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Study of lasing on the $^4F_{3/2} \to {}^4I_{13/2}$ secondary transition of Nd^{3+} ions in a phase-conjugate Nd^{3+} : YAG laser

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Abstract. **Lasing at a wavelength of 1.34 μm on the $^4F_{3/2} \to {}^4I_{13/2}$ secondary transition of Nd^{3+} ions in a phase-conjugate (PC) Nd^{3+} : YAG laser under four-wave mixing in a laser medium is theoretically and experimentally investigated. The influence of the amplified spontaneous emission at a wavelength λ = 1.064 μm on the parameters of phase-conjugate generation of the Nd^{3+} : YAG laser at λ = 1.34 μm under passive *Q* switching by a V^{3+} : YAG crystal using two-, three-, and four-loop open cavity schemes is analysed by mathematical simulation. It is shown that there is an optimal initial transmission of a passive *Q* switch (PQS), the value of which decreases with increasing number of cavity feedback loops. The generation in the Nd^{3+} : YAG laser at λ = 1.34 μm with an open PC multiloop cavity is experimentally obtained and studied for the first time. Emission in the form of a train of seven pulses with a total energy of 0.25 J and individual pulse energy and duration of 36 mJ and 150 ns, respectively, is obtained with an initial PQS transmission of 74%. The angular divergence of the laser beam is found to be 0.7 mrad at quality factors M_x^2 = 1.2 and M_y^2 = 1.1.**

Keywords: *phase conjugation, Nd^{3+} : YAG laser, secondary transition, amplified spontaneous emission.*

1. Introduction

The method of phase conjugation on holographic gratings recorded directly in an active laser medium to act as a positive feedback mirror [phase-conjugate (PC) mirror] makes it possible to compensate efficiently for wavefront dynamic distortions and implement lasing with a beam quality close to the diffraction quality using no additional control elements [1–6]. The diffraction efficiency of PC mirrors and, correspondingly, the *Q* factor of the PC cavity (in contrast to the linear cavity) depend on the active-medium gain; for this reason, as applied to solid-state lasers, PC lasing on the strongest $^4F_{3/2} \to {}^4I_{11/2}$ transition of Nd^{3+} ions with a wavelength of about 1 μm is investigated in the overwhelming majority of cases [6–11]. It was shown for the first time in [12, 13] that an application of the two-loop scheme for recording holographic gratings in active Nd^{3+} laser media makes it possible to reduce the threshold pump energy by more than a half and increase the PC radiation energy by a factor of almost 3 with preservation of high laser beam quality. The use of this approach in [14–16] made it possible to implement PC lasing at a wavelength λ = 1.06 μm in low-gain Nd^{3+} : YAG elements due to the increase in the number of recorded holographic gratings under multibeam mixing in the active medium within a multiloop (two-, three-, or four-loop) cavity scheme. Previously [14], we investigated for the first time single-mode lasing of the Nd^{3+} : YAG laser at λ = 1.34 μm with one-loop intracavity phase conjugation on holographic gratings in the active laser medium using high-power lamp pumping of active elements and spectral selection of radiation with λ = 1.06 μm with the aid of dichroic mirrors. Note that lasing was obtained only with a planar output mirror having a reflectance of 6% at λ = 1.34 μm, which served for preliminary recording PC mirrors in active elements in the initial stage of lasing evolution. In the absence of the output mirror, lasing did not occur, which may be related to the strong influence of amplified spontaneous emission (ASE) at λ = 1.06 μm. Since the gain cross section of Nd^{3+} : YAG at λ = 1.06 μm is larger than that at λ = 1.34 μm by a factor of 4.7 [17], spontaneous emission at λ = 1.06 μm, amplified per pass under high-power pumping, may significantly reduce the accumulated population inversion and suppress lasing on the weak secondary transition. In this paper, we report the results of studying the possibility of implementing lasing of a Nd^{3+} : YAG laser at λ = 1.34 μm with a multiloop PC cavity on holographic gratings in the active laser medium, with suppression of ASE at λ = 1.06 μm.

