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On the depolarisation of radiation of a transversely diode-laser-array-pumped Yb, Er-doped phosphate glass active element

L.V. Shachkin

Abstract. **Repetitively pulsed lasing in a Yb, Er-doped phosphate glass transversely pumped by a diode laser array is studied. Lasing on the lowest TEM_{00} resonator mode is obtained both in the quasi-continuous regime with an output power of 4.1 W and in the passive *Q*-switching regime (23-ns, 1.2-mJ pulses). The depolarisation of linearly polarised radiation of a He – Ne laser transmitted through the phosphate glass active element (AE) along the resonator axis is investigated. The dependences of depolarisation on the AE heating and experimental conditions are determined. It is shown that radiation losses caused by its depolarisation can present problems in the development of lasers emitting at 1.5 μm, in which polarisers should be used (for example, regenerative amplifiers).**

Keywords: *Yb, Er laser, phosphate glass, diode pumping, depolarisation.*

1. Introduction

Erbium lasers pumped by InGaAs diode lasers attract recent interest for a variety of applications, for example, in optical communication, location, remote sensing, and ophthalmology because the emission wavelength of these lasers ($\lambda \approx 1.5$ μm) is less hazardous for vision [1 – 8]. The use of diode lasers for pumping considerably reduces the heating of an active element (AE) compared to flashlamp pumping, provides an increase in the lasing efficiency and average output power, and makes the laser design more compact. However, lasing at ~ 1.5 μm in erbium lasers occurs in the three-level scheme, and various thermal effects caused by the heat release in the AE considerably restrict their output power [9, 10]. These effects are especially important upon longitudinal pumping, which is the most efficient in the case of miniature lasers with relatively low average output powers. As the laser power is increased, the efficiency of longitudinal pumping decreases because it is difficult to pump AEs of large volumes required at higher output powers, and longitudinal pumping results in a strong local heating of the AE, the appearance of a thermal lens, etc.

Transverse pumping is devoid of these disadvantages to a great extent, and in this case long AEs can be used. The main disadvantage of transverse pumping is the incomplete matching between the excited AE volume and the volume of laser modes, resulting in a lower lasing efficiency. Nevertheless, when high output powers are required, the transverse pumping becomes in fact the only pumping method both for generators and regenerative amplifiers of picosecond and femtosecond pulses [11].

One of the possible configurations of a transversely pumped AE is the grazing-incidence slab laser [12], when the laser mode is localised near the AE surface by using total internal reflection. The reflection of a laser beam from the AE surface in this configuration results in a considerable averaging of amplification during the propagation of radiation in a medium with the inhomogeneous distribution of the gain in the plane of incidence. Such a scheme was successfully used in Nd : YVO_4 [13, 14] and Er : YAG lasers [15, 16].

In this paper, the emission of a Yb, Er phosphate glass laser transversely pumped in the slab configuration is studied. Despite their low heat conduction and low thermomechanical damage threshold, phosphate glasses doped with Er^{3+} and Yb^{3+} ions are at present the best materials for erbium lasers emitting at ~ 1.5 μm and are one of the main candidates for using as AEs for regenerative amplification of picosecond and femtosecond pulses. For this purpose, the depolarisation of radiation upon AE heating and its dependence on experimental conditions is investigated.

2. Experimental results

2.1 Laser

Figure 1 presents the general scheme of a transversely pumped Yb, Er laser with the slab AE. The AE was pumped by a LIMO diode laser array (DLA) (Dortmund, Germany) emitting 6.8-ms, 30-W pulses at 972.5 nm. The diode laser array was mounted on a Peltier thermoelectric element, which maintained the temperature of the semiconductor and, hence, the emission wavelength λ_0 constant in different operation regimes of the DLA.

