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Nd^{3+} : YAG laser based on the $^4F_{3/2} \to {}^4I_{13/2}$ secondary transition with a phase-conjugate electro-optically *Q*-switched open multiloop cavity

M.N. Ershkov, S.A. Solokhin, S.N. Smetanin, A.V. Gavrilov, A.V. Fedin

Abstract. **Lasing on the $^4F_{3/2} \to {}^4I_{13/2}$ secondary transition (λ = 1.34 μm) in a Nd^{3+} : YAG laser with phase conjugation by four-wave mixing directly in the active laser medium was experimentally studied in the regime of electro-optic *Q*-switching of an open multi-loop cavity. The use of an electro-optic *Q*-switch with a controllable delay of its opening made it possible to increase the amplitude and temporal stabilities of the output laser parameters. The maximum laser pulse energy was 100 mJ at a pulse duration of 120 ns. The phase-conjugate radiation divergence was 0.8 mrad at beam quality $M_x^2 = M_y^2 = 1.3$. Nonlinear optical conversion of 1.34 μm laser radiation to visible radiation was achieved experimentally. Second and third harmonic generation at wavelengths of 0.67 and 0.446 μm with conversion efficiencies of 25 % and 8 %, respectively, was demonstrated.**

Keywords: *Nd^{3+} : YAG laser, secondary transition, phase conjugation, electro-optic Q-switching, stability of laser parameters.*

1. Introduction

Neodymium lasers operating on the $^4F_{3/2} \to {}^4I_{13/2}$ secondary transition can be used as sources of coherent optical pumping for generation of visible and near-IR radiation, because of which it is important to increase their spatial brightness. Of practical interest are both diode-pumped [1–5] and lamp-pumped [6–11] lasers emitting at $\lambda \approx 1.3$ μm. Diode-pumped lasers are characterised by higher stabilities of energy and temporal parameters, are more compact, and have a high efficiency at a rather high average output power. Lamp-pumped lasers are used to generate high-power pulses for consequent nonlinear-optical conversion. Since the gain cross section of the $^4F_{3/2} \to {}^4I_{13/2}$ secondary transition of Nd^{3+} ions is approximately fourfold smaller than the cross section of the fundamental $^4F_{3/2} \to {}^4I_{11/2}$ transition, lasing on the secondary transition with high-energy parameters requires much higher pump powers. High-power lamp or diode pumping induces static and dynamic thermooptical aberrations, which deteriorate the spatial and energy parameters of laser radiation. A steady-state thermal lens can be compensated either by an appropriate choice of the curvature of cavity mirrors [12] or by using a special cavity configuration [13, 14]. An effective method for compensating dynamic thermooptic aberrations is phase conjugation [15]. Phase-conjugation by stimulated Brillouin scattering (SBS) in a cell with perfluorohexane was used in [16, 17] to compensate for aberrations of radiation at λ = 1.319 μm in a high-power lamp-pumped Nd^{3+} : YAG amplifier. This approach allowed the authors to obtain a laser beam with a spatial quality close to the diffraction limit, a pulse energy of 80 mJ, and a pulse duration of 0.5 ns. The SBS phase conjugation threshold is high, which requires tight radiation focusing and using of high-purity-grade materials as SBS media to avoid optical breakdown. The mentioned factors make it difficult to adjust and exploit these systems. Phase conjugation by four-wave mixing (FWM) in an active medium [18] allows one to achieve a high laser beam quality without using additional elements and devices. In this case, phase conjugation occurs on dynamic holographic gratings inscribed directly in the active medium and playing the role of a positive feedback mirror [19–24]. Another advantage is that FWM phase-conjugate (PC) wave reflectivity may exceed unity, which makes it possible to use FWM PC lasers for both amplification and generation of high-quality radiation. In [25], we have developed and studied a multiloop FWM PC Nd^{3+} : YAG laser with passive *Q*-switching (PQS) by a V^{3+} : YAG crystal, which emitted at λ = 1.34 μm. We obtained a train of seven laser pulses with individual pulse energy of 35 mJ and duration of 150 ns. The beam quality was close to the diffraction limit ($M^2 \leqslant 1.2$). The spatial brightness at a beam divergence of 0.7 mrad was 5.5×10^{12} W cm^{-2} sr^{-1}.

