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Contactless method for studying temperature within the active element of a multidisk cryogenic amplifier

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Abstract. **A new original method has been developed and experimentally implemented, allowing temperature fields to be contactlessly measured in the pump region of active elements in high-power-diode-pumped laser amplifiers, including those operating at cryogenic temperatures. The presence of a temperature gradient of ~57 K mm^{-1} along the pump beam axis at the centre of the active element of the laser amplification unit operating at cryogenic temperatures with a pulse repetition rate up to 1 kHz is simulated and experimentally confirmed.**

Keywords: *diode pumping, high pulse repetition rate, cryogenic temperatures, laser amplifier, laser thermometry.*

1. Introduction

Currently, active research is underway in the world, aimed at developing laser systems with simultaneously high average and peak powers [1 – 3]. Such laser systems are in demand in designing installations for the generation of high-average-power attosecond pulses [4]. In modern attosecond installations, the pulse energy decreases with increasing pulse repetition rate, with the average power being preserved [5]. Therefore, the problem of increasing the energy of pump pulses while maintaining their high repetition rate remains urgent. At the Institute of Laser Physics (SB RAS), research is being conducted, aimed at developing the design principles, methods, and hardware components for a high-intensity source of extremely short radiation pulses with phase stabilisation of the envelope relative to the carrier, capable of operating at a high pulse repetition rate [6].

A key element of the systems with high average radiation power is output cascades of laser amplification with intense pumping. In laser amplifiers with diode pumping of high average power, the active element in the pump region is significantly heated, which leads to a decrease in the laser characteristics of the medium and to the appearance of phase distortions in the amplified radiation [7]. To optimise the laser amplification process, it is necessary to experimentally determine the temperature fields in active elements in the course of their pumping, which is especially important for elements operating at cryogenic temperatures. At room temperatures, thermal imagers are usually used for this purpose [8 – 10]. However, the centre wavelength of thermal radiation at T = 100 K is ~30 μm. For thermal imagers operating at this wavelength, it is very difficult to extract a useful signal from the ambient noises. This is especially true for elements located behind windows that are opaque to radiation with λ = 30 μm, for example, inside vacuum chambers. There are methods for measuring temperature while pumping the active elements doped with Yb^{3+}, based on the temperature dependence of the luminescence cross sections of impurities – Er^{3+} ions [11], but the disadvantages of this approach are the criticality of the telescope alignment in transmitting the image from the region under study to the spectrometer and the need for an additional exciting laser. Laser thermometry of solids (LTS) is a well-developed line of research in metrology [12]. There are a large number of LTS methods based on various temperature dependences of the parameters of the medium under study. With the use of LTS, contactless temperature diagnostics is performed both in technological processes and in solving research problems [13, 14]. Despite this, LTS has not yet found application in monitoring of the parameters of laser systems.

In this paper, a new method based on dynamic laser thermometry is proposed to measure the temperature of Yb^{3+}-doped laser media pumped at a high pulse repetition rate. The method employs the temperature dependence of the cross section of radiation absorption by Yb^{3+} ions at the amplification wavelength (1030 nm). At first, the temperature dependence of active element transmittance is experimentally determined. Under pumping with a high pulse repetition rate, the temperature distribution within the active element is stationary. The lowest transmittance value immediately after the pump termination is determined by the integral absorption along the crystal length at a stationary temperature distribution. This is due to the fact that the characteristic lifetime of the upper Yb^{3+} laser level is ~1 ms, whereas the thermalisation process (establishing uniform temperature distribution within the active element volume after the pump termination) has the characteristic times of ~1 s. Thus, the temperature distribu-

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tion along the pump beam axis in the stationary regime determines the dynamics of radiation absorption in the course of active element thermalisation.

2. Temperature distribution simulation

To test the method of dynamic laser thermometry, we used a multidisk multipass amplifier with a liquid-free closed-loop cryogenic cooling cycle [15]. The amplifier consists of diffusion-bonded crystals in the form of YAG/Yb : YAG disks with Yb doping concentration of 10 at %, attached to massive copper heatsinks. The diameters of the disks are 25 mm; the thickness of the doped parts is 3.75 mm, and that of the undoped ones is 2 mm. Each active element is pumped by pulsed radiation from a diode laser with a centre wavelength of 936 nm and a spectrum width of ~4 nm. The average power of pump radiation of a single element is 100 W; the intensity distribution has a hyper-Gaussian spatial profile with a diameter of 4 mm. Active elements of the laser amplifier are cooled with cryostats on pulse tubes with a closed-loop helium circulation cycle. Coolers of this type make it possible to reach a temperature of 40 K in the absence of pumping. A multipass amplifier was designed to produce output pulses with an energy exceeding 300 mJ provided pulses with energy of 10 mJ are injected.

