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Diode-pumped self-Q-switched erbium-doped all-fibre laser[*]

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***Abstract*. A diode-pumped self-Q-switched erbium-doped fibre laser is developed and studied. The laser has an all-fibre configuration containing a piece of an active heavily erbium-doped fibre and two fibre Bragg grating mirrors and does not require any additional intracavity elements to obtain short pulses. Analysis of the laser operation suggests that the most probable mechanism of passive Q-switching of the laser cavity is absorption from the excited state of erbium resulting in the thermally induced nonlinear change in the refractive index in the erbium-doped fibre.**

Keywords: *erbium-doped fibre lasers, self-Q-switching, excited-state absorption, nonlinear thermal lens.*

1. Introduction

Q-switched erbium-doped fibre lasers are now widely used in telecommunication systems, reflectometry, medicine, and distributed fibreoptic sensors.

The cavity of lasers, in particular fibre lasers, can be Q-switched either actively or passively. Fibre lasers can be actively Q-switched with the help of a fibre intensity modulator [1], by modulating the current of a pump diode laser [2] or using a modulator consisting of a pair of intracavity Fabry – Perot filters one of which is scanned in transmission [3]. In addition, Q-switching is most often performed by means of an intracavity acoustooptic modulator [4 – 7].

However, active Q-switching of laser cavities is almost always performed in bulk (non-fibre) optical elements, which considerably complicates the laser design. Because of this, great interest in the development of methods for passive Q-switching of fibre lasers, in particular erbium-doped fibre lasers has recently aroused. Such lasers have certain advantages over actively Q-switched lasers: a compact and simple design, which can be in principle all-fibre.

By now several methods for passive Q-switching of the cavity of an erbium-doped fibre laser have been proposed. These are the method of distributed backscattering [8], the method based on nonlinear reflection of light from a liquid gallium drop [9, 10], the method in which absorption is saturated in an intricate SESAM (semiconductor saturated-absorption mirror) structure [11], and also Q-switching with the help of a Co^{2+} : ZnSe crystal, which has been recently demonstrated in Refs [12, 13].

Each of the above methods for passive Q-switching of erbium-doped fibre lasers has its own advantages and disadvantages. As for disadvantages, note that all the lasers considered in Refs [8 – 13] are not all-fibre lasers and, therefore, their assembly and adjustment is always a rather complicated technical problem. In addition, each of these lasers has its own specific disadvantages. For example, a passively Q-switched ytterbium laser due to stimulated Brillouin backscattering [8] can produce short and high-power (up to 10 kW) light pulses, however, only when the threshold pump power is rather high (about 2.5 W). In this case, as the authors [8] themselves point out, the operation of an erbium-doped fibre laser of a similar design is very unstable. Passive Q-switching in lasers studied in Refs [9 – 11] also appears only at high threshold pump powers. For example, a laser, in which the effect of a nonlinear mirror in a liquid gallium drop is used, has the pump threshold of 0.9 W, whereas the threshold of a laser with a nonlinear SESAM is 2 W. However, a saturable absorber based on a gallium mirror is not technological because it represents a drop (gallium in the open air is in a liquid state), which is subject to external perturbations. It seems that the scheme of an erbium-doped fibre laser with an intracavity nonlinear SESAM [11] is the most convenient at present for achieving stable passive Q-switching. However, SESAM structures are expensive optical elements, which is not always acceptable. In addition, a laser containing a Co^{2+} : ZnSe crystal inside a fibre cavity [12, 13] is also quite promising. It has a simple design and a very low threshold for passive Q-switching (about 8 mW) for the peak power of pulses in a continuous train equal to 0.7 mW and their energy and duration equal to 3.2 nJ and 5.4 μs, respectively (for the diode pump power of 60 mW). However, this laser also has obvious disadvantages. First, Q-switching is observed in this laser within a rather narrow range of pump powers (20 – 85 mW), and the duration of laser pulses in minimal

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and their energy and peak power are maximal only near an optimal pump level (about 60 mW). Above this pump level, the laser parameters are drastically deteriorated, and then *Q*-switching disappears at all and the laser begins to operate in a continuous regime. Another drawback of the laser [12] is the long-term instability of passive *Q*-switching itself, pulses in the train being always randomly modulated in time [13].

