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Performance of gain-switched all-solid-state quasi-continuous-wave tunable Ti:sapphire laser system*

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We have made a gain-switched all-solid-state quasi-continuous-wave (QCW) tunable Ti:sapphire laser system, which is pumped by a 532 nm intracavity frequency-doubled Nd:YAG laser. Based on the theory of gain-switching and the study on the influencing factors of the output pulse width, an effective method for obtaining high power and narrow pulse width output is proposed. Through deliberately designing the pump source and the resonator of the Ti:sapphire laser, when the repetition rate is 6 kHz and the length of the cavity is 220 mm, at an incident pump power of 22 W, the tunable Ti:sapphire laser from 700 to 950 nm can be achieved. It has a maximum average output power of 5.6 W at 800 nm and the pulse width of 13.2 ns, giving an optical conversion efficiency of 25.5% from the 532 nm pump laser to the Ti:sapphire laser.

Keywords: gain-switched, all-solid-state, quasi-continuous-wave, narrow pulse width
PACC: 4260B, 4260D, 4260, 4255

1. Introduction

With the development of the nonlinear frequency conversion technology, such as optical parametric oscillator, frequency doubling, stimulated Raman scattering and so on, a giant pulse (GP) with narrow pulse width is required. Gain-switching technology is an available method to achieve GP emission by pumping the oscillators with pulses which are short compared to the buildup time of the oscillating mode. The mechanism and characteristics of gain-switching are different from Q-switching. In the buildup process of GP, the laser medium gains an extremely high inverted population in a time shorter than the buildup time of the oscillating mode. As a result, a fast-switching is formed, which switches the cavity Q in so short a time that Q can be regarded as invariable.[1] Recently, a number of gain-switched all-solid-state lasers have been reported:[2−6] Aspin *et al*[2] reported a gain-switched picosecond pulse, which was generated by a semiconductor laser, early in 1982. In 1985, a gain-switched laser-diode-excited monolithic Nd:YAG laser was reported by Owyoung *et al.*[3] At 200 mW of input diode power, 60 mW output with a 200 ns pulse width was achieved. In 2004, Sheng *et al*[4] reported a gain-switched Nd:YVO_4 laser pumped by laser diode (LD), and steady single-mode pulses with pulse-width of 60–140 ns were obtained.

Compared with the above laser mediums, Ti:sapphire crystal is a broadly tunable laser material whose gain-switching qualification has been studied widely.[7−11] Though the upper level lifetime of the Ti:sapphire laser is short (3.2 μs), when pumped by a frequency-doubled Q-switched Nd:YAG laser, which has a narrower pulse width (10–100 ns) and a high single-pulse energy, it will satisfy the qualification of the gain-switching model. A near-diffraction-limit output pulse of 430 mJ in 10 ns at 10 Hz was pro-

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duced by a gain-switched Ti:sapphire unstable laser, reported by Rines and Moulton in 1990.[10] In 2007, Li *et al*[11] reported a Ti:sapphire gain-switched pulse-laser at 780 nm with an energy of 0.86 mJ and a pulse duration of 15 ns.

In this paper, a gain-switched all-solid-state QCW tunable Ti:sapphire laser system is demonstrated, which is pumped by a 532 nm intracavity frequency-doubled Nd:YAG laser. Based on the deduction of the rate equations, a scheme for obtaining high power and narrow pulse-width output through designing the pump source and the resonant cavity of the Ti:sapphire laser is proposed. When the repetition rate is 6 kHz and the length of the cavity is 220 mm, at an incident pump power of 22 W, a tunable Ti:sapphire laser from 700 to 950 nm has been achieved, which has a maximum average power output of 5.6 W at 800 nm with the pulse width of 13.2 ns, giving an optical conversion efficiency of 25.5% from the 532 nm pump laser to the Ti:sapphire laser.

