Neodymium-doped Al_2O_3 channel waveguide amplifiers

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Neodymium-doped Al_2O_3 layers were deposited on thermally oxidized Si substrates by reactive co-sputtering and channel waveguides were patterned using reactive-ion etching. Internal net gain on the Nd^{3+} transition at 1064 nm was experimentally investigated with various Nd^{3+} concentrations. With approximately 12 mW of launched pump power at 800 nm, a maximum gain of 4.0 dB/cm was demonstrated in a 1-cm-long Al_2O_3:Nd channel waveguide sample with a Nd^{3+} concentration of $1.68x10^{20}$ cm^{-3}. Investigations of gain on the Nd^{3+} ground-state transition around 880 nm are under way. This wavelength range is of interest for amplification of signals transmitted through optical backplanes.

Introduction

Integrated optical channel waveguides doped with rare-earth ions have applications in telecommunication and on-chip sensing. Optical gain in neodymium-doped channel waveguides has been demonstrated in various host materials and with different waveguide fabrication techniques, such as channel fabrication by proton exchange in a $LiNbO_3$ host material (7.5 dB gain for 5.6 mm) [1] or laser-written channels in Nd-doped glass (1.5 dB/cm) [2]. More recently, gain has been demonstrated in Nd-doped sol-gel-based (3.75 dB/cm) [3] and polymer-based channel waveguides (1.4 dB/cm) [4]. In this paper, we report gain at 1064 nm in Nd-doped Al_2O_3 channel waveguides. This host material was successfully employed for Er^{3+} amplifiers [5] and the first integrated Er^{3+} laser in this material [6]. Amorphous Al_2O_3 provides a high refractive index contrast, allowing for small bending radii and correspondingly small devices, which is desirable for on-chip solutions. In addition, Al_2O_3 is compatible with silicon technology, as it can be deposited on thermally oxidized silicon [7] and patterned using standard lithography and reactive ion etching [8]. Channel waveguides with a background propagation loss in the order of 0.1 dB/cm can thus be obtained [8]. In this work, we report 4.0 dB of net optical gain on the $^4F_{3/2}$ to $^4I_{11/2}$ transition in a 1-cm-long Al_2O_3:Nd waveguide channel.

Experimental Results

Fabrication of Nd-doped Al_2O_3 Channel Waveguide Amplifiers

Al_2O_3:Nd layers with a thickness of 600 nm were reactively co-sputtered onto thermally oxidized 10-cm Si wafers. High-purity Al and Nd targets were sputtered using Ar guns, while oxygen was supplied as a gas. By varying the Nd-target power, different Nd^{3+} concentrations of $1.13x10^{20}$ cm^{-3} to $2.95x10^{20}$ cm^{-3} have been obtained, measured by Rutherford Backscattering Spectroscopy (RBS). Straight channel waveguides with a width of 2.0 μm were fabricated in the layers by means of Reactive Ion Etching (RIE). The channels were shallow etched by 100 nm. These channels are single-mode at a wavelength of 1064 nm and multi-mode at the pump wavelength of 800 nm. The channel waveguides use air as the cladding.

