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Wavelength switching in 2 μm narrow spectral bandwidth Tm: YAP laser

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ABSTRACT

A birefringent-etalon was used to achieve 2 μm narrow spectral bandwidth laser wavelength switching. The 660 mW narrow spectral bandwidth laser was achieved at the wavelength of 1987.6 nm by adjusting the inclination of the birefringent-etalon in relative to the optical axis of the resonator. The beam quality was $M^2 = 1.89$ and $M^2 = 1.96$ respectively in the x direction and y direction. The wavelength switching was accomplished by rotating the birefringent-etalon along its plane. Four thicknesses of birefringent-etalons were used to achieved switching wavelengths at 1988.7 nm, 1938 nm, 1964.7 nm and 1983 nm with the maximum power of 603 mW, 537 mW, 575 mW and 447 mW, respectively.

1. Introduction

Wavelength switching for 2 μm narrow spectral bandwidth laser shows great interest for many applications. It plays an important role in the atmosphere monitoring and laser radar because there are many important absorption lines near 2 μm. For example, the water vapor bands at 1.91 μm and carbon dioxide bands at 1.96 μm. There is also a potential use in medical applications due to a local absorption peak of liquid water at 1.94 μm [1–3]. Lasers at 2 μm are also being used as pump sources for solid-state lasers in the mid-infrared region, which have a growing number of applications in spectroscopy, medicine, defense, and fundamental research [4–6].

For wavelength switching, a broader fluorescence emission spectrum is necessary for gain material. The Tm: YAP has shown great superiority for the development of high-efficiency tunable diode-pumped lasers with the characteristics of good thermal conductivity, stable mechanical properties, and a broad tunable range in 2 μm region. Typical methods to obtain the wavelength tunable operation of the solid-state lasers are employed etalons [7] or Lyot filter [8] to be inserted in the laser cavities. Tilted etalons can be used to give single mode selection at particular points of the spectrum, but it has a very limited tuning range. Large tuning range could be achieved for Lyot filter. In 2008, Jelinkova et al. demonstrated tunability Tm:YAP laser from 1860 nm to 2040 nm using a Lyot filter [9]. In 2017, Cole et al. also demonstrated passively Q-switched Tm:YAP laser with a Cr:ZnS saturable absorber. A Lyot filter was also used to select 1.89 μm, 1.94 μm and 1.99 μm as output wavelength [10]. However, no information has been given concerning spectrum width. Therefore, a simple and easy method to accomplish tunable 2 μm narrow spectral bandwidth laser is necessary.

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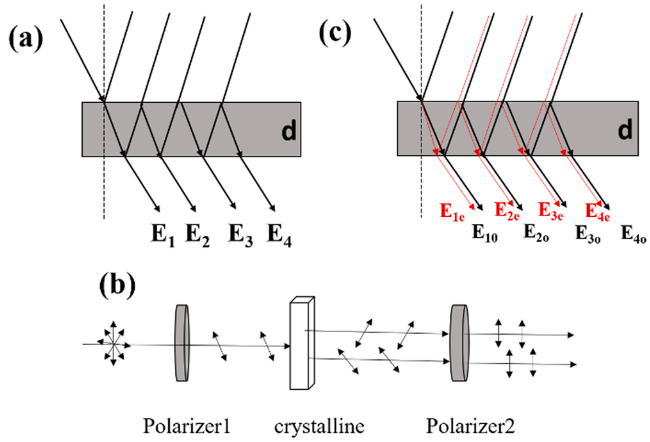

Fig. 1. The comparison of the principle of three filters, (a) etalon, (b) Lyot filter and (c) birefringent-etalon.

In this paper, the birefringent-etalon was proposed and applied in the 2 μm Tm:YAP laser. By adjusting the inclination angle, the narrow spectral bandwidth laser was achieved and the spectrum width was reduced to less than 0.1 nm. The output power and beam quality were also measured in experiment. It is found that the wavelength could be also switched by rotating the birefringent-etalon along its plane. The spectrum and the power of switched wavelengths were measured and the principle of wavelength switching was discussed.

