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Holmium fibre laser with record quantum efficiency

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***Abstract*. We report holmium-doped fibre lasers with a Ho^{3+} concentration of 1.6×10^{19} cm^{-3} and lasing wavelengths of 2.02, 2.05, 2.07 and 2.1 μm at a pump wavelength of 1.15 μm. The slope efficiency of the lasers has been measured. The maximum efficiency, 0.455, has been obtained at a lasing wavelength of 2.05 μm. The laser efficiency is influenced by both the optical loss in the wing of a vibrational absorption band of silica and active-ion clustering.**

Keywords: *fibre laser, holmium ions, laser quantum efficiency.*

1. Introduction

Ho^{3+}-doped fibre lasers operate in the range 2 – 2.15 μm and are of interest for laser ranging systems, open optical networks and medical applications. A key characteristic of such lasers is their efficiency with respect to pump power. Among the most attractive pump sources for holmium fibre lasers are ytterbium-doped fibre lasers operating in the range 1.12 – 1.16 μm, which enable high pump powers to be coupled into the core of holmium-doped fibre and allow the compact design and other inherent advantages of all-fibre lasers to be retained. In an earlier study [1], a number of fibre lasers with a high holmium concentration were demonstrated. They operated in the range 2.02 – 2.15 μm and showed a maximum output power and slope efficiency of 4.2 W and 0.34, respectively, at a wavelength of 2.1 μm. Note that the efficiency varied only slightly in the range 2.05 – 2.15 μm. Raising the pump power to 35 W enabled an increase in the output power of the holmium fibre laser to 10 W [2]. The highest slope efficiency, 41 %, was reported by Jackson and Li [3], with a maximum output power of about 1.6 W at 2.1 μm.

The purpose of this work is to optimise active-fibre and pump parameters in order to raise the slope efficiency of the holmium fibre laser. In addition, we examine the basic factors that limit the laser efficiency.

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2. Fibre and experimental arrangement

One fundamental factor that limits the efficiency of two-micron fibre lasers is the optical loss in the wing of a vibrational absorption band of SiO_2 molecules. Figure 1 shows the spectral dependence of the optical loss in a multimode fibre with a silica core doped with alumina and germania. A similar host glass composition was used in the fabrication of the holmium-doped fibre. The optical loss in the range 2 – 2.2 μm is seen to rise exponentially from 0.07 to 0.33 dB m^{-1}. This level of loss should have a marked effect on laser efficiency at an active-fibre length of the order of 10 m or more. The active-fibre length can be reduced by raising the holmium concentration.

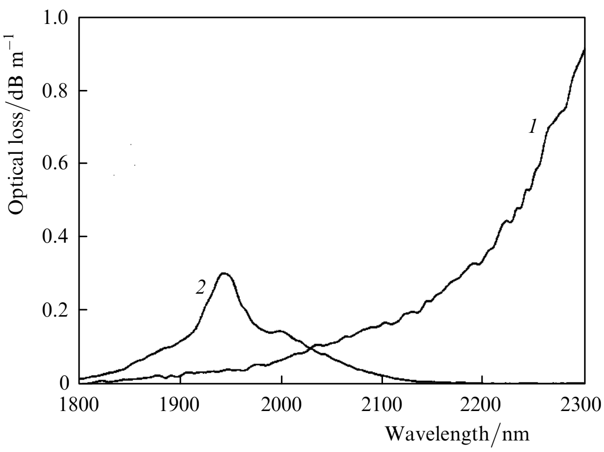

Figure 1. (*1*) Optical loss spectrum of a fibre with a silica core doped with alumina and germania; (*2*) absorption spectrum due to the relaxation of clustered ions to their ground level.

However, at high concentrations of active ions, these typically undergo clustering. As a result, a significant fraction of the active ions relax nonradiatively to their ground level, affecting the laser efficiency, which decreases with increasing active-ion concentration [4]. In view of this, to maximise the laser efficiency we used a fibre with an active-ion concentration of 1.6×10^{19} cm^{-3}. From the unbleachable absorption level [5], the fraction of clustered ions was estimated at 2 %. The absorption spectrum due to the fast relaxation of the clustered ions to their ground level is presented in Fig. 1. In addition, the active fibre showed a loss at a level of 0.03 dB m^{-1}, which was measured at 1.3 μm using a reflectometer.

Previous work [6] has shown that, at the holmium concentration in question and a pump wavelength of 1.125 μm, the optimal active-fibre length in the cavity exceeds 10 m, resulting in lower efficiency compared to a laser with a higher Ho^{3+} concentration (5.4×10^{19} cm^{-3}). To reduce the active-fibre length, the fibre was pumped by an ytterbium fibre laser operating at 1.15 μm, the peak-absorption wavelength of the holmium ion, which ensured efficient pump absorption at shorter fibre lengths. The highest pump power was about 9 W.

The laser configuration was similar to that in a previous study [4]. The cavity of the holmium fibre laser was formed by a high-reflectivity Bragg grating and the output fibre face. We examined four lasers with Bragg resonance wavelengths of 2.02, 2.05, 2.07 and 2.1 μm. The gratings were inscribed using two-beam interference.