One of the problems of pulse-pumped FWM PC lasers is instability of laser pulse parameters in free-running or self-modulation regimes. This is related to the fact that the formation of holographic gratings occurs under conditions when the gain, which determines the diffraction efficiency of recorded gratings and the *Q*-factor of the dynamic PC cavity, changes under the action of pumping. The change in the gain with time leads to different lasing conditions during the pump pulse, which causes instability of the energy and spatial parameters of individual laser pulses. Electro-optic *Q*-switching (EOQS) makes it possible not only to increase the spatial brightness of laser radiation but also to improve the pulse stability. Controlling the *Q*-switch opening instant, one can correlate the onset of laser pulse development with the instant of achieving the maximum gain of the laser medium, when the PC cavity *Q*-factor is maximum. The use of electro-optic *Q*-switches allowed one to achieve stable operation of single-loop FWM PC Nd^{3+} : YAG lasers emitting at λ = 1.064 μm

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and pumped by pulsed lamps or pulsed diodes [26–28]. The use of EOQS of multiloop FWM PC Nd^{3+} : YAG lasers emitting at λ = 1.34 μm is related to the problem of amplified spontaneous emission at λ = 1.064 μm. This is caused by the fact that the gain formed in the active elements (AEs) to the *Q*-switching opening instant is high, and the spontaneous emission amplified during multiple passage of the beam through the active medium may not only decrease the accumulated population inversion but also cause parasitic lasing at λ = 1.064 μm. Thus, to achieve efficient EOQS in a multiloop Nd^{3+} : YAG laser emitting at λ = 1.34 μm, it is necessary not only to control the *Q*-switch opening instant but also to suppress amplified spontaneous emission at λ = 1.064 μm.

The aim of the present work is to study operation of a FWM PC Nd^{3+} : YAG laser at λ = 1.34 μm in the regime of EOQS of an open multiloop cavity and to implement nonlinear optical conversion of the PC radiation at λ = 1.34 μm into visible radiation.

2. Study of PC lasing at λ = 1.34 μm

The principal optical scheme of the experimental laser setup for studying PC lasing at λ = 1.34 μm with EOQS is shown in Fig. 1. This scheme is based on our setup used in [25]. The laser consisted of two active Nd^{3+} : YAG elements (*1*) and (*2*) and a multiloop cavity formed by plane mirrors (*5*–*13*). The AEs with diameters of 6.3 mm and lengths of 130 mm were placed in a single-lamp laser heads with diffusive reflectors. The AEs were pumped by KDNP-6/120A lamps. The maximum pump pulse energy of one lamp was 72 J at a pulse duration of about 350 ns. The pump pulse repetition rate was varied within the range of 2–10 Hz. The cavity mirrors completely reflected radiation at λ = 1.34 μm ($R_{1.34}$ > 0.99) and transmitted radiation at λ = 1.064 μm ($T_{1.064}$ > 0.96). For EOQS, we used a Pockels cell based on a Glan prism (*3*) and two $LiTaO_3$ crystals (*4*) with crossed optical axes to compensate for thermally induced birefringence.

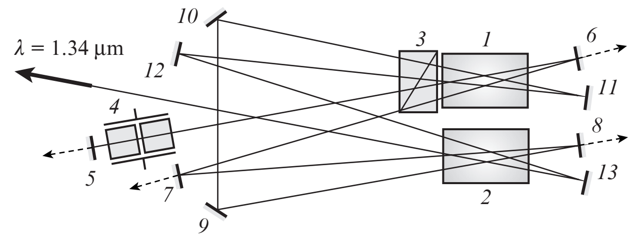

Figure 1. Optical scheme of the experimental setup: (*1*, *2*) AEs in the Nd^{3+} : YAG laser; (*3*) Glan prism; (*4*) $LiTaO_3$ electrooptic crystals; (*5*–*13*) cavity mirrors.

