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Passively *Q*-switched Yb, Er : phosphate glass laser

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Abstract. **The effect of thermal deformations of active elements (AEs) fabricated of phosphate glasses of two types on the mode structure and output energy of a passively *Q*-switched Yb, Er phosphate glass laser is studied upon longitudinal pumping of AEs by a diode laser array. A scheme of the laser resonator is proposed which simultaneously reduces the influence of a thermal lens induced in the AE on the laser radiation parameters and matches the active-medium volume with the lowest mode of the resonator when the cross section of the pump beam has nearly elliptical shape. In the passively *Q*-switched regime, output pulses of duration 26 ns and energy 1.4 mJ were obtained with this resonator.**

Keywords: *Yb, Er laser, phosphate glass, longitudinal diode-laser pumping, thermal deformation, passive Q switching.*

1. Introduction

Phosphate glasses doped with erbium (Er^{3+}) and ytterbium (Yb^{3+}) ions belong at present to the best materials for developing erbium lasers emitting at 1.5 μm. The main and important disadvantage of the phosphate glass is its low heat conduction and low thermomechanical damage threshold. The use of InGaAs diode lasers for pumping erbium lasers substantially reduced the thermal load on an active element (AE) compared to flashlamp pumping, increased the lasing efficiency and average output power, and made the laser design more compact. However, because erbium lasers operate in the three-level scheme, the Stokes shift between the frequencies of diode and erbium lasers is rather large. For this reason, various thermal effects caused by heat release in the AE are very important, which restricts the average power of erbium lasers [1, 2]. These effects are especially strong upon longitudinal pumping. In this connection, active studies are underway at present toward the improvement of optical and thermomechanical properties of glasses [3 – 7] and the methods for more efficient heat removal from AEs and increasing the lasing efficiency are investigated.

AEs in the form of a plane – parallel slab of width much greater than its thickness (the so-called slab geometry) have been widely used in Nd and Yb lasers in the last years [8 – 12]. Such AEs produce high-quality radiation with average powers exceeding the output power of lasers with cylindrical AEs. These properties were observed not only for slabs uniformly pumped over the entire volume but also for slabs in which the population inversion was produced only in the central part, so that the cross section of the active medium had the form of an ellipse with one of the axes much longer than another. In this case, one of the problems is the matching of the volumes of the active medium and the lowest mode of the resonator to obtain the maximum possible lasing efficiency [13].

The aim of this paper is to study lasing in a Yb, Er-doped phosphate glass in the passive *Q*-switching regime by using a stable resonator with the elliptical cross section of the fundamental mode. We present the results of the experimental study of the effect of thermal deformations of phosphate glass AEs on the radiation parameters and stability of the laser operating in this regime.

2. Experimental

The general scheme of the experiment is shown in Fig. 1. Pumping was performed by a LIMO diode laser array (DLA) (Dortmund, Germany) with a rated output cw power of 25 W at 975 nm and collimated radiation. The array was used in the quasi-continuous regime with the pulse duration τ_p up to 6 ms and power P_p up to 30 W. Figure 2 shows the pump radiation intensity distribution at the input face of the AE. Because the divergences of the DLA radiation in the horizontal and vertical directions were noticeably different, the shape of the pump radiation spot on the input face of the AE was close to an ellipse with axes $d_x \approx 1.1$ mm (along the x axis) and $d_y \approx 0.6$ mm (along the y axis) at the $1/e^2$ intensity level. The dimensions of the spot cross section and the pump radiation intensity distribution changed insignificantly over the AE thickness. The DLA was mounted on a thermoelectric Peltier element, which was used to change the emission wavelength by varying the semiconductor temperature. The AE was pumped by the DLA at $\lambda_0 \approx 968$ nm by maintaining the DLA temperature at (2 ± 1) °C.

