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Study of the radiation divergence and energy efficiency of a pulsed Nd^{3+} : YAG laser transversely pumped by laser diode arrays

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***Abstract*. The spatial and energy characteristics of radiation from a pulsed Nd^{3+} : YAG laser transversely pumped by laser diode arrays are studied experimentally by varying the resonator parameters. The differential efficiencies of the laser for multimode and close to single-mode free running lasing were measured to be 48 % and 40 % – 42 %, respectively.**

Keywords: *neodymium laser, beam divergence, transverse pumping, diode-laser pumping*.

1. Introduction

The development of lasers having simultaneously the high efficiency and low divergence of output radiation is an actual problem for many applications [1].

Longitudinal pumping by laser diodes is most favourable for producing diffraction-limited output beams from solid-state lasers because such pumping allows the matching between the spatial distributions of pump radiation and the fundamental transverse mode of the open resonator. However, the use of longitudinal pumping to increase the output energy becomes difficult because of the necessity of employing laser diode arrays, which leads to high radiation losses in complicated optical systems required for the pump-beam shaping and reduces the efficiency of single-mode lasing [2].

The transverse pumping of an active element (AE) by laser diode arrays (LDAs) seems to be more promising for achieving the high energy parameters of lasers. Transverse pumping allows one to change the pump level by varying both the number of LDAs assembled in one section around the AE and the total number of sections placed along the AE axis. Although transverse pumping cannot provide a complete matching between the spatial distributions of the pump radiation intensity and resonator modes, it was successfully used in Nd^{3+} : YAG lasers to achieve an average output power of 150 W in a nearly diffraction-limited beam ($M^2 = 1.1$) [3]. In the general case the main spatial characteristics of laser radiation, such as the far- and near-field energy distributions, are described by a superposition of the resonator eigenmodes with proper coefficients for which lasing conditions are fulfilled [4, 5]. The mode composition of the laser beam is determined by the selective properties of the resonator and the spatial distribution of the inverse population density in the AE cross section, which depends on the pump-module design and absorption of radiation from laser diodes in the active medium. Therefore, the experimental measurements of the relation between spatial and energy characteristics such as the beam divergence and the differential efficiency are important for the development of lasers with required parameters.

In this paper, we studied experimentally the energy and spatial characteristics of radiation emitted by a free-running or *Q*-switched Nd^{3+} : YAG laser whose cylindrical rod was transversely pumped by laser diode arrays. The aim of the paper was to determine the effect of the inhomogeneity of the pump intensity distribution and correspondingly of the inverse population density over the AE cross section on the energy and spatial parameters of output radiation.

2. Parameters of the pump module

We built a pump module for experiments that was similar to the module with eight LDAs symmetrically arranged in one section at a distance of approximately 0.8 mm from the cylindrical AE surface [5]. Unlike the previous design, the module under study consisted not of two but four sections containing eight LDAs each, which provided the increase in the total output pulse energy up to 500 mJ. A Nd^{3+} : YAG crystal of diameter 5 mm with the atomic concentration of Nd^{3+} ions equal to 1.2 % was used as an AE. LDAs were manufactured at the Polyus RDI and provided 60-W pulsed radiation each in the spectral range between 807.5 and 811 nm ($T = 20\,^{\circ}$C). The FWHM angular divergence of the LDA radiation beam was 10° and 45° with respect to 'slow' and 'fast' axes, respectively. We have chosen such a design of the pump module due to its compactness allowing the minimisation of the radiation losses during radiation transfer from a LDA to an AE. As shown in Ref. [5], for the LDA parameters given above, the module of such a design provided the use of up to 80 % of radiation from diodes (neglecting Fresnel losses at the air – AE interface) to obtain multimode radiation from the laser in the case of the nearly axially symmetric spatial distribution of the pump field in the AE.