2. Theoretical part

First we numerically simulated the PC lasing kinetics for Nd^{3+} : YAG lasers at λ = 1.34 km under passive *Q* switching by a V^{3+} : YAG crystal with two-, three-, and four-loop open cavity schemes, which implement, respectively, mixing of six, eight, and ten crossed beams in the active medium. This simulation made it possible to determine the degree of the influence of ASE at λ = 1.06 μm on the development and parameters of PC lasing on the secondary ('weaker') transition. We used the mathematical model developed by us in [18, 19] to analyse the lasing in PC loop cavities of neodymium lasers at λ = 1.06 μm under passive *Q* switching. Within this model, the values of the parameters of the Nd^{3+} : YAG crystal corresponding to the fundamental transition $^4F_{3/2} \to {}^4I_{11/2}$ were replaced with the values corresponding to the secondary tran-

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sition $^4F_{3/2} \rightarrow {}^4I_{13/2}$, and the parameters of a passive Q switch (PQS) on the $LiF:F_2^-$ crystal were replaced with the parameters of the PQS on the $V^{3+}:YAG$ crystal. In particular, the values of the gain cross section $\sigma_{1.06}$ and gain saturation energy density $U_{1.06}^{sat}$ at λ = 1.06 μm, 28 × 10^{-20} cm^2 and 0.67 J cm^{-2}, respectively [20], were replaced with the corresponding values at λ = 1.34 μm: $\sigma_{1.34}$ = 5.96 × 10^{-20} cm^2 and $U_{1.34}^{sat}$ = 2.49 J cm^{-2}. The following values of the parameters were set for the $V^{3+}:YAG$ crystal at λ = 1.34 μm [21]: absorption cross section, σ_q = 7.2 × 10^{-18} cm^2; upper level lifetime, τ_q = 22 ns; and absorption saturation energy density, U_q = 0.02 J cm^{-2}. The main parameter determining the PC lasing development is the diffraction efficiency of population gratings. If population gratings are recorded by the ith and jth crossed laser beams, with allowance for the active-medium gain nonlinearity, the grating diffraction efficiency has the form [18]

$$\eta_{ij} = G\sinh^2[(\alpha - \alpha_{ij})L/4], \tag{1}$$

where L is the active laser element (ALE) length; α is the gain averaged over the ALE length; α_{ij} is the gain in the interference maximum of the ith and jth laser beams intersecting in the ALE;

$$G = \exp[(\alpha - \kappa)L] \tag{2}$$

is the gain per ALE pass; and κ is the loss coefficient in ALE.

In this study, to take into account the ASE at λ = 1.06 μm, we modify the previously developed model [19] in the following way. The ASE intensity at the wavelength of the fundamental laser transition is found as [20]

$$I_{1.06} \approx \frac{\Omega}{4\sqrt{\pi^3}} \frac{U_{1.06}^{sat}}{\tau} \frac{(G_{1.06} - 1)^{3/2}}{(G_{1.06} \ln G_{1.06})^{1/2}}, \tag{3}$$

where $G_{1.06} = \exp(\alpha L \sigma_{1.06}/\sigma_{1.34} - \kappa L)$ is the gain per ALE pass at λ = 1.06 μm; $\Omega \approx \pi d^2/(4L^2)$ is the solid angle in which the ALE output end face is seen from the centre of the input end face (d = 6.3 mm and L = 13 cm are, respectively, the ALE diameter and length); and τ is the lifetime of the excited laser level. Here, we take into account that all mirrors forming the ray path in the loop PC cavity are highly reflective at λ = 1.34 μm but have a high transmission at λ = 1.06 μm, i.e., the spontaneous emission at λ = 1.06 μm is amplified only during one ALE pass to be then selected by mirrors.