To match properly the spatial parameters of the lowest resonator mode with the AE volume, we used a resonator consisting of a spherical and a cylindrical mirror (Fig. 1). Mirror M1 is a spherical, concave mirror with the radius of curvature $R_1 = +79$ mm and the reflection coefficient $r_1 \approx 99.8\,\%$ at a wavelength of ~1536 nm. The AE was pumped through this mirror. Mirror M2 is a cylindrical, convex mirror with the radius of curvature $R_2 = -39$ mm

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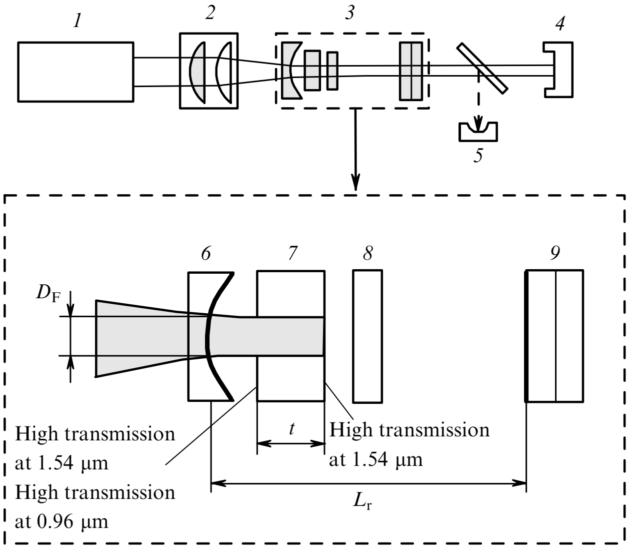

Figure 1. Scheme of the experimental setup: (*1*) diode laser array; (*2*) optical system for DLA radiation focusing; (*3*) resonator with an AE and a passive Q switch; (*4*) power meter; (*5*) germanium photodiode; (*6*) resonator mirror M1; (*7*) AE; (*8*) $Co^{2+}:MgAl_2O_4$ crystal; (*9*) resonator mirror M2.

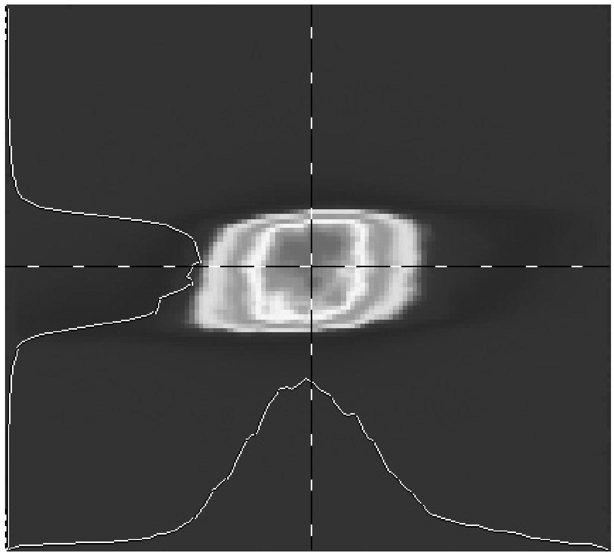

Figure 2. Distributions of the LDA radiation intensity on the AE input face.

and the reflection coefficient $r_2 \approx 89\,\%$ at the laser wavelength. The direction of the cylinder axis of mirror M2 in the resonator coincided with that of the minor axis y of the pump radiation spot. In this case, the cross section of the lowest mode of the empty resonator had the elliptical shape and could be matched with the active medium volume by selecting the radii of curvature of resonator mirrors and changing the distance between them.