2. Theory and experimental setup

2.1. Theory

In principle, the birefringent-etalon was different from traditional etalon and Lyot filter. An etalon is a Fabry-Perot interferometer and the principle is multi-beam interference, as shown in Fig. 1(a). The principle of etalon in the cavity can be expressed by the formula [11,12].

$$T(\lambda) = \frac{1}{1 + Fsin^2\left(\frac{2\pi \bullet n \bullet d \bullet cos\alpha}{\lambda}\right)} \tag{1}$$

Where, F is the finesse of the etalon, which can be defined as $F = \frac{4R}{(1-R)^2}$, n is the refractive index of the etalon, d is the thickness of the etalon; α is the angle of refraction through the etalon, λ is the wavelength. The free spectral range is $\Delta V_{FSR} = \frac{C}{2nd}$.

The principle of Lyot filter is interference of polarized light, as shown in Fig. 1(b). The transmission spectrum of the Lyot filter for parallel orientation of the polarizers is given by [13,14].

$$T(\lambda) = 1 - \sin^2(2\theta) sin^2\left(\frac{2\pi \bullet \Delta n \bullet d}{\lambda}\right) \tag{2}$$

Where, θ is the angle between the optic axes of the birefringent plate and the polarizing direction of the polarizers, $\Delta n = n_e - n_e$, $n_o$and n_e are the refractive indices for the ordinary and extraordinary rays. The free spectral range of the Lyot filter is $\Delta V_{FSR} = \frac{C}{\Delta nd}$. In general, the filter surfaces at Brewster's angle with the incident light beam is used as polarizers.

However, birefringent-etalon proposed in this paper is about zero angle with the incident light beam and there aren't any polarizers in the system. All polarization state of the light could pass though the birefringent-etalon. Meanwhile, it is made of an optically anisotropic material (crystalline quartz), which is different from the etalon. And the birefringence would be happened when the light passing through the birefringent-etalon. The principle of the wavelength tunable by using the birefringent -etalon in the cavity can be expressed, as shown in Fig. 1(c). There will be no interferences between the ordinary and the extraordinary rays due to perpendicular vibration directions with each other. But the multi-wavelength interference would be happened for the ordinary and the extraordinary rays themselves. When the inclination of birefringent-etalon in relative to the incident light is adjusted, the transmissivity longitudinal modes would be changed. Only when the transmissivity longitudinal modes of the etalon match very well with active cavity resonator, these laser modes had the highest gain whereas the other modes suffered high losses and were suppressed so that the laser spectrum width is narrowed. Meanwhile, since the birefringent-etalon is placed about 0°, it can also be regarded as a phase compensator. When rotating the birefringent-etalon, the amplitude of the ordinary and the extraordinary rays would be changed. As a result, the polarization state of the light passing through would also be changed accordingly so the final lasing wavelength would be changed by rotating the birefringent-etalon due to the variation of the polarization state of the feedback system.

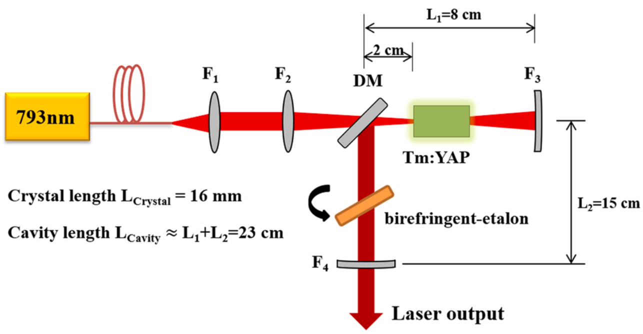

Fig. 2. Schematic diagram of the experimental setup.

