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Amplifying properties of heavily erbium-doped active fibres

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***Abstract*. The relative concentration of erbium ions undergoing nonradiative relaxation from the metastable to the ground level is measured in aluminosilicate glass fibres doped with erbium ions at concentration between 3×10^{18} and 10^{20} cm^{-3}. The dependence of the fraction of such ions on the Er^{3+} concentration is determined for fibres containing different amounts of aluminium oxide in a core. It is shown that the fraction of erbium ions not involved in amplification substantially decreases with increasing the Al_2O_3 concentration. It is found that clustering leads to a considerable decrease in the gain in heavily Er^{3+}-doped active fibres. The dependence of the quantum efficiency of a fibre amplifier on the erbium ion concentration is obtained based on the measurements performed. This dependence can be used for optimising the parameters of erbium-doped fibre amplifiers.**

Keywords: *optical fibres, erbium ions, gain.*

1. Introduction

Erbium-doped optical fibres belong to one of the most widespread types of active fibres which are widely used in fibre amplifiers in optical communication systems. One of the important characteristics of an amplifier is the length of its active fibre, which is mainly determined by the concentration of active ions. The dependence of the gain on the concentration of active ions in fibres was studied in a number of papers. Thus, it was shown in [1, 2] that the gain decreased when the concentration of erbium ions exceeded a certain limit, the limiting concentration being dependent on the presence and concentration of other dopants. In particular, it was found that doping a silica glass network with Al_2O_3 resulted in the increase in the limiting concentration of rare-earth ions.

The decrease in the gain was explained in [1, 2] by clustering of erbium ions, when the relative fraction of clustered ions increased with increasing the absolute concentration of erbium oxide. Upon excitation of two erbium ions in a cluster, energy transfer occurs from one ion to the metastable ion of another ion. As a result, one of the ions undergoes a transition to a higher energy level, while another undergoes the nonradiative transition to the ground level. Therefore, half the ions in clusters (assuming that clusters contain only two active ions) occupy the ground level, irrespective of the pump power, and are not involved in amplification. This leads to losses both in the pump power and amplified signal because the erbium amplifier operates according to the three-level scheme. For this reason, the maximum concentration of active ions in fibres used in amplifiers in communication links does not exceed 10^{19} cm^{-3} for the molar concentration of aluminium oxide equal to 1 % – 2 %. For such concentration of erbium ions, the active-fibre length is about 10 m.

Optical fibres heavily doped with Er_2O_3 attract recent interest due to the development of femtosecond fibre lasers emitting pulses of duration of a few tens and hundreds of femtoseconds [3, 4]. The average power of such lasers is usually low, and the pulse amplification is required for their successful applications. In this case, the length of the active fibre in the amplifier is important because the probability of the appearance of nonlinear effects and distortion of the pulse shape decreases in shorter fibres.

The aim of this paper is to measure the concentration of clusters in erbium oxide- and aluminium oxide-doped fibres fabricated by the MCVD technique. Compared to a popular method of doping from solution, this technique allows one to dope the fibre core with aluminium oxide up to considerably high concentrations. Fibres fabricated by this technique were used in [5] to demonstrate the possibility of the fabrication of short amplifiers. In addition, it is important to study the amplifying properties of such fibres and to determine the dependence of the gain on the concentration of impurity oxides in order to select a proper composition of the active medium for a short fibre amplifier.

2. Experimental samples

We studied 10 fibre samples, which were fabricated by the MCVD technique by doping with erbium and aluminium oxides from a gas phase. The basic parameters of the fibres are presented in Table 1. The concentration of Al_2O_3 was determined from the refractive index profile measured in a fibre preform, and the concentration of erbium ions from absorption measured at 1.53 μm taking into account the radial distribution of the radiation field.

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Table 1. Parameters of the fibres.