The shape and size of the LGS-XM phosphate glass AE with concentrations $[\mathrm{Yb}] = 2.2 \times 10^{21}$ cm^{-3} and $[\mathrm{Er}] = 1.56 \times 10^{19}$ cm^{-3} are shown in Fig. 1. The polished faces of the AE had no dielectric coatings. The angle between the resonator axis and normal to the end face of the AE was

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L.V. Shachkin State Research Center of Russian Federation ‘Troitsk Institute for Innovation and Fusion Research’, 142190 Troitsk, Moscow region, Russia; e-mail: tikhonov_vg@mail.ru

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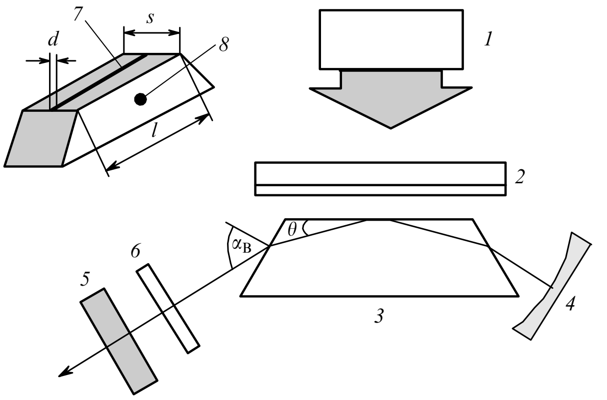

Figure 1. Scheme of the laser (at the left top: AE size and shape): (*1*) diode laser array; (*2*) cylindrical lens; (*3*) AE; (*4*, *5*) resonator mirrors; (*6*) $Co^{2+} : MgAl_2O_4$crystal; (*7*) position of the DLA radiation spot on the AE surface; (*8*) point at which the AE surface temperature is measured with a thermocouple; $d = 450$ μm is the spot width; l = 12 mm is the AE length; $s = 7$ mm is the AE width.

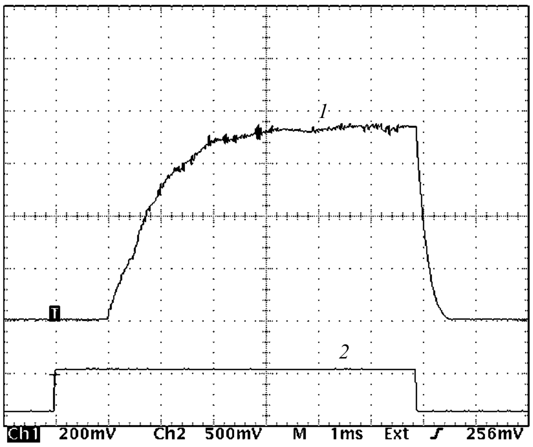

Figure 2. Oscillograms of the radiation pulse of the Yb, Er laser (*1*) and current pulse of the DLA power supply (*2*).

equal to the Brewster angle α_B. The active medium in the form of a thin layer ($d \approx 450$ μm at the $1/e^2$ level of the pump beam intensity) of length $l \approx 12$ mm was produced by two cylindrical lenses. The DLA power P_p incident on the AE face [(*7*) in Fig. 1] and absorbed in a glass, measured taking into account Fresnel reflection, was 24 W. The AE was mounted between two duralumin plates; the upper plate had a small hole for measuring the AE surface temperature. The AE was not cooled.

Two resonators, in which the distance between mirror (*4*) and the AE face along the resonator axis was 4 mm, were used in experiments. The first resonator consisted of spherical concave mirror (*4*) with the radius of curvature $R_4 = 79$ mm and reflection coefficient $r \approx 99.8$ % and plane mirror (*5*) with the reflection coefficient $r \approx 95$ % at 1536 nm.

For the DLA pulse repetition rate $F = 1$ Hz, the maximum output energy E_{out} in the free-running regime was obtained by using this resonator with the distance between mirrors $L_r \approx 30$ mm. In this case, multimode lasing was observed with $E_{\text{out}} = 25.4$ mJ. Figure 2 shows the shapes of the laser pulse and current pulse of the DLA power supply in this case. The optical efficiency η_o, defined as $E_{\text{out}}/P_p\tau_p$, was 15.6 %, the maximum slope efficiency η was 20.8 %, and the laser output power in the quasi-continuous regime was 5 W.

