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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 is 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 290°. 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 bromated 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

Figure 2 shows 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 i₁. 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 A = A₀. The polarization is rotated by θ (counterclockwise) from the initial polarization direction of the incident light, which is horizontal. The vector A can be decomposed into a = A₀cos(−θ)i along the X direction.

Fig. 1. Photo of sodium bromate crystal.

Fig. 2. Schematics of the optical filter.
From Eqs. (1), (3), and (4), we can obtain Eq. (5), which represents relative intensity of the output beam:

$$I_\lambda = r_S^2 (t_{p(\lambda)} \cos \theta \sin \delta + t_{s(\lambda)} \sin \theta \cos \delta \lambda)^2.$$  (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 $\theta_1$ 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

$$I_{\text{green}} = r_S^2 (t_{p(532 \text{ nm})} \cos \theta \sin \delta_{532 \text{ nm}} + t_{s(532 \text{ nm})} \sin \theta \cos \delta_{532 \text{ nm}})^2,$$  (6)

$$I_{\text{red}} = r_S^2 (t_{p(632.8 \text{ nm})} \cos \theta \sin \delta_{632.8 \text{ nm}} + t_{s(632.8 \text{ nm})} \sin \theta \cos \delta_{632.8 \text{ nm}})^2,$$  (7)

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

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 $80^\circ$ and $260^\circ$. For the red light, the angles are $116^\circ$ and $296^\circ$. These measured angles agree well with the theoretical ones, (i.e. $80^\circ$, $115^\circ$, $260^\circ$, and $295^\circ$), 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

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

the isolation at different $\theta$ 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

$$\alpha_{\text{ER}} = 10 \log \frac{P_{\text{MAX}}}{P_{\text{MIN}}},$$

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 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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References