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Effect of active-ion concentration on holmium fibre laser efficiency

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***Abstract*. We have measured the fraction of holmium ions that relax nonradiatively to the ground level as a result of interaction at a metastable level in optical fibres with a silica-based core doped with holmium ions to $2 \times 10^{19} - 2 \times 10^{20}$ cm^{-3}. The percentage of such ions has been shown to depend on the absolute active-ion concentration. The fibres have been used to make a number of 2.05-μm lasers, and their slope efficiency has been measured. The laser efficiency decreases with increasing holmium concentration in the fibres**

***Keywords*:** *holmium fibre laser, active-ion clustering, laser slope efficiency.*

1. Introduction

Fibre lasers are attractive emitters owing to their compact design and high efficiency, with the possibility of operating without mechanical adjustment. Lasers based on ytterbium-, erbium- and thulium-doped fibres are sufficiently well developed [1]. These sources find application in materials processing, medicine, optical radar systems, etc. Ho^{3+}-doped fibre lasers have been studied in much less detail, and such emitters have not been commercialised. The development of holmium fibre lasers is of high current interest because they operate in the range 2 – 2.2 μm, i.e., within one of the atmospheric windows. In addition, biological tissues show a significant absorption at these wavelengths, which makes holmium lasers potentially attractive for medical applications.

In recent years, the output power of holmium fibre lasers in the range 2.05 – 2.15 μm has been brought to 10 W [2, 3]. The maximum slope efficiency is 0.34 with respect to absorbed pump power at 1.125 μm, which corresponds to a differential quantum efficiency of 0.63. Although the performance achieved suggests that such lasers may be of practical use, there is high current interest in improving the efficiency of holmium fibre lasers. Active-ion clustering is known to reduce lasing efficiency. Such an effect in erbium-doped fibre has been studied in sufficient detail by Myslinski et al. [4] and Plotskii et al. [5]. Their results show that the fraction of clustered ions increases with active-ion concentration and that doping with alumina reduces the clustering probability. Excitation of two active ions in a cluster at a metastable level is followed by energy transfer from one ion to the other. As a result, the latter ion is promoted to a higher energy level and the former relaxes nonradiatively to the ground state. Therefore, half the ions in the clusters (if each cluster consists of only two active ions) are at the ground level, independent of the pump power, and are not involved in the amplification process. This leads to pump power and output power losses because holmium lasers operate as three-level systems.

One obvious way to prevent clustering is to reduce the active-ion concentration. In the case of holmium lasers, however, a reduction in concentration and the corresponding increase in active-fibre length in the cavity may lead to a reduction in laser efficiency because of the rather high optical loss at 2 – 2.2 μm due to the influence of the wing of the vibrational absorption band near 10 μm. This loss is estimated at 0.1 – 0.2 dB m^{-1}, so an increase in cavity length to 10 m or above may significantly degrade the laser performance. In earlier studies [2, 3], the Ho^{3+} concentration in fibre was above 10^{20} cm^{-3}, which ensured a cavity length of about 1 m. The purpose of this work was to investigate the effect of doping level on lasing efficiency. In addition, we studied one sample of alumina-free fibre.

2. Samples

We studied five samples of fibres produced by the MCVD process. The fibres were doped with holmium oxides via impregnation. The main parameters of the fibres are listed in Table 1. Samples 1 – 4 were codoped with alumina. The refractive-index profile in sample 5 was produced by doping with germanium oxide. Using an X-ray microscope, we measured the dopant profiles in the preforms of samples 2 – 4. Figure 1 shows the holmium and aluminium profiles across sample 2. The alumina concentration in sample 1 was evaluated from its refractive-index profile. The holmium concentration in samples 1 and 5 was determined from their absorption spectra in the 1.15 and 2 μm ranges with allowance for the field distribution in these fibres.

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Table 1. Main parameters of the fibres and lasers studied.

Sample No.	Δn_{max}	C_{Al} (%)	λ_c/μm	1.125-μm absorption/ dB m^{-1}	$C_{Ho^{3+}}/10^{19}$ cm^{-3}	$2k$ (%)	η (%)
1	0.009	3	1.8	28	19	38	26
2	0.006	2.4	1.55	21	12.5	26	30
3	0.005	2	1.25	17	9	24	32
4	0.003	1.4	1.2	7	4.1	11.4	–
5	0.012	–	1.5	4	2	66	20

Note: C_{Al} is the Al weight concentration; λ_c is the cutoff wavelength; $C_{Ho^{3+}}$ is the Ho^{3+} concentration; $2k$ is the fraction of clustered ions; and η is the slope efficiency.

