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On the possibility of increasing the pulse energy of a passively *Q*-switched erbium glass minilaser

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***Abstract*. A simple method to increase the output energy of a passively *Q*-switched erbium glass laser is proposed. Using the amplitude modulation of losses at the active element face, the fundamental mode was reliably suppressed and the laser operated in a selected higher-order mode. The output energy was experimentally increased by a factor of 2.1, and the range of allowable pump energy instability was extended threefold.**

Keywords: *erbium glass laser; passive Q-switch; TEM*$_{01}$*, TEM*$_{02}$*, and TEM*$_{04}$ *modes.*

1. Introduction

The progress achieved recently in the development of passive *Q*-switches for IR region [1 – 5] allows one to create compact, lightweight, reliable, and inexpensive passively *Q*-switched erbium glass lasers. All this contributes to widening the use of such lasers in devices for target designation, pulsed range finding, metrology, lidar measurements, and communication [6 – 8].

However, in practice the passively *Q*-switched erbium lasers are designed only as TEM$_{00}$ lasers. Due to the small gain cross section and a three-level lasing scheme of erbium, the reflectance of their output mirror is close to 85 %. Today, because of high field densities in the cavities with such mirrors, the output energy of passively *Q*-switched erbium lasers is limited by the radiation resistance of the coatings of optical elements and does not exceed 3 – 5 mJ, which is insufficient for long-range finders. In this work, we propose a method to increase the output energy of a passively *Q*-switched erbium laser.

It is known that the active *Q*-switching (using a rotating prism or a *Q*-switch based of a frustrated total internal reflection prism) allows one to easily obtain multimode radiation with a pulse energy up to 20 mJ and a duration of 30 – 40 ns. In the case of a saturable absorber, the mode composition of radiation is sharply restricted. The TEM$_{00}$ mode is generated when the pump energy slightly exceeds the laser threshold. As the pump energy increases, other low-order modes (TEM$_{01}$ and TEM$_{02}$) begin to appear in addition to the TEM$_{00}$ mode. Due to the nonuniform pumping of the active element (AE) and different Fresnel losses for these modes, the times of their development are also different, which leads to an increase in the laser pulse duration and to pulse splitting [9]. The mode composition strongly depends on the mirror misalignment, temperature, and pump pulse instability. A further increase in the pump energy under particular conditions can cause the appearance of a second pulse delayed by several microseconds.

As was shown in some works [10, 11], a saturable absorber in a cavity is similar to a dynamic spatial filter. Therefore, it causes splitting and broadening of pulses even in neodymium lasers [11], although the neodymium gain cross section is an order of magnitude higher than in erbium glass lasers. In the case of passively *Q*-switched neodymium lasers, this problem is overcome by increasing the AE diameter and obtaining the maximum number of generated modes. For erbium lasers, this approach is inapplicable because it leads to a too high pump threshold.

It was shown in [12] that, since the entropy of any single high-order mode is equal to the entropy of the fundamental TEM$_{00}$ mode, it is thermodynamically possible to transform a pure mode of any order into a Gaussian beam. Therefore, the problem was initially reduced to lasing of a single higher-order mode. Since such a mode occupies a larger volume in the AE than the TEM$_{00}$ mode, the pulse energy also should be higher. To eliminate the possibility of development of the TEM$_{00}$ mode, it is necessary to take steps to discriminate it.

In [13], the TEM$_{00}$ mode was discriminated by introducing into the cavity a binary phase element (BPE) comprising a glass plate with radial sectors formed by etching. The number of sectors corresponded to the chosen transverse mode (i.e., two sectors for TEM$_{01}$, four sectors for TEM$_{02}$, and eight sectors for TEM$_{04}$). The thicknesses of neighbouring sectors differed by a value needed to obtain a π phase shift at a wavelength of 1535 nm. This element causes an azimuthal discrimination of intracavity modes. The experimental ratio of the TEM$_{00}$, TEM$_{01}$, TEM$_{02}$, and TEM$_{04}$ modes was 1 : 1.14 : 1.6 : 2.19. The increase achieved in the output power was 15 % smaller than was predicted by calculations according to the model proposed in that work. The authors of [13] suggested that the difference between the experimental and calculated results is mainly caused by additional losses introduced into the cavity by the BPE.