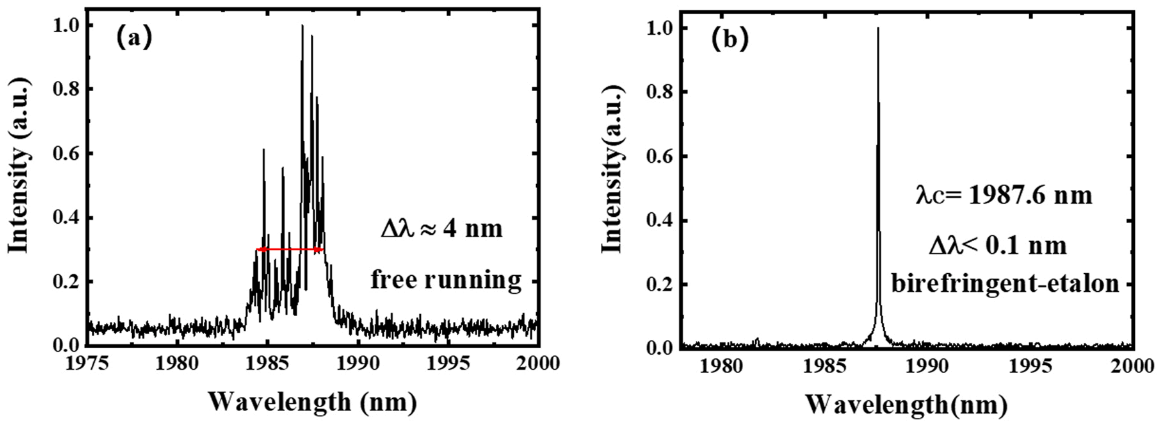

Fig. 3. Laser spectra of the Tm:YAP laser in (a) the free running and (b) the birefringent-etalon operation.

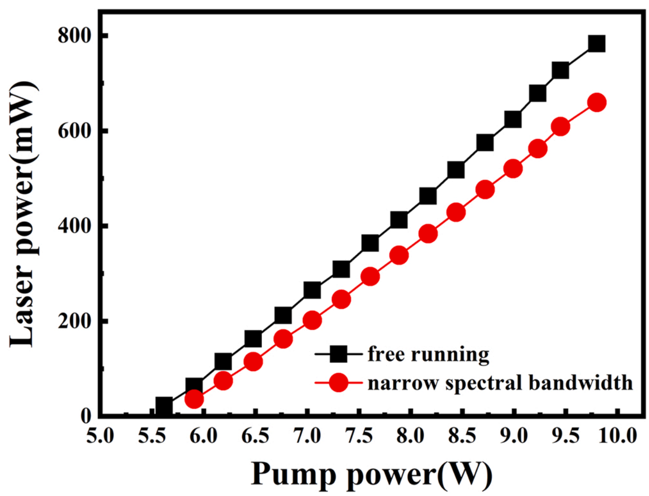

Fig. 4. Average output power curves of free running and narrow spectral bandwidth Tm:YAP laser.

2.2. *Experimental setup*

A L-shaped cavity configuration was shown in Fig. 2. The pump source was 793 nm fiber coupled diode laser with a maximum output power of 10 W. The diameter and numerical aperture of the fiber core were 100 μm and 0.22, respectively. The collimating lens F_1 (f=25 mm) and focusing lens F_2 (f=75 mm) were used to image the pump beam into the crystal and the pump diameter in the crystal was nearly 300 μm. The DM was 45 degrees dichroic mirror (HT@793 nm, HR@1900–2000 nm). An a-cut Tm:YAP crystal with a

