

Comparison of different composite Nd:YAG rods thermal properties under diode pumping

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ABSTRACT

Thinking about the pumping and generated power of the longitudinally diode-pumped solid-state laser enhancement, the question of an active material cooling should be solved. One of the possible solutions is the active material cooling surface enlargement. Besides the cylindrical surface of the crystal, the laser rod front surfaces could be cooled through undoped ends. The temperature gradient effect in three various samples was investigated in a computer experiment, and the differences in generated output power were measured experimentally. The samples were three Nd:YAG rods - one conventional, one with one undoped end, and one with two undoped ends. The crystal samples were placed in sequence into a resonator 6 cm long and longitudinally diode-pumped. The dependencies of the generated power on the absorbed pump power have shown that with the two undoped ends the output power is more than twice as high as against the conventional Nd:YAG sample. The results were explained by a computer experiment based on the heat transfer equation solution where the changes of the temperature gradient were least for the Nd:YAG rod with two undoped ends.

Keywords: diode pumped solid state lasers, Nd:YAG, composite laser active medium

1. INTRODUCTION

Since the first report on laser radiation by Maiman, many potential fields for its application have been investigated. Various kinds of lasers have already become irreplaceable tools of modern technology, microelectronics, metrology, holography, medicine, etc. For many of these fields, a more compact and even smaller laser system with improved efficiency could be very suitable.¹ For that reason the diode pumped solid state lasers could be the good compromise.² As concern the pumping and generated power of longitudinally diode-pumped solid-state laser enhancement, the question of active material cooling should be investigated. One possibility how to decrease thermal effects (such as thermal lensing and thermal stress-induced birefringence) and enhance the laser system performance is to use advanced solid-state laser composite crystals.³ Using of the doped and the undoped laser rod components enlarges the active material cooling surface and improves laser active media thermal uniformity and heatsink.

This concept was experimentally confirmed using the diode end-pumped composite solid state laser. Three types of crystals (the first was a conventional Nd:YAG, the second a Nd:YAG crystal with one undoped end, and the third a Nd:YAG crystal with two undoped ends) were tested in a resonator 6 cm long. The laser was end-pumped by a 20 W fibre coupled 808 nm laser diode. The output parameters and temperature of the sample holder were measured. For better understanding of such system's thermal behavior, its mathematical model was composed. This model was based on the numerical solution of the heat transfer equation using the *Finite Element Method* and allowed to calculate the temperature field, temperature gradient, and heat flux inside the laser crystal and in its nearest environment.

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2. EXPERIMENTAL COMPONENTS AND MATHEMATICAL MODEL

2.1. Active Nd:YAG material description

As the active material, three yttrium aluminum garnet rod samples doped with the neodymium ion (Nd-1 at. %) were investigated in a physical and later in a computer experiment. The diameter of all the three samples was equal to 5 mm. One of the samples was the conventional type Nd:YAG crystal 1 mm long (Fig. 1a). The second sample was composed of a Nd:YAG crystal 1 mm long and an undoped yttrium aluminum garnet 3 mm long (Fig. 1b). The third sample consisted of two undoped ends with a length of 3 mm each (Fig. 1c), and also of an yttrium aluminum garnet 1 mm long doped with neodymium. The outer frontal part of all the samples had antireflection coatings for the wavelength of pumping and generated radiation.

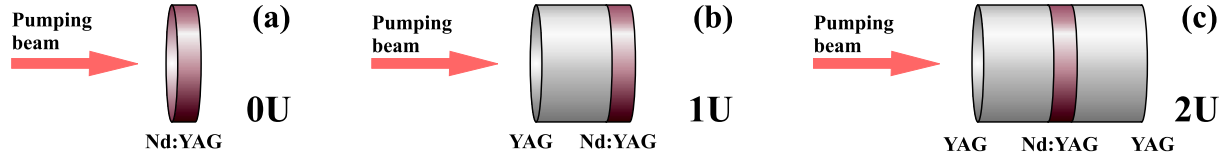


Figure 1. Schematic of three investigated samples - (a) Nd:YAG crystal (0U), (b) Nd:YAG crystal with one undoped part (1U), (c) Nd:YAG crystal with two undoped YAG parts (2U).