With allowance for the ASE on the fundamental transition, which reduces gains α and α_{ij}, the lasing kinetics on the secondary transition can be described by the corrected equations

$$\frac{d\alpha}{dt} = \frac{\sigma_{1.34} N_{ions} I_p / I_p^{sat} - \alpha}{\tau} - \frac{\alpha}{U_{1.34}^{sat}} \left(\sum_i I_i + \frac{U_{1.34}^{sat}}{U_{1.06}^{sat}} I_{1.06} \right), \tag{4}$$

$$\frac{d\alpha_{ij}}{dt} = \frac{\sigma_{1.34} N_{ions} I_p / I_p^{sat} - \alpha_{ij}}{\tau} - \frac{\alpha_{ij}}{U_{1.34}^{sat}} \left(\sum_i I_i + 2\sqrt{I_i I_j} + \frac{U_{1.34}^{sat}}{U_{1.06}^{sat}} I_{1.06} \right), \tag{5}$$

where $I_{1.06}$ is determined from formula (3); $\sigma_{1.34} N_{ions} I_p / I_p^{sat} = \alpha_0$ is the limiting ALE gain in the absence of lasing; N_{ions} is the concentration of active ions; I_p is the effective pump intensity [22]; $I_p^{sat} = \hbar\omega_p/(\sigma_{abs}\tau)$ is the absorption saturation intensity at a pump wavelength of 0.808 μm (I_p^{sat} = 16 kW cm^{-2} for the $Nd^{3+}:YAG$ crystal); $\hbar\omega_p$ is the photon energy at λ_p = 0.808 μm; $\sigma_{abs} = 6.7 \times 10^{-20}$ cm^2 is the absorption cross section of Nd^{3+} at λ_p = 0.808 μm; τ = 230 μs for the $Nd^{3+}:YAG$ crystal with an active-ion concentration N_{ions} = 1 at %; and I_i are the intensities of the laser beams involved in multibeam mixing in the ALE. These kinetic equations differ from the initial ones in [19] by the presence of the last term (in each equation), which describes the gain saturation under the ASE conditions.

We performed a comparative study of the lasing kinetics in lasers with two-, three-, and four-loop cavities at λ = 1.34 m, the same pump intensity (I_p = 1.8 kW cm^{-2}), and initial PQS transmission T_0 = 40%, both disregarding and taking into account the ASE at λ = 1.06 μm. The calculation results are presented in Fig. 1.

One can see from Fig. 1 that ASE leads to complete lasing suppression in a two-loop cavity, despite the high pump intensity (Fig. 1b). An increase in the number of cavity feedback loops to three leads to the development of stable lasing (Fig. 1d). In the case of a four-loop laser, ASE only slightly affects the lasing characteristics (Fig. 1f). The reason may be as follows: the negative effect of ASE reduces the gain on the secondary transition wavelength, thus reducing the population grating diffraction efficiency (1) and increasing the PC lasing threshold.

Figure 2 presents the calculated dependences of the threshold pump intensity on the initial PQS transmittance for two-, three-, and four-loop cavities in the range from 30% to 80%, disregarding and taking into account ASE. The threshold pump intensity was determined from the condition of reaching the lasing threshold G_{res} = 1, where G_{res} is the change in the lasing intensity for a cavity round trip [23], which is determined taking into account the recording and reading all population gratings:

$$G_{res} = \sum_{i=1}^{n} \sum_{j=1}^{n} \eta_{ij} (GT)^{i-j-1}. \tag{6}$$

Here, T is the transmittance per PQS pass; n is the total number of interacting waves; and $i \neq j$.

It follows from Fig. 2 that, with ASE disregarded, a decrease in the initial PQS transmittance in the aforementioned range reduces the lasing threshold. This pattern, which is in qualitative agreement with the results of studying the lasing on the fundamental transition [24], is explained as follows: the optically dense switch reduces the differences in the wave intensities involved in the four-wave mixing in an active medium, which leads to an increase in the population grating contrast and diffraction efficiency of the PC mirror in the active laser medium. The consideration of ASE makes the situation more complicated. One can observe an optimal initial PQS transmittance, which corresponds to the minimum lasing threshold; this optimal value decreases with increasing number of cavity feedback loops. The presence of an optimum is due to the fact that the use of an optically dense PQS for radiation at λ = 1.34 μm, which leads to a high loss in the initial lasing stage, is unfavourable because of the enhancement of the negative influence of ASE at λ = 1.06 μm. At the same time, the use of a PQS with a high initial transmittance does not increase the population grating contrast and the diffraction efficiency of the PC mirror in the active medium.

