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Research of the homogeneity of the pump distribution in the active element of powerful diode-pumped solid state Nd:YAG rod laser

© S.D. Tariverdiyev[1,2], A.E. Drakin[3], O.V. Pagaev[1], G.T. Mikaelyan[1,2,4], A.L. Koromyslov[3], A.V. Berezutskiy[1,2], A.I. Demidchik[1]

[1] LLC „Lassard“, Obninsk, Kaluga region, Russia
[2] National Research Nuclear University „MEPhI“, Moscow, Russia
[3] Lebedev Physical Institute, Russian Academy of Sciences, Moscow, Russia
[4] OOO „NPP „Inject“, Saratov, Russia
E-mail: tsamir0591@gmail.com

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Experimental investigations and calculations of various optical schemes of high-power DPSS and solid-state lasers with cylindrical active elements and transverse pumping by laser diode arrays are presented. Numerical simulations were used to solve hydrodynamic problems and problems of geometric optics for DPSS with rod active elements pumping by quasi-continuous laser diode arrays. The dependencies of the uniformity of active element illumination on the geometry of the optical scheme were studied, as well as the influence of the uniformity of coolant flows over different pump arms on the uniformity of the luminescence distribution pro-file from the end of the active element. An optical pumping scheme for active element of a high-power DPSS with an optimal geometry is proposed and implemented.

Keywords: solid-state laser, diode pumping, DPSSL, active element.

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Solid-state lasers are currently used widely in material processing, medicine, military machinery, scientific research, systems with radiation frequency conversion, and advanced laser thermonuclear synthesis systems. A laser head, which is basically an active element (AE), diode pumping, and a reflector housed in a common body, is the key functional part of a laser or a light amplifier. Optimization of optical pumping with the aim of maximizing the small-signal gain and the uniformity of the distribution profile of radiation from an AE end is one of the primary goals in design of laser heads and solid-state lasers. Physical models of laser heads with transverse diode pumping of cylindrical AEs have been examined in several studies [1–3]. However, such factors as a non-uniform distribution of radiation over the AE cross section, which is underpinned by the technological and design features of laser heads, and a realistic spread of wavelengths of diode lasers induced by non-uniform coolant flows over different pump arms were neglected in these models.

The following design features of laser heads were taken into account in calculations: diagram of arrangement of laser diode arrays (LDAs) around an AE; distances from the AE center to the emitting surfaces of LDAs; distribution of LDA radiation with respect to the AE axis (directions of fast and slow axes); and ratio of all geometric dimensions of emitting and illuminated elements.

Figure 1 presents the results of calculations for the hydrodynamic model of one laser head design and the corresponding distribution of temperature at heat exchangers *1–5*. Calculations were performed by solving numerically the Navier–Stokes equation for an incompressible fluid with the actual structure parameters taken into account:

$$\rho\left(\frac{\partial v}{\partial t} + V\nabla V\right) = -\nabla p + \mu\nabla^2 V + f, \qquad \nabla v = 0,$$

where ρ is density; v is the velocity at inlet; V is the velocity in channels; t is time; p is the fluid pressure; μ is the viscosity coefficient; f are other forces acting on a body, such as the force of gravity; and ∇ is the Hamiltonian operator (partial coordinate derivative). The thermodynamic properties of water are as follows: $\rho = 0.9982\,\mathrm{g/cm^3}$ and $\mu = 0.001\,\mathrm{Pa\cdot s}$.

Color gradients represent water velocities and temperatures of heat exchangers and a quartz tube. It follows from Fig. 1 (the top left diagram) that the velocity of coolant flow within AE cooling channel *6* and heat exchanger *1* is the lowest (and the corresponding LDA temperature is, consequently, the highest; see the bottom panel in Fig. 1). In contrast, the velocity of coolant flow within heat exchanger *2* is the highest (and the corresponding LDA temperature is the lowest). This distribution of coolant velocities translates into non-uniformity of the absorbed pump energy, which, in turn, leads to distortion of the luminescence profile pattern and low gain factors. A structural element establishing a uniform water distribution at the inlet collector was added to the coolant loop of a laser head in order to solve the problem of uniform extraction of heat from the pump arms of this laser head. The distribution of velocities of coolant flow within the heat-extraction channels of the laser head

