Fast quenching processes and their impact on 1.5-µm amplifier performance in $Al_2O_3:Er^{3+}$ waveguides

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***Abstract*—Spectroscopic investigations reveal the presence of a fast quenching process in erbium-doped aluminum oxide waveguides. We quantify the percentage of quenched ions and make predictions about the amplifier performance.**

Optical amplifiers; integrated optics materials; fast quenching processes; aluminum oxide

I. INTRODUCTION

$Al_2O_3:Er^{3+}$ 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 at 1.5 µm, which enables the fabrication of compact optical waveguide structures [1]. Our growth method allows for straightforward deposition on silicon wafers [2] and monolithic integration with silicon photonic circuits [3]. We have fabricated waveguide amplifiers with a broadband gain over a wavelength range of 80 nm and a peak value of 2.0 dB/cm, which however varies strongly with Er^{3+} concentration [4]. In this paper we report spectroscopic investigations in $Al_2O_3:Er^{3+}$ waveguides that reveal a fast quenching of a fraction of ions – undetected in typical luminescence decay measurements – which increases with concentration: in addition we investigate the effect of the fast quenching on the small-signal gain of $Al_2O_3:Er^{3+}$ integrated channel-waveguide amplifiers.

II. EXPERIMENTAL

$Al_2O_3:Er^{3+}$ layers with a thickness of 1.0 µm were deposited on thermally oxidized silicon substrates by reactive co-sputtering [2]. Ridge waveguides with a width of 4.0 µm were defined using reactive ion etching to an etch depth of ~ 50 nm [1]. The Er^{3+} concentration varied from 1.17 to 3.66×10^{20} cm^{-3}.

Small-signal gain measurements were carried out by launching either 976-nm from a Ti:Sapphire pump source or 1480-nm pump light from a Raman laser source together with 1533-nm signal light from a tunable laser into the channel waveguides using either a lens-coupling or a fiber-coupling setup [4]. The output signal light was separated from the residual pump light by a silicon filter in the 976-nm pumping case and a fiber wavelength division multiplexer in the 1480-nm case, and acquired by a detector and lock-in amplifier.

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III. RESULTS AND DISCUSSION

The results of the small-signal gain measurements were fitted with a simple amplifier model described in [4] in order to extract values for the coefficient W_{ETU} of energy-transfer upconversion (ETU) between neighboring Er^{3+} ions, an inter-ionic process which has a detrimental influence on the amplifier performance [5]. The resulting W_{ETU} values show a discrepancy of about one order of magnitude with the results obtained from luminescence decay measurements presented in [6]. 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 such quenching occurs on the ns-µs time scale [7,8]. 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, proposing a higher probability of fast quenching with increasing concentration.

These results were afterwards confirmed by nonsaturable absorption experiments, see Fig. 2, 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, whereas the former amplifier model could not.

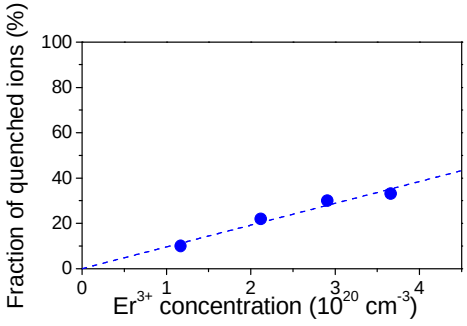

Figure 1. Fraction of quenched ions f_q as a function of Er concentration

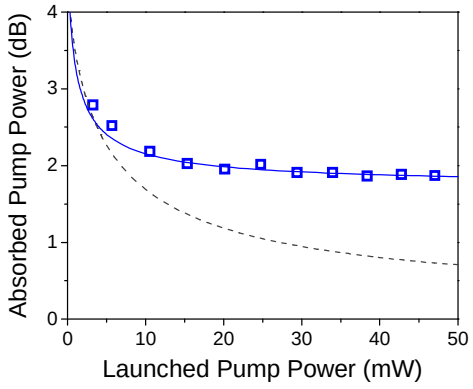

Figure 2. Absorbed versus launched pump power for a waveguide with an Er^{3+} concentration of 3.66×10^{20} cm^{-3} and 1 cm length. The squares are the experimental data, the solid line is a fit with the improved model resulting in f_q = 33%, and the dashed line is a tentative fit with the former amplifier model

