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Efficiency of transverse pumping of a solid-state pulsed Nd : YAG laser by laser diode arrays

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***Abstract*. A Nd^{3+} : YAG laser with a cylindrical active element transversely pumped by quasi-continuous laser-diode arrays located around its side surface is studied experimentally. The developed pumping modules with symmetric and asymmetric geometries provide the differential efficiency of 48 % and 55 % for multimode free-running lasing upon pumping of elements of diameter 3 and 5 mm, respectively. Under the conditions corresponding to this efficiency of utilisation of radiation emitted by laser diode arrays, laser pulses with energy of 28 and 55 mJ are generated in the *Q*-switching mode.**

Keywords: *laser diode array, solid-state laser transversely pumped by laser-diode arrays.*

1. Introduction

The maximum utilisation of the pump energy is an important problem emerging in the development of solid-state lasers. At the present time, a new class of coherent radiation sources has been developed, the so-called all-solid-state lasers representing diode laser-pumped solid-state lasers. These lasers feature a number of advantages, such as a high efficiency of utilisation of pump radiation, a high quality of the radiation beam, and a long service life, which make it possible to use such lasers successfully in various fields of science and technology [1].

However, for the realisation of the above-mentioned merits in developing diode laser-pumped solid-state lasers, an optimal scheme of pump module should be selected, which would provide the required energy characteristics of the laser together with certain space – time and spectral parameters of radiation. It is known that the pumping of the active element of a solid-state laser by laser diodes can be performed using one of the two known schemes (longitudinal or transverse), each of which has its own merits and drawbacks [2]. For example, the longitudinal pumping provides high-quality output beams along with a relatively high efficiency of utilisation of radiation from laser diodes [3]. However, the application of the longitudinal pumping is not optimal if the output energy of the laser has to be increased [4].

The transverse pumping is most promising for achieving high energy characteristics of laser radiation. Pumping elements in such systems are either single laser diode arrays (LDAs), or systems assembled from a large number of LDAs. These elements of the pumping system are arranged around the cylindrical side surface of the active element, and are grouped in sections. Therefore, the output laser pulse energy can be increased either by increasing the number of sections of the pumping system along the active element, or by changing the number of elements in a section [5 – 7].

During the designing a solid-state laser possessing the required energy, spectral, and space – time output characteristics, there emerges the problem of optimisation of the pumping module design for the efficient conversion of the pump energy into the laser output energy. Since in the case of transverse pumping, the active elements may have different shapes and volumes, it is necessary to solve the problem of the most efficient utilisation of LDA radiation and to determine the conditions under which the required energy of the solid-state laser can be attained.

In this work, we study experimentally the lasing efficiency of a Nd^{3+} : YAG laser operating in the free-running and *Q*-switching modes upon transverse pumping of its cylindrical active element by laser diode arrays located near the side surface of the element. The aim of the paper is to determine the optimal parameters of the system of transverse pumping of the cylindrical active element by radiation from the LDA, which makes it possible to generate pulses with an energy of several tens millijoule in the *Q*-switching mode. The experiments made by us continue the investigations described earlier in [8].

2. Estimate of the efficiency and the choice of configuration of the module for pumping the cylindrical active element of a Nd^{3+} : YAG laser by laser diode arrays

In the general case, the total efficiency of a pump module is determined by three main factors: the efficiency of transfer of radiation emitted by laser diodes to the active element; the absorption of pump radiation in the active medium; and the spatial matching of the region in which population inversion is created with the corresponding distribution of a set of transverse modes of the open cavity [9]. The simplest method of transmission of radiation emitted by the LDA with a standard length of 1 cm to the active medium is

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realised when they are arranged along the axis of the cylindrical active element in the immediate vicinity of its surface [10].

The absorption of radiation in the active element of the laser is determined by the matching of emission spectra of the LDA comprising the pumping module with the absorption spectrum of the active element itself, whose absorption coefficient is a function of the concentration of active ions and of the characteristic size of the region absorbing pump radiation, which in turn depend on the active element diameter and on the number of trips of pumping radiation through it. The maximum spatial matching between the inverse population distributed nonuniformly over the active element and a certain set of transverse modes of the cavity being used provides, as a result of competition, the fulfilment of the lasing condition precisely for this set of modes, which determines the spatial characteristics of laser radiation.