Sample number	Δn	$C_{Al_2O_3}$ (%)	$\lambda_c/\mu m$	$N_{Er^{3+}}/10^{18}$ cm^{-3}	k (%)
1	0.017	9	0.9	22	2.2
2	0.016	8.4	0.96	13	1.8
3	0.014	7.4	0.93	3	< 0.5
4	0.0167	8.8	0.82	65	4.2
5	0.0187	9.8	0.8	100	8.5
6	0.0025	1.3	1.44	17.5	6.3
7	0.0071	3.7	1.43	8	2.5
8	0.0033	1.7	1.44	12.5	4.5
9	0.0049	2.6	1.37	13	4.2
10	0.003	1.6	1.47	17	5.7

All the samples can be divided into two groups. Fibres Nos 1 – 5 have a large difference Δn of the refractive indices of the core and cladding, the molar content of aluminium oxide $C_{Al_2O_3}$ more than 7 % and the cut-off wavelength $\lambda_c < 1$ μm. These parameters provide the shift of the zero chromatic dispersion wavelength λ_0 above 1.55 μm; the chromatic dispersion in the gain region is $-15 \div -20$ ps nm^{-1} km^{-1}. Fibres Nos 6 – 10 have a small difference of the refractive indices of the core and cladding, the molar content of Al_2O_3 less than 4 %, and the cut-off wavelength lying between 1.4 and 1.5 μm. The zero chromatic dispersion wavelength λ_0 is ~ 1.3 μ and the chromatic dispersion in the gain region is 15 – 20 ps nm^{-1} km^{-1}. Therefore, these fibres have substantially different dispersion properties and can be used for example, for generation of short laser pulses and their compression during amplification.

3. Experimental setup

The scheme of the experimental setup is shown in Fig. 1. A 5-mW, 1.56-μm fibre laser was pumped by a 300-mW, 0.976-μm semiconductor laser with a pigtail. Fibre laser and pump radiations were combined by a multiplexer. The signal source and amplifier were optically decoupled with the help of an isolator. The output power of the amplifier was measured with a power meter.

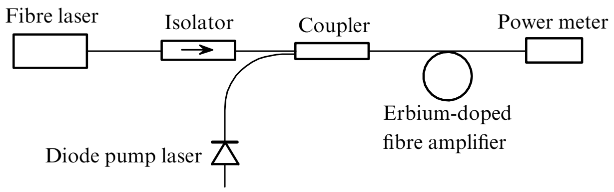

Figure 1. Scheme of the experimental setup.

4. Measurement of the clustering degree of Er^{3+} ions

The clustering degree of erbium ions in fabricated fibres was measured by the method proposed in [6]. The fraction $2k$ of ions combined in pairs was determined in [6] by measuring the transmission T of radiation in the 0.98-μm absorption band of Er^{3+} ions as a function of the pump power P. It was assumed that due to the interaction of active ions in clusters, the fraction k of ions rapidly relaxes to the ground state by absorbing the pump radiation irrespective of its power. Thus, by measuring $T(P)$, we determined the residual absorption. In [7], it was proposed to determine the waveguide parameters of the active fibre more correctly by comparing the measured dependence $T_m(P)$ with the corresponding calculated dependence $T_c(P)$ obtained by assuming the absence of energy transfer between ions. Then, the fraction k of ions relaxing to the ground level can be determined from the relation

$$k = \frac{10}{L\alpha} \lg \frac{T_c}{T_m}, \tag{1}$$

where L is the fibre length and α is the absorption coefficient measured for a weak input signal.

We calculated transmission by using the model [8] taking into account both the gain and waveguide properties of a fibre doped with erbium ions. As the initial data, we used the measured parameters of fibres and tabulated values of absorption and luminescence cross sections, as well as the metastable-level lifetimes of erbium ions in a silica glass doped with aluminium oxide. Note that in the saturation regime the results of calculations weakly depend on the variation in the initial data.

We tested this method by calculating and measuring the dependence of transmission on the pump power for a sample of length 4 m with a low (3×10^{18} cm^{-3}) concentration of erbium ions (No 3 in Table 1). Transmission was measured in the absence of a signal at 1.56 μm, by studying only the transmission of pump radiation. The results presented in Fig. 2a demonstrate good agreement between calculations and measurements, which suggests that the clustering degree of Er^{3+} ions is low. Taking into account