The stationary heat conduction equation with variable coefficients and boundary conditions of the 1st and 2nd kind describes the steady-state temperature distribution within the active element. In the case of end pumping with a hyper-Gaussian radiation intensity profile and cooling from the side of one face, a one-dimensional equation is valid, provided that the pump beam diameter is comparable to or greater than the element thickness [16], and the contact between the active element face and heatsink is perfect. Thermal conductivity increases approximately fivefold in cooling from room to cryogenic temperatures in the case of undoped Yb : YAG crystals, and 2–2.5 times when doped to 10 at.% [17], which necessitates allowance for the variable coefficient of thermal conductivity in simulation. Thus, the heat equation and boundary conditions can be written in the form:

$$\frac{\mathrm{d}}{\mathrm{d}z}\left[k(T(z))\frac{\mathrm{d}}{\mathrm{d}z}T(z)\right] + q(z) = 0, \qquad (1)$$

$$T(L) = T_0, \quad \frac{\mathrm{d}}{\mathrm{d}z}T(z)\big|_{z=0} = 0,$$

where z is measured from the uncooled input face of the element's doped part along the pump beam axis; L is the thickness of the element's doped part; and T is the heatsink temperature. Previously, it was experimentally established that, in the presence of diode pumping with an average radiation power of 100 W, the steady-state temperature T_0 of the copper heatsink is ~155 K [18]. The thermal conductivity coefficient $k(T)$ of the active element and the laser heat source $q(z)$ are described by the expressions:

$$k(T) = k_0 + k_1\exp\left(-\frac{T-T_\mathrm{c}}{\Delta T}\right), \quad q(z) = -\frac{\eta P}{\pi r^2}\alpha\exp(-\alpha z), \qquad (2)$$

where $\eta = 0.091$ is the quantum defect (the difference between the energies of pump quanta and amplified radiation quanta), $P = 100$ W is the pump radiation power; r is the pump beam radius, and $\alpha = 13.2$ cm^{-1} is the absorption coefficient of pump radiation with a centre wavelength of 936 nm at 300 K [17]. The absorption coefficient α is approximately twofold reduced in the transition from cryogenic to room temperatures. With a single passage of the element, more than 99% of pump radiation is absorbed even with allowance for the halved absorption coefficient. Thus, the main part (more than 50%) of radiation is absorbed when it passes a distance of 1 mm from the input face. This makes it possible not to take into account the temperature dependence of the absorption coefficient of pump radiation. The shape of the function $k(T)$ and the parameter values $k_0 = 7.46$ W m^{-1} K^{-1}, $k_1 = 32.68$ W m^{-1} K^{-1}, $T_\mathrm{c} = 43.11$ K, and $\Delta T = 58.91$ K were obtained on the basis of analysis of the literature data presented in [17, 19].

A solution to equation (1) is given by the function

$$T(z) = W[A_1\exp(-A_2 z + A_3)] + A_4 z + A_5\exp(-A_6 z) + A_7, \qquad (3)$$

where $W(x)$ is the Lambert W-function; and A_i are the constant coefficients. The plot of the function $T(z)$ at the specified parameters is shown in Fig. 1.

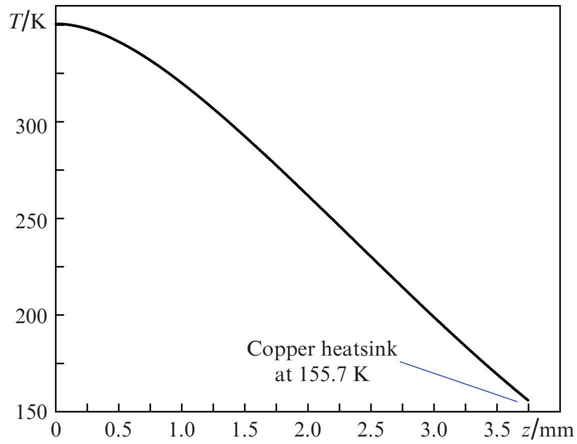

Figure 1. Temperature distribution in the active element along the pump beam axis. Point $z = 0$ corresponds to the uncooled input face of the doped part of the active element.

