

ACTIVE MEDIA. LASERS

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Diode-array-pumped repetitively pulsed neodymium phosphate glass laser

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***Abstract*. Repetitively pulsed generation (200 μs, 40 Hz) was obtained in a neodymium phosphate glass laser pumped by a 870-nm diode array. The maximum slope lasing efficiency with respect to the optical pump energy equal to 13 % is restricted by the factor (∼0.23) of active-medium filling by the mode field. By adjusting the laser cavity, the single-transverse mode regime, in particular, the generation of the TEM_{00} mode is obtained in the entire range of pump energies.**

Keywords: *neodymium phosphate glass, repetitively pulsed lasing, resonance pumping, diode arrays.*

1. Introduction

Neodymium phosphate glass is one of the well-studied and widely used active media for high-power lasers. It was shown in [1] that resonance diode pumping can be optimal for optical excitation of neodymium phosphate glass lasers. Resonance pumping in this paper, as in [1], means excitation of neodymium ions by radiation at a wavelength of ∼870 nm from the ground $^4I_{9/2}$ state to the first $^4F_{3/2}$ state, which is simultaneously the upper working level of the laser $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition. The advantages of such pumping over other pumping methods are as follows.

First, the quantum defect is minimal because relaxation from higher levels (for example, from the $^4F_{5/2}$ level upon usual pumping at 808 nm) to the upper working level is absent. Thus, the energy loss is reduced by one and a half even compared to usual diode pumping. This means that the active medium is heated weaker and thermoelastic stress is smaller. As a result, the optical perturbation of the medium is weak and therefore the quality of the optical beam is better, which is especially important for active media of large diameter (above 100 mm).

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Second, the absorption cross section upon resonance pumping at ∼870 nm is several times lower than that for radiation at 808 nm. For the Nd^{3+} concentration of 2×10^{20} cm^{-3}, which is typical for laser glasses, the absorption coefficient at 870 nm is ∼1 cm^{-1}, which permits the spatially uniform excitation of glasses of thickness up to 2 cm upon two-sided pumping. This is also an important advantage in the case of active media of large volumes in which high-quality optical beams should be obtained.

Finally, the third advantage is that laser diodes emitting at ∼ 870 nm, and the corresponding diode arrays have, as a rule, the highest radiation parameters and are more technological in manufacturing. In addition, their active medium does not contain Al. This can reduce the cost of production of laser diodes, which is especially important when they should be used in great amounts in laser systems. It should be emphasised once more than all the advantages of resonance pumping concern large laser systems. In the case of low-power lasers, resonance pumping can be even disadvantageous because of a low absorption cross section for pump radiation and, therefore, a low efficiency.

Investigations performed in [1] showed that the pump efficiency, the specific energy supply and optical amplification upon resonance pumping can be reliably simulated. These investigations were performed below the lasing threshold. More complete studies, including lasing, were prevented by the optical quality of the neodymium glass, which had optical losses of $\sim 5 \times 10^{-3}$ cm^{-1} at a wavelength of 1.06 μm.

In this paper, which is a continuation of [1], we investigate the lasing regime. The aim of the paper is to elucidate the possibility and accuracy of simulating the laser parameters of setups based on neodymium phosphate glasses resonantly pumped by diode arrays.

2. Experimental

We used the active element made of the GLS22 glass, as in [1], but with optical losses reduced approximately by four times due to the preliminary selection of glasses from different batches. The geometry of the active element, the optical pumping scheme, and the block diagram of the electronic part of the setup (Fig. 1) were close to those used in [1]. Except the use of the active medium with lower optical losses, we employed in our setup six diode arrays (instead of four in [1]) and the active element had different dimensions (length 100 mm, width 10 mm, and thickness 5.7 mm). The optical loss in the active element was measured to be $(1.3 \pm 0.2) \times 10^{-3}$ cm^{-1} at a wavelength of