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The method proposed in [13] implies fabrication of a rather complicated optical device. The introduction of an additional element into the cavity with a low-gain active medium requires careful alignment and imposes additional requirements on the mechanical stability of the pump cavity design.

In the present work, we study the radial discrimination of low-order modes with the help of an amplitude (scattering, absorption) mask (AM). This method of discrimination of transverse modes has been known for a long time [14, 15] and allows one to improve the characteristics of a light beam corresponding to a selected TEM_{mn} mode. Using nonuniform energy extraction through one of the higher-mode segments, it is possible to obtain a high-quality light beam with an equiphase front and a smooth amplitude distribution, whose quality is comparable to the quality of the lowest-order Gaussian mode beam [16]. However, such coupling out of radiation is impossible for erbium lasers due to a limited radiation resistance of the coatings of intracavity optical elements. In addition, it is possible to coherently sum the mode segments out of the cavity and obtain a near-Gaussian beam using an interference [17] or spiral [18] phase element.

The results of calculations and experiments on the selection of pure transverse modes in a helium – neon laser using amplitude and phase-shift masks (PMs) are published in [19]. The masks of both types were made in the form of circular strips with different widths deposited on the laser mirrors in the regions of the nodal lines of the selected mode. To obtain phase modulation, the reflectance of these mirrors was uniform over the entire surface, while the reflection phase on the strips was shifted by π with respect to the reflection phase on the other part of the mirror surface. In the case of PMs, the light wave incident on the strips is not absorbed but reflected in antiphase and interferes with the wave reflected form the main part of the mirror, which twofold increases the degree of mode discrimination compared to AMs. Both the calculation and experimental results of [19] show that AMs introduce smaller inactive losses (including losses for a selected mode) than PMs. We expected that the losses for a high-order mode of an erbium laser with the use of an AM will be smaller than with the use of a binary phase element [13], which will lead to a further increase in the output energy. Our experiments were performed in order to clarify the possibility of increasing the output power, as well as to study the stability of energy, transverse mode geometry, and duration of generated pulses, i.e., to understand whether the degree of mode discrimination in an erbium laser with the use of an AM is sufficiently high. In some cases, the discrimination of transverse modes using AMs is insufficient [20].

2. Experiment and discussion of results

We used an AE 2.5 mm in diameter and 35 mm long made of commercial LGS-KhM chromium – ytterbium – erbium glass (V.A. Kotel'nikov Institute of Radio Engineering and Electronics). The AE faces were antireflection coated for a wavelength of 1540 nm (reflectance $R < 0.2\,\%$). As a pump source, we used an INP-2/35 flashlamp, which was tightly packed together with the AE in a diffusion reflector made of $\mathrm{Al_2O_3}$ ceramics [21]. The cavity was formed by a spherical concave ($r = 2$ m) highly reflecting mirror and a plane output mirror with the reflectance $R = 85\,\%$ at a wavelength of 1535 nm. The AE was placed close to the highly reflecting mirror, the distance between the AE face and the mirror being 3 cm. Between the AE and the output mirror, we placed a passive Q-switch with an initial transmittance of 93 %, which was made of a $\mathrm{Co^{2+}:MgAl_2O_4}$ crystal. The Q-switch faces were antireflection coated for a wavelength of 1540 nm ($R < 0.15\,\%$). The laser operated in both the pulse-repetition and single-pulse regimes. The pulse repetition rate did not exceed 0.3 Hz.

Figure 1 shows the dependence of the output energy on the pump energy. At near-threshold energies (region I), the transverse TEM_{00} mode was emitted. The maximum pulse energy in this region was 3.9 mJ and tended to decrease as the pump energy decreased to the laser threshold. Our estimates show that the TEM_{00} mode diameter in this cavity configuration is 0.8 mm. With increasing the pump energy, the region with an above-threshold gain in the central part of the AE increases, which resulted in decreasing losses at the wings of the excited mode. The laser pulse duration was 45 ns at half maximum and 120 ns at the level of 0.1.