Calculated maximum temperature of the front uncooled face of the active element is ~350 K. According to Fig. 1, the temperature varies almost linearly in the range $z = 1.0–3.75$ mm, i.e., a temperature gradient of ~57 K mm^{-1} emerges in this area.

3. Dynamic laser thermometry method

This method was used to experimentally study the temperature distribution within the central region of the active element in a multidisk amplifier along the pump beam axis. First, the temperature dependence of transmittance was measured using radiation from a probe laser with a centre wavelength of 1030 nm in the absence of pumping. The scheme of the experiment is shown in Fig. 2. Average radiation power of the probe laser at the vacuum chamber input constituted ~50 mW.

The beam part reflected from the beam splitter of the probe laser was incident on power meter I and was used to control the input radiation power. The transmitted part of radiation was incident on power meter II, having twice passed

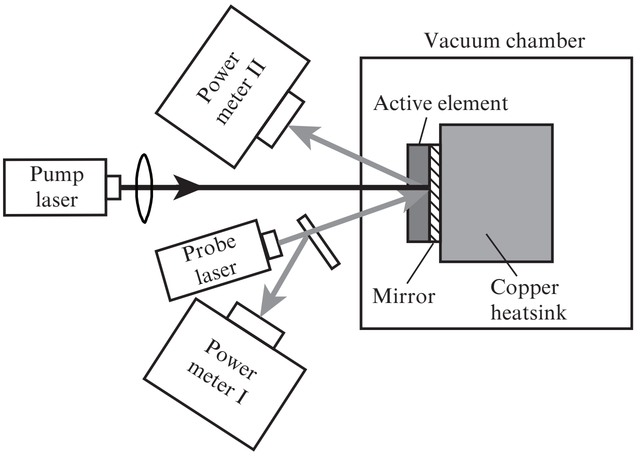

Figure 2. Scheme of measuring the absorption dynamics of diode pumping in the active element.

through the active element after reflection from the mirror coating on its rear surface.

Transmittance is defined as a ratio of readings of power meters II and I; its value at a heatsink temperature of 40 K is taken to be equal to unity. Due to the fact that, in the active element, absorption is practically absent at $\lambda = 1030$ nm and a temperature of less than 60 K, the transmittance defined in this way does not depend on any losses in the optical path, except for those caused by the temperature-dependent absorption in the crystal.

As a result of the experiment, time dependences of the probe radiation transmittance and active element temperature in the course of the system cooling were obtained. The copper heatsink temperature decreased at a rate of ~0.1 K s^{-1}, i.e. slower than the active element thermalisation occurred. The error of temperature measurements by means of a thermocouple does not exceed 0.1 K. To measure both dependences, a synchronous launch of recording systems was used, which made it possible to calculate a dependence of the transmittance B_{exp} on the element's temperature T (Fig. 3).

Next, an experiment was performed according to the scheme shown in Fig. 2, but with the use of diode pumping. The probe laser's beam diameter in the active element was ~ 150 μm, which was significantly less than the pump beam diameter at $\lambda = 936$ nm. This was necessary to measure the absorption rate only at the pumped region centre. The dynamics of active element transmittance after pumping was switched off is shown in Fig. 4.

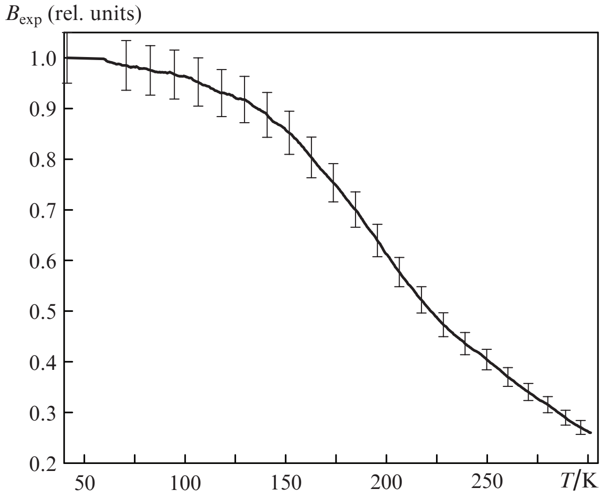

Figure 3. Experimental dependence of transmittance B_{exp} in the active element at $\lambda = 1030$ nm on temperature.