Thus, the mathematical simulation results indicate that a necessary condition for implementing PC lasing on the

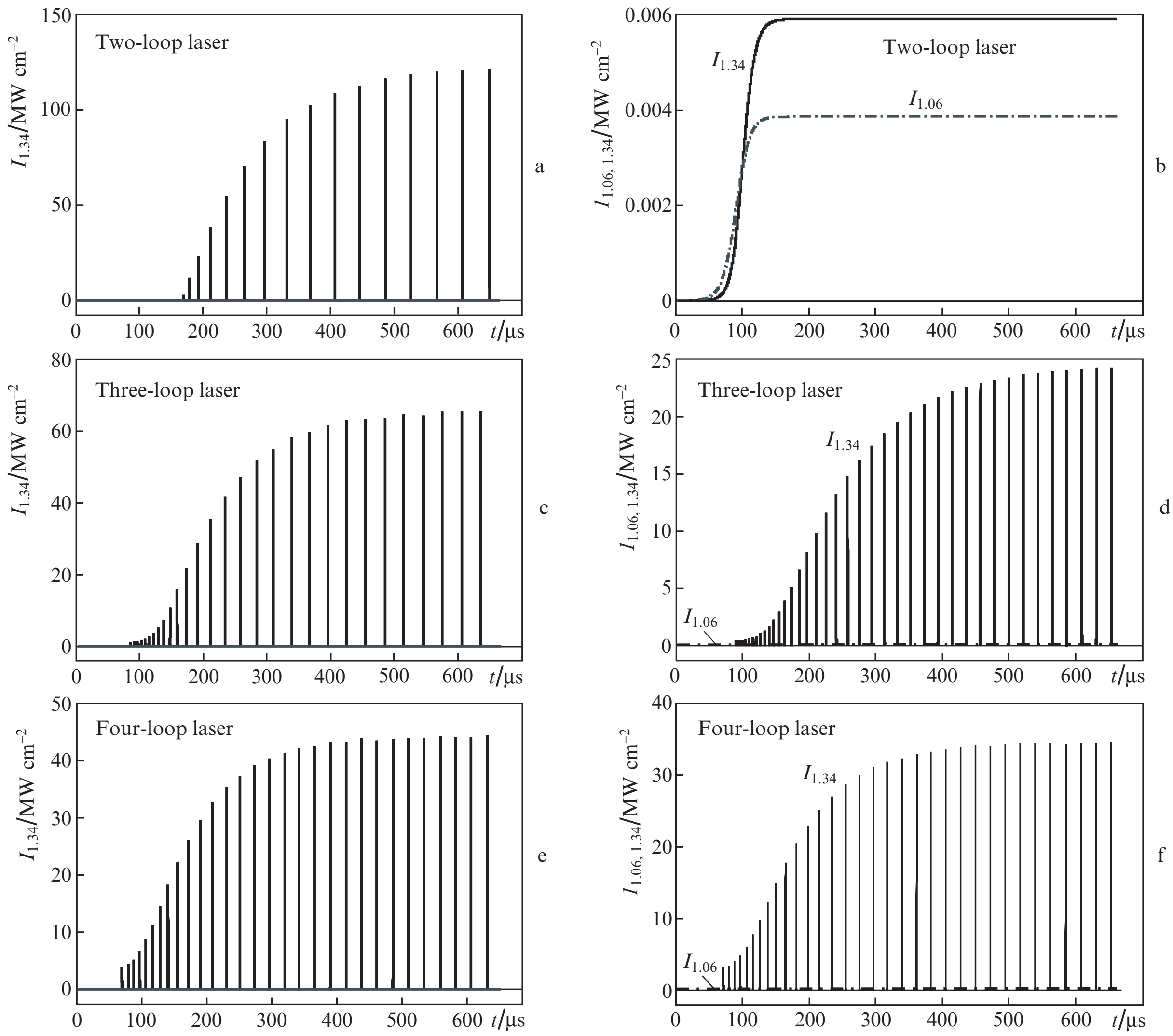

Figure 1. Results of calculating the lasing kinetics for multiloop lasers at a pump intensity $I_p = 1.8$ kW cm^{-2} and initial PQS transmittance $T_0 = 40\%$, found (a, c, e) disregarding and (b, d, f) taking into account amplified spontaneous emission in (a, b) two-loop, (c, d) three-loop and (e, f) four-loop lasers.

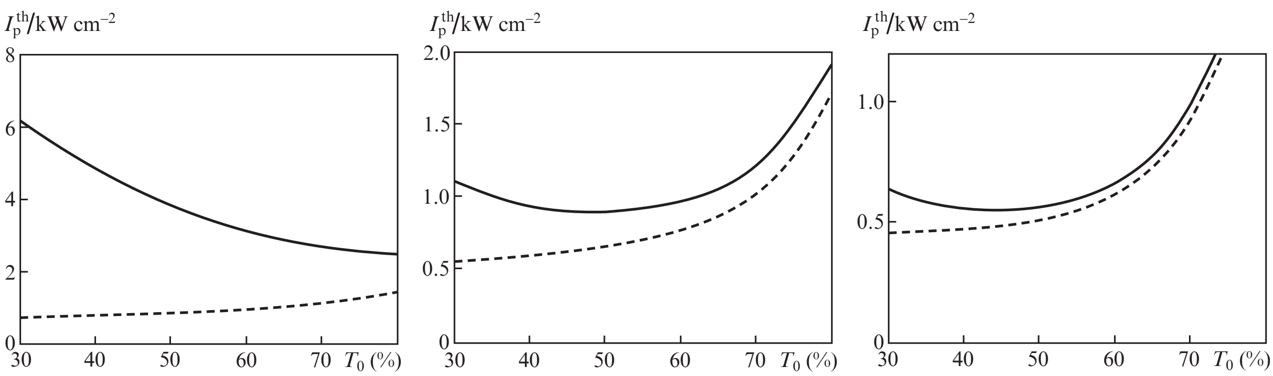

Figure 2. Dependences of the threshold pump intensity on the initial PQS transmittance for two-, three-, and four-loop PC lasers, calculated (dashed lines) disregarding and (solid lines) taking into account amplified spontaneous emission.

