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Single-mode Nd:GGG disk laser with three-beam diode pumping and a degenerate cavity

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Abstract. **The energy and spatial output parameters of a solid-state Nd:GGG disk laser with three-beam pumping and a degenerate cavity with a single output channel are studied. The radiation was coupled out of the cavity through either an auxiliary semitransparent output mirror or a variable-reflectivity mirror. The single off-axis intracavity beam successively propagated through all the pumped regions of the active element.**

Keywords: *solid-state lasers, disk active elements, degenerate cavities, multi-beam diode pumping.*

1. Introduction

The use of disk active elements (AEs) [1] and multi-beam optical pumping [2] may considerably decrease the negative influence of thermally induced optical effects (such as lens and birefringence) on the output parameters of solid-state lasers. Realisation of multi-beam pumping requires coordinated participation of all population inversion regions in lasing. This coordination can be achieved by using degenerate cavities [3]. This suggests the use of one of the important properties of degenerate cavities, namely, the existence of an off-axis intracavity beam, which closes on itself after several cavity round-trips (see, for example, [4–9]). The cavity parameters should be chosen so that the intracavity beam passed the disk active element (DAE) only within the pump spots. The aim of the present work was to develop a disk laser with three-beam pumping and a single output channel. The existence of only one output channel was achieved by using either an auxiliary semi-transparent output mirror or one of the cavity mirrors with reflectivity variable over the cross section. The laser operated in the TEM_{00} mode.

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2. Experimental conditions

The optical scheme of the experimental setup is shown in Fig. 1. The schemes of the two laser cavities and the geometric paths of beams in these cavities are presented in Fig. 2. The plane of Fig. 2 is orthogonal to the plane of Fig. 1.

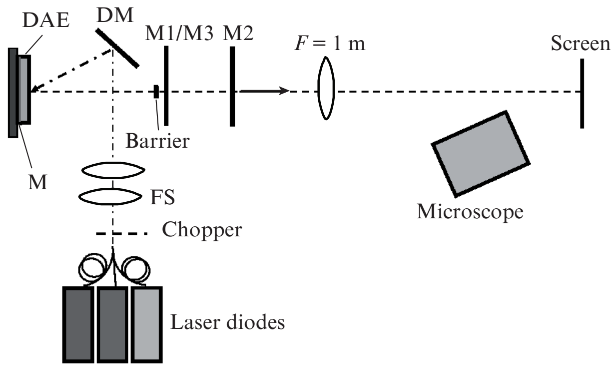

Figure 1. Optical scheme of the experiment: (M, M1/M3, M2) cavity mirrors; (DM) deflecting mirror of the pump channel; (FS) pump focusing system.

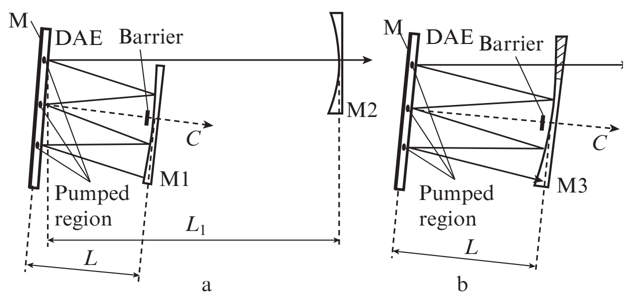

Figure 2. Optical schemes of cavities with (a) an auxiliary mirror and (b) a variable-reflectivity mirror.

In the first case (Fig. 2a), the laser cavity was formed by highly reflecting mirrors M and M1 and output mirror M2. In the second case (Fig. 2b), the auxiliary mirror M2 was not used and mirror M1 was replaced by mirror M3 with a semi-transparent region through which the radiation was coupled out of the cavity.

The plane mirror M with a reflectivity exceeding 99.5% at wavelengths of 1062 and 808 nm was deposited on the rear surface of the DAE. The mirrors M1 and M3 were spherical with radius of curvature R_{curve} = 200 mm. The reflectivities of mirror M1 and of the highly reflecting part of mirror M3 exceeded 99.5% at a wavelength of 1062 nm. In the course of the experiments, we used mirrors M2 with reflectivities of 75%, 80%, 85%, 88%, 94%, and 98%. The reflectivity of mirror M3 in the region through which radiation was coupled out of the cavity was 95%.