Two types of AEs used in experiments were made of different phosphate glasses in the form of plane–parallel slabs with both faces covered by high-transmission multilayer dielectric coatings. One of the faces, through which the AE was pumped, had the transmission coefficient $T = 99.8\,\%$ at 1.54 μm and $T > 98\,\%$ at 970 nm. On the second face, only the AR coating at the lasing wavelength was deposited. The first AE (No 1) of size 7 × 7 mm, thickness 4 mm, and the concentration of ytterbium ions $[\mathrm{Yb}] = 2.2 \times 10^{21}$ cm^{-3} and erbium ions $[\mathrm{Er}] = 8.5 \times 10^{19}$ cm^{-3} was made of the LGS-DE glass synthesised at the Institute of Radio Engineering, RAS. A specific property of this glass is its low thermooptic constant $W \approx (15 - 25) \times 10^{-7}$ K^{-1}. The second AE (No 2) of size 5 × 5 mm, thickness 3.3 mm, and the concentration $[\mathrm{Yb}] = 1.7 \times 10^{21}$ cm^{-3} and $[\mathrm{Er}] = 1 \times 10^{20}$ cm^{-3} was made of the SELG glass synthesised at the General Physics Institute, RAS. The thermooptic constant of this glass is noticeably greater ($W \approx 66 \times 10^{-7}$ K^{-1}), but it has a higher thermal damage threshold and is capable of withstanding high-power pumping [4, 14].

Passive Q-switching of the resonator was performed by using $Co^{2+}:MgAl_2O_4$ (MALO) crystals [15, 16]. Each of the working faces of the crystals was covered with a dielectric coating, and reflection losses at 1.54 μm did not exceed a few fractions of percent.

All the results were obtained at a pulse repetition rate of 1 Hz. No special cooling of AEs was performed.

3. Results and discussion

3.1 Thermal deformation of AEs

The shape of output pulses observed upon pumping by 3–6-ms, 10-kW cm^{-2} pulses in the quasi-continuous regime demonstrated the influence of thermal deformations of glass AEs on lasing. This influence was observed for both AEs, but it was more noticeable for AE No 2 made of the SELG glass with a higher thermooptic constant. The optical power of a lens induced by AE heating can be estimated by the method of measuring the focal distance F_t of a thermal lens in short-length solid-state lasers based on the observation of quenching of laser action [17]. For this purpose, the design of a stable resonator shown in Fig. 1 was changed, and a plane mirror with the reflection coefficient $r \approx 95\,\%$ at 1536 nm was used as mirror M2. The resonator length L_r was changed in experiments by moving mirror M2 with the accuracy $\delta = \pm 10$ μm. The focal distance F_t of the lens was determined assuming that the instant of laser action quenching for each value L_r corresponds to the transition of resonator operation to the unstable region. The parameters of the laser with a thermally induced lens in its volume were calculated in the geometrical optics approximation by using the ray matrix method [18].

Figure 3 shows the time dependences of F_t obtained for both AEs pumped by 6-ms pulses. Taking into account the real distribution of the pump radiation intensity in the AE volume and that the characteristic dimension of the region of heat transfer $L_t \approx 2\sqrt{\chi\tau_p}$ for the time $\tau_p = 6$ ms is noticeably smaller than the radius of the pump beam on the AE surface, we can assume that deformations of the AE surface and the temperature distribution in its volume hardly could produce a perfect spherical lens and the values of F_t correspond to an efficient focal distance of a lens-like medium. The minimal value $F_t \approx 17$ cm for the AE made of the SELG glass proved to be almost three times smaller than that for the AE made of the LGS-DE glass ($F_t \approx 49$ cm).

3.2 Effect of thermal deformations of AEs on the parameters of the lowest resonator mode

The influence of thermal deformations of AEs on the parameters of the lowest mode of the resonator consisting

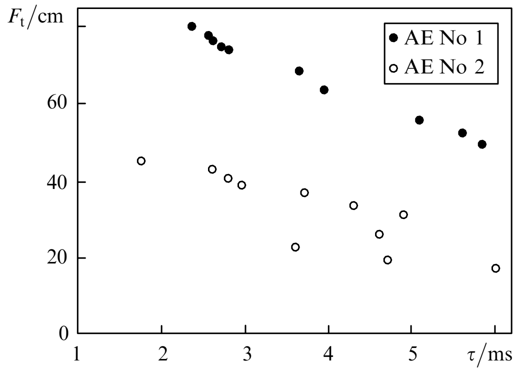

Figure 3. Time dependences of the focal distance F_t of a thermally induced lens for the pump pulse duration $\tau_p = 6$ ms for AE No 1 (LGS-DE glass) and AE No 2 (SELG glass).