secondary transition $^4F_{3/2} \rightarrow {}^4I_{13/2}$ is to increase the field intensity in the active medium at $\lambda = 1.34$ μm. To this end, the number of cavity feedback loops must be no less than three in order to exclude lasing suppression (caused by the negative effect of ASE). To obtain modulated radiation using a PQS, it is expedient to choose the initial transmittance of the latter corresponding to the minimum lasing threshold.

3. Experimental

The optical scheme of the experimental laser setup is presented in Fig. 3. To suppress ASE at λ = 1.06 μm, we used a three-loop cavity (eight-beam mixing in each ALE), the ray path in which was formed by spectrally selective dichroic mirrors, totally reflecting radiation at λ = 1.34 μm ($R_{1.34} > 0.99$) and transmitting at λ = 1.06 μm ($T_{1.06} > 0.96$).

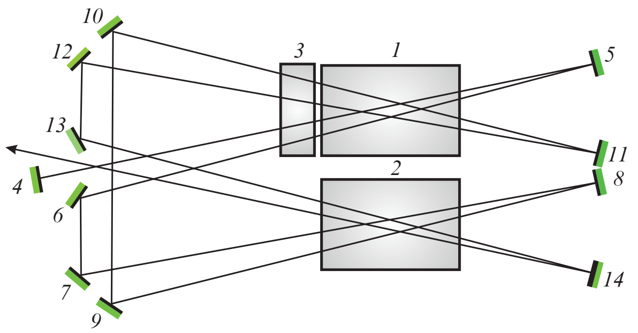

Figure 3. Optical scheme of the experimental setup: (*1*, *2*) Nd^{3+}:YAG ALEs, (*3*) V^{3+}:YAG PQS; (*4*–*14*) cavity mirrors.

