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Longitudinally diode-pumped ytterbium-erbium glass minilaser

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***Abstract*. The prototype of a passively *Q*-switched, longitudinally diode-pumped erbium glass laser is fabricated. A slope efficiency of 38 % is achieved in the free-running lasing regime. It is shown that a pump energy of only 42 mJ is required to generate a 9-ns, 1.8-mJ output pulse with efficiency 4.2 %.**

Keywords: *erbium laser, ytterbium-erbium phosphate glass, passive Q-switch, cobalt spinel, lanthanum – magnesium hexaaluminate single crystals* $Co^{2+}: LaMgAl_{11}O_{19}$.

1. Introduction

In recent years, considerable progress has been achieved in the field of production of laser diodes and diode arrays, opening new prospects for using erbium glass lasers in pulsed radars and range finders in the eye-safe spectral region. Many radar systems require a high pulse repetition rate. The low thermal conductivity of erbium glass is the main factor limiting the pulse repetition rate to the level of 0.2 – 1 Hz during flashlamp pumping (without forced cooling). Semiconductor lasers are more efficient and release less heat than traditional pump flashlamps. Diode pumping allows one to increase the pulse repetition rate in erbium glass lasers (with a pulse energy of 1 mJ and higher) to 50 Hz [1].

Due to a long lifetime of erbium ions (8 ms) and a broad absorption band of ytterbium ions (910 – 970 nm), it is possible to use relatively low-power laser diodes and diode arrays emitting long pulses (up to 5 – 8 ms) without thermal stabilisation of the wavelength. Heating of the erbium element occurs only due to Stokes 'exchange' of the 10400 cm^{-1} pump photons to the 6510 cm^{-1} laser photons. The rest of the absorbed energy is released in the form of luminescence of ytterbium and erbium ions having a quantum yield close to unity.

At the present time, several diode-pumped erbium lasers are commercially available in the market. The output energy of such lasers varies from 1 to 15 mJ in a pulse of duration 10 – 30 ns and a repetition rate of up to 10 Hz. The lasers are side-pumped by 25 – 100-W diode arrays.

Like flashlamp pumping, such pumping cannot provide a uniform excitation of erbium ions over the active element (AE) cross section. This problem is solved by using several arrays whose radiation is incident on the AE at various angles to the side surface (Y-configuration is used most frequently) or, as in the case of flashlamp pumping, by using a reflector with an aperture to admit radiation from the array. In both cases, the design becomes complicated and hence the device becomes more expensive. Attempts have also been made to create a more or less uniformly pumped region by selecting an appropriate absorption coefficient and by focusing the pump beam appropriately.

A new class of 1.5-μm radiation modulators, phototropic switches based on divalent cobalt ions, has appeared recently in the market. It was shown in Refs [2 – 5] that good results were obtained by using glass-ceramics containing nanocrystals (5 – 10 nm) of cobalt spinel [2] or aluminium – zinc spinel [5] with 0.1 % – 0.3 % Co^{2+} ion impurities, aluminium – magnesium spinel single crystals $Co^{2+}: MgAl_2O_4$ with cobalt (the cross section for the ground-state absorption is $\sigma = 3 \times 10^{-19}$ cm^2) [3], lanthanum – magnesium hexaaluminate single crystals Co^{2+}: $LaMgAl_{11}O_{19}$ ($\sigma = 4.4 \times 10^{-19}$ cm^2 for $E \| c$ and $\sigma = 1.4 \times 10^{-19}$ cm^2 for $E \perp c$) [4].