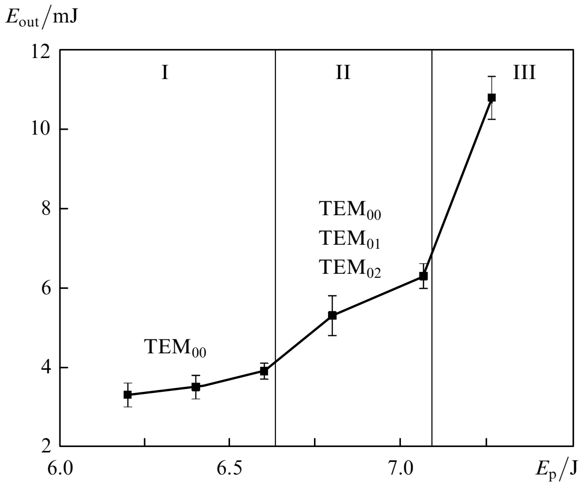

Figure 1. Dependence of the output energy E_{out} on the pump energy E_{p} without transverse mode selection.

With increasing the pump energy (region II), the output energy varied form pulse to pulse. This instability was caused by a change in the mode composition of the laser pulse. The TEM_{01} and sometimes TEM_{02} mode were observed in the emitted pulse simultaneously or in turn with the fundamental TEM_{00} mode. This caused fluctuations both in the beam spatial parameters and in the laser pulse duration. Sometimes, the pulse had two peaks. At pump energies close to the right edge of region II, the radiation contained mainly the TEM_{02} mode. A further increase in the pump energy (region III) lead to the appearance of a second pulse delayed by 350 μs. Thus, the maximum energy of one pulse did not exceed 6 mJ.

Based on these results, we can made the following conclusions. First, there exists a very narrow region of pump energies (6.4 ± 0.2 J) at which a sufficiently stable fundamental-mode pulse is formed. Small deviations form these pump energies cause disruption of lasing or mode-hopping to a higher-order mode, which changes the beam divergence and the pulse duration. Thus, since the needed pump energy also depends on some other factors (in particular, on the environment temperature), these lasers can hardly be used for pulsed range finding under the field conditions. Second, the losses for the transverse modes with indices higher than two are so significant that the field of the corresponding geometry has no time to form before the development of the conditions for lasing of the second pulse of the lower-order mode.

All the above simplifies the problem of selection of a single non-zero mode. To do this, it is enough to introduce losses that are maximum for the TEM_{00} mode and insignificant for higher modes. To discriminate the low-order modes, beginning from the fundamental mode, we modified one of the AE faces by forming in its centre a round scattering zone (SZ). We prepared several AEs with different SZ diameters. The AEs were oriented so that their modified faces were directed to the output mirror. First, comparing the size of the TEM_{00} mode on the AE face and the AE diameter, we estimated the minimum SZ diameter at which this mode cannot appear at all. We reasoned that the radial size of the ring between the SZ edge and the outer diameter of the AE must not exceed the TEM_{00} mode diameter. Excluding bevels, the working diameter of the AE face was 2.4 mm, and, therefore, the needed SZ diameter must not exceed 0.8 mm. However, the final choice of the SZ diameter was made taking into account that the SZ with such a large diameter will not only cause suppression of the TEM_{00} mode but also introduce unacceptably high losses for higher modes. Therefore, we prepared for experiments a set of AEs with SZ diameters from 200 to 600 μm.

