

Optical filter based on internal reflection and optical rotatory dispersion of NaBrO₃ crystal

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Based on the optical rotatory dispersion and zero reflection of the p-polarization light at the Brewster angle, a novel optical filter that employs only one NaBrO₃ crystal and one polarizer are proposed and demonstrated. Performance of the optical filter is studied both theoretically and experimentally. Results show that the green light becomes nearly extinct when the angles of the polarizer are set at 80° and 260°, whereas the red light becomes nearly extinct when the angles of the polarizer are set at 116° and 296°. Isolation of more than 8 dB can be achieved. The measured extinction ratios are 12.3 and 12.6 dB for green and red lights, respectively.

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As a wavelength selector, optical filters are used to select a certain narrow band or line(s) of spectrum from a broad band of spectrum^[1]. In optical communication and optical sensing, optical filters play important roles in wavelength division multiplexing^[2,3]. Optical filters are also very useful in some other areas such as solar physics^[4], laser, radar, and so on. Optical filters are widely used as the Lyot filters, atomic resonance filters^[5], Faraday anomalous dispersion optical filters^[6], Fabry-Perot filters, fiber Bragg grating filters^[7], Mach-Zehnder interferometers, acousto-optic tunable filters^[8], and compact optical filters, such as those based on photonic crystal^[9].

In 2003, Ye reported a wavelength-tunable optical filter^[10] based mainly on the optical rotatory dispersion effect of quartz crystal. However, quartz crystals are anisotropic. As a result, the optical rotation only occurs along the direction of the optical axis of quartz crystal, which limits the application of the optical filter. In contrast, the optical rotation resulting from chiral media of electromagnetic waves, such as sodium bromate crystal has attracted a lot of interest recently^[11–14]. However, few studies on sodium bromate based devices such as optical filter have been reported. In this letter, we report a very large sodium bromate crystal successfully grown from a water solution. A new optical filter based on the obtained isotropic crystal (i.e., sodium bromate) is designed and fabricated. The optical filter is based on the rotatory dispersion effect and the zero reflectivity of the p-polarization at the Brewster angle. The optical properties of the optical filter are studied.

Figure 1 shows a picture of a sodium bromate crystal grown from a water solution. The length of the crystal is approximately 3.86 cm. To the best of our knowledge, this is the largest value reported to date on sodium bromate crystal. Notably, a large sodium bromate crystal is essential in fabricating optical devices such as optical

filter.

Figures 2 and 3 show the diagrams of the design of the optical filter based on sodium bromate crystal.

As shown in Figs. 2 and 3, a beam incident passes through Interface 1 at the angle i_1 . The illustration of light vector decomposition on Interfaces 1 and 2 is shown in Fig. 3. The polarization intensity after the polarizer is set is $\vec{A} = A_0$. The polarization is rotated by θ (counterclockwise) from the initial polarization direction of the incident light, which is horizontal. The vector \vec{A} can be decomposed into $\vec{a} = A_0 \cos(-\theta)\vec{i}$ along the X direction

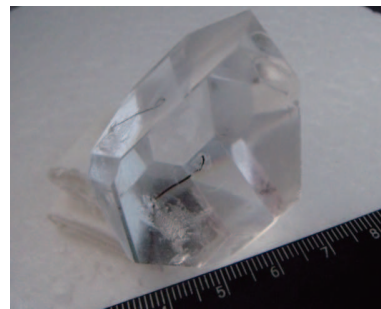


Fig. 1. Photo of sodium bromate crystal.

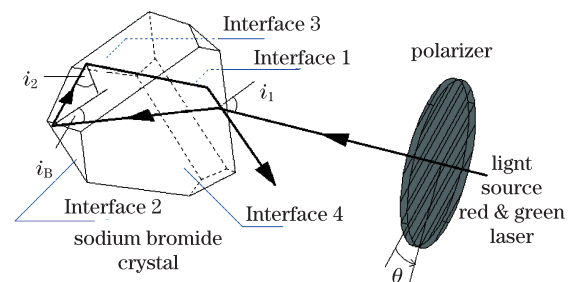


Fig. 2. Schematics of the optical filter.

