$Al_2O_3:Er^{3+}$ Waveguide Amplifiers on a Silicon Chip

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We have pioneered rare-earth-ion-doped integrated amplifiers and lasers on a silicon chip. Such low-cost, compact components are useful for signal generation or amplification within an integrated optical circuit (Fig. 1). In particular, Er^{3+}-doped waveguides provide light generation and amplification at the all-important telecom wavelengths [1]. We have investigated the amplifier performance in $Al_2O_3:Er^{3+}$ on the basis of the underlying spectroscopy.

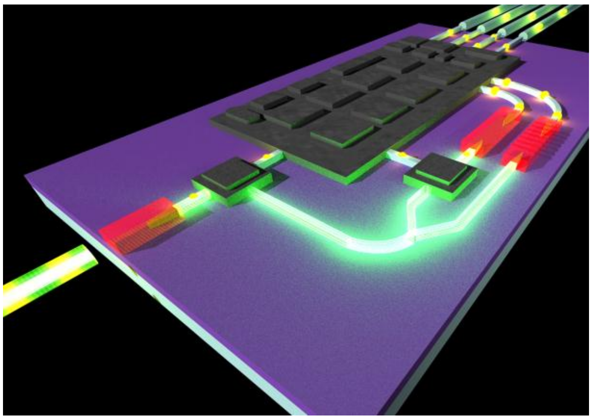

Fig. 1. Illustration of advanced photonic circuit with integrated Er-doped waveguide amplifiers and lasers [1]

1. Fabrication of Rare-earth-doped Al_2O_3 Waveguides and Integration with Si Waveguides

We deposit Er^{3+}-doped amorphous aluminum oxide ($Al_2O_3:Er^{3+}$) by RF reactive co-sputtering onto thermally oxidized silicon wafers [2]. We structure these layers by reactive ion etching, thereby obtaining channel waveguides (Fig. 2, left) with losses as low as 0.2 dB/cm [3]. Also focused-ion-beam nano-structuring of Bragg gratings has been explored [4]. Compared to other glass materials, the high refractive index in Al_2O_3 of ~1.65 enables a tighter light confinement, resulting in lower gain threshold and total required pump power, as well as low-loss propagation along sharp bends. Wafer-scale monolithic integration of active $Al_2O_3:Er^{3+}$ waveguides with silicon-based photonics technology has been demonstrated (Fig. 2, right) [5].

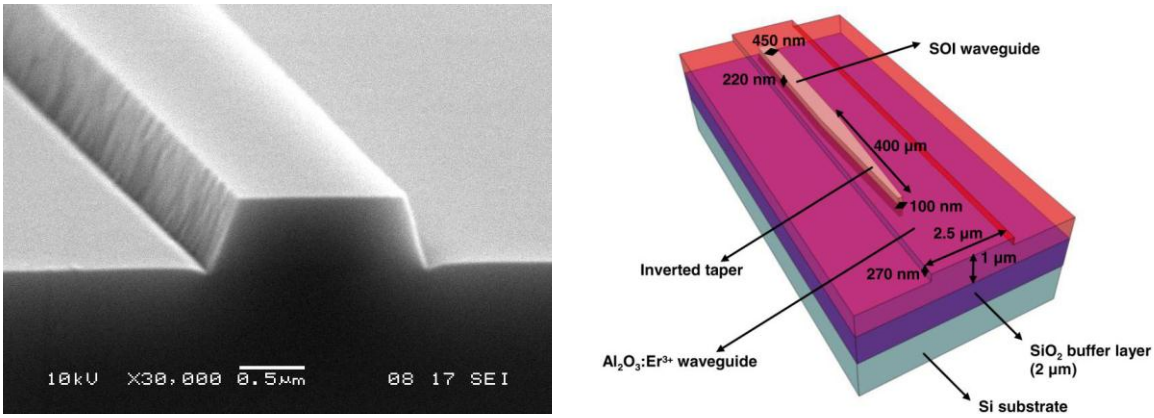

Fig. 2. (left) SEM micrograph profile of an Al_2O_3 channel waveguide [3]; (right) schematic of an adiabatic inverted taper structure to couple light from Si to $Al_2O_3:Er^{3+}$ waveguides [5]

2. Spectroscopy and Optical Gain in $Al_2O_3:Er^{3+}$

$Al_2O_3:Er^{3+}$ exhibits a broad emission spectrum [6], which makes it a very interesting material for integrated amplifiers that provide gain across a wide wavelength range, as well as integrated tunable and ultrashort-pulse laser sources. For Er^{3+} concentrations in the range of 1–2 × 10^{20} cm^{-3}, an internal net gain of up to 2.0 dB/cm at 1533 nm was measured (Fig. 3, left) [6]. For a launched 977-nm pump power of 80 mW, gain was obtained over a large wavelength range of 80 nm between 1500-1580 nm (Fig. 3, right) [6].