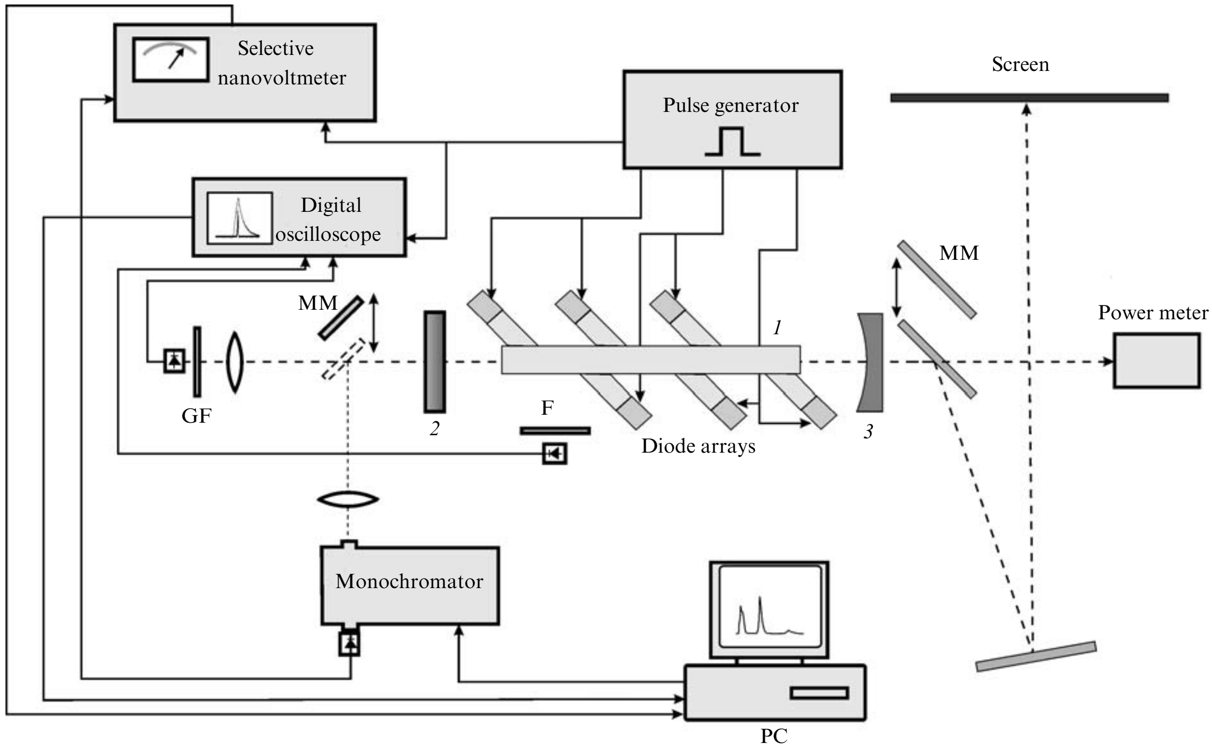

Figure 1. Block diagram of the experimental setup: (*1*) active element; (*2*) highly reflecting mirror; (*3*) output mirror.

1.06 μm. The laser cavity was formed by a highly reflecting plane mirror with the reflectance 99.9 % and the output concave mirror with the radius of curvature 287 mm and the reflectance 99.9 % or 96.0 %. The optical length of the cavity L was $\sim$200 mm.

A current pulse from a pulse generator was fed to diode arrays whose radiation was coupled to active element (*1*) through prisms. Laser radiation coupled out through output mirror (*3*) was measured with a NOVA II power meter with a L50 (150)A measurement head (OPHIR) or was deflected by a movable mirror MM to a screen located in the far-field zone of the optical beam and recorded with a digital camera.

The control laser beam coupled out through high reflecting mirror (*2*), and therefore strongly attenuated, was used to record the laser spectrum and laser pulse dynamics by using an MDR-4 monochromator and a Tektronix TDS2022 digital storage oscilloscope. The dynamics of spontaneous emission from the upper $^4F_{3/2}$ level could be recorded simultaneously with the laser pulse. The recording was performed with an additional photodetector located on the side surface of the active element. The contributions of laser radiation and pump radiation scattered in the active element to the recorded signal were reduced with the help of an InP filter F with an aperture mounted in front of a PD-24K photodiode. The setup was automated by using a PC in which the results of all measurements were stored.

Preliminary measurements of the lifetime τ of the upper excited $^4F_{3/2}$ state of the glass by the method described in [1] gave the value 319 $\pm$ 2 μs. Taking this into account, we used the pump pulse duration $T = 300$ μs in all experiments. For this relation between the pump pulse duration and the upper-level lifetime, the ratio μ_τ of the number of ions in the excited state by the end of the pump pulse to the number of ions involved in the absorption of pump radiation during the entire pulse is $\sim$0.648 [1].

Pumping could be performed by single pulses or with a pulse repetition rate of up to 40 Hz. The pump pulse was nearly rectangular, as in [1], with fronts of 2–3 μs and the top nonuniformity not exceeding $\sim$2 %. The output characteristic of each array (dependence of the radiation pulse energy on the current pulse amplitude) was measured in preliminary experiments. Then, the total pump pulse energy for all the arrays was found from these characteristics and measured current pulse amplitudes.

The active element was air-cooled and diode arrays were water-cooled.

Figure 2 shows the absorption spectrum of the active element and the emission spectrum of diode arrays. One can see that absorption is no less than 0.6 cm^{-1} even in the wings of the emission band. By performing averaging over the paths of the pump beam in the rod and spectral averaging,

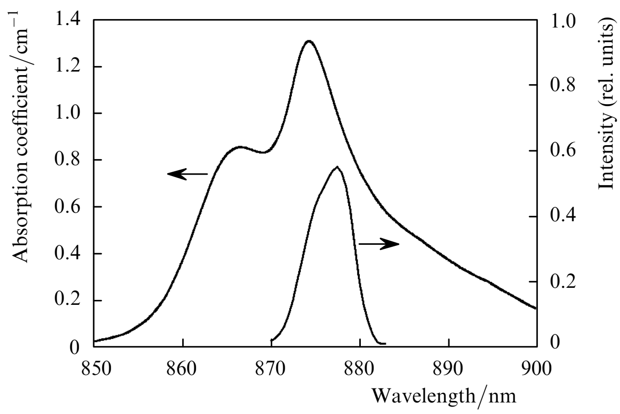

Figure 2. Emission spectrum of diode arrays and the $^4I_{9/2} - ^4F_{3/2}$ absorption line of the active element.

we found the fraction of the absorbed pump energy $\mu_s = 0.90 \pm 0.02$.

