Suppressing the disturbance in the transmission spectrum of Glan-Thompson-type prism polarizers

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We analyze the random disturbance in the transmission of light through a spinning Glan-Thompson-type prism polarizer. The disturbance makes the dependence of the transmission on the rotation angle significantly deviates from the Malus cosine-squared law and severely spoils the output light quality. Slight vibration of the polarizer as it rotates combing the multi-beam-interference effect raises the disturbance. Further analysis reveals the sensitive dependence of the disturbance on the composing material of the prism gap, and the appropriate selection of such material can make the disturbance minimize to very desirable levels. The model results show quite good agreement with experiments.

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As one important individual optical component, the prism polarizer has been widely used in modern optical experiments and technological applications[1,2]. Among different designs of the prisms, the Glan-Thompson-type is a superior one due to its high transmission over most spectral region from the near infrared to the near ultraviolet, its large extinction ratio, and the widest field angle of all designs. In some cases, the polarizer is often needed to rotate along the light path to generate linearly polarized light with continuously tunable transmissions, such as polarimetric imaging, achromatic phase shifting, and ellipsometer, etc.[3−8] Under such circumstances, the light transmission is subjected to obey the Malus cosine-squared law, leading to a smooth transmission curve. But in practice random disturbances often arise in the transmission curves[9,10], which spoils the output-light quality thereby lowers the measurement accuracy when the prism is used in optical devices. In this letter, we experimentally and theoretically study the disturbances for the Glan-Thompson-type prism polarizers with different gaps. Our study reveals the critical role of the gap in determining the magnitude of the disturbance, and that by choosing an appropriate gap the disturbances can be minimized to be nearly negligible. The numerical results show good agreement with the measured ones.

A 650-nm light beam from a laser diode was used as the light source. It was firstly turned into linearly polarized by a normal polarizer and then normally incident on the front surface of the spinning Glan-Thompson-type prism polarizer that was driven by a step motor. The polarizer comprises two prisms that are combined together either by an air-space or by some cement (the gap), and the former is also called a Glan-Foucault prism. The gap thickness of the Glan-Thompson-type prism used here is 0.02 mm. We found that for a Glan-Foucault prism, the transmission curves strongly deviate from the Malus cosine-squared law, with some random disturbances arising (Fig. 1(a)). It can be seen that the disturbances are higher at positions where the ideal transmissions are greater. Surprisingly, when the air-spaced Glan-Thompson-type prism was substituted by a cemented Glan-Thompson-type prism with the gap refractive index of 1.54, we found that the disturbance almost disappeared (Fig. 1(b)). Further measurements suggest that such a huge contrast in the disturbance for such two prisms always exists when we change the incident light wavelength. We shall investigate it theoretically below to find out the physical mechanism behind it so as to find the optimal method for reducing the disturbance.

Figure 2 depicts the Glan-Thompson-type prism. Its entrance and exit surfaces are parallel. Solid dots indicate the optical axis of each constituent prism that is made of calcite, which is a negative uniaxial birefringent material. The linearly polarized incident beam will be broken up into orthogonally polarized components in the prism, known as the ordinary and extraordinary waves, with the former totally internally reflected at the gap, while the latter transmitted through.

As the Glan-Thompson-type prism rotates driven by the step motor, it will unavoidably sustain slight stochastic vibrations, with the deviation angle denoted as δ in

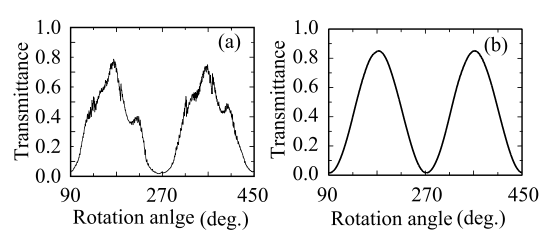

Fig. 1. Measured transmission versus the rotation angle for spinning (a) air-spaced and (b) cemented Glan-Thompson-type (with the gap refractive index n_G=1.54) prisms for 650-nm linearly polarized light. The thickness of each prism gap h is 0.02 mm.

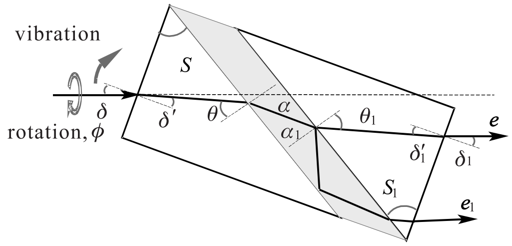

Fig. 2. Schematic diagram showing the passage of a beam of light transmitted through a spinning Glan-Thompson-type prism. δ is the vibration angle of the prism, and it together with the gap between constituent prisms are exaggerated for clarity.

