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Compact *Q*-switched Yb : Er laser with a pulse repetition rate of 10 Hz

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Abstract. **A compact acousto-optically *Q*-switched Yb : Er laser emitting 20-ns pulses at λ = 1.5 μm with an energy of 8 mJ and a repetition rate of 10 Hz is developed. The laser radiation divergence at the exit of an optical forming system is 1 mrad. The experimental sample can stably operate in a wide temperature range with unchanged output parameters. The developed laser is 110×30×30 mm in size taking into account the dimensions of the optical forming system. Life tests demonstrated stable continuous operation of the sample for 50000 pulses.**

Keywords: *Yb:Er glass, diode pumping, Q-switching, acousto-optic Q-switch.*

1. Introduction

Application of solid-state pulsed lasers operating in the eye-safe spectral range of 1.5–1.6 μm as radiation sources in range finding not only allows one to use such systems in densely populated areas but also provides high accuracy and large range of measurements [1–3].

One of the most widely used types of solid-state lasers emitting in the range of 1.5–1.6 μm are lasers with active elements (AEs) made of Yb : Er glass. This is first of all explained by a long lifetime of the upper laser state in the active medium (from 6 to 10 ms), which allows pumping by long pulses and efficient energy storage. In addition, the existence of broad absorption bands of Yb : Er glass in the spectral range of commercially available laser diodes makes it possible to use these lasers without precision temperature stabilisation systems. Besides, lasing occurs directly at a wavelength of 1.54 μm and does not require additional frequency conversion. All this in combination with the commercial availability of phosphate glass AEs makes Yb : Er lasers very attractive for use as radiation sources in range finding.

However, the development of these lasers runs into some problems. First, lasers used in portable devices must be compact, which requires high energy efficiency. Second, the scheme and design of the laser must provide not only a high efficiency but also a high operation stability in a wide temperature range [4–6].

To date, the only *Q*-switch used in compact Yb : Er lasers operating with a pulse repetition rate of 10 Hz and higher is a *Q*-switch based on frustrated total internal reflection, which replaced optomechanical *Q*-switches with a rotating prism [6, 7]. However, to apply such *Q*-switches in devices operating in a wide temperature range, it is necessary to use additional systems to stabilise the *Q*-switch temperature. Therefore, the complex production technology in combination with the necessity of using a special control system results in the low commercialisation of these devices.

The present work is devoted to the development of a compact laser with an Yb : Er phosphate glass AE and *Q*-switching by a small-size acousto-optic *Q*-switch [8–11]. The designed laser emitting at λ = 1.5 μm stably operates in a wide temperature range with a pulse repetition rate from 1 to 10 Hz, an output energy of 8 mJ, a pulse duration no longer than 20 ns, and a beam divergence no larger than 1 mrad after an optical forming system. These laser characteristics, taking into account the small laser size (110×30×30 mm), allow us to suggest that it satisfies the latest requirements imposed on devises for application in pulsed eye-safe laser range finding. It should be noted that the developed laser is comparable in pulse energy and size to devices from Kigre Inc. [12] (a world leader in the production of eye-safe lasers) and, at the same time, has a smaller beam divergence and is equipped with a built-in cooling system.

2. Laser design

The optical scheme of a compact diode-pumped *Q*-switched Yb : Er glass laser is presented in Fig. 1.

The laser cavity 40 mm long is formed by a highly reflecting mirror (*1*) and an output mirror (*4*). The output mirror reflectivity and the radius of curvature of the highly reflecting mirror were experimentally selected to achieve the maximum output energy in the case of active *Q*-switching with a pulse repetition rate of 10 Hz and pumping by laser diode pulses with a total energy of 750 mJ. First, at a fixed 2000-mm radius

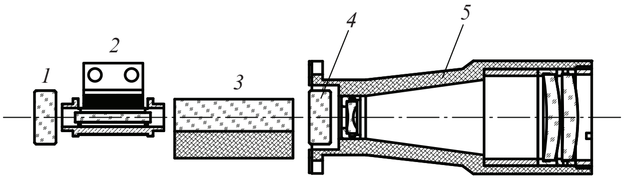

Figure 1. Optical scheme of the Yb : Er glass laser: (*1*) highly reflecting mirror; (*2*) laser head; (*3*) acousto-optical *Q*-switch; (*4*) output mirror; (*5*) optical forming system (objective).