Mirror pairs M–M1 and M–M3 formed degenerate cavities. Length L of each of these cavities was 50 mm. A specific feature of degenerate cavities is that the trajectory of the off-axis beam closes after N longitudinal and K transverse cavity roundtrips, which are related to L and R_{curve} as [5]

$$\frac{L}{R_{\text{curve}}} = \frac{1}{2}\left(1 - \cos\frac{2\pi K}{N}\right). \quad (1)$$

In our case, $K = 1$ and $N = 6$. In a resonator with such parameters, any beam closes on itself after six longitudinal and one transverse roundtrips. After three longitudinal round trips, any beam becomes symmetric to the initial beam with respect to the resonator axis C. Distance L_1 passed by the beam (Fig. 2a) between mirrors M and M2 was 150 mm. Length L_1 and the radius of curvature of output mirror M2 were chosen so that they do not disturb the TEM_{00} beam parameters determined by the characteristics of the auxiliary resonator M–M1. The angles between cavity axes C and the beam axes in both cases were 42 mrad.

As a DAE, we used in both lasers a Nd:GGG crystal 50 mm in diameter and 1.5 mm thick with a Nd^{3+} concentration of $\sim 2 \times 10^{20}$ cm^{-3}. The DAE was pumped by three K808DAECN (BWT Beijing LTD) fibre-coupled (core diameter 400 μm) laser diodes. The pump wavelength was 808 nm. A focusing system composed of two objectives (with spherical aberration correction) projected the images of the output ends of the fibres onto the DAE surface. The use of this pumping system, in contrast to [3], allowed us to obtain the required pump beam parameters in the DAE at random distances between the beams. The radii of pump beams in the AE volume at the $1/e^2$ level were 250, 220, and 280 μm. The distance between the neighbouring pump beams in the DAE was 6.3 mm. Deflecting mirror DM served to decrease the angle between the pump beams and the cavity axis C. This angle inside the AE was about 5°.

The experiments were performed under cw and repetitively pulsed pumping. In the latter case, we used a mechanical chopper in the form of a disk with an aperture, which rotated with a frequency of 2.5 Hz. This reduced the average pump power by a factor of ten, while the pump pulse duration was approximately 40 ms. This time was comparable with the temperature relaxation time over the beam cross section $t_T \approx \omega^2/\chi = 30$ ms, where $\omega = 0.028$ cm is the pump beam radius at the $1/e^2$ level and $\chi = 0.026$ cm^2 s^{-1} is the thermal diffusivity of the Nd:GGG crystal. The time during which the chopper is closed was 0.36 s. This time was considerably longer than t_T but shorter than the time of temperature stabilisation over the entire AE volume $t \approx L^2/\chi = 0.8$ s, where $L = 0.15$ cm is the AE thickness.

To prevent the development of lasing from the pump spot centre along the cavity axes C, nontransparent screens (barriers) 2 mm in diameter were positioned near the M1 and M3 mirrors.

3. Experimental results and discussion

We experimentally studied the dependences of the output laser power and the total laser beam divergence 2θ at half maximum on the output mirror transmittance and the pump power absorbed in the AE. The absorbed powers were approximately the same for all the pump beams. The output beam divergence was studied by measuring the transverse intensity distribution of the laser beam in the waist, i.e., in the focal plane of a converging lens with focal length $F = 1$ m. The measurements were performed using a microscope equipped with an image visualisation and processing system.

3.1. Cavity with an auxiliary mirror

The dependences of the output laser power on the total absorbed pump power for the cw and repetitively pulsed regimes of the laser with the cavity shown in Fig. 2a are presented in Figs. 3a and 3b, respectively.

The highest laser efficiency η = 35% (slope efficiency 44%) in the repetitively pulsed regime was achieved using a mirror with a reflectivity of 88%. In the case of cw pumping, the maximum efficiency η = 24.5% was achieved by using an output mirror with a reflectivity of 94%. The decrease in the output power in the cw regime was related to the influence of thermally induced lenses in the DAE due to its relatively large thickness. In this case, the influence of changes in the trajectories of intracavity beams due to their off-axis propagation through thick lenses and non-normal incidence on these lenses is especially pronounced.

The total laser beam divergence angle 2θ (FWHM) was about 2.9 mrad. This value was almost independent of the laser operation regime (cw or repetitively pulsed), the pump power, and the output mirror reflectivity. The dependence of the beam divergence on the absorbed cw pump power for R = 88 % is shown in Fig. 4. The calculated total divergence angle of the TEM_{00} beam was 2.4 mrad. Thus, the output beam quality parameter M^2 under all experimental conditions was about 1.2 and was close to that of a single-mode beam. This result well agrees with the results of works [10, 11], in which the mode composition of radiation of degenerate resonators with Gaussian gain distribution in the active medium was studied theoretically and it was shown that modes of lower orders in these resonators are excited with the largest weight.