2.2. Nd:YAG diode pumped laser

2.2.1. Nd:YAG diode pumped laser construction

The pumping source used was a laser diode HLU20F400 (LIMO Laser Systems) with the maximum output power 20 W at the end of the fiber (fibre core diameter: 400 μm , numerical aperture: 0.22). The diode radiation was focused into the active Nd:YAG crystal by two plan-convex lenses (L1, L2) with the focus length $f = 50$ mm. The measured diameter of pumping beam focus inside the crystal was 390 μm . The resonator of the Nd:YAG laser was formed by a planar dielectric mirror R1 with high transmissivity for the pumping radiation ($R_{R1} < 1\%$ @ 808 nm) and high reflectance for the generated radiation ($R_{R1} = 100\%$ @ 1.06 μm), and by a concave ($r = 100$ mm) dielectric mirror R2 serving as an output coupler (reflectance for the generated wavelength $R_{R2} = 98\%$ @ 1.06 μm). The open resonator length was 60 mm (Fig. 2). Each active crystal was inserted into the laser cavity to have the active (doped) part in the focus of the pumping beam.

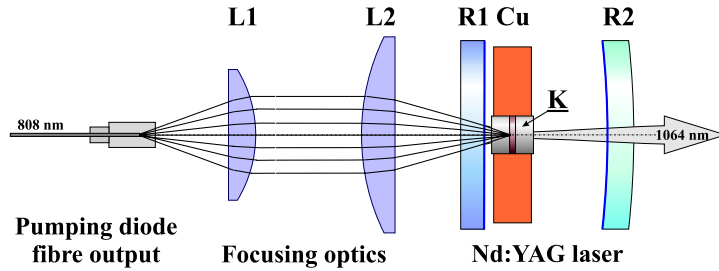


Figure 2: Layout of diode pumped Nd:YAG laser.

2.2.2. Nd:YAG diode pumped laser model

The mathematical model for unstable diffusion of heat in a body of some kind is a parabolic partial differential equation.⁴ The general differential equation of heat conduction for a stationary, homogenous, isotropic solid with heat generation within the body is

$$\nabla \cdot (k \nabla T) + Q = \rho C_p \frac{\partial T}{\partial t}, \quad (1)$$

where T is temperature distribution within the body, Q heat generation rate in the medium [W/m^3], and t is time; parameter k is thermal conductivity coefficient of the material [$W.m^{-1}.K^{-1}$], ρ is density of the medium [kg/m^3], and C_p is the corresponding specific heat [$J.kg^{-1}.K^{-1}$].

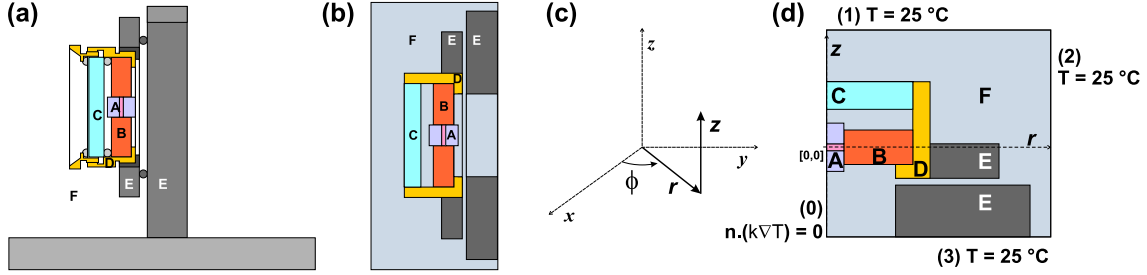


Figure 3. The layout of the crystal mount, its simplified model, cylindrical coordinates, and model geometry used for calculations with specified boundary conditions. Subdomains: A - laser crystal (composite), B - cuprous ring, C - high-reflecting flat mirror, D - brass socket, E - duralumin kinematic mirror mount, F - air. Boundary conditions: (0) - the Neumann homogenous boundary condition, (1), (2) and (3) - the Dirichlet boundary condition.