of a spherical and cylindrical mirrors (see Fig. 1), was determined by calculating the change in the radii of the elliptical TEM$_{00}$ mode during the pump pulse of duration 6 ms. The calculations were performed for resonators with different distances L_r between mirrors by approximating the time dependences of F_t presented in Fig. 3. Figure 4 shows the radii $R0_x$ (Fig. 4a) and $R0_y$ (Fig. 4b) of the TEM$_{00}$ mode on the surface of mirror M1 calculated for the resonator with AE No 1 and Fig. 5 presented these radii calculated for the resonator with AE No 2. Because the AE was placed at a distance of 3 mm from mirror M1, the mode radii on this mirror weakly differ from those on the AE surface. Although, unlike the radius $R0_y$, which remains almost constant, the mode radius $R0_x$ considerably changes during the pump pulse, it is important to note that the values of L_r exist for the resonator of this type at which modes remain virtually invariable during the pump pulse even for AE No 2 where the effect of thermal deformations on lasing is more noticeable. This can be important for lasers whose parameters should be more stable.

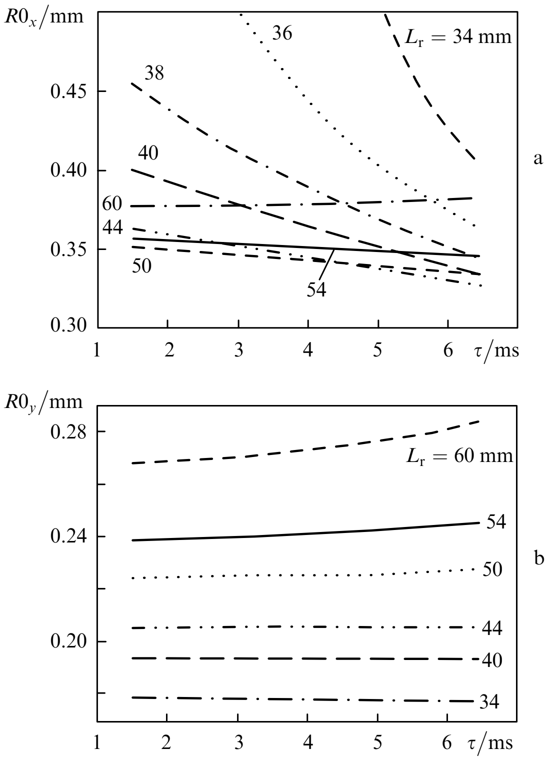

Figure 4. Radii of the lowest mode of the resonator $R0_x$ (a) and $R0_y$ (b) during the pump pulse of duration $\tau_p = 6$ ms for AE No 1 calculated for different lengths L_r of the resonator.