The active laser elements were two identical Nd^{3+}:YAG crystals (diameter 6.3 mm, length 130 mm), pumped by KDNP-6/120A krypton lamps. We applied a commercial four-channel power supply GND-13 (designed for the technological LTI-130 laser), which makes it possible to change the pump pulse repetition rate from 1 to 30 Hz at a pulse FWHM of 400 μs (100-μF accumulating capacitors) and pulse energy up to 72 J per lamp. The Q switching regime was implemented by PQSs based on V^{3+}:YAG crystals with initial transmittances T_0 = 47, 59, 74, and 84%.

The best results were obtained using the PQS with T_0 = 74%, for which the threshold pump energy was about 30 J. This value is larger by a factor of 1.5 than the threshold value of 20 J for the free-lasing regime in the absence of a PQS (Fig. 3) but smaller than that obtained with other PQSs (T_0 = 47%, 59% and 84%), the threshold for which was 35 J or higher. These data are in agreement with the numerical simulation results. They show that, among all PQSs under study, the crystal with T_0 = 74% is optimal for implementing passive Q switching for the PC cavity in the laser scheme under consideration. Using this PQS with a maximum energy of pump pulses of 72 J and their repetition rate of 2 Hz, we obtained a train of seven laser pulses with a total energy of 250 mJ, individual pulse energy of about 36 mJ, and average radiation power of 0.5 W.

Figure 4 shows oscillograms recorded using an LFD-2A photodiode avalanche (for the laser radiation) and PD-256 photodiode (for the pump radiation), connected to a two-channel Agilent 546441A oscilloscope (350 MHz). Figure 5 presents the dependences of the energies of the pulse train and individual pulse in train on the energy of a pump pulse from one lamp, recorded using an Ophir power/energy meter.

One can see from Fig. 4 that the generation of a train of modulated pulses for the PQS with T_0 = 74% is developed with a delay of about 150 μs with respect to the pump pulse onset. In the case of free lasing, this delay is about 200 μs, as well as for the other PQSs. The delay in the train generation development may be due to the fact that the gain $\alpha_{1.34}$ is smaller than the gain $\alpha_{1.06}$ by a factor of almost 5. Hence, at a given pump rate, a higher inverse population must be accumulated in ALE to overcome the self-PC threshold. The high intensity of the waves recording gratings in ALE leads to a decrease in the delay time under passive V^{3+}:YAG –PQS Q switching.

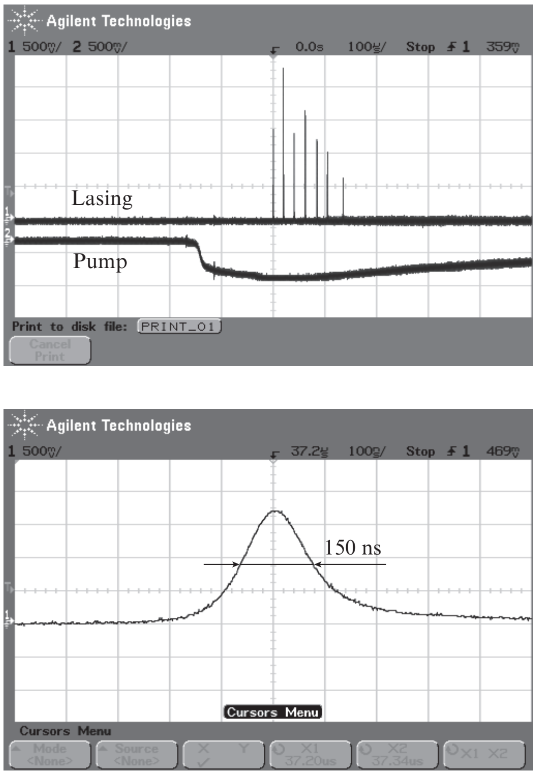

Figure 4. Oscillograms of (a) a laser pulse train and (b) an individual laser pulse obtained using a PQS with T_0 = 74%; the pump pulse energy and repetition rate are, respectively, 72 J and 2 Hz.