2. Gain-switching theory of Ti:sapphire laser

2.1. Rate equations of Ti:sapphire

First of all, Ti:sapphire crystal is a broadband two-level medium, whose energy level structure can be regarded as an equivalent four-level system. On the other hand, the pump pulse-width of 10–100 ns is much less than the lifetime of Ti^{3+} upper level (3.2 μs) and the Ti:sapphire crystal has no stimulated absorption. Supposing that $N(t)$ denotes the inverted population density of the Ti:sapphire crystal and $\Phi(t)$ the photon density in the cavity, we obtain two nonlinear differential equations that are simpler than the general Statz–Demars equations:

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = W(t)N_0 - N/\tau_f - c\sigma_\mathrm{e}\Phi N, \tag{1}$$

$$\frac{\mathrm{d}\Phi(t)}{\mathrm{d}t} = c\sigma_\mathrm{e}\Phi N - \Phi/\tau_c. \tag{2}$$

Here, $W(t)$ is the pumping rate, N_0 is the population density of the lower level, τ_f, c, σ_e and τ_c denote the lifetime of Ti^{3+} upper level, the light speed in the crystal, the stimulated emission cross-section and the photon lifetime in the cavity, respectively; $\tau_c = 2L/c\delta_c$, in which L is the optical length of the cavity and $\delta_c = 0.4$ is the optical loss of a round trip in the cavity.

2.2. Influencing factors for narrow pulse-width output[9]

At the very beginning of the output pulse buildup, $N_i \approx N_\mathrm{max}$, the spontaneous and stimulated radiations are neglected. From Eq.(1) we have

$$N_\mathrm{max} = N_T[1 - \exp(-W \cdot t_\mathrm{p})], \tag{3}$$

where N_max is the maximum inverted population, N_T is the doping concentration in the Ti:sapphire crystal; and W satisfies

$$W \cdot t_\mathrm{p} = \sigma_\mathrm{a}(\nu_p)E_\mathrm{p}/A \cdot hc_\mathrm{p}. \tag{4}$$

Here $\sigma_\mathrm{a}(\nu_\mathrm{p})$ is the stimulated absorption cross-section, hc_p is the photon energy of the pumping laser, A is the cross-section of the pumping spot, and E_p is the pumping single-pulse energy.

When $\frac{\mathrm{d}\Phi(t)}{\mathrm{d}t} = 0$, photon density $\Phi(t)$ rises to its maximum and N decreases to the threshold N_th which satisfies the equation

$$N_\mathrm{th} = 1/c\sigma_\mathrm{e}\tau_c = \delta_c/2\sigma_\mathrm{e}L. \tag{5}$$

In the period of the output pulse buildup, due to the narrow pump pulse-width, the pump process has nearly finished, which is described as $W(t) = 0$ in Eq.(1). We neglect the spontaneous radiation term and define a parameter $r = N_i/N_\mathrm{th}$ to represent the pump level ($N_i \approx N_\mathrm{max}$ denotes the initial inverted population). The maximum photon density can be obtained

$$\Phi_\mathrm{max} = [(r - 1 - \ln r)/r] \cdot N_i. \tag{6}$$

If a new variable $\varphi(r) = (r-1-\ln r)/r = \Phi_\mathrm{max}/N_i$ is used, the physical significance of $\varphi(r)$ is the conversion ratio of inverted population to photon quantity at the peak point. Obviously, the bigger the $\varphi(r)$ is, the more the inverted population will be consumed and the narrower the output pulse-width will be.

If we define the output pulse width Δt as

$$\Delta t = E/P_\mathrm{p}, \tag{7}$$

where the peak output power P_p satisfies

$$P_\mathrm{p} = \Phi_\mathrm{max} \cdot Vh\nu/\tau_c. \tag{8}$$

In Eq.(8) V denotes the mode volume and ν denotes the frequency of the laser. So the output energy is

$$E = a(N_i - N_f)Vh\nu. \tag{9}$$

Here, $1 < a < 2$, N_f is the surplus inverted population. From Eqs.(7)–(9) we obtain

$$\Delta t = \frac{a(N_i - N_f)}{N_i} \cdot \frac{N_i}{\Phi_{\max}} \cdot \tau_c = a \cdot \tau_c \cdot \eta/\varphi(r), \tag{10}$$

in which $\eta = (N_i - N_f)/N_i$ denotes the extracting efficiency of stored energy. When $\Phi = 0$, $N = N_f$, thus we obtain the relationship between r and η[1]

$$r = -\ln(1-\eta)/\eta. \tag{11}$$

Define $F(r) = \eta/\varphi(r)$, then Eq.(10) becomes

$$\Delta t = \frac{2aF(r)L}{c\delta_c}. \tag{12}$$

From Eq.(12), we can see that if the other parameters keep constant, Δt follows the change of r as a function of $F(r)$. However, when referring to L, we cannot consider the change of Δt as following the change of it, only because the change of L will bring the change of r as a function of $N_{\rm th}$. From Eq.(5), we have

