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An all-solid-state high power quasi-continuous-wave tunable dual-wavelength Ti:sapphire laser system using birefringence filter*

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This paper describes a tunable dual-wavelength Ti:sapphire laser system with quasi-continuous-wave and high-power outputs. In the design of the laser, it adopts a frequency-doubled Nd:YAG laser as the pumping source, and the birefringence filter as the tuning element. Tunable dual-wavelength outputs with one wavelength range from 700 nm to 756.5 nm, another from 830 nm to 900mn have been demonstrated. With a pump power of 23 W at 532 nm, a repetition rate of 7 kHz and a pulse width of 47.6 ns, an output power of 5.1 W at 744.8 nm and 860.9 nm with a pulse width of 13.2 ns and a line width of 3 nm has been obtained, it indicates an optical-to-optical conversion efficiency of 22.2%.

Keywords: all-solid-state, dual-wavelength, Ti:sapphire laser, birefringence filter
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1. Introduction

The dual-wavelength tunable laser is known for its important applications including laser spectrum, atmospheric pollution monitor and differential absorption lidar (DIAL), etc. Ti:sapphire crystals, with large stimulated emission cross sections[1,2] and the broadest tuning ranges from visible band to near-infrared band for single solid-state laser media, are ideal materials for simultaneously producing multiple wavelengths, especially two wavelengths.

A dual-wavelength pulsed Ti:sapphire laser was first reported by Gizbrekht *et al* in 1989,[3] although the output power was low and the tuning range of the two wavelengths was rather limited. In 1992, a dual-wavelength CW and quasi-CW a Ti:sapphire laser was reported by Scheps and Myers, which was pumped by an Ar+ laser.[4] In 1995, a passively self-injection locked dual-wavelength CW Ti:sapphire laser was obtained.[5] Then an injection-seeded dual-wavelength pulsed Ti:sapphire with a novel stabilization scheme and capability was reported.[6] A mode-locking dual-wavelength Ti:sapphire was also demonstrated.[7,8] Different methods have been used to realize dual-wavelength lasing operation, including double-prism-dispersion cavity, two-mirror resonator with birefringence filter (BF) as the tuning element, two independent seeds injection,[9] and controlling dual wavelengths by the acousto-optic tunable filter.[10,11]

The dual-wavelength Ti:sapphire laser reported by this paper was characterized by its high power, all-solid-state, broad tuning, high repetition rate, short pulse width and simple cavity configuration as well. With a pump power of 23 W at 532 nm, a repetition rate of 7kHz and a pulse width of 47.6 ns, an output power of 5.1 W at 744.8 nm and 860.9 nm with a pulse width of 13.2 ns and a line width of 3 nm has been obtained, it indicates an optical-to-optical conversion efficiency of 22.2%. To the best of our knowledge, it is the highest power of all-solid-state quasi-continuous-wave dual-wavelength Ti:sapphire laser.

2. Dual-wavelength laser theory

Due to the actions of the crystal field, the lower energy level of a Ti:sapphire crystal is split into a num-

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ber of Stark's sublevels. The transitions between the Stark's sublevels of different manifolds can generate corresponding wavelengths. Owing to the differences of the stimulated emission cross section, fluorescent lifetime, fluorescent quantum efficiency as well as the operation condition of laser, the Ti:sapphire laser oscillates generally at one wavelength. However, if inverted population transits from the same upper energy level to two different lower Stark sublevels, dual-wavelength laser radiations will be produced as long as the gain at dual wavelengths surpasses the loss.

Based on the above analysis and the rate equations of a quasi-four-energy-level tunable solid-state laser system, a dual-wavelength operating Ti:sapphire laser system can be constructed as follows:[12,13]

$$\mathrm{d}N/\mathrm{d}t = W_\mathrm{p} - (\sigma_\mathrm{A}\phi_\mathrm{A} + \sigma_\mathrm{B}\phi_\mathrm{B})\upsilon N - N/\tau_0, \quad (1)$$

$$\mathrm{d}\phi_\mathrm{A}/\mathrm{d}t = \sigma_\mathrm{A}\upsilon N\phi_\mathrm{A} l/L_\mathrm{A} - \phi_\mathrm{A}/\tau_\mathrm{RA}, \quad (2)$$

$$\mathrm{d}\phi_\mathrm{B}/\mathrm{d}t = \sigma_\mathrm{B}\upsilon N\phi_\mathrm{B} l/L_\mathrm{B} - \phi_\mathrm{B}/\tau_\mathrm{RB}, \quad (3)$$

where N is the population inversion density, W_p is the pumping rate, ϕ is the photon density, ν is the centre frequency of laser pulse in resonator, σ is the stimulated-emission cross-section

$$\sigma_\mathrm{A} = \frac{A^\mathrm{A}_{32} g(\nu, \nu_\mathrm{A})}{n\nu_\mathrm{A}\nu}, \quad \sigma_\mathrm{B} = \frac{A^\mathrm{B}_{32} g(\nu, \nu_\mathrm{B})}{n\nu_\mathrm{B}\nu},$$