As follows from Fig. 5, at a pump pulse repetition rate of 2 Hz, the linear dependences of pulse train and individual pulse energies and the absence of saturation indicate that the energy parameters can be increased even more by increasing the pump energy. Under these conditions, the Q-switching efficiency (the train energy is 250 mJ) exceeds 55% (the free-lasing pulse energy is 450 mJ). At a repetition rate of 5 Hz, the number of laser pulses in the train was retained; however, the highest train energy was 195 mJ at an individual pulse energy of 28 mJ. The average laser power was 1 W. At a pulse repetition rate of 7 Hz and a pump pulse energy less than 50 J, one can observe the most rapid rise in the train and individual pulse energies, which can be related to the positive effect of thermal lens, which provides an additional beam focusing and facilitates the occurrence of optimal thermo-optical conditions for the formation of a dynamic PC cavity. The average laser power reached 1.1 W. The energy of a four-pulse train was 160 mJ, with a maximum energy for an individual pulse recorded to be 40 mJ. With an increase in the pump pulse energy to 60 J, the average laser power reached a maximum value of 1.3 W, the number of pulses in the train increased to six, and the individual pulse energy reduced to 32 mJ. As in the free-lasing regime, at a pump pulse repetition rate of 10 Hz, an increase in the pulse energy was accompanied by the formation of an anomalously strong thermal lens, which rapidly suppressed lasing.

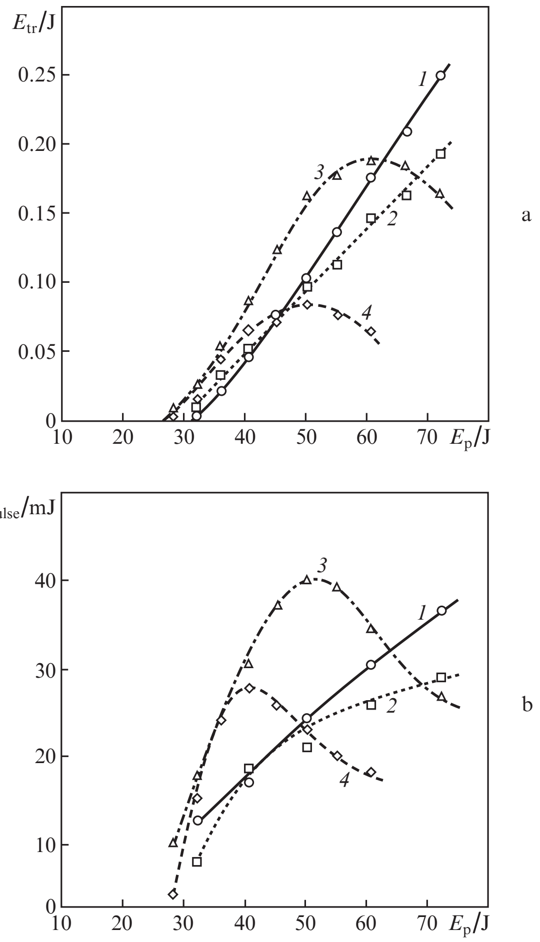

Figure 5. Dependences of the energies of (a) a pulse train and (b) an individual pulse on the pump energy at pump pulse repetition rates f = (*1*) 1, (*2*) 5, (*3*) 7 and (*4*) 10 Hz for the case of using a PQS with T_0 = 74%.