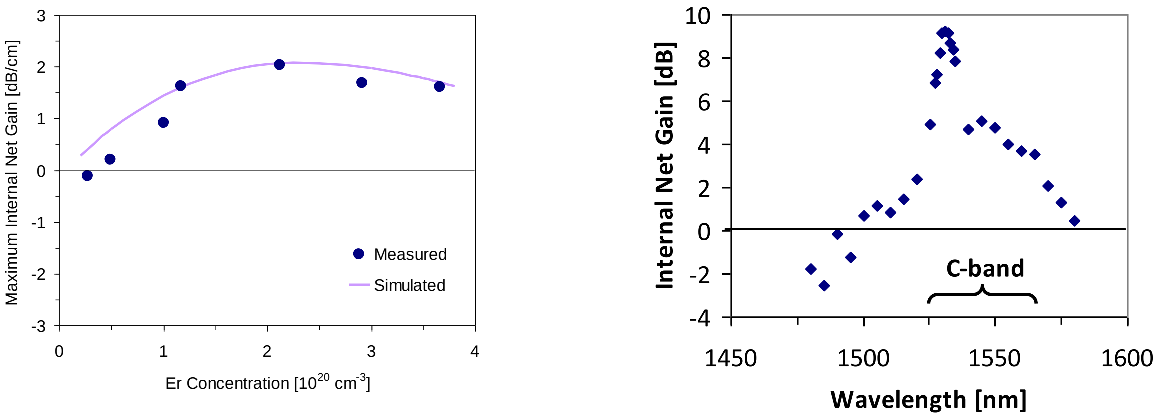

Fig. 3. (left) Internal net gain per unit length for each concentration and sample lengths optimized for a launched pump power of 80 mW [6]. (right) Internal net gain as a function of wavelength for an amplifier length of 5.4 cm, Er concentration of 1.17 × 10^{20} cm^{-3}, and a launched 977-nm pump power of 80 mW [6].

Our spectroscopic investigations indicate that not only the typical energy-transfer upconversion from the $^4I_{13/2}$ upper level of the 1.5-µm transition, but also a fast quenching process which does not reveal its existence in luminescence decay curves must be taken into account in order to understand the population mechanisms in $Al_2O_3:Er^{3+}$ [7]. The fast quenching process induces a significant amount of non-saturable absorption (Fig. 4, left). The fraction of quenched ions increases with dopant concentration and is significantly larger in $Al_2O_3:Er^{3+}$ compared to $Al_2O_3:Yb^{3+}$ (Fig. 4, center), indicating that static energy-transfer upconversion within Er^{3+} clusters may play a role. This process limits the achievable gain to 2 dB/cm (Fig. 4, right) [7]. Despite their rather short lifetime due to multiphonon relaxation in oxide materials, also the higher-lying energy levels of Er^{3+} in Al_2O_3 were spectroscopically investigated. Among other results, we showed that the relative behavior of green and red upconversion luminescence is influenced by an ETU process which is usually not taken into account in the rate-equation analysis of the Er^{3+} system [8].

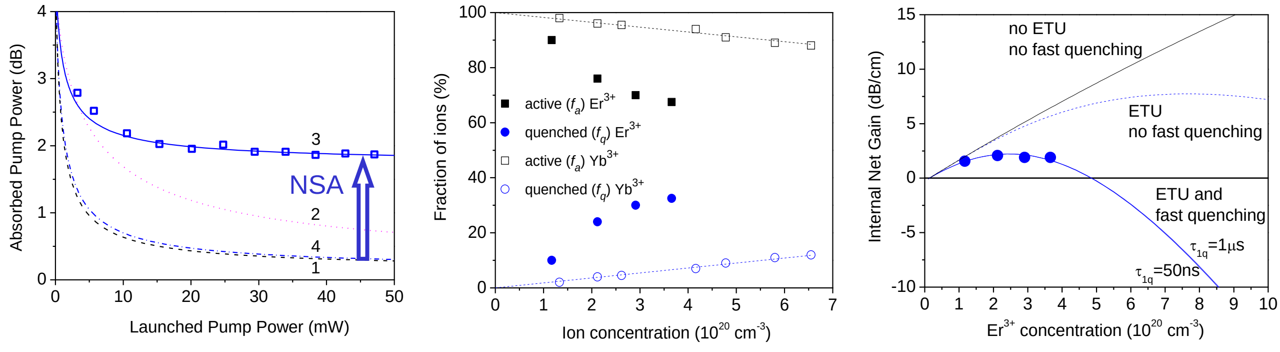

Fig. 4. (left) Non-saturable pump absorption in $Al_2O_3:Er^{3+}$ [7]; (center) fraction of quenched ions in $Al_2O_3:Er^{3+}$ and $Al_2O_3:Yb^{3+}$ versus dopant concentration [7]; (right) influence of ETU and fast quenching on the amplifier performance in $Al_2O_3:Er^{3+}$ [7]. The dots denote the measured gain [6].

