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RESEARCH

Design and construction of a tunable pulsed Ti:sapphire laser

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Abstract In this paper, design and construction of a tunable pulsed Ti:sapphire laser and numerical solution of the corresponding rate equations are reported. Rate equations for a four-level system are written and their numerical solution is examined. Furthermore, an optical setup is introduced. In this setup, a Ti:sapphire crystal is longitudinally pumped by the second harmonics of a Q-Switched Nd:YAG laser, and a prism is used as a wavelength-selective element as well. This setup is established for two 10 and 50 % transmission output couplers. In case of using the 10 % coupler, the output energy of the laser, for the pump energy of 36 mJ, is pulses with 3.5 mJ energy and for the 50 % coupler, with 50 mJ of pump energy, pulses with 10 mJ energy are generated. A wavelength tuning range of more than 160 nm is possible. The repetition rate of this laser is 10 Hz and the temporal duration of the pulses is about 30 ns.

Keywords Nano second · Tunable · Rate equations · Prism · Pulsed Ti:sapphire laser · Nd:YAG

List of symbols

Φ	Photon density
n	Center frequency of laser pulse in resonator
σ	Stimulated emission cross-section
g	Small-signal gain coefficient
A_{mn}	Rate of spontaneous transition between energy levels E_m and E_n
S_{mn}	Non-radiative emission rate between energy levels E_m and E_n
W_{mn}	Stimulated transition probability between energy levels E_m and E_n
l	Length of Ti:sapphire crystal
L_c	Length of resonator
V	Velocity of light in Ti:sapphire crystal
δ	Single-pass loss in resonator
τ_0	Upper laser level lifetime
$\tau_{ph} = \frac{L}{\delta c}$	Photon lifetime in resonator
ω	The radius of the pump beam on the crystal
n_i	Population density at every energy level E_i, $i = 1, 2, 3, 4$
n_{tot}	Total population density
$\mathcal{G}(\mathcal{V})$	Line shape factor
R_{14}	Pump rate from energy level E_1 to E_4

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Introduction

In 1960, Maiman [1] invented the first laser. The active medium of this laser was a ruby ($Cr{:}Al_2O_3$) crystal. Twenty-two years later, Moulton [2] reported the development of the first Ti:sapphire laser by substituting titanium ion instead of chromium ion as an impurity into the sapphire crystal. In 1986 by growth of crystals with smaller losses, construction of the first Ti:sapphire laser that operated at room temperature was reported [3, 4]. In the 1990s, applications of this laser expanded dramatically, which resulted from the growth of Ti:sapphire crystals with considerably smaller losses and also advances in ultrashort-pulse generation methods [5]. The titanium sapphire

($Ti{:}Al_2O_3$) laser is the broadest tunable solid-state laser capable of emitting light in a wide area. Ti:sapphire lasers have been replacing dye lasers as tunable lasers and ultrashort-pulse lasers [6].

Nowadays, using pulsed lasers with varying wavelengths is an interesting field of research [7, 8]. One of the most important applications of the these types of lasers is the pulse THz radiation, which could be generated by the mode-locked Ti:sapphire laser owing to their high output power, excellent frequency stability, operational robustness, and large continuously tuning range in wavelengths [9].

In this paper, the theory of a tunable pulsed Ti:sapphire laser according to the rate equations is reported. This theory is aimed to describe the experimental results of this laser. In this paper, we used the approach mentioned in Moulton [10] for deriving the rate equations. In the next section, rate equations and the corresponding numerical solution and also construction of a tunable pulsed Ti:sapphire laser are presented.

Rate equations of a tunable pulsed Ti:sapphire laser

The absorption spectrum of the Ti:sapphire crystal is in the range of 400–600 nm and its peak is at 495 nm. Emission spectrum of this laser is in the range of 660–1,100 nm and its peak is at 795 nm [9]. The broad absorption and emission spectra depend on the structure of the energy levels. The energy levels of a Ti:sapphire crystal split into two energy bands that consist of many closely spaced energy levels. This is the basic reason why a Ti:sapphire laser can operate within a tunable wavelength range. In the case of a resonator with a wavelength-selection element, the laser will oscillate at one tuned wavelength. E_3 is the upper state, and E_2 is one state in the lower energy band. The resonator causes a transition of the population inversion from the E_3 to the E_2 level and the laser oscillates at λ wavelength. Based on the above description and the rate equations of tunable solid-state lasers [10], a four-energy-level system can explain a tuned wavelength operation of a Ti:sapphire laser. The rate equations can be written as follows:

$$\frac{dn_1}{dt} = n_4(A_{41} + S_{41}) + n_2 S_{21} - n_1 R_{14} \tag{1}$$

$$\frac{dn_3}{dt} = n_4 S_{43} + n_2 W_{23} u(\mathcal{V}) - n_3 (W_{32} u(\mathcal{V}) + A_{32} + S_{32}) \tag{2}$$

$$\frac{dn_4}{dt} = n_1 R_{14} - n_4 (A_{41} + S_{41} + S_{43}) \tag{3}$$

$$\frac{d\Phi}{dt} = n_3 W_{32} - n_2 W_{23} u(\mathcal{V}) - \frac{\Phi}{\tau_{ph}} + \alpha n_3 \tag{4}$$

In the four-level system of a Ti:sapphire laser, $n_2 \approx n_4 \approx 0$, so that the population inversion density $\Delta n \approx n_3 - \frac{g_3}{g_2} \approx n_3 \approx n$. Considering $A_{32} \gg S_{32}$ (the transition from level E_3 to level E_2 is dominating, and non-radiative transitions can be neglected), $S_{43} \gg A_{41}$ then $S_{43} \ll S_{41}$ (because the population in level E_4 decays immediately to level E_3 non-radiatively) and $\frac{dn_4}{dt} \approx 0$ (since the population of the pump level de-excites rapidly to the upper laser level E_3 [11]), we have $n_4 S_{43} = n_1 W_{14} = Wp$ from Eq. (3), where W_p stands for the pumping rate. To obtain rate equations we can use these relations [12, 13]:

$$W_{mn} = \frac{c\sigma_{mn}(\mathcal{V})}{h\mathcal{V}\mathcal{G}(\mathcal{V})} \tag{5}$$

$$\Phi = \frac{u(\mathcal{V})}{h\mathcal{V}\mathcal{G}(\mathcal{V})} \tag{6}$$

Then using the above relations and the Eqs. (2) and (4) we have:

$$\frac{dn}{dt} = n_1 R_{14} - c\sigma_{mn}(\mathcal{V}) n_3 \Phi - n_3 A_{32} \tag{7}$$

$$\frac{d\Phi}{dt} = c\sigma_{mn}(\mathcal{V}) n_3 \Phi - \frac{\Phi}{\tau_{ph}} + \alpha n_3 \tag{8}$$

(N_0 is the concentration of Ti^{+3}). So the normalized rate equations of a tunable pulsed laser are as follows:

$$\frac{dN}{dt} = W_p - \frac{c\sigma}{\Pi\omega^2 L_c} N\varphi - \frac{N}{\tau_0} \tag{9}$$

$$\frac{d\varphi}{dt} = \frac{c\sigma}{\Pi\omega^2 L_c} N(\varphi + 1) - \frac{\varphi}{\tau_{ph}} \tag{10}$$

where N is the normalized population inversion, which is also denoted as Δn.

Numerical calculation of rate equations

The Eqs. (9) and (10) can be solved numerically. For parameters we used the typical experimental values: $N_0 = 3 \times 10^{19}\ \mathrm{cm}^{-3}$, $l = 1.5$ cm, T is the transmission of the output coupler, and the single loss in the cavity $\delta = \beta - \frac{1}{2}\ln(1 - T)$.

We used the values $a = 0.05$ for the total loss of the cavity and $\tau_0 = 3.2\ \mu s$ for the self-emission lifetime. The pumping rate is assumed to be Gaussian:

$$W_p = \frac{2E_p}{\sqrt{2\Pi} T_0 h\nu_p} \left(1 - \exp(-\alpha_p l)\right) \exp\left(\frac{-2t^2}{T_0^2}\right) \tag{11}$$

where E_p is the pumping energy, T_0 the pulse width of the pump laser, and α_p the absorption coefficient of the Ti:sapphire crystal at the wavelength of the pump laser.

