Monolithic integration of erbium-doped amplifiers with silicon waveguides

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Abstract: We present the monolithic integration of $Al_2O_3:Er^{3+}$ active waveguides with underlying passive silicon-on-insulator waveguides. Signal enhancement of 7 dB at 1533 nm was measured, thus establishing $Al_2O_3:Er^{3+}$ as a medium which can potentially provide on-chip amplification and lasing within complex wafer-scale fabricated integrated photonic circuits.

OCIS codes: (140.4480) Optical amplifiers; (130.3130) Integrated optics materials

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1. Introduction

The aim of integrated optics is to develop compact optical devices of high functionality on a chip-scale platform. Silicon-on-insulator (SOI) is usually the material platform of choice for photonic integration because of the already existing processing infrastructure for the electronic counterpart that allows low-cost manufacturing of optical components. While being highly integrated, SOI devices exhibit relatively high losses [Lipson]. Gain is usually provided via III-V semiconductor optical amplifiers (SOAs), but doing the hybrid integration [Fang,Roelkens] in a CMOS fabrication line is far from trivial . As an alternative, we propose the integration of an Er-doped glass amplifier with silicon waveguides. While Er-doped dielectric materials cannot compete with SOAs regarding gain per unit length (few dB/cm in the former, as opposed to hundreds of dB/cm in the latter), there are nevertheless applications for which Er-doped glasses can be preferable to III-V semiconductor materials. One of these is high-speed amplification up to 170 Gbit/s without noise penalty or patterning effects [Jon speed], which cannot be achieved by SOAs due to their short carrier lifetime. In addition, the linewidth of dielectric-based Er lasers can be as low as 3 kHz [Broquin], while the typical linewidth of III-V lasers is in the order of a few MHz in a DFB configuration [linewidth Semiconductor DBF]. Furthermore, when temperature rises, the gain in SOAs decreases and the gain spectrum shifts in wavelength; for the same reason, mode hopping can occur for semiconductor lasers; thus temperature stabilization is often required, while Er-doped glass devices show good thermal stability [Broquin].

We have selected Er-doped amorphous aluminum oxide ($Al_2O_3:Er^{3+}$) as the gain material. Its broad emission spectrum and high Er solubility make Al_2O_3 an excellent host for Er [van den Hoven]. Its higher refractive index (n = 1.65 at 1.55 μm) compared to other typical glass hosts, such as silica (n = 1.45) or phosphate (n = 1.55) glass, allows for smaller waveguide bend radii, thus higher integration density, and smaller waveguide cross-sections allowing higher pump intensities, thus lower pump-power requirements. Our growth method allows straightforward deposition on different substrates, resulting in low-loss films [Kerstin growth]. Recently we have demonstrated a peak gain of 2.0 dB/cm, which is competitive with other Er-doped glasses, in combination with broadband gain over a wavelength range of 80 nm [Jon gain]. This performance has led to the realization of an on-chip integrated zero-loss optical power splitter [Jon splitter] and wavelength-selective laser [Jon laser], both operating across the telecom C-band, as well as a narrow-linewidth DFB laser [Edward DFB laser].

In this paper we describe wafer-scale monolithic integration of active Er-doped waveguides with passive Si waveguides. A signal enhancement of 7.2 dB at 1533 nm for a pump power of ~50 mW in an $Al_2O_3:Er^{3+}$-Si-$Al_2O_3:Er^{3+}$ structure was achieved, thus paving the way for future on-chip amplification and lasing in complex photonic circuits, as proposed in the simplified schematic of Fig. 1. Here we depict a SOI optical circuit including monolithically integrated $Al_2O_3:Er^{3+}$ waveguide amplifiers and lasers (red sections). No hybrid integration is required. The active sections can be fabricated in multiple copies at any position on the chip by a simple two-step parallel process: wafer-scale $Al_2O_3:Er^{3+}$ deposition and subsequent reactive ion etching. As long as sufficient pump power is available, pumping of multiple amplifier and laser sections can be achieved by coupling a single diode laser, splitting its power on-chip and launching it into the Er-doped sections. Si-$Al_2O_3:Er^{3+}$ couplers transfer light from the world of passive Si photonics through inversely tapered Si waveguides into an active $Al_2O_3:Er^{3+}$ section and back into another Si waveguide. The optical mode size inside the Si waveguide increases when travelling along the inverse taper and eventually matches the mode profile inside the $Al_2O_3:Er^{3+}$ waveguide. At the chip facet, where pump and signal light are coupled, an $Al_2O_3:Er^{3+}$ segment of appropriate length can, firstly, facilitate converting a large fiber mode into the tiny Si-waveguide mode [MIT coupler] and, secondly, compensate the losses due to the optical mode mismatch between fiber and waveguide by an initial amplifying section, creating a loss-less fiber-to-chip coupler, while other $Al_2O_3:Er^{3+}$ sections can be inserted anywhere in the optical circuit to amplify signals traveling in the SOI chip, even at a high bit rate of 170 Gbit/s [Jon speed] and specific light sources, e.g. DFB [Edward DFB laser] or femtosecond [Pudo fs laser] lasers, can be integrated within the circuit.