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of curvature of the highly reflecting mirror, we selected the optimal output mirror reflectivity, which was found to be 82% (Fig. 2a). Then, we performed an experiment in which the output mirror had the optimum reflectivity and the radius of curvature of the highly reflecting mirror was varied. It turned out that the optimal radius of curvature is 2000 mm, as was chosen previously (Fig. 2b).

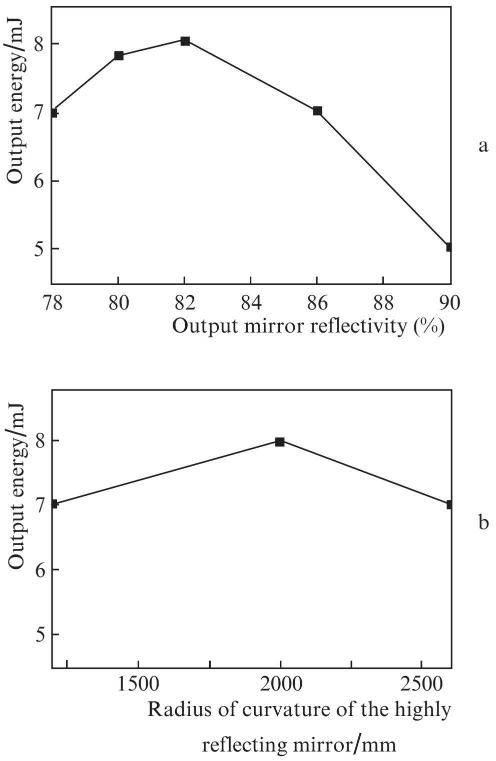

Figure 2. Experimental results of determination of the optimal parameters of cavity mirrors in the active Q-switching regime with a pulse repetition rate of 10 Hz at a pump-pulse energy of 750 mJ: dependences of the output laser energy (a) on the output mirror reflectivity for the highly reflecting mirror with a 2000-mm radius of curvature and (b) on the radius of curvature of the highly reflecting mirror at an output mirror reflectivity of 82%.

To develop a highly efficient compact laser without considerable increase in its dimensions and complication of its design, as well as to provide uniform pumping of the active medium, we proposed a laser head with a three-side pumping system shown in Fig. 3. The laser head was developed using the approaches and methods described in [13].

For optical pumping, we used three laser diode bars (LDBs) (*1*) (Fig. 3) with a centre wavelength of 940 nm at room temperature. The bars were pumped by current pulses with a duration of 5 ms. To maintain the working temperature of LDBs, they were mounted on copped heat sink (*2*) cooled with a thermoelectric module (not shown in Fig. 3). The thermoelectric module with an attached pin fan heat sink allowed the LDBs to operate at a pulse repetition rate of 10 Hz with pulse energies up to 750 mJ at passive convective cooling and up to 1230 mJ at cooling with a fan.

Active element (*3*) was made in the form of a cylindrical rod 2.2 mm in diameter and 12 mm long from Yb : Er phosphate glass with erbium and ytterbium concentrations of 3×10^{19} and 2.4×10^{21} cm^{-3}, respectively. The AE was glued into reflector (*7*) with special optically transparent organosilicon composition (*8*). The use of this material provides not only heat removal from the AE (which is especially important for operation with a pulse repetition rate of 10 Hz) but also compensation of the difference between the thermal expansions of the AE and reflector. The reflector is a sapphire tube, whose outer surface is coated with a reflecting silver layer (*5*). Farther cooling of the AE and reflector is performed by copper heat sink (*4*) attached to the main housing of the laser.