Subdomain	Material	C_p - specific heat [$W.s.g^{-1}.K^{-1}$]	k - thermal conductivity [$W.cm^{-1}.K^{-1}$]	ρ - density [$g.cm^{-3}$]
A	YAG composite	0.59	0.13	4.56
B	Copper	0.38	3.9	8.98
C	BK7 Glass	0.86	0.0011	2.51
D	Brass	0.35	1.2	8.50
E	Duralumin	0.88	1.7	2.78
F	Air	1.00	0.00026	0.0012

Table 1: Specific heat, thermal conductivity, and density of used materials

The region, for which the heat conduction equation was numerically solved, covered the following parts: the laser crystal, cuprous ring, high-reflecting flat mirror, brass socket, duralumin kinematic mirror mount, and air. The laser crystal was placed inside the cuprous ring fixed together with the high-reflecting flat BK7-glass mirror inside a brass socket. It was screwed in a duralumin kinematic mirror mount surrounded by air. The arrangement is shown in Fig. 3a. The necessary physical properties of the materials used are presented in Table 1. For the sake of simplicity, the geometry of the crystal mount was reduced so as to be axially symmetric (Fig. 3b). Thus a cylindrical coordinate system could be used and the problem reduced from 3D to 2D. The final 2D-geometry used for calculations is shown in Fig. 3d. The heat conduction equations in the cylindrical coordinate system (r, ϕ, z) shown in Fig. 3c thus become,

$$\frac{\partial}{\partial r} \left(kr \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + rQ = \rho C_p r \frac{\partial T}{\partial t} . \quad (2)$$

The differential equation of heat conduction will have numerous solutions unless a set of boundary conditions and an initial condition are prescribed. The initial condition specifies temperature distribution in the medium at the origin of the time coordinate. In this case, the temperature of the system is $30^\circ C$ at the time $t = 0$. The boundary conditions specify the temperature or heat flow at the boundaries of the region. The surrounding temperature at the outer boundary is set to be $25^\circ C$. The cylinder axis $r = 0$ is not a boundary in the original problem, but in this 2-D treatment it is. Thus it is assigned the artificial boundary condition here - the Neumann homogenous boundary condition, which demonstrates the axial symmetry of the temperature field (Fig. 3d).

The only heat source in this model is non-radiate transitions inside the doped part of the laser crystal. The power transfer efficiency from the pump to heat losses is given by:

$$\eta = \frac{\lambda_{laser} - \lambda_{pump}}{\lambda_{laser}}, \quad (3)$$

where λ_{laser} is the laser transition wavelength and λ_{pump} is the pump transition wavelength. When the Nd:YAG is pumped by the 808 nm laser diode radiation, the heat losses reach at least 24 % of the absorbed power. If the light intensity is $I(r, z)$ and the active medium absorption coefficient is α , the local heat generation rate is given by:

$$Q(z, r) = \eta \alpha I(z, r). \quad (4)$$

If the pump beam diffraction inside the active medium is neglected, the pump beam profile has a gaussian of five order shape, and the total pump power is P_{pump} , then the heat generation rate is given by:

$$Q(z, r) = \eta \alpha \frac{3P_{pump}}{2\pi w_0^5} \exp[-\alpha z] \exp\left(-\frac{2r^5}{w_0^5}\right). \quad (5)$$

To calculate the heat conduction differential equations, the following values of parameters were used: $h = 30\%$, $a = 2.2 \text{ cm}^{-1}$, $w_0 = 0.029 \text{ cm}$, and $P_{pump} = 10 \text{ W}$.

3. EXPERIMENTAL RESULTS

3.1. Physical experiment

The characterization of this laser system was accomplished for all the three samples investigated 0U, 1U and 2U. The dependence of the output power on the absorbed diode pumping power was measured with the Molectron Laser Power Meter Max 500A (probe PM3 and PM10). The results measured are summarized in Fig. 4a. The time development of laser output power was monitored also by the PIN photodiode HP 4207 and recorded by the oscilloscope Tektronix TDS 3032. The active crystal starting temperature value was 30°C - being the same for all the three measurements. The dependencies measured are displayed in Fig. 4b. The measured decay of power at the beginning of measurements shows an instantaneous temperature increase and its sequential stabilization. The maximum power was achieved for the sample with two undoped ends (Fig. 4a).