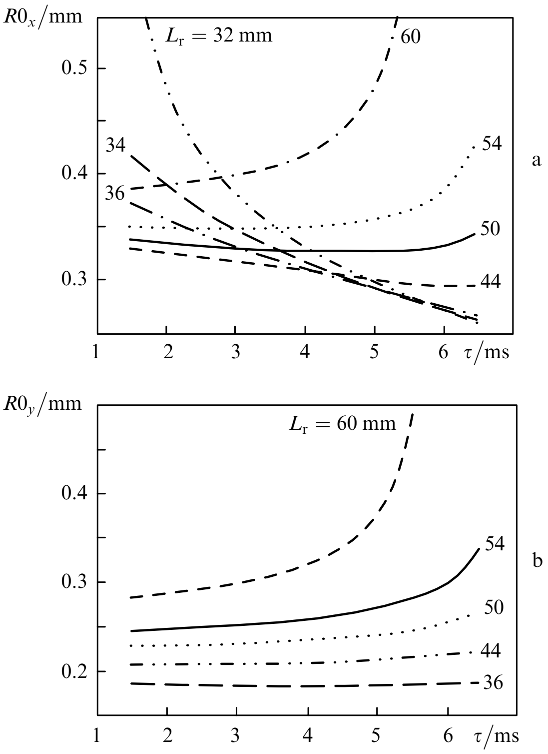

Figure 5. Radii of the lowest mode of the resonator $R0_x$ (a) and $R0_y$ (b) (b) during the pump pulse of duration $\tau_p = 6$ ms for AE No 2 calculated for different lengths L_r of the resonator.

3.3 Passive *Q* switching of the resonator

Passively *Q*-switched lasing was obtained for the resonator lengths L_r varied from 36 to 52 mm. The diameters of the laser beam in the resonator on mirror M1 in this regime were measured experimentally assuming that lasing occurs at the fundamental TEM$_{00}$ mode of the resonator. The laser radiation intensity distribution I_{LB} was recorded with a Pyrocam I pyroelectric camera for each value of L_r at three distances L (32, 52, and 74 cm) from the output mirror of the resonator. Figure 6 shows the typical shape of the laser beam cross section. The dependences of the intensity I_{LB} on the coordinate in the horizontal (x) and vertical (y) directions (Fig. 6) were well described in most cases by Gaussians. The dependence of the obtained mode radii on the distance L corresponded with good accuracy to the propagation law of Gaussian beams in a free space, which made it possible to determine the radii R_x and R_y of the radiation mode on resonator mirror M1.

Figure 7 presents the values of R_x and R_y on mirror M1 determined in this way for different lengths L_r of the resonator with AE No 1. Also, are presented the calculated radii $R0_x$ and $R0_y$ of the lowest TEM$_{00}$ mode on this mirror, which correspond to each specific instant of generation of a short pulse. For the direction along the axis of cylindrical mirror M2, the values of R_y and $R0_y$ virtually coincide, whereas for the direction perpendicular to the cylinder axis,

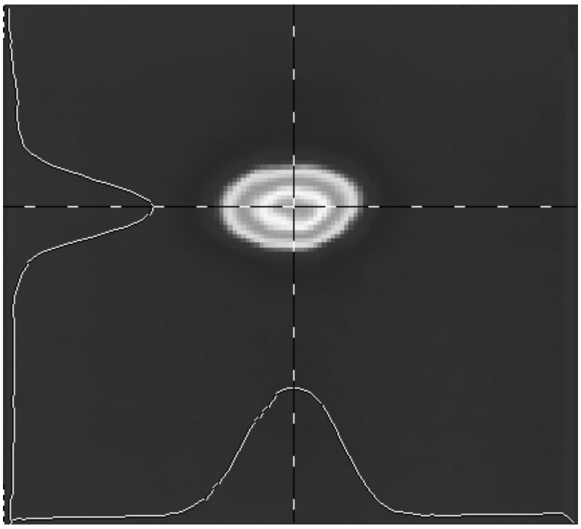

Figure 6. Distributions of the radiation intensity in the laser beam cross section in the Q-switching regime.

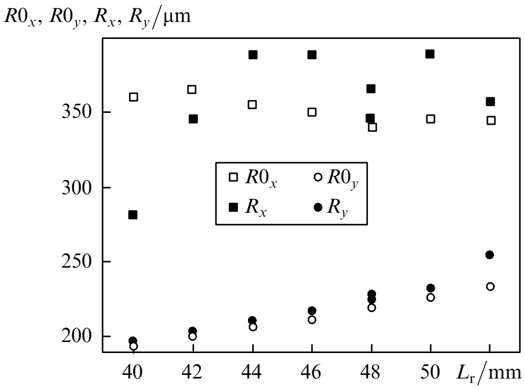

Figure 7. Calculated radii of the lowest mode of the resonator $R0_x$ and $R0_y$ and experimental radii of the radiation mode R_x and R_y on mirror M1 for different resonator lengths L_r.

the coincidence of R_x and $R0_x$ is not so good; however, it suggests that passively Q-switched lasing occurs at the lowest TEM$_{00}$ mode at least in the range $L_r = 42 - 52$ mm.

