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Theoretical and experimental research on the birefringent filter applied for the high power tunable Ti: sapphire laser

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Investigating from the classical theory of the birefringent filter (BF), we calculate out the appropriate parameters that fit for the high power tunable Ti: sapphire laser experiment greatly. Then from the experiment we validate its effect and achieve continuous tuning from 750 nm to 920 nm with the maximum output power of 5.8 W and average power of 3.83 W that tops this field so far.

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1. Introduction

Because the advantages of broad tunable spectrum range and high gain, Ti: sapphire laser has been used in many fields such as laser radar, nonlinear optics, atmosphere optics and iatrology. Among the various wavelength tuning and line width compressing instruments, BF is most popular employed in the continuously tunable lasers for its merits of small insert loss, high damage threshold (with uncoated quartz crystal)、broad tunable range, easy operating method and so on. There have been a lot of reports on BF's theory and design [1], so in this paper we just analyze the new specific requirement according to the recent development of tunable lasers, especially Ti: sapphire laser. In terms of wavelength width and tuning range, the main engineering work is to decide the thickness of the quartz crystal and the separation angle between optical axis and crystal surface.

2. Experimental theory

BF is placed with Brewster angle in the light path of the laser system. Tuning BF by its surface normal, we can tune the oscillating laser in the cavity. Because BF's theory、fabrication and application method are very mature, the following content only concern about the correlative theory of selecting BF in our practical experiment.

At first, the smaller the minimum wafer's thickness is, the wider the tuning range is, however the more difficult the BF's fabrication is. So we should consider the crystal thickness integrally. Conventional thickness is about 0.4～1.0 mm. Owing to the limitation of the coating technology, the bandwidth of our cavity mirror is 100 nm; so long as the wafer's tuning range of 100 nm is taken into account. Consequently, we could employ a thicker wafer, which is 1mm, and the proportion of the three wafers' thickness is routine 1:2:4.

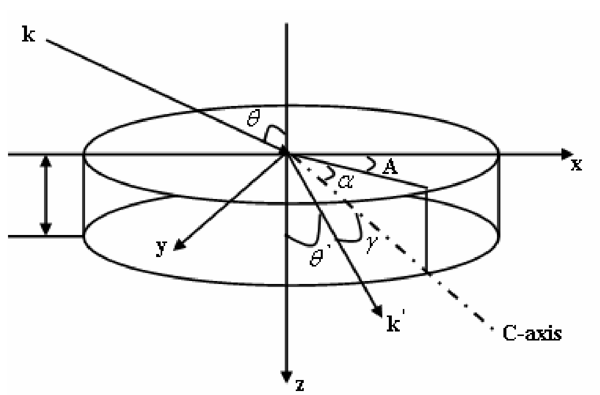

Fig. 1. Physical arrangement of the birefringent filter.

In quartz crystal, the phase delay between ordinary light and extraordinary light can be expressed as [2]

$$\sigma = \frac{2\pi d(n_o - n_e)\sin^2\gamma}{\lambda \sin\theta} \tag{1}$$

Where n_0, n_e is the refractive index of ordinary and extraordinary light separately, *d* is the thickness of the minimum wafer, γ is the separation angle between refracted light vector *k* and the crystal optic axis, λ is the wavelength of incident light, θ is incident angle, namely Brewster angle. Obviously, when σ = 2kπ, the emergent light is still polarized in horizontal direction, BF can be regarded as inexistence and the loss is very small. Hereby only wavelength which satisfy the following equation can pass the BF without loss

$$\lambda_k = \frac{d(n_o - n_e)\sin^2\gamma}{k\sin\theta} \tag{2}$$

Where k is the interference order. When employing BF as tuning component, we always choose λ_0 of a certain order as tuning wavelength. By changing γ (rotating BF), λ_0 changes correspondingly, thereby we tune the wavelength. The relationship between γ and rotating angle A can be expressed as

$$\cos\gamma = \cos\theta\cos a\cos A + \sin\theta\sin a \tag{3}$$

Where a is the separation angle between optical axis and crystal surface.

From equation (2) we obtain the peak wavelength difference of the adjacent interference order is

$$\lambda_{k-1} - \lambda_k = \lambda_k / k \tag{4}$$

As mentioned above, the coating bandwidth of the cavity mirror is 100 nm generally, so we divide the whole tuning range (750~950 nm) into two bands with the width of $\Delta\lambda = 100$ nm in each band. Applying different interference order in different band, we can boost up the ability to suppress the secondary peak so as to improve the BF's capability.