$$L = \delta_c r/2\sigma_{\rm e} N_i. \tag{13}$$

It indicates that when N_i and other parameters are kept constant, the change of cavity length is proportional to r. Defining $F'(r) = \eta r/\varphi(r)$, Eq.(12) becomes

$$\Delta t = \frac{aF'(r)}{c\sigma_{\rm e} N_i}. \tag{14}$$

From $F(r)$ in Fig.1, we can see that when the parameters of the cavity are kept unchanged, the output pulse width becomes narrower as r increases. So increasing the value of r by raising the pumping rate can narrow the output pulse width. $F'(r)$ in Fig.1 shows that if the pump parameter N_i is unchanged and $r > 3$, the output pulse width will be proportional to L or $1/\delta_c$, deduced from Eqs.(5) and (14). Thus shortening the cavity length or increasing the transmission of the output mirror can also narrow the output pulse width. Certainly, the change of the cavity length must be carried out under the conditions that the mode volumes of the 532 nm pump laser and the Ti:sapphire laser are matched well, and the Ti:sapphire laser is operated at the stable-power point in the stable region.

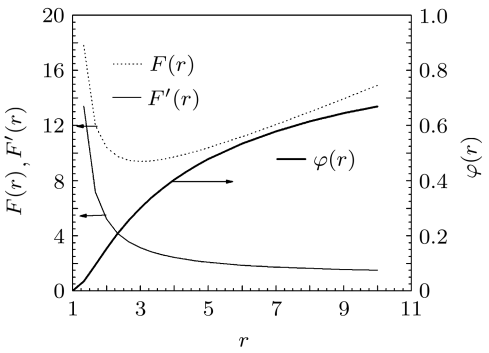


Fig.1. $F(r), F'(r)$ and $\varphi(r)$ as functions of r.

3. Experiments and results

The experimental setup is schematically depicted in Figure 2. The pump source is a 532 nm acousto-optic Q-switched intracavity frequency-doubled Nd:YAG laser with a bilateral-symmetrical cavity. F is a focusing lens with a focal length of 150 mm, which is used to enhance the density of pump power and make the coupling of the pump beam and the oscillating beam better. The Ti:sapphire oscillator consists of a tunable flat-flat reflective mirror (M_4), a flat-flat output coupler (M_5), two dense flint glass prisms and a block of Ti:sapphire with dimensions of 7 mm × 7 mm × 16 mm and figure of merit (FOM) value of 150, which was cut at Brewster angle at both ends with respect to the direction of the c-axis for better coupling with the pump source and lower loss of the Ti:sapphire laser. M_4 is high-reflection coated for 700–950 nm ($R > 99.8\%$) and M_5 coated for a transmission of 15% from 700–950 nm. The absorption coefficient of the 532 nm laser in the Ti:sapphire crystal is 0.9 $\rm cm^{-1}$, with $N_T = 1.4 \times 10^{18}$ /cm, $\sigma_{\rm e} = 3.8 \times 10^{-19}\,\rm cm^2$, $\sigma_{\rm a}(\nu_{\rm p}) \approx 4.9 \times 10^{-20}\,\rm cm^2$, $hc_{\rm p} \approx 3.7 \times 10^{-19} J$, $A = 5 \times 10^{-3}\,\rm cm^2$; the optical loss δ_c for a round-trip in the cavity is 0.4, other losses in the cavity are $a_0 = 0.5$ and $a = 1.5$.

According to the theory given before, first, we carried out experiment on the 532 nm pump source to obtain optimum single-pulse energy (also pumping rate) by tuning the repetition frequency and the pumping power. When the pumping power was 22 W and the repetition frequency was 6 kHz, a maximum single pulse energy of 3.67 mJ was obtained. At this time, the $\rm TEM_{00}$ mode spot radius of the 532 nm pump laser at the focus point was 200 μm and the thermal-lens focus length of the Ti:sapphire crystal

was 195 mm obtained by measurement. To generate high efficiency of the Ti:sapphire laser, the mode of the Ti:sapphire laser should be well matched with that of the 532 nm pump laser in the Ti:sapphire crystal. Besides, taking the thermal-lens effect of the Ti:sapphire crystal into account, to obtain higher output power and better beam quality, the Ti:sapphire laser must be operated at the stable-power point of the U-shaped curve, which is the TEM_{00} mode spot radius in the Ti:sapphire crystal versus the change of the thermal-lens focus length.[12] In addition, to obtain a large stable region for tuning the cavity length, a symmetric cavity of the Ti:sapphire laser should be chosen.