A special feature of a passively *Q*-switched erbium laser is that if the resonator field is not restricted by the fundamental TEM_{00} lasing mode, higher-order modes are generated with a time delay relative to the fundamental mode [6]. The use of radiation consisting of several randomly emitted spikes in pulsed laser ranging is problematic and the designers often endeavour to single out a pulse. One of the methods of selecting the fundamental mode of a laser is to increase its size, mainly by increasing the resonator base. This makes it possible to obtain pulses with energy up to 10 – 12 mJ, but their duration increases to 70 – 75 ns [7]. Another method uses an aperture to eliminate higher-order modes in small-base resonators. In this case, the diameter of the active medium from which the energy is extracted is 0.8 – 1 mm (the laser pulse duration does not exceed 30 ns). Due to such a restriction of the volume, the TEM_{00} pulse energy does not exceed 3 mJ [8]. The efficiency of *Q*-switched erbium lasers side-pumped by laser diodes is low due to a poor matching of the excited volume and the lasing-mode volume.

In view of all that has been stated above, it seems expedient to use longitudinal pumping by diode lasers. Considering that the power of single laser diodes in the range 940 – 970 nm is no more than a few watts at present,

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radiation from several diodes must be collected and focused in order to achieve the power required for longitudinal pumping of erbium lasers. Such designs have been long known and they can produce beams of diameter up to 0.4 mm with the numerical aperture NA = 0.1 [9]. The power of such devices is several kilowatts at present.

Several papers have been devoted to longitudinally-pumped ytterbium-erbium lasers [10–12]. These works, in which the pump power was in the range 100 mW–1 W, were aimed at attaining a single-frequency lasing [10] or pulsed lasing with a relatively low power [11]. A free-running erbium laser with a pulse energy of 100 mJ and a slope efficiency of 16 % was demonstrated in Ref. [12]. Radiation from a 80-W, 980-nm diode array was focused into a 1.5 × 1.5-mm spot on the end-face of the active element with the help of a non-imaging optic concentrator.

2. Experiment

As the active medium, we used ytterbium-erbium phosphate LGS-DE glass with the erbium ion concentration 8.5×10^{19} cm^{-3}, synthesised at the Institute of Radio Engineering and Electronics, Russian Academy of Sciences. The laser element was in the form of a 3-mm-thick plane–parallel plate (with a nonparallelism of 20″) of cross section 7 × 7 mm. There was no dielectric coating on the polished working surfaces. The scheme of the laser is shown in Fig. 1. The 960-nm radiation from pump source (*1*) with the beam diameter 200 μm and numerical aperture NA = 0.2 [the DL-20 pigtail diode laser system (IRE-Polyus Research and Production Association)] was focused by objective (*2*) to erbium active element (*4*). The diameter of the pumped region in the AE ($\lambda = 1535$ nm) was 600–700 μm. The laser resonator was formed by two plane mirrors – highly reflecting mirror (*3*) with $R_{1535\,\mathrm{nm}} = 100\,\%$, $T_{960\,\mathrm{nm}} = 90\,\%$, and output mirror (*6*) with $R_{1535\,\mathrm{nm}} = 86.5\,\%$, 89.2 % and 95 %. The resonator base was 35 mm. A passive *Q*-switch, whose adjustment was not envisaged, was placed between the AE and the output mirror. The pump duration could be varied over a wide range from a few microseconds to continuous pumping. The maximum pump power behind the objective was 14 W. About 80 % of the power incident on the AE was absorbed.

Figure 2 shows the dependences of the output energy E_{out} in the pulse on the absorbed pump energy E_{abs} for different reflection coefficients of the output mirror. The pulse repetition rate was 2 Hz, the pump pulse duration was 5 ms, and the pump energy was varied by changing the current through laser diodes. The maximum slope efficiency for the mirror with $R = 89.2\,\%$ was 38 %. The figure also shows (dashed curve) the dependence of the output energy on the absorbed energy for this mirror, obtained for a constant absorbed pulse power of 10 W by varying the pump pulse duration.

