' shown in Fig. 1. The field angle of the prism is twice the smaller AOA. So, the field angle reaches the maximum when the structure angle of the prism meets the condition that i_1' equals to i_1. In order to guarantee o-ray being totally reflected and e-ray transmitted, the angle i_2 in Fig. 1 should satisfy

$$\frac{n_2}{n_o} \leq \sin i_2 \leq \frac{n_2}{n_e}. \quad (1)$$

The minimum i_2 is just corresponding to the maximum i_1, which is determined by

$$n_1 \sin(i_1)_{\max} = (n_o^2 - n_2^2)^{1/2} \cos\theta - n_2 \sin\theta. \quad (2)$$

As for light beam B, there are two different cases.

Firstly, if $n_2 \geq n_e$, total internal reflection cannot occur for e-ray. When the refractive e-ray is parallel to the cutting surface, i_1' is the limited angle. So we have

$$\frac{\sin(i_1')_{\max}}{\sin\theta} = \frac{n_e}{n_1}. \quad (3)$$

Let $(i_1)_{\max} = (i_1')_{\max}$, from Eqs. (2) and (3), we obtain

$$\tan\theta = \frac{(n_o^2 - n_2^2)^{1/2}}{n_e + n_2}. \quad (4)$$

Secondly, if $n_2 < n_e$, e-ray also has a critical angle, the maximum of i'_1 is then given by

$$n_1 \sin(i'_1)_{\max} = n_2 \sin\theta - (n_e^2 - n_2^2)^{1/2} \cos\theta. \quad (5)$$

Let $(i_1)_{\max} = (i'_1)_{\max}$, from Eqs. (2) and (5), we obtain

$$\tan\theta = \frac{(n_o^2 - n_2^2)^{1/2} + (n_e^2 - n_2^2)^{1/2}}{2n_2}. \quad (6)$$

Equations (4) and (6) are the relation between the structure angle and the refractive index of optical cement when the field angle of the prism gets its maximum value. From Eq. (2), $\sin(i_1)_{\max}$ decreases with the increment of n_2. When $\sin(i_1)_{\max}$ equals to zero, we have

$$(n_2)_{\max} = n_o \cos\theta. \quad (7)$$

Using Eqs. (4), (6), and (7), we can obtain the relation between structure angle θ and refractive index n_2, as shown in Fig. 2. From the curves A and B in Fig. 2, it can be seen that the smaller the refractive index of cement is, the larger the structure angle of the prism is, and the smaller the length-width ratio L/A is. So, material can be saved with the smaller refractive index of cement for reaching the same field angle.

So far, we have discussed the effect of n_2 on the structure angle under the condition of the maximum field angle. In this case, L/A is much larger (e.g., if $n_2 = 1.54$, $L/A = 4$). So, bigger Iceland crystal is necessary in the fabrication of prisms with the same aperture. This will increase the cost. When we design prisms, 3 or 2.5 is often taken as the value of L/A. In the following, we take the two special designs as examples to analyze how the index affects the field angle.

Let $L/A = 3$ and 2.5, then, $\theta = 18.5°$ and $22.5°$, respectively. With the light beam wavelength λ is 589 nm, taking $n_1 = 1$, $n_o = 1.65835$, and $n_e = 1.48640$, the relationship between the field angle and n_2 can be obtained using Eqs. (2) and (3), as shown in Fig. 3. From Fig. 3, the following conclusions can be drawn. 1) The field angles will firstly increase and then decrease with the increment of n_2 in both situations. 2) For the prism with the L/A value of 3, the range of n_2 is 1.40—1.59; while for the prism with the L/A value of 2.5, the range of n_2 is 1.38—1.54. 3) As for the field angle of Glan-Thompson prism, if $L/A = 3$, the prism has the optimal field angle of 29.55° with the n_2 value of 1.470; if $L/A = 2.5$, the optimal field angle is 24.18° with the n_2 value of 1.450.

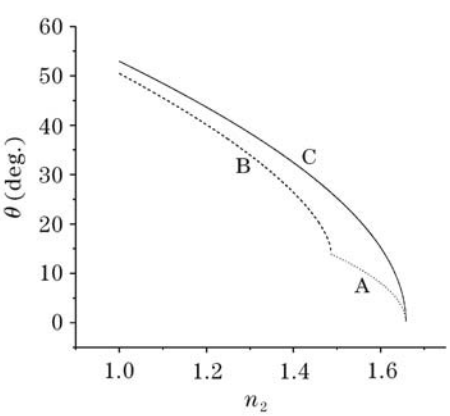

Fig. 2. Structure angle θ of the Glan-Thompson prism versus refractive index n_2 of the cement. Curves A, B, and C are calculated from Eqs. (4), (6), and (7), respectively.