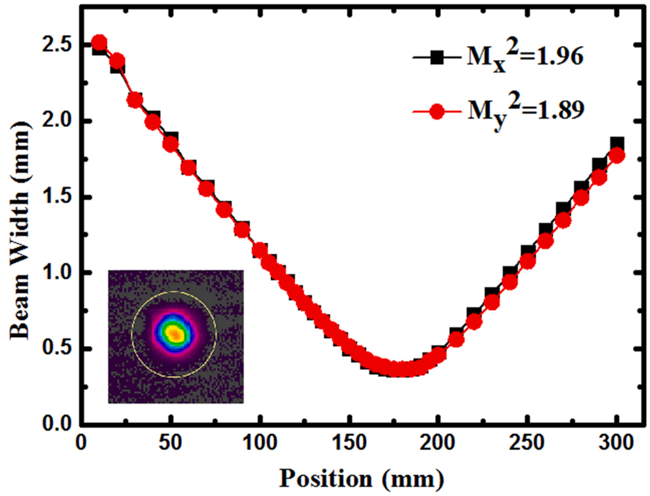

Fig. 5. Beam quality of narrow spectral bandwidth Tm:YAP laser at the maximum laser power.

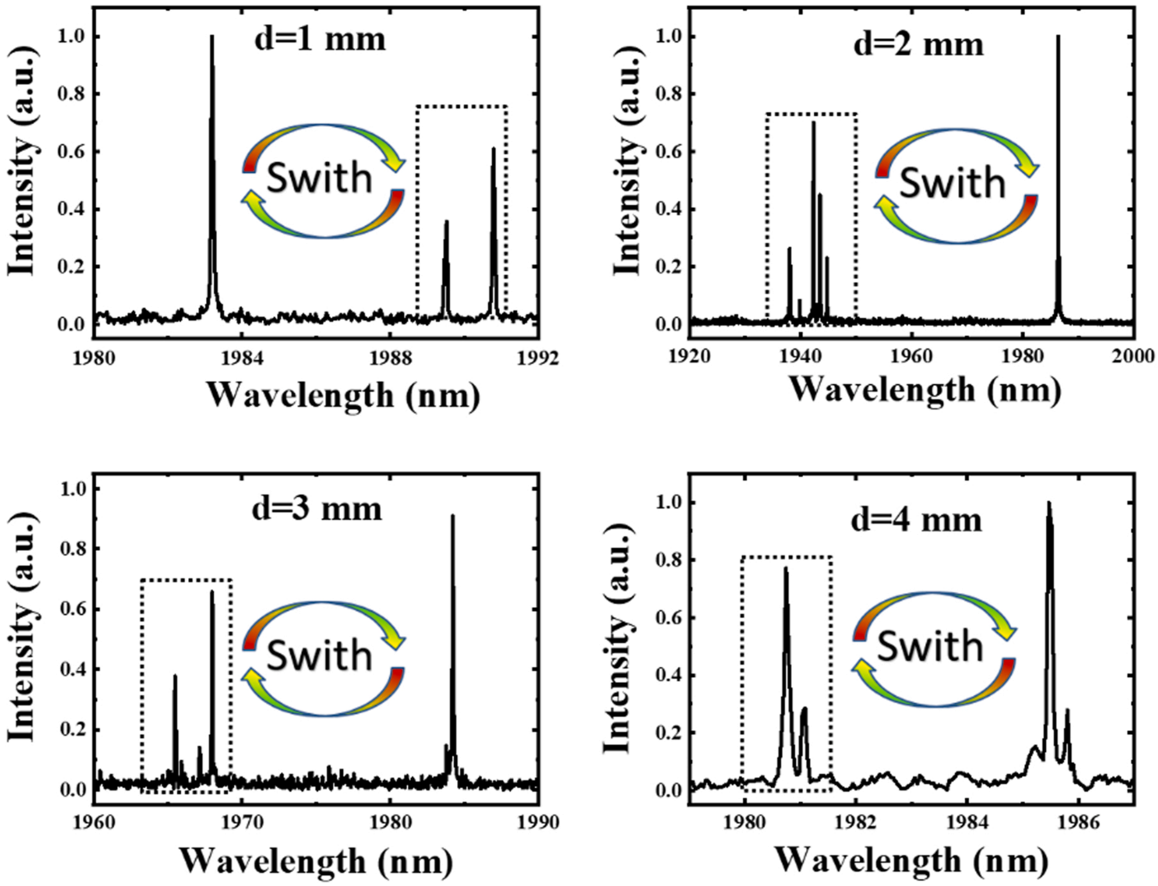

Fig. 6. Wavelength switching of Tm:YAP laser under different thickness of the birefringent-etalon operation.