The aim of this paper is to realise experimentally and study the properties of self-*Q*-switching in the cavity of a diode-pumped erbium-doped all-fibre laser. Such a laser, being a very simple device, can produce highly stable submicrosecond pulses in a broad range of diode pump powers. We also present the experimental data, which suggest that the most probable physical mechanism of self-*Q*-switching in this laser should be excited-state absorption in erbium resulting in the production of a strong thermally induced nonlinear lens in the active erbium-doped fibre.

2. Experiment

The scheme of the laser is shown in Fig. 1. The laser resonator consists of a piece of heavily erbium-doped fibre of length from 30 to 200 cm spliced at both ends with fibre Bragg gratings (FBGs). Each FBG had the maximum reflectivity (at a wavelength of 1560 nm) from 85 % to 95 %. The active erbium-doped fibre (the molar concentration of Er_2O_3 was 0.23 %, the diameters of the fibre core and cladding were 2.7 and 125 μm, respectively, the numerical aperture was 0.27, and the cut-off wavelength was 1.04 μm) was pumped through a WDM multiplexer by a commercial low-power 200-mW, 980-nm laser diode with a fibre pigtail. The total length of undoped intracavity fibre 'tails' containing FBGs was 30 cm.

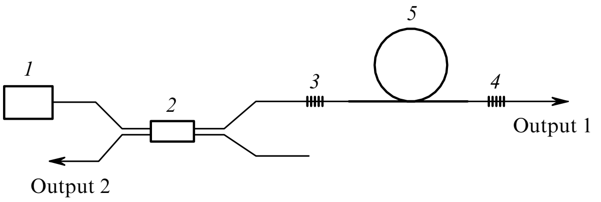

Figure 1. Scheme of the erbium-doped fibre laser: (*1*) pump diode laser; (*2*) WDM multiplexer; (*3*, *4*) FBG mirrors; (*5*) erbium-doped fibre.

We found that the laser of a simplest design described above, whose resonator consists of only a piece of an active fibre and a pair of FBG mirrors, operates in the free-running regime when the pump power is below 40 mW, although it should be noted that its output power in this case is also weakly modulated at the frequency of relaxation oscillations (Fig. 2a). At higher pump powers, the laser emits stable short pulses in a rather broad power range (Fig. 2b). For example, in the active erbium-doped fibre of length 77 cm, when the reflectivity of each of the FBG mirrors is 95 %, this operating regime is established at the pump power of 45 mW and is observed up to the maximum power achieved in experiments (200 mW).

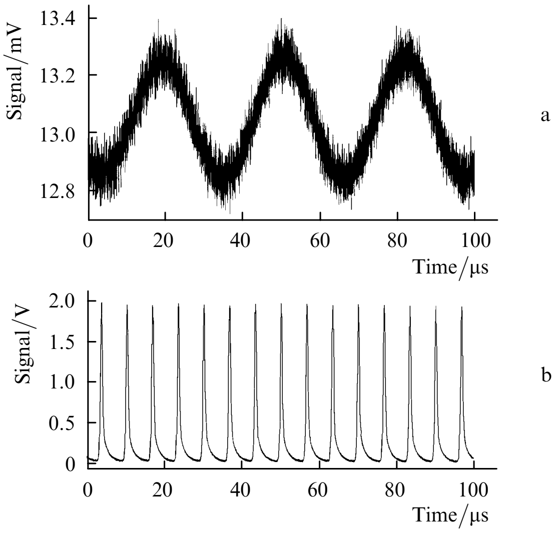

Figure 2. Time diagrams of the output intensity of the erbium-doped fibre laser pumped by the 15-mW (a) (free-running regime, pulses are weakly modulated at the frequency of undamped relaxation oscillations) and 150-mW radiation (b) (self-*Q*-switching regime). The active fibre length is 77 cm.

In passing from the free-running regime to emission of short pulses in the self-*Q*-switching regime, the shape of the laser emission spectrum did not change substantially (Fig. 3) and its half-width was less than 0.1 nm (the spectral resolution of a spectrum analyser). Note only that the maximum of the lasing spectrum coincided with the maximum of the spectral dependence of the reflectivity of FBG mirrors (1560.5 nm for both gratings) and only slightly shifted in the Stokes direction with increasing pump power (less than by 0.15 nm in the pump power range from 15 to 200 mW).