The output parameters of AEs with SZ diameters of 200 – 350 μm were not very stable. The output energy varied from 3.7 to 8 mJ depending on the alignment of mirrors, the shift of the SZ from the AE centre, and the pump energy. In this case, the mode composition discretely changed from the TEM_{00} to TEM_{03} mode. Figure 2 shows the dependences of the output power on the pump power in the cases when we managed to reliably select the TEM_{01} and TEM_{02} by aligning the cavity mirrors. Note that the range of pump energies corresponding to the conditions of single-pulse lasing at these modes increased almost threefold (to 1.2 J) compared to the that value for the TEM_{00} mode in the case of an AE without a SZ. The output energy increased to 5.2 and 7 mJ for the TEM_{01} and TEM_{02} modes, respectively. In the case of SZ diameters of 350 – 380 μm, lasing occurred in both the TEM_{02} and TEM_{03} modes depending on the alignment of mirrors.

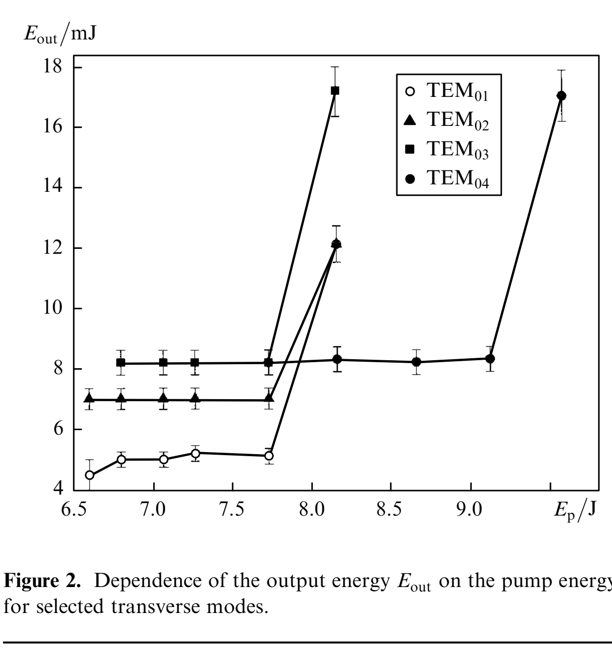

Figure 2. Dependence of the output energy E_{out} on the pump energy E_{p} for selected transverse modes.

At SZ diameters above 380 μm, we observed stable operation in the TEM_{03} transverse mode. As the SZ diameter increased to 430 μm, the output energy slightly decreased due to increasing losses for this mode. The dependence in Fig. 2 for the TEM_{03} mode is given for the SZ diameter of 380 μm. The pump energy ranged from 6.7 to 7.7 J, and the output energy was 8.2 mJ. At the SZ diameters of 430 – 470 μm, depending on the alignment of mirrors, the laser operated both in the TEM_{03} and TEM_{04} mode.

Beginning from the SZ diameter of 470 μm, it was possible to excite only the TEM_{04} mode. The output energy was the same as in the case of the TEM_{03} mode (8.2 mJ). This is explained by a lower population inversion near the side surface of the AE and, hence, to higher diffraction losses. As the SZ diameter increased to 600 μm, the output energy decreased to 8 mJ, while the stability range increased to 7.7 – 9.2 J.

With increasing order of the generated mode, the pulse duration changed as follows. The duration at the level of 0.1 of the maximum intensity for the TEM_{01}, TEM_{02}, TEM_{03}, and TEM_{04} modes decreased to 90 ns compared to 120 ns for the fundamental mode. The duration at half maximum was 43 ns for TEM_{01}, 40 ns for TEM_{02}, and 48 ns for TEM_{04}.

Let us compare these data with the calculation and experimental results obtained when mode discrimination was achieved using a binary phase element [13]. The transverse distribution of the mode field in any cross section of a cavity with circular symmetry is described by the Laguerre polynomials ($L_p^{(l)}$) of the corresponding order [22],

$$E_{pl}(r,\theta) = E_0\zeta^{l/2}L_p^{(l)}(\zeta)\mathrm{e}^{-\zeta/2}\cos(l\theta), \tag{1}$$

where $\zeta = 2r^2/w_{00}^2$ and w_{00} is the radius of the Gaussian TEM_{00} mode. The mode field intensity inside a cavity P_{pl}^{in} is found by squaring expression (1). A model for determining the output energy of a laser with a passive Q-switch was proposed in [13]. This model suggests that lasing occurs at a transverse mode whose field distribution radius is equal to the radius of the passive cavity mode field distribution and that the losses in the Q-switch are identical for all modes. Then, it is possible to obtain from (1) the energy ratio of any mode and the TEM_{00} mode. According to calculations, the energies of the TEM_{00}, TEM_{01}, TEM_{02}, TEM_{03}, and TEM_{04} modes inside the cavity relate as $1:1.37:1.85:2.23:2.56$.

