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Transversely diode-pumped passively *Q*-switched erbium glass laser emitter

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***Abstract*.** **The properties of a laser diode array-pumped passively *Q*-switched ytterbium-erbium glass laser emitter are studied. It is found experimentally that the maximum output energy is achieved when the diameter of the TEM$_{00}$ mode is 0.65 – 0.77 of the transverse size of the active element. By using two 100-W linear laser diode arrays with the output power not exceeding 70 % of the maximum power, 5 mJ was achieved in a 50-ns diffraction-limited single pulse for the efficiency (with respect to the pump radiation energy) of 1.35 %.**

Keywords: *ytterbium-erbium glass, linear laser diode array, diode pumping, lowest transverse mode, passive mode locking, laser ranging.*

1. Introduction

The use of pulsed diode pumping of ytterbium-erbium glass lasers in portable laser radars emitting at the eye-safe wavelength of 1.54 μm makes it possible to employ in full measure the advantages of such pumping and the possibilities of the active medium [1, 2]. Indeed, the absorption band of ytterbium ions can be used for efficient pumping by radiation from linear laser diode arrays (LDAs) at 940 nm at +20 °C. In this case, no special measures for the thermal stabilisation of LDAs should be taken in the regime of generation of single pulses in the temperature range of the environment from −40 °C to +50 °C. Due to the long excited-state time of erbium in glass (~ 8 ms), the sufficient population inversion can be achieved by using the minimal number of LDAs, providing thereby a low cost of the emitter. Thus, by using only one 100-W LDA and a frustrated total internal reflection gate based on a ∅2 × 10 mm active element (AE) the authors of paper [3] obtained 30-ns, 7.5-mJ pulses. However, the operation of LDAs at limiting powers causes their gradual degradation [4].

To simplify the emitter design and the system providing its operation, passive laser *Q* switches are widely employed in recent years [2, 5, 6]. The longitudinal pumping of AEs, which is promising for achieving the maximum lasing efficiency (4.2 % with respect to the absorbed energy or 3.3 % relative to the energy emitted by diodes) was considered in [2]. However, the necessity of using spectrally selective (dichroic) mirrors reduces the service life of the emitter due to the absence of reliable technologies for the deposition of laser radiation-resistant selective coatings. By using the transverse pumping of a ∅2.5 × 65-mm AE by thirty 25-W LDAs, the authors of [5] obtained 9.7 mJ of output energy in the TEM$_{00}$ mode. A very great number of LDAs and a low efficiency (~ 0.3 %) make this variant of the emitter unattractive for practical applications. The attempt to reduce the number of LDAs leads to a drastic decrease in the output energy. Thus, by pumping a 1.7× 1.7 × 10-mm AE by two LDAs, the authors of paper [6] obtained 10-ns, 0.5-mJ pulses with the lasing efficiency of 0.23 %.

The aim of this paper is to increase the output pulse energy by optimising the pump scheme and resonator parameters by using the minimum number of LDAs. The methods for optimising the efficiency of flashlamp-pumped low-threshold passively *Q*-switched erbium glass lasers were studied previously in paper [7]. The optimisation was performed by varying the degree of filling the AE aperture by the lowest transverse mode field. The output energy achieved in emitters of diameter from 1.7 to 2.5 mm was from 6.5 to 11.5 mJ. The maximum lasing efficiency was achieved for the same degree of filling the AE (the mode radius ω was approximately 0.6 of the AE radius). The output pulse energy achieved in the emitter with the AE of diameter 2 mm was ~ 8 mJ, which corresponds at $\lambda = 1.54$ μm to the maximum eye-safe energy level.

2. Experimental results

Compared to flashlamp pumping, when the pump radiation is concentrated at the AE centre by an illumination system and the AE can be excited uniformly over its cross section, upon the transverse diode pumping the situation is different. The radiation pattern of LDAs has a large angular divergence (~ 40°) and nonuniformity. As a result, the distribution of the absorbed power over the AE cross section is also nonuniform. As the pump radiation propagates from the side surface inside the AE, the pump power density decreases due to absorption and divergence. The pump efficiency depends on the absorption coefficient of

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the active medium, the AE geometry, and the separation between the AE and LDA.

Pumping was performed by two 100-W LDAs of length 10 mm emitting at 940 nm at +20 °C. The operating current of LDAs was restricted by the value 100 A, the total output radiation power being 120 – 140 W depending on the pump cycle duration. The radiation divergence in the plane perpendicular to the LDA achieved 30° at the half maximum of a nearly Gaussian angular radiation distribution.

