Wafer-Scale Monolithic Integration of $Al_2O_3:Er^{3+}$ Amplifiers with Si Waveguides

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Abstract: Co-sputtering and structuring active erbium-doped aluminum oxide waveguides directly on top of processed SOI passive waveguides provides coupling losses of 2.5 dB between active and passive waveguides and a signal enhancement of 7.2 dB.

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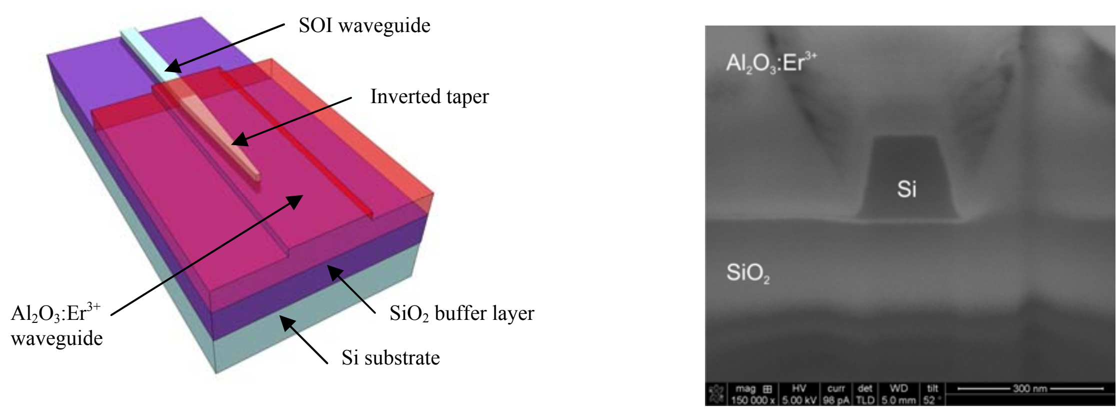
1. Introduction

Silicon is the ideal material to realize photonic integrated circuits, thanks to its high refractive index and the possibility of using the highly developed CMOS processing infrastructure for device fabrication [1]. However, efficient light emission and amplification directly from silicon remains a bottleneck. For applications in the telecommunication field, emission at 1.55 µm is desirable. Amorphous aluminum oxide (Al_2O_3) can be deposited directly on silicon substrates [2] and is an excellent host for erbium, allowing the incorporation of high erbium concentrations without clustering (~10^{20} cm^{-3}) and showing a wide emission spectrum around 1533 nm. Recently we have obtained 2 dB/cm peak gain and 80 nm gain bandwidth in $Al_2O_3:Er^{3+}$ [3]. Here we propose the monolithic integration of active Er-doped Al_2O_3 waveguides with a silicon nanophotonic circuit.

2. Experimental

Silicon-on-insulator (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 [4] and 2.0-µm-wide ridge waveguides were defined by reactive ion etching to a depth of 270 nm [5]. 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 to adiabatically transform the silicon waveguide mode to that of the $Al_2O_3:Er^{3+}$ waveguide. The chip was then diced to expose the end facets. A schematic of the whole structure is shown in Fig. 1a, along with a cross-sectional SEM picture in Fig. 1b. The total length of the chip was 1.35 cm.



(a) (b)

Fig. 1 (a) Schematic of the adiabatic inverted taper structure and (b) SEM picture of the tapered Si waveguide covered by the $Al_2O_3:Er^{3+}$ overlay

Propagation losses in the SOI waveguide were measured by the cutback method, while losses in straight $Al_2O_3:Er^{3+}$ waveguides were determined by the streak-of-scattered-light method. Fiber-to-chip coupling losses were determined by insertion loss measurements, while losses in the SOI waveguide-$Al_2O_3:Er^{3+}$ coupling section were determined by comparing the transmission of 1533-nm light in $Al_2O_3:Er^{3+}$ waveguides both with and without Si-photonic taper couplers. Signal enhancement measurements were carried out by launching simultaneously 1480-nm pump light from a laser diode and modulated 1533-nm signal light from a tunable laser into the channel waveguides using a 1.48/1.55-μm WDM fiber coupler. The output signal light was separated from the residual pump light by a second WDM coupler and acquired by a detector and lock-in amplifier.

3. Results and Discussion

Propagation losses amounted to 3 dB/cm in the SOI waveguides and 7.6 dB/cm in the $Al_2O_3:Er^{3+}$ waveguides. Coupling losses of 2.5 dB per coupler were determined in the Si taper couplers. Figure 2 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. The much higher-than-expected losses in the $Al_2O_3:Er^{3+}$ waveguides of 7.6 dB/cm as compared to the typical 0.2 dB/cm in our $Al_2O_3:Er^{3+}$ waveguides fabricated on thermally oxidized Si wafers [3] and the somewhat higher-than-expected losses of the couplers prevented us from achieving internal net gain in $Al_2O_3:Er^{3+}$-Si-$Al_2O_3:Er^{3+}$ or Si-$Al_2O_3:Er^{3+}$-Si integrated waveguide devices, but the causes were readily identified: the etching removal of some redundant Si features left a rough surface under the $Al_2O_3:Er^{3+}$ waveguides, which in addition turned out to be multi-mode. The recognition of such issues makes us confident that net gain in such active-passive integrated structures will be achieved with an optimized fabrication process and waveguide design.

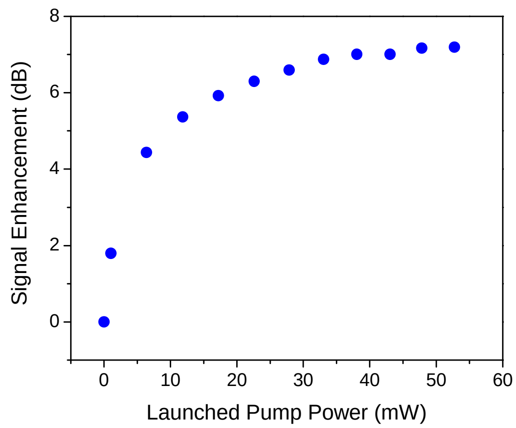


Fig. 2. Signal enhancement (dB) vs. launched pump power in an $Al_2O_3:Er^{3+}$-Si-$Al_2O_3:Er^{3+}$ structure

4. Conclusions

Monolithic integration of active $Al_2O_3:Er^{3+}$ waveguides with an underlying passive Si-photonic circuit was demonstrated. A signal enhancement of up to 7.2 dB was measured for an Er concentration of 2×10^{20} cm^{-3}. This result, in addition to the identification and removal of the loss mechanisms, will enable us to provide amplification within a passive Si waveguide circuit via monolithic integration.

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5. References

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