The gain of the laser is related to the emission cross-section $\sigma(v)$ of the Ti:sapphire crystal. $\sigma(v)$ is itself related to the wavelength (or frequency), which can be described as [14]:

$$\sigma(\mathcal{V}) = \sigma_s \frac{<m>^p}{p!} \quad (12)$$

$$p = \frac{(v_0 - v)}{v_p} \quad (13)$$

where v is the laser frequency, v_0 (cm^{-1}) equals 16,178, v_p (cm^{-1}) equals 543.4, $<m>$ equals 7.074 and σ_s (10^{-21} cm^2) equals 1.663.

Calculated results from rate equations

The establishment of the pulse is shown in Fig. 1. At the beginning of the pump pulse, the population inversion $\Delta n(t)$ increases rapidly, while at the end of the pump pulse, with the pump rate decreasing and the photon densities at the wavelength of the laser increasing, $\Delta n(t)$ rises slowly. As soon as photon densities reach a certain value, laser oscillation sets in (in calculations for the 50 % transmission output coupler shown in Fig. 1, we have assumed the numerical values $\delta = 0.4$, $\lambda = 790$ nm, $E_p = 50$ mJ). The results of rate equations for the 50 % coupler are shown in Table 1.

Experimental setup

Figure 2 shows the optical setup of the tunable pulsed Ti:sapphire laser. The beam from a pulsed frequency-doubled Nd:YAG laser was leaded by mirrors 5 and 6 to pump the Ti:sapphire crystal. Gain-switching performance is obvious in longitudinally pumped Ti:sapphire laser because the width of pump pulse is much less than the upper level lifetime (3.2 µs). The focal length of the lens is 400 mm, the distance between the lens and the crystal is 300 mm, and the diameter of the pumping spot at the face of the crystal is about 2 mm. The resonator consists of the parts 8–11. Prism 10 acts as a wavelength-selection element. Mirror 11 acts as an output coupler for the resonator. This setup is established for both 10 and 50 % transmission output couplers. As prism 10 introduces dispersion into the feedback path, mirror 8 is adjusted to produce feedback at laser wavelength. Its coating provides a reflection of 100 % at wavelengths from 700 to 900 nm. The wavelength can be tuned by adjusting mirror 11.

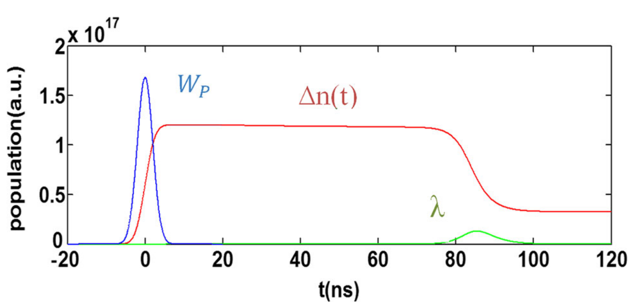


Fig. 1 Establishment of pulse

Table 1 Results of rate equations

Pump energy	50 mJ
Output energy of laser	14.6 mJ
Pulse width	14 ns
Delay time	110 ns

Experimental results

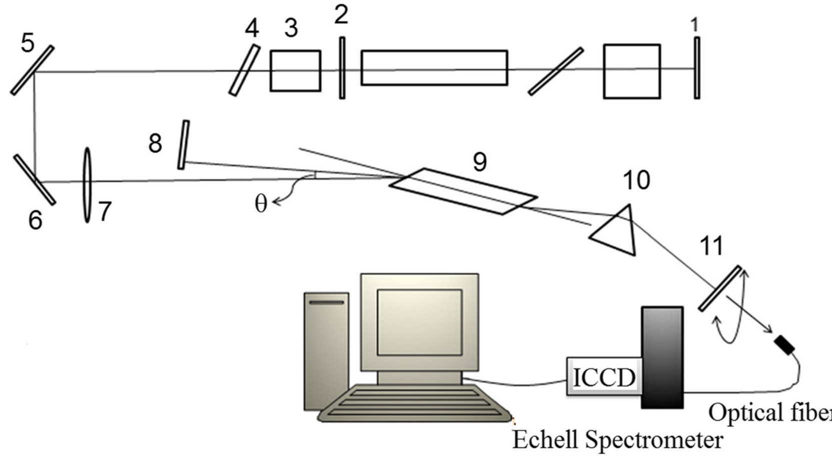
This setup is established for both 10 and 50 % transmission output couplers. In case of using the 10 % coupler, the output energy of the laser for the pump energy of 36 mJ is pulses with 3.5 mJ energy. Figure 3 shows the output spectrum of the laser with the output coupler adjusted at different times. As you can see in Fig. 3, the tunable range is over 160 nm. Due to the coating of the mirrors, tuning range is limited. The repetition rate of the laser is 10 Hz and the temporal duration of the pulse is about 34.8 ns which is shown in Fig. 4. For the case of the 50 % coupler, pumping energy can be more powerful. In this case, the output energy of the laser for the pump energy of 50 mJ is pulses with 10 mJ energy at 10 Hz which results in a 20 % laser efficiency.