The dots in Fig. 3 show the measured internal net gain per unit length for varying Er^{3+} concentration (taken from [4]) for a launched pump power of 100 mW at 976 nm (top graph) and at 1480 nm (bottom graph) and signal power of 1 μW at 1533 nm. The solid lines represent the simulated gain versus Er^{3+} concentration, according to the improved model, under the assumption that f_q keeps on increasing linearly with Er^{3+} concentration even at higher Er^{3+} concentrations than those measured. Since the exact decay time τ_{1q} of the quenched ions is not known, we have performed simulations for three different τ_{1q} values that approximately cover the range found in the literature.

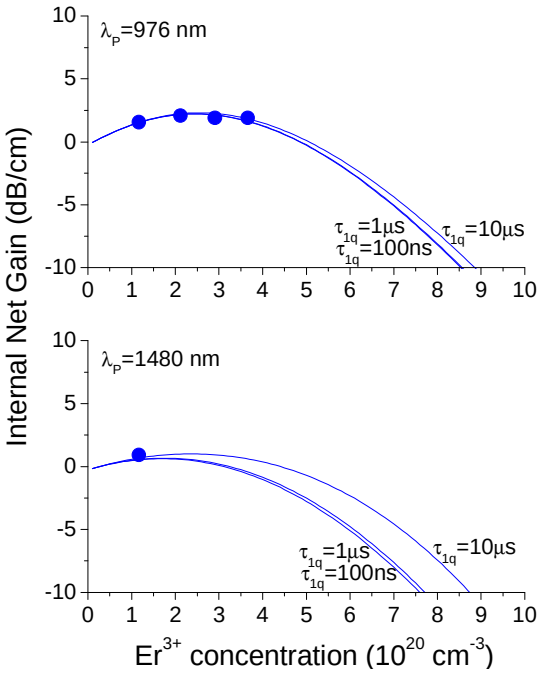

Figure 3. Measured internal net gain per unit length at 1533 nm (dots) versus Er^{3+} concentration. The solid lines represent a gain simulation where fast quenching with three different τ_{1q} values is considered

In the 976-nm case the gain initially grows with Er^{3+} concentration, reaches a maximum value of 2 dB/cm at a concentration of ~ 2×10^{20} cm^{-3}, and then decreases due to the increasingly stronger impact of ETU and fast quenching with Er^{3+} concentration.

In the 1480-nm pump case only one small-signal gain measurement at a concentration of 1.17×10^{20} cm^{-3} was performed [4]. Predictions with the improved model, depending on the different τ_{1q} values, result in a ~ 0.7-1 dB/cm peak at a concentration of ~ $1.5\text{-}2.5\times10^{20}$ cm^{-3}. The gain is lower than in the 976-nm pump case because of the lower population inversion caused by stimulated emission at the pump wavelength from the $^4I_{13/2}$ metastable state.

In both 976-nm and 1480-nm pump cases we observe a difference among the simulations with different τ_{1q} values at high Er^{3+} concentrations for τ_{1q} = 10 μs. This can be attributed to the onset of bleaching of the quenched ions due to the high pump intensity in our channel waveguides. Small-signal gain experiments under 1480-nm pumping are under way to fully investigate the gain behavior at this pump wavelength and further clarify this last point.

V. CONCLUSIONS

A fast quenching mechanism, revealed by spectroscopic investigations, strongly affects the Al_2O_3:Er^{3+}amplifier performance. Simulations that account for the fast quenching predict a higher gain under 976-nm pumping.

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