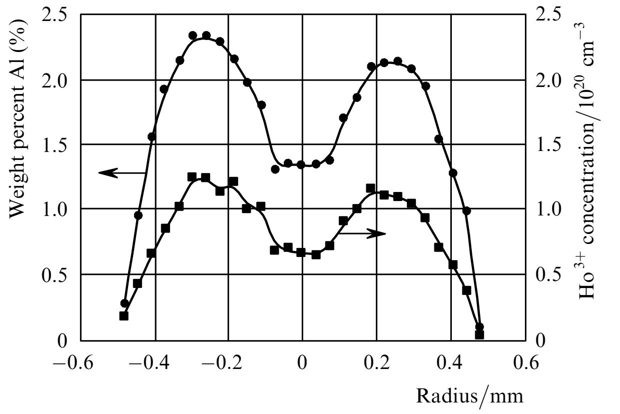

Figure 1. Dopant profiles across the preform of sample 2.

3. Measurement of the degree of Ho^{3+} clustering

The degree of holmium-ion clustering in the fibres was assessed by the method proposed by Myslinski et al. [4] for erbium-doped fibres and modified by Plotskii et al. [5]. To determine the fraction of ion pairs, $2k$, the transmittance T at 1.125 μm (one of the absorption bands of Ho^{3+}) was measured as a function of launched pump power P. The pump source used was an ytterbium fibre laser. We assumed that, as a result of the interaction between clustered active ions, a fraction k of the ions rapidly relaxed to the ground state via energy transfer, absorbing the pump energy independent of the pump intensity. Therefore, we measured the residual absorption. To more accurately take into account the guidance properties of the active fibre, the measurement results, $T_m(P)$, were compared to T_c calculated under the assumption that there was no ion–ion energy transfer. The fraction of ions relaxing to the ground state was determined as

$$k = \frac{10\lg(T_c/T_m)}{L\alpha}, \quad (1)$$

where L is the fibre length and α is the small-signal absorption coefficient.

Transmittance was calculated with allowance for the guidance properties of the holmium-doped fibre. Figure 2 plots the calculated and measured transmittances against launched pump power for sample 1, which had the highest active-ion concentration. The fibre length corresponded to a small-signal absorption at a level of 10 dB. From comparison of the calculation results and experimental data, the fraction of ions that relax nonradiatively to the ground level can be estimated at 19%.

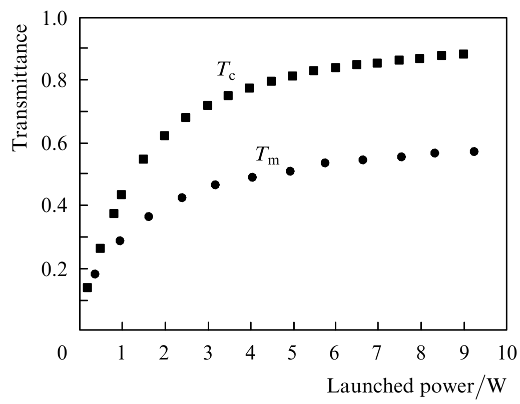

Figure 2. Calculated (T_c) and measured (T_m) transmittances vs. launched pump power for sample 1.

Figure 3 plots the measured transmittance as a function of launched pump power for a number of samples. The curves are numbered according to the sample number in Table 1. In all cases, the fibre length corresponded to a small-signal absorption of 10 dB. The curve obtained for sample 3 differed little from that for sample 2. The difference in k between these samples was mainly due to the fact that they differed in guidance properties. The k values for all the samples studied are given in Table 1. As seen, k increases with active-ion concentration. Note that the fraction of clustered ions in the aluminium-free fibre is much higher than that in the other samples.

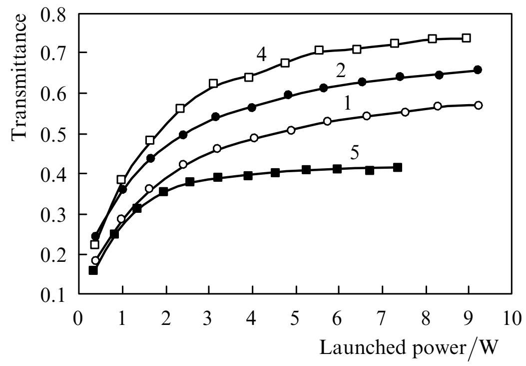

Figure 3. Measured transmittance vs. launched pump power (the curves are numbered according to the sample number).