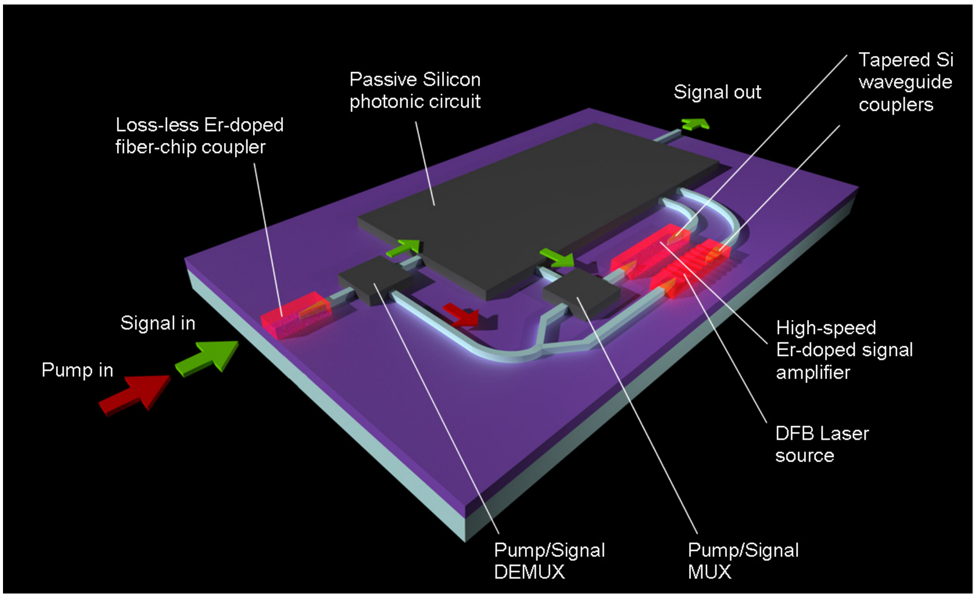

Fig. 1. Schematic of a SOI on-chip optical circuit including monolithically integrated $Al_2O_3:Er^{3+}$ waveguide amplifiers and lasers (red sections)

2. Coupling between Si and $Al_2O_3:Er^{3+}$

Efficient Si-$Al_2O_3:Er^{3+}$ couplers are fundamental elements for the integration of the two materials. Optical coupling was obtained with an inverted taper, which adiabatically transformed the Si waveguide mode to the fundamental mode of the $Al_2O_3:Er^{3+}$ waveguide. This type of structure has been shown to result in a high efficiency and large optical bandwidth coupling [tapers]. The design parameters, shown in Fig. 2, were optimized to obtain the best possible coupling efficiency. Calculations were based on a 3-dimensional fully vectorial eigenmode expansion method. A coupling loss as low as 0.5 dB was predicted for the optimal design.

