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Effect of the active-ion concentration on the lasing dynamics of holmium fibre lasers

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***Abstract*. The lasing dynamics of fibre lasers with a core based on quartz glass doped with holmium ions to concentrations in the range of $10^{19} - 10^{20}$ cm^{-3} is investigated. It is shown that fibre lasers with a high concentration of active holmium ions generate pulses, but a decrease in the holmium concentration changes the lasing from pulsed to cw regime. At the same time, a decrease in the active-ion concentration and the corresponding increase in the fibre length in the cavity reduce the lasing efficiency.**

Keywords: *holmium fibre laser, lasing dynamics, up-conversion.*

1. Introduction

Holmium fibre lasers with an output average power to 10 W and a radiation wavelength of 2.05 – 2.1 μm, pumped by a fibre ytterbium laser, were described recently in [1]. These lasers used fibres with a high concentration of active ions (more than 10^{20} cm^{-3}) as an active medium; their differential efficiency with respect to the pump power was as high as 34 % [2]. It was shown in [3] that active ions in such concentrations form clusters; as a result, many of them nonradiatively relax to the ground level, thus affecting the lasing efficiency. The ions relaxing to the ground level can play the role of a saturating absorber, which results in the pulsed lasing regime. The pulsed regime was observed for lasers based on heavily erbium-doped fibres [4, 5]. In [6] a holmium laser based on a fibre with an active holmium concentration of 1.9×10^{20} cm^{-3} was also found to operate in the pulsed regime.

The purpose of this study was to analyse the effect of the holmium ion concentration in active fibres on the dynamic properties of the lasers based on these fibres and choose the active-ion concentration ensuring cw lasing. In addition, we compared the efficiencies of lasers using heavily and lightly holmium-doped fibres as active media.

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2. Experimental

We investigated three samples of active fibres with the following concentrations of holmium ions: 9×10^{19}, 5.4×10^{19}, and 1.6×10^{19} cm^{-3} (Nos 1 – 3, respectively). All samples were MCVD-fabricated, applying impregnation of the fibre core with holmium oxides and additional doping with aluminum oxide. The holmium concentration in sample 1 was determined by X-ray microscopy. In samples 2 and 3 the concentration was found by measuring the absorption spectra near 1.15 and 2 μm, taking into account the field distribution in these fibres.

The scheme of the experiment was similar to that described in [3]. Pumping was performed by an ytterbium laser based on a GTWave fibre, with a radiation wavelength of 1.125 μm. The holmium-laser cavity was formed by a highly reflecting Bragg grating with a resonant wavelength of 2.1 μm and the output fibre face. The laser dynamic characteristics were measured by an InGaAs photodetector, operating in the spectral range of 1.2 – 2.6 μm and having a frequency band up to 15 MHz.

3. Results and discussion

The laser based on sample 1 (with a maximum active-ion concentration) was found to stably generate in the pulsed regime in the entire range of pump powers (up to 10 W). A characteristic shape of the laser pulse is shown in Fig. 1. The pulse repetition frequency and width depended on the pump power. The corresponding dependences are presented in Fig. 2. It can be seen that the pulse repetition rate increases nonlinearly with increasing pump power, whereas

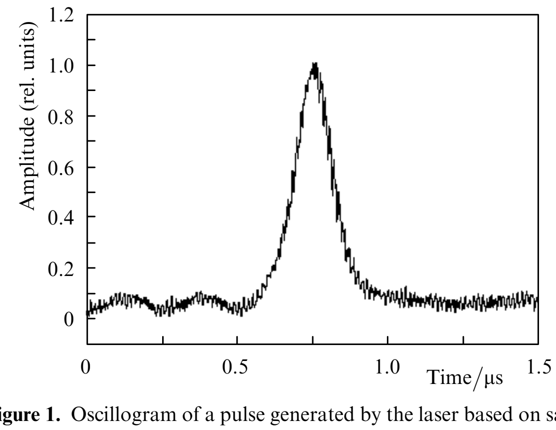

Figure 1. Oscillogram of a pulse generated by the laser based on sample 1.

the pulse width decreases nonlinearly. The peak power of the holmium laser also increases, reaching 10 W at a pump power of 10 W. With a decrease in the fibre length in the cavity from 1.8 to 0.3 m, the pulsed regime retained up to its suppression because of the small length of the active medium. On the whole, these results are similar to those obtained in [6], where a fibre with somewhat higher concentration of active ions (1.9×10^{20} cm^{-3}) was used.

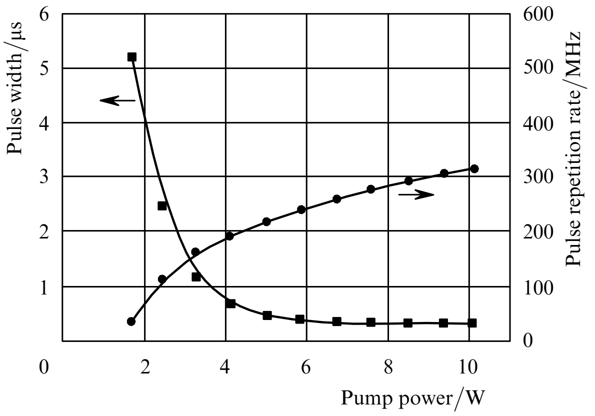

Figure 2. Dependences of the pulse repetition rate and width on the pump power for the laser based on sample 1.

