$Al_2O_3:Er^{3+}$ waveguide amplifiers at 1.5 μm

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***Abstract*— We report optical amplification in $Al_2O_3:Er^{3+}$ with a gain bandwidth of 80 nm and peak gain of 2.0 dB/cm at 1533 nm, data transmission at 170 Gbit/s without added bit-error penalty and monolithic integration of these active $Al_2O_3:Er^{3+}$ waveguides with passive silicon-on-insulator waveguides.**

Optical amplifiers; Integrated optics materials; High-speed amplification; Monolithic integration with SOI waveguides

I. Introduction

Silicon-on-insulator (SOI) is emerging as a platform for realizing compact integrated photonic circuits at wavelengths in the telecom range. However, SOI devices – though highly integrated – show relatively high losses [1]. Amplifiers are thus an indispensable feature of integrated optical systems, with the task of regenerating signals that have been attenuated during their propagation within an optical circuit. We have selected Er-doped amorphous aluminum oxide ($Al_2O_3:Er^{3+}$) as the amplifier material due to its high Er solubility and higher refractive index contrast compared to other typical glass hosts, which allows more compact devices. Our straightforward fabrication process allows deposition on a variety of substrates such as silicon [2], resulting in low background losses (typically 0.1-0.2 dB/cm). Here we report on internal net gain over a wavelength range of 80 nm, with a peak value of 2 dB/cm at 1533 nm [3]. The great potential of this material is demonstrated by high-speed amplification at 170 Gbit/s without noise penalty or patterning effects and wafer-scale monolithic integration of active Er-doped Al_2O_3 waveguides with passive SOI waveguides.

II. Gain in $Al_2O_3:Er^{3+}$ waveguide amplifiers

$Al_2O_3:Er^{3+}$ layers with a thickness of approximately 1.0 μm were deposited on thermally oxidized silicon substrates by reactive co-sputtering [2] and 4.0-μm-wide ridge waveguides were defined by reactive ion etching to a depth of 50 nm [4]. The Er concentration varied from 0.27 to 3.66×10^{20} cm^{-3}. Gain measurements were carried out by launching simultaneously 977-nm pump light from a Ti:Sapphire pump source and 1533-nm signal light from a tunable laser into the channel waveguides using a lens-coupling setup. The output signal light was separated from the residual pump light by a silicon filter and acquired by a detector and lock-in amplifier. For optimum Er concentrations in the range of 1 to 2×10^{20} cm^{-3}, internal net gain of up to 2.0 dB/cm was obtained. Furthermore, net gain was obtained over a wavelength range of 80 nm with a peak gain of 9.3 dB at 1533 nm (Fig. 1), for an amplifier length of 5.4 cm and Er concentration of 1.17×10^{20} cm^{-3}. These high gain values demonstrate that $Al_2O_3:Er^{3+}$ is a competitive technology for active integrated optics.

III. 170 Gbit/s high-speed amplifier

In collaboration with colleagues from the University of Rennes, France, we performed signal transmission experiments at 170 Gbit/s in an integrated $Al_2O_3:Er^{3+}$ waveguide amplifier to investigate its potential application in high-speed photonic integrated circuits [5]. Figure 2 shows typical eye diagrams measured (a) without the EDWA and (b) with the EDWA included in the experimental transmission setup. In the case with the EDWA included 0.1 mW of signal and 65 mW of pump power were launched into the device, and a single input signal polarization was selected. The eye pattern is open and the pulse FWHM is 2 ps in both cases. Bit error rate (BER) assessments were also performed with and without the device in the transmission setup. Identical bit error rate vs. received optical power curves were obtained with and without the EDWA in the system, verifying that negligible noise is added by the amplifier.

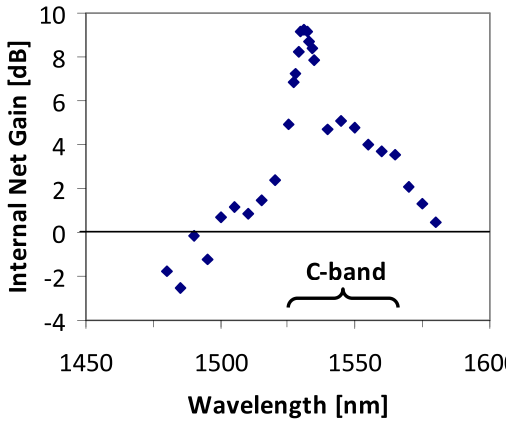

Figure 1. Internal net gain in an Al_2O_3 channel waveguide amplifier with an Er^{3+} concentration of 1.17×10^{20} cm^{-3} as a function of wavelength

Funding was provided by the Smartmix Memphis programme of the Dutch Ministry of Economic Affairs.

