Journal of Engineering Physics and Thermophysics, Vol. 70, No. 6, 1997

THERMALLY STRESSED STATE AND OPTICAL QUALITY OF A GLASS ACTIVE MEDIUM OF A POWERFUL SOLID-STATE LASER

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UDC 621.373.826

Results of a comprehensive investigation of a thermally stressed state and optical quality of a cylindric active medium of a high-power solid-state laser are presented. A comparative analysis of the effects of the temperature-induced gradient of the refractive index, variation of the shape of the active medium, and induced birefringence is carried out.

A number of works (see, e.g., [1-3]) are devoted to various phenomena in solid-state lasers. They deal mainly with processes of quantum energy exchange or describe mechanisms of forming of an active medium in certain solid-state structures. On the other hand, the low energy efficiency of the lasers makes it necessary to concentrate on the macroscopic energy balance and its consequences [4], which can affect substantially, e.g., the output radiation parameters of high-power laser installations.

It is known that a substantial portion of the pumping energy of a solid-state laser goes into direct heating of the active medium (AM) and parts of its construction [1]. Up to 11% of the pumping energy can be released in the AM in the form of heat [1]. Inhomogeneities of the energy liberation profile lead, especially in cylindrical matrices with large cross-sectional dimensions, to the emergence of substantial gradients of the refractive index of glass, which affects the beam pattern of the output radiation. This difficulty is aggravated when the laser operates in the pulse-periodic mode.

A quantitative estimate of the effect of the thermally stressed state of a glass AM can be obtained by proper numerical modeling of thermal and elastic processes and reliable experimental investigations, as has been carried out for gaseous lasers [5]. The most important factors affecting the optical state of the AM – the temperature-induced gradient of the refractive index of glass, temperature-induced deformation of the AM, and photoelastic phenomena – have been determined in [2]. In this case the Shtrel number (Sh) can be used to describe the optical uniformity. The number has the meaning of the efficiency of energy transfer to the utilization zone (the Fraunhofer diffraction zone) [6] and can be used for estimation of the extent to which each of the factors chosen affects lasing. The number makes it possible to compare properly theoretical predictions with the results of experimental diagnostics.

Numerical modeling of the optical state included solution of the time-dependent heat equation with a source of spatially distributed energy liberation and boundary conditions of the second kind describing the cooling of the external surface of the rod [7]. The elastic problem was also solved in two dimensions, but already in a steady-state formulation, which was possible since the propagation velocity of elastic perturbations in the solid state is substantially higher than the rate of the heat conduction. The source of the spatially distributed energy liberation was calculated for both etched and polished external surfaces of the cylinder being illuminated [8].

Figure 1 presents calculated profiles of the energy-liberation power density along the radius of a cylindrical AM with an etched surface for various pumping energies [8] with allowance for the fact that, accoring to calculations [8], up to 5% of the pumping energy is liberated in the form of heat in a rod of the given geometry. It should be

D. F. Ustinov Baltic State Technical University, St. Petersburg, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 70, No. 6, pp. 1020-1024, November-December, 1997. Original article submitted October 30, 1995.

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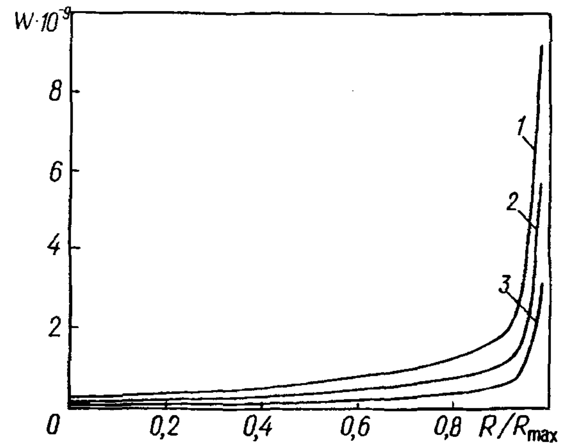


Fig. 1. Calculated profiles of energy liberation power density in AM: 1) pumping energy 30 kJ, 2) 60, 3) 90. W, W/m^3.

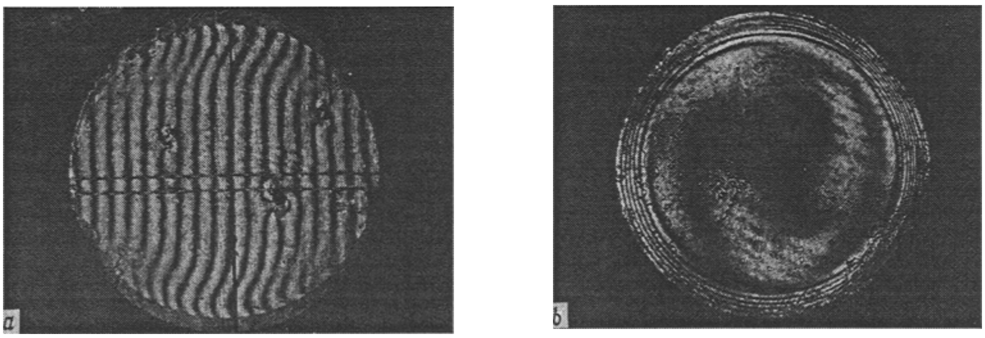


Fig. 2. Typical shift interferogram (a) and polariscopic pattern (b).

pointed out that the inhomogeneity of the energy liberation profile is one of the main reasons for the emergence of optical distortions in the glass matrix.