For the laser based on sample 2, with a length of about 3.5 m and lower holmium concentration, we observed a change not only in the pulse parameters but also in the lasing character with a change in the pump power. At pump powers up to 6 W the lasing was pulsed, with parameters similar to those of the laser fabricated on sample 1. However, with a further increase in the pump power the lasing dynamics first exhibited an intensity-modulated background and then transformed into continuous. The corresponding oscillograms of the output radiation are shown in Fig. 3. This behaviour of the holmium laser is qualitatively the same as that of the erbium fibre lasers [4].

Obviously, to obtain cw lasing in a wide range of pump powers, it is necessary to reduce even more the concentration of active ions and, correspondingly, the relative concentration of their pairs (involved in up-conversion) [7]. Indeed, using the laser based on sample 3 with a length of

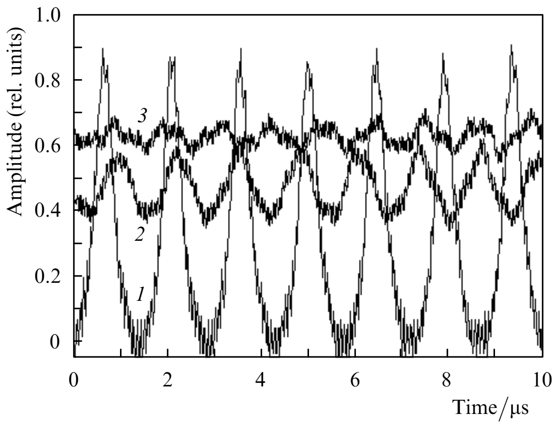

Figure 3. Oscillograms of output radiation for the laser based on sample 2 at pump powers of (*1*) 6, (*2*) 8, and (*3*) 10 W.

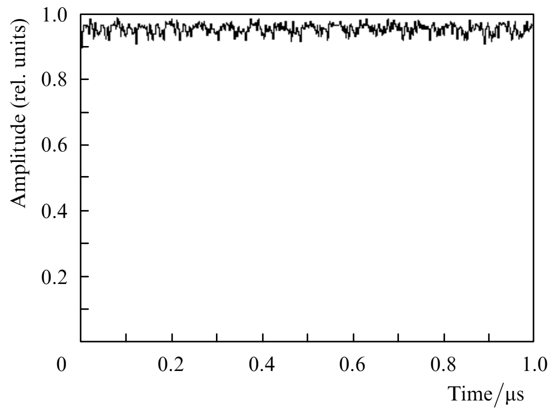

Figure 4. Oscillograms of output radiation for the laser based on sample 3.

13 m, we obtained cw lasing beginning with pump powers only slightly exceeding the threshold (the corresponding oscillogram is shown in Fig. 4).

The above results suggest that fibres doped with holmium to a concentration of $\sim 10^{19}$ cm^{-3} or lower should be used to obtain cw lasing. However, a decrease in the concentration significantly increases the fibre length in the laser cavity, and the optical loss caused by the IR absorption edge of SiO_2 molecules near 10 μm can be pronounced. The lasing efficiency was measured to verify the effect of increase in the fibre length in the lasers based on samples 2 and 3 on their operating characteristics.

The measurement results are shown in Fig. 5. One can see that an increase in the active fibre length in the cavity significantly reduces the lasing efficiency. For example, the laser based on sample 2 (with a length of about 3.5 m) had a differential efficiency of 34 %, whereas the laser on sample 3 with a fibre length of about 13 m had an efficiency of 27 %. There are several ways to reduce the fibre length in the cavity with the active-ion concentration preserved. In particular, optimisation of the fibre waveguide structure and active impurity distribution in the core have good prospects. Another promising way is to use an ytterbium fibre laser with a wavelength of 1.15 μm (which corresponds to the maximum of holmium absorption band) for pumping. The possibility of developing effective ytterbium lasers for this spectral range was discussed in [8].

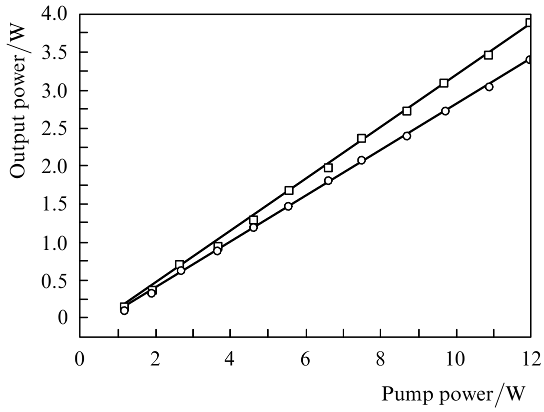

Figure 5. Dependences of the output power on the pump power for the lasers based on samples (□) 2 and (○) 3.

4. Conclusions

It was shown that the lasing dynamics of a fibre holmium laser depends on the active-ion concentration in the fibre core. Lasing is pulsed at concentrations of about 10^{20} cm^{-3} or higher. The transition from the pulsed to cw lasing occurred in lasers based on fibres doped to $\sim 5 \times 10^{19}$ cm^{-3} with an increase in the pump power. At holmium concentrations reduced to 10^{19} cm^{-3} cw lasing was observed in the entire range of pump powers. This behaviour is caused by the following: the fraction of ions that nonradiatively relax to the ground level and play the role of saturating absorber is higher in fibres with a high concentration of active ions. A decrease in the active-ion concentration and the corresponding increase in the fibre length in the cavity reduce the lasing efficiency.

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