Fig. 2. As a result, the incident angle of the extraordinary wave at the gap becomes $\theta=\theta_0-\delta'$, where θ_0 is the original incident angle without vibrations, equal to the cut angle S of the prism, and δ' is the refractive angle at the entrance surface of the polarizer induced by vibrations. $-\delta'$ will be denoted by $\Delta\theta$ below. The beam incident on the gap will be multiply reflected within the gap before transmitted through. All outgoing rays stemming from the same beam will interfere, and the relative interference intensity can be obtained by Airy's formulae[11]:

$$F(\theta)=\frac{\left[1-\frac{\sin^2(\theta-\alpha)}{\sin^2(\theta+\alpha)}\right]^2}{\left[1+\frac{\sin^4(\theta-\alpha)}{\sin^4(\theta+\alpha)}-2\frac{\sin^2(\theta-\alpha)}{\sin^2(\theta+\alpha)}\cos\frac{4\pi h n_{\mathrm{G}}\cos\alpha}{\lambda}\right]}, \quad (1)$$

where λ is the wavelength in vacuum, and α is the refractive angle at the gap, it is related to the incident angle via Snell's law:

$$n_{\mathrm{e}}\sin\theta=n_{\mathrm{G}}\sin\alpha, \quad (2)$$

where n_{e} is the refractive index of calcite for the extraordinary wave. Thus the final light intensity from the Glan-Thompson-type prism can be obtained as

$$I=I_0\cos^2\phi\cdot F(\theta). \quad (3)$$

Notice that the intensity transmission coefficient at the entrance or exit surface of the polarizer is regarded as constant, since the varying incident angle δ is small enough, generally within 0.05°. Additionally, the light absorptions in the constituent prisms as well as in the gap are neglected[12].

The last term in Eq. (3), $F(\theta)$, will not retain a constant when there are vibrations for the Glan-Thompson-type prism, and we call it the disturbance factor below. In Fig. 3(a), we plot $F(\theta)$ numerically for a Glan-Foucault prism with the gap thickness of 0.02 mm and the wavelength in vacuum of 650 nm by substituting these parameters into Eq. (1). To ensure the rejection of the ordinary wave and the transmission of the extraordinary wave, we can achieve the allowable range for the incident angle θ, $37.2° < \theta < 40°$. We can see that $F(\theta)$ is a strongly and quickly oscillatory function of θ, hence a minor change of θ caused by the prism vibration will cause a big change in $F(\theta)$, thus the corresponding transmission will be significantly changed. This is the origin of the transmission disturbance. Quite differently, for a cemented (n_{G}= 1.54)

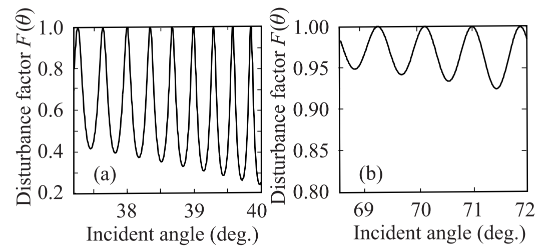

Fig. 3. Numerical disturbance factor as a function of the incident angle θ at the gap for the (a) air-spaced and (b) cemented (n_{G}=1.54) Glan-Thompson-type prisms, with h=0.02 mm and λ=650 nm.

Glan-Thompson-type prism, whose $F(\theta)$ curve is much flatter (Fig. 3(b)), hence under the same vibration and the same corresponding variation of $\Delta\theta$, its ΔF is much lower than that in the air-spaced Glan-Thompson-type prism. As a result, it will have much weaker disturbances in the transmission curve.

Figure 4 displays the numerical curves of transmission versus rotation angle for the air-spaced and cemented (n_{G}=1.54) Glan-Thompson-type prisms by use of Eqs. (1) and (3). We have applied the random number generator in MATLAB to simulate the stochastic variations of θ, with its amplitude chosen as 0.05°. The wavelength is assumed to be 650 nm, and the gap thickness is 0.02 mm. The cut angle S is 38.07° for the air-spaced prism, and 69.5° for the cemented prism, each of which is located halfway between one maximum point and its neighboring minimum point on respective $F(\theta)$ curve, and the prisms with such cut angles will display the strongest disturbances. The model curves resemble those measured ones as shown in Figs. 1(a) and (b) either for the air-spaced or for the cemented prisms, and the magnitude of the disturbance for the former is very large, while the latter is almost negligible. In addition, the higher the transmisison on each curve, the stronger the disturbance is. For the cemented prism, the numerical value of maximum transmission is around 0.95, a little greater than the measured value of 0.85, such a difference is due to the neglection of light absorption in the constituent prisms and in the gap. For the air-spaced prism, the numerical value of maximum transmission is around 0.74, nearly equal to the measured value of 0.76, and this much smaller difference in maximum transmission implies that the light absorption in calcite is much lower than in the cement, which is Canada balsam in this case. Fit of the experimental transmission curve shows that the maximum relative disturbance for the air-spaced prism reaches around