The output spectrum and the temporal duration of the pulse for the 50 % output coupler are shown in Figs. 5 and 6, respectively. In the case of using an output mirror with 10 % transmission, the pump energy threshold of cavity is lower and has a relatively narrow bandwidth. On the other hand, in the case of using the 50 % transmission mirror, instead of the 10 %, output energy of the laser increases and in conclusion the efficiency rises as well. Furthermore, in the case of using the 50 % coupler, the pulse width of the laser decreases.

The difference between the energy obtained by rate equations and the experimental setup is because of the angle θ [15]. The angle θ between the pump beam and the cavity axis is because of the fact that the active region is not able to cover the oscillating region completely (in this case population inversion cannot participate in forming laser wavelengths completely).

In this paper the wider tuning range, over 160 nm, has been achieved compared to that of Ref. [10], 110 nm, with a simpler setup. Also for the first time, this paper

Fig. 2 Optical setup of tunable pulsed Ti:sapphire laser. (*1*–*2*) Pulsed Nd:YAG laser, (*3*) KTP, (*4*) filter (1,064 nm HR and 532 nm HT) (*5*, *6*) 45° placed 532 nm high reflectivity mirror, (*7*) lens, (*8*) HR mirror (700–900 nm), (*9*) Ti:sapphire rod, (*10*) prism, (*11*) output coupler