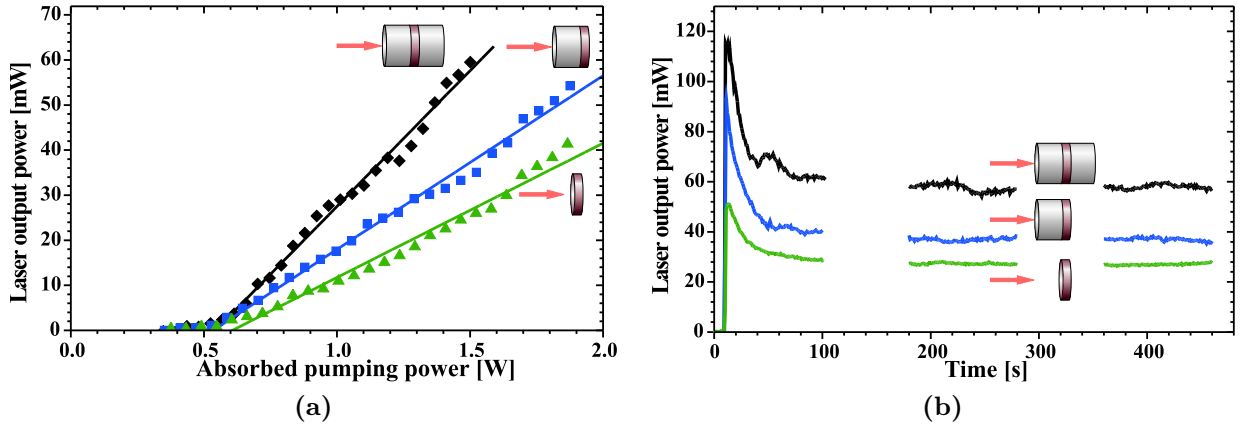


Figure 4. (a) The dependency of the diode pumped Nd:YAG laser output power on the power absorbed in active material for three different types of the active material. (b) The diode pumped Nd:YAG laser output power long-term time dependency for the constant absorbed power 1.5 W.

For better characterization of the laser system, the output beam space structure for all the three types of the active medium arrangement was recorded by CCD camera ELECTRIM EDC - 1000HR. The results for the Nd:YAG sample 0U and the sample with the two undoped ends 2U are plotted in Fig. 5.

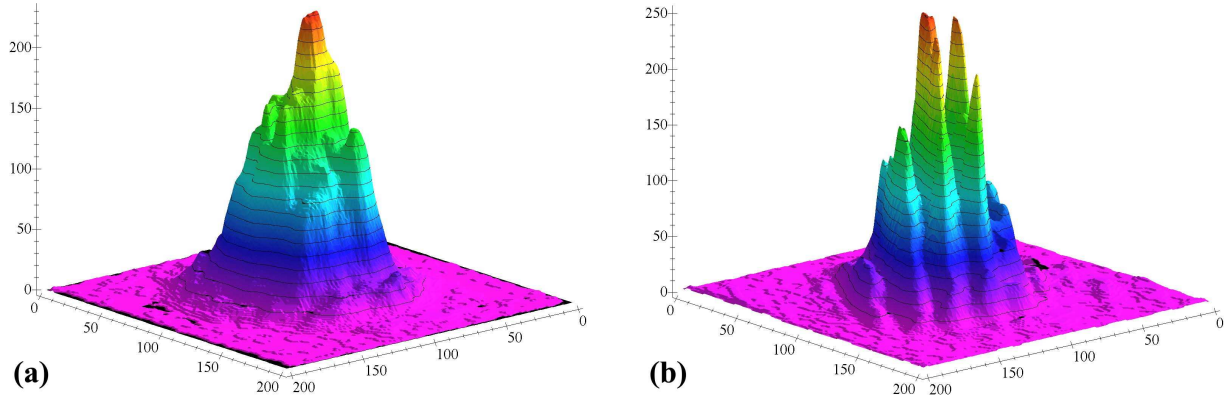


Figure 5. Diode pumped Nd:YAG laser output radiation space structure (the Nd:YAG laser crystal 0U (a), the Nd:YAG laser crystal with two undoped parts 2U (b) (horizontal axis 10 $\mu\text{m}/\text{div}$, vertical axis - normalized unit of intensity).

3.2. Computer experiment

The differential equation of heat conduction (2) was solved using the *Finite Element Method* in the region shown in Fig. 3d. The part of the the laser crystal and its heatsing rz -plane cat used for the data imaging is shown in Fig. 6. The calculation was made for all the three crystals samples (the crystal 0U, 1U and 2U - Fig. 1). Fig. 7 shows the calculated temperature field and heat flux inside the laser crystal and in its nearest surrounding at the time $t = 400 \text{ s}$.