In the course of experiment, we measured the energy, temporal, and spatial parameters of laser radiation at λ = 1.34 μm. The laser energy was measured using an Ophir energy and power meter. The temporal parameters were recorded by an LFD-2A avalanche photodiode and an Agilent 546441A oscilloscope (frequency band 350 MHz). In addition to PC lasing at λ = 1.34 μm, we observed parasitic lasing at λ = 1.064 μm and measured its parameters in directions indicated by dashed lines in Fig. 1.

Figure 2a shows the dependences of the laser pulse energy at λ = 1.34 μm on the pump lamp energy W_p at different pump pulse repetition rates f_p. One can see that the laser pulse energy monotonically increases with increasing pump energy only at f_p = 2 Hz. The highest laser pulse energy in this case was 80 mJ. At higher pump pulse repetition rates (f_p = 3, 5, and 10 Hz), the laser pulse energy first increases as the pump pulse energy increases to 40–50 J and then rapidly decreases until oscillation ceases (at f_p = 10 Hz and W_p > 55 J). The maximum achieved laser pulse energy was 100 mJ at f_p = 3 Hz and W_p = 50 J. Comparing the achieved results with the energies of PC radiation at λ = 1.34 μm measured previously in the PQS regime [25], one can see that the corresponding dependences have different characters. In particular, in the case of PQS, the dependence of laser pulse energy at f_p = 2 Hz was linear, while this dependence at f_p = 5 Hz slowed down and saturated but did not decrease. The decrease in the pulse energy in the case of active *Q*-switching and the slowing of the pulse growth in the case of PQS are related to the development of parasitic lasing at λ = 1.06 μm. One can see from Fig. 2b that the energy at λ = 1.064 μm sharply increases with increasing f_p. The increase in the average pump power with increasing f_p leads to the appearance of a thermal lens in the AEs, which worsens the conditions of recording of holographic gratings and decreases their contrast, thus decreasing the *Q*-factor of the multiloop cavity. Therefore, the energy of