A_nm is the rate of spontaneous transition between energy levels E_m and E_n, g is the small-signal gain coefficient, n_i is the population density at every energy level E_i $(i = 1, 2, 3, 4)$, l is the length of Ti:sapphire crystal, L is the length of resonators, δ is the loss per pass in resonator, $\tau_\mathrm{R}(\tau_\mathrm{R} = l/\delta_\mathrm{c})$ is the photon lifetime in resonator.

Based on $P^1_\mathrm{th} = P^2_\mathrm{th}$, the threshold condition of oscillation for the simultaneous dual-wavelength laser can be written as[14]

$$\ln\Big(\frac{1}{\gamma_i}\Big) = 2l\Big[\frac{\sigma_i\nu}{\sigma\nu_i}\alpha - \alpha_i\Big] + \frac{\sigma_i\nu}{\sigma\nu_i}\ln\Big(\frac{1}{\gamma}\Big), \quad (4)$$

where σ, α, γ and ν are the stimulated emission cross section, the loss per pass, reflectivity of output mirror and the frequency of one wavelength respectively, while σ_i, α_i, γ_i and ν_i are the parameters of another. l is the length of the bar of the Ti:sapphire. The reflectivity of the total-reflection mirror was 100% and the two radiations had the same loss and fluorescent quantum efficiency, on which the Eq.(4) was based. If the output mirrors have the similar reflectivity of the dual wavelengths, Eq.(4) will be satisfied as long as there is proper loss, and the dual wavelengths will operate stably on condition that the gain surpasses the loss at the dual wavelengths.

In our experiment, BF was employed as not only the wavelength-turning component but also the loss-turning component to realize the operation of the dual wavelengths. Its transmission formulator is described as follows:

$$T = 1 - 4\cot^2\gamma \frac{\Big(\dfrac{\sin\theta}{\cos E} - \mathrm{tg}E\cos\gamma\Big)^2}{1 - \Big(\dfrac{\sin\theta}{\cos E} - \mathrm{tg}E\cos\gamma\Big)^2} \times \left[1 - \mathrm{ctg}^2\gamma \frac{\Big(\dfrac{\sin\theta}{\cos E} - \mathrm{tg}E\cos\gamma\Big)^2}{1 - \Big(\dfrac{\sin\theta}{\cos E} - \mathrm{tg}E\cos\gamma\Big)^2}\right] \times \sin^2\frac{\delta}{2}. \quad (5)$$

In the equation, d is the thickness of the BF. γ is the angle between the wave vector K of the refracted light and the optic axis. θ is the angle of the incidence.

$$\delta = \frac{2\pi d(n_\mathrm{o} - n_\mathrm{e})\sin^2\gamma}{\lambda\sin\theta}$$

is a relative phase delay between an ordinary and extraordinary rays produced by the optically anisotropic BF medium, E is the angle between the surface of the BF medium and the optic axis of the crystal.

Rotating BF medium around its axis, tuning angle A $(\cos A = (\cos\gamma - \sin\theta\sin E)/(\cos\theta\cos E))$ will be changed. The difference of phase δ will be changed with alternating γ, which will alternate the transmission of the wavelengths and the wavelengths of $T = 1$, and then the purpose of tuning wavelength will be achieved. The difference of phase δ is the periodic function of the wavelength λ, that is $\delta = \delta\ (\lambda)$, Therefore, transmission is the periodic function of the wavelength too: $T = T\ (\lambda)$. When the transmitted spectrum shifts from short wavelength to long wavelength, the separation of the transmission peaks of the BF medium and its full width at half maximum (FWHM) will increase, but with the increasing of the thickness of BF medium, the separation of the transmission peaks of the BF medium and its FWHM will diminish.