The results of preliminary experiments on transverse pumping of the Nd^{3+} : YAG active elements of diameters 1.5 and 5 mm by sections of two LDAs arranged at 45° to each other [8] revealed that the effective coefficient of LDA radiation absorption amounts approximately to 3.5 and 4.7 cm^{-1} for crystals with a concentration of activator ions equal to 0.8 and 1.2 at. % respectively. This led to the conclusion that upon transverse pumping of the Nd^{3+} : YAG active element of diameter not exceeding 3 mm and the Nd ion concentration of 0.8 % – 1.2 %, at least two trips of LDA radiation through the element cross section are required for its efficient absorption by the active medium. In active elements of diameter 4 and 5 mm having an activator concentration of 1.2 % and 0.8 % respectively, one trip of the LDA radiation through the active medium is sufficient for its efficient absorption and for the creation of the required population inversion.

We used in our experiments two different pump modules with symmetric and asymmetric arrangement of LDAs at 45° relative to each other around the cylindrical active element (Fig. 1). In the first scheme (Fig. 1a), eight LDAs were arranged in sections symmetrically around a Nd^{3+} : YAG crystal at a distance of approximately 0.5 mm from it. In the second scheme (Fig. 1b), the cylindrical element was fixed in a copper radiator so that approximately half its lateral surface was covered by a silver foil specularly reflecting the pump radiation, while sections containing four LDAs each were arranged at the opposite side of the element. Consequently, a double-pass scheme of utilisation of pump radiation was realised in the simplest way in the module with the asymmetric arrangement of LDAs, while a single-pass scheme was realised in the module with eight LDAs.

For the experimental investigation of the above-described pump modules, we used quasi-continuous LDAs designed and fabricated at the Polyus Research and Development Institute. The length of the LDA along the 'slow' axis was 10 mm for the FWHM beam divergence of 10° along this axis, while the beam divergence along the 'fast' axis was 45°. The LDAs were assembled on copper plates whose geometry made it possible, first, to efficiently remove heat flows from the active elements of the laser diodes and, second, to arrange LDAs compactly around Nd^{3+} : YAG cylindrical elements of diameter 3 – 5 mm.

For our experiments, we selected LDAs with the required energy and spectral parameters of radiation, their pulse power being no less than 60 W (for measurements within an angle of 60°) in the spectral range 806.3 – 810.5 nm. For the above-mentioned spatial parameters of the LDA beam in the symmetric module and for an active element diameter of 5 mm, the fraction of pump radiation incident on the active medium was determined only by Fresnel losses at the crystal surface and amounted approximately to 90 %. In the asymmetric module (with four LDAs arranged in the most compact form; Fig. 1b), a part of the spatial diagram of the pump radiation was not matched with the surface of the element and, hence, the fraction of the LDA radiation falling on the active medium did not exceed 75 %.

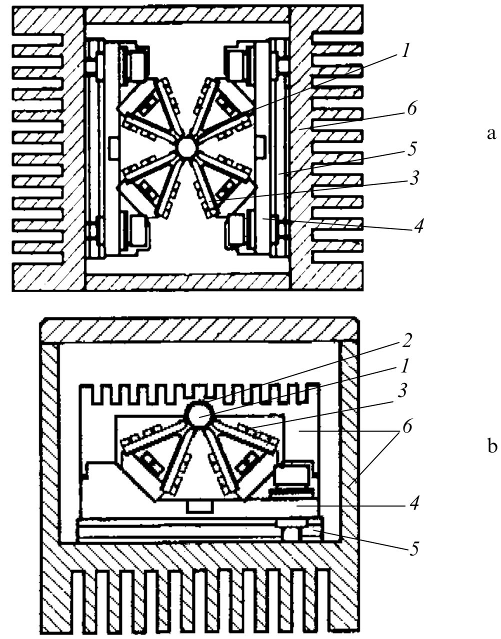

Figure 1. Schemes of modules for transverse pumping of the cylindrical active element by laser diode arrays with (a) eight arrays arranged symmetrically in sections around the active element without a reflector, and (b) four arrays arranged asymmetrically in sections around the active element with a reflector on the opposite face of the active element: (*1*) active element; (*2*) reflector; (*3*) LDA; (*4*) foundation for fastening LDA; (*5*) thermoelectric element; (*6*) radiator.