3. Amplifier Devices in Al_2O_3:Er^{3+}

Signal transmission experiments were performed at 170 Gbit/s in an integrated Al_2O_3:Er^{3+} waveguide amplifier [9] to investigate its potential application in high-speed photonic integrated circuits. A differential group delay of 2 ps between the TE and TM fundamental modes of the 5.7-cm-long amplifier was measured. When selecting a single polarization, open-eye diagrams (Fig. 5) and bit error rates equal to those of the transmission system without the amplifier were observed for a 1550 nm signal encoded with a 170 Gbit/s return-to-zero pseudo-random 2^7-1 bit sequence [9], showing that the EDWA does not add any penalty to the system.

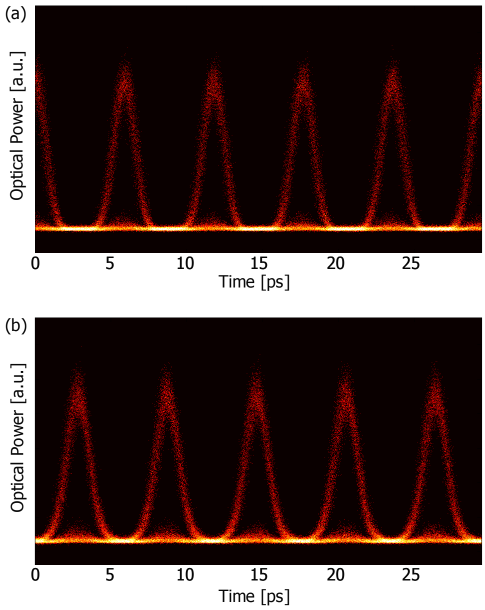

Fig. 5. Transmission eye diagrams at 170 Gbit/s (a) without EDWA and (b) with EDWA and a launched signal power of 0.5 mW and counter-propagating pump power of 65 mW [9].

A zero-loss splitter in Al_2O_3:Er^{3+} was demonstrated [10]. Furthermore, in order to compensate for the rather low gain per unit length, spiral amplifiers were designed (Fig. 6, left) that delivered a total gain of 20 dB (Fig. 6, right) [11].

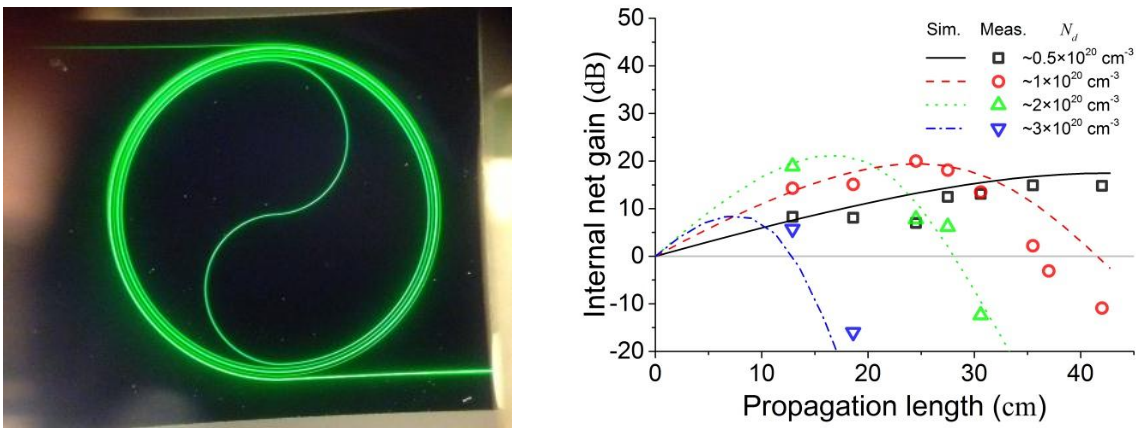

Fig. 6. (left) Photograph of an Al_2O_3:Er^{3+} spiral waveguide amplifier [11]; (right) Internal net gain measured in Al_2O_3:Er^{3+} spiral waveguides with different Er^{3+} concentrations (symbols) and simulated gain (lines) as a function of propagation length for different Er^{3+} concentrations [11]. The rate-equation model presented in [7], which includes ETU and a fraction of fast-quenched ions, was used for the simulations.

Collaborations

1. Photonics Research Group, Department of Information Technology (INTEC), Ghent University, Belgium.
2. FOTON Laboratory, CNRS UMR 6082 / PERSYST Platform,University of Rennes 1 / ENSSAT, France.
3. PhoeniX BV, Enschede, The Netherlands.
4. Optical Sciences Group, University of Twente, The Netherlands.

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