In order to make the line width narrower, three chips of the quartz birefringence filter were employed and placed at the Brewster angle 57° (λ = 790 nm) in our experiment, with the proportion of the thickness h 1:2:4 and the thickness of the thinnest chip d = 0.5 mm. The separation of the transmitted peaks is

determined by the thinnest chip and FWHM is determined by the thickest chip. In terms of the dispersion equations for quartz crystal, the transmission curve of the assembled BF medium in the Ti:sapphire waveband was plotted (Fig.1), with $E = 0°$, $A = 31.5°$, $38.5°$, $41.5°$. As shown in Fig.1, rotating BF medium around its axis, the output wavelengths range, from 700 nm to 900 nm, includes two transmission peaks of the BF medium. Generally, the wavelength which is near the peak transmission of BF medium can operate. However, with the same output mirror transmissions at 700 nm–900 nm, the peak wavelengths whose simulated emission cross sections are similar can satisfy the Eq.(4) $P^1_{\rm th} = P^2_{\rm th}$ and the threshold condition of oscillation for the simultaneous dual-wavelength laser, and the operation of dual-wavelength Ti:sapphire can be realized. In addition, at some angles of the BF medium, if the simulated emission cross sections of the two wavelengths in the transmission peak are different, as long as the corresponding transmissions of the BF medium are also different and the pump power is large enough, Eq.(4) can also be satisfied and dual-wavelength laser can also operate.

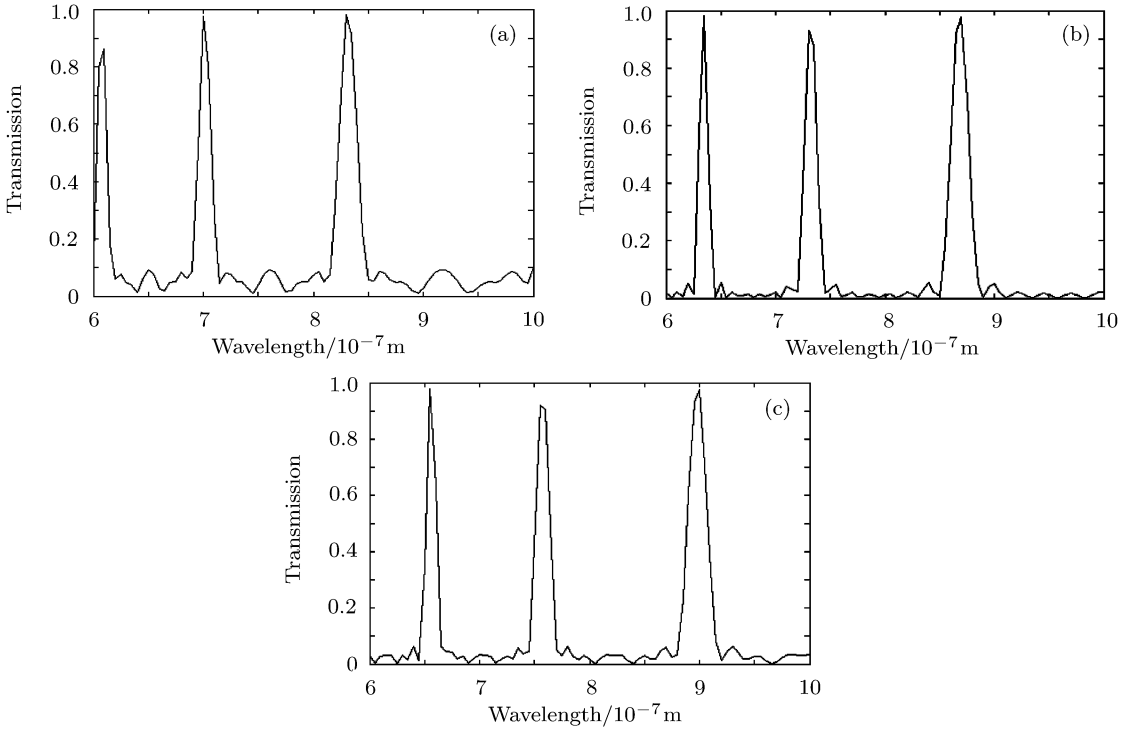


Fig.1. The curve of the transmission of the assembled BF medium (the proportion of the thickness: 1:2:4). (a) $d = 0.5$ mm, $E = 0°$, $A = 31.5°$, (b) $d = 0.5$mm, $E = 0°$, $A = 38.5°$, (c) $d = 0.5$ mm, $E = 0°$, $A = 45°$.