For the resonator with AE No 2, the situation is similar, although is should be noted that in this case the discrepancy between R_x and $R0_x$ is larger. This can be explained by the fact that radiation in the direction x is formed by the 'part' of the resonator that is noticeably more sensitive to the appearance of weak optical inhomogeneities of the active medium, which vary from pulse to pulse during the pump pulse. Because the radiation intensity distribution was recorded with a Pyrocam I camera by accumulating several radiation pulses to obtain the maximum contrast, a small change in the direction of the axis of the resonator probably resulted in a small increase in the laser spot in this direction. The estimates showed that a decrease in the spot size only by 1 % – 2 % for AE No 1 and by 2 % – 4% for AE No 2 resulted in a complete coincidence of R_x and $R0_x$.

A stable generation of short pulses in this resonator was achieved for the initial transmission of the Q switch $T_0 = 94\%$ and the reflection coefficient of mirror M2 $r \approx 89\,\%$. For AE No 1, pulses of energy $E_{QM} \approx 1.4$ mJ and duration $\tau_{em} \approx 26$ ns were obtained (Fig. 8); and for AE No 2, pulses of energy $E_{QM} \approx 1.25$ mJ and duration $\tau_{em} \approx 24$ ns were generated. In both cases, the resonator length L_r was ~ 50 mm. The optical lasing efficiency defined as $\eta_{opt} = E_{QM}/(P_p \alpha \tau_p)$, where α is the fraction of pump energy absorbed by the active element, was 1 % for both AEs. The use of the Q switch with $T_0 = 90\,\%$ resulted in the damage of the AR coating on one of the faces of the MALO crystal by each first laser pulse. The radiation intensity averaged over the laser spot on the face of the passive Q switch during lasing with the initial transmission $T_0 = 94\,\%$ was estimated as 500 MW cm^{-2}. The replacement of cylindrical mirror M2 by a plane mirror with the same reflection coefficient reduced E_{QM} under the same conditions almost by half.

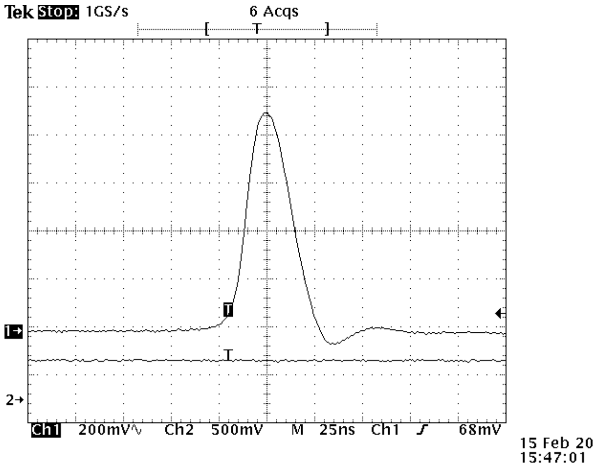

Figure 8. Output pulse shape in the Q-switching regime (AE No 1, $E_{QM} = 1.4$ mJ).

4. Conclusions

The design of the resonator used in this study provided the matching of the active-medium volume with the lowest resonator mode for the case when the cross section of the pump beam had almost an elliptical shape. Passively Q-switched lasing was obtained at the fundamental TEM$_{00}$ mode in the resonator with the elliptic cross section of the mode. The energy of output pulses generated in this regime was $E_{QM} \approx 1.4$ mJ, duration $\tau_{em} \approx 26$ ns, and power ~ 54 kW at a pulse repetition rate of 1 Hz.

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