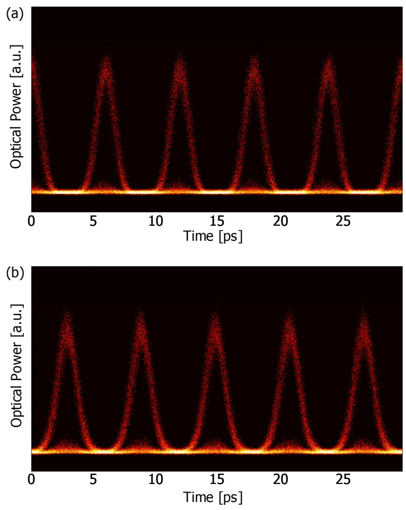

Figure 2. Transmission eye diagrams at 170 Gbit/s (a) without EDWA and (b) with EDWA and a launched signal power of 0.5 mW and counter-propagating pump power of 65 mW

IV. MONOLITHIC INTEGRATION OF $Al_2O_3:Er^{3+}$ WITH SOI WAVEGUIDES

In collaboration with colleagues from Ghent University, Belgium, the $Al_2O_3:Er^{3+}$ waveguide amplifiers were integrated with SOI passive waveguides [6]. SOI rib waveguides with a cross section of 450 nm × 220 nm were defined by deep UV lithography. A 1-µm-thick $Al_2O_3:Er^{3+}$ layer was grown directly on top by reactive co-sputtering [2] and 2.0-µm-wide ridge waveguides were defined by reactive ion etching to a depth of 270 nm [4]. The Er concentration was approximately 2×10^{20} cm^{-3}. In order to achieve highly efficient coupling the Si waveguides were tapered down to 100 nm over a length of 400 µm (inset, Fig. 3) to adiabatically transform the silicon waveguide mode to that of the $Al_2O_3:Er^{3+}$ waveguide. Losses in the Si-$Al_2O_3:Er^{3+}$ couplers were measured by comparing the transmission of 1533-nm light in $Al_2O_3:Er^{3+}$ waveguides both with and without Si-taper couplers, resulting in a value of 2.5 dB per coupler. Simulations indicate that this loss can be reduced to 0.5 dB. Signal enhancement measurements were performed in an $Al_2O_3:Er^{3+}$-Si-$Al_2O_3:Er^{3+}$ structure, with a method similar to that described in Sect. I, but with a pump wavelength of 1480 nm. The two $Al_2O_3:Er^{3+}$ sections had a total length of 9.5 mm, while the Si waveguide was 4 mm long, including the tapers. Figure 3 shows the signal enhancement as a function of pump power coupled into the waveguide at 1533 nm, indicating saturation at around 50 mW of input power.

To our knowledge, this is the first time that monolithic integration of rare-earth-ion-doped waveguides with SOI waveguides is achieved and signal enhancement is measured. These fundamental results will allow us to make use of potential Er-doped gain devices and their performance in passive Si photonic circuits. By improving the coupling losses and exploiting Yb^{3+} co-doping [7], significantly less than 1 cm of amplifier length will potentially provide net amplification at high speed across the entire telecom C-band, making such an amplifier highly interesting for silicon photonics.

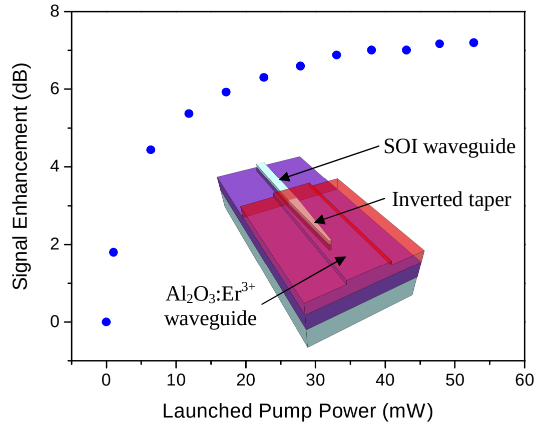

Figure 3. Signal enhancement (dB) vs. launched pump power in an $Al_2O_3:Er^{3+}$-Si-$Al_2O_3:Er^{3+}$ structure

V. CONCLUSIONS

Internal net gain over a wavelength range of 80 nm with a peak gain of 2.0 dB/cm at 1533 nm was obtained in $Al_2O_3:Er^{3+}$ amplifiers. A high-bit-rate amplifier was demonstrated, and active $Al_2O_3:Er^{3+}$ waveguides were monolithically integrated with passive SOI waveguides.

ACKNOWLEDGMENTS

The authors thank M. Dijkstra from the MESA+ Institute for Nanotechnology for assisting with fabrication of the samples, M. Costa e Silva, M. Gay, L. Bramerie, and J.C. Simon from the FOTON Laboratory, University of Rennes for assistance with the high-speed transmission measurements as well as G. Roelkens and R. Baets from the Photonics Research Group, Ghent University for preparing the SOI chip.

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