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Specific features of lasing in Ti^{3+}: Al_2O_3 crystals pumped by two pulses of a Nd:YAG laser

Yu V Zaporozhchenko, R G Zaporozhchenko, V S Mezen, N A Tylets

***Abstract*. The results of experiments and numerical calculation of parameters of a Ti^{3+}:Al_2O_3 laser pumped by one and two pulses of the second harmonic from a Nd:YAG laser are presented. It is shown that upon excitation by two pulses separated by a time delay, the laser efficiency increases compared to that for one-pulse pumping owing to a more efficient use of the energy of each of the pulses for the pumping in the linear-absorption regime and a faster change in the population of the working level.**

***Keywords*:** *double-pulse pump, Ti^{3+}:Al_2O_3 laser.*

1. Introduction

The Ti^{3+}:Al_2O_3 lasers are well known as a source of coherent tunable emission in the visible and IR regions of the spectrum. Nevertheless, the generation of high-power radiation with a narrow spectral width in these lasers remains a rather complicated problem. This is caused by the fact that the selective elements used for narrowing the spectral line introduce high losses in a laser cavity, which increases the laser threshold and the lasing development time and decreases the laser efficiency. The problem is commonly solved by using a master oscillator in combination with an amplifier, as well as injection [1] and self-injection [2] of radiation from a Ti^{3+}:Al_2O_3 laser.

Moreover, preliminary excitation of an active medium by double pump pulses has been successfully used in tunable dye lasers [3]. In this case, a second high-power pulse is sent to the system after its excitation by the first pump pulse at a relatively small excess over the threshold, and the second pulse causes efficient superregenerative amplification of radiation present in the laser cavity. The application of this method to dye lasers provided an increase in the laser efficiency by $\sim 30\,\%$, and the radiation linewidth was decreased by a factor of about two.

It is of interest to study the application of this pumping method to Ti^{3+}:Al_2O_3 lasers. A substantial difference of the Ti^{3+}:Al_2O_3 laser from dye lasers is that the former has a large lifetime of the excited state (~ 3.2 μs) and a relatively small amplification cross section ($\sigma \sim 10^{-19}$ cm^2 [4]. Because of this, lasing in Ti^{3+}:Al_2O_3 lasers is developed in a time that is considerably larger than the typical pulse duration in Q-switched lasers (~ 10 ns), which causes instability of parameters of a Ti^{3+}:Al_2O_3 laser and the jitter of its output radiation.

The aim of this work was to study the feasibility of improving the output characteristics of a Ti^{3+}:Al_2O_3 laser and controlling its energy, spectral, and time parameters upon pumping by two pulses of the second harmonic ($\lambda = 532$ nm) from a Nd:YAG laser with electrooptical *Q*-switching.

2. Experiment

The Ti^{3+}:Al_2O_3 laser was pumped by double pulses of the second harmonic from a Nd:YAG laser (we used an LS-2134D laser produced by the Lotis-TII Joint Venture).

The laser worked at a pulse repetition rate of 10 Hz and produced second-harmonic pulses with an energy of about 150 mJ. The output beam was 6 mm in diameter, the half-amplitude duration of radiation pulses was 10 – 12 ns, and the angular divergence of laser radiation at a level of 0.5 was about 2.5 mrad.

A special design of a laser head provided simultaneous pumping of two laser elements, each having its own cavity, by one flash lamp. The time delay between two radiation pulses with the same energy was determined by the switching times of electrooptical shutters, and it could be varied in a range of 0 – 80 μs with a step of 1 μs. In addition, the laser design provided fine tuning of the switching time with an accuracy of about 5 ns. By using polarisers, we combined output radiation from two laser cavities at the fundamental frequency (1064 nm) in one beam and doubled the beam frequency in a KTP crystal. We used type II phase matching in the crystal (the oee interaction).