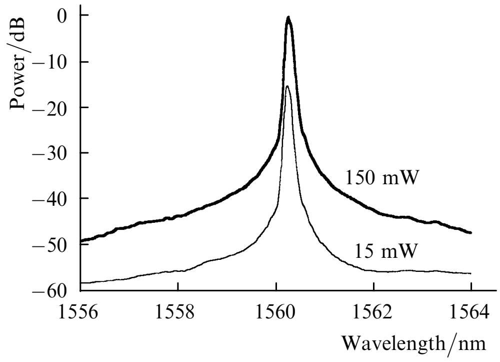

Figure 3. Spectra of the erbium-doped fibre laser at pump powers of 15 mW (free-running regime with weak self-oscillations) and 150 mW (self-*Q*-switching regime). The active fibre length is 77 cm.

The absolute efficiency of the laser estimated from the output power at both its ends did not exceed 6 %. The lasing efficiency decreased with increasing the length of the active erbium-doped fibre in the resonator (Fig. 4a). The latter circumstance can imply the influence of some nonlinear processes proceeding in the laser resonator, which could be responsible for the appearance of self-*Q*-switching itself (see section 3). Note finally that the long-term instability of the amplitude of short pulses in a train did not exceed 2 % – 3 %

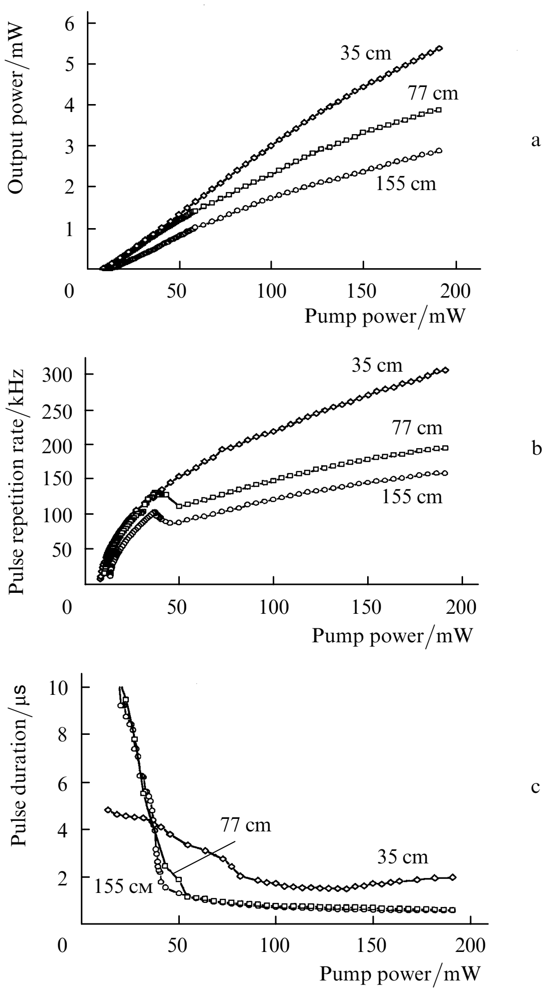

Figure 4. Dependences of the output power (a), pulse repetition rate (b), and pulse duration (c) on the pump power for erbium-doped fibres of different lengths.

and no jitter was observed between pulses in the train (see Fig. 2a).

It is interesting that self-Q-switching appeared in the laser only when the length of the active erbium-doped fibre exceeded 40 cm. The free-running regime in shorter fibres did not pass to Q-switching at any pump powers available. Figure 4b shows the dependences of the frequency of relaxation oscillations (in the free-running regime) and the repetition rate of short pulses in a continuous train (in the self-Q-switched regime) on the pump power. A rather sharp transition from a continuous regime (at weak modulation at the relaxation frequency) to Q-switching is clearly observed in the range of diode pump powers between 40 and 50 mW for erbium-doped fibres of length over 40 cm. Note that no hysteresis effects were observed for the output parameters of the laser with increasing or decreasing the pump power. In addition, the high frequency of relaxation oscillations in the laser (before the appearance of self-Q-switching) is in itself caused by rather large intracavity losses (which are most probably due to excited-state absorption in erbium, see section 3). Finally, one can see from Fig. 4c that immediately after the establishment of self-Q-switching, the pulse duration rapidly decreases with increasing pump power and then, beginning from the power of the order of 100 mW, it remains almost constant (700 – 800 ns).

Although the laser has a comparatively low efficiency (due to the induction of additional nonlinear losses in the resonator during the development of lasing, see section 3), the simplicity of its design and high stability of short output pulses (compared to other passively Q-switched fibre lasers [7 – 13]) give grounds to hope that it can be used as a master oscillator for a number of practical applications.