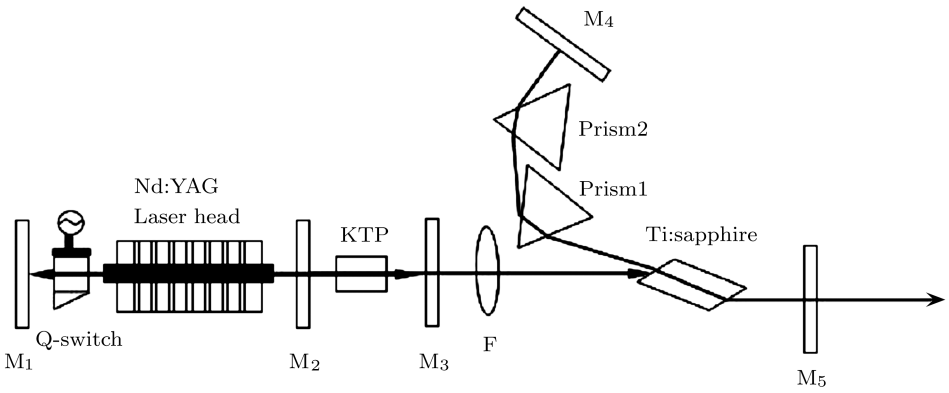


Fig.2. The all-solid-state QCW tunable Ti:sapphire laser system.

Through theoretical calculation, the cavity length of the Ti:sapphire laser was chosen to be 220 mm. As a result, the TEM_{00} mode spot radius ($\omega_1 = 220\,\mu$m) of the Ti:sapphire laser could match the pump beam waist spot radius 200 μm well, and the Ti:sapphire laser could be operated at the stable-power point of the U-shaped curve when the thermal-lens focus length of the Ti:sapphire crystal was 195 mm, as shown in Fig.3.

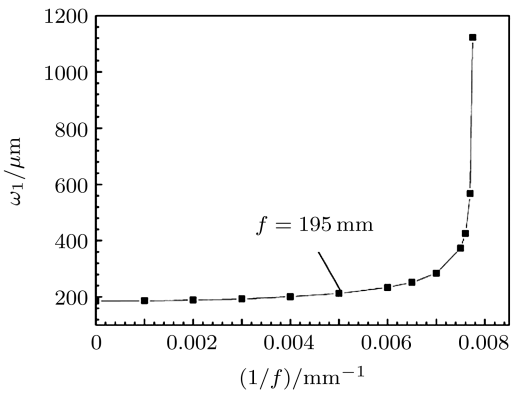


Fig.3. The U-shape curve of the Ti:sapphire laser (ω_1 is the fundamental mode spot radius in the Ti:sapphire crystal, f is the thermal-lens focus length of Ti:sapphire).

By recording the power output and the spectrum of the tunable Ti:sapphire laser using a power meter (Molectron: EPM1000) and an optical spectrum analyser (Agilent Technologies: 6842B) respectively, the tunable output power from 700 to 950 nm is shown in Fig.4, and the optical conversion efficiency corresponding to the power output of Ti:sapphire laser at 800 nm is shown in Fig.5. When the Ti:sapphire laser operated at 800 nm, the threshold of pump power was around 6 W due to the insertion loss of the prisms and the reflection loss of M_5. When the pump power was 22 W, the maximum output power of 5.6 W was achieved, resulting in an optical-optical conversion efficiency of 25.5%. Simultaneously, the output pulse width of 13.2 ns (recorded by an oscilloscope of Tektronix: TDS620B) at 800 nm was obtained when the pulse width of the 532 nm pump laser was 47.6 ns, as shown in Fig.6.

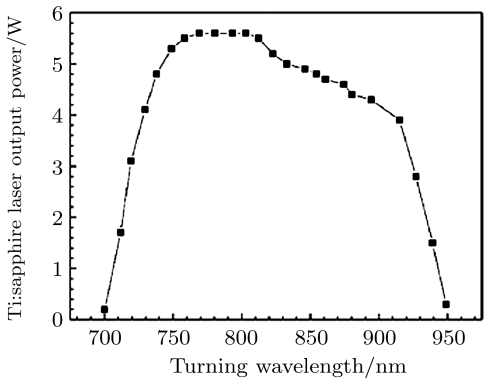


Fig.4. The output power of the tunable Ti: sapphire laser from 700 to 950 nm.