The optical scheme of the tunable Ti^{3+}:Al_2O_3 laser is presented in Fig. 1. The laser cavity had an optical length of about 400 mm, and Ti^{3+}:Al_2O_3 active elements *4* were 9 mm long and had Brewster faces. The transmission of both elements at 532 nm was about 22 %, with the ratio of the absorption coefficient on the pump wavelength to the one on the lasing wavelength ~ 100. The pump radiation was focused into the active crystal by a lens *3* with a focal distance of ~ 500 mm. The transmission of output mirror *5* at $\lambda = 770$ nm was $\sim 80\,\%$. A three-prism dispersion element *7* and intracavity telescope *8* provided spectral selec-

Yu V Zaporozhchenko, V S Mezen, N A Tylets Belarussian-Japanese Joint Venture 'Lotus TII', ul. Surganova 6, 220072 Minsk, Belarus
R G Zaporozhchenko B I Stepanov Institute of Physics, National Academy of Sciences of Belarus, prosp. F.Skoriny 70, 220072 Minsk, Belarus

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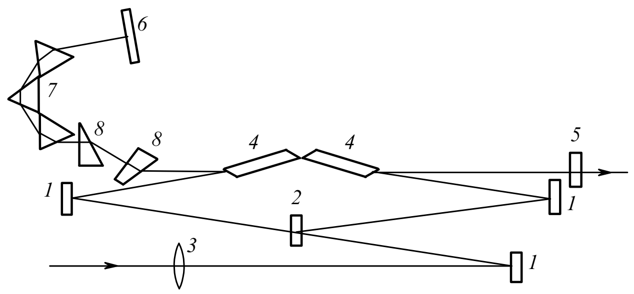

Figure 1. Optical scheme of the Ti^{3+}:Al_2O_3 laser: (*1*) mirrors with $R = 99.9\,\%$ at 532 nm; (*2*) beamsplitter with $R = 50\,\%$ at 532 nm; (*3*) focusing lens; (*4*) Ti^{3+} : Al_2O_3 active elements; (*5*) output mirror; (*6*) totally reflecting plane mirror; (*7*) three-prism dispersion element; (*8*) intracavity prism telescope.

tion and wavelength tuning of the output radiation. In this work, we did not optimise parameters of Ti^{3+}:Al_2O_3 crystals and the reflectivity of the output mirror for obtaining the maximum efficiency.

The laser radiation energy was measured with an Rm-3700 pyroelectric meter (Laser Probe). The time parameters of lasers were measured with an S1-75 oscillograph and an LFD-2 photodiode. The spectral characteristics of radiation were measured and controlled with an MSD-1000 monochromator (Solar TII) with a resolution of 0.01 nm.

The results of our measurements of the efficiency, the tuning range, and time characteristics of the Ti^{3+}:Al_2O_3 laser upon two-pulsed pumping were compared with the similar data obtained by pumping the laser with one pulse whose energy was chosen equal to the total energy of double pump pulses.

The main energy dependences (see Fig. 2) were studied near the maximum of the tuning curve of the Ti^{3+}:Al_2O_3 laser at 770 nm. The delay $\Delta\tau$ between the two pump pulses in the case of two-pulse pumping is taken equal to the time between their peaks. Upon pumping by one pulse with an energy of 150 mJ, which corresponded to exceeding the laser threshold by a factor of about 2.5, the delay of the output laser pulse relative to the pump pulse was ~ 28 ns, with the output pulse duration and the laser efficiency being equal to $\sim 12 - 13$ ns and 22 %, respectively.

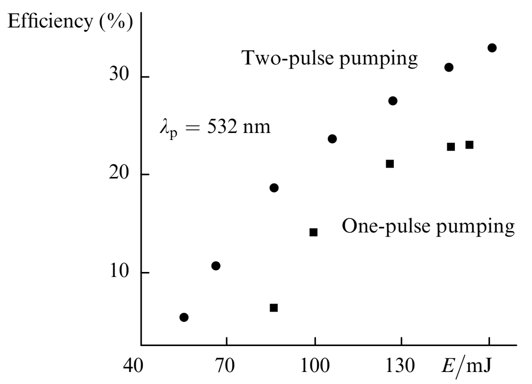

Figure 2. Ti^{3+}:Al_2O_3 laser efficiency for two- and one-pulse pumping schemes.