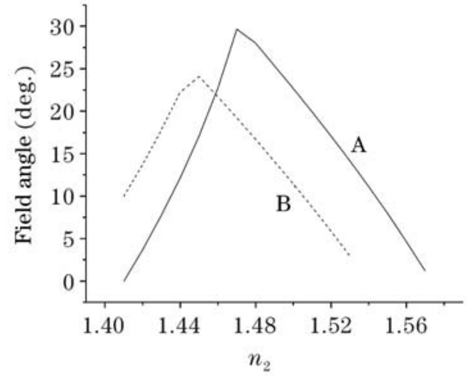

Fig. 3. Field angle versus refractive index of cement for two routine designs of Glan-Thompson prism. A, $L/A = 3$; B, $L/A = 2.5$.

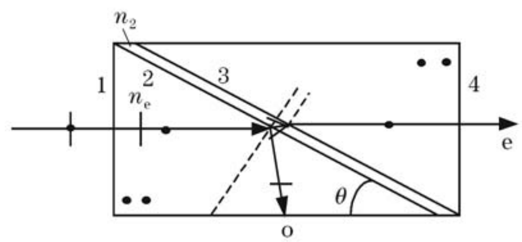

Fig. 4. Beam path of Glan-Thompson prism in the case of normal incidence.

Transmission is also an important parameter of polarization prism[7,8]. Now we analyze how the refractive index of optical cement affects the transmission in the case of normal incidence. Because the value of n_2 is similar to that of n_e, the multi-beam interferometry on the surface of optical cement could be neglected, therefore, the depth of the cement should not be taken into accout. The beam path in Glan-Thompson prism is illustrated in Fig. 4, where 1 and 4 stand for incidence side surface and exit surface, 2 and 3 for cement surfaces. According to the refraction law and Fresnel equation[9], the reflectivities on each surface are given by

$$R_1 = R_4 = \frac{(n_e - 1)^2}{(1 + n_e)^2}, \quad (8)$$

$$R_2 = R_3 = \frac{\sin^2(90° - \theta - \theta_1)}{\sin^2(90° - \theta + \theta_1)} = \frac{\cos^2(\theta + \theta_1)}{\cos^2(\theta - \theta_1)}, \quad (9)$$

where θ_1 is the refractive angle in cementing layer. The relation between θ_1 and θ is

$$n_e \cos\theta = n_2 \sin\theta_1, \quad (10)$$

Thus, the total transmission of e-ray is

$$T = (1 - R_1)^2 (1 - R_2)^2 = \frac{16 n_e^2 \sin^2 2\theta \sin^2 2\theta_1}{(1 + n_e)^4 \cos^4(\theta - \theta_1)}. \quad (11)$$

Substituting Eq. (10) into Eq. (11), we have

$$T=\frac{16n_e^2}{(1+n_e)^4}\sec^4\left(\theta-\arcsin\frac{n_e\cos\theta}{n_2}\right)\times\sin^2 2\theta\cdot\sin^2\left(2\arcsin\frac{n_e\cos\theta}{n_2}\right). \tag{12}$$

Taking the two routine designs ($L/A=3$ and 2.5) as examples, the curve of transmitance T versus n_2 can be drawn with the n_e value of 1.48640, as shown in Fig. 5. From the curve, the following conclusions can be obtained. 1) The two designs both reach the maximum transmission ($T=0.925$) when n_2 equals n_e. 2) When the ranges of n_2 are 1.454—1.552 ($L/A=3$) and 1.440—1.599 ($L/A=2.5$), the transmitances are larger than 90%. 3) Taking field angle into consideration, it is a better choice with the cement whose refractive index range is 1.47—1.49 for $L/A=3$ or 1.45—1.46 for $L/A=2.5$.

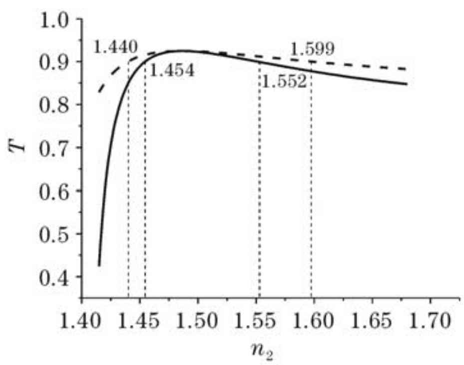

Fig. 5. Transmittance T of Glan-Thompson prism versus n_2 with fixed structure angle. Solid curve: $\tan\theta=1/3$; dashed curve: $\tan\theta=2/5$.

In conclusion, the refractive index of optical cement has obvious influence on structure angle, field angle, and transmission of Glan-Thompson prisms. When optical cements are chosen, the refractive index is also a key factor besides the range of transmitted spectrum, shearing strength, and so on. It is much better to use the optical cement whose refractive index ranges from 1.45 to 1.46 adopting the design with the L/A value of 2.5. In this way, we can not only get the prism with transmission greater than 90% and field angle greater than 20°, but also save much expensive calcite.

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