3. Results

The dependences of the laser output power P_{las} on the pump pulse energy E_p for pulse repetition rates $f = 10$ and 40 Hz are presented in Fig. 3. The output powers were measured as functions of the pump pulse energy rather than of the average pump power to obtain both curves $P_{las}(E_p)$ in the same range of the argument. Figure 3 demonstrates a considerable effect of the active-element overheating. Indeed, as the pulse repetition rate was increased by four times (from 10 to 40 Hz), the slope of the dependence of the average power on the pump power increased only by three times. We found in experiments that the average power of the repetitively pulsed laser slowly decreased with time, the decrease being more noticeable for $f = 40$ Hz. Of course, this is explained by the fact that heat removal from the active element provided by the air-cooling system used in experiments was not efficient enough. Nevertheless, even in the case of more efficient heat removal, the problem of heat removal from glass active elements operating at pulse repetition rated above 10 Hz remains actual.

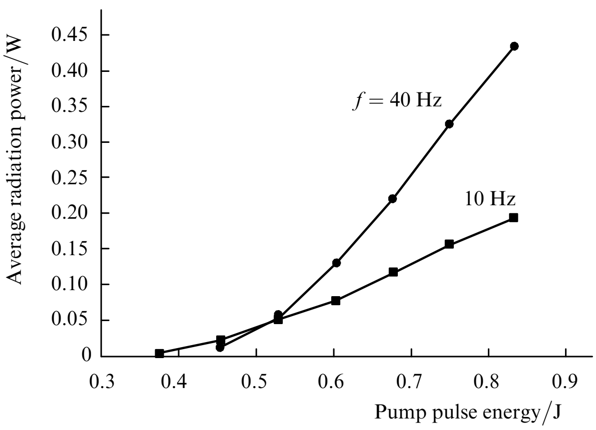

Figure 3. Average output power of the laser in the repetitively pulsed regime. The pump pulse duration is 300 μs, $R_{out} = 96\,\%$.

In our case, the heating of the active element enhanced apparently the thermal population of the lower working $^4I_{11/2}$ level, thereby reducing inversion and, hence, amplification. In principle, the manifestation of another temperature effect, for example, photoelastic effect caused by thermoelastic stresses in the active element could be also observed, which could produce optical inhomogeneities in the medium resulting in the misalignment of the laser cavity. However, the study of the mode structure of the optical beam did not reveal this effect.

Figure 4 shows far-field radiation patterns of the laser ($f = 10$ Hz) for the different alignments of the cavity. By adjusting the cavity mirrors, it was possible to obtain lasing at some transverse mode, beginning from the lowest TEM_{00} mode (Fig. 4a) to a mode with large transverse indices. This configuration of the field remained strictly fixed during the entire observation time. The exposure time during photographing was 10 – 15 s. The spatial noise observed in the far-field radiation pattern is not speckles but is related to a weak sensitivity of the camera at a wavelength of 1.06 μm.

The output power depended considerably on the lasing mode, lasing at the high-order mode being most efficient (Fig. 4f) because this mode filled the active medium most completely. Indeed, an effective aperture forming the optical beam in the cavity has a rectangular cross section specified by the cross section of the active element. Therefore, the field of a mode with the transverse intensity distribution closest to the rectangular one will be overlapped most completely with the amplifying region. The far-field intensity distribution for this mode is close to the classical intensity distribution for a wave diffracted from a rectangular hole [2]. The diffraction rectangle has almost equal sides, although the sides of the rectangular cross section differ almost twice. However, it should be taken into account here that the cross section of the optical beam emerging from the active element at the Brewster angle