In the case of two-pulse pumping with pulse energies of about 70 and 80 mJ ($\Delta\tau \sim 40$ ns), the output laser power reached a maximum within 18 ns after the second pump pulse, and a change in the time delay between the pump pulses from ~ 10 ns to the time of appearance of lasing in the Ti^{3+}:Al_2O_3 crystal under the action of the first pump pulse (~ 60 ns) had only a weak effect on the laser efficiency. One can see from Fig. 2 that the laser efficiency at the maximum of the tuning curve in the case of two-pulse pumping was greater by a factor of about ~ 1.5 than that for the laser pumped by one pulse.

Note that in the case of an appropriately chosen $\Delta\tau$, a change from one-pulse pumping to two-pulse pumping increases the Ti^{3+}:Al_2O_3 laser efficiency at the edges of the tuning range by a factor of more than two and the tuning range expands from 675 – 980 nm to 660 – 1015 nm. In both cases, the spectral width of laser radiation is ~ 0.08 nm.

If the energy of the first pump pulse exceeds the Ti^{3+}:Al_2O_3 laser threshold, the accuracy of time synchronisation of the laser could be considerably improved compared to the case of one-pulse pumping by choosing an appropriate time delay between the pump pulses. For instance, a change from the one-pulse pumping to the two-pulse pumping with $\Delta\tau = 40$ ns decreased the jitter of Ti^{3+} : Al_2O_3 laser pulses at the maximum of the tuning range from ~ 3 to ~ 1.5 ns.

3. Numerical calculation

To analyse the experimental results, we calculated numerically the development of lasing in the Ti^{3+}:Al_2O_3 laser pumped by single and double radiation pulses. The active medium was modelled by a four-level scheme [4], and the calculation was made for the optical scheme presented in Fig. 1. To simplify the simulation conditions, the active elements (Ti^{3+}:Al_2O_3 crystals) were assumed to be pumped from one side. Because the pump pulse duration was considerably greater than the phase relaxation time of the active medium ($\tau_1 \gg 1/\gamma_1$, where $\gamma_1 \sim 10^{13}$ s^{-1} is the width of the $^2T_{2g}$ level [4]), lasing was analysed in the quasi-stationary approximation, i.e., we neglected the polarisation of the active medium.

The system of equations describing lasing contained equations for the fields of pump waves E_p and laser waves $E_g^{\pm}$, propagating in opposite directions, and equations for the level populations N_i:

$$\frac{\partial E_p}{\partial t} + \upsilon_p \frac{\partial E_p}{\partial z} = -G_p E_p (N_1 - N_2) - G_1 E_p,$$

$$\frac{\partial E_g^+}{\partial t} + \upsilon_g \frac{\partial E_g^+}{\partial z} = G_g E_g^+ (N_3 - N_4) - G_2 E_g^+ + \sigma_s^+ N_3, \quad (1)$$

$$\frac{\partial E_g^-}{\partial t} - \upsilon_g \frac{\partial E_g^-}{\partial z} = G_g E_g^- (N_3 - N_4) - G_2 E_g^- + \sigma_s^- N_3,$$

$$\frac{dN_1}{dt} = \gamma_1 N_4 - \alpha E_p^2 (N_1 - N_2),$$

$$\frac{dN_2}{dt} = \alpha E_p^2 (N_1 - N_2) - \gamma_2 N_2, \quad (2)$$

$$\frac{dN_3}{dt} = -\beta\left[(E_g^+)^2 + (E_g^-)^2\right](N_3 - N_4) + \gamma_2 N_2 - \frac{N_3}{T_1},$$

$$N_4 = N_0 - (N_1 + N_2 + N_3).$$

Here, γ_1 and γ_2 are the widths of the levels ${}^2T_{2g}$ and ${}^2E_g$; $\alpha = \sigma_{em}/\hbar\omega_p$; $\beta = \sigma_{ex}/\hbar\omega_g$; σ_{em}, σ_{ex}, and σ_s are the cross sections for absorption and stimulated and spontaneous emission; ω_p, ω_g are the pump and laser frequencies; T_p is the luminescence lifetime; υ_p and υ_g are the phase velocities of pump and laser radiation; $G_p = \upsilon_p\sigma_{em}/2$ and $G_g = \upsilon_g\sigma_g/2$ are the amplitude coefficients for pump radiation absorption and laser radiation amplification; G_1 and G_2 are nonresonant losses for pump and laser radiation; N_0 is the density of active Ti^{3+} ions.