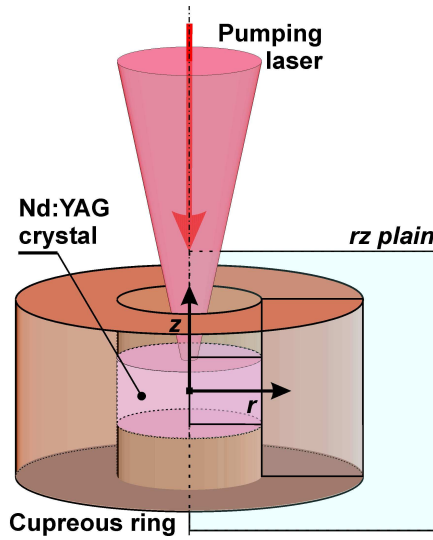


Figure 6. Layout of diode pumped Nd:YAG crystal with a housing.
The data displayed in Fig. 7 correspond to marked rz -plane

4. DISCUSSION

From the experimental results it follows that for the same absorbed pumping power, the output power of the laser whose active medium is composed of doped and undoped parts (described in detail above) is higher than the output power for the system with the conventional active medium design. The differences observed can be explained by a more homogeneous distribution of the thermal field into the doped part of the active material and by its efficient cooling.

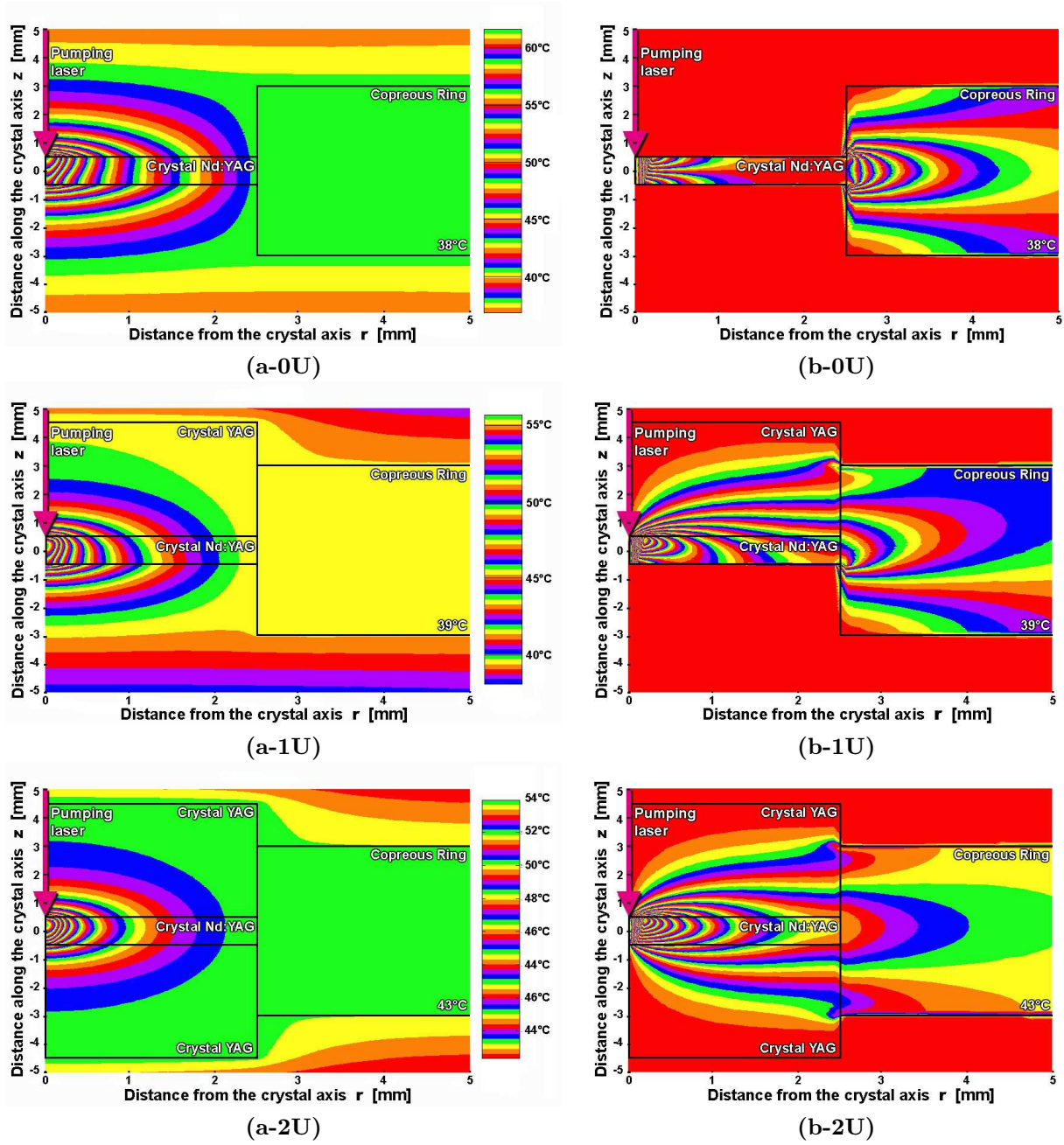


Figure 7. The results summarization of the calculated temperature field (a) and heat flux (b) inside the laser crystal and in its vicinity (the rz-plane cut) in time $t = 400\text{ s}$ for the particular cases. 0U - conventional type of the active Nd:YAG medium, 1U - Nd:YAG crystal with the one undoped end 1U), 2U - Nd:YAG crystal with two undoped ends - see Fig. 1

For better understanding of the temperature distribution inside a laser material, a computer experiment based on the numerical solution of the heat transfer equation was performed. This model gave the possibility to calculate the temperature arrangement inside the laser crystal and for its nearest surrounding in the case of continuous diode pumping. Good agreement was obtained when the calculated and measured values (in the vicinity of the active crystal) were compared.

It is the thermal gradient inside the active crystal that plays the most important role in the crystal's optical characteristics. Its value affects the refractive index and the thermal lens creation, and, therefore, the thermal gradient mostly affects the output beam parameters. From the mathematical model it follows that in case of the active medium with two undoped ends in comparison with the conventional type of crystal, i.e. without the undoped ends, the value of the thermal gradient is one half. From Fig. 7 it can be seen that if only the conventional Nd:YAG crystal is placed in the laser resonator, the heat is dissipated through the cylindrical surface of the active crystal only. From the computer model it follows that for this