4. Lasing efficiency

To assess the effect of holmium-ion concentration and glass network composition on lasing efficiency, we performed experiments with the above samples as gain media. The laser configuration is shown in Fig. 4. The pump source used was an ytterbium-doped GTWave fibre laser emitting at 1.125 μm. Ytterbium laser pumping of holmium lasers was first proposed by Kurkov et al. [6] and was examined in detail in later studies [7, 8]. The ytterbium fibre laser was pumped by a Milon semiconductor laser. The cavity of the holmium fibre laser was formed by the output fibre face and a high reflectivity Bragg grating with a resonance wavelength of 2.05 μm. The grating was inscribed using two-

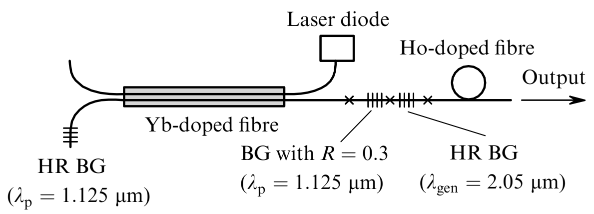

Figure 4. Fibre laser configuration: (HR BG) high-reflectivity Bragg grating; (R) reflectivity; (×) fusion splice.

beam interference [9]. The resonance wavelength was checked using the second-order resonance. All of the active-fibre samples except sample 4 showed laser action. Sample 4 had considerable radiative losses in the 2-μm range because of its poor guidance properties, which prevented lasing.

Figure 5 shows the output power at 2.05 μm as a function of absorbed pump power at 1.125 μm. The curves are numbered according to the sample number in Table 1. For all the lasers, we determined the optimal cavity length corresponding to the maximum output power, because this is essential for three-level laser operation. The unabsorbed pump power was eliminated by a filter with an absorption of −27 dB at the pump wavelength and −1 dB at the lasing wavelength. The experimental data were used to determine the laser slope efficiency for each active fibre (Table 1). It follows from these data that the lasing efficiency correlates with the fraction of ions that relax nonradiatively to the ground level, k: the slope efficiency is highest at the lowest value of k. In the fibres having an aluminium-doped core, the efficiency decreases with increasing holmium concentration. Sample 5, containing no alumina, showed low lasing efficiency, even though the active-ion concentration in it was relatively low. Note that, even in sample 3, which had the highest slope efficiency, 32 %, the differential quantum efficiency was 58 %, i.e., well below the quantum limit. Since this sample had a rather high k value, it seems likely that it is active-ion clustering which is responsible for the drop in efficiency. Therefore, it is reasonable to expect that reducing the holmium concentration in the active fibre will improve the laser efficiency. At the same time, the active-ion concentration cannot be below 10^{19} cm^{-3} because otherwise the cavity length will exceed 10 m and additional optical losses typical of silica fibres in the spectral range in question will become essential.

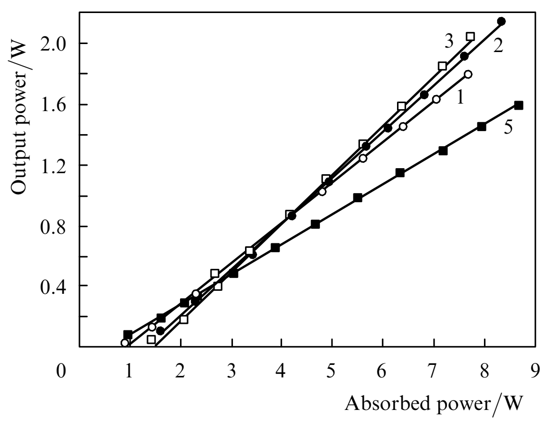

Figure 5. Output power of the holmium fibre laser at 2.05 μm as a function of absorbed pump power.

5. Conclusions

The present results show that holmium-doped optical fibres exhibit concentration effects due to active-ion clustering. It causes a significant fraction of the holmium ions to relax nonradiatively to the ground level. As a result, the holmium fibre laser efficiency decreases with increasing active-ion concentration. The concentration effects are less pronounced in the aluminosilicate core fibres. To improve the holmium fibre laser efficiency, it is necessary to optimise the holmium concentration in the gain medium.

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