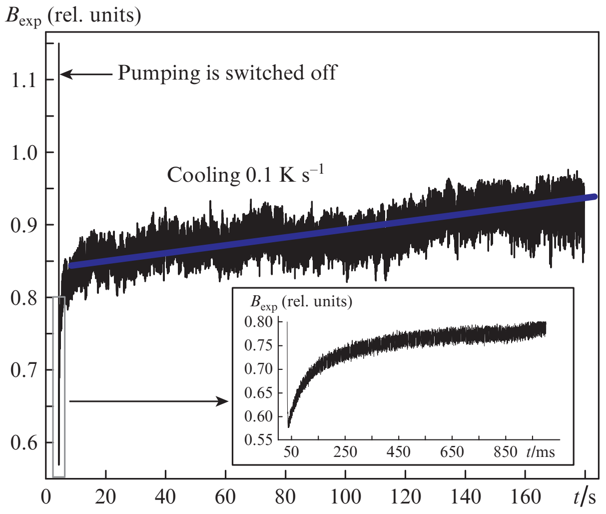

Figure 4. Time dependence of transmittance after switching off pump.

The process of reaching a stationary temperature regime was controlled by a thermocouple placed in a copper heatsink near the active element. After pumping was switched off, the cooling rate was also ~0.1 K s^{-1}; therefore, the heatsink cooling process in studying the dynamics of active element thermalisation could be ignored. The lowest transmittance value after pumping termination was 0.59 ± 0.02. The accuracy of ± 0.02 was determined as a standard deviation of the transmittance value in the region of its minimum during 4 ms (800 points). According to the dependence shown in Fig. 3, this value corresponds to a temperature of ~210 K for a uniformly heated active element. The copper heatsink temperature is 155 K, and the active element temperature being 'equivalent' in absorption is much higher, which means that there is a temperature gradient in the element along the pump beam axis.

The transmittance B of probe radiation is calculated according to the Beer–Lambert–Bouguer law:

$$B = \exp\left[-2\int_0^L \alpha_{\mathrm{exp}}(T(z))\,\mathrm{d}z\right], \tag{4}$$

where $T(z)$ is defined by formula (3), and the absorption coefficient $\alpha_{\mathrm{exp}}(T)$ is calculated from the normalised transmittance $B_{\mathrm{exp}}(T)$ as $\alpha_{\mathrm{exp}}(T) = -\ln(B_{\mathrm{exp}}(T))/(2L)$, and reaches ~1.7 cm^{-1} at $T = 300$ K.

Factor 2 in the exponent is due to the fact that probe radiation passes through the crystal twice – in the forward and reverse directions. The transmittance B calculated by formula (4) is ~0.62. The transmittance $B = 0.61$ in model (1) corresponds to the heatsink temperature $T_0 = 157$ K, and $B = 0.57$ corresponds to a temperature of 175 K. The difference between the experimentally measured temperature (155 K) and the calculated data (157–175 K) allows us to conclude that the temperature difference between the element and heatsink is no less than 2 K and does not exceed 20 K. The value of 20 K constitutes 13 % of the experimentally measured temperature of 155 K. It seems possible to quantify thermal contact quality between the active element and heatsink by means of refining the simulation parameters, passing on to a nonstationary three-dimensional model and carrying out precision transmittance measurements.

4. Conclusions

Our studies confirm the applicability of the new method for measuring temperature fields and quality control of thermal contacts in laser amplifiers with high-power diode pumping, operating at cryogenic temperatures. The results of temperature distribution simulation at the active element centre along the pump beam axis have been confirmed experimentally. A method for quantifying the quality of thermal contact between the active element and heatsink is proposed. The results obtained make it possible to optimise the laser radiation amplification by the diode pumping parameters to obtain radiation with simultaneously high peak and average powers at the output of amplifiers.

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