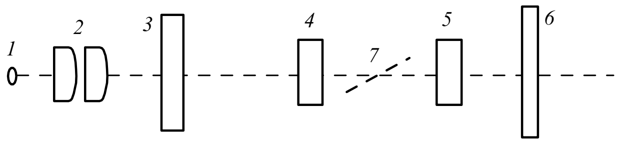

Figure 1. Scheme of the laser prototype: (*1*) pump source; (*2*) objective; (*3*) highly reflecting mirror; (*4*) active medium; (*5*) passive *Q* switch; (*6*) output mirror; (*7*) glass plate.

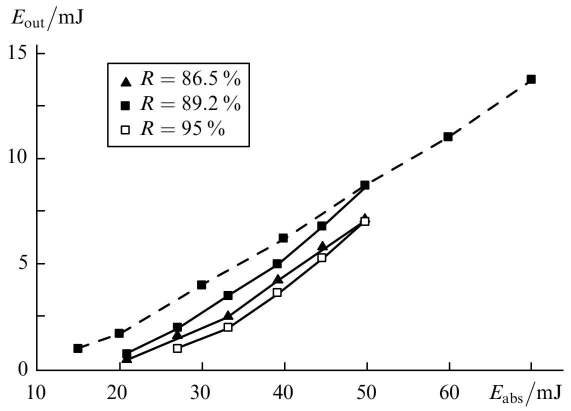

Figure 2. Experimental dependences of the output energy on the pump energy in free-running mode for different reflection coefficients of the output mirror, and the dependence of the output power for a constant pump power (10 W) upon a variation of the pump pulse duration (dashed curve).

Figure 3 [curve (*1*)] shows the dependence of the output power P_{out} on the pump pulse repetition rate F for $R = 86.5\,\%$. The energy absorbed by the AE per pulse was 50 mJ (10 W, 5 ms). One can see that the dependence remains linear as the pulse repetition rate is increased up to 20 Hz.

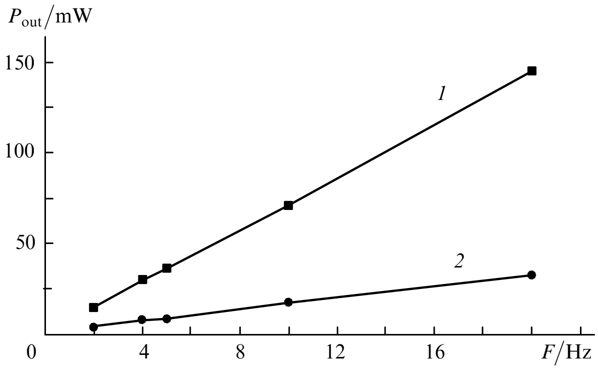

Figure 3. Dependences of the output power on the pump pulse repetition rate in the free-running (*1*) and *Q*-switching (*2*) regimes. The initial transmission of the $\mathrm{Co}^{2+}:\mathrm{ZnAl_2O_4}$ glass ceramic saturable absorber is 89 %.

Table 1 shows the experimental results obtained with intracavity passive *Q*-switches made of lanthanum–magnesium hexaaluminate single crystals $\mathrm{Co}^{2+}:\mathrm{LaMgAl_{11}O_{19}}$ and glass ceramic with $\mathrm{Co}^{2+}:\mathrm{ZnAl_2O_4}$ nanocrystals (both *Q*-switches were fabricated at the ELS-94 Research and Production Center, Moscow), as well as of the $\mathrm{Co}^{2+}:\mathrm{MgAl_2O_4}$ glass ceramic. The working planes of the *Q* switches had an antireflective coating for a wavelength 1535 nm. When $\mathrm{Co}^{2+}:\mathrm{LaMgAl_{11}O_{19}}$ was used to separate the polarisation $E \| c$, thin plane–parallel plate (*7*) was introduced into the resonator at an angle close to the Brewster angle. When the plate was removed, lasing with polarisation $E \perp c$ was observed.

The pump pulse repetition rate was 2 Hz. The pump power absorbed by the active element was 10 W, while the pump pulse duration was varied. When a modulator based

Table 1.