The output intensity P_{pl}^{out} is related to the intensity P_{pl}^{in} by the expression

$$P_{pl}^{\mathrm{out}} = (1-\beta_{\mathrm{d}}-\beta_{\mathrm{a}})(1-\beta_{\mathrm{oc}})P_{pl}^{\mathrm{in}}, \tag{2}$$

where β_{d}, β_{a}, and β_{oc} are the diffraction losses, the losses related to the mode discrimination, and the radiative losses, respectively.

A similar model proposed in [23] differs from the model considered above by taking into account the excited-state absorption losses and the absorption in the shaded ends of the AE. The authors calculated the ratio of the output energy of a generated mode to the energy of the TEM_{00} mode. It is expected that the energies of the TEM_{01} and TE_{04} modes should increase by 1.3 and 1.9 times, respectively.

Normalising the output energies of all modes realised in our experiment to the energy of the TEM_{00} mode (Figs 1 and 2), we find that the energies in the sequence of modes in ascending order of their indexes relate as $1:1.33:1.8:2.1:2.1$. The experimental energy ratios of the TEM_{03} and lower modes to the TEM_{00} mode were smaller than the calculated intracavity ratios no more than by 6 %. This testifies that the additional losses for these modes caused by the introduction of a discriminating element in the form of a SZ deposited onto the AE face are smaller than in the case of a binary phase element [13], when, recall, the corresponding difference reached 15 %. In our case, this difference increased to 17 % only for the TEM_{04} mode.

We performed a similar experiment for an AE 2.2 mm in diameter. The cavity parameters and the position of the AE in the cavity were the same. The highest mode that we managed to obtain with this AE was TEM_{03}. The SZ diameter in this case was 360 μm. The output energy was 7.2 mJ, which is 1.13-fold smaller than the energy achieved for this mode using the AE with a diameter of 2.5 mm. An increase in the SZ diameter lead to a further decrease in the output energy, which was found to be 6.4 mJ at a diameter of 500 μm. Thus, for each resonator size there exist optimal dimensions of both the AE and SZ at which the losses for a selected mode are minimal.

Choosing a non-round SZ shape, it was possible to stabilise the azimuthal position of spots of generated modes. This provides the possibility of subsequent out-of-cavity transformation of the obtained radiation into a near-Gaussian beam using the above-mentioned methods described in [17, 18].

Finally, note that the proposed method of amplitude modulation of losses in erbium lasers turned out to be more efficient than the method previously used in [23] for experimental demonstration of the discrete character of changes occurring in the pulse energy as the oscillation type changes from one to another. In that study, the mode discrimination was achieved by placing a filament 40 μm in diameter into the cavity. In experiment performed in [23], the energies of the TEM_{01} and TEM_{04} modes were increased by factors of 1.3 and 1.8, respectively. In addition, the authors run into some technical problems related to the selection of a particular mode, which caused a spread in the experimental values of the output energy.

3. Conclusions

Thus, we have proposed a technically simple method to suppress the fundamental mode of erbium lasers using amplitude modulation of losses. By choosing SZ dimensions, we managed to:

(i) Obtain controllable generation of pure high-order modes TEM_{01}, TEM_{02}, TEM_{03}, and TEM_{04}.

(ii) Increase the output pulse power by a factor of 2.1 compared to the TEM_{00} mode energy without distorting the shape and increasing the duration of pulses.

(iii) Extend the region of the allowable pump instability by three times.

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