3. Experimental results

To analyse the efficiency of pumping of Nd^{3+} : YAG cylindrical active elements by laser arrays, we measured in our experiments the energy of a pulse from a laser operating in the free-running and *Q*-switching modes with the symmetric and asymmetric pump modules presented in Fig. 1. In the symmetric module, two series-connected sections containing eight LDAs each were used (see Fig. 1a). The module with asymmetric pumping consisted of three sections containing four LDAs each (see Fig. 1b).

Since the aim of our experiments was to study precisely the energy efficiency of transverse pumping of Nd^{3+} : YAG crystals of different geometries without taking into account thermooptical effects, the repetition rate of LDA pulses of duration 200 μs was 5 Hz. For the same reason, we used in our experiments a cavity whose geometry ensured generation of a multimode beam in which the spatial distribution of radiation corresponded to the inverse population density distribution created in the active element by the corresponding pump module. In order to sustain the LDA radiation wavelength in the given spectral range, the temperature of the copper base on which the arrays were mounted (see Fig. 1) was controlled and maintained by thermoelectric microcoolers.

The pulse energy of a laser operating in the free-running and Q-switching modes was measured for different reflection coefficients R_1 of the output mirror of the cavity. The radius of curvature of the highly reflecting mirror was 100 cm and the cavity length was 22 cm. For an active element diameter of more than 3 mm and the chosen cavity geometry, the Fresnel number of the cavity was much greater than unity, which ensured the essentially multimode type of generation. In the series of experiments made under the above-described conditions, we obtained the results presented in Figs 2, 3, and 5 for a symmetric pump module and in Figs 4 and 6 for an asymmetric module. The obtained main energy parameters of the laser under investigation (the differential efficiency η and the 'straightened' lasing threshold E_{th}) are presented in the corresponding figures.

An analysis of the presented results shows that the maximum differential efficiency of at least 55 % and 48 %, which was in fact independent of the concentration of active ions was attained for Nd^{3+} : YAG crystals of diameter 5 mm for the symmetric pumping without a reflector and of diameter 3 mm for the asymmetric pumping with a reflector in the free-running mode, respectively. Fig. 3 shows that, for a crystal of diameter 4 mm and the symmetric pump module, the result weakly depends on the atomic concentration of Nd^{3+} ions. For example, for an activator concentration of 1.2 % and 0.8 %, the differential efficiency of lasing was 48 % and 45 %, respectively. However, other conditions being identical, the threshold energy of a pump pulse for the active ion concentration of 0.8 % (Fig. 3b) was approximately 20 % higher than in the case of the concentration of 1.2 %.

A comparison of Figs 2a and 4a shows that the energy parameters of lasers with symmetric pumping of element having diameters of 5 and 4 mm were close. The approximate equality of differential efficiencies of the schemes being compared can be explained by a sufficiently high degree of LDA radiation transfer and absorption in the bulk of the elements, while the equality of the lasing thresholds apparently indicates an incomplete filling of the active element having a diameter of 5 mm with pump radiation, namely, a more intense circulation in its axial region as compared to the periphery.

The above-mentioned differential efficiencies characterise the energy efficiency of utilisation of LDA radiation in the multimode regime [9]. Thus, the pump system parameters for which the above-indicated maximum efficiency was attained can be regarded as optimal parameters for the operation mode under investigation. Indeed, the differential efficiencies for elements of diameters 5 and 4 mm obtained with the symmetric pump module indicate a high efficiency of utilisation of LDA radiation, which amounts to approximately 80 % after taking into account the Stokes and Fresnel losses.