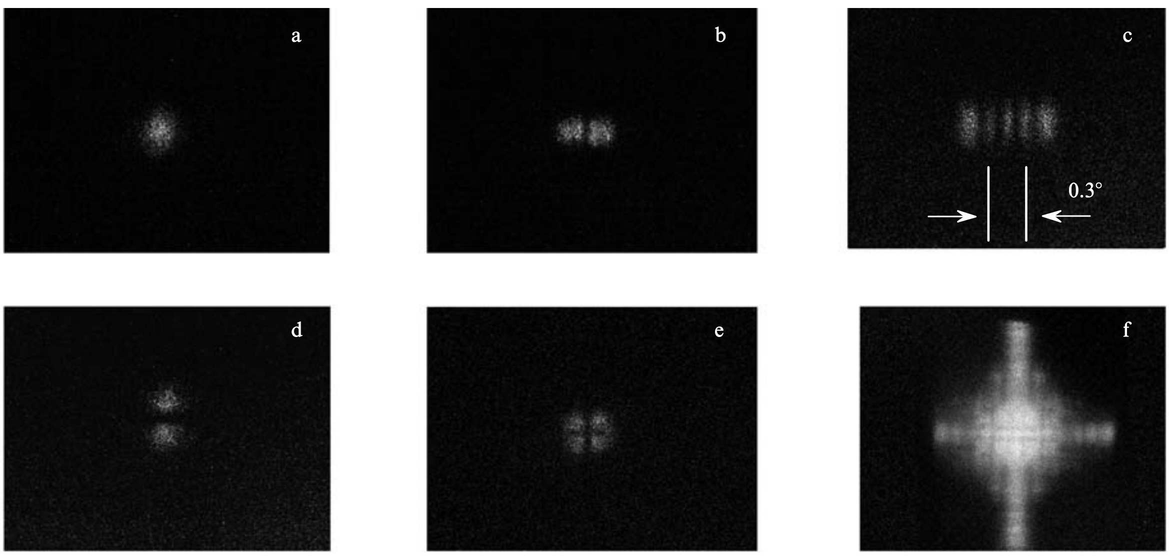

Figure 4. Far-field radiation pattern of the laser in the repetitively pulsed regime. The pulse repetition rate is 10 Hz, the pulse duration is 300 μs.

becomes close to a square, which determines the observed diffraction pattern. Taking all this into account, the output power was always measured by adjusting the cavity to this efficient mode, which has the far-field intensity distribution shown in Fig. 4f.

Figure 5 shows the emission spectra of the laser with the output mirror with the reflectance $R = 96\,\%$. Figure 5a demonstrates that the laser line is shifted to the blue by ~ 1.5 nm with respect to the maximum of the spontaneous emission band, whereas in the cavity with the highly reflecting output mirror the laser line coincided within 0.1 nm with the maximum of the luminescence band. The emission spectra of the laser at different pump levels are presented in Figs 5b–d. The individual longitudinal modes were not spectrally resolved by the recording method used in our experiments and only their envelope was recorded. This envelope has a quasi-periodic form with a spectral period of ~ 0.3 nm. We did not study the reason for this periodicity. It can be produced by a random internal

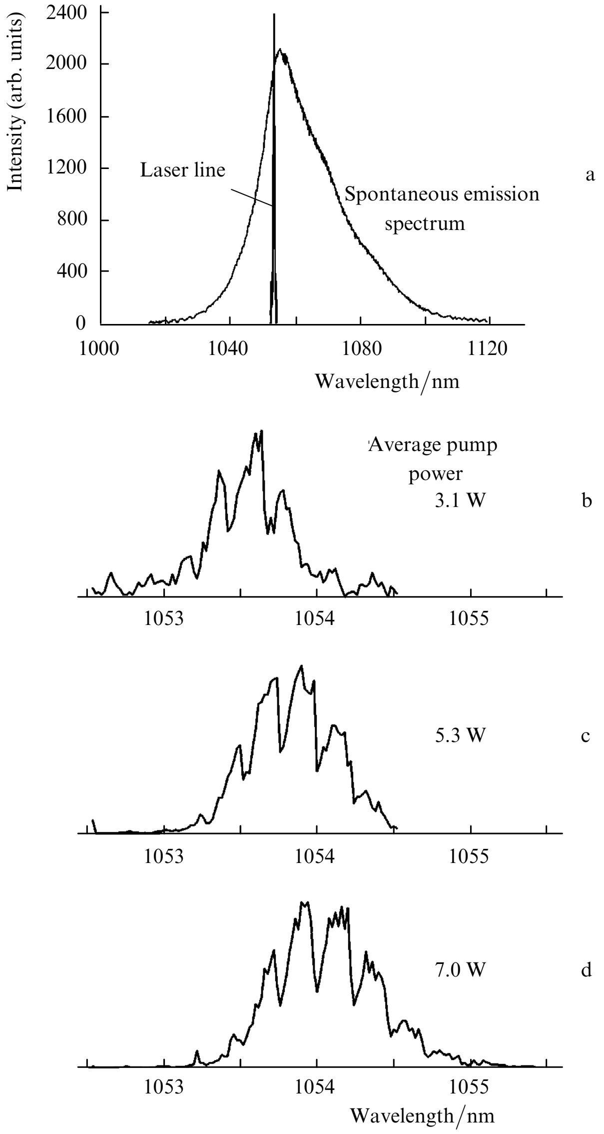

Figure 5. Emission spectra of the laser in the repetitively pulsed regime: (a) laser line and the luminescence band of the active element; (b–d) lasing spectra at different pump powers. The pulse repetition rate is 10 Hz, the pump pulse duration is 300 μs, $R_{out} = 96\,\%$.

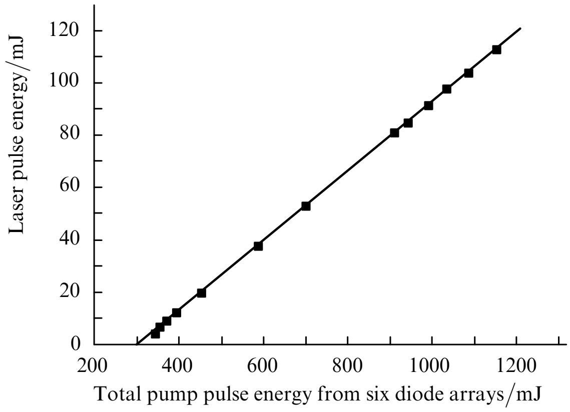

Figure 6. Output characteristic of the laser pumped by single pulses for $R_{out} = 96\,\%$.