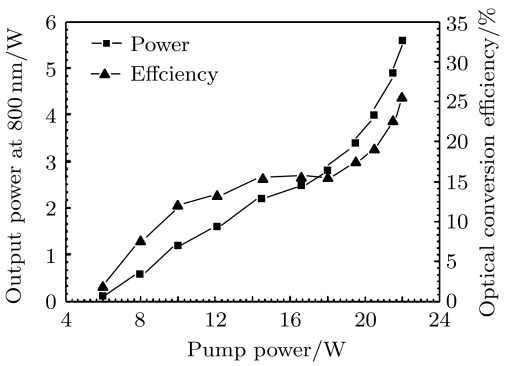


Fig.5. The power output and optical conversion efficiency of the Ti: sapphire laser at 800 nm.

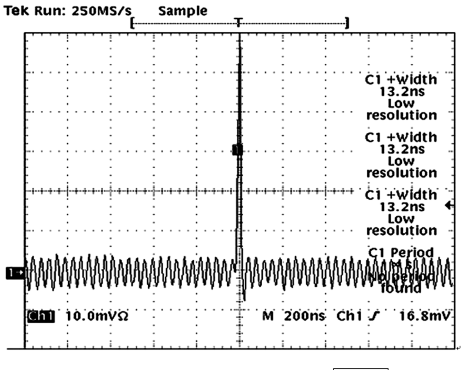


Fig.6. The pulse width of the Ti:sapphire laser at 800 nm.

The influence of r on the pulse width due to changing the pump power as a function of N_i was investigated when other parameters, including the length of the cavity, were already fixed. The theoretical results and the experimental data of the output pulse width at 800 nm following the change of the single-pulse energy E_p as a function of r are shown in Fig.7. The decreasing trend of the output pulse width goes on slowly and the theoretical results agree well with the experimental data of the output pulse width when $r > 2$. When the pump power was 22 W, the single-pulse energy was 3.67 mJ. At this point, $r = 5.4$ was obtained and the theoretical and the experimental values of the output pulse width were 10.9 ns and 13.2 ns respectively. As we know, the light intensity at the pump beam's cross-section in the centre part is stronger than that of the other parts. As a result, the inverted population in the centre part is more than that of the parts far away, so the buildup time of the pulse in the centre part is shorter than that of the other parts along the radial direction. Actually, the output pulse width is a little wider than the theoretical value because the output pulse is made of a lot of pulses from centre to edge.

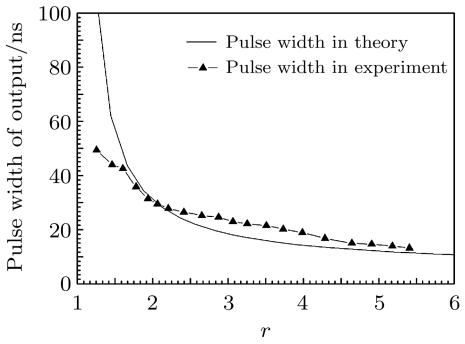


Fig.7. The pulse width versus r caused by pump power.

The effect of cavity length on the output pulse width was investigated too. As shown in Ref.[11], the output pulse width increased with the increase of L which is a function of r ($r > 3$), and its changing trend accorded with $F'(r)$ in Fig.1. However, the variation of L would affect the whole design of the laser, so we just fixed it at 220 mm in this Ti:sapphire laser.

4. Conclusions

In this paper, we have demonstrated a gain-switched all-solid-state QCW tunable Ti:sapphire laser system, which was pumped by a 532 nm intracavity frequency-doubled Nd:YAG laser. After studying the theory of gain-switching and the influencing factors of the output pulse width, an effective method for obtaining high power and narrow pulse width output was proposed. Then we verified the theory through changing the pumping rate and the cavity length. When the repetition rate was 6 kHz and the length of the cavity was 220 mm, at an incident pump power of 22 W, the tunable Ti:sapphire laser from 700 to 950 nm was achieved, with the maximum average power output of 5.6 W at 800 nm and the pulse width of 13.2 ns, giving an optical conversion efficiency of 25.5% from the 532 nm pump laser to the Ti:sapphire laser.

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