The active medium was an ytterbium-erbium glass synthesised at the Institute of Radio Engineering and Electronics, RAS (Fryazino). The concentration of activator ions was 3×10^{19} cm^{-3} for Er^{3+} and 1.8×10^{21} cm^{-3} for Yb^{3+}. The absorption coefficient at a wavelength of 940 nm was 4.5 ± 0.5 cm^{-1}. A 2-mm-thick sample of such a glass absorbs only $\sim 60\,\%$ of the pump power, while a 3-mm-thick sample absorbs $\sim 75\,\%$ of the pump power. In the case of samples with a square cross section, the absorbed power density averaged over the volume will be 1.8 times higher in the first case than in the second one. These factors should be taken into account in the choice of the AE geometry. Note that the pump power fraction absorbed by a thin AE layer can be increased by returning the unabsorbed part to the AE volume with the help of a reflecting coating deposited on the AE surface opposite to the LDA.

We fabricated two AEs with rectangular cross sections of sizes $1.5 \times 1.7 \times 20$ mm (long AE1) and $2 \times 2.2 \times 10$ mm (short AE2) without AR coating on their faces. Pumping was performed through wide faces, normally to the side surface. The short AE was pumped by LDAs located oppositely to each other at equal distances from the AE side faces to provide the symmetric pump radiation distribution over the AE cross section. The long AE was pumped by using a similar geometry, but LDAs were separated by the AE length and the opposite AE faces were covered by a BGO-1 hermetic layer serving as a retroreflecting mirror. The size of the pump region and the distribution of the absorbed power could be changed by varying the distance Δ from LDAs to the AE surface.

Figure 1 presents the computer-simulated maps of the volume power density distribution of the absorbed pump radiation over the cross section of the short AE for counter located LDAs. The calculation was performed taking into account the refraction of the LDA radiation at the AE input, its absorption and Fresnel reflection from the input face. The LDA power was set equal to 65 W. Absorption was calculated by using the Lambert – Bouguer law. One can see that, when the LDA is placed directly against the AE ($\Delta = 0.1$ mm), a long and narrow pump region (2×0.8 mm) is produced in it, the greatest part of the AE volume remaining unexcited. As Δ is increased up to 0.8 mm, the pump region broadens up to 1.35 mm. A further increase in Δ leads to almost entire filling of the AE aperture with radiation. However, the expansion of the pump region is accompanied by a strong decrease in the power density. The increase in Δ from 0.1 to 1.5 mm reduces the power density at the AE centre almost by a factor of three. It is reasonable to assume that there exists the optimal distance between the LDA and AE that provides the maximum output power and efficiency. Indeed, the expansion of the pump region allows one to increase the output pulse energy; however, to compensate for a decrease in the pump level, it is necessary to increase either the pump pulse power or its duration. One of the methods for increasing the pulse energy and the efficiency of an erbium glass emitter is the optimisation of the AE filling by radiation of the lowest transverse mode [7]. In this connection the main goal of our paper was to match the pump region in the AE with the size of the lowest transverse resonator mode.

The size of the lowest transverse mode in the AE was specified by the geometry of a stable resonator of length 185 mm, which consisted of the plane output mirror with the transmission coefficient $\tau = 14\,\%$ and a concave spherical highly reflecting mirror whose radius of curvature was optimised. The passive Q-switching of the resonator was performed by using a Co^{2+}:LaMgAl$_{11}$O$_{19}$ crystal mounted near the output mirror. When the electric field vector of a light wave was parallel to the crystal axis c, the initial transmission of the crystal at the laser wavelength was 88 %. The radiation with this polarisation was selected by using a Brewster plate in the optical scheme of the emitter. The transmission coefficients of the output mirror and the Q switch were the same for AE1 and AE2 and were chosen by using the results obtained in [7]. The pump energy was changed by varying the duration of the injection current through LDAs connected in series and its spatial distribution was controlled by varying the distance Δ between the AE and LDAs. For each calculated mode radius ω and the selected value of Δ, the output pulse energy E and the minimal pump pulse energy $E_{\rm p}$ required for lasing were determined experimentally.

