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Diode-pumped ytterbium – erbium glass microlasers with optical *Q*-switching based on frustrated total internal reflection

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Abstract. An optical system is proposed in which a switch based on frustrated total internal reflection (FTIR) is used to vary actively the *Q*-factor of longitudinally pumped erbium glass microlasers. Continuous pumping (with a power of 320 mW) generated giant pulses, of 500 – 600 W peak power and of 10 – 12 ns duration, at a repetition rate of 1 kHz. An FTIR switch in a laser transversely pulse-pumped by a linear laser-diode array delivering 100 W produced pulses of up to 7.5 mJ energy and of 30 ns duration.

1. Introduction

The interest in ytterbium – erbium glass lasers by the radiation of InGaAs diode lasers has increased recently. This is due to a wide range of potential applications of such lasers in communications, location, and telemetry and is related to the eye-safe wavelength of their radiation (1.54 μm), compactness, and potentially low cost (when mass produced).

The diode-pumped ytterbium – erbium glass lasers described hitherto can be divided quite clearly into two types in accordance with their structure: microlasers longitudinally pumped by the radiation of one (more rarely, several) diode lasers and transversely pulse-pumped lasers. The vast majority of the applications of lasers of both types require *Q*-switching of the cavity.

A typical gain in transversely diode-pulse-pumped lasers amounts to tens percent per pass, whereas in lasers with continuous longitudinal diode pumping it amounts to several percent. It is also noteworthy that the maximum attainable gain in erbium glass (considered as a three-level active medium) is determined (to a first approximation) by the concentration of the active species, which as a rule does not exceed $(1 - 1.5) \times 10^{20}$ cm^{-3}. Thus, as a consequence of the small gain of the medium, the choice of a *Q*-switch with fairly low losses constitutes a very important task in the construction of erbium glass lasers.

Until recently, the only *Q*-switching method in longitudinally pumped microlasers involved accordingly the introduction of intracavity mechanical devices such as rotating disks with cuts or vibrating tuning forks [1, 2]. However, the giant pulses thus generated were long and accompanied by parasitic spikes. There were reports of passive modulation of erbium microlasers by semiconductor mirrors with saturable absorption [3], and by a saturable filter based on a cobalt-doped $LaMgAl_{11}O_{19}$ crystal [4].

This communication describes a study of the feasibility of active *Q*-switching of both longitudinally and transversely diode-pumped erbium microlasers with the aid of optical switches based on frustrated total internal reflection (FTIR). The known advantages of the FTIR switches in *Q*-switching of low-gain lasers are low optical losses (not more than 1% – 2% per pass) and the possibility of modulating radiation with any polarisation. The finite response time of FTIR switches is as a rule insignificant in lasers with a low gain and hence with a long duration of the generation of a giant pulse.

2. Longitudinally diode-pumped microlasers

As mentioned above, the gain attainable in lasers of this type is several per cent. The placing of an FTIR switch in the cavity of such a laser in the usual way therefore leads to losses comparable with the gain in the active medium or exceeding it, and precludes any kind of effective lasing. In order to avoid undue optical losses, we propose the optical laser system illustrated in Fig. 1. The laser contains an active element (*1*) made of ytterbium – erbium laser glass and consisting of a plane-parallel plate and carrying a dichroic

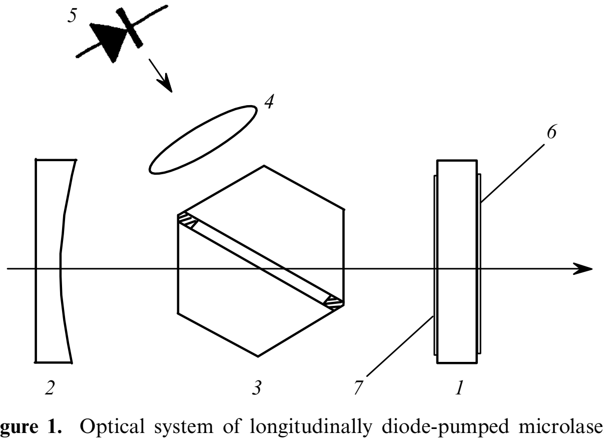

Figure 1. Optical system of longitudinally diode-pumped microlasers: (*1*) active element; (*2*) totally reflecting spherical mirror; (*3*) FTIR switch; (*4*) focusing system; (*5*) laser diode; (*6*, *7*) output and intermediate mirrors.