For the purpose of continuously smooth tuning in each band, the identical interference order in the same band was needed, moreover the separation of the peak wavelength from adjacent interference order should be larger than the band width $\Delta\lambda$, viz. $(\lambda_{k-1} - \lambda_k) > \Delta\lambda$. We substitute it into equation (4) and derive:

$$k < \lambda / \Delta\lambda = \lambda_{\min} / \Delta\lambda \tag{5}$$

Where $\lambda_{\min}$ is the lower limit of the wavelength. For 750 nm~850 nm band, we figure out k <7.5 and we select k =5; for 850 nm~950 nm, we get k <8.5 and we define k =4. The reason is that from equation (2) we could detect if k is slightly lower for the longer wavelength band, $\sin^2\gamma$ would not vary much in the whole tuning range (750~950 nm) [3].

To limit the secondary peak while tuning BF, the separation angle between the optical axis and the crystal surface should also satisfy the following expression:

$$\sin a = \cos\theta\cos\gamma_0\left(tg\theta - tg\gamma_0/\sqrt{2}\right) \tag{6}$$

where $\gamma_0 = (\lambda_{\min} + \lambda_{\max})/2$. We substitute λ_{01} =800 nm and $\lambda_{02} = 900$ nm into equation (2) and deduced $\gamma_{01} = 38.44^0$ and $\gamma_{02} = 36.14^0$. Then substitute them into equation (6), we identified $a_1 = 27.63^0, a_2 = 29.74^0$.

It is clear to see that a varied in response to the interference order of k in different waveband. So we should take the second-peak-suppressing ability of BF into account furthermore [4].

When the horizontal polarization laser was passing through BF, owing to the interference of ordinary and extraordinary light, beam intensity ratio of the horizontal part of the emergent light and incident light is

$$T = I/I_0 = 1 - \sin^2(2\varphi)\sin^2(\delta/2) \tag{7}$$

where φ is the separation angle of the horizontal polarization plane (incident plane) and the electric displacement of refract ordinary light, determined by the following expression [5]

$$\sin\varphi = ctg\gamma\left(tg\theta - \frac{\sin a}{\cos\theta\cos\gamma}\right) \tag{8}$$

From equation (7) we calculate out the contrast

$$D = \frac{T_{\max}}{T_{\min}} = \frac{1}{1-\sin^2(2\varphi)} = \sec^2(2\varphi) \tag{9}$$

the higher the value of D is, the stronger the secondary peak suppression is. Thereby φ is supposed to be $\pi/4$ or so. Namely $\sin^2(2\varphi)$ is close to 1.

It is obvious to know from equation (8) that the selection of a determines the value of $\sin^2(2\varphi)$. Substituting equation (8) into equation (2) and erasing γ we could attain

$$\sin\varphi = \sqrt{\frac{d(n_0-n_e)-k\lambda\sin\theta}{k\lambda\sin\theta}}\left[tg\theta - \frac{\sin a}{\cos\theta}\sqrt{\frac{d(n_0-n_e)}{d(n_0-n_e)-k\lambda\sin\theta}}\right] \tag{10}$$

Using a derived from equation (6) we could yield $\sin^2(2\varphi)$ in the whole tuning range. When $a_1 = 27.63^0, a_2 = 29.74^0$ for the 750 nm～850 nm and 850 nm～950 nm waveband, respectively, Ti: sapphire laser versace $\sin^2(2\varphi)$ is above 0.99, which indicates fine secondary peak suppression, illustrated as Fig. 2.

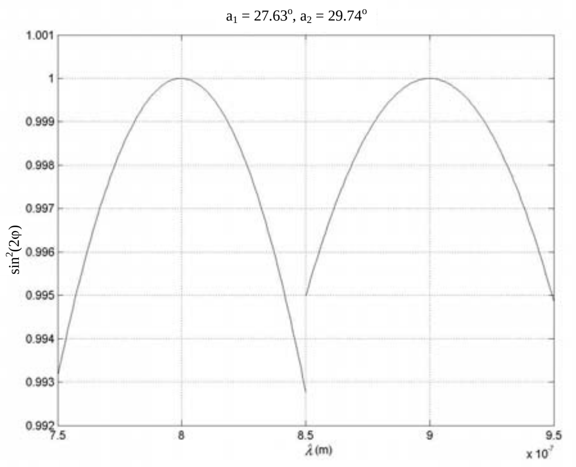

Fig. 2. Ability to suppress the secondary peak at $a = 27.63^o$ and $a = 29.74^o$ in 750 nm ~ 850 nm and 850 nm~950 nm, respectively.