The much lower differential efficiency of a crystal of diameter 3 mm with a reflector (Fig. 4), in which the pump radiation path length was 6 mm, as compared to the efficiency of Nd^{3+} : YAG elements of diameters 4 and 5 mm (See Figs 2 and 3), can be explained by the peculiar construction of the pump module used and by the fact that a part of the LDA radiation does not fall directly to the active element (see above). The threshold energies of a pump pulse presented in Figs 2 – 4 characterise the effective gain for the spatial structure of the radiation field realised in the experiment [9].

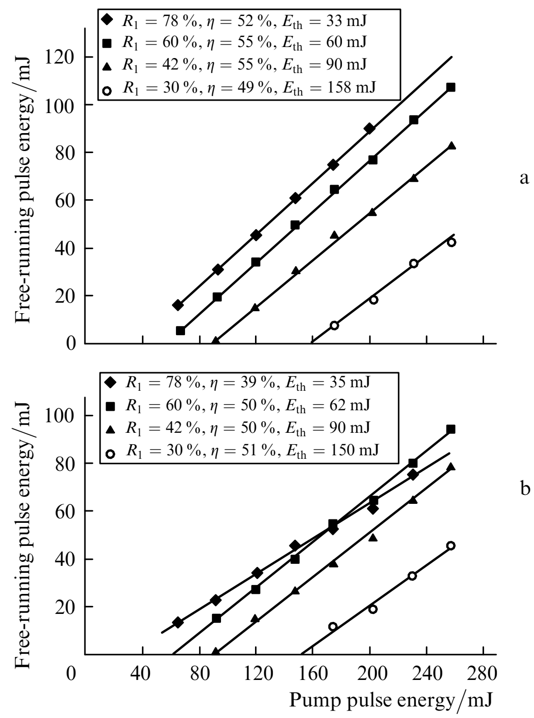

Figure 2. Energy parameters of a free-running laser with a pump module formed by two sections containing eight LDAs each, arranged around a Nd^{3+} : YAG crystal of diameter 5 mm, for an Nd concentration (a) 1.2 and (b) 0.8 at. %.

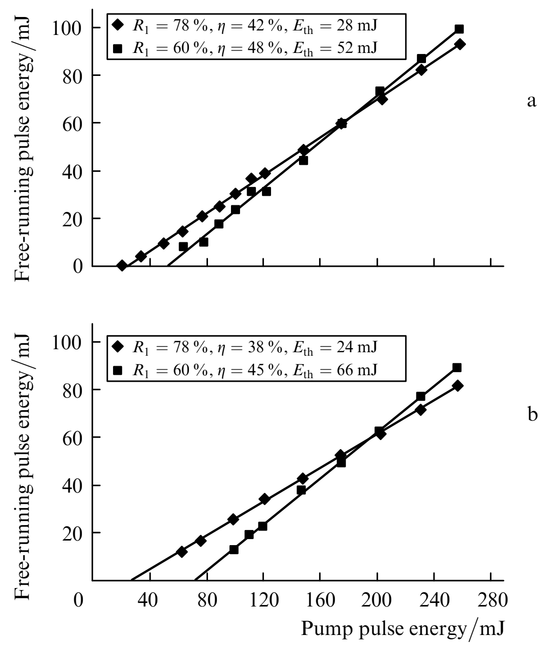

Figure 3. Energy parameters of a free-running laser with a pump module formed by two sections containing eight LDAs each, arranged around a Nd^{3+} : YAG crystal of diameter 4 mm, for an Nd concentration (a) 1.2 and (b) 0.8 at. %.

