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Evaluation of quenching effect on gain characteristics in silica-based erbium doped fiber using numerical simulation

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Abstract

The effect of Er^{3+} concentration quenching on the gain characteristics of silica-based Er^{3+} doped fiber (EDF) was investigated at 77 and 300 K, focusing on the pair induced quenching (PIQ) in silica-based EDF. By the measurements of gain spectra and the gain saturation at 77 and 300 K, the degradation of the gain in EDF with higher Er^{3+} ion concentration was verified to exist, which is due to the interaction between Er^{3+} ions. Also, the degrees of PIQ in four EDFs were examined by the numerical model. It is estimated that even about 2% paired Er^{3+} ions in EDF can cause 15% degradation of the population density of the $^4I_{13/2}$ level, which leads to about 1 dB degradation of the gain spectrum in the C-band wavelength region. The degradation of the population density of the $^4I_{13/2}$ level is discussed in connection with the number of paired Er^{3+} ions in silica-based EDF.

Keywords: Disordered systems; Luminescence

1. Introduction

One of the serious limiting factors to the performance of the Er^{3+}-doped fiber amplifier (EDFA) is the effect of the concentration quenching of the Er^{3+} ions on the gain.

A significant degradation of gain from 18.3 to 6.9 dB has been reported for the gain characteristics of EDFA, which includes 6.4×10^{25} m^{-3} ions [1]. In addition, the concentration quenching effect can be serious problems also for the Er^{3+}-doped waveguide amplifier (EDWA) and Er^{3+}-doped fiber laser (EDFL) [2,3]. The concentration quenching effect of the 1.5 μm emission of Er^{3+} is usually caused by the energy transfers between homogeneously distributed Er^{3+} ions and locally clustered Er^{3+} ions in the host glass. In particular, it has been suggested that, in highly Er^{3+}-doped fiber, Er^{3+} ions tend to cluster in pairs and that a rapid cross-relaxation process, pair induced quenching (PIQ) take place between the doubly excited Er^3 ion pairs to the $^4I_{13/2}$ level. In this process, one of the two ions transfers its energy to the other ion and is then nonraditively transferred to the ground state $^4I_{15/2}$, while the other ion is upconverted to the $^4I_{9/2}$ level, where it mostly relaxes rapidly to the metastable level $^4I_{13/2}$. Thus, doubly excited state decays very quickly and can be disregarded in the metastable state. Usually, two states of Er^{3+} ion pairs to be populated are taken into consideration: either none or one of the ions in the pair can be in its excited state $^4I_{13/2}$.

In order to study the effect of concentration quenching, particularly about PIQ, on the gain performance of the highly Er^{3+}-doped fiber focusing on the degradation of the population density of the $^4I_{13/2}$, both the numerical and experimental evaluations of the silica-based EDF with different Er^{3+} ion concentration were carried out.

2. Numerical simulation model for the gain characteristics of EDF

In order to analyze the gain characteristics, the simulation based on the Giles model [4] was implemented for the single and paired Er^{3+} ions. In this simulation procedure, the

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contributions of the excited state absorption cross-section σ_{ESA} are not taken into consideration.

For the total Er^{3+} ion concentration, N_t, the paired ion concentration was introduced to as $N_p = mkN_t$, where k is the relative number of clusters and m is the fraction of clusters. The concentration of single ions is $N_s = (1 - mkt)N_t$. Firstly, the two-level system that consists of the first excited state $^4I_{13/2}$ and the ground state $^4I_{15/2}$ was adopted in order to describe the 1.5 μm transition of Er^{3+} ions. The total inversion is given by,

$$N_2 = N_{s2} + N_{p2} \tag{1}$$

$$N_1 = N_{s1} + N_{p1} \tag{2}$$

where N_2 and N_1 are the total population densities of the $^4I_{13/2}$ and the $^4I_{15/2}$ level for the single Er^{3+} ions, respectively. N_{s1} and N_{p1} ($i = 1$ and 2) are the total population densities of the single and paired ions, respectively, in the $^4I_{13/2}$ and the $^4I_{15/2}$ level. The time evolution of N_{s2} and N_{s1} are described by the population rate equation considering the homogeneous up conversion effect and by the population conservation law:

$$N_s = N_{s1} + N_{s2} \tag{3}$$

$$\frac{dN_{s2}}{dt} = -\frac{dN_{s1}}{dt} = -(A_{21} + W_{21})N_{s2} + (W_{12} + R)N_{s1} - CN_{s2}^2 \tag{4}$$

$$W_{21(12)} = \int \frac{\sigma_{as(es)}(\nu)P_s(\nu)}{h\nu\pi b^2}\,d\nu \tag{5}$$

$$R = \int \frac{\sigma_{ap}(\nu)P_p(\nu)}{h\nu\pi b^2}\,d\nu \tag{6}$$

where A_{21} is the spontaneous emission rate, W_{12} and W_{21} are the stimulated emission and absorption rates of the signal, R the stimulated pump rate, $h\nu$ the photon energy, b the radius of the uniformly Er^{3+}-doped region, P_s and P_p are the signal and pump power, σ_{as}, σ_{es} and σ_{ap} are the absorption and emission cross-section for the signal and pump, respectively. The A_{21}, W_{12}, W_{21}, σ_{as}, σ_{es} and σ_{ap} are assumed to be the same for the single and paired Er^{3+} ions. In addition, the following steady solution for the paired ions were used,

$$N_{p2} = N_p - N_{p1} = N_p \frac{R + W_{12}}{A_{21} + m(R + W_{12}) + W_{21}} \tag{7}$$

The evolutions of pump, signal and bidirectional ASE powers, P_p, P_s and $P_{\pm ASE}$, along the fibers were given by,

$$\frac{dP_p(z)}{dz} = -\sigma_{pa}N_1P_p(z) \tag{8}$$

$$\frac{dP_s(z)}{dz} = (\sigma_{se}N_2 - \sigma_{sa}N_1)P_s(z) \tag{9}$$

$$\frac{dP_{ASE}(z)}{dz} = \pm(\sigma_{se}N_2 - \sigma_{sa}N_1)P_{ASE}(z)_{\pm}\, mh\nu\,\Delta\nu\,\sigma_{se}N_2 \tag{10}$$

where h is the Plank constant, m the number of guided modes, normally 2, propagating at the signal wavelength and $\Delta\nu$ is the ASE bandwidth. For the ASE bandwidth, $\Delta\nu$, which corresponds to the resolution of OSA, $\Delta\lambda = 0.2$ nm, was chosen uniformly for all wavelength. Using the obtained population densities by the propagation and rate equations, the gain coefficient γ (dB m^{-1}) is given by:

$$\gamma(\nu, z) = N_2(z)(\sigma_e(\nu) + \sigma_a(\nu)) - N_{total}\sigma_a(\nu). \tag{11}$$

The total gain of EDF in linear scale is obtained by accumulating the gain coefficient γ along the fiber as follows:

$$\text{Gain}(\nu, z) = \exp\left[\int (N_2(z)(\sigma_e(\nu) + \sigma_a(\nu)) - N_{total}\sigma_a(\nu))\,dz\right] \tag{12}$$

This indicates that the decrease in the population density of the $^4I_{13/2}$ level directly leads to the degradation of the gain. Therefore, the gain characteristics of the EDF samples with different Er^{3+} concentration, which have the same cross-section, were evaluated in order to investigate the effect of Er^{3+} ion concentration on the degradation of the population densities.

3. Experimental

3.1. EDF samples

Four silica-based EDF samples with different Er^{3+} ion concentration were used.

The Er^{3+} ions concentrations of samples were 180, 280, 1600, and 2600 ppm. Optical parameters for each EDF are shown in Table 1. The fiber length of each EDF was determined to include the same number of the total Er^{3+} ion. The refractive indices of EDF samples were measured with a reflectometer (Ando, AQ7413). The refractive indices of EDF samples at 1.3 μm are around 1.47.