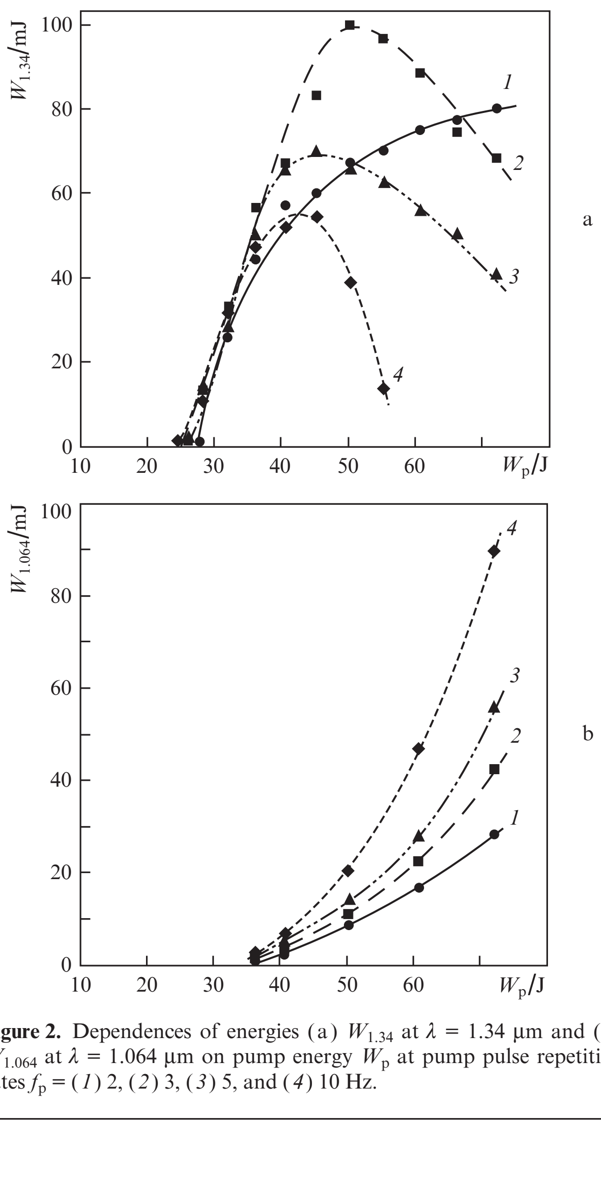

Figure 2. Dependences of energies (a) $W_{1.34}$ at λ = 1.34 μm and (b) $W_{1.064}$ at λ = 1.064 μm on pump energy W_p at pump pulse repetition rates f_p = (*1*) 2, (*2*) 3, (*3*) 5, and (*4*) 10 Hz.

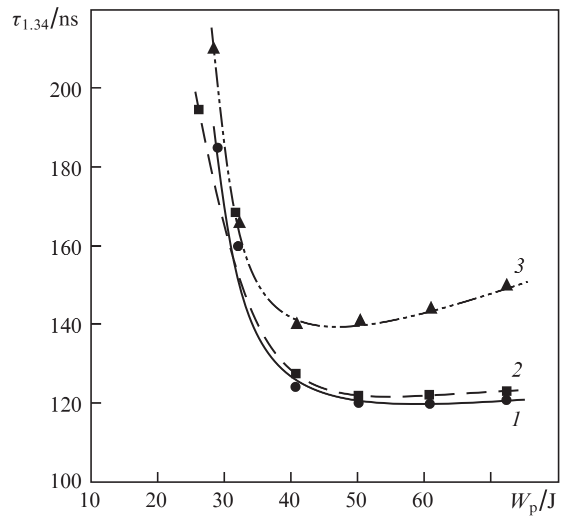

Figure 3. Dependences of laser pulse duration $\tau_{1.34}$ on pump energy W_p at pump pulse repetition rates f_p = (*1*) 2, (*2*) 3, and (*3*) 5 Hz.

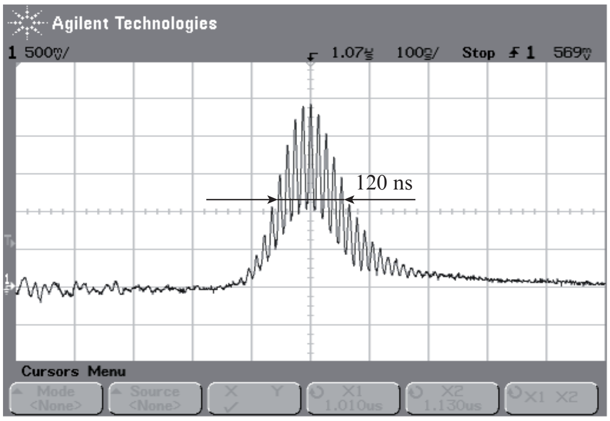

Figure 4. Oscillogram of a laser pulse at λ = 1.34 μm.

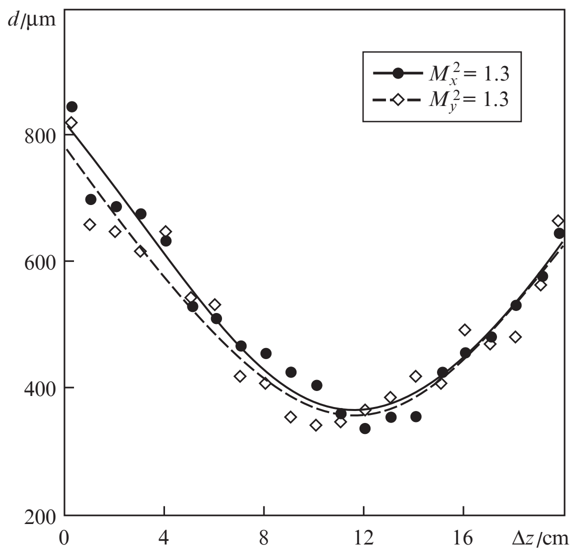

Figure 5. Beam waist diameter d as a function of distance Δz from the lens focus.

radiation at λ = 1.34 μm decreases and the accumulated inverse population decreases due to radiation at λ = 1.064 μm.

