Enhanced Gain in Er-doped Al_2O_3 Channel Waveguide Amplifiers

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Erbium-doped aluminum oxide amplifiers with varying erbium concentration have been fabricated on thermally oxidized silicon substrates. Significant net internal gain of up to 1.6 dB/cm has been measured at 1533 nm for the optimum Er concentration. Furthermore, net gain has been demonstrated over a wavelength range of 40 nm, including the telecom C-band, demonstrating the potential for amplifiers or tunable lasers on a silicon platform at these critical wavelengths.

Introduction

Rare-earth-ion-doped dielectric waveguides have recently received significant attention for applications such as on-chip amplifiers and lasers [1]. In particular, integrated erbium-doped waveguides offer amplification and active functions around the telecom C-band (1525-1565 nm) in compact devices. Of the various materials explored as a host for erbium, amorphous aluminum oxide (Al_2O_3) is known to have excellent properties, including low background losses and a moderate refractive index contrast with the cladding material (SiO_2), which allows compact devices and deposition on silicon substrates [2]. In addition, high erbium concentrations without clustering (~10^{20} cm^{-3}) and a wide emission spectrum around 1533 nm (~55 nm full width half maximum) have been demonstrated in Al_2O_3:Er^{3+} layers. The key drawback of this material until now has been the significantly lower peak internal gain per unit length (0.8 dB/cm) compared to other rare-earth-ion-doped glass materials (~ 3 to 5 dB/cm), which effectively negates the advantage of stronger confinement because longer devices are required to achieve the same total gain [3-5]. In this work, Al_2O_3:Er^{3+} amplifiers have been fabricated by a combination of reactive co-sputtering, standard lithography and reactive ion etching, a highly reliable and relatively low-cost method [6]. The deposition process, waveguide design and Er concentration have been optimized, and the gain has been significantly enhanced, up to a value of 1.6 dB/cm at 1533 nm. The results are being applied to the design and realization of active devices based on a silicon platform.

Experimental Results

Fabrication of Er-doped Al_2O_3 Channel Waveguide Amplifiers

Al_2O_3:Er^{3+} layers approximately 1 μm thick were deposited on thermally oxidized 10-cm Si wafers by reactive co-sputtering using an AJA ATC 1500 sputtering system. High purity metallic Er and Al targets were sputtered separately using Ar guns, while oxygen was supplied as a gas. The sputtering power applied to the Al target was held constant at 200 W, while the Er-target power was varied between 6 to 20 W in order to vary the

Er concentration. The Er concentration, which is uniform throughout the layer, was determined by Rutherford Backscattering Spectroscopy (RBS). Fig. 1 shows the resulting Er concentration versus sputtering power applied to the Er target. Layer thicknesses and refractive index were measured in the centre of the wafer by the prism coupling method. The layer thickness has been shown to be highly uniform (± 1.4 %) within a radius of 3 cm from the center of the wafer, while the refractive index varied slightly (1.648 ± 0.008 at 1550 nm), increasing with Er concentration. In order to investigate the background losses and the absorption at the pump and the signal wavelengths, the optical propagation losses were measured at 633 nm, 977 nm, 1320 nm and 1533 nm by the moving prism method. Low background losses were observed at 633 nm and 1320 nm in all the films, indicating the excellent repeatability of the deposition process, while the absorption at both 977 nm and 1533 nm increased with Er concentration, as expected. The results are shown in shown in Fig. 2.