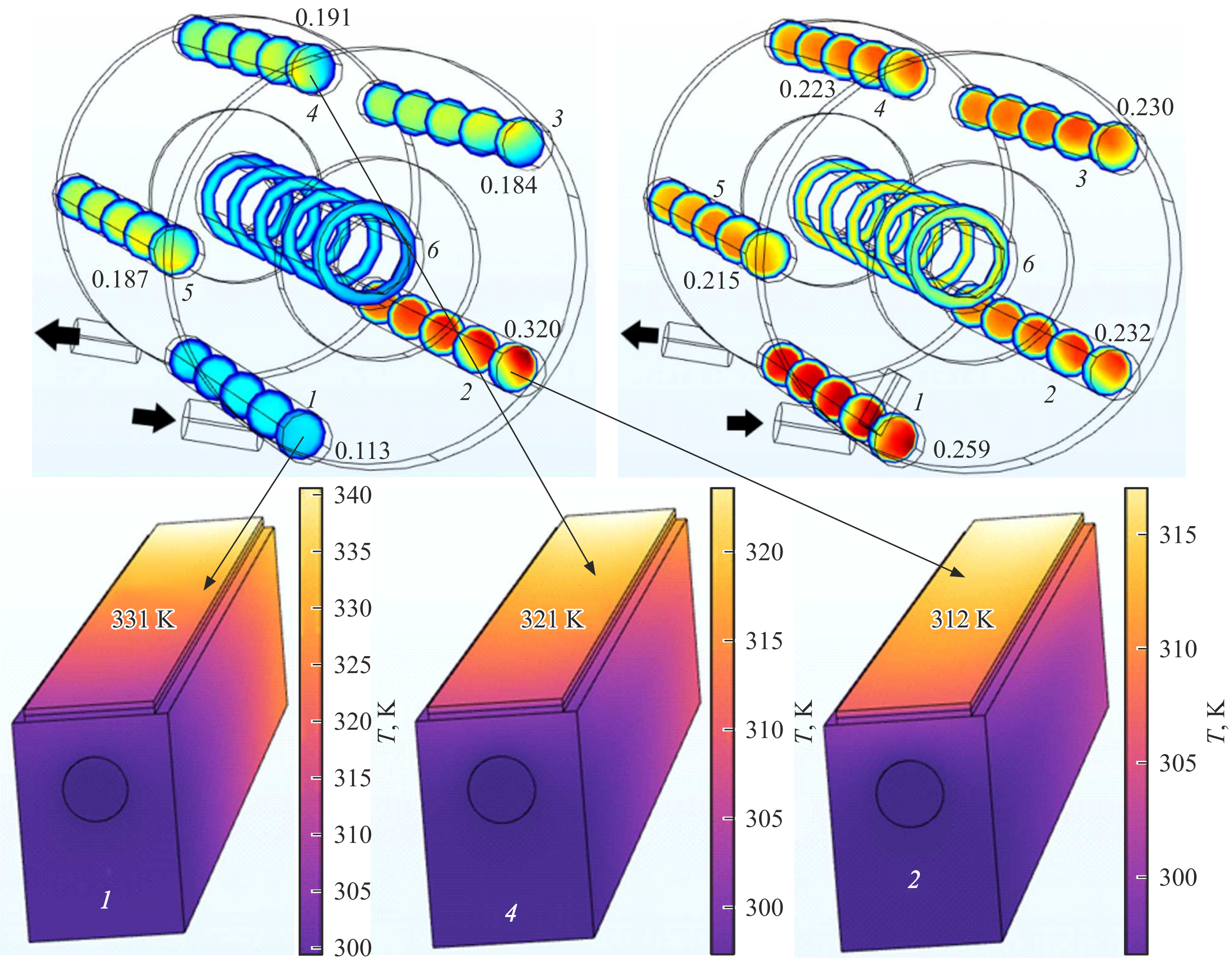

Figure 1. Hydrodynamic model of a laser head obtained using a finite element modeling application for structural simulations. Models with a non-uniform water supply and with a structure establishing a uniform supply of water are shown in the top left and right panels, respectively; bottom panel — temperature distribution at heat exchangers *1*, *2*, and *4*. Flow velocities (in m/s) are indicated in the top panels.

was made more uniform as a result (Fig. 1, the top right diagram).