case the maximum crystal temperature achieved in the pumping area center is 62 °C (Fig. 7a-0U). In case of the crystal with one undoped end placed in the input of the pumping radiation, the heat is removed from the center of the crystal more effectively (Fig. 7b-1U). The maximum temperature inside the crystal settles down to 54 °C (Fig. 7a-1U). The most effective cooling is obtained for the crystal with two undoped ends. The heat added the pumping is dissipated more uniformly (Fig. 7b-2U). For this case the maximum active medium center temperature reaches 52 °C only (Fig. 7a-2U).

5. CONCLUSION

In the computer and physical experiments, three Nd:YAG rods sample designs (one conventional, one with undoped end, and one with two undoped ends) intended for longitudinal diode pumping were investigated. Both experiments have proved the positive influence of the Nd:YAG undoped ends on the output laser radiation characteristics. The dependencies of the generated laser power on the absorbed pumping diode power have shown that the output power for the active crystal with two undoped ends is more than twice as high in comparison with the conventional Nd:YAG sample (i.e., sample without undoped ends). These results are in good agreement with the computer results where the temperature gradient changes were the smallest for the Nd:YAG rod with two undoped ends.

For the same level of the absorbed power (1.5 W - continuous pumping) for the case of the crystal with two undoped ends, the laser output power was two times higher as compared with the conventional type of crystal. This corresponds also to the computer experiment results. The computed temperature gradient inside the crystal with two undoped ends is two times lower than this value calculated for the conventional crystal. When these two cases were compared, the difference of the maximal temperatures in the doped part of the crystal was as high as 10 °C. For the system in which the active medium with two undoped ends is used, the temperature conditions in the active medium are more homogeneous.

Composite solid-state laser crystals are attractive for the possibility of improving thermal management especially of high power diode-pumped lasers.

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