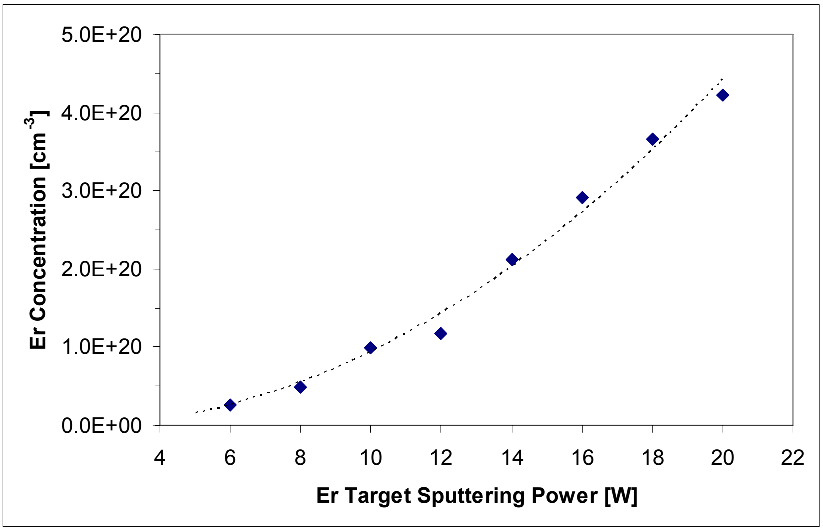

Fig. 1. Er concentration vs. Er target sputtering power (data points) and polynomial fit (dashed line)

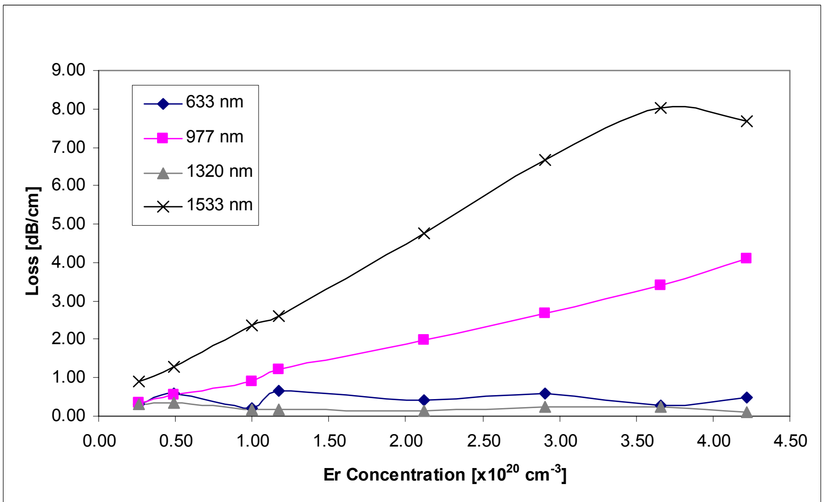

Fig. 2. Optical propagation loss as a function of Er concentration. The lines are a guide for the eye.

Straight channel waveguides with a width of 4.0 μm and etch depths varying from 40 to 100 nm were fabricated in the layers The etch depth, layer thickness and waveguide width were selected to ensure strong confinement of the propagating optical signal within the uniformly doped $Al_2O_3:Er^{3+}$ layer (≥ 85% at 1533 nm) and single mode behaviour with excellent overlap of both signal and pump modes. The samples were cleaved to lengths varying from 5.4 to 6.35 cm.

Gain

The small-signal net internal gain of the different samples was investigated by simultaneously launching 977 nm pump light and 1533 nm signal light into the waveguide and coupling out via lenses. A lock-in detection and a silicon filter were used to separate the signal from the residual transmitted pump light collected at the output of the waveguide. The propagation loss at the signal wavelength was subtracted from the signal enhancement measured in this manner in order to calculate the net internal gain in the channel waveguide. The propagation loss in the channel waveguide was assumed to be the same as the slab loss due to the relatively shallow etch depths, which are expected to introduce very little extra scattering loss as the signal propagates in the channel waveguide [6], and very similar confinement factors of the optical mode within the $Al_2O_3:Er^{3+}$ layer in both the slab and the channel waveguide case. The results for a calculated launched pump power of (155 ± 5) mW and varying Er concentration are shown in Fig. 3a. The launched pump power was estimated by measuring the pump power supplied from a tunable Ti:Sapphire laser operating at 977 nm at the waveguide input and multiplying by the simulated overlap integral of the waveguide mode and the approximately Gaussian pump beam and taking into account the Fresnel reflection at the facet. Although the waveguide length varies by about 1 cm, this gives a reasonable comparison of the maximum gain which would be achievable for each concentration using readily available low-cost laser diode pumping. The optimum Er concentration lies around 1.2×10^{20} cm^{-3} where net gain of up to 1.6 dB/cm was observed, about twice the previously reported maximum value [3]. In addition, significantly higher gain was observed across the entire C-band. The results for varying launched pump power for the optimum sample are shown in Fig. 3b. Above the optimum concentration reabsorption of the pump light and energy-transfer upconversion appear to play an important role. These effects are currently under investigation.