3. Experiment and results

An experimental setup of the tunable dual-wavelength Ti:sapphire laser is illustrated in Fig.2. Dual-wavelength Ti:sapphire laser was pumped by intra-cavity frequency-doubled Nd:YAG laser. The pump laser power of Nd:YAG laser at 532 nm was 23 W, with the repetition rate of 7 kHz and pulse width of 47.6 ns. Dual-wavelength Ti:sapphire flat–flat resonator was optically symmetrical and the cavity length was 150mm. Ti: sapphire crystal(provided by Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences) has dimensions of 7mm×7mm×16mm, and a FOM (Figure of Merit) = 150. The end surfaces of the rod were cut at Brewster angle relative to the c axis. To extract the deposited heat, the laser crystal was mounted on a water-cooled copper plate. M3 was coated for high transmission at 532 nm pump laser and high reflection at 700 nm–900 nm, M4 was coated for a transmission of $T = 15\%$ at 700 nm – 900 nm. The plano-concave lens F with a focal length of 150 mm was used to enhance the density of pump power and improve the coupling efficiency and the output beam quality. The pump beam was focused to a waist diameter of about 400 μm in the crystal. The focal length of pump-induced ther-

mal lens of Ti:sapphire crystal was 195 mm when the pump power was 23 W. The diameter of the output beam at 800 nm in the crystal was 434 μm. It could be seen that the oscillating mode volume matched the pump beam's well, and the laser operated at the power-stable point.

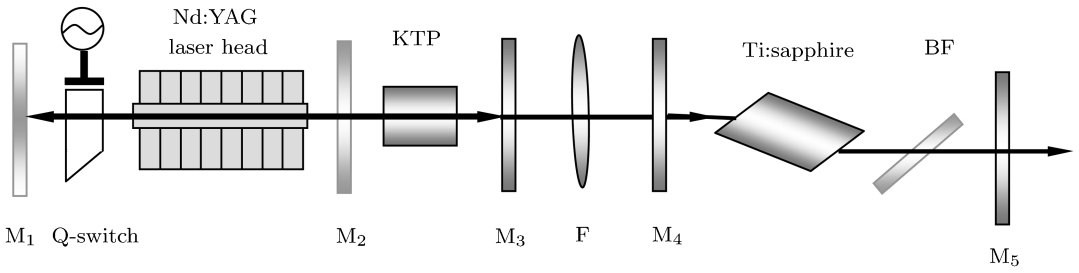


Fig.2. Schematic diagram of the quasi-continuous-wave dual-wavelength Ti:sapphire laser.

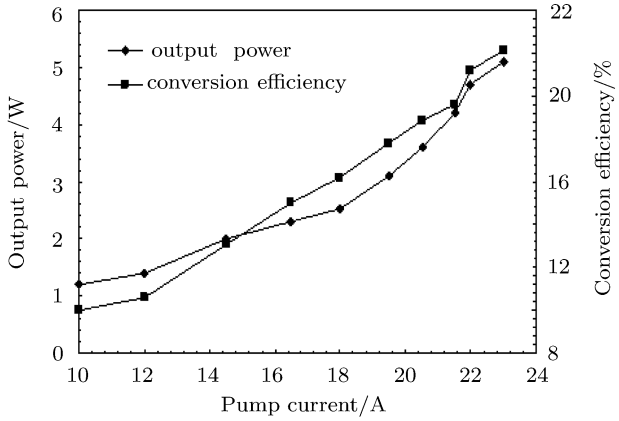


Fig.3. Output power and conversion efficiency of the dual-wavelength Ti:sapphire laser at 744.8 nm and 860.9 nm.

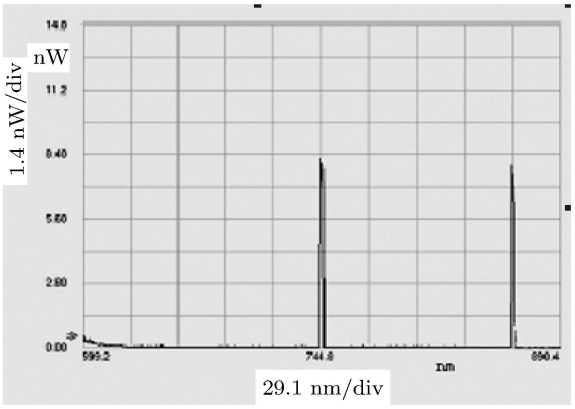


Fig.4. Spectra of the dual-wavelength Ti:sapphire laser operating at 744.8 nm and 860.9 nm. The total output power obtained in this case was 5.1 W.

