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Compact transversely diode-pumped Nd:YAG laser with a self-pumped phase-conjugate multiloop cavity

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Abstract. **A compact high-power repetitively pulsed Nd:YAG laser with transverse diode pumping and a multiloop self-pumped phase-conjugate cavity is presented. The obtained pulse trains have an energy of 2.55 J with beam quality $M^2 \leqslant 1.2$, a divergence of 0.35 mrad, and a spatial brightness of 7×10^{14} W cm^{-2} sr^{-1}. The peak power of single-frequency pulses exceeds 21 MW at a pulse energy of 230 mJ. The laser bandwidth is 300 MHz.**

Keywords: *self-phase conjugation, gain gratings, passive Q-switching.*

Practical application of optoelectronic complexes based on solid-state laser systems requires compact high-energy solid-state lasers with modulated beam quality close to the diffraction limit. Progress in laser diode pumping technology has renewed interest in lasers with self-pumped phase-conjugate loop cavities, in which the laser medium not only serves as an amplifier of laser radiation but is also responsible for optical self-phase conjugation via degenerate four-wave mixing. The use of self-phase conjugation principles allows one to develop adaptive laser systems for compensation of laser radiation distortions [1, 2].

Studies of radiation of self-phase-conjugate lasers showed that it is necessary to write at least two self-conjugate mirrors on dynamic gratings to achieve high-energy regimes with a high spatial brightness. These can be either dynamic gratings recorded simultaneously in one active element (AE) [1, 3] or a set of gratings recorded in different AEs [4]. The use of a passive *Q*-switch (PQS) in a self-phase-conjugate laser enhances diffractive feedback and leads to generation of high-power single-mode pulses in the case of recording of dynamic holographic gratings in the PQS [3–5]. A high efficiency of a Nd:YAG laser with self-phase-conjugation in the active medium and PQS was shown in [5, 6]. Using two Nd:YAG AEs with dimensions of ∅ 6.3 × 100 mm, pump energy E_p = 63.5 J supplied to the flashlamp of each laser head, a pulse duration of 200 μs, and a pulse repetition rate of 4 MW, the authors obtained lasing with an individual pulse energy of 200 mJ and a peak power of 4 MW at the initial LiF : F_2^- PQS transmittance T_0 = 58 %, while the energy and peak power of laser pulses in the case of a PQS with T_0 = 20 % were 350 mJ and 17.6 MW, respectively. However, the length of this system was about 180 cm, which considerably restricts its practical application.

One of the solutions of this problem is to increase the diffraction efficiency of dynamic gain gratings, which makes it possible to improve the spatial-energy and spectral parameters of lasing and to decrease the size of the system.

In the present work, we present a compact laser system with self-phase conjugation via multiwave interaction in the active (amplifying) medium and in the PQS, in which a dynamic loop cavity is formed in the process of generation development.

To study lasing with transverse diode pumping, we developed and fabricated a laser head with a Nd:YAG laser crystal with a Nd^{3+} concentration of 0.9 at % and dimensions of ∅ 8 × 180 mm. Transverse repetitively pulsed pumping of the AE was performed by 16 SLM 3-2 laser diode arrays with a peak power up to 2 kW each. The arrays were positioned along the AE in four lines, four arrays in each line. The maximum total pump energy was E_p = 14.5 J.

The optical scheme of the laser is shown in Fig. 1. The laser consists of one AE (*1*), two highly reflecting mirrors (*2*), six folding mirrors (*3*) , and PQS (*4*) based on a LiF:F_2^- crystal with initial transmission T_0 = 14 % (the PQS length was 51.5 mm). The best results were achieved with the characteristic length *L* = 60 cm (Fig. 1).

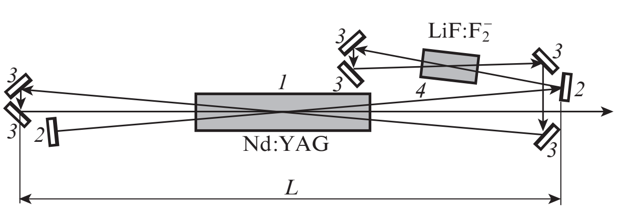

Figure 1. Optical scheme of a Nd : YAG laser with self-phase conjugation via multiwave interaction:
(*1*) AE; (*2*) highly reflecting mirrors; (*3*) folding mirrors; (*4*) LiF : F_2^- passive *Q*-switch.

Lasing begins from noise radiation in the AE. As lasing develops, crossing intracavity beams write transmission gain gratings and refractive index gratings in the PQS, thus forming a self-adaptive laser cavity. The formed gratings are responsible for the radiation field redistribution and phase conjugation [6]. These gratings select the spatial, spectral, and polarisation characteristics. The PQS allows one to obtain radiation in the form of a train of nanosecond pulses.