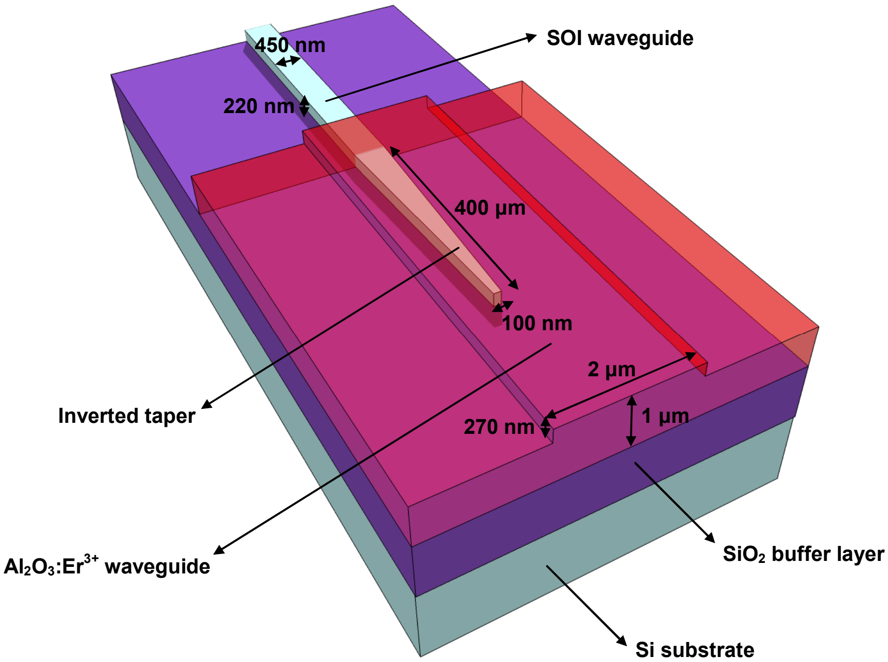

Fig. 2. Schematic of the adiabatic inverted taper structure to couple light from Si to $Al_2O_3:Er^{3+}$ waveguides

The process flow for the fabrication of Si-Al_2O_3:Er^{3+} couplers is depicted in Fig. 3. The Si waveguides were first fabricated using state-of-the-art CMOS fabrication tools in a 200 mm CMOS pilot line. 193 nm deep UV lithography was used to define the 450 nm waveguides and inverted taper structures, which were 400 µm long and tapered down to a 100 nm tip (Fig. 4a). An Al_2O_3:Er^{3+} layer was deposited directly onto the structured SOI wafer (Figs. 4b and 4c) by reactive co-sputtering [Kerstin growth] and ridge waveguides were defined by use of standard lithography and reactive ion etching [Jon etching]. The resulting Al_2O_3:Er^{3+} waveguides were 1 µm high and 2.0 µm wide, with an etch depth of 270 nm.

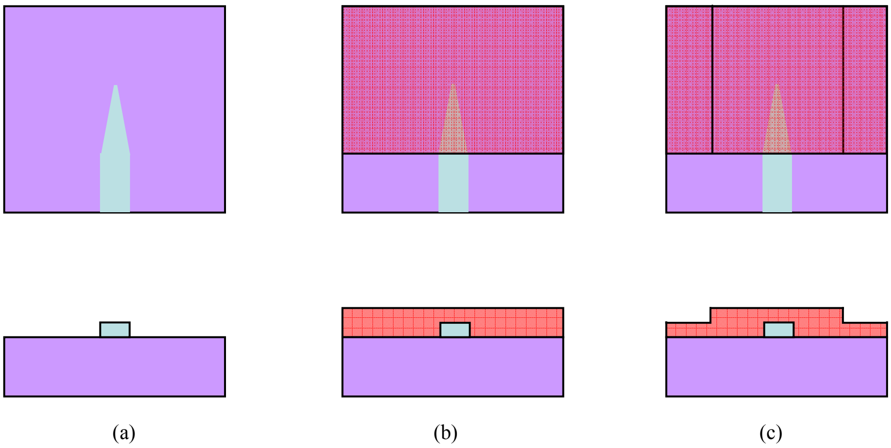

Fig. 3. Process flow for integration of Al_2O_3:$Er^{3+}$and Si waveguides (top view and cross-sectional view). (a) SOI waveguide; (b) Deposition of the Al_2O_3:Er^{3+} layer; (c) Structuring of the Al_2O_3:Er^{3+} layer