We investigated a laser with a cylindrical AM with a length of 914 mm and a diameter of 45 mm. We had an opportunity to study matrices from silicate (GLS-6 brand) and phosphate (GLS-22 brand) glasses with differing thermophysical properties. In order to obtain quantitative experimental information on distortion levels in glass, shift- [9] and Talbot-interferometry and circular polariscopy [10] optical systems were set up with argon (0.514 μm) and pulsed Nd:YAG (1.06 μm) lasers used as illumination sources. Figure 2 presents a typical shift interferogram (a) and polariscopic pattern (b) for an AM of GLS-6 glass obtained 0.5 sec after triggering of pumping lamps (the duration of the pumping pulse was approximately 0.001 sec, its energy 90 kJ). The interferogram and polariscopogram obtained with the Ar laser used for illumination show that the source of thermal perturbation is localized within a small region in the vicinity of the outer rod surface, which completely agrees with the calculated energy liberation profiles (Fig. 1). The optical sensing scheme made it possible to carry out measurements of distortions in the active medium through the cavity, which provided information on the extent to which the latter affects the entire optical quality. We also managed to carry out interferometry of the face of the ASM. This in its turn yielded an estimate of the contribution of the variation of the AM shape to the general structure of phase distortions of the probing radiation.

In the course of the numerical modeling and experimental diagnostics we recovered wave fronts of probing radiation whose phase was matched to the lasing wavelength of the laser under investigation, i.e., 1.06 μm. Figure 3 presents isometric images of the wave fronts. Calculations have also shown that the highest distortion levels are localized in the peripheral regions; the perturbations propagate along the rod axis with time, and in this case the absolute level of phase distortions decreases. Cooling of the outer rod surface virtually does not affect the structure of the wave front during the first 10 sec after turning the pumping system on. During cooling, the redistribution of heat takes place not only along the axis, but even more intensely towards the outer surface of the rod.

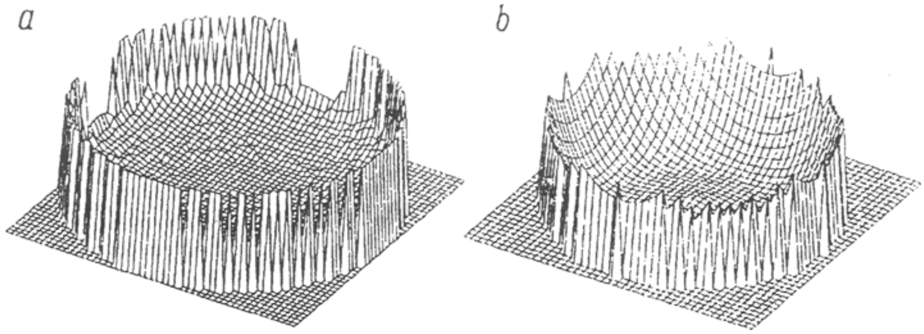
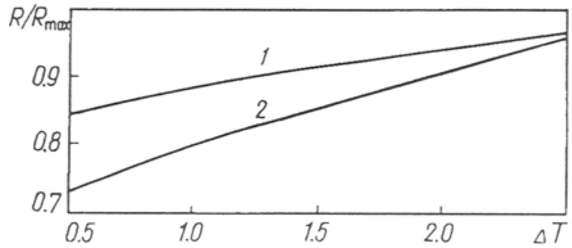


Fig. 3. Isometric images of wave fronts obtained from numerical modeling (a) and experimental diagnostics (b).



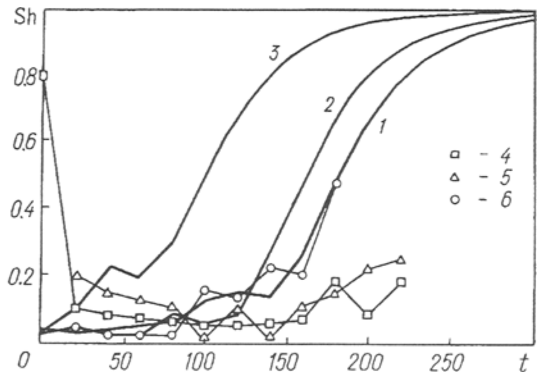


Fig. 4. Temperature profiles along the radial direction: 1) experiment, 2) calculation.

Fig. 5. Time dependences of the Sh number: 1) on the temperature-induced gradient of the refractive index, 2) on induced birefringence, 3) on the total action of 1 and 2, 4) diagnostics by an Ar laser (0.514 μm), 5) diagnostics by an Nd:YAG laser (1.06 μm), 6) diagnostics by an Ar laser through the cavity. t, sec.