The initial and boundary conditions had the form

$$N_1(t=0) = N_0, \quad N_i = 0, \quad i = 2-4,$$

$$E_g^{\pm}(t=0, z) = 0,$$

$$E_p = E_0 \exp\left[-2\ln 2\left(\frac{t-t_0}{\tau_p}\right)^2\right],$$

$$E_g^{+}(t, z=0) = R_1 E_g^{-}(t, z=0),$$

$$E_g^{-}(t, z=L_0) = R_2 E_g^{+}(t, z=L_0),$$

where τ_p is the pump pulse duration; L_0 is the optical cavity length; and R_1 and R_2 are the amplitude reflectivities of the cavity mirrors at the laser wavelength.

The calculations were made for the following values of parameters of the active medium: $\sigma_{em} = 10^{-19}$ cm^2; $\sigma_{ex} = 4\times10^{-19}$ cm^2; $N_0 = 2\times10^{18}$ cm^{-3}; $T_1 = 3.2\times10^{-6}$ s; $\gamma_1 = 10^{13}$ s^{-1}; $\gamma_2 = 3.2\times10^{12}$ s^{-1}; $\sigma_s = \hbar\omega_g N_0 \Delta\Omega/4\pi T_1$; $R_1 = 1$, $R_2 = 0.2$; $L_0 = 400$ mm; $\Delta\Omega = 10^{-2}$ rad (the solid angle in which the pump radiation propagated). The loss of radiation in separate elements of the cavity was determined by fitting the experimental data to the results of calculation for single-pulse pumping.

The system of equations (1), (2) was solved by using the algorithm described in Refs [5, 6]. The algorithm uses an iterative calculation of the difference system of equations that approximate equations for pump and laser waves (1) with a simultaneous solution of the system of equations for populations (2) by the Euler method. Based on the amplitudes E_p and $E_g^{\pm}$ calculated for the transmitted-pump and laser fields, we analysed the time dependences of the intensities $J_1 = (c/2\pi)E_p^2$, and $J_g^+ = (c/2\pi)(E_g^+)^2$and the time dependence of the upper-level population N_3, which determines the energy and the duration of laser pulses. The results of calculations are shown in Fig. 3.

4. Discussion of results

In the calculations, we obtained the dependences of the maximum output intensities of laser pulses J_g^+, their durations τ, and the time delay t_z of the laser pulse peak relative to the peak of the transmitted pump pulse as functions of pump intensity J_1. Near the threshold, the laser pulse was longer than the pump pulse by a factor of about five. An increase in pump intensity caused a decrease in the laser pulse duration τ (down to the pump pulse duration τ_1) and the time of its developments, which agrees well with the results of Ref. [7]. The laser pulse development time depends on the absorbed-pump intensity and the level of spontaneous emission, which is proportional to σ_s. For the given laser frequency, the latter is determined to a considerable extent by the geometry of the experiment (the solid angle $\Delta\Omega$).

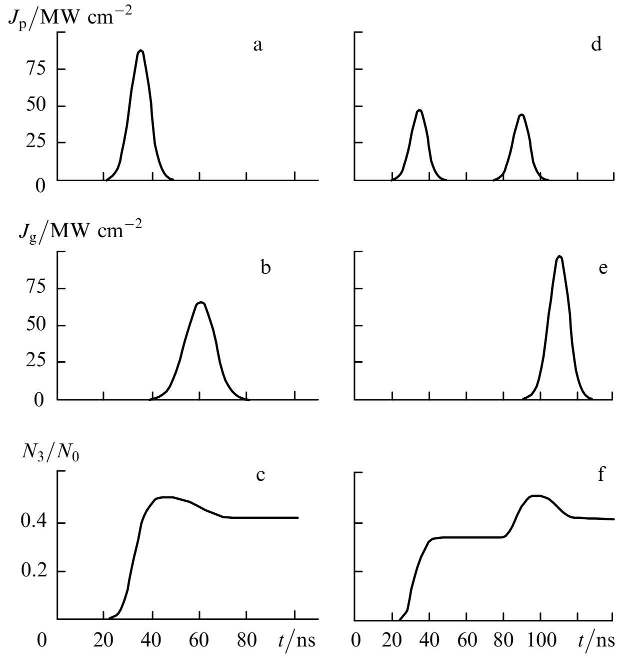

Figure 3. Time envelopes of transmitted pump pulses (a, d) and laser pulses (b, e) and the time dependences of the population of the working level N_3 (c, f) for one-pulse (a–c) and two pulse (d–f) pumping schemes.