3.2. Cavity with a variable-reflectivity mirror

The reflectivity of the spherical mirror region through which radiation was coupled out of the cavity was 95%. This value is close to the optimum reflectivity for the cavity with an auxiliary mirror. The dependences of the output power in the case of cw and quasi-cw pumping of the laser with the cavity shown in Fig. 2b are presented in Fig. 5. The highest lasing efficiency in the cw regime was 28% (η_{dif} = 34%). In the repetitively pulsed regime, we obtained η = 33% at η_{dif} = 42%.

The output beam divergence was measured to be ~3 mrad (Fig. 6) and, similar to the case with the use of an auxiliary mirror, almost did not depend on the laser operation regime and the pump power absorbed in the DAE. The total divergence 2θ at half maximum calculated for our experimental conditions was 2.5 mrad at the beam quality factor $M^2 \approx 1.2$.

The experimental results showed that the influence of the thermally induced lens in the AE on the output parameters

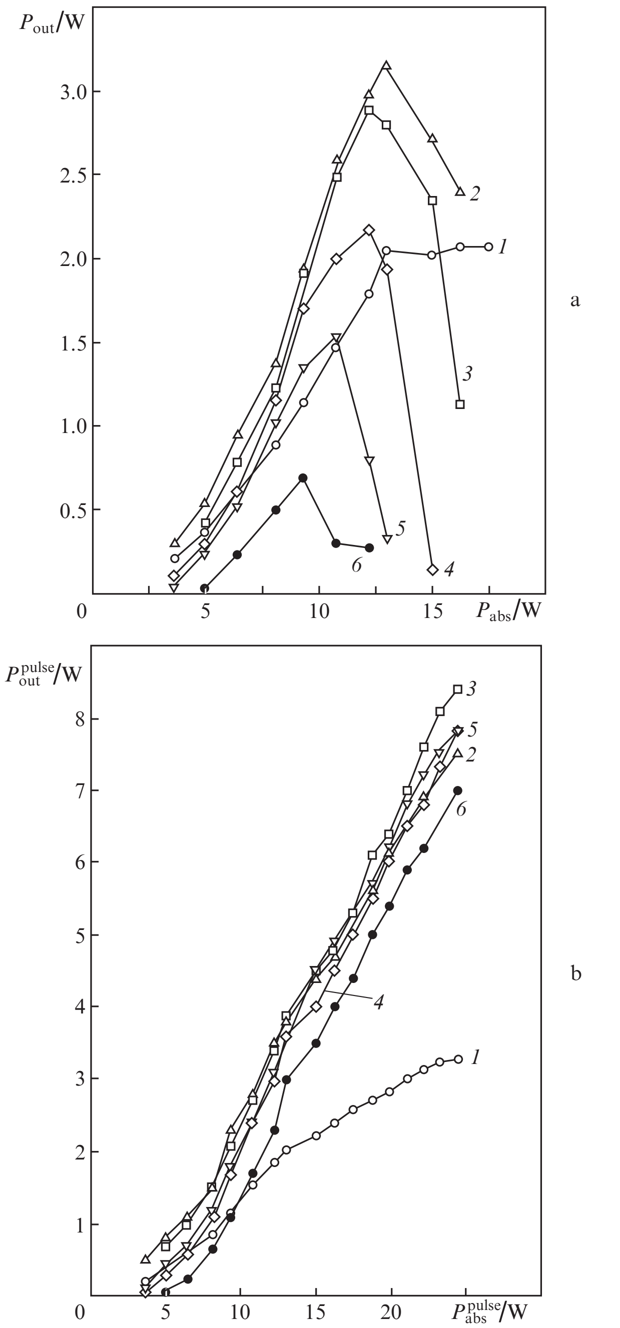

Figure 3. Dependence of the (a) cw (P_{out}) and (b) pulsed (P_{out}^{pulse}) output laser powers on the total absorbed (a) cw (P_{abs}) and (b) pulsed (P_{abs}^{pulse}) pump powers at output mirror reflectivities R = (*1*) 98%, (*2*) 94%, (*3*) 88%, (*4*) 85%, (*5*) 80%, and (*6*) 75%.

is weaker in the laser with the degenerate cavity presented in Fig. 2b. In particular, we did not observe oscillation suppression in the entire range of total cw pump power (up to 23 W) and at a rather large thickness (1.5 mm) of the Nd : GGG crystal. At the same time, oscillation suppression in the three-mirror cavity (Fig. 2a) took place even at a total cw power of 8 W. This conclusion is confirmed by the results of calculations performed for these cavities. The dependences of the total beam divergence on the optical power of the lens thermally induced in the AE in each of the pump channels, which were calculated for both types of cavities with the aforementioned parameters, are presented in Fig. 7.