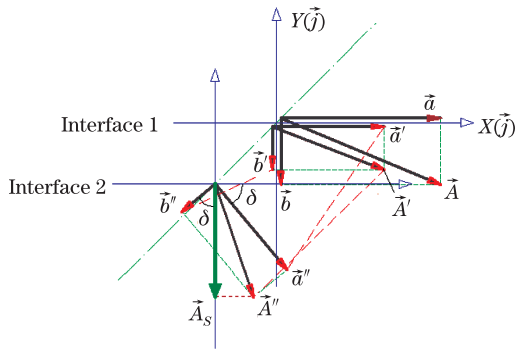


Fig. 3. Illustration of light vector decomposition.

and $\vec{b} = A_0 \sin(-\theta) \vec{j}$ along the Y direction. According to the Fresnel formula, after transmission through Interface 1, the two components of the light along the X , Y directions change into $\vec{a}' = A_0 t_P \cos(-\theta) \vec{i}$ and $\vec{b}' = A_0 t_S \sin(-\theta) \vec{j}$, respectively, whereas t_P , t_S represent the transmissivities of the light along the X , Y directions. Due to the optical rotatory effect of the chiral crystal, the polarization orientation of linearly polarized light will rotate by an angle δ after propagating a distance l in the crystal:

$$\delta = \alpha(\lambda) \times l, \quad (1)$$

where α is the specific rotation of the crystal, which depends on wavelength.

The electric field of linear polarized light is rotated by an angle of δ when it arrives at Interface 2. As a result, after rotating an angle of δ , the vectors \vec{a}' and \vec{b}' turn into \vec{a}'' and \vec{b}'' . Their s-polarization and p-polarization components (i.e., the electric field along Y and X directions) are given by

$$\vec{A}_S = [A_0 t_P \cos(-\theta) \sin(-\delta) + A_0 t_S \sin(-\theta) \cos(-\delta)] \vec{j}, \quad (2)$$

$$\vec{A}_P = [A_0 t_P \cos(-\theta) \cos(-\delta) + A_0 t_S \sin(-\theta) \cos(-\delta)] \vec{i}. \quad (3)$$

If the internal reflection angle agrees with the Brewster angle, the reflectivity of the p-polarization component is zero, implying that the polarization in X direction cannot be reflected. In contrast, based on the crystal structure, the light will be fully reflected at Interfaces 3 and 1 successively, after which it is refracted at Interface 4. Therefore, the output light intensity depends on the reflected light at Interface 2, which is given by

$$I \propto |\vec{A}_S|^2. \quad (4)$$

From Eqs. (1), (3), and (4), we can obtain Eq. (5), which represents relative intensity of the output beam:

$$I_\lambda = r_S'^2 (t_{P(\lambda)} \cos \theta \sin \delta_\lambda + t_{S(\lambda)} \sin \theta \cos \delta_\lambda)^2. \quad (5)$$

In our experiments, red light ($\lambda=632.8$ nm) from He-Ne laser was mixed together with green light ($\lambda=532$ nm) from a diode pumped solid-state laser. The refractive index of sodium bromate crystal is 1.611 at $\lambda=694.3$ nm and 1.661 at $\lambda=374.15$ nm^[12,15]. Taking these data into

the Cauchy's formula^[16], we obtained refractive index of sodium bromate crystal 1.614 at $\lambda=632.8$ nm and 1.623 at $\lambda=532$ nm. Therefore, the Brewster angle is 31.8° for the red laser and 31.6° for the green laser, respectively. To make the reflected angles of two coaxial beams from red and green laser closer to the Brewster angles at the Interface 2, the incident angle i_1 was set as 58.3° based on the average of the refractive indices of the green and red lights.