doped concentration of 3 at% and a dimension of $2 \times 6 \times 16\text{mm}^3$ was used in the experiment. Both ends of the crystal were polished to be parallel with an antireflection film of 793 nm and 2000 nm. The crystal was wrapped with indium foils and held in a brass heat sink. The F_3 was a concave mirror with a radius of curvature of r = 100 mm. F_4 was a flat concave output couple mirror with a radius of curvature of r = 200 mm and 10% transmittance at 2000 nm. The cavity length was around 23 cm. The 3 mm thickness single quartz plate without coating was inserted into the cavity, which was used as a birefringent-etalon to narrow the spectrum and switch the

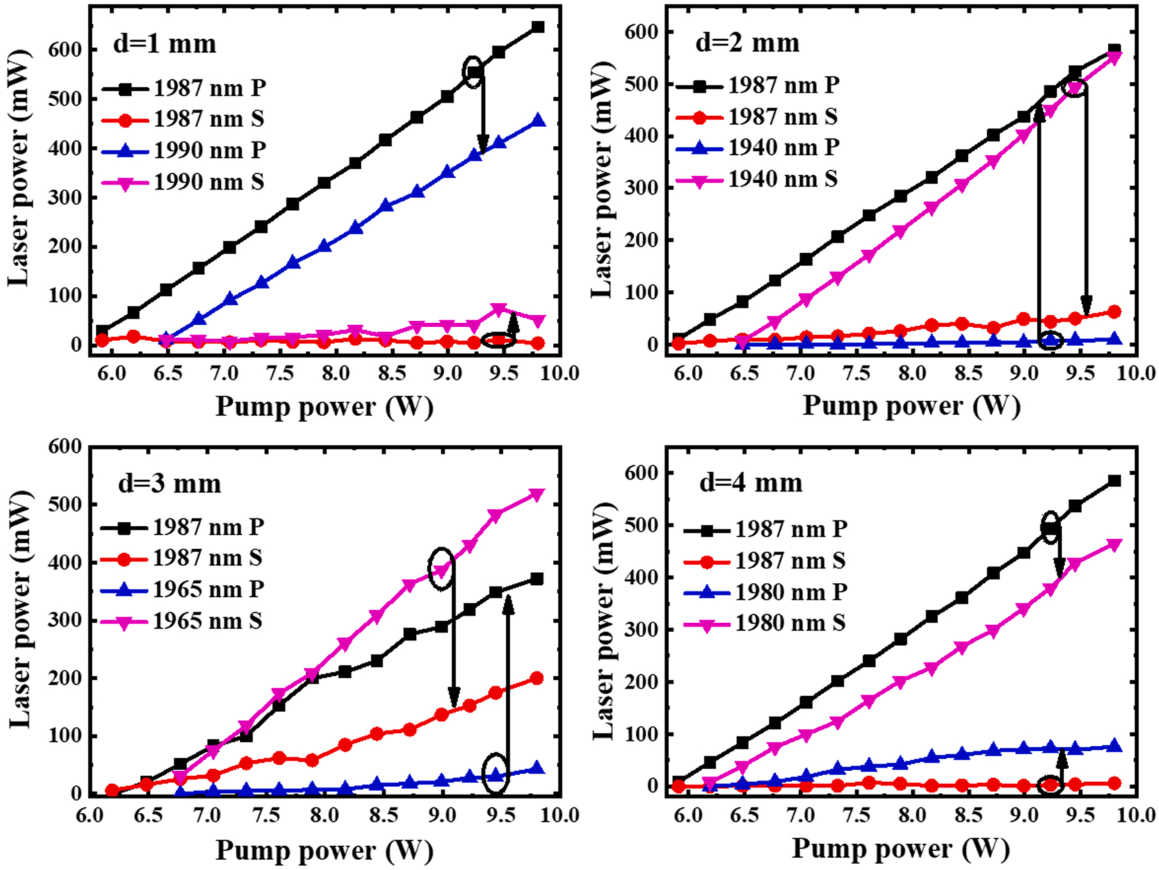

Fig. 7. The polarization power curves corresponding to wavelength switching under the different thickness of birefringent-etalons.

wavelength.

3. Results and discussion

3.1. 1987 nm narrow spectral bandwidth laser

First, the output performance of the Tm:YAP laser without intracavity birefringent-etalon (free running) was investigated. The laser spectrum was measured by a Fourier transform spectrometer, as shown in Fig. 3(a). The spectrum width was about 4 nm. In order to reduce the spectrum width, a 3 mm thickness single quartz birefringent plate was inserted into the cavity and used as an etalon (birefringent-etalon). By adjusting the inclination angle of the birefringent-etalon in relative to the optical axis of the resonator, the narrow spectral bandwidth laser was achieved as shown in Fig. 3(b). The center wavelength was 1987.6 nm and the spectrum width was less than 0.1 nm, which was limited by the resolution of spectrometer analyzer.