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Figure 2 shows the experimental energy of a train of Q-switched pulses, their period in the train, and the free-running pulse energy as functions of the pump pulse energy at a repetition rate of 10 Hz. The number of pulses in the train is shown near each experimental point of curve (*1*). One can see from Fig. 2 that, with increasing pump pulse energy, the number of pulses in the train increases and their repetition period decreases. At the same time, the duration of individual pulses in the train (11 ns) and their energy (230 mJ) remain unchanged, as well as the peak power (21 MW). Therefore, the pulse train energy increases with increasing pump pulse energy. At a maximum pump energy of 14.5 J, the energy of a train of 11 pulses is 2.55 J [curve (*1*), Fig. 2], which corresponds to 83% of the maximum energy of free-running pulses (3.05 J), which was also obtained at a maximum pump energy in this laser without PQS. Note that the radiation energy achieved at the maximum pump energy in a plane-parallel cavity 40 cm long with the output mirror transmittance $T_0 = 54\%$ reached 5.95 J, which corresponds to the optical efficiency of 41%. The energy parameters of the laser were measured using an Ophir PE50BF-DIV-V2 pyroelectric detector and a Vega Ophir universal head.

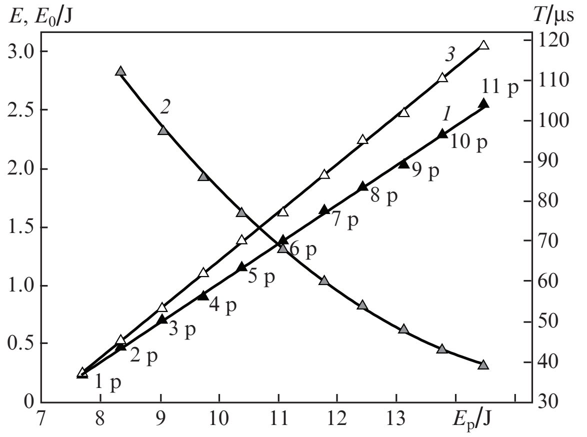


Figure 2. Experimental dependences of (*1*) pulse train energy E, (*2*) pulse repetition period in a train T, and (*3*) free-running pulse energy E_0 of the Nd:YAG laser on the pump pulse energy E_p at pump pulse duration $\tau = 475$ µs and a pump pulse repetition rate of 10 Hz.

An oscillogram of a pulse train consisting of 11 high-power laser pulses and a temporal profile of an individual pulse are shown in Fig. 3. One can see that the modulated pulses have a smooth temporal profile, which indicates that the laser emits single-mode and almost single-frequency radiation [6–8]. The oscillograms are recorded using an Ophir FPS1 SENSOR ROHS avalanche photodiode and a LeCroy WaveJet 352A (500 MHz) double-beam oscilloscope, in which the first (upper) channel recorded the pump pulse shape and the second (lower) channel recorded the laser pulse.

Figure 4a shows the transverse laser beam profile. The intensity distribution in the beam cross section is close to Gaussian. The beam quality parameter was estimated from a beam waist artificially formed by a positive lens with a focal length of 41 cm by measuring the beam diameter by the Foucault knife-edge method at the $1/e^2$ level of the maximum in the transverse intensity distribution. It is found that the beam quality parameter M^2 determined in two orthogonal directions did not exceed 1.2, which turned out to be lower

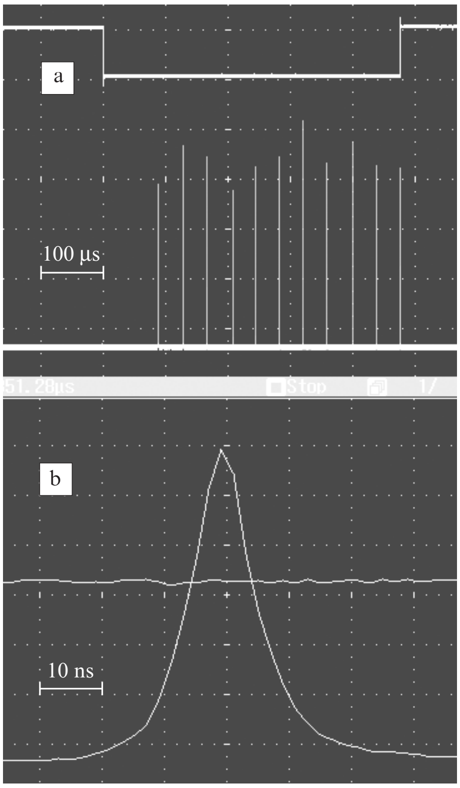
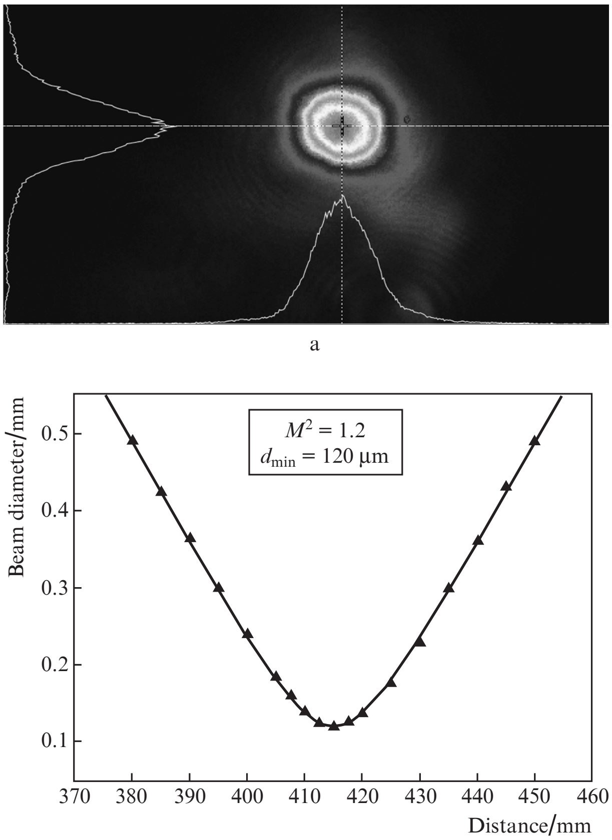


