Quartz optical filter for wavelength selection of frequency-doubled laser based on optical rotatory dispersion effect

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Based on the optical rotatory dispersion effect, an optical filter for selecting the second harmonic of a frequency-doubled laser is constructed from quartz in combination with polarizers. The operating principle is analyzed by matrix formulation, and the result indicates that the second harmonic of a frequency-doubled laser will be obtained when the rotation angle has a difference of $(2n+1)\pi/2$ $(n=0,1,2,3,\cdots)$ between the two polarizations of the second-harmonic laser and the fundamental laser. The spectrum of the output laser is taken by the AQ-6315A spectrometer, and the experimental results are in good agreement with the theoretical results.

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Filter is a wavelength selector, which is used to select a certain spectral band from a continuous spectrum or spectral line from some line-spectra. Recently, the research on filter has attracted an increasing interest and developed quickly. The filters' principles and their performances are different, such as birefringent filters[1] and polarization interference filters[2] which are based on the dispersion effect of the optical retardation, and Faraday atomic dispersion optical filter[3] which is based on the Faraday dispersion effect. An extended range of them has widely been used in astronomical research, solar physics[2,4,5], and imaging equipments[2,5−7].

The nonlinear optical frequency conversion technology, which is used to obtain the different lasers, is the most important branch in the laser and nonlinear optical field[8]. In particular, the frequency-doubled lasers have found many applications in atmospheric sounding, microelectronics, photochemistry, and photobiology. However, many papers about the frequency-doubled lasers reported that there is the fundamental laser in the beam, which is mainly determined by the conversion efficiency of nonlinear crystal[9−11]. So, the coated filter and Brewster prism are commonly used to select the frequency-doubled laser[12,13].

It is well known that the plane of linearly polarized light will be rotated when it passes through the quartz along the optical axis of the crystal. The relationship between the rotation angle and the thickness of quartz can be expressed as[14]

$$\theta = \alpha \cdot d, \qquad (1)$$

where d is the thickness of the quartz in the direction of optical axis, α is the specific rotation. The magnitude of α is related to some factors such as wavelength and temperature[15], and the unit of α is degree/mm. Under room temperature, α is described as[16]

$$\alpha = \frac{9.5639}{\lambda^2 - 0.0127493} - \frac{2.3113}{\lambda^2 - 0.000974} - 0.1905, \qquad (2)$$

where λ is the wavelength of the incident light in μm. So when the linearly polarized lights with different wavelengths pass through the same quartz, the rotation angles are different. This phenomenon is known as the optical rotatory dispersion effect. Thus the designed quartz can make a difference of $(2n+1)\pi/2$ $(n=0,1,2,3,\cdots)$ in rotation angle for different wavelengths, and then the monochromatic light can be obtained by a polarizer.

As recently reported, a new type of wavelength-tunable spectral filter can be constructed based on the optical rotatory dispersion effect[17]. The basic arrangement for such a filter consists of a set of dispersive polarization rotators sandwiched by linear polarizers (see Fig. 1 in Ref. [17]). But the structure and operation of this spectral filter are particularly complicated. In this paper, an optical filter for selecting the wavelength of a frequency-doubled laser is constructed from a few quartz plates in combination with polarizers. We analyze its operating principle by the Muller matrix and prove that the output laser is frequency-doubled laser when the beam generated by the nonlinear crystal enters this filter.

Take the quartz optical filter for the second-harmonic laser for example. The structure of the combination device, the light path, and the coordinates are shown in Fig. 1, where the x and y axes are located at the horizontal and vertical directions, respectively, the z axis is located at the direction of light propagation. The transmission axis of polarizer P_1 is parallel to the x axis. The angle between the transmission axis of P_2 and x axis is

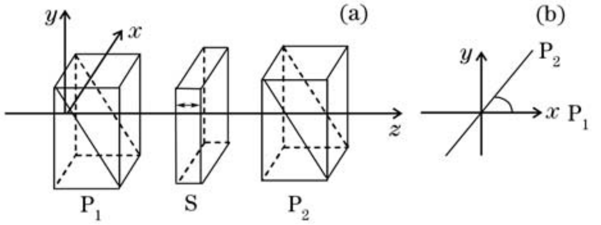

Fig. 1. (a) Light path and (b) coordinates of the quartz optical filter composed of two polarizes P_1, P_2, and one quartz crystal S.

β. In this case, the sign of angle is defined as follows: observing against the direction of light propagation, the angle formed by the x axis counter-clockwise rotation is positive; the angle formed by x axis clockwise rotation is negative. The quartz S, whose optical axis is parallel to the z axis, is put in the interspace between polarizers P_1 and P_2, and the thickness along the optical axis is d.

For generalization, the Stokes parameter of the incident light is[18]

$$S_{\text{in}} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}. \tag{3}$$

The Muller matrices of polarizers P_1, P_2, and quartz crystal S are given as

$$M_{\mathrm{P}_1} = \frac{1}{2}\begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \tag{4}$$

$$M_{\mathrm{P}_2} = \frac{1}{2}\begin{bmatrix} 1 & c_2 & s_2 & 0 \\ c_2 & c_2^2 & c_2 s_2 & 0 \\ s_2 & c_2 s_2 & s_2^2 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \tag{5}$$

$$M_{\mathrm{S}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\theta & \sin 2\theta & 0 \\ 0 & -\sin 2\theta & \cos 2\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{6}$$

where $c_2 = \cos 2\beta$, $s_2 = \sin 2\beta$, and $\theta = \alpha \cdot d$.