Due to the loss of birefringent-etalon in cavity, the output power of narrow spectral bandwidth laser would be different from the free running laser. Fig. 4 showed the average output power curves for free running and narrow spectral bandwidth lasers. The thresholds were 5.2 W and 5.7 W, respectively, with maximum laser powers of 783 mW and 660 mW at the pump power of 10 W.

In addition to the longitudinal mode, transverse mode was also a very important parameter for solid-state laser. The transverse beam profiles during narrow spectral bandwidth operation at the maximum laser power was measured by a beam profiling camera (Spricon Inc. Pyrocam IV). The beam diameters were recorded at different locations along the propagation direction and fitted with a hyperbola, as shown in Fig. 5. The M^2 values were 1.89 and 1.96, respectively, in the x and y directions.

3.2. Wavelength switching 2 μm narrow spectral bandwidth laser

The narrow spectral bandwidth laser could be accomplished by adjusting the angle of the birefringent-etalon with respect to the optical axis of the resonator. However, it was found that the center wavelength would also been switched when rotating the birefringent-etalon, and the switched wavelengths were different under different thickness of birefringent-etalon. The thicknesses of 1 mm, 2 mm, 3 mm and 4 mm birefringent-etalons were tried in experiment to switch the wavelength from ∼1987 nm to 1990 nm,