Figure 3 shows the dependences of the laser pulse duration at λ = 1.34 μm on the pump energy at different pump pulse repetition rates. The minimum pulse duration was 120 ns at f_p = 2 and 3 Hz and W_p > 50 J. Figure 4 presents a pulse oscillogram recorded at f_p = 2 Hz and W_p = 72 J. In comparison with the PQS regime, PC lasing with EOQS is multifrequency. The single-frequency PC lasing at PQS is achieved due to the use of a V^{3+}:YAG passive *Q*-switch, which plays the role of a longitudinal-mode selector.

The spatial characteristics of PC radiation were measured by the Foucault knife-edge method using an aberration-free collecting lens with a focal length of 0.5 m to focus the radiation (W_p = 60 J, f_p = 2 Hz). The measured beam waist diameters are presented in Fig. 5. It was found that the beam divergence in the transverse directions (along the *x* and *y* axes) did not exceed 0.8 mrad. The intensity distribution corresponded to the TEM_{00} mode. The beam quality factors were M_x^2 = 1.3 and M_y^2 = 1.3. The spatial brightness of radiation in the case of EOQS was 13.2×10^{12} W cm^{-2} sr^{-1}, which is higher than in the case of PQS by a factor of 2.4.

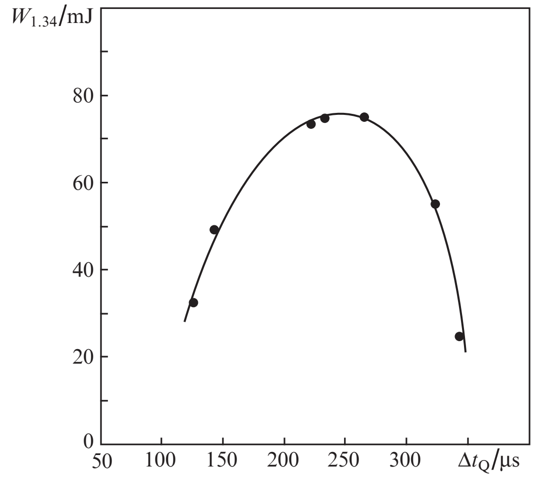

Figure 6. Dependence of laser pulse energy $W_{1.34}$ on *Q*-switch opening delay Δt_Q.

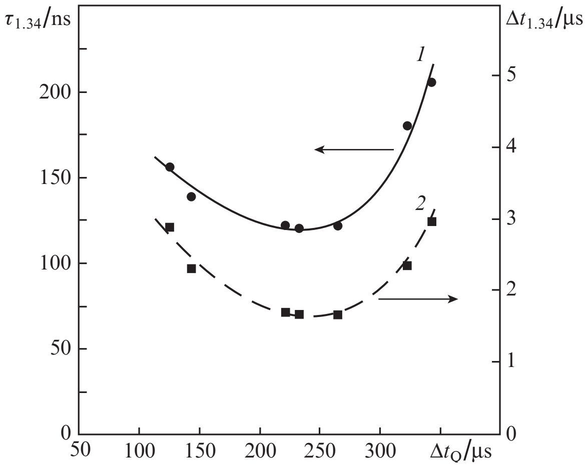

Figure 7. Dependences of (*1*) laser pulse duration $\tau_{1.34}$ and (*2*) lasing development time $\Delta t_{1.34}$ on *Q*-switch opening delay Δt_Q.