As shown in Fig. 4, because the green laser is partially polarized light, in order to maintain the uniformity of the intensity of input light when the polarizer is rotated, the polarization of the two beams was changed into circular polarization using a Glan prism and a Fresnel rhomb. A fiber optic spectrometer was employed to receive the light from the crystal, and the detected signal was sent to a computer. Polarizer data were recorded at 5° rotations, as show in Figs. 5 and 6.

According to the measurements, the specific rotations of sodium bromate crystal were 2.98° and 1.81° per millimeter for the green (532 nm) and red (632.8 nm) lights, respectively. The optical paths were 33.9 and 34.0 mm for the green and red lights, respectively. According to the Eq. (5), we can obtain

$$I_{\text{green}} = r_S'^2 [t_{P(532 \text{ nm})} \cos \theta \sin \delta_{532 \text{ nm}} + t_{S(532 \text{ nm})} \sin \theta \cos \delta_{532 \text{ nm}}]^2, \quad (6)$$

$$I_{\text{red}} = r_S'^2 [t_{P(632.8 \text{ nm})} \cos \theta \sin \delta_{632.8 \text{ nm}} + t_{S(632.8 \text{ nm})} \sin \theta \cos \delta_{632.8 \text{ nm}}]^2, \quad (7)$$

which represent relative intensity of the output beam for green and red light, respectively.

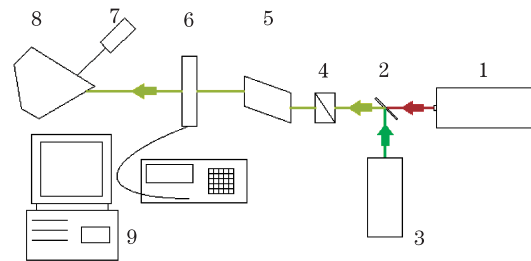


Fig. 4. Schematics of experimental apparatus: 1: He-Ne laser; 2: spectroscop; 3: diode pumped solid state laser (532nm); 4: glan prism; 5: Fresnel rhomb; 6: polarizer; 7: fiber spectrometer; 8: sodium bromate crystal; 9: computer.

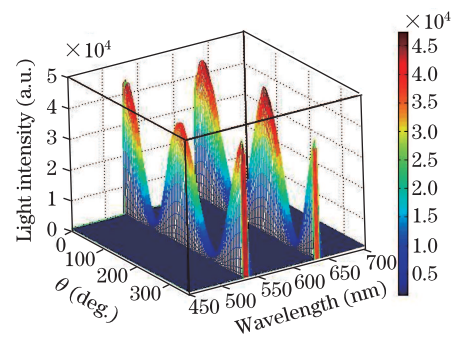


Fig. 5. Three-dimensional diagram of the output spectrum at different angles of the polarizer.

According to Eqs. (6) and (7), the output beam intensity of the green light from the crystal is zero when the angles of the polarizer are 80° and 260° . For the red light, the angles are 116° and 296° . These measured angles agree well with the theoretical ones, (i.e. 80° , 115° , 260° , and 295°), as shown in Fig. 6.

Figure 7 shows the normalized curves of output beam intensity as a function of the angle of the polarizer. The dashed and solid lines represent the theoretical results for green and red light, respectively. These results were obtained from Eqs. (6) and (7), in which the triangles and diamonds represent the measured data for green and red lights. As shown in Fig. 7, the experimental data agree very well with the theoretical simulations over the entire measurement range. Using

$$N_{\text{green(red)}} = 10 \lg \frac{P_{\text{out,green(red)}}}{P_{\text{out,red(green)}}}, \quad (8)$$

the isolation at different θ angles is shown in Fig. 8.

As shown in Fig. 8, maximum isolation is more than 8 dB. In our experiments, the intensities of the green and red lights were regarded as double-channel binary-value signals. Therefore, the extinction ratio can be calculated using

$$\alpha_{\text{ER}} = 10 \lg \frac{P_{\text{MAX}}}{P_{\text{MIN}}}, \quad (9)$$

which gives us values of 12.3 and 12.6 dB for the green and red lights, respectively.