Fabry–Perot etalon formed, for example, by the external surfaces of mirrors without AR coatings.

To analyse the energy parameters of the laser correctly and to exclude poorly controllable thermal effects, we performed measurements upon single-pulse pumping by using the output mirror with $R = 96\,\%$ (Fig. 6). The extrapolated pump energy $E_{th}(0.96)$ corresponding to the lasing threshold was ~ 300 mJ. The slope of the output characteristic

$$\mu_{las} = E_{las}/[E_p - E_{th}(0.96)], \tag{1}$$

where E_{las} is the laser pulse energy and E_p is the pump energy, was $\sim 1.3 \times 10^{-1}$. Measurements carried out with the cavity formed by two highly reflecting mirrors with $R = 99.9\,\%$ showed that the threshold pump energy $E_{th}(0.999)$ was 120 mJ. The total output characteristic of this cavity is not presented here and its slope was not analysed because such analysis requires the knowledge of the reflectance (transmission) of cavity mirrors with a high accuracy; in addition, it was necessary to measure the total energy from both optical outputs. Nevertheless, the obtained threshold pump powers are sufficient for the independent measurements of optical losses α_0 in the active element and the stimulated transition cross section σ:

$$\alpha_0 = \Delta\alpha_m E_{th}(0.999)/E_{th}(0.96), \ \sigma = \Delta\alpha_m \hbar\omega V/(\Delta E_{th}\mu_\tau\mu_s), \tag{2}$$

where $\Delta\alpha_m = (2L)^{-1}\ln R^{-1}$ is the change in the reduced (to the active-element length) optical losses in passing from the highly reflecting output mirror with $R = 99.9\,\%$ to the mirror with the reflectance $R \approx 96.0\,\%$; $\Delta E_{th} = E_{th}(0.96) - E_{th}(0.999)$; $\hbar\omega$ is the pump photon energy; and $V = 5.7$ cm^3 is the active element volume. By using the values presented above, we obtain $\alpha_0 = (1.3 \pm 0.1) \times 10^{-3}$ см$^{-1}$ cm^{-1} and $\sigma \approx (2.5 - 2.7) \times 10^{-20}$ cm^2. Note that α_0 contains both nonresonance losses α_{nres}, which appear due to scattering and absorption of radiation by optical inhomogeneities and uncontrollable impurities, and resonance absorption α_{res} at the laser transition due to the thermal population of the lower level:

$$\alpha_0 = \alpha_{nres} + \alpha_{res}. \tag{3}$$

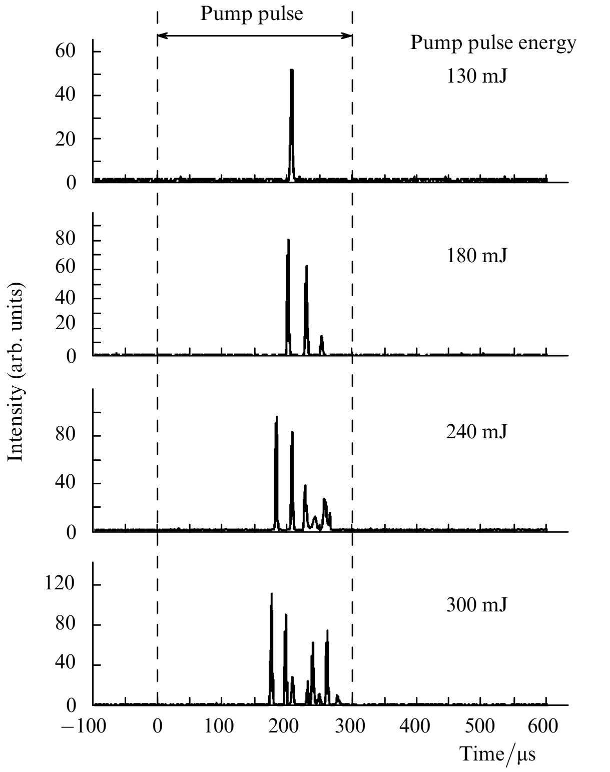

Figure 7. Pulsating lasing at different pump levels and $R_{\rm out} = 99.9\,\%$.

According to data [3], for the Nd^{3+} concentration 2×10^{20} $\rm cm^{-3}$ and temperature 300 K, the resonance absorption is $\alpha_{\rm res} \approx 4 \times 10^{-4}$ $\rm cm^{-1}$, and we obtain from (3) $\alpha_{\rm nres} \approx (9 \pm 1) \times 10^{-4}$ $\rm cm^{-1}$.

The study of the laser dynamics showed that the laser pulse duration did not exceed 200 μs. This means that even in the case of the maximal pump pulse energy $E_{\rm p} = 1.2$ J, the time required for inversion accumulation is ~100 μs. The output intensity oscillates during the pump pulse (Figs 7, 8), which is typical for free running lasing. The spike regime is observed most distinctly near the lasing threshold and for the cavity with highly reflecting mirrors (Fig. 7).

The pulsating free running lasing regime is known in fact from the advent of lasers [4] and has been investigated in many papers, in particular, devoted to flashlamp-pumped neodymium glass lasers. The physical interpretation of this regime was also proposed in many papers, one of the first among them being [5]. Various physical mechanisms of the free running regime are discussed in monograph [6].

