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Mathematical modeling of the beam spatial distribution for the laser with ceramic active elements

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Abstract. Numerical calculations of the formation of the radiation spatial distribution in the near field by laser amplifiers of pulsed solid-state lasers are performed. On the basis of mathematical modeling, a method is proposed for ensuring spatial homogeneity of laser radiation, based on the use of ceramic active elements with a non-uniform distribution of population inversion over the active element cross-section. The method allows for increasing the spatial homogeneity of laser beams of amplifiers operating in the saturated gain mode.

Ensuring a high spatial homogeneity of the radiation beam throughout the laser path will reduce the radiation load in all optical elements of the laser, which is especially important for single-frequency single-mode lasers [1]. This creates the prerequisites for the use of active elements of smaller diameter and, as a consequence, an increase in the efficiency of the laser, a decrease in its weight and size characteristics and cost.

In some cases, the spatial smoothing of laser radiation is one of the key tasks, for example, in experimental physics of high energy densities using high-power lasers of nanosecond pulse duration. In studies on laser thermonuclear fusion, the irregularity of target irradiation leads to a violation of the symmetry of the compression of thermonuclear fuel, the appearance of hydrodynamic instabilities, and to the occurrence of undesirable effects of stimulated scattering and the generation of hot electrons. In experiments with flat targets for the study of the equations of state and the shock compressibility of substances, the irregularity of irradiation makes it difficult to interpret the experimental data and reduces the accuracy of measurements. Extremely achievable spatial characteristics of the output laser radiation are also necessary when conducting high-precision measurements of the characteristics of electromagnetic radiation in moving media [2-5] when studying the processes of generation and detection of high-frequency gravitational waves in dielectric media by exciting them with high-intensity laser radiation [6] and others.

Considering this, a solution is required to design a laser amplifier with a high degree of beam homogeneity throughout the amplifying path and forming the output radiation with the required amplitude-phase distribution.

One of the main causes of the occurrence of the beam spatial inhomogeneity is diffraction at the edges of optical elements (apertures, active elements, mirrors, etc.). At the same time, an increase in the intensity of a diffracted beam at local points can reach hundreds of percent relative to the initial beam, especially with repeated vignetting of the beam by optical elements of a laser emitter.

One of the methods, which allows for increasing the homogeneity of the laser beam in the near field, is based on the use of the population inversion level in the active laser elements that is not uniform over the cross section [7].

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Recently, semiconductor pump sources have become increasingly common for creating population inversion in laser media. Their use allows changing the population inversion distribution over the cross-section of the active element in a wide range [8]. The distributions in which the active element on its axis has a greater gain than in the region of its generator are in the greatest interest in this. In this case, the active element, in addition to its main function of amplifying laser radiation, can act as a soft or apodized aperture.

In the amplification mode of a weak signal, the influence of a change in the spatial distribution of the beam with a uniform transverse gain profile can be neglected. In the case when the active element is pumped in the center, its effect on the amplified laser beam turns out to be similar to a soft aperture with a degree of apodization of the order of 1 and the contrast

$$\chi = \exp\left(kL\left(\frac{k_0}{k} - 1\right)\right),$$

where ko, k are the gains of the active element in the center and in the region of the generatrix, L is the active element length.

At kL = 3.8 and 30% transfer in the center, the contrast will be slightly more than 3, which will reduce the amplitude of inhomogeneities by about a third [1] in the weak signal amplification mode.

Obviously, due to the low contrast, especially in the saturated gain mode, the apodizing effect exerted by the active element pumped in the center is relatively small. However, this method is characterized by the absence of radiation losses, and the redistribution of the gain over the beam section helps to improve the energy output in the active element.

To increase the contrast and, accordingly, the degree of apodization of laser beams in the process of their amplification is possible using ceramic active elements with a non-uniform degree of doping over the cross-section. This paper is devoted to mathematical modeling of the spatial distribution of radiation in the near field for lasers with ceramic active elements and active elements made according to traditional techniques.

To describe the interaction of laser radiation with an amplifying medium, the following system of equations was used:

$$\frac{\partial E_{m}}{\partial z} + \frac{1}{\upsilon^{2}} \frac{\partial E_{m}}{\partial t} = \frac{1}{2} (k(x, y, z, t) - \beta_{ae}) |E_{m}(x, y, z, t)|,$$

$$\frac{k(x, y, z, t)}{dt} = -\frac{k(x, y, z, t)}{\tau_{21}} - \frac{k(x, y, z, t)|E_{m}(x, y, z, t)|^{2}}{240\pi Q_{s}}.$$

where E_m is the electric field amplitude, β_{ae} is the coefficient of non-resonant radiation losses in the active medium, τ_{21} is the lifetime of the upper laser level, Q_s is the saturation energy density.

The calculation of the change in the amplitude-phase distribution of laser radiation during its propagation along the z-axis is based on the calculation of the Kirchhoff diffraction integral:

$$\dot{E}_{2}(x_{2}, y_{2}, z_{2}) = \frac{1}{i\lambda\Delta z} \iint_{A} \dot{E}_{1}(x_{1}, y_{1}, z_{1}) \dot{G}(x_{2}, y_{2}, x_{1}, y_{1}, \Delta z) dx_{1} dy_{1},$$

where \dot{E}_1 and \dot{E}_2 are amplitude-phase distributions of the electromagnetic field in the planes with coordinates z_1 and z_2 , respectively, $\dot{G}(x_2, y_2, x_1, y_1, \Delta z)$ is the Green function for layer of thickness Δz ; $\Delta z = z_2 - z_1$.

Figure 1 shows the simulation results of the transverse distribution of the radiation energy density at a distance of 0.6 m from a single-pass pulsed laser amplifier with a crystalline and ceramic active element when it is excited by a beam with a hyper-Gaussian distribution.

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Figure 1. The radiation intensity distribution across the beam section at a distance of 0.6m from the amplifier with crystalline a) and ceramic b) active element for input radiation with hyper-Gaussian amplitude distribution.

The calculations are given for the active element YAG: Nd₃₊ with a length of 130 mm with a uniform distribution of population inversion by volume. The diameter of the crystalline active element is 8 mm, and the diameter of the ceramic active element is 9 mm with a diameter of 8 mm of the neodymium-doped area along the central axis of the element. The amplification mode is close to the amplification mode of a strong signal, the output energy in both cases is equal to 500 mJ. Figure 2 shows similar dependences for the case of excitation of a laser amplifier with a beam with a uniform distribution.

The distributions shown in Figures 1 and 2 show a significant improvement in the homogeneity of the output beam when using ceramic active elements in laser amplifiers operating in the saturated gain mode.



Figure 2. The radiation intensity distribution across the beam section at a distance of 0.6m from the amplifier with crystalline a) and ceramic b) active element for input radiation with a uniform amplitude distribution.

The simulation results showed that the use of ceramic active elements with no activator ions doping in the region of their generatrix allows for reducing the spatial inhomogeneity of the beams due to their vignetting with optical elements of the laser path.

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