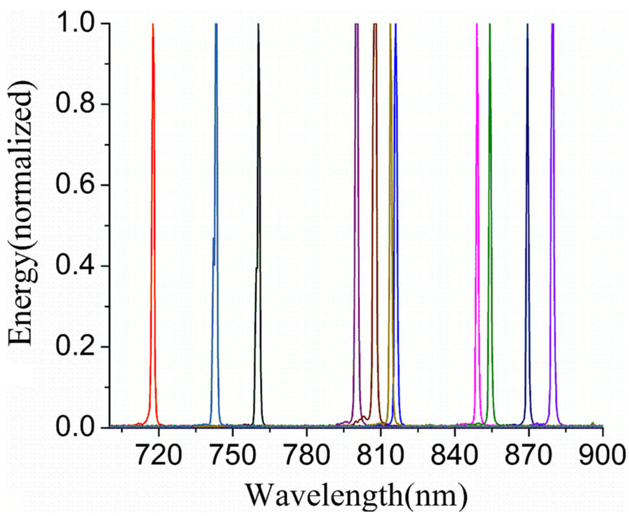


Fig. 3 Output spectrum at different times for the 10 % output coupler

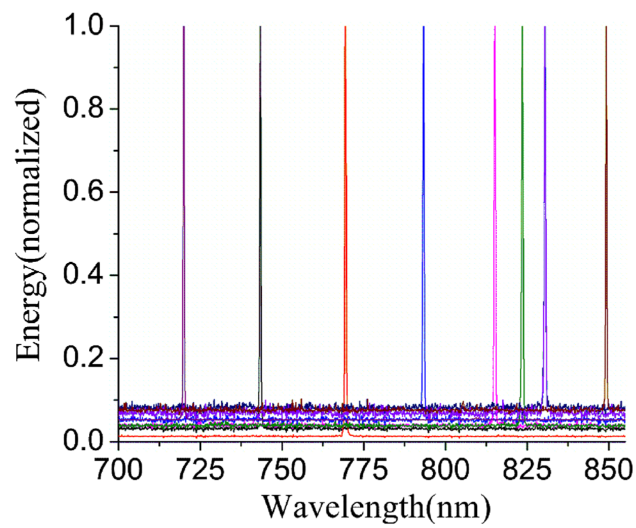


Fig. 5 Output spectrum at different times for the 50 % output coupler

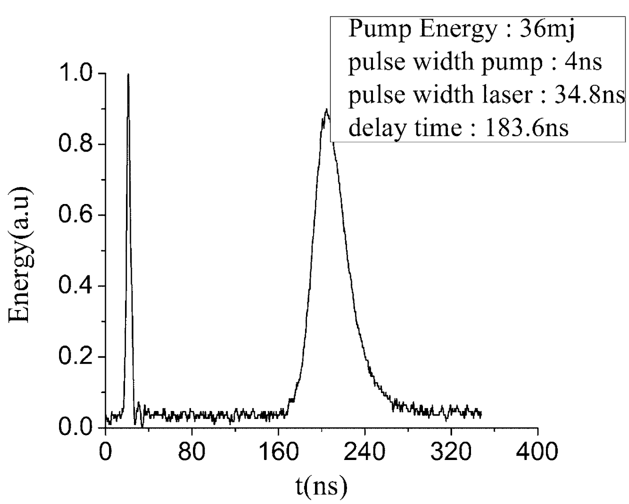


Fig. 4 Pulse width for the 10 % output coupler

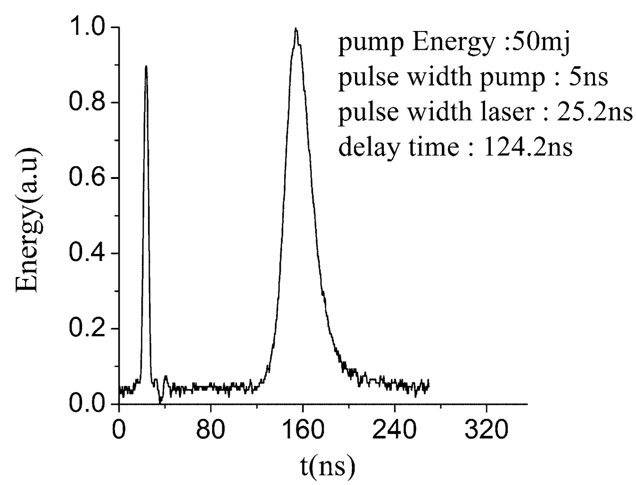


Fig. 6 Pulse width for the 50 % output coupler

discussed the advantages and disadvantages of the output mirrors with 10 and 50 % transmission. It was observed that in case of using the output mirror with 10 % transmission, the width of the output beam was 0.2 nm, while in case of using the output mirror with 50 % transmission the width of the output beam was 0.34 nm. Also in case of using the 10 % output mirror, the tuning range increased. While in case of using the 50 % output mirror, the output energy increased and the temporal duration of the pulse decreased. Therefore, depending on the importance and priority of the purpose, energy of the pulse, tuning range, the output beam width and the temporal duration, the transmittance of the output mirror is chosen as 10 or 50 %.

Conclusions

The concept of a four-energy-level system is used to explain the single-wavelength operation of a Ti:sapphire laser. The results of numerical calculation are given. A single-wavelength pulsed Ti:sapphire laser with a simple optical setup is constructed for two 10 and 50 % transmission output couplers with a tuning range of more than 160 nm. The setups for both output couplers are explained and their advantages are discussed. In case of using the 10 % coupler, the output energy of the laser for a pump energy of 36 mJ is pulses with 3.5 mJ energy at 10 Hz. The duration of these pulses are 34 ns while the delay time between pump and laser beams is 183 ns. For the 50 % coupler, the output energy of the laser for the pump energy of 50 mJ is pulses with 10 mJ of energy at 10 Hz. The duration of these pulses is 25 ns while the delay time between the pump and laser beams is 124 ns. Rate equations predicted the output energy of 14 mJ, which shows a good agreement with the experimental results.

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