To improve the matching of the lowest resonator mode with the AE active medium volume, the second resonator, consisting of spherical and cylindrical mirrors, was used [17]. Mirror (*4*) is the same as that in the first resonator, mirror (*5*) is a cylindrical convex mirror with the radius of curvature $R_5 = -39$ mm and the reflection coefficient $r \approx$ 89 % at the laser wavelength. The axis of cylindrical mirror (*5*) is directed perpendicular to the figure plane. The cross section of the lowest TEM_{00} mode in this resonator had the shape of an ellipse and could be matched with the active medium volume by selecting properly the radius of curvature of resonator mirrors and varying the distance between them. In this case, stable single-mode lasing was obtained at the lowest resonator mode with the pulse energy $E_{\text{out}} =$ 18.4 mJ, the slope efficiency $\eta \approx 17.1$ %, and 4.1-W output power in the quasi-continuous regime. Note that these results were obtained without optimisation of the reflection coefficient of the cylindrical mirror in the second resonator.

Lasing in the passive Q-switching regime was obtained by using $Co^{2+} : MgAl_2O_4$ (MALO) crystals [18, 19]. A dielectric coating deposited on each of the working faces of crystals reduced reflection losses at 1.54 μm down to fractions of percent. Although the concentration of erbium ions in our AE was far from optimal, stable 23-ns, 1.2-mJ pulses were obtained in the second resonator when the initial transmission of the Q switch was $T_0 = 94$ %. The radiation intensity distribution over the beam cross section was recorded with a Pyrocam I pyroelectric camera at several distances from the output mirror of the resonator. Figure 3 demonstrates the typical shape of the laser beam cross section under these conditions. The measurements showed that lasing occurred on the lowest TEM_{00} resonator mode and were used to determine the mode size $a \times b$ on mirror (*4*) (the method is described in detail in [17]). The mode cross section had the shape of an ellipse with the major axis diameter $a \approx 1.15$ mm (in the plane of incidence) and the minor axis diameter $b \approx 0.37$ mm at the $1/e^2$ intensity level.

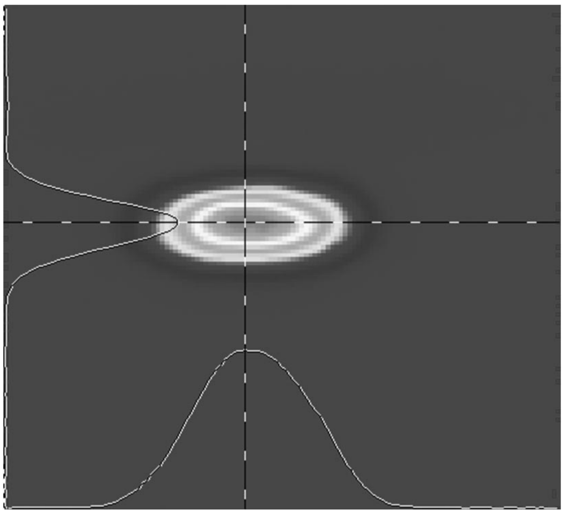

Figure 3. Distribution of the radiation intensity in the laser beam cross section in the Q-switching regime.

All the results presented above were obtained for the pulse repetition rate $F = 1$ Hz, at which no negative effects of AE heating were observed. However, the influence of thermal deformations of the AE on lasing became noticeable already for $F = 2$ Hz and drastically increased with increasing the pulse repetition rate. This is illustrated in Fig. 4 by the time dependences of the average output power in the free-running regime (when the first resonator was used) for different values of F. For $F = 12.5$ Hz, the average power P_{out} decreased from 300 mW to zero for the time $t \sim 1$ min. For the AE of this form, this effect can be explained by an increase in the resonator losses caused by the depolarisation of laser radiation due to AE heating.

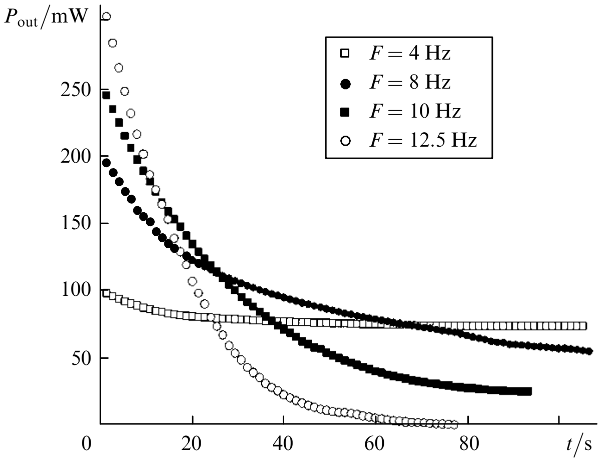

Figure 4. Time dependences of the average radiation power in the free-running regime (the first resonator) for different pulse repetition rates F.