Note that this laser is the first highly stable all-fibre source of short pulses, whose operation regime substantially differs from the operations regimes of the known self-Q-switched erbium-doped fibre lasers [14 – 16].

3. Discussion of results

Analysis of the possible nonlinear effects that can be responsible for the dynamic properties of the laser under study shows that excited-state absorption in erbium is the dominant and most probable physical mechanism of self-Q-switching in the laser [17]. This additional absorption depending on the moment in the development of lasing leads in turn to a strong heat release, which is inhomogeneous over the fibre section, i.e., to the production of a thermally induced nonlinear lens inside the active erbium-doped fibre.

Indeed (see Fig. 4a), the output power saturates noticeably with increasing pump power, which can be explained by a decrease in the effective volume of the active medium. In our opinion, this is related to two main factors.

The first factor is the depletion of pump radiation during its propagation along the active heavily erbium-doped fibre, which should result in the reabsorption of output radiation in the unexcited part of the fibre (the part adjacent to mirror (*4*), output 1 in Fig. 1). Note, by the way, that an erbium-doped fibre is in fact a three-level laser medium in which the reabsorption of output radiation can be quite considerable. Undoubtedly, this factor can be reflected in the laser dynamics. However, the simulation of this effect showed that it does not produce self-Q-switching in a continuously pumped three-level laser.

Another factor responsible for a decrease in the field volume in the laser under study can be the formation of a nonlinear lens inside the active fibre due to its heating (which is inhomogeneous over the fibre section). The fibre is heated due to two specific processes of losses: the Stokes losses, which are determined by the relation between the pump and lasing wavelengths, and losses due to excited-state absorption in erbium both at the pump and lasing wavelengths [17, 18]. The short-lived (compared to the lifetime of the working laser level of erbium ions) upper states can themselves cause self-Q-switching in the laser [19]. However, which is more important, excited-state absorption can cause a strong additional heat release and losses in the active medium [20].

The study of the latter mechanism shows distinctly that it plays a dominant role in the establishment of self-Q-switching in this laser. The simulation of the erbium-doped fibre laser with the help of rate equations well explains all its properties: the passage from the free-running regime to Q-switching, the dependences of the repetition rate of short pulses and their duration on the pump power, etc. (the results of the laser simulation and their detailed comparison with experimental data are beyond the scope of this paper and will be published elsewhere [21]).

Here, we present only additional experimental data, which, in our opinion, also can confirm a dominant role of excited-state absorption in an erbium-doped fibre and of a nonlinear thermal lens produced in a fibre resonator due to this absorption in the development of self-*Q*-switching.

Figure 5 shows the dependences of the divergence of the laser beam (directly at the exit of the FBG mirror (*4*) of length 0.8 cm in Fig. 1) on the erbium-doped fibre length and the pump level. The transverse intensity distributions measured at a small distance of 2 cm from the corresponding FBG mirror demonstrate a noticeable increase in the divergence of the output beam with increasing the erbium-doped fibre length or the pump power. We assume that this effect is caused by self-focusing of the beam resulting in the increase in the numerical aperture of the fibre or the efficient decrease in the diameter of the fibre mode.

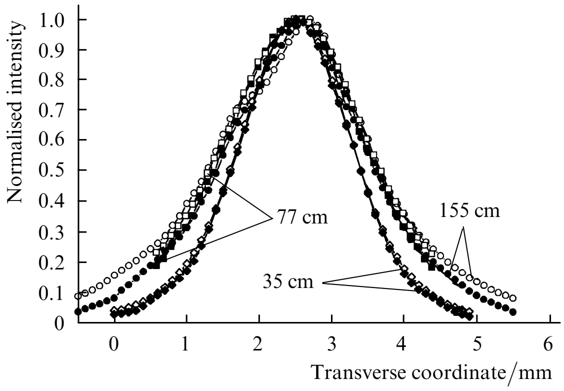

Figure 5. Intensity distributions of the 1560-nm input laser beam measured at a distance of 2 cm from the input FBG mirror (*4*) (Output 1) for erbium-doped fibres of different lengths at the pump power of 30 mW (dark circles) and 180 mW (open circles).

The corresponding data are presented in Fig. 6 showing the dependences of the laser beam radius inside the fibre resonator on the length of the active erbium-doped fibre for pump powers equal to 30 and 180 mW. We can assume that this behaviour of the divergence of the laser beam is caused by the influence of a nonlinear excited-state-absorption lens induced inside the active erbium-doped fibre. At the same time, because the divergence of the laser beam considerably changes during its propagation over a reflection FBG of length 0.8 cm written in the inactive fibre, the experimental properties considered above only indirectly confirm our assumption.