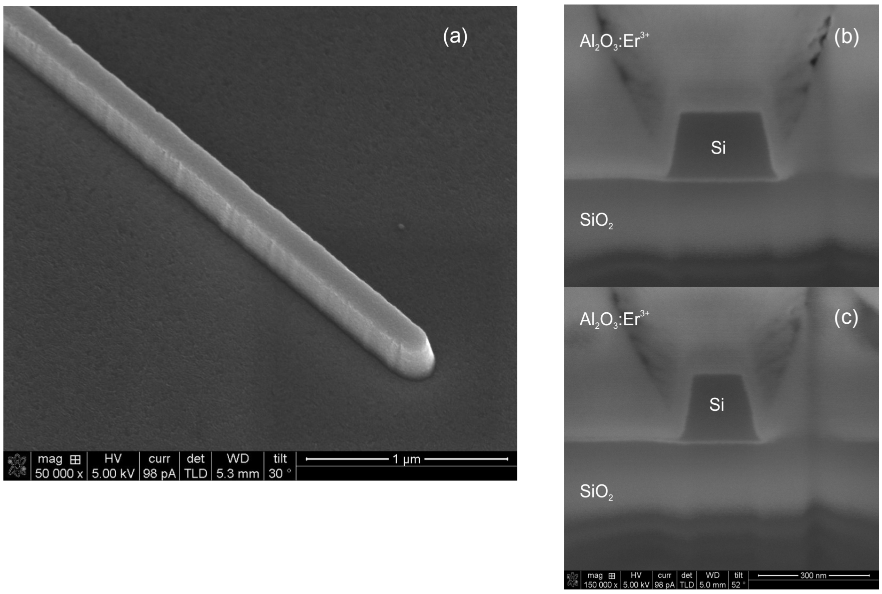

Fig. 4. (a) Scanning electron microscope (SEM) picture of an inversely tapered Si waveguide end before deposition of $Al_2O_3:Er^{3+}$. (b and c) SEM cross-sectional pictures of the tapered Si waveguide with decreasing horizontal size, covered by the $Al_2O_3:Er^{3+}$ overlay

Losses in the Si-$Al_2O_3:Er^{3+}$ coupler were measured by comparing the transmission of 1533-nm light in $Al_2O_3:Er^{3+}$ waveguides both with and without Si-taper couplers. Reasonable losses of 2.5 dB per coupler were determined for our first, non-optimized structures. The difference between this value and the simulated coupler losses of 0.5 dB was due to the mode leaking from the $Al_2O_3:Er^{3+}$ overlay on top of the Si inverted taper to some residual silicon structures on both sides of the coupling section (Fig. 5).

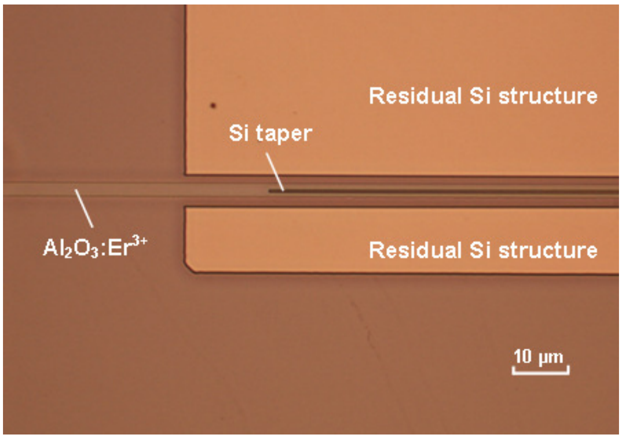

Fig. 5. Microscope picture of an $Al_2O_3:Er^{3+}$-Si coupler surrounded by residual silicon structures

3. Signal enhancement measurements

Signal enhancement measurements were then performed in an $Al_2O_3:Er^{3+}$-Si-$Al_2O_3:Er^{3+}$ structure. The chip was prepared as explained in Sect. 2. The two $Al_2O_3:Er^{3+}$ sections had a total length of X mm, while the Si waveguide was 4 mm long, including the tapers. The $Al_2O_3:Er^{3+}$ waveguides were designed for randomly polarized pump and signal light, good overlap of pump and signal mode profiles (97% for 1480-nm pumping) and strong confinement of the propagating pump and signal within the active region (>80%). The Er concentration was 1.95×10^{20} cm^{-3}. 1480-nm pump light from a laser diode and modulated 1533-nm TE-polarized signal light from a tunable laser were launched simultaneously in the device through a 1.48/1.55-µm WDM fiber coupler. Another WDM coupler placed at the output of the chip and standard lock-in detection were employed to separate the output signal light from any residual pump light and amplified spontaneous emission. Based on insertion loss measurements, it was found that the percentage of pump power launched into the waveguide was 19%, in very good agreement with the 20% value calculated using the modesolver software PhoeniX FieldDesigner [Phoenix]. Approximately 1 µW of signal power was launched into the chip to ensure the signal enhancement measurement was within the small signal limit. The signal transmission change through the 1.35-cm-long structure as a function of the launched pump power is shown in Fig. 6. An enhancement of 7.2 dB was reached at a pump power of 53 mW in the waveguide.