2.2 Depolarisation of radiation

The negative influence of radiation depolarisation produced by the AE heating on the lasing efficiency was studied on the setup assembled for measuring the degree of polarisation of the linearly polarised (in the plane of incidence) radiation of a He–Ne laser transmitted through the AE along the resonator axis (Fig. 5). The cw radiation from a Uniphase, model 1125P He–Ne laser (USA) propagated through a slit in a screen, the AE, and a polariser and was focused by a short-focus lens on a PD-10G-A germanium photodiode. The dynamic range of the detector in the linear region of its sensitivity was no less than 10^4 and provided a linear dependence of the output signal on the incident radiation power varied in the region no less than 5×10^3. The polarisation of the probe radiation of a He–Ne laser was measured; in the absence of pumping, the ratio of powers of radiation with p- and s-polarisations was $\sim 2000:1$ (the photodiode signal was ~ 5 V for p-polarisation and did not exceed 2 mV for s-polarisation for two orthogonal directions of the principal polarisation plane). Filter (*8*) excluded the influence of the AE luminescence on the results of measurements.

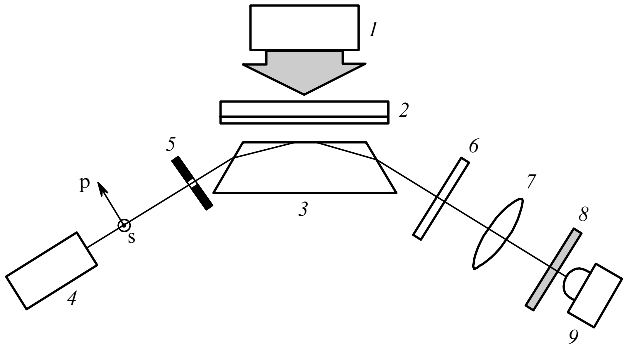

Figure 5. Scheme of the experimental setup for studying radiation depolarisation: (*1*) diode laser array; (*2*) cylindrical lens; (*3*) active element; (*4*) He–Ne laser; (*5*) aperture; (*6*) polariser; (*7*) lens; (*8*) filter; (*9*) photodiode; p and s are polarisation directions.

Measurements were performed by using three apertures of different shapes: two rectangular apertures of size 0.23×1.1 and 0.4×1.1 mm and a circular aperture of diameter 1 mm. In the case of rectangular apertures, the direction along the slit length was parallel to the plane of incidence. Each of the apertures could be displaced with respect to the resonator axis in the direction perpendicular to the plane of incidence. The output signal of the photodiode being measured was proportional to the s-polarised radiation power of the He–Ne laser.

The typical oscillogram of the photodiode signal during the pump pulse is shown in Fig. 6. Figure 7 presents oscillograms of signals detected after the establishment of the stationary regime.

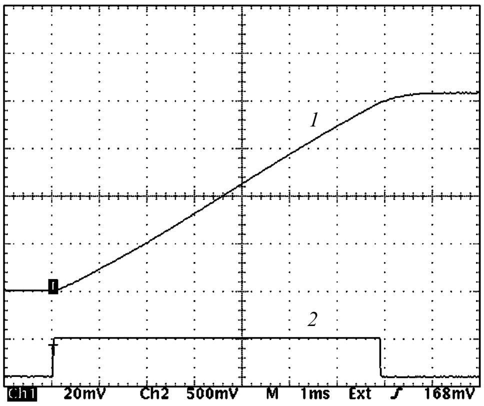

Figure 6. Oscillograms of the photodiode signal (*1*) and current pulse of the DLA power supply (*2*) during the pump pulse.