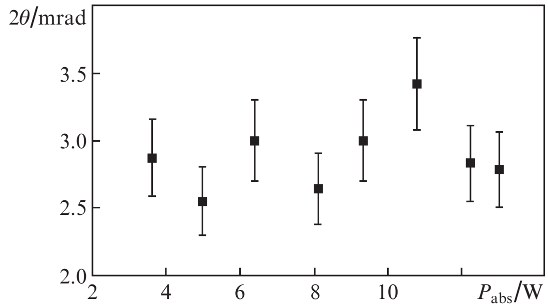

Figure 4. Dependence of the total laser divergence angle 2θ on absorbed cw pump power P_{abs} at R = 88%.

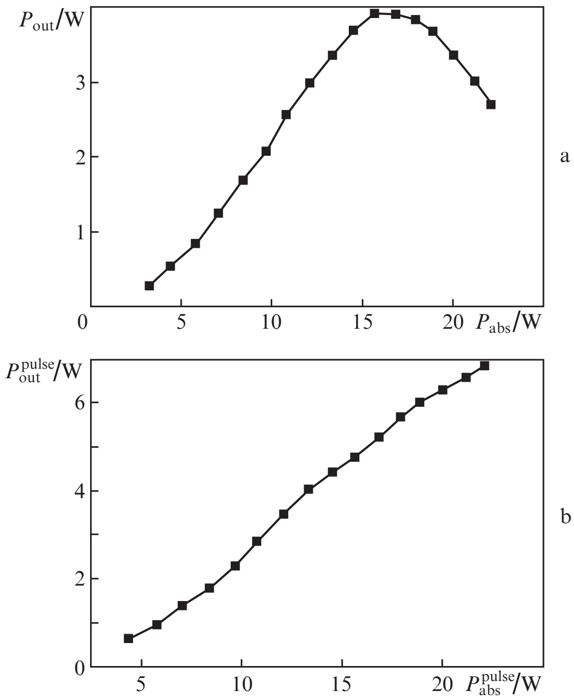

Figure 5. Dependences of the (a) cw (P_{out}) and (b) pulsed (P_{out}^{pulse}) output laser powers on the total absorbed cw (P_{abs}) and pulsed (P_{abs}^{pulse}) pump powers, respectively, at R = 95%.

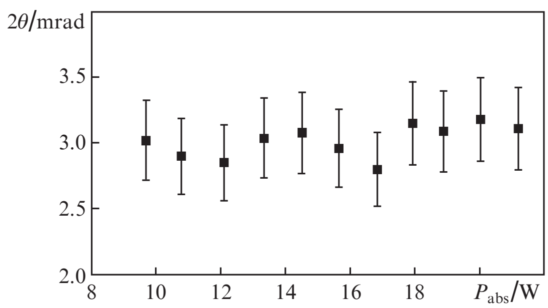

Figure 6. Dependence of the total laser divergence angle 2θ on the absorbed quasi-cw pump power at R = 88%.

The calculations were performed in the approximation of thin lenses localised in the immediate vicinity of the surface of the highly reflecting plane mirror. The difference observed in the behaviour of the two laser types was related to the

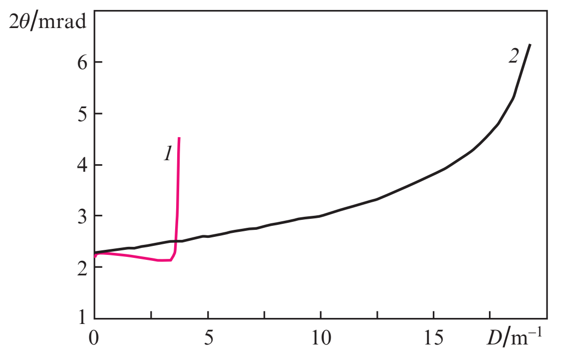

Figure 7. Dependences of the total divergence angle 2θ on optical power D of the lens thermally induced in DAEs in each pump channel for lasers with (*1*) a cavity with an auxiliary mirror and (*2*) a two-mirror cavity.

existence of the longer M – M2 shoulder in the cavity with an auxiliary mirror.

Thus, we have created and studied a disk laser with three-beam diode pumping and a degenerate cavitiy with a single output channel realised by two different methods. The energy and spatial characteristics of the laser radiation were studied upon cw and repetitively pulsed pumping. The maximum lasing efficiency was 35% (slope efficiency 44%). The beam quality factor M^2 was 1.2. The possibility of using a degenerate cavity and multibeam diode pumping of a disk active element to create an efficient laser with a high output beam quality was demonstrated.

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