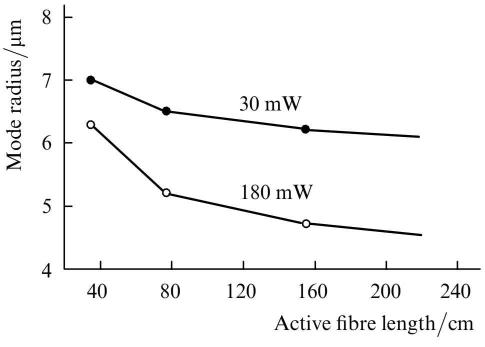

Figure 6. Dependences of the laser beam radius inside the fibre resonator on the length of the active erbium-doped fibre (for pump powers of 30 and 180 mW).

We also studied the role of excited-state absorption as a possible source of nonlinear losses in the erbium-doped fibre laser in a series of extracavity experiments (Fig. 7). The pieces of an erbium-doped fibre of different lengths were pumped by radiation from two cw lasers with fibre pigtails emitting at wavelengths 980 and 1560 nm corresponding to the pump and lasing wavelengths in the laser experiment described above (Figs 1 – 5). Figure 7 shows that there exists a strong nonlinear dependence of the transmission coefficient of the erbium-doped fibre (for both wavelengths) on the input power and the fibre length. Deflections of the transmission curves for these wavelengths ('dynamic darkening' of the fibre) can appear due to losses caused by excited-state absorption (although a more complicated process of a nonlinear change in the numerical aperture of the fibre caused by a thermal lens also can make a contribution to the effective change in the fibre transmission).

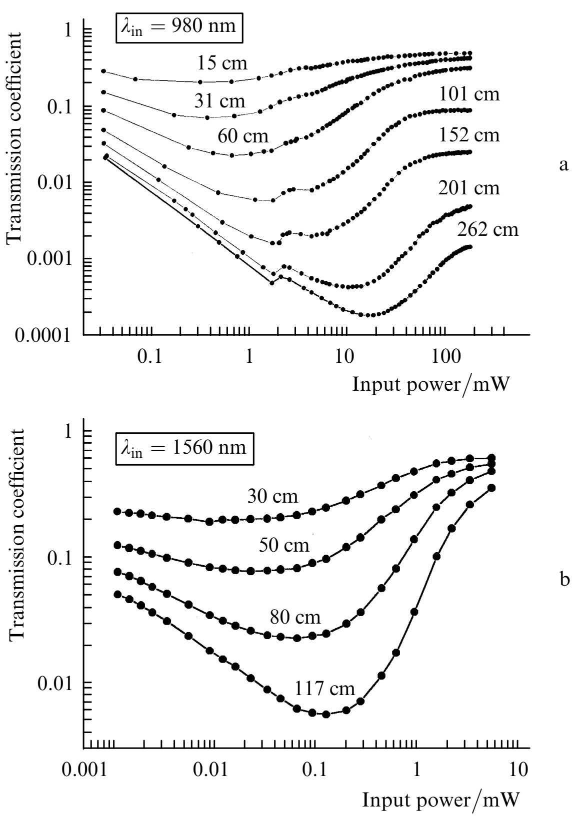

Figure 7. Dependences of the transmission coefficient of the erbium-doped fibres of different lengths on the power of input continuous radiation at 980 (a) and 1560 nm (b).

4. Conclusions

We have demonstrated stable self-*Q*-switching in an erbium-doped fibre laser of the simplest design with FBG mirrors in a broad range of pump powers. The laser emits a continuous train of short submicrosecond pulses (~ 750 ns) with pulse repetition rates from 100 to 300 kHz. We have studied experimentally the features of the laser dynamics, in particular, the passage of the laser from the free-running regime (with a weak modulation of radiation at the frequency of relaxation oscillations) to passive (total) *Q*-switching, as well as the dependences of the pulse repetition rate and duration of short pulses on the pump power and the active fibre length. We have analysed physical mechanisms that can be responsible for the appearance of self-*Q*-switching in the laser. The analysis has shown that the most important mechanism is the thermal self-induction of a nonlinear lens inside the erbium-doped fibre, which appears due to excited-state absorption in erbium ions (the concentration of these ions in our fibre is high). This absorption results in a strong heat release inside the active fibre.

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