The degree α of radiation polarisation is defined by the expression

$$\alpha = \left| \frac{I_{\text{p}} - I_{\text{s}}}{I_{\text{p}} + I_{\text{s}}} \right|,$$

where I_{p} and I_{s} are the powers of p- and s-polarised radiations. The degree of polarisation of radiation propagated though the AE was measured from this expression, where $I_{\text{s}} = \Delta_{\text{s}}$ is the maximum power of s-polarised radiation (taking into account reflection losses on the AE face) (Fig. 7); $I_{\text{p}} + I_{\text{s}} = I_{0\text{p}}$ is the He–Ne laser power incident on the input face of the AE. However, it is more convenient for clarity to describe the fraction of radiation depolarised during the pump pulse by the ratio $\xi(t) = [\delta_{\text{s}}(t)/I_{0\text{p}}] \times 100\,\%$ (see Figs 7 and 8). Figure 8

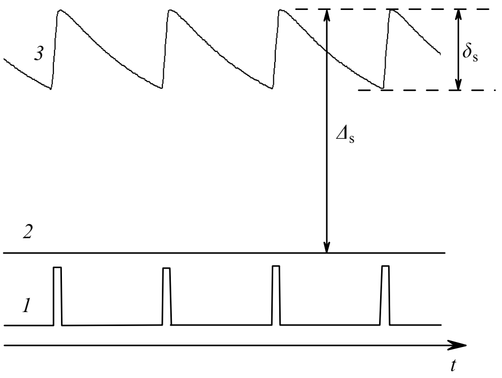

Figure 7. Oscillograms of detected signals in the stationary regime: (*1*) current pulses of the DLA power supply; (*2*) photodiode signal in the absence of pumping; (*3*) photodiode signal upon repetitively pulsed pumping of the AE.

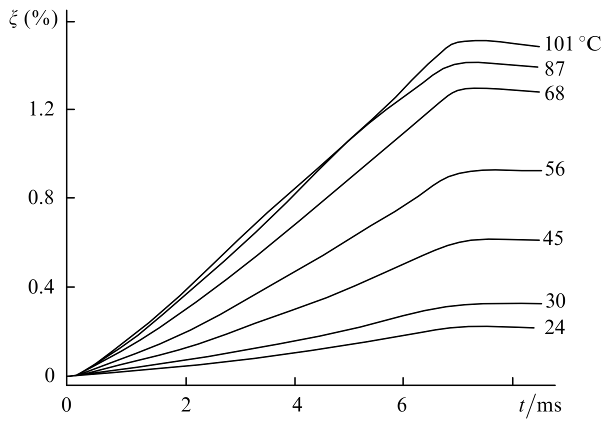

Figure 8. Changes in the fraction of radiation $\xi(t)$ depolarised during the pump pulse for different DLA pulse repetition rates in the stationary regime. The aperture size is 0.4×1.1 mm; numbers at the curves are stationary temperatures measured at point (*8*) on the AE side surface (Fig. 1).

shows the change in $\xi(t)$ during the pump pulse for different pulse repetition rates of the LDA in the stationary regime. Dependences of the degree of polarisation α of probe radiation propagated through the AE on the pulse repetition rate F and aperture size are presented in Fig. 9.

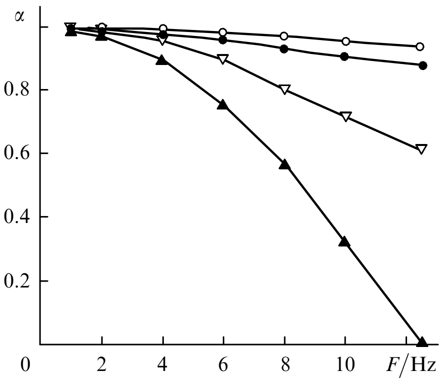

Figure 9. Dependences of the degree α of polarisation of radiation propagated through the AE on the pulse repetition rate F for apertures of size 0.23×1.1 mm (○), 0.4×1.1 mm (●), ∅1 mm (▽) (probe beam passes through the middle of the active layer), and 0.23×1.1 mm (▲) (probe beam is displaced by 0.7 mm in the direction perpendicular to the plane of incidence).