The propagation of radiation from eight LDAs through the AE cross section was analysed in the geometrical optics

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approximation for the pump scheme used in the experiments. We found that the maxima of the inverse population density with approximately equal amplitudes were formed both in the central region with the effective diameter 2.2 mm and at the AE periphery where the cross sections of the beams from eight LDAs were minimal. Such a distribution of the inverse population density suggests the existence of two types of transverse modes with the maximum gain. The low-order modes propagating near the resonator axis belong to the first type, while modes with the higher-order radial indices, which remove the inverse population at the AE periphery belong to the second type. We can estimate the influence of these types of transverse modes on the parameters of the beam being formed by studying, in particular, the energy and spatial characteristics of laser radiation for different resonator schemes.

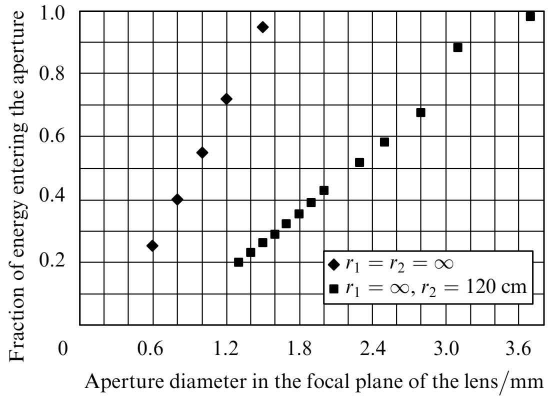

Figure 2. Divergence of radiation from the Nd^{3+} : YAG laser measured for the resonator of length 38 cm with plane or plane and spherical mirrors. The reflectivity of the output mirror $R_1 = 30\,\%$.

3. Method and experimental results

We measured the energy and spatial characteristics of radiation from a Nd^{3+} : YAG laser with a pump module consisting of 32 LDAs described above. The energy characteristics (the lasing threshold P_{th}, output energy, and slope lasing efficiency) and the laser beam divergence were measured at a fixed pump energy of 350 mJ using different resonator schemes. The far-field spatial characteristics of the laser beam were determined by measuring the radiation energy passing through an aperture at the focal plane of a lens as a function of the aperture diameter [6]. The numerical value of the beam divergence was measured as the ratio of the aperture diameter to which 86 % of the total energy of the laser pulse enters to the focal length of the lens equal to 50 cm. Because we did not study the influence of various thermooptic effects on the laser radiation parameters (which is a separate problem), the 200-μs LDA pump pulse repetition rate was 5 Hz.

At the first stage of the experiment, we measured the energy and spatial characteristics of the laser with a new four-section module under the conditions similar to those in Ref. [5]. We used a stable plane – spherical resonator of length $L = 38$ cm and the radius of curvature of a highly reflecting mirror $r_2 = 120$ cm. The results of measurements presented in Figs 1, 2 demonstrate the generation of a multimode beam with a high divergence (6.2 mrad). The maximum slope lasing efficiency η was 48 %, which is somewhat lower than 55 % obtained for a module consisting of 16 LDAs [1 – 5]. This can be explained by the non-optimal matching between a broader emission spectrum of the module containing 32 LDAs and the absorption spectrum of a Nd^{3+} : YAG crystal.

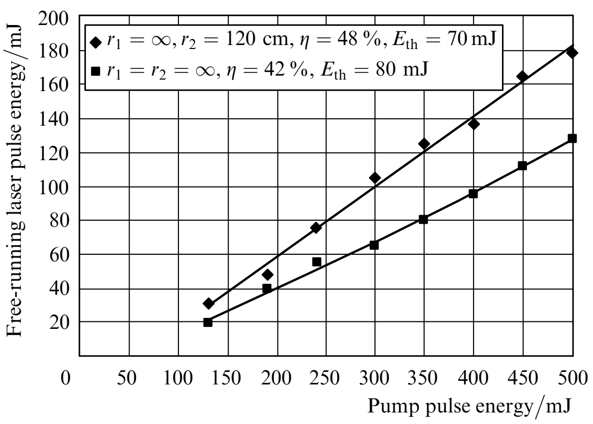

Figure 1. Energy parameters of the Nd^{3+} : YAG laser with the resonator of length 38 cm with plane mirrors or plane and spherical mirrors. The reflectivity of the output mirror is $R_1 = 30\,\%$.