Figure 3. Oscillograms of (a) a pulse train and (b) an individual pulse in the train.



a

b

Figure 4. (a) Beam profile with transverse intensity distribution and (b) dependence of the beam diameter on the distance to the 41-cm lens.

than for free-running pulses (M^2 = 1.35) due to the spatial selection by the LiF : F_2^- PQS. The dependence of the laser beam diameter on the distance to the lens for the horizontal direction is shown in Fig. 4b. The beam diameter measured at the 1/e^2 level at the exit from the laser was 5.4 mm. The modulated radiation divergence was 0.35 mrad, and the spatial brightness was 7×10^{14} W cm^{-2} sr^{-1}. The output laser beam profile was recorded using a BeamGage SP620U (Ophir-Spiricon) camera.

The laser bandwidth was measured using a Fabry–Perot etalon with the free dispersion range interval $\Delta\lambda$ = 4.7 pm. The laser radiation was converted into the second harmonic to observe an interferogram. Figure 5 presents an interferogram obtained in a single-pulse regime with a pulse repetition rate of 30 Hz. In this regime, the interferogram consists of a series of narrow equidistant fringes. This means that lasing occurs at one longitudinal mode with bandwidth $\Delta\nu$ = 300 MHz ($\Delta\lambda$ = 0.28 pm).

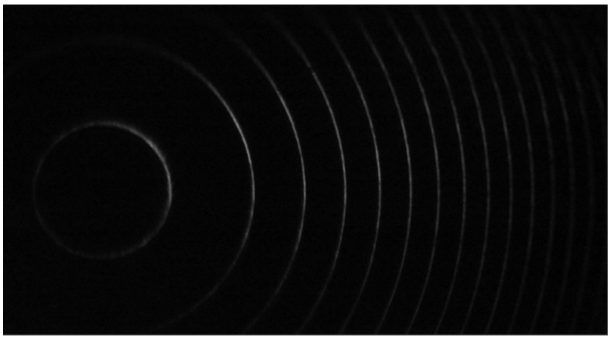


Figure 5. Interferogram of an individual pulse (pulse repetition rate 30 Hz).

Investigations showed that the radiation is vertically polarised with a polarisation degree exceeding 0.9. The radiation in the above-mentioned plane-parallel cavity was unpolarised. The radiation in the free-running regime at short pump pulses (60–100 μs) was vertically polarised with a degree no lower than 0.9. The polarisation degree decreased with increasing pump pulse duration, and the radiation became unpolarised at a pump pulse duration of 475 μs. The lowest polarisation degree was observed when the pump pulse duration exceeded the lifetime of Nd^{3+} ions.

It should be noted that a shift of the PQS from the intermediate position (Fig. 1) by 2–3 cm along the optical axis led to a considerable deterioration of the spatial-energy characteristics. The pulse energy and peak power decreased from 230 mJ and 21 MW to 120 mJ and 11 MW, respectively. The obtained results show that a decrease in the interaction length in the PQS decreases the positive feedback in the self-phase-conjugate cavity and deteriorates the energy and temporal parameters of lasing [6].

Thus, the studied compact Nd : YAG laser with a dynamic loop cavity and a passive Q-switch based on a LiF : F_2^- phototropic crystal with initial transmittance T_0 = 14% and self-phase conjugation via multiwave interaction makes it possible to produce high-power single-frequency radiation with a beam quality close to the diffraction limit. The use of a multi-loop cavity scheme for creating phase-conjugate mirrors in the AE and PQS with a higher diffraction efficiency allows one to achieve high energy and spatial parameters of a self-phase-conjugate Nd : YAG laser with a LiF : F_2^- PQS.

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