3. Discussion

The influence of thermally-induced deformations of the AE on lasing is well studied for active elements in the form of a cylindrical rod or a thin plate when the pump radiation is uniformly pumped in the AE volume [20, 21]. In the case of nonuniform absorption, the situation is considerably complicated. A thermal lens produced upon one-sided transverse pumping of a $Nd:YVO_4$ laser by diode lasers was analysed in paper [22], where a numerical model was proposed for determining the three-dimensional temperature distribution in an AE and variations in the refractive index caused by temperature changes and photoelastic processes were estimated. For a thin plate cut from a uniaxial YVO_4 crystal with a high intrinsic anisotropy, the contribution of the photoelastic component proved to be negligible compared to temperature variations in the refractive index.

It is well known [20, 21] that the inhomogeneity of thermally-induced anisotropy in thin AE plates is manifested only in the coordinate dependence of the phase shift between the intrinsic polarisations of the AE, whereas the orientations of the principal axes are invariable over the entire AE cross section coinciding with the orientations of the principal stresses in the AE. The situation does not change upon uniform pumping of the volume of such an AE in the slab configuration when the angle θ between the resonator axis and the plane through which the AE is pumped (see Fig. 1) is nonzero, if the polarisation of radiation is linear and its vector lies in one of the principal planes. But a considerable depolarisation of radiation observed in our experiment suggests that stresses are oriented in the AE volume in a much more complicated way. In regimes when the AE was heated most strongly, the probe beam from a He–Ne laser even split after passing through the AE into two beams of different intensities, propagating at a small angle ($\sim 10^{-2}$ rad) to each other. Taking into account that the phase difference for the two orthogonal polarisations acquired during the propagation of radiation in an anisotropic medium is inversely proportional to the wavelength, we can assume the fraction of radiation at 1.5 μm depolarised after propagation through the AE will be smaller, but it is difficult to estimate α quantitatively due to a complicated picture of the orientation of stresses.

The influence of a thermally-induced lens in the AE on a decrease in the average output power P_{out} with increasing F (see Fig. 4) was studied by measuring the focal distances f_p and f_s of this lens in two orthogonal planes parallel to the directions of p- and s-polarisations. These focal distances were assumed equal to the distance from the AE to the point where the He–Ne laser-beam cross section in these planes was minimal. Measurements showed that $f_p \approx 16$ cm and $f_s \approx 11.5$ cm for $F = 12.5$ Hz. The calculations of the parameters of a resonator with a thermally-induced lens inside it, performed in the geometrical approximation by using the ray matrix method [22], showed that the presence of ideal lenses with such values of f_p and f_s inside the first resonator not only cannot quench lasing but even should not affect noticeably its parameters. The time dependence of the average output power P_{out} cannot be also explained by the deviation of the resonator axis from its optimal position caused by optical inhomogeneities in the AE because the attempts to find new positions of mirrors that would be more favourable for lasing have failed.

The shapes of absorption and luminescence lines and their position depend on temperature, but taking into account large absorption and gain linewidths in the Yb, Er-doped phosphate glass, these dependences should not considerably affect laser radiation parameters.

4. Conclusions

The experimental results obtained in the study show that the slab configuration of AEs can be successfully used in Yb, Er phosphate glass lasers transversely pumped by a diode laser array. For a resonator with the elliptic cross section of the mode, lasing on the lowest TEM_{00} mode were obtained both in the quasi-continuous regime with an output power of 4.1 W and upon passive Q-switching when 1.2-mJ, 23-ns, 52-kW pulses were emitted. The experimental study of the depolarisation of linearly polarised radiation from a He–Ne laser propagated through the AE along the resonator axis has shown that depolarisation losses are considerable and can present a challenge to the development of radiation sources emitting at 1.5 μm, in which polarisers should be used (for example, regenerative amplifiers).

The reduction of the AE length down to 1 mm will provide the efficient heat removal, thereby considerably lowering the AE temperature, and can probably ensure a more favourable orientation of stresses in the AE from the point of view of depolarisation losses of laser radiation. However, temperature gradients can be comparable with those observed in the AE studied in the paper. Therefore, the question of how the degree of radiation depolarisation will change in this case requires the additional study and can be obtained in further experiments.

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