It is known that unstable resonators in which low-order modes efficiently fill the active medium are used in the development of high-power lasers emitting low-divergence beams [7]. However, diffraction losses in such resonators substantially increase with increasing the magnification coefficient of the beam diameter per transit of radiation in the resonator, which prevents obtaining a high lasing efficiency. For this reason, we used plane mirrors in the resonator of the same length (38 cm) in the next experiment. Under the conditions when thermooptic distortions in an AE could be neglected, such a resonator was at the boundary of regions of the stable and unstable states [6]. This allowed an increase in the filling of the AE by low-order radiation modes with a relatively low divergence, without a substantial increase in diffraction losses. Indeed, it follows from Figs 1, 2 that the beam divergence decreased from 6.2 to 2.6 mrad compared to the case of a plane – spherical stable resonator, while the maximum slope lasing efficiency decreased only slightly (from 48 % to 42 %). However, despite a positive result, the use of a resonator with plane mirrors in lasers that should be highly stable under various external perturbations is undesirable because the energy parameters of the laser are unstable at small angular deviations of plane mirrors from their optimal alignment.

This problem can be solved by using a stable resonator with convex – concave mirrors, which, however, admits a significant variation in the diameter of the fundamental mode inside the AE [7]. In this connection we performed experiments with a resonator formed by a pair of mirrors with the radii of curvature of the inner surface $r_1 = +64$ cm for the output mirror with the reflectivity $R_1 = 34\,\%$ and $r_2 = -83$ cm for the highly reflecting mirror. The degree of resonator stability and the AE filling were varied by changing the distance between these mirrors, the distance between the output mirror and the near end of the AE being fixed (~ 3 cm).

The energy and spatial lasing parameters were measured for resonator lengths equal to 25 and 58 cm (Figs 3, 4).

These resonator lengths were chosen because in the first case the diameter of the fundamental-mode field (at the e^{-1} level) was approximately five times smaller than the AE diameter, and the resonator had low diffraction losses for high-order modes. In the second case, losses for these modes were higher and the fundamental-beam diameter coincided approximately with the effective width of the maximum of the inverse population density at the AE centre. It follows from the results obtained in this series of experiments that, when the resonator length L is increased to the nearly critical value, the beam divergence decreases substantially from 6 to 3 mrad, whereas the energy parameters change only slightly (Fig. 3).

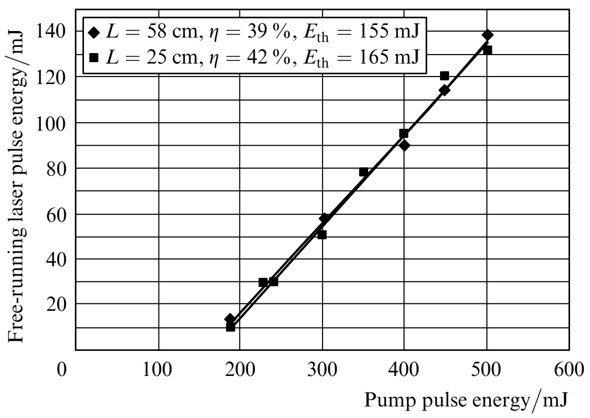

Figure 3. Energy parameters of the Nd^{3+} : YAG laser for different lengths of the convex – concave resonator.

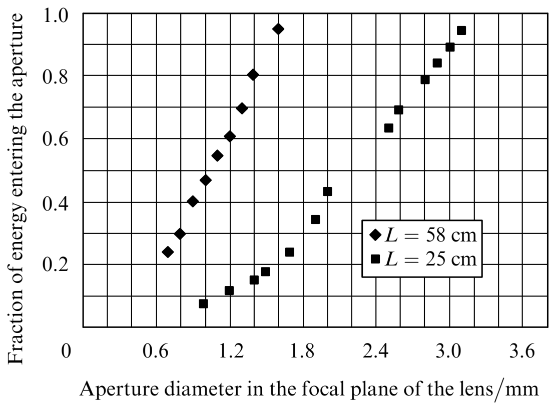

Figure 4. Divergence of radiation from the Nd^{3+} : YAG laser measured at different lengths of the convex – concave resonator.