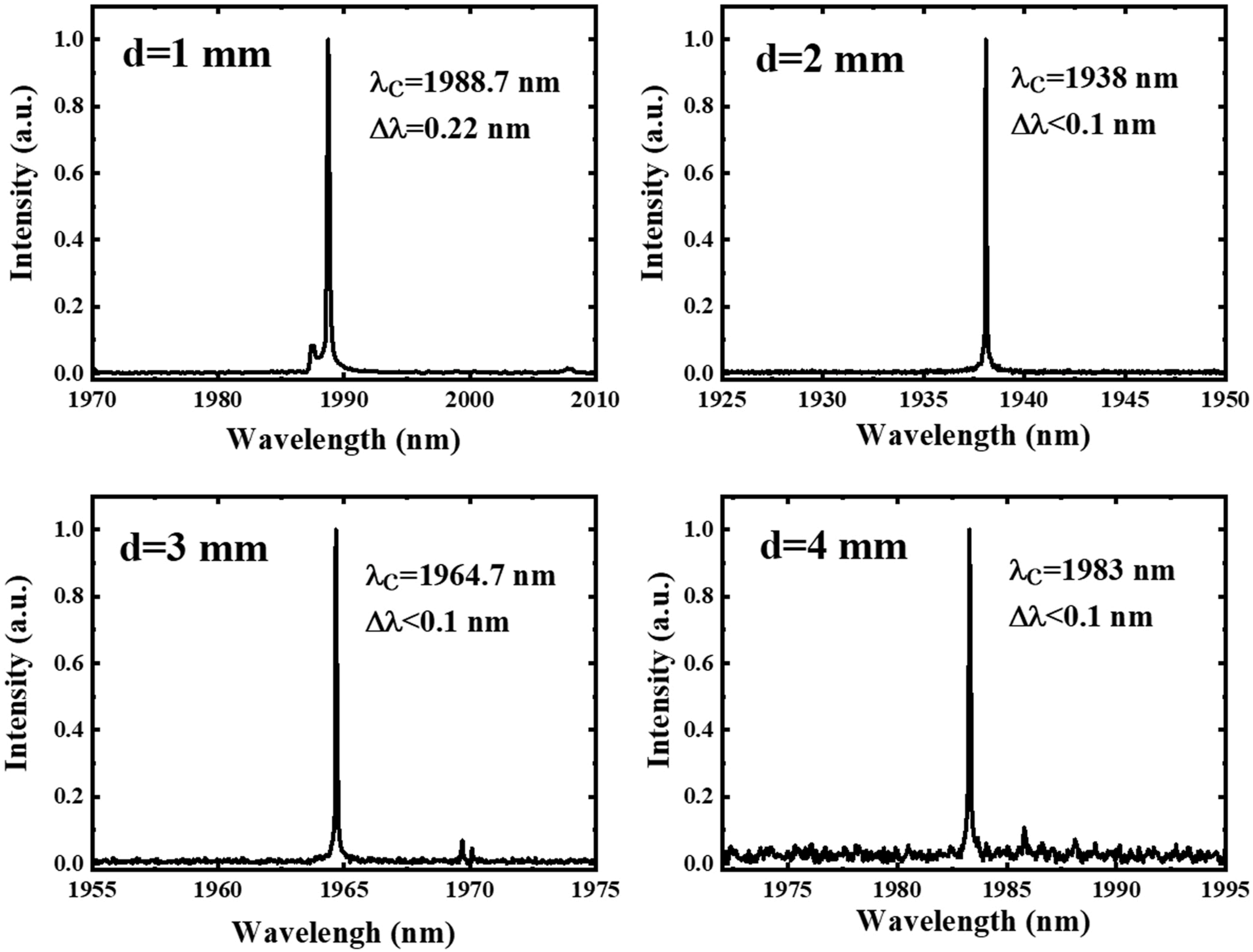

Fig. 8. The narrow spectral bandwidth switching wavelengths of 1988.7 nm, 1938 nm, 1964.7 nm and 1983 nm.

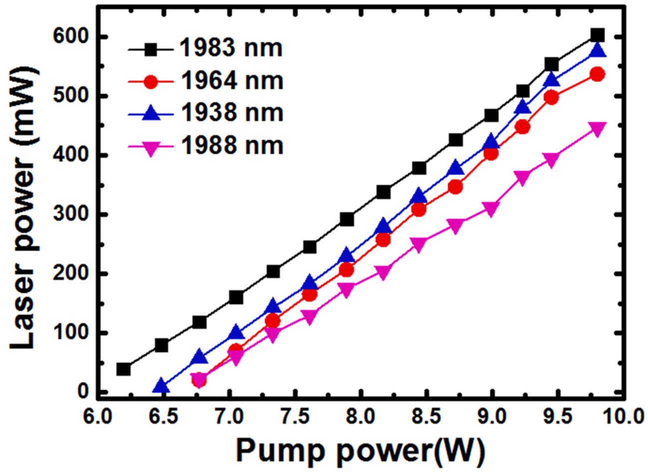

Fig. 9. The narrow spectral bandwidth laser power curves of 1988.7 nm, 1938 nm, 1964.7 nm and 1983 nm.