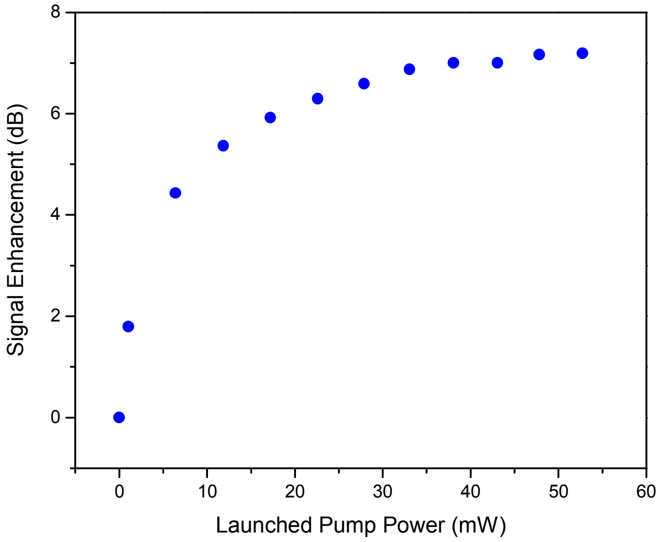

Fig. 6. Optical signal enhancement at 1533 nm in a 1.35-cm-long Al_2O_3:Er^{3+}-Si-Al_2O_3:Er^{3+} structure as a function of launched pump power

To our knowledge, this is the first time that wafer-scale monolithic integration of Er-doped waveguides with Si waveguides is achieved and signal enhancement is measured. A comparison between the performance of the devices presented in this paper and our standard Al_2O_3:Er^{3+} channel waveguides deposited on thermally oxidized Si wafer [Kerstin growth] is now drawn. Signal enhancement in the latter case is calculated by simply adding the total losses at 1533 nm to the net gain reported in [Jon gain] for a waveguide similar to those investigated in this study. A value of 6.75 dB over a 1-cm-long waveguide is obtained, which is comparable to the 7.2 dB achieved here in a 1.35-cm-long Al_2O_3:Er^{3+}-Si-Al_2O_3:Er^{3+} structure; this indicates that Al_2O_3:Er^{3+} integrated with Si waveguides can potentially achieve the same gain demonstrated in plain, straight Al_2O_3:Er^{3+} waveguides. An additional strong point in favor of the integration of Al_2O_3:Er^{3+} with Si waveguides is that the 2-µm-thick SiO_2 buffer layer, which is standard in SOI devices but small if compared to the normal 8-µm-thick layer usually employed in our devices, does not introduce any unwanted mode coupling between the Al_2O_3:Er^{3+} layer and the silicon substrate. Simulations were performed, and even for such small SiO_2 thickness the predicted loss value was 0.2 dB/cm for the TE mode, which the same value typically obtained with a 8-µm-thick SiO_2 layer. Demonstration of these fundamental results principally enable one to make use of any potential Er-doped gain device and its performance in passive Si photonic circuits. With the gain of 1.1 dB/cm achieved in Al_2O_3:Er^{3+} amplifiers under 1480-nm pumping, as inferred from [Jon gain], a 4.5-cm-long section could compensate the current losses of 2.5 dB per coupler in a Si-Al_2O_3:Er^{3+}-Si integrated amplifier at the peak wavelength. In addition, a segment of Al_2O_3:Er^{3+} placed between the chip facet and a Si waveguide could compensate the losses due to the mode mismatch between optical fiber and waveguide modes. This segment can be pumped at 976 nm thus leading to an even higher gain of 2 dB/cm [Jon gain]; a 4.75-cm-long Al_2O_3:Er^{3+} section would be necessary to compensate the current 7 dB losses originating from the mode mismatch between a single mode fiber and the Al_2O_3:Er^{3+} waveguide and the 2.5 dB losses of the subsequent Al_2O_3:Er^{3+}-Si coupler. With improved coupler losses of 0.5 dB and exploiting Yb^{3+} co-doping in conjunction with higher Er^{3+} concentrations [Patel], significantly less than 1 cm of amplifier length will potentially provide net amplification across the entire telecom C-band, making such an integrated amplifier a highly desirable device for Si photonics.

4. Conclusions

$Al_2O_3:Er^{3+}$ gain structures were integrated with Si waveguides, establishing $Al_2O_3:Er^{3+}$ as a medium which can provide gain within silicon – and potentially other – photonic circuits. This enables the monolithic integration of Er-doped active devices with passive Si waveguide structures to achieve complex optical functionalities on a wafer scale.

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