The most efficient LDA arrangements were determined in the present study. Figure 2 shows the calculated distributions of pump radiation in the AE. The laser head structure was modeled using the finite element method. The following physical processes and mechanisms were taken into account in simulations: the reflection coefficient was determined (depending on the polarization of radiation) in accordance with the Fresnel equations [4]; the absorption of radiation in all optical elements and assemblies was determined using the Bouguer law $I = I_0 \exp(-k_\nu l)$, where k_ν is the absorption coefficient and l is the distance within the medium over which absorption takes place [4]; and the refraction of light at interfaces was $n_1 \sin i = n_2 \sin r$, where n_1 and n_2 are the refraction indices of the media from which a ray is incident onto the interface and within which the ray propagates after having passed through the interface, respectively, and i and r are the angle of ray incidence onto the interface and the ray refraction angle, respectively [4].

A uniform distribution of pump radiation in the active element is achieved when arms are shifted away from radial positioning. The optimum structure has the center of the array of diode arms shifted by 1 mm (Fig. 2, *b*) at an emitting LDA length on the order of 3 and 5 mm for laser heads with an AE diameter of 5 and 10 mm, respectively.

Figure 3 shows the transverse luminescence distribution profiles for two studied laser heads (KV-5 with an AE diameter of 5 mm, AE length of 100 mm, and five pump arms and KV-10 with an AE diameter of 10 mm, an AE length of 130 mm, and five pump arms). The off-center shift of the luminescence maximum is attributable to the non-uniformity of heat extraction. A star-shaped non-uniform distribution over the cross section is the result of an imperfect pumping arrangement and reveals the positions of heat exchangers with LDAs. The non-uniformity of the profile of luminescence distribution over the AE cross

