Upconversion spectroscopy of $Al_2O_3:Er^{3+}$

L. Agazzi[1], J.D.B. Bradley[1], F. Ay[1], A. Kahn[2], H. Scheife[2], K. Petermann[2], G. Huber[2], R.M. de Ridder[1], K. Wörhoff[1], and M. Pollnau[1]

[1]Integrated Optical MicroSystems (IOMS) Group, MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

[2]Institute of Laser-Physics, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

The spectroscopic properties of $Al_2O_3:Er^{3+}$ thin films have been investigated by lifetime measurements. The luminescence decay curves show an initial non-exponential component, followed by an exponential tail, whose decay time decreases with increasing Er^{3+} concentration. This behavior can be described with good accuracy by a microscopic treatment that takes into account both energy migration and energy-transfer upconversion among Er^{3+} ions. Parameters such as the migration mean time τ_0 and the donor-acceptor transfer probability C_{DA} are derived. We show that, in the concentration range of interest for waveguide amplifiers at 1.5 µm, upconversion occurs mostly in the static regime.

Introduction

Erbium-doped amorphous aluminum oxide thin films are of great interest for applications such as integrated amplifiers and lasers. Due to the amorphous host structure, the Er^{3+} $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition typically results in a broad emission peak centered at 1535 nm (within the standard telecommunications wavelength window), allowing amplification over a wide wavelength range.

To achieve gain in such short-length (cm scale) integrated devices, it is necessary to reach Er^{3+} concentrations of 10^{20}-10^{21} cm^{-3} [1]. However, when the Er^{3+} concentration increases, energy transfer processes such as energy migration and energy-transfer upconversion (ETU) can decrease the performance of Er-doped devices, thus limiting the useful level of Er doping. Hence it is important to obtain a good understanding of these effects.

Theory

In a macroscopic treatment, the effect of ETU in the rate equations for population dynamics is expressed by a term Wn^2, where W is the time-independent but Er^{3+}-concentration-dependent upconversion parameter and n is the concentration of excited ions. However, this approach is valid only in the "kinetic limit" of the migration-accelerated regime of ETU. In order to describe our experimental results correctly, we need to include the static regime, in which energy migration is low. Hence a microscopic treatment is required. A comprehensive approach that takes into account both energy migration and ETU individually has been developed by Zubenko *et al.* [2]. We adapted this model to describe properly the population dynamics in $Al_2O_3:Er^{3+}$. The equation for luminescent decay from the $^4I_{13/2}$ first excited level of Er^{3+} reads:

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

where $n(t = 0) = n(0)$ is the initial excitation density of the $^4I_{13/2}$ level, τ_D is its intrinsic lifetime, C_{DA} is the microparameter for the ETU process from $^4I_{13/2}$, and τ_0 is the mean time of a migration hop of excitation energy in the $^4I_{13/2}$ level.