When tuning angle A was altered from 31.5° to 45°, with d=0.5mm, E = 0°, the output dual wavelengths, with one wavelength range from 700 nm to 756.5 nm, another from 830 nm to 900 mn, were correspondingly tuned. With a pump power of 23 W at 532 nm, a repetition rate of 7 kHz and a pulse width of 47.6 ns, an output power of 5.1 W at 744.8 nm and 860.9 nm with a pulse width of 13.2 ns and a line width of 3 nm has been obtained, it indicates an optical-to-optical conversion efficiency of 22.2% as shown in Fig.3.

Figure 4 shows that a line-width of 3 nm at 744.8 nm and 860.9 nm has been achieved. The two spectral lines are of similar power, duration and shape, which could be accounted for the net gain.[15]

Figure 5 shows a pulse with a duration 13.2 ns generated by the dual-wavelength Ti:sapphire laser. It can be seen that the pulse duration is narrower than that of 532 nm pump laser because of the effect of gain switch. The pulse shape has not any difference with single wavelength, operation and the dual duration of dual wavelengths have the same delay value relative to a pump pulse.

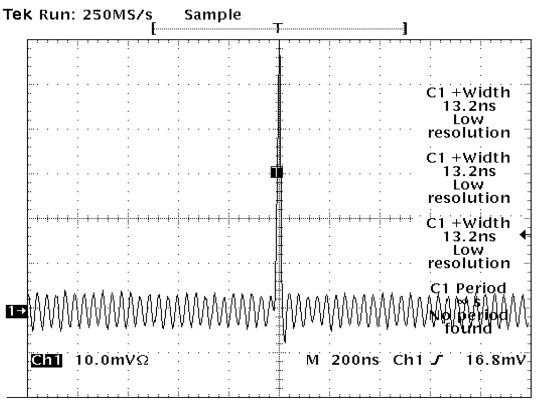


Fig.5. Duration of dual-wavelength Ti:sapphire laser.

As was mentioned above, BF gives higher power

and ensures the dual wavelengths to emit collinearly, but there is an obvious limitation that the separation between the dual wavelengths cannot be changed after fabrication. As a consequence, the range for dual-wavelength operation is limited. And if we rotate the BF medium continuously, dual wavelengths turn to be only one wavelength for the reason that gain competition prevents operating at two frequencies when the net gain of one is substantially lower than that of the other. The single wavelength of 810.0 nm is shown as Fig.6.

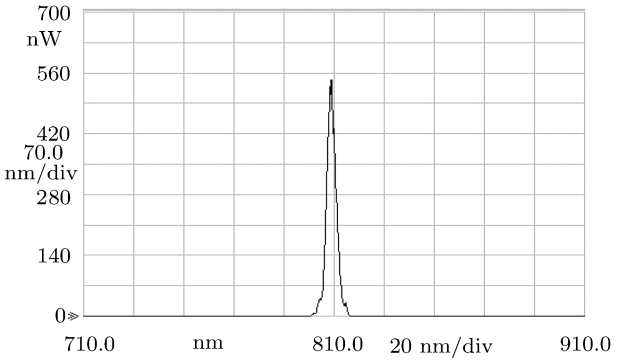


Fig.6. Spectrum of the single wavelength at 810.0 nm.

In the experiments, we found that dual-wavelength operation was difficult to be achieved in comparison with single-wavelength operation. First, since the threshold of dual-wavelength laser is higher than that of single-wavelength laser, the pump power should be larger to overcome the cavity loss at dual wavelengths. Second, in dual-wavelength oscillation, as the tail of the population inversion did not deplete well and the pumping pulse energy was not utilized effectively, the threshold was higher than that of single-wavelength oscillation. Third, the fluctuations observed in the experiment is doubled, in comparison with those observed during single-wavelength operation. This could be elucidated by the competition between the dual wavelengths. According to Norihito Saito's theory,[11] when the energy of the pump pulse changed, the variation of output power of dual wavelengths was twice as much as that of single-wavelength. Namely, stability requirement of dual-wavelength for pump pulse was twice as critical as that of the single-wavelength operation.

4. Conclusions

In this paper, a quasi-continuous-wave, dual-wavelength Ti:sapphire laser has been demonstrated. The rate equation and the simultaneous dual-wavelength oscillation threshold condition have been analysed. A method of obtaining dual wavelengths has been illustrated with a figure. A broad tuning range of the dual-wavelength operation has been achieved. With a pump power of 23 W at 532 nm, a repetition rate of 7 kHz and a pulse width of 47.6 ns, an output power of 5.1 W at 744.8 nm and 860.9 nm with a pulse width of 13.2 ns and a line width of 3 nm has been obtained, it indicates an optical-to-optical conversion efficiency of 22.2%.

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