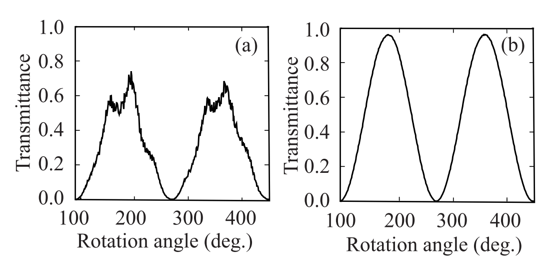

Fig. 4. Numerical transmission versus the rotation angle for the (a) air-spaced and (b) cemented (n_{G}=1.54) Glan-Thompson-type prisms, with h=0.02 mm and λ=650 nm. The cut angle is 38.07° for the former and 69.5° for the latter.

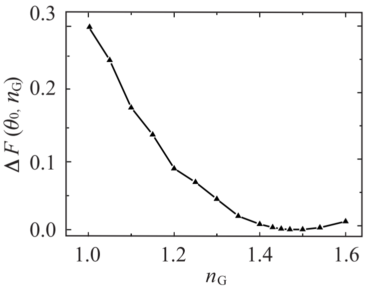

Fig. 5. Difference in disturbance factor $\Delta F(\theta_0,\ n_{\rm G})$ between a maximum point θ_0 and a corresponding nearby point θ_0+ $0.05°$ as a function of $n_{\rm G}$.

0.187, whereas it is only 0.0030 for the cemented prism and is nearly two orders of magnitude lower than that for the air-spaced prism. The numerical results are obtained as 0.208 and 0.0044 for air-spaced and cemented prisms, respectively, showing good quantitative agreement with experiments.

To reveal the specific and quantitative dependence of the magnitude of the disturbance on the refractive index of the gap, we evaluated a quantity which measures the magnitude of the disturbance:

$$\Delta F(\theta_0, n_{\rm G}) = F\left(\theta_0 + \Delta\theta, n_{\rm G}\right) - F(\theta_0, n_{\rm G}), \qquad (4)$$

where θ_0 corresponds to a maximum point on the $F(\theta,$ $n_{\rm G})$ curve and it has different values for different n_G. $\Delta\theta$ is taken as a constant value of $0.05°$. Figure 5 plots $\Delta F(\theta_0,\ n_{\rm G})$ versus $n_{\rm G}$. From this curve we conclude that the magnitude of the disturbance quickly decreases firstly as the refractive index of the gap increases between $\sim$1 and $\sim$1.4; then it decreases slowly and reaches a minimum at 1.4844; from that point on it shows slow increases with increasing refractive index. Hence to maximally suppress the disturbance in the transmission, one had better design a Glan-Thompson-type prism with its refractive index of the gap located between $\sim$1.4 and $\sim$1.6.

In conclusion, we study the random disturbances that arise in the transmission in air-spaced and cemented Glan-Thompson-type prisms. The vibrations of the prism generated due to its rotation and the effect of the multi-beam-interference together induce the random disturbances. The analysis reveals the strong dependence of the magnitude of the disturbance on the prism gap, and indicates an efficient method for minimizing the disturbance. Our results are important guidance for the design and the applications of Glan-Thompson-type prisms.

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References

1. T. Wang, S. Lan, J. Jiang, and T. Liu, Chin. Opt. Lett. **6,** 812 (2008).
2. Q. Gong, C. Fan, F. Zhang, and J. Yao, Chin. Opt. Lett. **6,** 905 (2008).
3. J. Q. Peterson, G. L. Jensen, J. A. Kristl, and J. A. Shaw, Proc. SPIE **4133,** 292 (2000).
4. D. E. Aspnes, J. Opt. Soc. Am. A **21,** 403 (2004).
5. Y. Watanabe, Y. Hayasaka, M. Sato, and N. Tanno, Appl. Opt. **44,** 1387 (2005).
6. W.-C. Huang, M.-S. Tsai, C.-R. Wang, I.-M. Jiang, and W.-H. Cheng, Appl. Opt. **46,** 3493 (2007).
7. M. Gilliot, A. E. Naciri, L. Johann, J. P. Stoquert, J. J. Grob, and D. Muller, J. Appl. Phys. **101,** 014319 (2007).
8. Y. Kraftmakher, Eur. J. Phys. **30,** 271 (2009).
9. H. Zhu, L. Song, J. Chen, H. Gao, R. Li, and Z. Xu, Opt. Commun. **245,** 1 (2005).
10. J. Y. Fan, H. X. Li, and F. Q. Wu, Opt. Commun. **281,** 197 (2008).
11. G. R. Fowles, *Introduction to Modern Optics* (Dover Publications, New York, 1989).
12. R. Appel, C. D. Dyer, and J. N. Lockwood, Appl. Opt. **41,** 2470 (2002).