Figure 2 shows the dependences of the output energy E

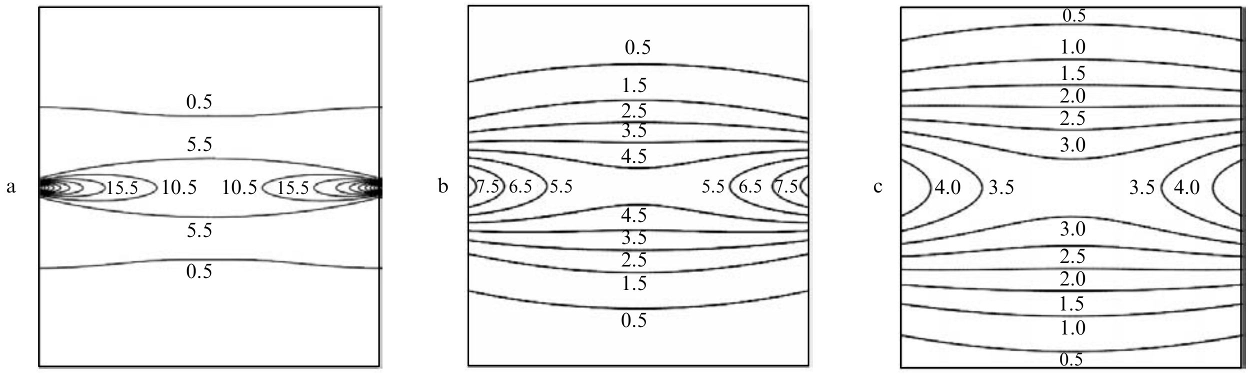

Figure 1. Distribution maps of the absorbed pump power density (in kW cm^{-3}) over the AE cross section for the distance to the LDA $\Delta = 0.1$ mm (the power density at the AE centre is $I = 9.280$ kW cm^{-3}) (a), $\Delta = 0.8$ mm ($I = 4.742$ kW cm^{-3}) (b), and $\Delta = 1.5$ mm ($I = 3.185$ kW cm^{-3}) (c).

and pump pulse energy E_p on Δ for AE1. The numerical parameter of the curves is the mode radius ω in the AE. For a fixed mode size, the output pulse energy E increases with increasing Δ, this dependence tending to saturate. The increase in E is accompanied by the increase in the required pump pulse energy E_p. The larger the mode size, the larger the pump energy required to generate the output pulse for the same Δ. The dependence $E(\omega)$ is more complicated.

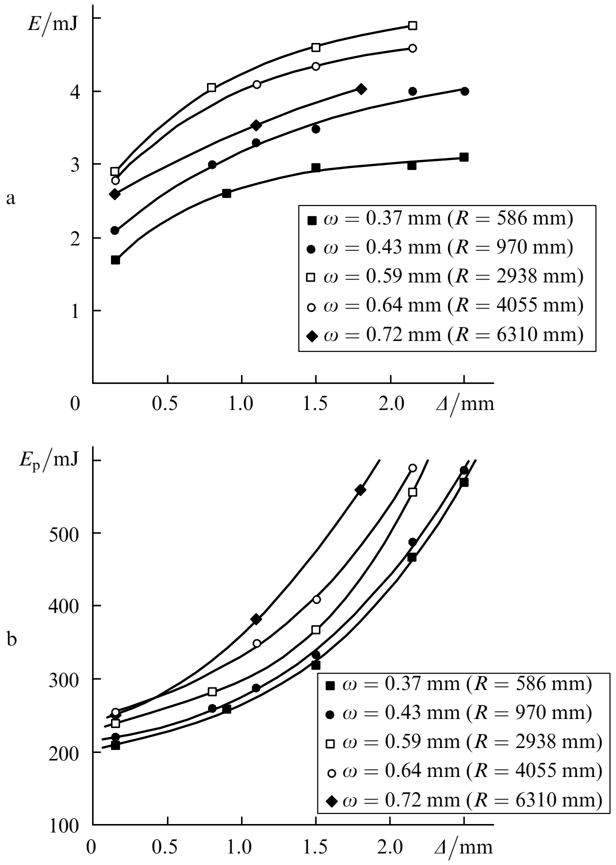

Figure 2. Dependences of the output energy E (a) and pump pulse energy E_p (b) on the distance for different mode radii ω for AE1; in the parentheses is given the radius of curvature R of the highly reflecting resonator mirror.

The dependences of E on ω for different values of Δ for AE1 presented in Fig. 3 show that the output pulse energy is maximal for $\omega \approx 0.58$ mm (the filling factor is 0.77) irrespective of the value of Δ. We can assume that the optimal filling of the AE aperture by the fundamental transverse mode also exists for AEs of different geometry, the filling factor being virtually independent of the spatial pump radiation distribution and dependent mainly on the diffraction loss at the AE aperture. As for the output pulse energy, it considerably depends on the size of the pump region, which is directly related to Δ. For the high enough pump level, the larger the pump region size in the AE, the higher the output pulse energy. For the optimal size of the mode in AE1, the increase in Δ from 0.1 to 2 mm resulted in the increase in the energy E from 2.8 to 4.8 mJ, which was accompanied by the increase in E_p from 240 to 490 mJ.

The conditions for generating the output pulse of the maximum energy do not coincide with conditions required for obtaining the maximum lasing efficiency. The dependences of the laser efficiency (with respect to the pump energy) on the distance Δ between the LDA and AE in Fig. 4 show that for each fixed value of ω the optimal value of Δ exists which corresponds to the maximum efficiency. Note that in this case the output pulse energy is noticeably lower than its maximum value for the same radius ω. The maximum efficiency of the emitter for the optimal filling (0.77) of the AE1 aperture by the fundamental transverse mode field was achieved for $\Delta \approx 0.6 - 0.8$ mm, whereas the maximum energy of the output pulse was obtained for $\Delta \approx$ 2 mm. Figure 5 (dark squares) presents the summary characteristic of the emitter with AE1, which was plotted by using the best combinations of ω and Δ realised in our experiments. The maximum efficiency (1.42 %) corresponds to $E = 4$ mJ, whereas the maximum output pulse energy (4.8 mJ) is achieved for the efficiency equal only to 0.96 %.