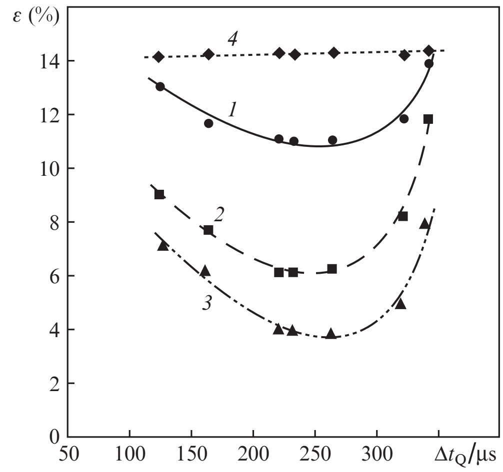

Figure 8. Dependences of relative instabilities ε of (*1*) pulse energy, (*2*) pulse duration, (*3*) lasing development time, and (*4*) pump pulse amplitude on the *Q*-switch opening delay.

Lasing in FWM PC lasers begins to develop at a zero *Q*-factor of the dynamic cavity. At the initial stage, holographic gratings in AEs are recorded and the cavity *Q*-factor increases with increasing reflectivity of the PC mirrors. This determines a longer time of the linear stage of lasing development than in the case of a steady-state cavity. Variations in the gain at this stage lead to instability of the PC lasing parameters. The use of controlled EOQS makes it possible to decrease the time of the initial stage of the PC lasing development and to weaken the effect of gain variations. For these reasons, the electro-optic *Q*-switch should be opened at the instant when the gain reaches its maximum. In the present work, we studied the stability of the PC lasing parameters upon changing delay Δt_Q of the *Q*-switch opening with respect to the pump pulse onset. The measurements for each Δt_Q were performed for no less than 20 pump pulses at W_p = 60 J and f_p = 2 Hz. It was found that lasing did not occur at Δt_Q below 110 μs and above 350 μs. The measured pulse energies and the temporal PC lasing parameters versus Δt_Q are presented in Figs 6 and 7, while Fig. 8 shows the dependences of relative instability of PC lasing parameters on Δt_Q. These dependences show that there exists an optimal range of Δt_Q which is characterised not only by the highest energies (75 mJ) and shortest pulse durations (120 ns) but also by the minimum instability of these parameters. At optimum Δt_Q = 220–270 μs, the pulse amplitude instability was 11% and the pulse duration instability was 6%. The instability of the PC laser pulse parameters was considerably lower than the instability of the pump pulse amplitude (14%), which is important for practical application of solid-state FWM PC lasers.

3. Nonlinear optical conversion of PC radiation at λ = 1.34 μm to visible radiation

Conversion of the fundamental harmonic radiation at λ_ω = 1.34 μm to visible radiation is of practical interest. The second harmonic radiation at wavelength $\lambda_{2\omega}$ = 0.67 μm, which falls into the absorption spectrum of Cr^{3+} : LISAF and Cr^{3+} : LICAF crystals, can be used for coherent optical pumping of these crystals. The third harmonic at $\lambda_{3\omega}$ = 0.446 μm, which coincides with the minimum of the sea water absorption, can be used in underwater communications, hydrolocation, and underwater imaging. In the present work, we studied generation of the second and third harmonics of a PC Nd^{3+} : YAG laser operating at λ_ω = 1.34 μm in the EOQS regime. Experiments were performed on a setup schematically shown in Fig. 9. The PC laser operated at W_p = 50 J and f_p = 3 Hz. In this case, the pulse energy at λ_ω = 1.34 μm was 100 mJ at a pulse duration of 120 ns.