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output mirror (*6*), reflecting the pump radiation ($\lambda = 0.93 - 0.98$ μm), on its external (right-hand) surface. A intermediate dichroic mirror (*7*), transmitting the pump radiation and reflecting a definite proportion of the generated radiation, is deposited on the inner (left-hand) surface of the active element. The latter mirror (*7*) is necessary to reduce the sensitivity of the laser to optical losses in the *Q*-switch, because in its presence only part of the laser radiation passes through an FTIR switch during its round trip through the cavity.

The FTIR switch (*3*) consists of two rigidly clamped fused-quartz prisms. Between the prisms there is a gap, of the order of 0.5 μm, which can be rapidly (in hundreds of nanoseconds) 'collapsed' with the aid of piezoelectric elements attached to the prisms. The two faces of the switch located in the laser cavity are antireflection-coated for $\lambda = 1.54$ μm. An antireflection coating, tuned to the pump wavelength and located on the face turned towards the laser diode, is also desirable.

It is noteworthy that in the proposed system the optical FTIR switch fulfils two functions: it is responsible for the cavity *Q*-switching and it effects the spatial – temporal separation of the pump and lasing radiation beams. As can be seen from Fig. 1, the pump radiation from a diode laser (*5*) passes through a focusing system (*4*), is reflected from the active surface of the FTIR switch (in the closed state), and enters the active element. Pumping can thus be continuous with the exception of short (lasting several microseconds) time intervals when the switch is open. Moreover, the pump radiation passes freely through the switch and giant pulses are generated in the laser cavity at the expense of the energy stored in the active medium. The brief period of the open state of the switch, compared with the lifetime of the highest laser level (~7 ms) of erbium, makes the pump radiation losses completely insignificant.

The intermediate mirror (*7*), deposited on the active element, and a totally reflecting mirror (*2*) form a Fabry – Perot interferometer. The internal losses of this interferometer are determined mainly by the characteristics of the FTIR switch in the open state. It can be shown that the maximum reflection coefficient of such an interferometer is given by the formula

$$R_{\max} = \frac{R_1 + R_2 + 2(R_1 R_2)^{1/2}}{1 + R_1 R_2 + 2(R_1 R_2)^{1/2}},$$

where R_1 is the reflection coefficient of the intermediate mirror at the lasing wavelength; R_2 is the equivalent (taking into account the radiation losses in a double pass through the switch) reflection coefficient of the totally reflecting mirror. It follows from the above formula that a combination of the two mirrors makes it possible, even in the presence of losses introduced by the switch, to attain reflection coefficients greatly exceeding 99%. The fabrication of the usual dielectric mirrors with their reflection coefficients of the order of 99.7% and above at $\lambda = 1.54$ μm, but still exhibiting a sufficient optical strength, meets with considerable technological difficulties. The ability to dispense with such mirrors is an important advantage of the system described.

In the lasing experiments, we used a silicoborophosphate laser glass with the ion concentrations $[\mathrm{Yb}^{3+}] = 4 \times 10^{21}$ cm^{-3} and $[\mathrm{Er}^{3+}] = 1.5 \times 10^{19}$ cm^{-3} [5]. The thickness of the active element was 0.8 mm. Pumping was provided by one InGaAs diode laser emitting at the wavelength of 0.93 μm, which corresponds to an absorption coefficient of the laser glass of about 10 cm^{-1}. The power of the pump radiation incident on the active element was 320 mW and the transverse dimensions of the pumped region were ~150 μm × 150 μm. The cavity was nearly semiconfocal (the concave mirrors had radii of curvature of 5 cm and reflection coefficients of about 99.5%). The remaining parameters of the two microlasers, assembled in accordance with the scheme shown in Fig. 1, are listed in Table 1.

In the experiments on the first microlaser, when the total transmission coefficient of the mirrors deposited on the active element was less than the gain attainable in it, free lasing (in the time intervals between the instants at which the switch was triggered) as well as giant pulses were observed. The appearance of free lasing, i.e. of 'seed' radiation in the laser cavity, led to a sharp reduction in the duration of the giant pulses, which became less than the time needed to move the switch from the closed to the fully open state (in this case, about 0.5 μs). Since the giant pulses were generated before complete opening of the switch, lasing produced several (4 – 5) pulses of relatively long duration (30 – 40 ns).

The partial transparency of the switch during generation of these pulses led to additional energy losses owing to the reflection from the active surface of the switch. In our experiments, the radiation with an energy representing 30% of the energy coupled out through the output mirror was reflected away from the diode laser and 19% was reflected towards it.