In conclusion, a new tunable optical filter based on the sodium bromate crystal is designed and demonstrated. Unlike the traditional optical rotatory crystal based optical filter that requires two polarizers, only one polarizer is needed in the proposed optical filter due to the employment of the isotropy property and the rotatory dispersion effect of sodium bromate crystal, together with the zero reflection of the p-polarized light at the

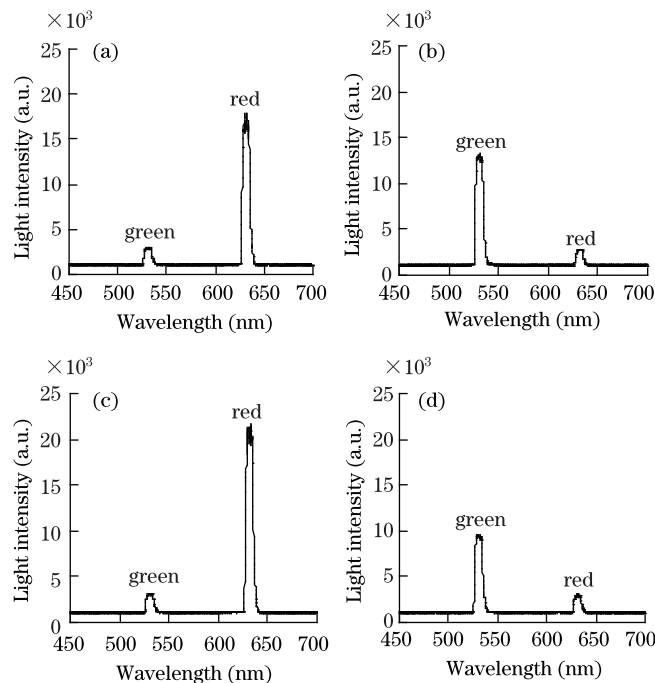


Fig. 6. Experimental emerged spectrum when the angle of the polarizer is (a) 80° ; (b) 115° ; (c) 260° ; (d) 295° .

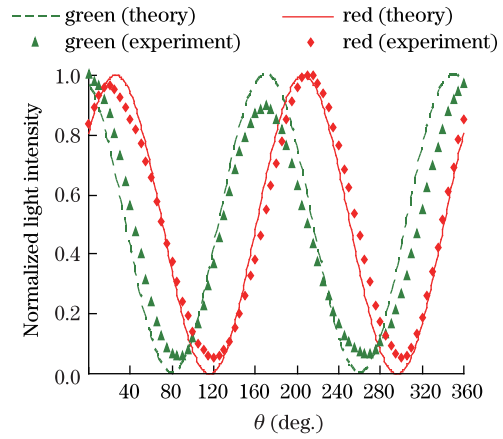


Fig. 7. Normalized light intensity changes with the rotation angle of the polarizer.

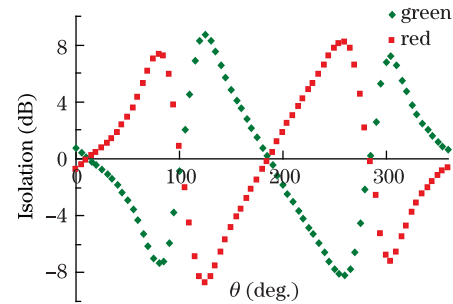


Fig. 8. Isolation of the red and green emergent lights at different angles of the polarizer.

Brewster angle. Both the experimental and theoretical results show that high performance can be achieved using the proposed of the optical filter. Isolation of more than 8 dB is achieved. Extinction ratios of 12.3 and 12.6 dB are obtained for the green and red lights, respectively. The performance of the optical filter can further be enhanced by improving quality polarizer, polishing surfaces of the crystal, and the antireflection coating used in our experiments.

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