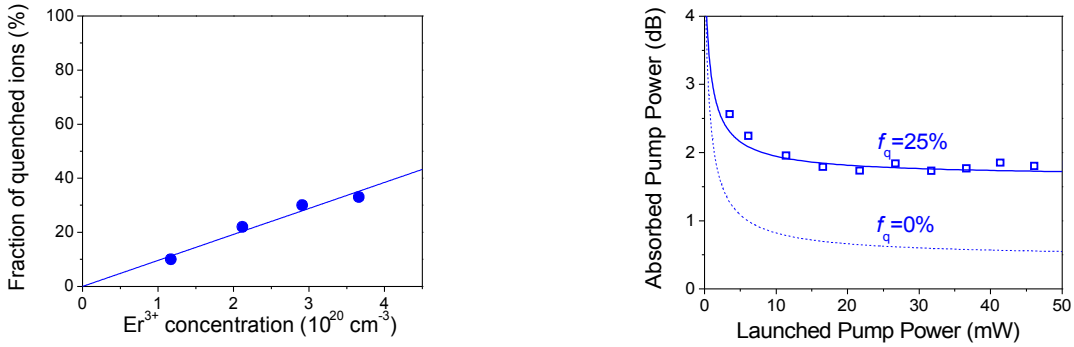
Excitation quenching in Er^{3+}-doped Al_2O_3 amplifiers

L. Agazzi, K. Wörhoff, and M. Pollnau
Integrated Optical Microsystems Group, MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

$Al_2O_3:Er^{3+}$ is an established material for integrated amplifier applications, offering several advantages such as low background losses, a broad emission spectrum, and a relatively high refractive index of 1.65, which enables the fabrication of small optical waveguide structures [1]. Our growth method allows for straightforward deposition on silicon wafers [2] and direct integration with silicon photonic circuits [3]. Net gain over a bandwidth of 80 nm (1500-1580 nm) and with a peak value of 2.0 dB/cm at 1533 nm was measured in our waveguide amplifiers [4]. By fitting the gain measurements with a simple Er^{3+} rate-equation model described in [4] one can extract values for the coefficient W_{ETU} of energy-transfer upconversion (ETU) between neighboring Er^{3+} ions, which has a detrimental influence on the amplifier performance. In the model, unlike other authors [5], we have discarded the excited-state absorption (ESA) process $^4I_{13/2} \rightarrow {}^4I_{9/2}$, because our direct ESA measurements show that this process lies outside the gain bandwidth. In further experiments we prove the existence of an additional ETU process $(^4I_{13/2},{}^4I_{11/2}) \rightarrow (^4I_{15/2},{}^4F_{9/2})$, whose influence on gain, however, turned out to be small.

The resulting W_{ETU} values show a clear discrepancy of about one order of magnitude with the results obtained from luminescence decay measurements. The discrepancy is explained by the fact that a certain fraction of Er^{3+} ions undergoes fast quenching which is not resolved in our decay measurements owing to the time response of the set-up. This quenching can be induced by, e.g., active ion pairs and clusters, undesired impurities, or host material defects. Other investigations indicate that the characteristic time constant of such quenching may be on the order of 1-10 µs [6]. By modifying the model to account for these fast quenching effects, we derived that the fraction of quenched ions f_q increases from 10% to 33% when the Er^{3+} concentration increases from 1.17 to 3.66 × 10^{20} cm^{-3}, as shown in Fig. 1 (a), suggesting a higher probability of fast quenching with increasing concentration. These results were afterwards confirmed by nonsaturable absorption experiments, see Fig. 1 (b), in which 1480-nm pump light was launched into the waveguide, and the transmission as a function of launched power was recorded. The transmission is strongly dependent on the amount of quenched ions, and our improved model could fit the results with good accuracy.



(a) (b)

Fig. 1 (a) Fraction of quenched ions as a function of Er concentration; (b) absorbed versus launched pump power for a waveguide with an Er^{3+} concentration of 2.12 × 10^{20} cm^{-3} and 1 cm length. The squares are the experimental data, while the solid and dashed lines represent the calculations for 25% and 0 % quenched ions, respectively.

The quantitative understanding of the influence of the different quenching processes leads to an improved simulation that predicts a gain of ~3 dB/cm for an optimized Er^{3+} concentration when pumping at 1480 nm.

References

[1] 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 (2007).
[2] K. Wörhoff, J. D. B. Bradley, F. Ay, D. Geskus, T. P. Blauwendraat, and M. Pollnau, "Reliable low-cost fabrication of low-loss $Al_2O_3:Er^{3+}$ waveguides with 5.4-dB optical gain," IEEE J. Quantum Electron. **45**, 454 (2009).
[3] L. Agazzi, J. D. B. Bradley, M. Dijkstra, F. Ay, G. Roelkens, R. Baets, K. Wörhoff, and M. Pollnau, "Monolithic integration of erbium-doped amplifiers with silicon-on-insulator waveguides," Opt. Express **18**, 27703 (2010).
[4] J. D. B. Bradley, L. Agazzi, D. Geskus, F. Ay, K. Wörhoff, and M. Pollnau, "Gain bandwidth of 80 nm and 2 dB/cm peak gain in $Al_2O_3:Er^{3+}$ optical amplifiers on silicon," J. Opt. Soc. Am. B **27**, 187 (2010).
[5] G. N. van den Hoven, E. Snoeks, A. Polman, C. van Dam, J. W. M. van Uffelen, and M. K. Smit, "Upconversion in Er-implanted Al_2O_3 waveguides," J. Appl. Phys. **79**, 1258 (1996).
[6] E. Delevaque, T. Georges, M. Monerie, P. Lamouler, and J.-F. Bayon, "Modeling of pair-induced quenching in erbium-doped silicate fibers," IEEE Photon. Technol. Lett. **5**, 73 (1993).