The interferometry of the AM face has proved the absence of noticeable distortions of its surface. A similar conclusion has been drawn on the basis of the numerical modeling. The presence of a region about 10 mm in length near the face cut which is not subjected to the action of the pumping radiation compensates for the nonuniform longitudinal thermal expansion of the entire rod. The high elasticity of glass provides virtually complete leveling of nonuniform longitudinal displacements, which in turn leads to identical displacements of all points of the side face surface by a value proportional to the temperature integral-averaged along the lateral direction. The absence of deformations of the face surface of the rod also provides Sh = 1 for this component over the entire time interval under investigation, irrespective of the level of initial energy input. Therefore, to compensate for shape distortions, especially in cylindrical AM with small diameters, it will suffice to provide small compensating zones near face cuts, which, in the absence of energy release, will "absorb," due to the elasticity of the material, the nonuniform longitudinal expansion of the rod.

An analysis of polariscopic patterns has shown the absence of nonuniformities of pumping along the azimuthal direction, since the isochromes in this case have the form of almost concentric circles (see Fig. 2b). This has also been substantiated by radial shift interferometry. The latter circumstance bears witness to the radial symmetry of the temperature and stresses induced by the nonuniform character of the transverse temperature profile. By using relationships from [1, 10], radial temperature profiles were recovered from polariscopic patterns similar to these presented in Fig. 2b. A temperature profile for a pumping energy of 90 kJ five seconds after the pumping pulse is presented in Fig. 4. The figure also presents similar information obtained by numerical modeling. Certain differences in absolute temperature levels not exceeding 10% are explained by the inaccuracy of evaluation of the volume energy liberation in the AM in the calculations.

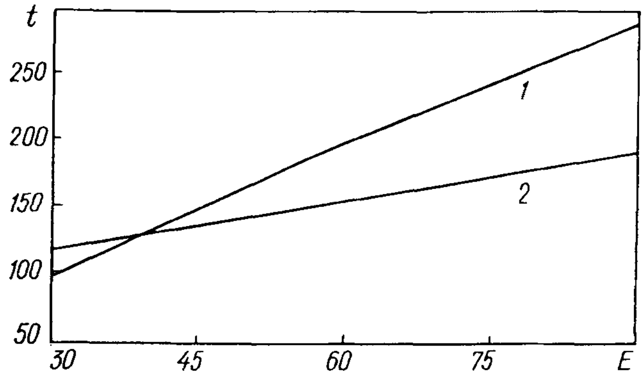


Fig. 6. Time of the integral leveling of temperature profiles along the radial direction: 1) in the presence of cooling, 2) without cooling. E, kJ.

The integrated criterion of optical inhomogeneity was evaluated from phase distributions over the exit aperture obtained in both experiments and numerical modeling. The behavior of the Sh number was considered as a function of the duration of the relaxation of thermal perturbations starting with the instant when the pumping system was turned on, for various levels of the total energy input (Fig. 5). The results presented are for the maximum (90 kJ) energy level and an operating cooling system. The same figure also presents data of interferometric sensing by infrared light and diagnostics through the cavity.

The minimum value of Sh is achieved approximately at the 40th sec, although a rather intense leveling of temperature perturbations begins immediately after pumping due to heat transfer to the AM center. Heat propagation deep into the rod leads to a decrease in the absolute level of perturbations, but in this case the inhomogeneities begin to occupy a greater aperture area. Calculated values of Sh have a similar character except for the fact that the time dependence of the total phase is periodic during the initial time interval. This is explained by the character of the interaction of significant, i.e., temperature and birefringence-induced, phase components (Fig. 5).

A decrease in the pumping energy does not affect significantly the behavior of the Sh number with time, but only augments its absolute values, mainly due to leveling of the radial profile of the function of the spatially distributed energy liberation (Fig. 1). As has been shown by calculations and experiments, at energies of less than 30 kJ, the optical quality remains acceptable (Sh > 0.8) during the entire time interval under consideration.

In the case of the complete thermal insulation of all surfaces, the temperature within the rod levels off a certain integral-averaged value. Intense cooling of the external side surface (the heat transfer coefficient is about 20,000 $W/(m^2 \cdot K)$) reduces the temperature to the initial level. The cooling liquid reduces rapidly the temperature in the surface region of the cylinder, but the low heat conductivity of the glass prevents intense redistribution of the heat from central regions of the AM to the surface being cooled. This leads to an increase in the time of leveling of temperature profiles when the cooling is turned on (Fig. 6), which is especially noticeable at high pumping energies, which additionally cause greater heating of the central region of the cylinder. When calculating the time of temperature leveling, the state characterized by Sh = 0.9 was taken as the initial level of optical homogeneity.

GLS-22 glass differs in its thermophysical and thermooptical parameters from GLS-6 glass [2]. This explains the greater heating of the phosphate glass with identical optical pumping. However, experiments and calculations have shown similar results for both types of glass in both the structure of the integral wave surfaces and the absolute Sh values. Factors affecting the integral optical state vary in such a manner that their total effect does not undergo substantial changes.

Thus, the investigations made it possible to obtain reliable quantitative information on the integral level of phase distortions in the AM of a high-power solid-state laser.

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