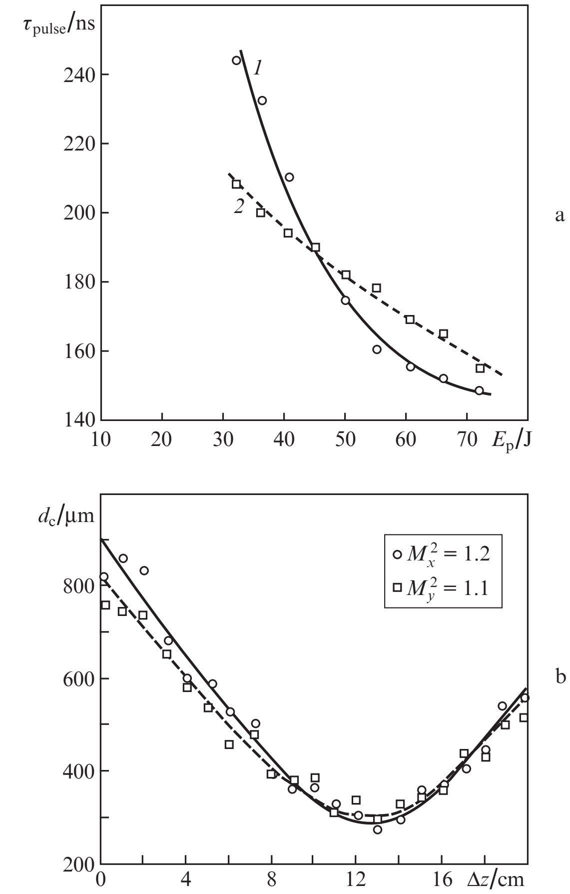

Figure 6. (a) Dependences of the pulse duration at pump pulse repetition rates f = (*1*) 2 and (*2*) 5 Hz and (b) the distributions of beam caustic diameters with respect to the lens focus for the case of using a PQS with T_0 = 74%.

The results of measuring the temporal and spatial parameters of passive Q-switched laser pulses are presented in Fig. 6.

As can be seen in Fig. 6a, the pulse duration decreases with increasing pump pulse energy, which is related to the rise in the rates of recording and erasure of holographic gratings by intense intracavity radiation. At the maximum pump pulse energy, the laser pulse duration was 150 and 155 ns at pump pulse repetition rates of 2 Hz and 5 Hz, respectively. The generated pulses had a smooth temporal profile (Fig. 4b), which is indicative of close-to-single-frequency lasing.

The divergence and quality factor of radiation were measured by the Foucault knife-edge method; the radiation was focused by a collecting lens with a focal length of 0.5 m (pump pulse energy 60.5 J, pulse repetition frequency 5 Hz). The lasing was found to be single-mode, with an intensity distribution similar to Gaussian. The beam divergence in the transverse cross section along the x and y axes did not exceed 0.7 mrad. The quality factors were found to be $M_x^2 = 1.2$ and $M_y^2 = 1.1$.

Thus, we theoretically substantiated and experimentally implemented lasing of a Nd^{3+}:YAG laser with a PC multiloop cavity on holographic population gratings at the wavelength of the secondary transition $^4F_{3/2} \rightarrow {}^4I_{13/2}$ of the Nd^{3+} ion. The conditions for efficient suppression of amplified spontaneous emission with a wavelength of 1.06 μm were determined based on numerical simulation. The developed scheme of the PC multiloop cavity on holographic gratings, recorded in the active laser medium Nd^{3+}:YAG, made it possible to obtain for the first time lasing at a wavelength of 1.34 μm. In the free-lasing regime, the maximum laser energy was 0.45 J, and the average power reached 2 W. Passive Q switching by V^{3+}:YAG crystals with different initial transmittances made it possible to find the optimal initial transmittance of the passive Q switch (74%), which provides generation of trains of repeating pulses of highest power, with an energy up to 0.25 J in a train of seven pulses, at an individual pulse energy up to 36 mJ and a pulse duration of 150 ns. The beam divergence was 0.7 mrad at quality factors $M_x^2 = 1.2$ and $M_y^2 = 1.1$.

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