In our case, pulsations were irregular, and because of this the dynamics was recorded only during one laser pulse. The results presented in Fig. 8 are divided into series I, II, and III corresponding to different pump energies. Three different realisations A, B, and C of a single pulse for the same pump energy are shown in each of the series. In the case A, the dynamics of spontaneous emission is shown simultaneously with the laser pulse. It is obvious that the spontaneous emission signal is proportional to the population of the excited Nd^{3+} ions at the concentration N

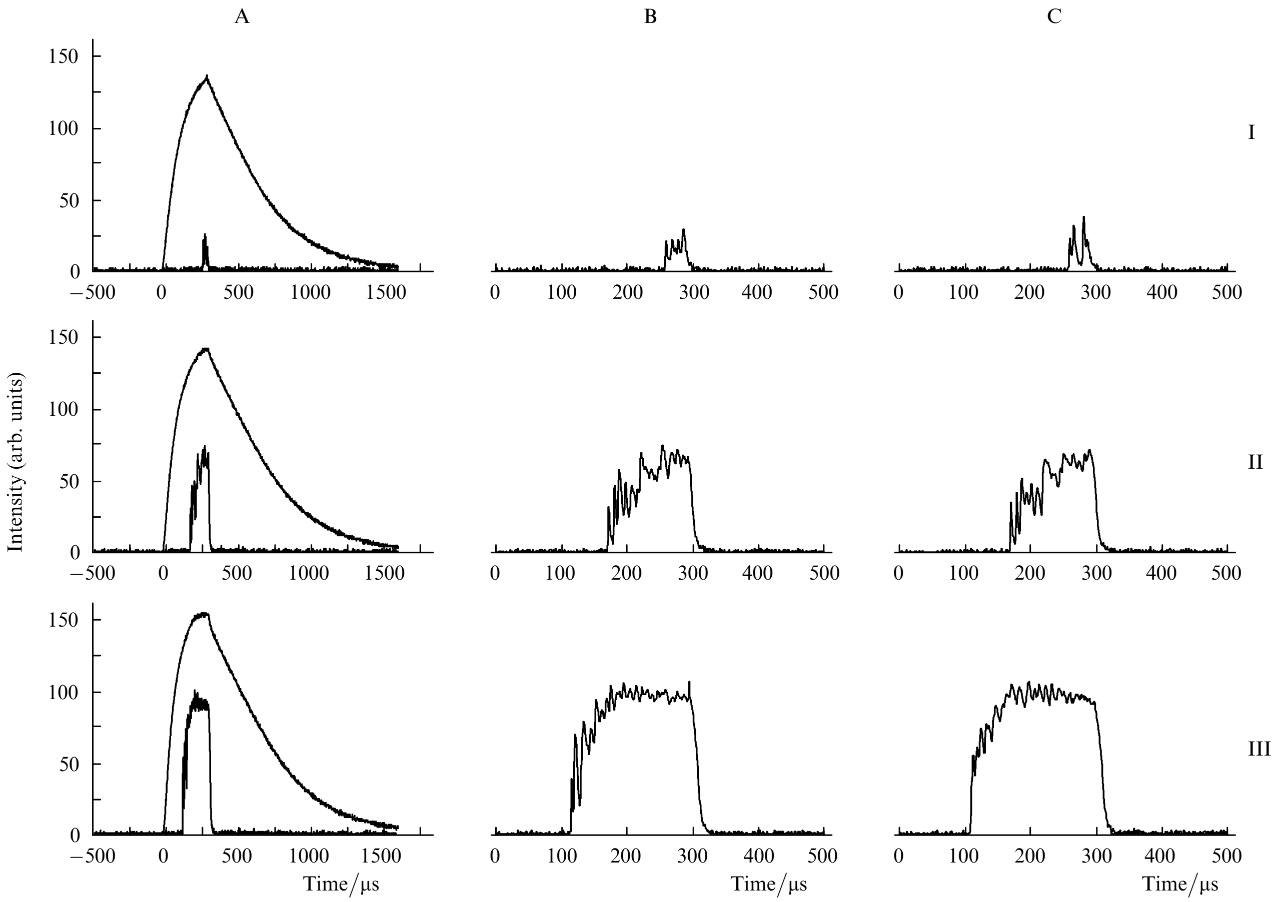

Figure 8. Dynamics of lasing and spontaneous emission (inversion). A, B, C are different realisations of spectra upon pumping by single pulses with energies 320 mJ (I), 900 mJ (II), and 1200 mJ (III). The pump pulse duration is 300 μs, $R_{\rm out} = 96\,\%$.