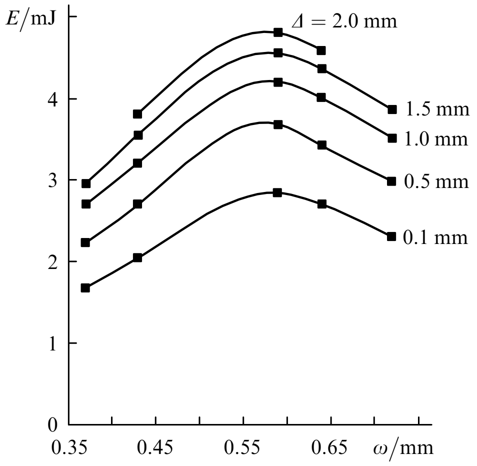

Figure 3. Dependences of the output energy E on the mode radius ω for different distances Δ for AE1.

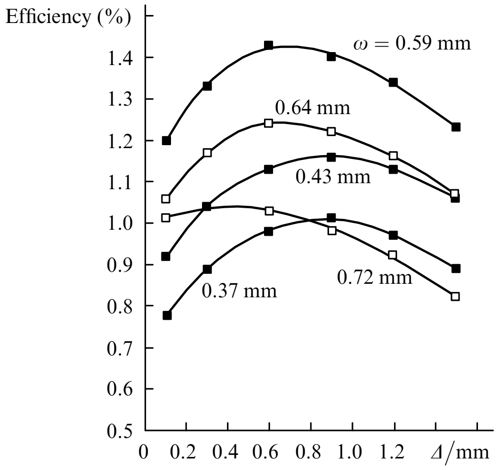

Figure 4. Dependences of the lasing efficiency on the distance Δ for different mode radii for AE1.

The results obtained with AE2 qualitatively agree with the data presented above for AE1. The main difference is that the optimal radius ω of the mode for AE2 was 0.65 mm (the filling factor was 0.65). The similar summary characteristic for AE2 is shown by open squares in Fig. 5. The maximum efficiency (1.4 %) was achieved for $E = 4.7$ mJ,

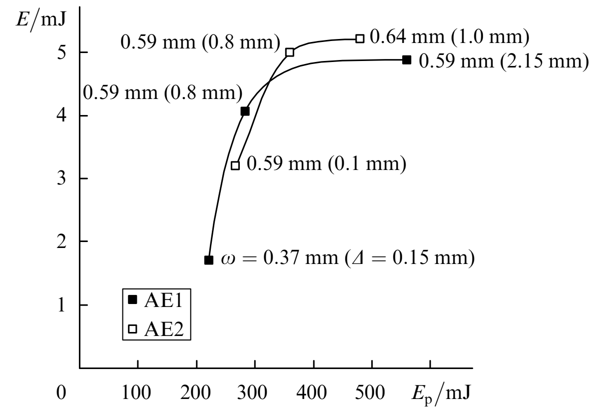

Figure 5. Dependences of the output energy E on the pump energy E_p for the best combinations of the mode radius and distance Δ.

while the maximum output pulse energy (5.2 mJ) corresponded to the efficiency equal to 1.2 %. Some quantitative difference between the results obtained for AE1 and AE2 can be explained by their different geometries and slightly different pump conditions (see above).

The full width at half-maximum of the output pulse in all our experiments with AE1 and AE2 was 50 ns and the divergence of the output radiation was nearly diffraction-limited ($M^2 < 1.5$).

3. Conclusions

By using in experiments two LDAs operating at moderate currents, we have obtained the results of interest for a number of applications. Thus, diffraction-limited single 50-ns, 5-mJ pulses emitted with the efficiency ~ 1.35 % can be used for safe laser ranging.

The experiments performed in our study allow us to formulate some general conclusions, which can be useful for the development of transversely diode-pumped passively Q-switched erbium glass emitters:

(i) To increase the output pulse energy and the emitter efficiency, it is necessary to try to obtain the optimal filling of the AE by the lowest transverse mode field, up to the filling coefficient of the AE aperture 0.6–0.8, and to select the optimal distance between the LDA and AE.

(ii) To increase the output pulse energy by neglecting the lasing efficiency (when the pump level is high enough), it is necessary to excite the entire volume of the active medium.

It is also possible to attempt to optimise the transmission coefficients of the output mirror and passive Q-switch.

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