Conclusions

Gain of up to 1.6 dB/cm has been demonstrated in an $Al_2O_3:Er^{3+}$ waveguide, making this technology competitive with other rare-earth-ion-doped glass waveguide devices. The optimum Er concentration was found to be around 1.2×10^{20} cm^{-3}.

Acknowledgment

This work was supported by funding through the European Union's Sixth Framework Programme (Specific Targeted Research Project “PI-OXIDE”, contract no. 017501).

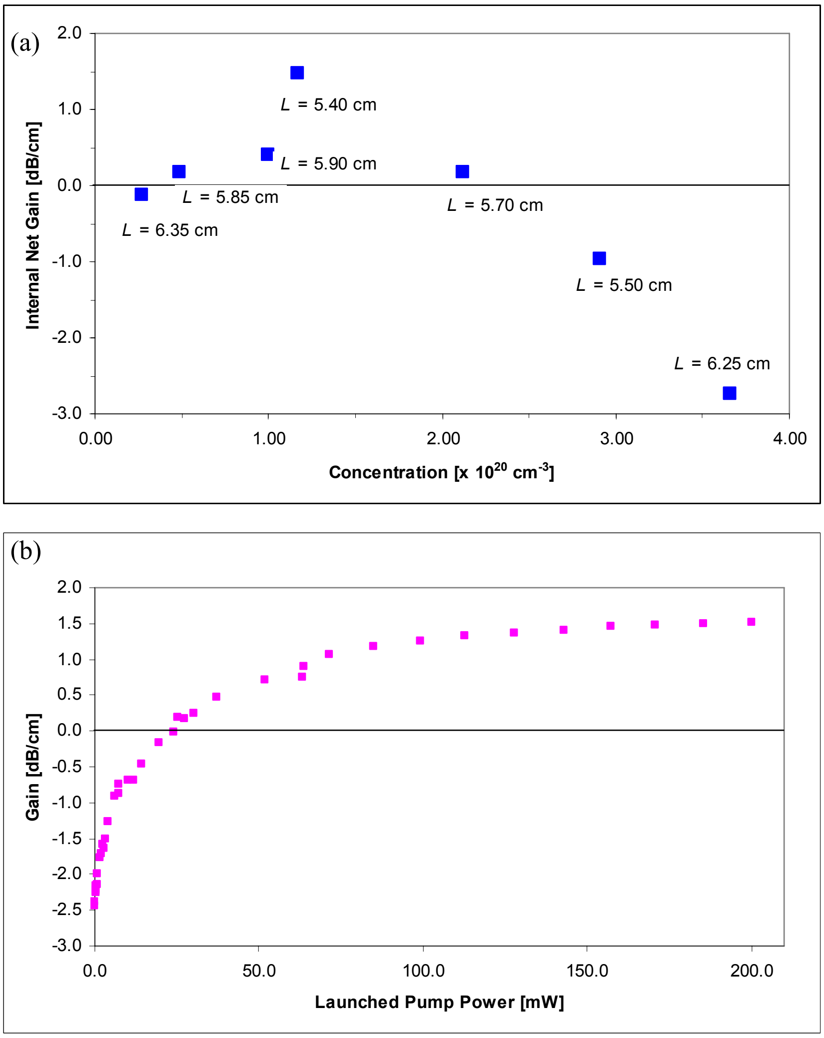

Fig. 3. (a) Net internal gain at 1533 nm as a function of Er concentration, for a launched pump power of (155 ± 5) mW. The waveguide length, *L*, is indicated next to each point. (b) Gain vs. launched pump power for an Er concentration of 1.2×10^{20} cm^{-3}

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