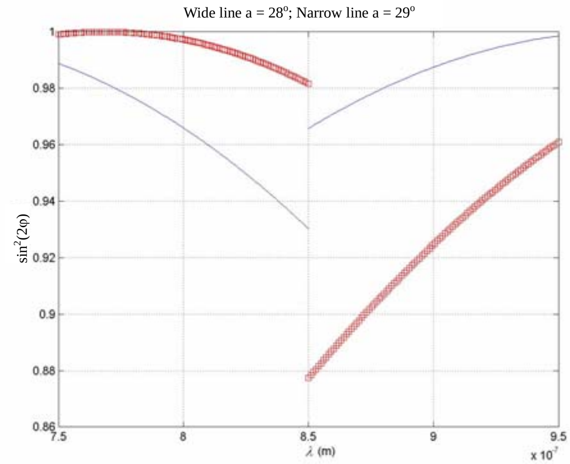

Fig. 3. Ability to suppress the secondary peak at $a = 28^o$ and $a = 29^o$ in the whole Ti: sapphire spectrum, respectively.

Whereas for the factual BF there should be only one *a*, so we plan to fix it as $a = 28^o$ or 29^o. Comparing these two cases in the Fig. 3 we know that when $a = 29^o$, $\sin^2(2\varphi)$ is above 0.93 in the whole tuning range. This is helpful for the secondary peak suppression.

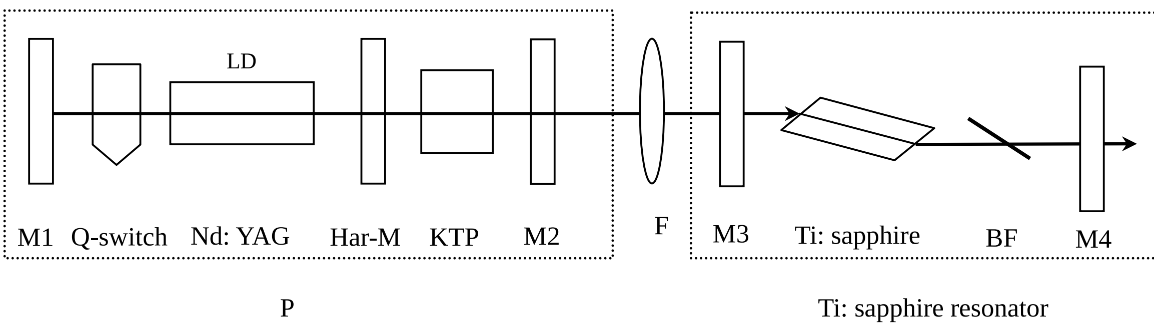

Fig. 4. All solid state quasi-continuous tunable Ti: sapphire laser system.

3. Experimental setup and results

The experimental setup is illustrated as Fig. 4. The figure lists the LD pumped frequency-doubled Nd: YAG laser and Ti: sapphire resonant cavity. P is the pump resource of Ti: sapphire resonator; F is the focusing lens with the focus of 150 mm, so as to reduce the pump beam diameter to 100 um or so when passing through it; M3 and M4 form Ti: sapphire resonant cavity with two groups of cavity mirror: 750～850 nm and 850～950 nm; The ends of the Ti: sapphire rod are Brewster angle cut and in the direction of c axis. To extract the deposited heat, the laser crystal is in contact with a water-cooled copper plate.

In the experiment, while no BF inserted, we used the spectrum analyzer from Agilent Technologies to measure Ti: sapphire broadband spectrum when applying 750~850 nm cavity mirror, shown as Fig. 5. We find that the fluorescence spectrum of Ti: sapphire is broad and its peak power falls at 796.8 nm.

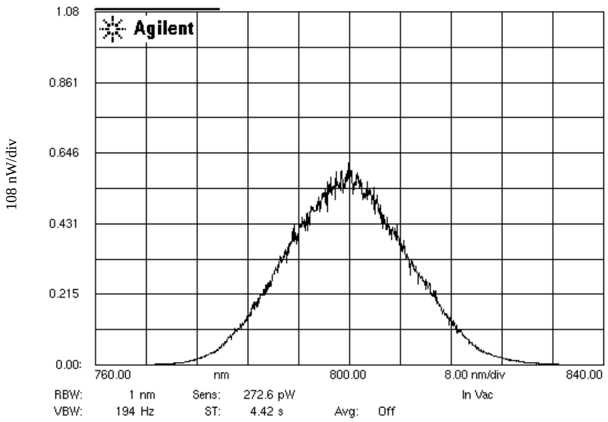

Fig. 5. Ti: sapphire laser output spectrogram.