Red radiation at $\lambda_{2\omega}$ = 0.67 μm was generated in a $LiNbO_3$ crystal 8 × 10 × 20 mm in size. The $LiNbO_3$ crystal has the best nonlinear optical characteristic for generation of the second harmonic of lasers emitting at $\lambda_\omega \approx$ 1.3 μm [29]. Blue radiation at $\lambda_{3\omega}$ = 0.446 μm was generated in a DKDP crystal (diameter 20 mm, length 60 mm) by summing the frequencies of the fundamental (λ_ω = 1.34 μm) and second ($\lambda_{2\omega}$ = 0.67 μm) harmonics of the PC laser. The DKDP crystal has a high damage threshold and low losses for the studied optical harmonics. The crystal faces had no antireflection coatings for interacting wavelengths. The pump energy at λ_ω = 1.34 μm was measured using calibrated attenuators, i. e., plane mirrors with known transmittances; the pump radiation intensity was increased using a twofold telescope, which decreased the beam diameter from 4 to 2 mm. The telescope transmission was 80%. The maximum pulse energy at λ_ω = 1.34 μm at the telescope output was 80 mJ.

Figure 10 presents the dependences of the measured energies of optical harmonics on the pump pulse energy at λ_ω = 1.34 μm, and Fig. 11 shows the dependences of the conversion efficiency calculated taking into account reflection from the crystal faces. One can see that the use of a telescope made it possible to increase the radiation energy at $\lambda_{2\omega}$ = 0.67 μm to 15 mJ with a conversion efficiency of 25%, which is almost twice as high as in the scheme without a telescope. The energy at $\lambda_{3\omega}$ = 0.446 μm in the scheme with a telescope increased to 4 mJ at a conversion efficiency of 8%. The low radiation parameters at $\lambda_{3\omega}$ = 0.446 μm are related, first of all, to a non-optimal ratio between energies at λ_ω = 1.34 μm and $\lambda_{2\omega}$ = 0.67 μm.

Figure 12 shows the oscillograms of red and blue radiation pulses at a pump pulse energy of 80 mJ. The pulse duration at $\lambda_{2\omega}$ = 0.67 μm was 90 ns, i. e., decreased by a factor of 1.3 compared to the pulse duration at λ_ω = 1.34 μm, while the

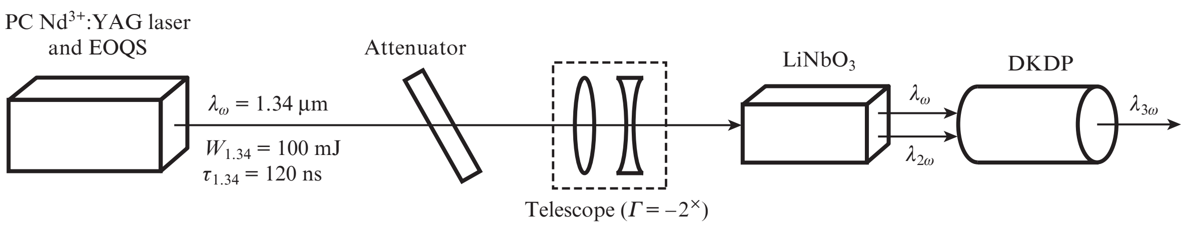

Figure 9. Principal scheme of nonlinear-optical conversion of PC radiation at λ = 1.34 μm into visible radiation.

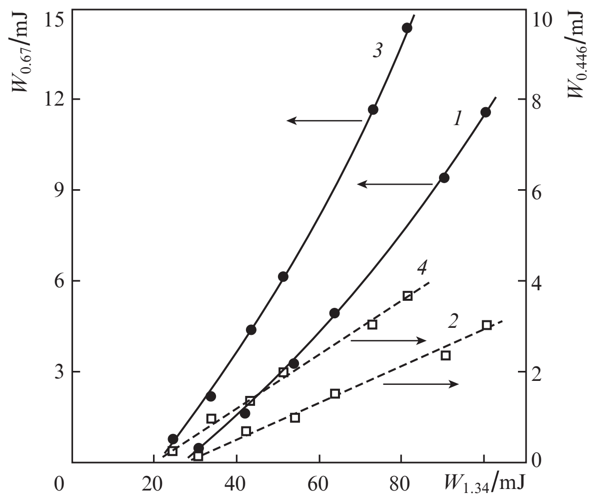

Figure 10. Dependences of laser pulse energies ($1, 3$) $W_{0.67}$ at $\lambda_{2\omega}$ = 0.67 μm and ($2, 4$) $W_{0.446}$ at $\lambda_{3\omega}$ = 0.446 μm on pulse energy $W_{1.34}$ at λ_{ω} = 1.34 μm in schemes ($1, 2$) without and ($3, 4$) with a telescope.