3.2. Absorption spectra measurements

Absorption spectra of EDF samples were measured with three tunable laser sources (Santec, TSL210) and an optical spectrum analyzer (OSA) (Anritsu, MS9780A) at room temperature in the wavelength region 1420–1640 nm. The TLS and OSA were controlled by a personal computer. Signal input power was −30 dB m in order not to saturate the

Table 1
Optical parameters of four EDF samples

Sample	Er^{3+} ion (ppm wt.%)	Fiber length (m)	$n_{1.3\,\mu m}$ (−)
EDFI	180	23.2	1.476
EDFII	280	15.7	1.470
EDFIII	1600	2.9	1.470
EDFIV	2600	1.5	1.470

$^4I_{13/2}$ level by the strong excitation of probe signal. The obtained absorption cross-sections of four EDF samples were used to simulate the gain characteristics in the wavelength region 1420–1640 nm to compare with the experimental results.

3.3. Gain saturation measurements

Gain saturation measurements of silica-based EDF were performed at 77 and 300 K. For the gain saturation measurements at 77 K, EDF sample was cooled directly by liquid nitrogen in a dewar. Two EDF pairs, which have the same absorption cross-section, were used in order to compare the degradation of the population inversion ratio.

Probe signal wavelength is 1530 nm. Input signal power was varied from −40 to about 5 dB m using a variable ATT (Santec). In the gain saturation measurements, EDF samples were forwardly pumped by a 979 nm LD (FITEL). Pump power was varied from 10 to 30 mW.

3.4. Gain spectra measurements

The gain characteristics of EDF were measured at room temperature in the wavelength region 1420–1640 nm to evaluate the gain degradation caused by the Er^{3+} concentration quenching. Signal input power was −30 dB m. The EDF sample was forwardly pumped with a 979 nm LD. Pumping power was varied from 10 to 50 mW.

4. Results and discussion

4.1. Absorption cross-sections

Fig. 1 shows the absorption cross-sections of four EDF samples. Pairs of EDFI and EDFIII, and EDFII and EDFIV have almost the same absorption cross-sections, respectively. Therefore, the degradation of the population density of the $^4I_{13/2}$ level can be estimated by the comparison of the gain characteristics of the EDF sample pair, which has the same absorption cross-section.

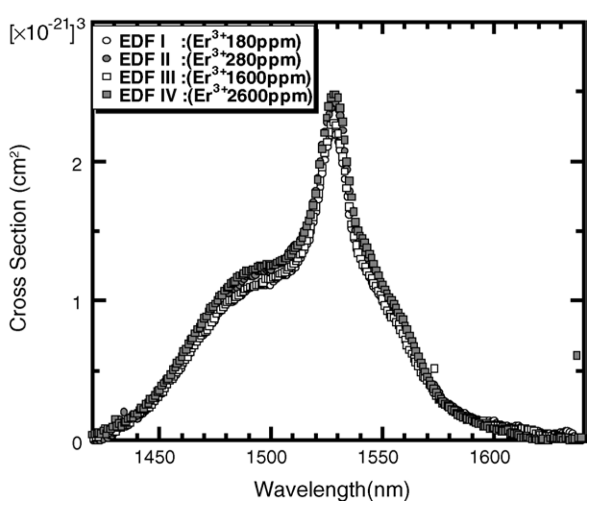

Fig. 1. Cross-sections of four EDF samples.

4.2. Gain saturation measurements

In the gain saturation measurements at room temperature, the difference between the gain saturation characteristics was observed for four EDF samples. Fig. 2(a) and (b) shows the gain saturation characteristics of the EDF sample pairs EDFI and EDFIII, and EDFII and EDFIV, respectively. These samples were forwardly pumped at three pumping power (10, 15 and 30 mW). About 1 dB degradation of the gain saturation was observed for the EDF (EDFIII). This degradation between the saturation gains of two EDF samples was also found at 77 K (solid lines). Therefore, this degradation of the gain saturation of EDFIII is considered to be caused by the Er^{3+}–Er^{3+} ion interactions because the interaction between Er^{3+} ions have little temperature dependence and is supposed to be maintained even at 77 K. In addition, more apparent degradation of the gain saturation (about 4 dB) was observed in the EDF sample EDFIV. For two pairs of EDF samples, the degradation of the gain saturation became most significant at 15 mW of pumping power.