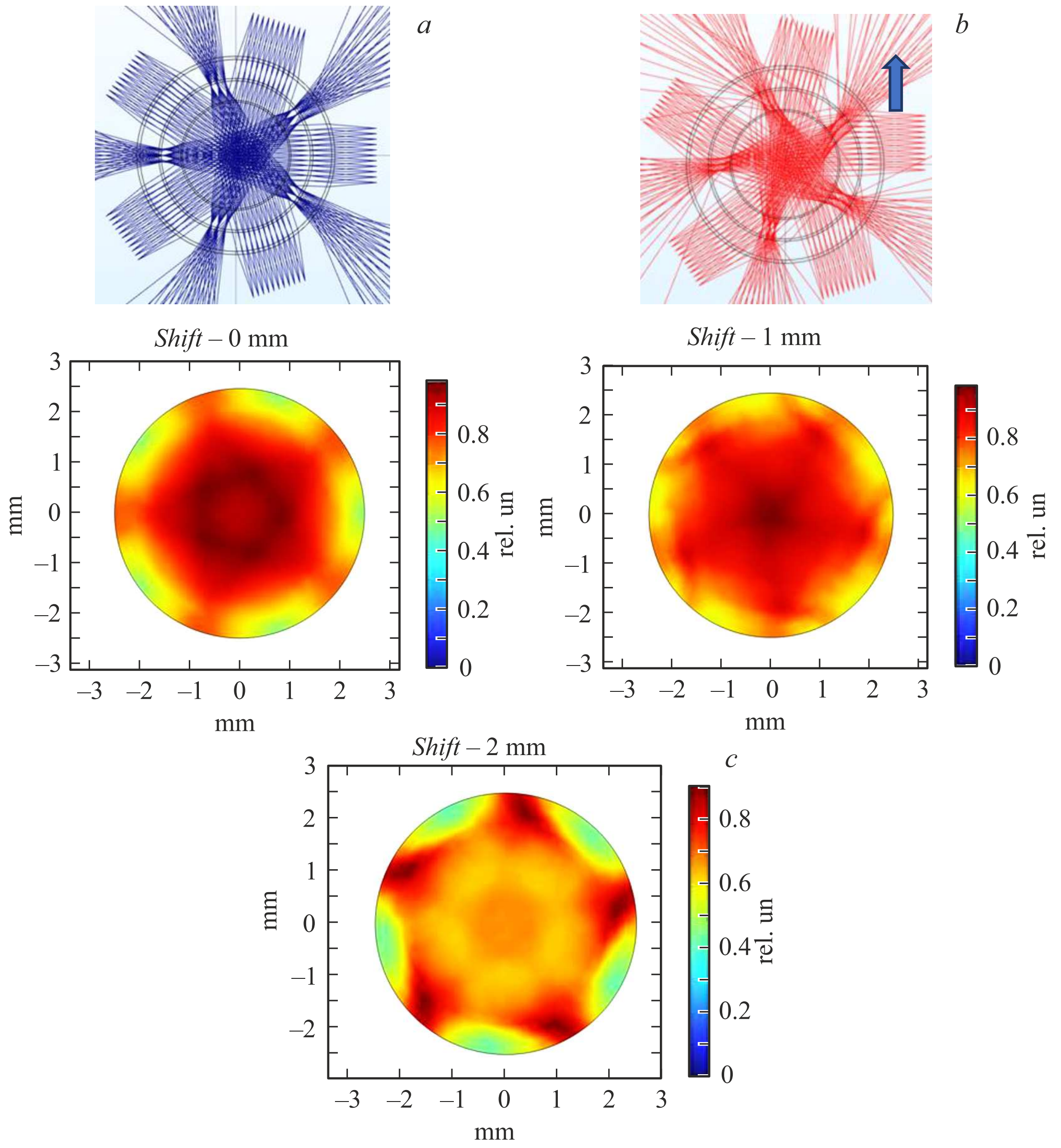

Figure 2. Distribution of pump radiation in an active element 5 mm in diameter: *a* — with zero arm shift, *b* — with a 1 mm arm shift, and *c* — with a 2 mm arm shift.

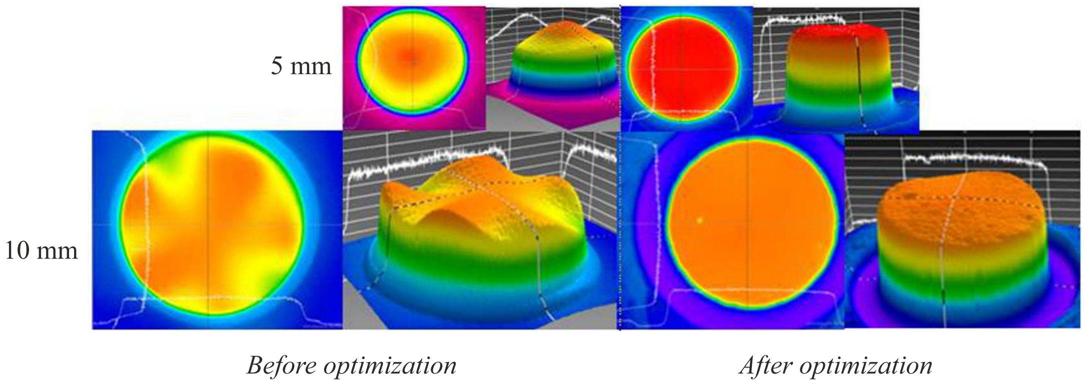

Figure 3. Luminescence distribution profiles for laser heads with AE diameters of 5 and 10 mm before and after optimization.

section is 20–30% for non-optimized laser head designs and below 10% for optimized ones.

The operation of laser heads in a solid-state laser was also examined. A cavity 45 cm in length with two planar mirrors with reflection coefficients of $R_1 = 99.8\%$ and $R_2 = 70\%$ was used. In the free running mode (with a pulse length of $250\,\mu$s and a repetition rate of 30 Hz), pulse energy $E = 1$ J at pulsed pump power $P = 25$ kW was obtained for the AE with a diameter of 5 mm and a pump length of 84 mm, and $E = 2$ J at pulsed pump power $P = 30$ kW was obtained for the AE with a diameter of 10 mm and a pump length of 124 mm.

The dependence of the small-signal (1 kW) gain (K_0) on the pump current for solid-state amplifiers with AEs 5 and 10 mm in diameter and 100 and 130 mm in length, respectively, was also studied. No saturation of gain with the pump current of diode laser sets was observed up to $K_0 = 80$. The maximum gain for the laser head with the AE 5 mm in diameter was $K_0 = 370$.

Laser heads with diode pumping and cylindrical AEs 5 and 10 mm in diameter and 100 and 130 mm in length, respectively, were examined and optimized. The optimum design, which was determined with the positioning of LDA sets around the AE taken into account, was proposed. A uniform distribution of pump radiation in the active element was achieved by shifting the heat exchangers with LDAs away from the radial line. Small-signal gain $K_0 \geqslant 370$ and $K_0 \geqslant 80$ was obtained with rod diameters of 5 and 10 mm, respectively. The non-uniformity of gain distribution over the cross section was below 10% in both cases.

Conflict of interest

The authors declare that they have no conflict of interest.

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