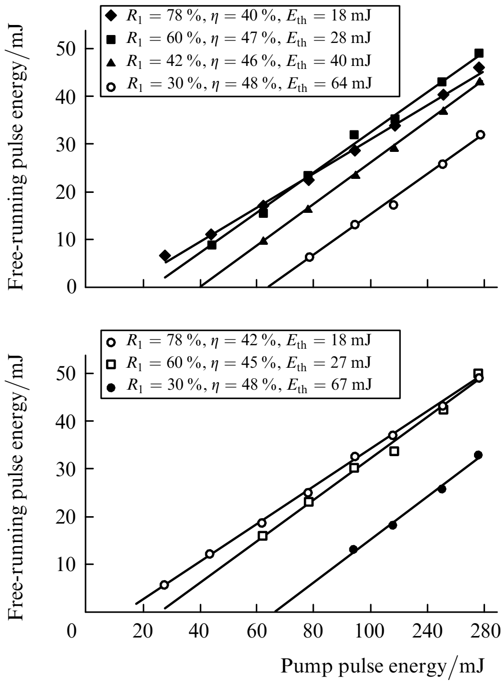

Figure 4. Energy parameters of a free-running laser with a pump module formed by three sections containing four LDAs each, arranged around a Nd^{3+} : YAG crystal of diameter 3 mm (with reflector), for an Nd concentration (a) 1.2 and (b) 0.8 at. %.

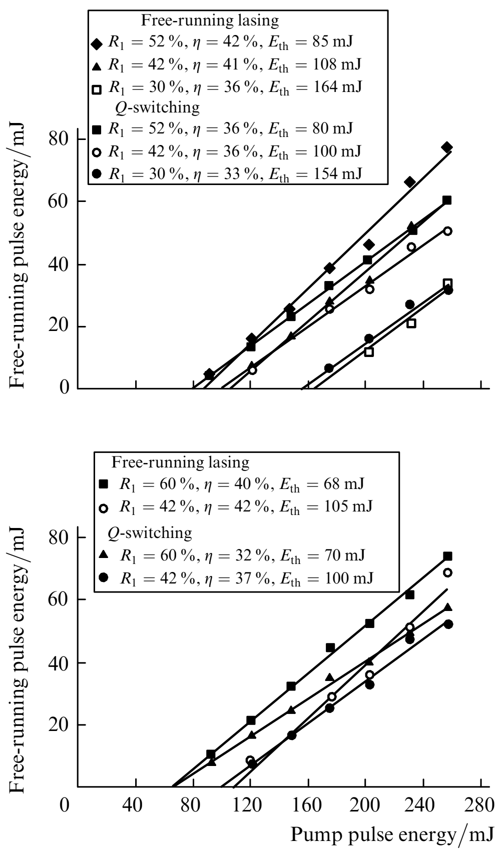

Figure 5. Energy parameters of a Q-switched and a free-running laser with a pump module formed by two sections containing eight LDAs each, arranged around a Nd^{3+} : YAG crystal of diameter 5 mm, for an Nd concentration (a) 1.2 and (b) 0.8 at. %.

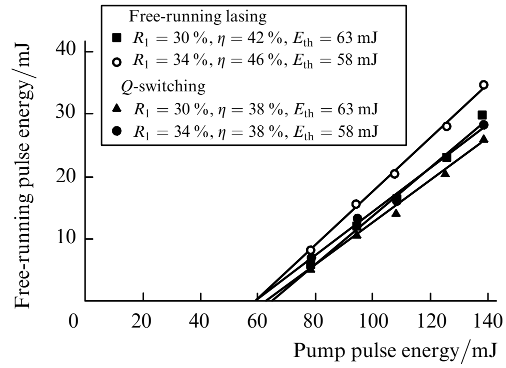

Figure 6. Energy parameters of a Q-switched and a free-running laser with a pump module formed by three sections containing four LDAs each, arranged around a Nd^{3+} : YAG crystal of diameter 3 mm (with reflector), for an Nd concentration (a) 1.2 and (b) 0.8 at. %.

In order to realise the Q-switching mode, a polariser and a quarter-wave elecrooptical shutter (EOS) based on a lithium niobate crystal and with its input faces arranged at the Brewster angle to the cavity axis were placed in the laser cavity. The presence of the polariser and the EOS in a cavity with an output mirror with a reflection coefficient of 30% led to an increase in the intracavity losses and (see Figs 5 and 6) to a 20 % and 25 % decrease in the energy parameters of the laser for active elements of diameter 3 and 5 mm, respectively.