Then we inserted BF in the Ti: sapphire laser resonant cavity. In this case, when the pump current is 23 A, the maximum output power of 532 nm is 27 W with the repetition rate of 9 kHz; the maximum output power of 5.8 W at 796.8 nm was achieved. This index tops this field so far [6].

As described before, we defined k=5 while tuning from 750 nm to 850 nm. Tuning BF from A=29.2^o to A=36.6^o we attained the tuned wavelength from 750 nm to 850 nm continuously. Then we defined k=4 at 850~950 nm.

Tuning BF from A=23.0^o to A=30.1^o we attained the tuned wavelength from 850 nm to 920 nm. As shown in Fig. 5, the gain center of Ti: sapphire laser is situated at ~ 800 nm, wavelengths longer than 920 nm have relatively lower gain, furthermore with the ideal coating technology, we didn't get longer wavelength. In the whole tuning range, the secondary peak was suppressed fewer than 10%. Fig. 6 and 7 are the tuned wavelength at 767.4 nm and 886.5 nm, respectively.

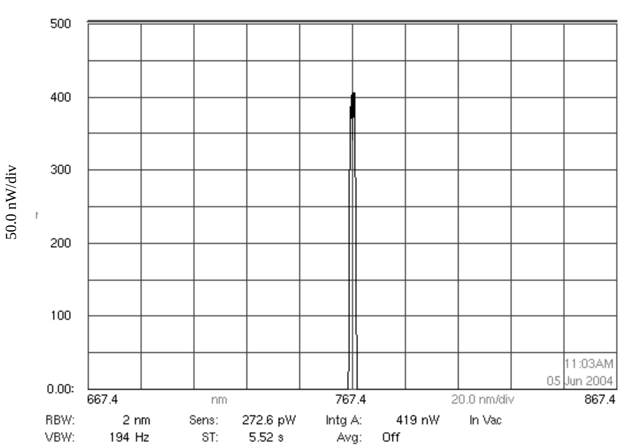

Fig. 6. Tuning output wavelength of Ti: sapphire laser at 767.4 nm.

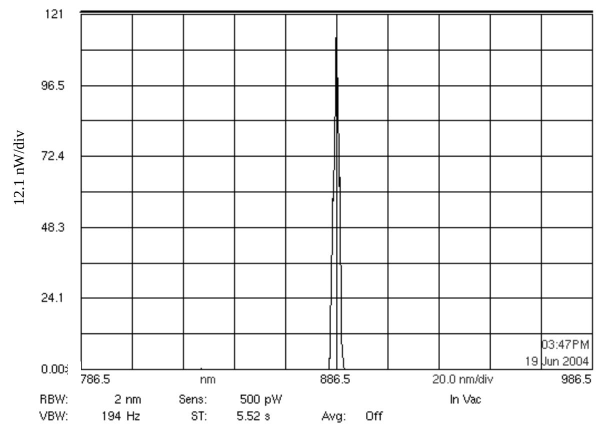

Fig. 7. The tuning output wavelength of Ti: sapphire laser at 886.5 nm.

We measured the output power and output wavelength and illustrated it in Fig. 8.

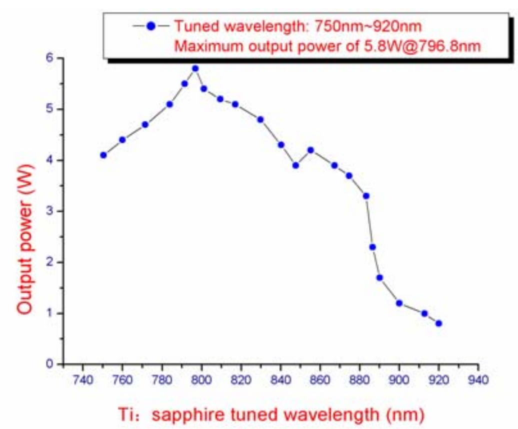

Fig. 8. Output wavelength of Ti: sapphire laser versus output power.

4. Conclusions

Though the study of the classic theory of BF's design we calculate out its parameters which are suit well for the operation of the high power tunable Ti: sapphire laser. When applying the designed BF (thickness of the minimum wafer is 1mm and the separation angle between optical axis and crystal surface a =29^o) into the practical experiment, we successfully suppress the secondary peak in the level of less than 10% and finally attain the maximum tuned power of 5.8 W at 796.8 nm and the average tuned power of 3.83 W from 750 nm to 920 nm. If we exchange better coating mirrors and higher pumping souce, we should attain higher tuned power, meanwhile wider tuning range. Continuing development is currently underway.

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