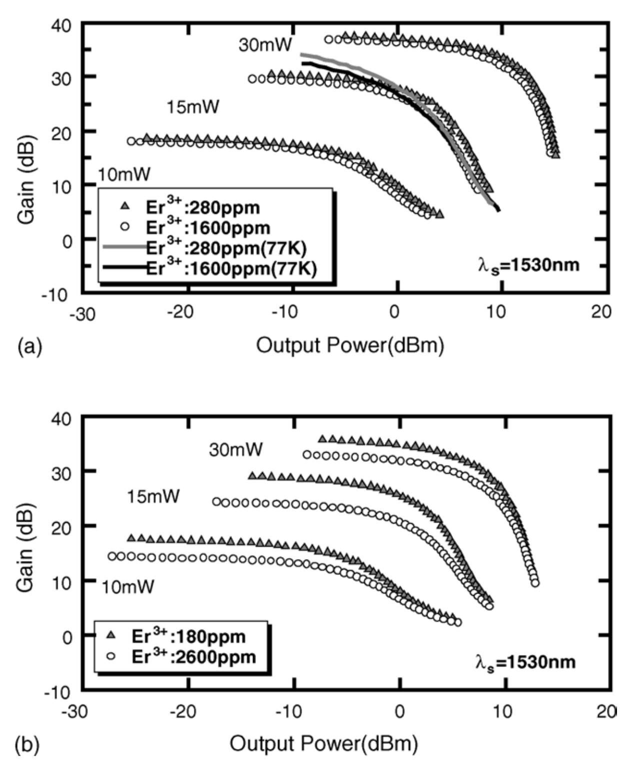

Fig. 2. Power dependences of gain saturations: (a) EDFI (280 ppm), EDFIII (1600 ppm); (b) EDFII (180 ppm), EDFIV (2600 ppm).

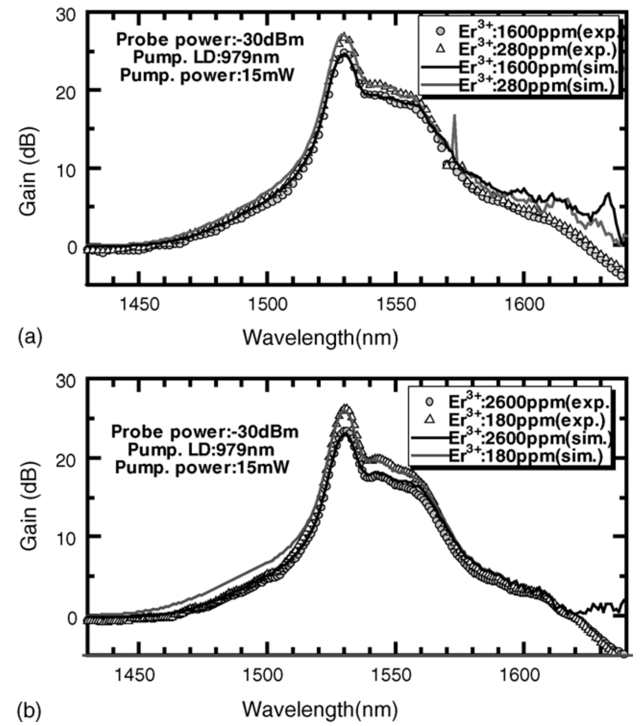

Fig. 3. Comparison between the experimental and numerical gain: (a) EDFI (280 ppm), EDFIII (1600 ppm); (b) EDFII (180 ppm), EDFIV (2600 ppm).