Fig. 3 presents the dependences calculated for $J_p = 400$ MW cm^{-2}, which corresponds to the experimental data for the pump energy $W_p = 150$ mJ, $\tau_p = 10$ ns, and the beam cross section $S_0 = 0.0318$ cm^2. One can see from Fig. 3a that the maximum of a 13.5-ns laser pulse is delayed by 25 ns, which corresponds to a conversion efficiency of 25 %. The relative population of the third level N_3/N_0, which determines the laser energy density, reaches a maximum after the passage of the pump pulse and is determined by the absorbed energy (Fig. 3c). The calculation results agree well with the experimental data for one-pulse pumping.

The data in Figs 3d–3f correspond to $\Delta\tau = 40$ ns. One can see from Fig. 3f that the output laser intensity in the case of pumping by two pulses, whose total energy is close to the energy of the pump pulse in Fig. 3a, is higher by a factor of 1.3, which is close to the experimental data. In this case, the laser pulse duration only insignificantly differed from the pump pulse duration and was equal to 12 ns. A further increase in $\Delta\tau$ (within the limits of 10 ns), like in the experiment, had only a weak effect on the laser efficiency.

As follows from the calculation, the two-pulse pumping leads to the fact that in the case of t_z corresponding to the accumulation of population inversion after the passage of the first pulse the switching of the second pulse causes a rapid increase in the population of the working level and it becomes greater than the population in the case of one-pulse pumping (Fig. 3f), which leads to an increase in the rate of growth of laser intensity. Because further lasing is developed from the level of population formed by the first pulse, the single-trip gain is higher, which is responsible for a higher efficiency of energy extraction from the active medium. Moreover, in the case of one-pulse pumping, the nonlinear absorption at a high pump intensity decreases the population intensity, whereas the presence of the second pulse in the two-pulse pumping provides a virtually linear absorption regime, which additionally increases the population inversion.

5. Conclusions

The results obtained in the experiments and the calculations show that the formation of radiation in a Ti^{3+}:Al_2O_3 laser with two-pulse pumping substantially differs from the process in the case of one-pulse pumping. The data presented here show that the Ti^{3+}:Al_2O_3 laser with pre-liminary excitation by an additional pulse has a higher efficiency than the conventionally pumped laser, which agrees with the data for dye lasers [3].

Moreover, this pumping of the active Ti^{3+}:Al_2O_3 medium has additional advantages:

(1) Two-pulse pumping of a Ti^{3+}:Al_2O_3 laser provides a substantial increase in stability and a considerable decrease in the time jitter of laser pulses. In the case of one-pulse pumping, the development time of a laser pulse can be decreased only by way of increasing the gain of the active medium, i.e., increasing the pump pulse energy. In the case of two-pulse pumping, one can obtain a large decrease in the pulse development time (measured relative to the second pump pulse) by varying the time delay between the pump pulses, provided the amplitude of the first pulse exceeds the threshold value. The preliminary study gave a decrease in the time jitter of laser pulses at 770 nm in the case of two-pulse pumping in comparison with one-pulse pumping by a factor of about two. Near the edges of the tuning curve of the Ti^{3+}:Al_2O_3 laser, the effect was even stronger;

(2) Two-pulse pumping provides an extension of the tuning range, a considerable increase in the laser efficiency, and an improvement of the synchronisation accuracy at the edges of the tuning curve of the Ti^{3+}:Al_2O_3 laser;

(3) In the case of two-pulse pumping, the ray load in active elements due to pump radiation absorption is lower by a factor of two, whereas the laser efficiency at the maximum of the tuning curve is higher by a factor of about 1.5;

(4) Two-pulse pumping makes feasible the development of a two-pulse two-colour Ti^{3+}:Al_2O_3 laser [8].

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