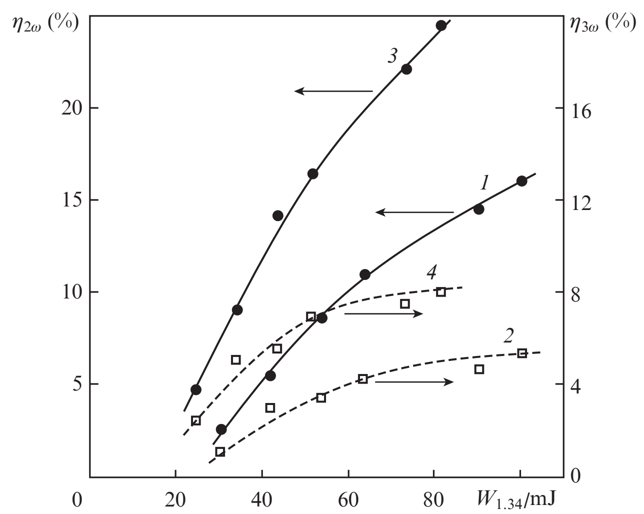

Figure 11. Dependences of conversion efficiencies ($1, 3$) $\eta_{2\omega}$ and ($2, 4$) $\eta_{3\omega}$ into the second and third harmonic, respectively, on pulse energy $W_{1.34}$ at λ_{ω} = 1.34 μm in schemes ($1, 2$) without and ($3, 4$) with a telescope.

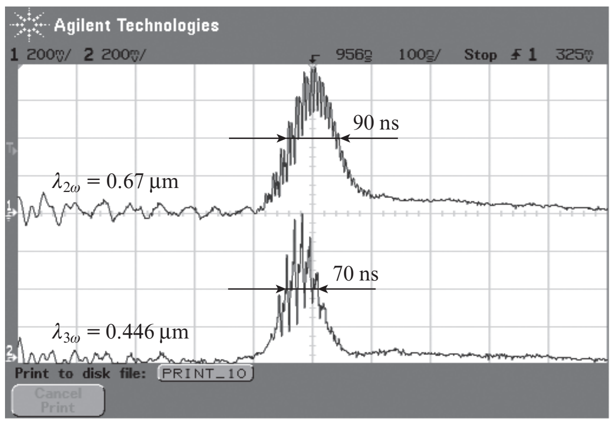

Figure 12. Oscillograms of optical harmonic pulses.

pulse duration at $\lambda_{3\omega}$ = 0.446 μm decreased by 1.7 times and was equal to 70 ns. The powers of red and blue pulses were 125 and 57 kW, respectively.

4. Conclusions

Thus, we experimentally studied lasing of a FWM PC Nd^{3+} : YAG laser operating at a wavelength of 1.34 μm in the EOQS regime. The maximum pulse energy was 100 mJ at a pulse duration of 120 ns. The beam divergence was 0.8 mrad at beam quality factors $M_x^2 = M_y^2 = 1.3$. It is shown that there exist optimal time delays of electro-optic Q-switch opening with respect to the pump pulse, at which the relative instabilities of the laser pulse energy and duration do not exceed 11% and 6%, respectively. Nonlinear optical conversion of PC radiation into visible radiation was performed. The second-harmonic ($\lambda_{2\omega}$ = 0.67 μm) pulse energy was 15 mJ at a conversion efficiency of 25%, while the third-harmonic ($\lambda_{3\omega}$ = 0.446 μm) pulse energy was 4 mJ at an efficiency of 8%.

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