Q-switch material	T_0 (%)	R (%)	$T_{\mathrm{p1}}/\mathrm{ms}$	$T_{\mathrm{p2}}/\mathrm{ms}$	E/mJ	$\tau_{\mathrm{p}}/\mathrm{ns}$
$\mathrm{LaMgAl_{11}O_{19}:Co^{2+}}$ ($E\Vert c$)	90	86.5	–	–	no	–
		89.2	3.0	5.0	1.2	8 – 9
		95	2.9	4.8	1.0	8 – 9
$\mathrm{LaMgAl_{11}O_{19}:Co^{2+}}$ (without polariser)	97^{**}	86.5			1.5	150
Glass ceramic with $\mathrm{MgAl_2O_4:Co^{2+}}$	91.4^{*}	89.2	2.5	2.9	0.7	9 – 10
Glass ceramic with $\mathrm{ZnAl_2O_4:Co^{2+}}$	89^{*}	89.2	4.2	6.3	1.8	9

Note: T_{p1} is the pump pulse duration for which one radiation pulse with maximum energy was observed; T_{p2} is the pump pulse duration for which the second radiation pulse was observed; T_0 is the initial transmission of the Q switch; E is the output energy; τ_{p} is the duration of the radiation pulse; * – passport data; **– transmission obtained by recalculating the passport data (90 %, $E\Vert c$) taking into account the difference between the absorption cross sections for $E\Vert c$ and $E\perp c$ [7].

on $\mathrm{Co^{2+}:LaMgAl_{11}O_{19}}$ was used without the polarisation plate, the output pulse consisted of a train of short 15 – 20-ns pulses. The duration of the envelope of these pulses increased with pump energy. The parameters of such a pulse obtained for a pump energy of 30 mJ (10 W, 3 ms) are given in Table 1.

When Q-switching was performed using the $\mathrm{Co^{2+}:ZnA_2O_4}$ glass ceramic [curve (*2*) in Fig. 3] or the $\mathrm{Co^{2+}:LaMgAl_{11}O_{19}}$ single crystal Q switch without the polarisation plate, the radiating pulse energy remained almost unchanged upon an increase in the pulse repetition rate up to 20 Hz. A different picture was observed for the $\mathrm{Co^{2+}:LaMgAl_{11}O_{19}}$ Q switch with $E\Vert c$. The operation of such a laser was stable if the pulse repetition rate did not exceed 3 Hz. For a pulse repetition rate of 5 Hz, lasing was quenched. Such a behaviour was attributed to depolarisation of radiation upon heating of the active element.

3. Conclusions

Thus, we have demonstrated clearly the possibility of using longitudinal pumping of ytterbium-erbium laser elements by semiconductor diodes. Pulses with an energy of 1.8 mJ and a duration of 9 ns were obtained in the Q-switching mode. The absorbed pump energy was only 42 mJ. From the point of view of the lasing efficiency, these results are record-high. Pumping with an energy of 25 mJ is required for obtaining a single pulse with energy 0.7 mJ.

Optimisation of laser parameters – antireflective coating of the end faces of the active element at the lasing wavelength and reflective coating of the output end face at the pump wavelength – decreases the intracavity losses and increases the homogeneity of the population inversion of erbium ions along the AE, which must increase the efficiency of the laser. A correct choice of the reflection coefficients of the output mirror and the transmission coefficient of the Q switch, as well as the choice of the optimal concentration of erbium ions, should lead to a considerable increase in the output energy [7].

According to our estimates, single-mode end-pumped ytterbium-erbium lasers are capable of emitting an energy of 2 – 3 mJ in a pulse of duration 5 – 8 ns for a pulse repetition rate of 10 – 20 Hz. In these calculations, restrictions imposed by actually attainable radiation resistance of dielectric mirrors and antireflecting coatings are taken into account. Pulses with such an energy can be used for laser ranging (over 10 – 20 km).

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