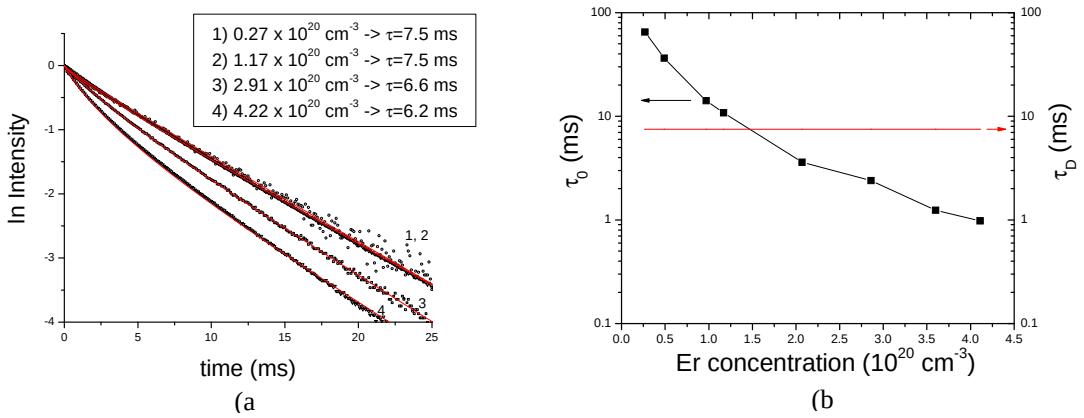
Experiment and Results

1-μm-thick Er^{3+}-doped Al_2O_3 slab waveguides were reactively co-sputtered on thermally oxidized Si <100> substrates [3]. Approximately 4-cm-long channel waveguides were then etched to a depth ≤ 50 nm with a width of 4 μm [4]. Luminescence decay measurements were performed on eight different Er^{3+}-doped samples, with Er^{3+} concentrations ranging from 0.27 to 4.22×10^{20} cm^{-3}. The samples were excited with 976-nm pump light from a diode laser modulated by an external square-pulse generator. The pulse had a duration of 40 ms, allowing the populations of the Er^{3+} system to reach a steady state before the pump was switched off (at $t = 0$). The modulated pump light was coupled into the waveguide with an optical fiber and the luminescence was collected using a high N.A. liquid fiber mounted normal to the sample surface. The luminescence was then diffracted by a monochromator and detected by an InGaAs photodiode. The resulting signal was acquired with a digital oscilloscope.

The decay curves for four different Er^{3+} concentrations are shown in Fig. 1(a) along with the fit from Eq. 1. They show an increasingly fast non-exponential initial component induced by ETU, while at long delay times we observe an exponential tail which exhibits an asymptotic decay time. Its value is reported in the inset of Fig. 1(a). The intrinsic lifetime τ_D of the $^4I_{13/2}$ level was measured in the sample with the lowest dopant concentration and had a value of 7.5 ms. $n(0)$ was calculated by a rate-equation simulation of the Er^{3+} energy-level system, hence C_{DA} and τ_0 were the only free parameters of the fit.

The result for C_{DA} is $(6.25 \pm 0.15) \times 10^{-41}$ cm^6/s, while the results for τ_0 are shown in Fig. 1(b). As expected, τ_0 decreases from 65 ms down to 1 ms when the Er^{3+} concentration increases: the ions become closer and closer, the energy migration increases, hence the migration time becomes shorter.

For the four samples with the lowest Er^{3+} concentration, $\tau_0 > \tau_D$, i.e. according to Ref. [2] we are in the static regime of ETU, while for the samples with the highest Er^{3+} concentration, $\tau_0 < \tau_D$, hence we are approaching the migration-accelerated regime.



(a (b

Fig. 1. (a) Luminescence decay curves (black dots) along with the fits (red lines) for different Er^{3+} concentrations and (b) the results for the migration time τ_0 (dots) as a function of Er^{3+} concentration. The intrinsic lifetime τ_D is also shown for comparison (red line).

Conclusions

Luminescence decay measurements have been performed in Al_2O_3:Er^{3+} channel waveguides for different Er^{3+} concentrations. The upconversion microparameter C_{DA} and the migration mean time τ_0 have been evaluated and will be used in on-going amplifier simulations.

References

[1] A. Polman, "Erbium implanted thin film photonic materials", J. Appl. Phys. **82**, 1 (1997).

[2] D.A. Zubenko, M.A. Noginov, V.A. Smirnov, and I.A. Shcherbakov, "Different mechanisms of nonlinear quenching of luminescence", Phys. Rev. B **55**, 8881-8886 (1997).

[3] K. Wörhoff, F. Ay, and M. Pollnau, "Optimization of low-loss Al_2O_3 waveguide fabrication for application in active integrated optical devices", ECS Transactios **3**, 17-26 (2006).

[4] J.D.B. Bradley, F. Ay, K. Wörhoff, and M. Pollnau, "Fabrication of low-loss channel waveguides in Al_2O_3 and Y_2O_3 layers by inductively coupled plasma reactive ion etching", Appl. Phys. B **89**, 311-318 (2007).