1938 nm, 1965 nm and 1980 nm, respectively, as shown in Fig. 6. Because of the birefringent property of the etalon, when the etalon was rotated, the polarization state of light passing through it changed accordingly. Compared to the Lyot filter, birefringent-etalon didn't have to be placed inside the optical resonator at the Brewster angle to ensured horizontal polarization. It was inserted into the cavity with the minimum angle to reduce the insertion loss. Therefore, all the state of polarization light would pass the birefringent-etalon and the polarization of passing light would be changed as rotating the angle.

The variation of polarization state for wavelength switching was also investigated in experiment. The P-polarization was defined as the horizontal polarization direction of output laser, and S-polarization was orthogonal to the P-polarization. A polarizing beam splitter was used to separate the output laser into P-polarization and S-polarization and the polarization power curves corresponding to wavelength switching under different thickness birefringent-etalons were shown in Fig. 7. It was obvious that the polarization state of output laser was changed as wavelength switching. Because the etalon was birefringent crystal and the polarization state of the light would be changed by rotating the optic axis of crystal. Therefore, the polarization of feedback light in the cavity would be influenced by rotating the birefringent-etalon. Moreover, the laser host Tm:YAP was an anisotropic orthorhombic crystal and the emission wavelength was 1980 nm (a-axis and c-axis) and 1940 nm (b-axis). Under different polarization feedbacks, the emission wavelength would be changed. For instance, at the thickness of 2 mm, the polarization was changed from P-polarization to S-polarization and the wavelength was also switched from 1987 nm to 1940 nm, which correspond to the emission wavelengths of a-axis and b-axis of the host Tm:YAP.

Since there was no limitation of Brewster angle, the switching wavelengths could also accomplish narrow spectral bandwidth laser by adjusting the inclination of the birefringent-etalon with respect to the optical axis of the resonator, as shown in Fig. 8. The wavelength would be shifted a little by adjusting the angle of birefringent-etalon. The narrow spectral bandwidth wavelengths were achieved at 1988.7 nm, 1938 nm, 1964.7 nm and 1983 nm and the spectrum width were all less than 0.1 nm except at 1988.7 nm. The spectrum width was about 0.22 nm for 1988.7 nm corresponding to 1 mm thickness birefringent-etalon. The transmissivity mode linewidth of the thin etalon would be wider than that of the thick one. Hence the spectrum width of the birefringent-etalon of 1 mm thickness was wider than those of others.

The laser output power curves for each narrow spectral bandwidth switching wavelength were also measured as shown in Fig. 9. Under the pump power of 10 W, the output powers were 603 mW, 537 mW, 575 mW and 447 mW at 1983 nm, 1964 nm, 1938 nm and 1988 nm, respectively.

4. Conclusion

In summary, the birefringent-etalon was proposed and used to achieve wavelength switching of narrow spectral bandwidth Tm: YAP laser. The narrow spectral bandwidth laser emitting at 1987.6 nm with the spectrum width less than 0.1 nm was demonstrated by adjusting the inclination of the birefringent-etalon with respect to the optical axis of the resonator. The maximum laser power was 660 mW and the M^2 value were 1.89 and 1.96, respectively, in the x and y direction. Meanwhile the narrow spectral bandwidth switching wavelengths of 1988.7 nm, 1938 nm, 1964.7 nm and 1983 nm were achieved by adjusting inclination and rotating the angle of birefringent-etalon. The maximum output powers were 603 mW, 537 mW, 575 mW and 447 mW, respectively. The wavelength switching of 2 μm narrow spectral bandwidth Tm:YAP laser would find variety of applications, ranging from differential absorption spectroscopy, and coherent Doppler wind lidars to THz wave generation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the plots within this paper and other findings of this study are available from the first author upon reasonable request.

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