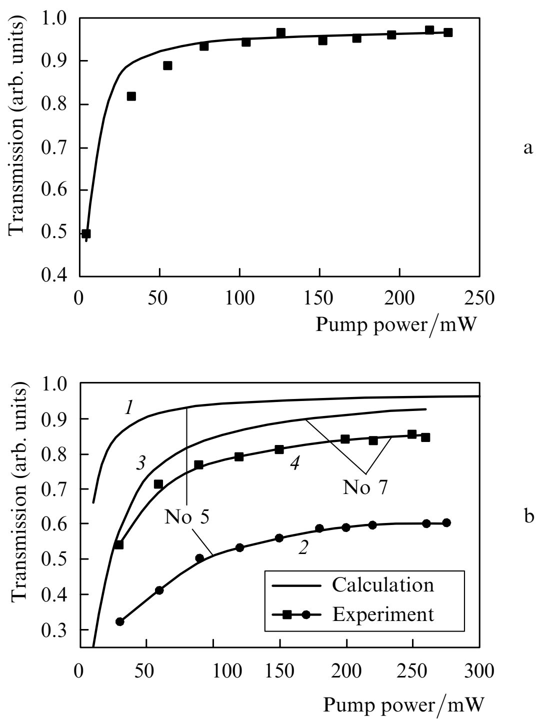

Figure 2. Calculated and measured dependences of transmission on the pump power for sample No 3 (a) and samples No 5 (*1*, *2*) and No 7 (*3*, *4*) (b).

the scatter of experimental points and the measurement error of the fibre parameters, the measurement error of the fraction k of relaxing ions can be estimated as 0.5 %. Therefore, we can assume that $k < 0.5\,\%$ for this sample. A similar result was obtained in [6] for a fibre with the close concentration of erbium ions.

Figure 2b shows the dependences of transmission on the pump power for two fibres with the erbium ion concentrations equal to 10^{20} and 8×10^{18} cm^{-3} (samples Nos 5 and 7 in Table 1). The lengths of fibres Nos 5 and 7 were 0.3 and 2 m, respectively, providing approximately the same absorption of weak radiation. The difference in the behaviour of the calculated transmission [curves (1) and (3)] is explained by the increase in the power density in sample No 5 due to a smaller diameter of its core. These results show that the calculated and measured transmission coefficients for these samples are substantially different, the discrepancy increasing at higher concentrations of erbium ions.

By using the above-described method, we performed measurements for all the samples presented in Table 1. The corresponding values of the parameter k are also given in the table. Figure 3 presents these data as the dependences of the ion fraction k on the Er^{3+} concentration for fibres with the molar concentration of Al_2O_3 higher than 7 % and lower than 4 %, which demonstrates a strong influence of aluminium oxide on the probability of erbium ion clustering. A comparison with the results obtained in paper [9], where the value $k = 12\,\%$ was obtained for a fibre fabricated by doping from solution and containing 6×10^{19} cm^{-3} erbium ions, demonstrates the advantage of fibres fabricated by the MCVD technique by doping with aluminium and erbium oxides from a gas phase allowing to achieve a higher concentrations of Al_2O_3. In our case, sample No 4 with the erbium ion concentration close to that in paper [9] had the parameter k equal only to 4.2 %.

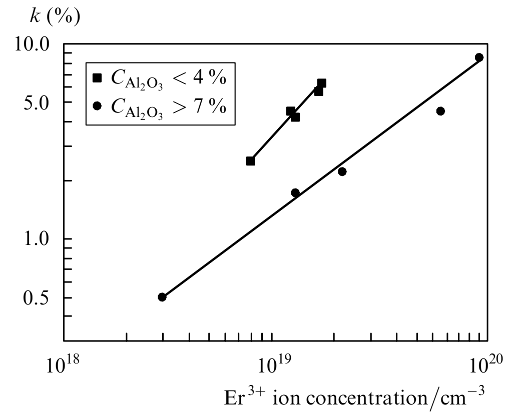

Figure 3. Fraction k of ions undergoing nonradiative relaxation to the ground level as a function of the erbium ion concentration for fibres with the molar concentration of Al_2O_3 higher than 7 % and lower than 4 %.

5. Measurement of the gain

We measured the gain for several active fibres by using the setup shown schematically in Fig. 1. Figure 4 presents the dependences of the gain on the pump power for two fibres with high concentrations of erbium ions (6.5×10^{19} and 10^{20} cm^{-3} for samples Nos 4 and 5, respectively). Measurements were performed for the 1-mW cw input signal at 1.56 μm. The length of the active fibres Nos 4 and 5 was 1.6 and 0.8 m, respectively. Curve (1) in Fig. 4 shows the dependence of the gain on the pump power calculated by neglecting the interaction between erbium ions in clusters and using the model proposed in [8]. One can see that the measured gain is approximately 3 and 5 dB lower than the calculated one for samples Nos 4 and 5, respectively.

This discrepancy can be explained by the nonradiative relaxation of a part of excited ions. The fraction of such ions for each of the samples was determined in section 4. The results of corresponding calculations are presented by curves (2) and (3) in Fig. 4. One can see that these curves are in good agreement with the experimental results. This means that the gain in fibres heavily doped with erbium ions is mainly reduced due energy transfer in erbium clusters.