We studied the effect of the dynamics of laser-pulse formation on the process of competition between the transverse modes by measuring the spatial characteristics of radiation from the laser operating in the free-running and Q-switching regimes. This experiment was performed with a convex – concave resonator of length $L = 58$ cm having mirrors described above. Q switching was performed by placing into the resonator a polariser and a quarter-wave electro-optical lithium niobate gate. A dc blocking voltage and pulsed gate trigger voltage with a front duration of ~ 25 ns were applied to the gate at the instant of time corresponding to the trailing edge of the LDA pump current pulse. The results of this experiment are presented in Fig. 5.

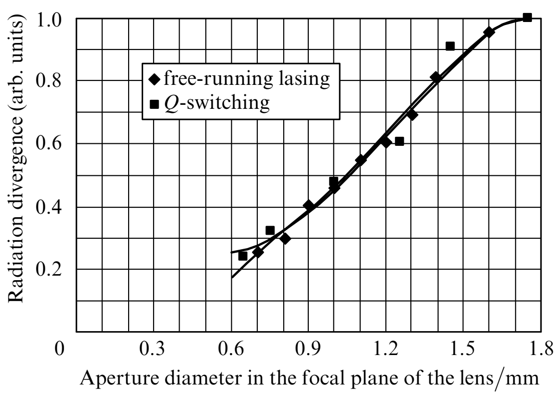

Figure 5. Divergence of radiation from the symmetrically transversely pumped Nd^{3+} : YAG laser measured in the free-running and Q-switching regimes.

4. Analysis of the experimental results

The mode composition of laser radiation was quantitatively estimated by calculating by the ABCD matrix method the spatial parameters of fundamental-mode beams for stable resonators used in the experiments. The results of these calculations and measurements of the beam divergence are presented in Table 1. Their comparison demonstrates that we have obtained laser emission with different mode compositions. The laser beam obtained in experiments with a convex – concave resonator of length 25 cm and a plane – spherical resonator of length 38 cm can be characterised as a strongly multimode one (see Table 1). The spatial emission spectrum of the laser with a plane resonator of length 38 cm or a convex – concave resonator of length 58 cm contained mainly low-order modes.

Table 1.

r_1/cm	r_2/cm	L/cm	φ_{exp}/ mrad	φ_{theor}/ mrad	D_1/μm	N	D_2/μm
∞	∞	38	2.6	–	–	–	–
∞	+120	38	6.2	1.6	900	7	1740
+ 64	− 83	25	6	2	960	5	1600
+ 64	− 83	58	3	3	1680	1	1680

Note: φ_{exp} and φ_{theor} are the experimental and theoretical divergence angles, respectively; N is the number of excited modes; D_1 is the diameter of the fundamental-mode caustic in the AE; D_2 is the diameter of the total caustic of radiation modes.

Using the known properties of a thin lens [6], we can assert that the results of measurements of the spatial parameters of the laser beam allow us to determine the far-field angular distribution of laser radiation. Because laser radiation can be represented as a certain superposition of transverse modes with different divergences [4], the knowledge of the far-field radiation parameters permits us to estimate the energy distribution over modes of different orders.

Indeed, by comparing the results of the corresponding experiments, we can see that the far-field spatial radiation distribution for laser beams from low-selective resonators was smoother than that for beams emitted from high-selective resonators. Taking the data of Table 1 into account, we can conclude that in the first case the radiation was uniformly distributed among modes of different orders, and the fundamental mode with the diffraction-limited divergence made a comparatively small contribution to the total superposition. In the second case, the fundamental mode and low-order modes forming a low-divergence beam dominated in the laser emission. Note here that, as comparison of the data in Table 1 shows, the formation of the mode composition of laser radiation was determined namely by the inhomogeneous distribution of the inverse population density in the active medium rather than the diffraction of radiation from the AE aperture.

This resulted, in particular, in the generation of laser beams with somewhat lower divergence than it follows from a comparison of the calculated sizes of the high-order modes and the AE aperture (see Table 1). By comparing the calculated and experimental beam divergences presented in Table 1, we found the diameter of the AE region (1.6 – 1.8 mm) where the inverse population determined the conditions for generation of transverse modes for all resonator schemes used. This diameter of the region with a high gain is in good agreement with the results of analysis of the propagation of radiation from LDAs over the AE cross section. The effect of the above-mentioned local maxima of the inverse population near the AE surface on the energy parameters of laser radiation can be understood from the analysis of the following results.