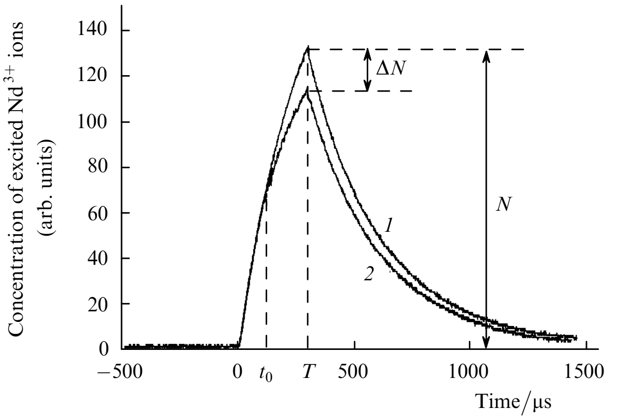

Figure 9. Time dependence of the luminescence signal (concentration of excited Nd^{3+} ions). The pump pulse duration and energy are 300 μs and 1.2 J, respectively; $R_{out} = 96\,\%$. Curve (*1*) corresponds to blocked mirrors (lasing is absent); curve (*2*) corresponds to open mirrors (lasing appears within $t_0 = 122$ μs after the pump pulse onset).

occupying the upper laser level. Note that the gain g in the active element does not affect the luminescence signal because the parameter $ga \ll 1$, where $a = 0.57$ cm is the active rod thickness.

We found the factor μ_v of filling the active element volume by the mode field from the spontaneous emission dynamics. This could be done most conveniently by using the maximum pump level. Figure 9 presents the spontaneous emission (inversion) dynamics in the absence of lasing [with blocked cavity mirrors, curve (*1*)] and in the presence of lasing [curve (*2*)]. One can see that the spontaneous emission level and, hence, the inversion level (the concentration of excited Nd^{3+} ions) in the active element is not saturated with the development of lasing but continues to grow. However, this growth occurs already differently than before the lasing threshold. If lasing appears within the time t_0 after the pump pulse onset, it can be readily shown that the dependence $N(t)$ has the form

$$N(t) = \frac{E_p(\tau/T)\mu_s}{\hbar\omega V}[1 - \exp(-t/\tau)] \quad \text{for} \quad t < t_0. \qquad (4)$$

In the lasing regime for $t > t_0$, when the mode field fills only a part μ_v of the active medium volume, the concentration N will change as

$$N(t) = \frac{E_p(\tau/T)\mu_s}{\hbar\omega V}\{(1 - \mu_v)[1 - \exp(-t/\tau)] + \mu_v[1 - \exp(-t_0/\tau)]\}. \qquad (5)$$

The value of μ_v can be determined from the difference of luminescence signals at the pulse end measured with blocked mirrors, when lasing is absent and the signal is proportional to $N(T)$ determined by expression (4), and measured with opened mirrors, when the signal is proportional to $N(T)$ determined by expression (5). According to (4) and (5), the difference of concentrations of excited ions is

$$\Delta N = \frac{E_p\tau\mu_s}{\hbar\omega VT}[\exp(-t_0/\tau) - \exp(-T/\tau)]\mu_v. \qquad (6)$$

Then, we have

$$\Delta N/N = \frac{\mu_v[\exp(-t_0/\tau) - \exp(-T/\tau)]}{1 - \exp(-T/\tau)}. \qquad (7)$$

By using expression (7), we find that the filling factor lies in the range $0.2 < \mu_v < 0.23$ depending on the choice of time t_0. Note that the development of lasing itself takes some time δt_0, which introduces a certain error to the value of μ_v. The spike lasing regime deteriorates the accuracy of measuring μ_v. In this case, $N(t)$ is some concentration averaged over the characteristic time between laser spikes. In addition, the accuracy of measuring μ_v is obviously poor when μ_v is small.

The lasing efficiency μ_{las} can be found from the expression

$$\mu_{las} = \mu_q\mu_s\mu_v\Delta\alpha_m/(\Delta\alpha_m + \alpha_{nres}), \qquad (8)$$

where $\mu_q = \hbar\omega_{las}/\hbar\omega$; $\hbar\omega_{las}$ is the laser photon energy; and μ_q is the coefficient of conversion of a pump photon to a laser photon (in our case, $\mu_q = 0.82$). Thus, it follows from the indicated values of $\Delta\alpha_m$, μ_s, μ_q and experimental losses $\alpha_{nres} \approx 9 \times 10^{-4}$, as well as from the value of μ_v found from dynamic measurements that the expected lasing efficiency lies in the range $0.10 < \mu_{las} < 0.12$. This coincides with the results of direct measurements of μ_{las} with an accuracy of $\sim 10\,\%$ (by the upper boundary) (see Fig. 6).

The factor $\Delta\alpha_m/(\alpha_m + \alpha_{nres})$ in (8) depends on the ratio between useful losses $\Delta\alpha_m$ on the output mirror and nonresonance losses inside the optical rod. It is obvious that this factor can be increased by increasing $\Delta\alpha_m$ and decreasing α_{nres}. A decrease in α_{nres} is more advantageous because an increase in $\Delta\alpha_m$ requires an increase in the energy supply, which leads to increasing the thermal load on the active element. In our case, according to data in Fig. 6 and after recalculation to the accumulated energy, the maximum 'pure' (after the subtraction of losses) energy supply was ~ 110 mJ cm^{-3}, which provided approximately four-fold excess over the lasing threshold.

4. Discussion and conclusions

Thus, we have obtained repetitively pulsed lasing with a pulse repetition rate of up to 40 Hz and laser pulse duration up to 200 μs. The maximum slope efficiency μ_{las} of the resonantly diode-pumped laser is $\sim 13\,\%$. Although the repetitively pulsed regime of the neodymium glass laser has been achieved exclusively due to efficient pumping, the output parameters of the laser (see Figs 3 and 6) cannot be considered well enough from the point of view of wide practical applications.