3. Results and discussion

In our experiments, the output power of a holmium fibre laser was measured as a function of absorbed pump power. For each laser, the fibre length in the cavity was optimised so as to reach the highest output power. In the 2.1-μm laser, the fibre length was about 5.5 m. With decreasing lasing wavelength, the fibre length decreased, down to 4 m at $\lambda = 2.02$ μm. The unabsorbed pump power and lasing signal were separated by a filter with an absorption of −27 dB at the pump wavelength. The unabsorbed power amounted to about 5 % of the launched power. Figure 2 plots the output power against absorbed pump power for the 2.05-μm laser. Its slope efficiency was determined to be 0.455 ± 0.01.

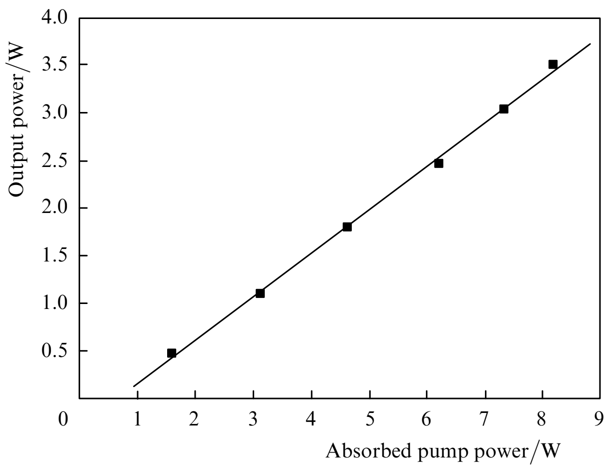

Figure 2. Output power as a function of absorbed pump power for the 2.05-μm laser.

Figure 3 shows the spectral dependence of slope efficiency for the four lasers, with a maximum of 0.455 at $\lambda = 2.05$ μm. Comparison with the data in Fig. 1 leads us to conclude that the decrease in efficiency in the longer wavelength part of the spectrum is caused by the sharp rise in the fundamental optical loss in the wing of a vibrational absorption band of SiO_2. The reduction in efficiency is aggravated by the necessity to increase the active-fibre length because of the decrease in luminescence cross section in the longer wavelength part of the spectrum.

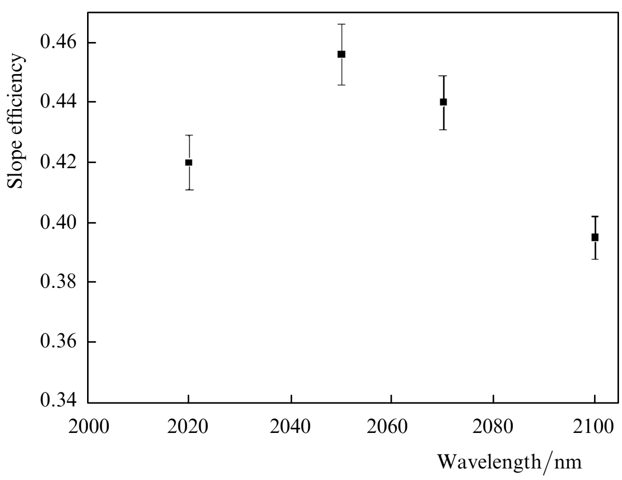

Figure 3. Spectral dependence of laser slope efficiency.

In the shorter wavelength part of the spectrum in Fig. 3, the laser efficiency is influenced by the absorption due to the fast relaxation of a fraction of the ions to their ground level because of the interaction in clusters. It is therefore reasonable to conclude that the holmium concentration in the active fibre should be adjusted to the desired laser wavelength. In particular, lasers with $\lambda > 2.1$ μm should have an increased holmium concentration in order to reduce the fibre length and, hence, the effect of fundamental optical losses. The clustering effect on the laser efficiency will then be less significant. At the same time, shorter wavelength lasers ($\lambda < 2.05$ μm) should have a somewhat lower active-ion concentration, which would reduce the clustering probability. An increase in active-fibre length will then have a relatively weak effect on the laser efficiency.

The highest slope efficiency achieved corresponds to a quantum efficiency of 0.81. The total optical loss at 2.05 μm is about 0.2 dB m^{-1}. At a cavity length of 5 m, this corresponds to 1 dB per pass. Thus, the slope efficiency achieved is close to the theoretical limit. The results above can be compared to those reported by Kim et al. [7], who reached a slope efficiency of 0.64 using a 1.98-μm thulium fibre laser as a pump source. This slope efficiency corresponds to a quantum efficiency of 0.67, indicating that the active fibre quality and cavity design in that study were far from optimal.

4. Conclusions

We have demonstrated a holmium fibre laser with a record differential quantum efficiency of 0.81 and examined the influence of the optical loss in the wing of a vibrational absorption band and active-ion clustering on the spectral laser efficiency. The results suggest that the holmium concentration in the active fibre should be adjusted to the desired laser wavelength.

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