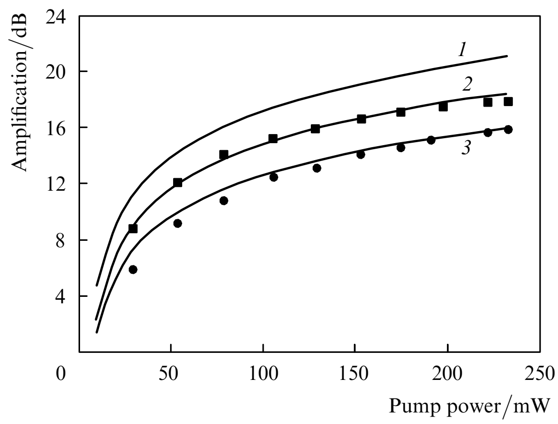

Figure 4. Dependence of the gain on the pump power calculated by neglecting energy transfer in clusters (1) and the gains measured and calculated taking into account energy transfer in clusters for samples No 4 (2) and No 5 (3).

6. Effect of the active ion concentration on the gain

By measuring the concentration dependence of the fraction k of ions undergoing nonradiative relaxation, we calculated the dependence of the efficiency of conversion of the pump radiation to the amplified signal on $N_{Er^{3+}}$. The waveguide parameters used in calculations were close to those for samples Nos 1–5: the refractive-index difference for the fibre core and cladding was $\Delta n = 0.015$ and the cut-off wavelength for the first (fundamental) mode was $\lambda_c = 0.85$ μm. Note that these parameters correspond to those of fibres heavily doped with aluminium oxide. The input signal and pump powers were assumed equal to 1 and 200 mW, respectively.

Figure 5 shows the calculated dependence of the quantum efficiency of the amplifier on the erbium ion concentration and experimental data obtained for three active fibres. One can see that the quantum efficiency of the fibre doped with erbium ions at low concentration (10^{18} cm^{-3}) achieves approximately 85 %, whereas in fibres with the erbium ion concentration of 10^{20} cm^{-3}, it is reduced down to 33 %. The calculation is confirmed by the experiment. This result can be used to optimise an

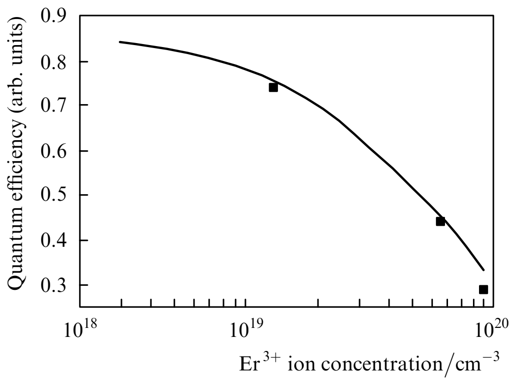

Figure 5. Calculated and measured dependences of the quantum efficiency of the amplifier on the erbium ion concentration for the fibre heavily doped with Al_2O_3.

amplifier of short pulses by using the output peak power as a parameter. In this case, the balance can be achieved between a decrease in the gain due a high concentration of active ions and the pulse broadening caused by a large length of the active medium.

7. Conclusions

We have measured the relative concentration of erbium ions undergoing nonradiative relaxation from the metastable to the ground level in aluminosilicate glass fibres doped with erbium ions at concentrations from 3×10^{18} to 10^{20} cm^{-3}. The dependence of the fraction of such ions on the concentration of erbium ions is determined for fibres with the molar concentration of aluminium oxide in the fibre core higher than 7 % and lower than 4 %. It is shown that the fraction of Er^{3+} ions not involved in amplification considerably decreases with increasing concentration of Al_2O_3. Because the MCVD technique with the deposition of aluminium and erbium oxides from a gas phase provides high concentrations of these dopants in active fibres, this technique has the advantage over other methods.

The study of the amplifying properties of active fibres has shown that ion clustering substantially reduces the gain in fibres heavily doped with erbium ions. Thus, the strong-signal gain loss was ~ 5 dB in the fibre with the erbium ion concentration equal to 10^{20} cm^{-3}. Based on the measurements performed in the study, the dependence of the quantum efficiency of the amplifier on the erbium ion concentration is obtained, which can be used to optimise erbium-doped fibre amplifiers.

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