Q-switching of the cavity in the above experiments was carried out by supplying a gate trigger voltage to the EOS at the instant corresponding to the fall-off of a rectangular LDA pump current pulse. In this case, a Q-switched pulse was formed in the laser cavity, i.e., a single pulse with the energy parameters presented in Figs 5 and 6 for the symmetric and asymmetric schemes of the pump module, respectively. The obtained results show that the differential efficiency of a Nd^{3+} : YAG element having a diameter of 5 mm and operating in the Q-switching mode with an output mirror reflection coefficient of 42 % was 36 %, while the efficiency of a Nd^{3+} : YAG element of diameter 3 mm was 38 %. The lower value of the differential efficiency of a laser operating in this mode is associated with an increase in the intracavity losses due to the use of polarising elements and with an inadequate utilisation of the rectangular pump pulse of duration 200 μs for an inverse population lifetime of 240 μs in a Nd^{3+} : YAG crystal.

Note that for the pump schemes used, the radiation emitted by the LDA from one section was summed so that the population inversion distributed nonuniformly in space had a peak near the active element axis. As a result, the local radiation power density for single pulse energy of several tens of millijoules was close to the limiting value for the intracavity elements used. For this reason, the reflection coefficients for the output mirrors used in the Q-switching mode did not exceed 34 % for an element of diameter 3 mm and 60 % for an element of diameter 5 mm.

For the total radiation energy of a pump pulse of 140 and 250 mJ in the asymmetric and symmetric modules, respectively, the maximum energies of single pulses obtained in experiments were 28 and 55 mJ. The total efficiency of (light – light) generation for a Q-switched Nd^{3+} : YAG laser was 20 % in both cases. The radiation beam had an inhomogeneous spatial structure corresponding, as in the case of the free-running lasing mode, to a set of a certain number of transverse modes of the cavity used.

It should be noted that the total efficiency of the laser attained in the experiments (20 %) is not the maximum possible for both pumping schemes under investigation and was limited in our experiments by a relatively low coefficient (approximately 75 %) of radiation transfer from the LDA to the active element of diameter 3 mm and also by an insufficient excess of the pump pulse energy (250 mJ) over the lasing threshold for the active element of diameter 5 mm. These factors are consequences of structural features of the created pumping modules and of LDAs used in our experiments and can be eliminated in the process of a subsequent analysis and an improvement of the pumping scheme for a cylindrical active element.

4. Conclusions

We have determined experimentally the energy characteristics of a free-running and Q-switched Nd^{3+} : YAG laser pumped by LDAs arranged around its cylindrical active element. The application of pump modules with a symmetric arrangement of LDAs relative to the active element of diameter 5 mm and an asymmetric arrangement relative to the element of diameter 3 mm (with a reflector) resulted in the differential efficiency of 55 % and 48 %, respectively, for a free-running laser.

For such an efficiency of utilisation of LDA radiation, lasing in the Q-switching mode was obtained with a radiation pulse energy of 55 and 28 mJ for pumping of active elements of diameters 5 and 3 mm, respectively. This leads to the conclusion that the scheme of a pump module with the symmetric arrangement of eight LDAs in each section may form the basis for developing the pumping schemes of solid-state lasers with an active element of diameter 5 mm, operating in the Q-switching mode and generating pulses with energy no less than 50 mJ. The total energy of a radiation pulse from LDAs assembled from two consecutive sections should be at least 250 mJ.

The pumping scheme with an asymmetric arrangement of four LDAs in a section at the surface of the Nd^{3+} : YAG active element with diameter 3 mm and with reflecting coating may be used in lasers with a radiation pulse energy not exceeding 30 mJ in the Q-switching mode. The variation of the neodymium ion concentration in crystals with different diameters showed that a high coefficient of LDA radiation absorption by the active medium was realised in the chosen scheme of transverse pumping modules for elements of various diameters; consequently, the variation of the neodymium ion concentration in the interval from 0.8 to 1.2 % did not noticeably affect the energy parameters of the lasers under investigation.

The experimentally established parametric dependences between the energy characteristics of lasing and the parameters of the transverse pumping module of the given construction may be interesting as initial data for simulation, numerical estimation, and optimisation of the basic energy parameters of more complex and promising schemes of pump modules, which will make it possible to increase the radiant energy in a single pulse (to above 100 mJ), as well as the pulse repetition rate, i.e., the average power of laser radiation.

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