Energy Migration Governs Upconversion Losses in Er^{3+}-doped Integrated Amplifiers

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Energy-transfer upconversion (ETU) is a detrimental effect in many rare-earth-ion-doped infrared amplifiers and lasers [1], among them Er^{3+}-doped waveguide amplifiers [2]. Er^{3+} concentrations in the order of 10^{20} cm^{-3} are usually necessary to attain high gain values on the centimeter length scale of an integrated optical device. At such high Er^{3+} doping, electric dipole-dipole interactions between neighboring ions such as energy migration and ETU take place, thereby reducing the population inversion and negatively affecting the gain performance of the amplifier. We investigated these effects by lifetime and gain measurements, see Figs. 1 (a) and (c), respectively, in Al$_2$O$_3$:Er^{3+} waveguides and analyzed the results in the frame of the microscopic model developed by Zubenko *et al.* [3]. The luminescent decay from the ^{4}I$_{13/2}$ first excited level of Er^{3+} can be described by the equation

$$n(t) = \frac{n(0)\exp(-t/\tau_D)}{1 + n(0)(\pi^2/3)\sqrt{\frac{C_{DA}}{\tau_0}}\tau_D\left\{\sqrt{1+\frac{\tau_0}{\tau_D}}\mathrm{erf}\left(\sqrt{t\left(\frac{1}{\tau_0}+\frac{1}{\tau_D}\right)}\right) - \exp(-t/\tau_D)\mathrm{erf}\left(\sqrt{\frac{t}{\tau_0}}\right)\right\}}, \text{ where } \mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x \exp(-t^2)dt$$

is the error function, $n(t=0) = n(0)$ is the initial excitation density of the ^{4}I$_{13/2}$ level, τ_D is its intrinsic lifetime, C_{DA} is the microparameter of ETU from the ^{4}I$_{13/2}$ level, and τ_0 is the mean time of a migration hop. By fitting the experimental decay curves measured in samples with 7 different Er^{3+} concentrations, out of which only 4 are shown in Fig. 1 (a) for simplicity, we find $\tau_D = 7.6$ ms and $C_{DA} = (6.1\pm0.6)\times10^{-41}$ cm^6/s, while τ_0 decreases from 65 ms down to 1 ms with increasing Er^{3+} concentration, see Fig. 1(b). This behavior is due to decreasing distance among Er^{3+} ions with increasing concentration, which enhances the probability of the energy-migration process.
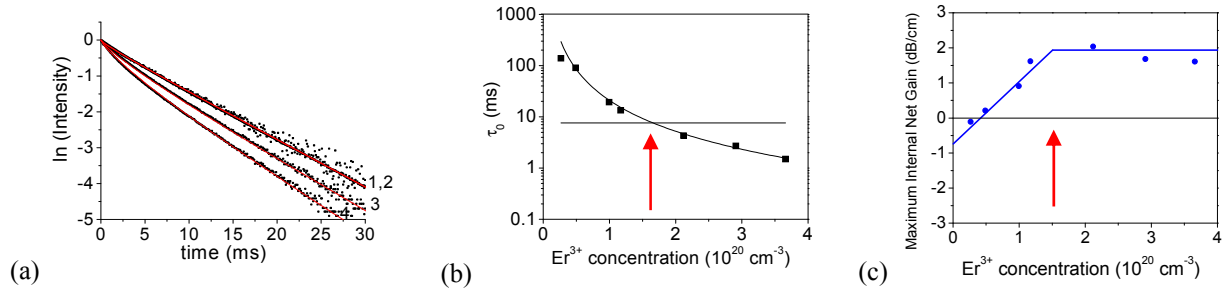

Fig. 1. (a) Selected normalized luminescence decay curves at 1530 nm of Al$_2$O$_3$ doped with Er^{3+} concentrations of 1) 0.27, 2) 1.17, 3) 2.91, 4) 3.66×10^{20} cm^{-3}; (b) migration mean time τ_0 (black squares) as a function of Er^{3+} concentration; the intrinsic lifetime τ_D is shown for comparison (horizontal line); (c) small-signal internal net gain per unit length for each Er^{3+} concentration. Red arrows indicate the onset of migration-accelerated ETU.

These results allow for a direct understanding of the physical mechanism that influences the Al$_2$O$_3$:Er^{3+} amplifier performance. The internal net gain per unit length, see Fig. 1 (c), initially increases with Er^{3+} concentration and then saturates at about the same concentration, indicated by red arrows in Figs. 1 (b) and (c), at which the migration mean time τ_0 becomes faster than the intrinsic luminescence lifetime τ_D, i.e., where the transition from static to migration-accelerated upconversion occurs. At higher Er^{3+} concentrations energy can migrate efficiently between neighboring Er^{3+} ions at time scales shorter than the intrinsic lifetime τ_D, thus enhancing ETU, which consequently reduces the population inversion and leads to a decrease in the optical gain.

We believe that this quantitative correlation between competition of migration mean time τ_0 with intrinsic decay time τ_D and the impact of ETU on amplifier performance is a pattern of general nature, which can be found in many rare-earth-ion-doped gain materials. Investigations in other doped materials are in progress.

References

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