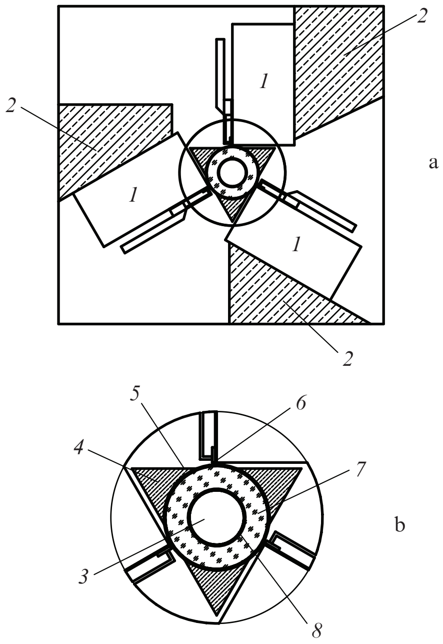

Figure 3. Schemes of (a) laser head pumping and (b) laser head on an enlarged scale: (*1*) laser diode bars; (*2*) heat sink for laser diode bars; (*3*) AE; (*4*) heat sink for the AE; (*5*) reflecting coating; (*6*) emitting surface; (*7*) reflector; (*8*) organosilicon heat-conductive coating.

The theoretical efficiency of the three-side pumping scheme $\eta_{\rm theor}$, which is calculated as the ratio of the radiation power absorbed in the active medium volume to the pump power, was determined by the method described in [14] to be ~78%.

As active Q-switch (*3*), we used a new-generation acousto-optic Q-switch made of crystalline quartz and characterised by small dimensions compared to standard Q-switches [8–11]. The Q-switching was controlled by an electric signal with an amplitude of 30 V and a frequency of 80 MHz applied to a piezoelectric transducer. The region of the Q-switch aperture optimal for the interaction with laser radiation was chosen based on the results of work [15].

Ten-fold three-lens objective (*5*) was developed and used to collimate the laser radiation and compensate the geometric divergence of the output beam.

3. Experimental

To estimate the proposed pumping system efficiency, we determined the dependence of the output laser energy in the absence of Q-switching on the pump energy (Fig. 4). One can see that the lasing threshold is achieved at a pump pulse energy of 360 mJ. The pumping system efficiency, which is estimated by the ratio of the free-running energy to the pump energy taking into account the output mirror transmission, Stokes losses, and losses for relaxation of the upper laser level population, can be determined by the formula [16]

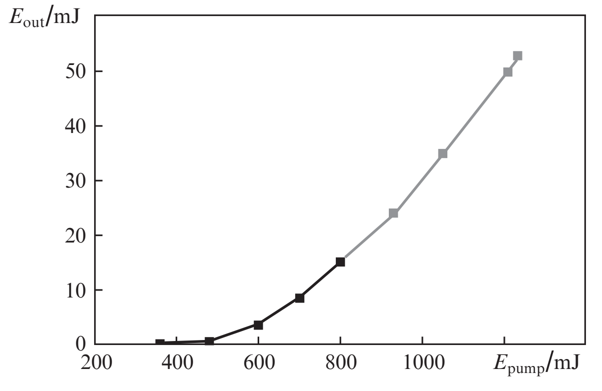

Figure 4. Dependence of free-running energy E_{out} on pump energy E_{pump} at a pulse repetition rate of 10 Hz. Black colour indicates output energies obtained upon passive cooling of the LDBs, and grey points correspond to cooling of the pin fit heat sink with a fan.

$$\eta_{exp} = \frac{E_{out} r}{E_{pump}(1-r)} \frac{\tau_{decay}}{\tau_{pump}} \left[1 - \exp\left(\frac{\tau_{pump}}{\tau_{decay}}\right)\right] \left(1 - \frac{\lambda_{pump}}{\lambda_{laser}}\right),$$

where r is the output mirror reflectivity, $\tau_{decay} = 8$ ms is the upper laser level lifetime, $\tau_{pump} = 5$ ms is the pump pulse duration, $\lambda_{pump} = 940$ nm is the pump wavelength, and $\lambda_{laser} = 1535$ nm is the laser wavelength.

The pumping system efficiency calculated by this formula was $\eta_{exp} \approx 66\%$, which is lower than $\eta_{theor} \approx 78\%$ obtained above by theoretical modelling. The difference between the experimental and theoretical values can be explained by the existence of parasitic losses in the laser cavity that were not taken into account in the modelling.