A comparison of the energy characteristics of the laser in experiments with plane – spherical and plane resonators (Fig. 1) shows that in the first case the dependence of the output pulse energy on the pump pulse energy is to a great extent nonlinear. This suggests that, as the total gain increases, the relative contribution of the high-order transverse modes of the plane – spherical resonator to the total output energy increases. In the case of the plane resonator, the level of diffraction losses of similar modes exceeds the maximum level of the gain achieved, which prevents the efficient use of the inverse population at the AE periphery. However, such a decrease in the AE working volume leads only to a slight decrease (approximately by 10 %) in the maximum slope efficiency of free-running lasing. In this case, an increase in the fundamental mode volume and exclusion of high-order modes from the beam can reduce the total divergence of the beam by half.

Similar conclusions can be made by comparing the characteristics of radiation from a Nd^{3+} : YAG laser in experiments with a variable length of the convex – concave resonator (Figs 3, 4). Indeed, in this case a change in the mode composition of the beam also leads to a substantial (approximately by a factor of three) decrease in the beam divergence, the energy parameters of the laser being preserved. All these facts suggest that the contribution of local maxima of the inverse population near the AE surface to the energy characteristics of laser radiation is relatively small, except for the case when the conditions for the generation of high-order transverse modes in a stable resonator are specially produced.

The results of the experiment, in which the spatial characteristics of radiation from a Nd^{3+} : YAG laser operating in the free-running and *Q*-switching regimes (Fig. 5) were studied in the far-field zone, showed that the beam was close to the single-mode one in both regimes and its divergence was approximately the same. However, the gain and dynamics of the laser pulse formation were substantially different in these regimes. Therefore, this means that in the case of the inhomogeneous distribution of the gain in the AE, the spatial characteristics of radiation did not change noticeably during the variation of the dynamics of laser pulse formation in a broad range.

5. Conclusions

Experiments reported in this paper have shown that the symmetric transverse pumping of a cylindrical AE (a Nd^{3+} : YAG crystal) by radiation from LDAs leads to the efficient generation of laser beams with different mode compositions and divergences when the resonator parameters are properly chosen. In particular, when the fundamental-mode diameter increased up to 40 % of the AE diameter, the beam divergence coincided approximately with the calculated divergence namely for this mode in the free-running and *Q*-switching regimes.

It is important to note that for the obtained increase in the fundamental-mode volume and decrease in the number of transverse radiation modes, the inhomogeneity of the distribution and the concentration of the pump radiation near the AE axis did not reduce significantly the energy parameters of the laser. However, an obvious disadvantage of the inhomogeneity of the inverse population distribution over the AE cross section is the fact that it can restrict the maximum energy of a single pulse in the *Q*-switching regime because the local power density can exceed the admissible level. In particular, for this reason the maximum energy of a single pulse was only 25 mJ when a module with a Nd^{3+} : YAG crystal rod of diameter 3 mm transversely pumped by the LDA was used [8].

This problem can be solved by using a convex – concave resonator and filling the AE by the low-order radiation modes, which, as was shown experimentally, should not reduce substantially the pump efficiency. It seems that the beam divergence of 2.5 – 3 mrad (at the 0.86 level of the total radiation energy) obtained in these experiments corresponds to the minimum value that can be achieved in a laser with a module for transverse pumping of the AE of diameter 5 mm without a considerable reduction of the lasing efficiency. To obtain the efficient generation of beams with a lower divergence, it is necessary to use resonators with the appropriate parameters of transverse modes and pump modules with AEs of smaller diameters. In this case, to preserve high energy parameters, the laser should have a more complicated design (containing an efficient master oscillator emitting a low-divergence beam and a multistage multipass amplifier).

Therefore, the results obtained in this paper show that the further studies of lasers transversely pumped by LDA radiation are promising for the development of efficient lasers with high energy and spatial output radiation parameters.

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