So the Stokes parameter of the output light is

$$S_{\text{out}} = M_{\mathrm{P}_2} M_{\mathrm{S}} M_{\mathrm{P}_1} S_{\text{in}} = \frac{\cos^2(\beta+\theta)}{2}\begin{bmatrix} 1 \\ \cos 2\beta \\ \sin 2\beta \\ 0 \end{bmatrix}. \tag{7}$$

This shows that the output light is a linearly polarized light and the angle between the light vector's vibration direction and the x axis is β, and the intensity is $\frac{\cos^2(\beta+\theta)}{2}$.

As Zhou *et al.* reported, the beam generated by KTP crystal is composed of 532-nm green laser and 1064-nm fundamental laser[9]. Thus, the intensities I_1 and I_2 of the output fundamental laser and the second-harmonic laser respectively can be expressed as

$$I_1 = \frac{\cos^2(\beta+\theta_1)}{2}, \tag{8}$$

$$I_2 = \frac{\cos^2(\beta+\theta_2)}{2}, \tag{9}$$

where θ_1 and θ_2 are the rotation angles of the fundamental laser and the second-harmonic laser, respectively.

Therefore the second-harmonic laser can be obtained when $I_1 = 0$, $I_2 = 1$, that is, β and d satisfy

$$(\alpha_2 - \alpha_1)d = (2m+1)\pi/2, \tag{10}$$

$$\beta = -\alpha_2 d. \tag{11}$$

We can also construct the quartz optical filter for the third- or fourth-harmonic laser by using two quartz plates and three polarizers based on the same principle.

In the arrangement of quartz optical filter for selecting the 532-nm frequency-doubled laser (see Fig. 1), the thickness of the quartz is 4.350 mm. The filtering capacity was tested with the experimental setup shown in Fig. 2. Firstly, the spectrum of output laser was measured by the spectrometer when the filter was not put into the light path, the spectrum is shown in Fig. 3. Then the filter was put into the light path, and the angle between the transmission axis was kept 117.4°. The spectrum of the output laser is shown in Fig. 4. From Figs. 3 and 4, the following results can be obtained. 1) The fundamental laser (1064 nm) and the second-harmonic laser (532 nm) all exist in the output laser when there is no quartz optical filter. 2) When the filter is put into the light path, the fundamental laser (1064 nm) is blocked, and the output laser is the second-harmonic laser. From

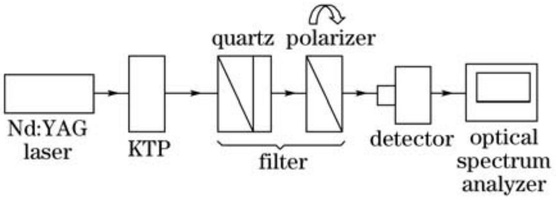

Fig. 2. Light path for testing the quartz optical filter.

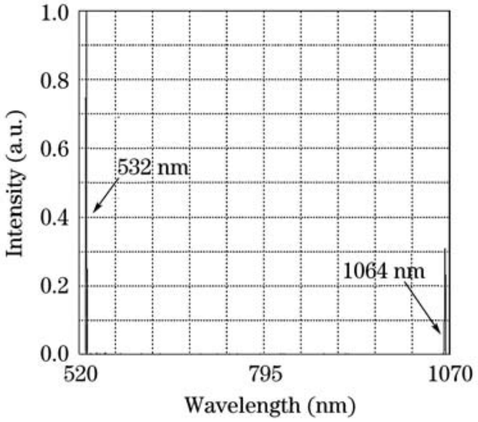

Fig. 3. Measured spectrum of the output laser for the light path without quartz optical filter.

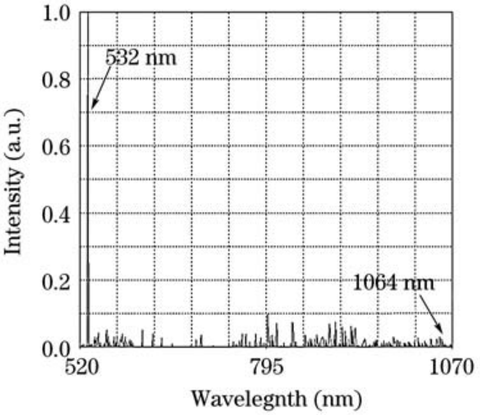

Fig. 4. Measured spectrum of the output laser when the quartz optical filter is put into the light path.

Figs. 3 and 4 we also find some secondary peaks which are caused by the system noise. But it has no influence on testing the filtering capacity.

In this paper, we analyzed the operating principle of the quartz optical filter for selecting the wavelength of frequency-doubled laser by the Muller matrix and tested the filtering capacity of a certain quartz optical filter. The analysis proved that the filtering principle of quartz optical filter based on the optical rotatory dispersion effect of the quartz crystal is correct. And the experimental results are in good agreement with the theoretical analysis. The quartz optical filter has some merits such as small size and easiness to operate. It is proved perfect for the wavelength selection of frequency-doubled laser.

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