The use of a Q-switch allowed stable laser operation with a pulse repetition rate up to 10 Hz in a wide temperature range. The output laser pulse energy of the laser was stable and equal to 8 mJ in the steady-state regime. This regime corresponded to a pump pulse energy of 750 mJ and a free-running laser pulse energy of 13.5 mJ. The efficiency of the free-running output energy conversion to the single-pulse energy was 60%. The pulse duration at an output energy of 8 mJ was 20 ns. The limiting unit in the scheme of the developed laser that did not allow us to achieve an output pulse energy exceeding 8 mJ at a pulse repetition rate of 10 Hz was the cooling system, which was not designed to remove so high thermal load with passive cooling. The oscillogram of a laser pulse in the case of a pulse repetition rate of 10 Hz is shown in Fig. 5.

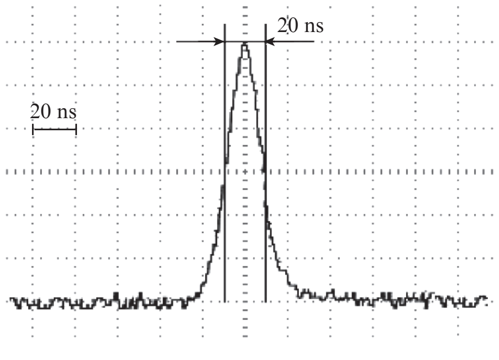

Figure 5. Laser pulse oscillogram at a pulse repetition rate of 10 Hz.

The use of the optical forming system with a tenfold magnification makes it possible to achieve a laser beam divergence of 1 mrad.

The laser in a housing with the cooling system allowing its continuous operation has dimensions of 110×30×30 mm. In the course of climatic and service life tests, the laser demonstrated stable operation at temperatures from −40°C to +60°C with unchanged output parameters for more than 50000 pulses. It should be noted that, to prevent failure of laser diode arrays due overall overheating at high environmental temperatures without changing the cooling system, the laser operation with a pulse repetition rate of 10 Hz had to be cyclic, i.e., 1 min of operation and 1 min of cooling.

A photograph of the developed experimental sample with the optical forming system is presented in Fig. 6.

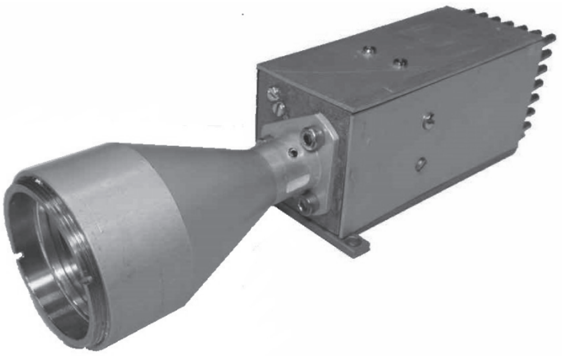

Figure 6. Photograph of the developed laser.

4. Conclusions

We presented a pulsed Yb : Er glass laser operating with a pulse repetition rate up to 10 Hz. The maximum output energy in the single-pulse regime is 20 mJ at a pump pulse energy of 1050 mJ (the maximum pump energy that can be achieved with the used laser diodes is 1350 mJ). This corresponds to the maximum possible intracavity power density and may cause damages of the surfaces of optical elements. In addition, this regime in the presented design can be achieved only with active cooling of the laser with a fan. Since the choice of the output mirror was performed at lower pump levels, we can conclude that, by increasing the cooling system efficiency and using a proper output mirror transmittance, it is possible to develop an Yb : Er glass laser with a pulse energy of 20 mJ at a pump pulse energy of 1050 mJ with a pulse repetition rate up to 10 Hz. Despite the fact that the theoretically determined efficiency of the developed pumping system with optimised parameters was $\eta_{theor} = 78\%$, in experiment we obtained only $\eta_{exp} = 66\%$. This discrepancy is most probably related to the existence of unaccounted parasitic losses in the cavity.

The developed laser with $\lambda \sim 1.5$ μm demonstrated stable operation in a wide temperature range with a pulse repetition rate from 1 to 10 Hz, an output energy of 8 mJ, a pulse duration no longer than 20 ns, and a divergence after the optical forming system not exceeding 1 mrad. The laser has a small size (110×30×30 mm), which is important for creating new-generation systems of laser range finding. The laser is comparable in output pulse energy and size with devices from Kigre Inc. [12], which is a world leader in the production of lasers of this type, and has a smaller beam divergence.

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