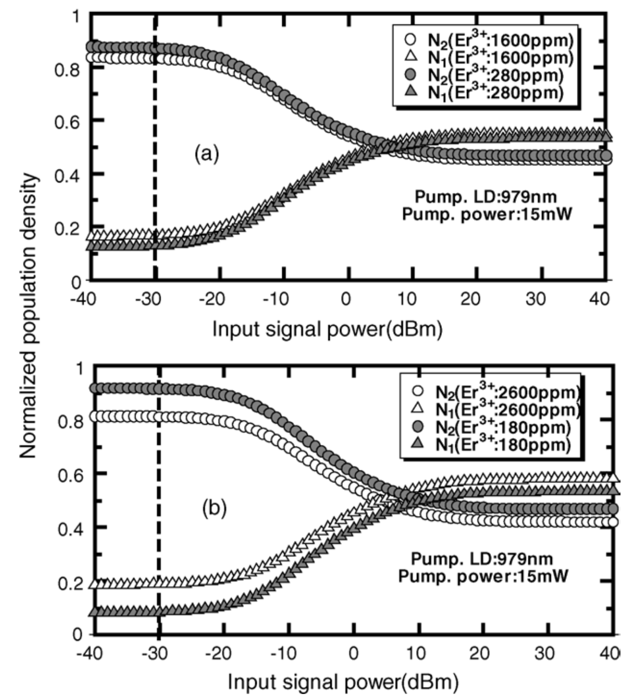

Fig. 4. Input power dependence of the normalized population densities: (a) EDFI (280 ppm), EDFIII (1600 ppm); (b) EDFII (180 ppm), EDFIV (2600 ppm).

4.3. Gain spectra evaluations

Fig. 3(a) and (b) shows the gain characteristics of the EDF sample pairs EDFI and EDFIII, and EDFII and EDFIV, respectively. The samples were pumped at 15 mW of pumping power because the most apparent gain degradation was expected from the obtained gain saturation results. Dots and solid lines show the experimental and numerical results, respectively. About 1 and 4 dB degradations of the gain characteristics was observed for the EDF sample pairs EDFI and EDFIII, and EDFII and EDFIV, respectively. The difference between the experimental and simulated gain spectra in the L-band wavelength region is considered to be caused possibly by the $^4I_{13/2}$–$^4I_{9/2}$ excited-state absorption (ESA) because the ESA cross-section is not taken into account in the simulation model.

In addition, the effect of concentration quenching originated from the Er^{3+}–Er^{3+} ion interactions was examined using the experimentally obtained gain characteristics by the Er^{3+} concentration dependent simulation model considering homogeneous upconversion quenching and pair induced quenching effects mentioned above. The ratio of the paired ions in the sample EDFI was assumed to be 0% because the saturated loss of the fiber was verified to be 0 dB in the high input signal power region. As a result of the numerical analysis, the ratio of the paired ions to the total ions increases with increasing Er^{3+} ion concentration. For the sample EDFIII about 2% of total Er^{3+} ions were estimated to be paired. Fig. 4(a) and (b) shows the signal input power dependence of the simulated normalized population densities of the $^4I_{13/2}$ and the $^4I_{15/2}$ level considering the degradation caused by the Er^{3+}–Er^{3+} ion interaction. Except the signal input power, the simulation parameters were the same in the gain characteristic simulation.

The obtained population densities in the gain characteristics evaluation correspond to those at −30 dB m of input signal power shown in Fig. 4(a). The degradation of the normalized population densities is found to be more significant in the EDF sample that has higher Er^{3+} ion concentration. In addition, the degradation of the population densities in the EDF samples was found to occur more significantly in small signal power region rather than in large signal power region. In addition, the normalized population density of the $^4I_{13/2}$ decreases at a constant rate with increasing Er^{3+} ion concentration in the concentration region above 280 ppm. Taking into account that the total Er^{3+} ion number included in each EDF is the same for all four EDF samples, the degradation of the population density of the $^4I_{13/2}$ level obtained by the gain characteristics analysis is considered to be caused by the Er^{3+}–Er^{3+} ion interactions.

5. Conclusion

The effect of Er^{3+} concentration quenching on the gain characteristics of silica-based EDF was investigated. It is estimated that even about 2% paired Er^{3+} ions in silica-based EDF can cause about 15% degradation of the population density of the $^4I_{13/2}$ level, which leads to about 1 dB degradation of the gain spectrum.

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