In the experiments on the second microlaser, the total transmission through the mirrors deposited on the active element exceeded the gain in this element. Free lasing could not occur and *Q*-switching resulted in the generation of single giant pulses of 10 – 12 ns duration and of 500 – 600 W peak power. During the generation of such pulses, the FTIR switch was in a virtually fully open state: the radiation, of energy which did not exceed 1% of the energy coupled out through the output mirror of the laser, was reflected from its active surface. Thus, for generation of short powerful giant pulses, the reflection coefficient of the intermediate mirror must be chosen so that the occurrence of free lasing on the mirrors deposited on the active elements would be impossible.

Table 1. Parameters of longitudinally pumped microlasers.

Microlaser	λ/μm	T_6 (%)	T_7 (%)	Δt/ms	P_m/mW	Nature of radiation
1	1.54 0.93	1.8 5	4.5 95	1	6	Series of 4 – 5 pulses with a total duration of ~1 μs, $\tau = 20 - 40$ ns
2	1.54 0.93	2.5 6	8 97	7	0.8	Single pulses, $\tau = 10 - 12$ ns

Note. Here, T_6 and T_7 are, respectively, the transmittances of the output mirror (*6*) and of the intermediate mirror (*7*) (Fig. 1); Δt, P_m, and τ are, respectively, the interval between the pulses, the average lasing power in the giant-pulse regime, and the duration of the giant pulses.

3. Laser with transverse pulsed pumping by an array of diode lasers

As mentioned above, the attainable gains in lasers with transverse pulsed diode pumping can amount to tens percent, so that Q-switching does not require construction of systems analogous to that illustrated in Fig. 1. However, the output characteristics of such lasers depend greatly on the losses introduced by Q-switches of a particular type. Comparative tests of the FTIR switch and of an electro-optical switch based on a BBO crystal showed that the former is much more effective for erbium glass lasers with transverse pulsed diode pumping [6].

The pump source was a linear array, 1 cm long, of InGaAs diode lasers. The maximum output power was 100 W (for a current of 120 A) and the pump pulse duration was 4.8 ms. The active element, consisting of a polished $\varnothing 2 \times 10$ mm cylinder with antireflection-coated plane-parallel silicoborophosphate glass end-faces and with the activator concentrations $[\mathrm{Yb}] = 4 \times 10^{21}$ cm^{-3} and $[\mathrm{Er}] = 3 \times 10^{19}$ cm^{-3}, was placed near the diode array and parallel to it (at a distance of about 100 μm). Part of the cylindrical surface of the active element, not directly illuminated by the diodes, was covered by silver foil, ensuring backreflection into the laser element of the radiation transmitted through the active element. No measures were taken to provide forced cooling of the active element. The plane – plane laser cavity was 5 cm long and the reflection coefficient of the output mirror was 91.2% in the free-lasing regime (without an FTIR switch in the cavity) and 87.5% in the Q-switched regime.

Fig. 2 presents the output characteristics of the laser at a pulse repetition rate of 1.3 Hz. At the maximum pump energy, the output energy reached 23 mJ in the free-lasing regime and 7.5 mJ in the Q-switched regime with a pulse duration of 30 ns at FWHM. In the Q-switched regime, the structure of the radiation for an output energy of 4 mJ and below corresponded to the TEM_{00} mode. The inflection in the experimental curve at an output energy of about 5 mJ can be accounted for by the appearance of higher-order modes in the output radiation. The output characteristics approach closely the requirements which must be met by lasers needed in portable rangefinders with a radius of action of 10 – 15 km.

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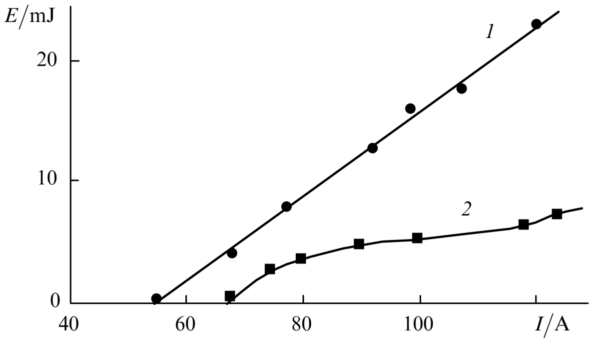

Figure 2. Dependences of the output energy of a transversely pumped laser on the current through an array of laser diodes in the free-lasing (*1*) and Q-switched (*2*) regimes.

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