Nevertheless, we believe that the aim of our study demonstrating the possibility of sufficiently accurate simulations of the energy parameters of a resonantly diode-pumped laser has been achieved. This gives immediately the answer to the main question: how the slope efficiency μ_{las} of such a laser can be increased? The main factor in the solution of this problem is the coefficient μ_v of the spatial overlap of the optical beam of the mode with the volume of the amplifying medium. In our case, the value of μ_v was restricted only by the technical possibility of using a system of diode arrays and the active element in the certain geometry. It can be shown that the coefficient μ_v can be easily increased by several times by constructing active elements with a large laser beam aperture, and its value can be close to unity. Therefore, the increase in μ_v is a potential and quite accessible resource for increasing μ_{las}.

The obtainment of efficient lasing in the repetitively pulsed regime is, however, a much more complicated problem. This is explained by a low heat conduction of glass, resulting in its overheating. This problem cannot be completely eliminated by improving a cooling system of the active element because heat removal is prevented by a thermal 'plug' formed inside the active medium.

It may seem that the only solution of this problem is to use crystals having the high heat conductivity coefficient. However, the manufacturing technology of high-quality crystals of large volumes is a separate problem. The use of various ceramics, for example, of the Nd : YAG type, which are now quite popular, also cannot solve this problem, in our opinion. Although ceramic lasers with high output parameters have been developed (see, for example, [7, 8]), it seems that such parameters cannot be achieved in large setups at least for two reasons. One of them is high optical losses caused by scattering and the other is narrow absorption lines and narrow laser lines corresponding to a too high cross section for the laser transition. The narrow absorption line requires the precise tuning of laser diodes to this line. For large systems and integrated laser diodes, this problem cannot be solved. The narrow laser line poses a problem of amplification of short pulses; in addition, the high cross section leads to the parasitic depletion of inversion by spontaneous emission, which automatically restricts the energy stored in the active medium.

Narrow absorption and amplification lines are inherent in most crystalline media, and therefore the above-mentioned problems appear when materials with the high heat conduction are used. In this connection the phosphate glass is still applied for manufacturing active elements in large laser systems [9, 10], although the application of such systems in the repetitively pulsed regime is restricted.

The problem of overheating requires the maximal reduction of optical absorption at the laser wavelength. Indeed, because the overheating restricts the specific energy supply to the active element, thereby limiting the unsaturated gain g, it is necessary to reduce losses for providing the efficient energy release in the form of laser radiation. It can be easily shown that the energy release efficiency depends on the gain-loss ratio g/α_{nres} (see, for example, [3, 11]). In our case, this ratio is determined by the factor $\Delta\alpha_m/(\Delta\alpha_m + \alpha_{nres})$ in (8).

It should be taken into account that along with non-resonance absorption α_{nres}, glass also has resonance absorption α_{res}, which is caused by the thermal population of the lower laser level increasing with temperature. Resonance absorption may not affect directly the slope efficiency of a laser; however, it reduces amplification (upon constant pumping) and enhances the lasing threshold, which finally reduces the total lasing efficiency, as was observed in our paper. This can be an additional overheating problem for Yb-doped active media, as was pointed out in [12]. Of course, one should bear in mind that absorption from the lower working level can be saturated. For example, the local slope (in some pumping range) of the output characteristic obtained in [13] due to saturation was $\mu_{las} > 1$ (namely, 140 %). However, it is unlikely that such a situation can be realised in large laser systems, because, first, it requires too high pump powers and, second, absorption saturation at the thermally populated working transition automatically causes the proportional decrease in absorption of pump radiation. As a result, the lasing efficiency will inevitably decrease due to the decrease in the factor μ_s. In this connection it seems that the quantum defect should not be reduced (μ_q increased) too strongly by decreasing the difference between the energies of the ground and lower working levels of ions in active media. The resonance absorption increases exponentially with decreasing this energy difference, while the heat release decreases only linearly, which resulted in the enhanced temperature sensitivity of a Yb^{3+} : S-FAP laser [12].

Thus, we have obtained the following results:

(i) Repetitively pulsed lasing with the pulse duration up to 200 μs and a pulse repetition rate up to 40 Hz has been obtained in neodymium phosphate glass upon resonance pumping providing the minimal perturbation of the optical properties of the glass, which is confirmed by single-mode lasing at all pump levels;

(ii) the specific energy supply was $\sim$110 mJ cm^{-3}. The energy supply can be increased by two – three times by choosing the appropriate geometry of the active medium and illuminator, including diode arrays available at present. In this case, the lasing parameters of the excited active element fall into the range typical for high-power large-aperture laser systems;

(iii) the maximum slope lasing efficiency with respect to the pump energy equal to 13 % was mainly limited by the spatial factor of filling the active element by the mode field;

(iv) the radiation parameters of the laser coincide with an accuracy of $\sim$10% with calculated parameters, which suggests that higher-power lasers and amplifiers based on resonantly diode-pumped neodymium glass can be also quite accurately simulated.

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