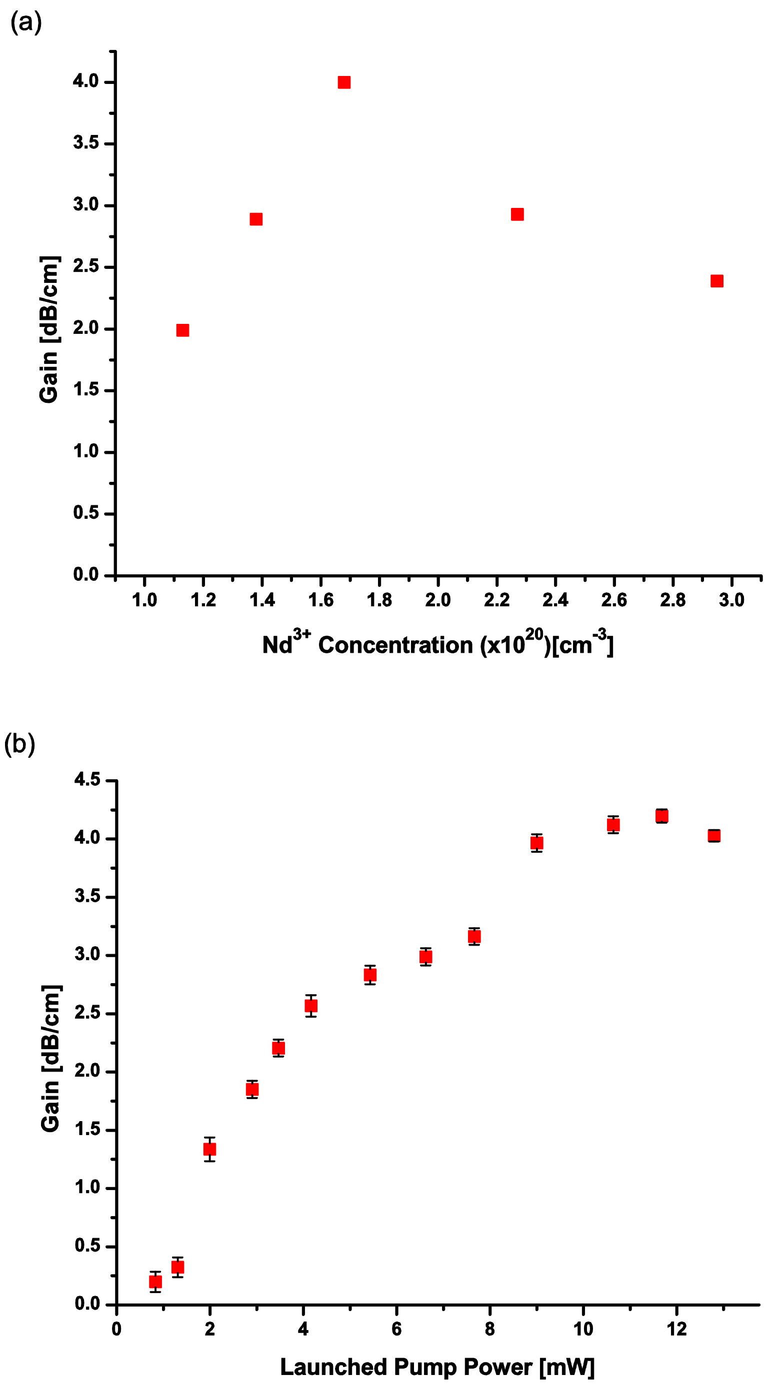

Figure 1. (a) Internal net gain at the signal wavelength of 1064 nm as a function of Nd^{3+} concentration, for a launched pump power of 12 mW. The optimum concentration is 1.68×10^{20} cm^{-3}, with a gain of 4.0 dB/cm. (b) Internal net gain at the signal wavelength of 1064 nm as a function of launched pump power for a Nd^{3+} concentration of 1.68×10^{20} cm^{-3}.

Gain

Small-signal, internal net gain investigations were performed using a Ti:Sapphire laser (Spectra-Physics 3900S) at 800 nm as the pump source. Signal light at 1064 nm was simultaneously coupled into a 1-cm-long waveguide using a 0.85 NA microscope lens. Light was collected by a second microscope lens and focussed onto a Germanium detector connected to a lock-in amplifier. A filter with a cut-off at 850 nm was used to separate the signal from the residual pump light collected at the output of the channel waveguide. Signal enhancement was calculated by dividing pumped signal power by the unpumped signal power. Slab propagation loss measurements by prism coupling average to 0.6 dB/cm at 1064 nm. An additional 0.1 dB/cm was assumed due to channel etching [8]. The total propagation loss of 0.7 dB/cm at the signal wavelength was subtracted from the measured signal enchancement in order to obtain the internal net gain. The launched power was estimated by measuring the pump power at the waveguide input and multiplying this value by the simulated overlap integral between the incident Gaussian pump beam and the waveguide mode and taking into account the Fresnel reflections. A correction for imperfect waveguide facets was applied by measuring the power after the outcoupling lens at the non-absorbing wavelength of 845 nm and comparing with the simulated outcoupled power, assuming identical losses at the incoupling and outcoupling facets. The saturated gain results for a calculated launched pump power of 12 mW is shown in Fig. 1a. The optimum Nd^{3+} concentration is around $1.68x10^{20}$ cm^{-3}, which yields a net gain of 4.0 dB/cm. Figure 1b shows the results for varying pump power for the optimum sample. The observed lower gain for higher Nd^{3+} concentrations is expected to have its origin in energy-transfer upconversion processes [9].

Conclusions

Gain of up to 4.0 dB/cm has been demonstrated in a Nd-doped Al_2O_3 waveguide, where the optimum Nd^{3+} concentration was found to be $1.68x10^{20}$ cm^{-3}. The observed gain is competitive with other rare-earth-ion-doped waveguide devices, while the Al_2O_3 material is fully compatible with silicon-based technology. The observed gain is sufficient for Nd^{3+}-based integrated amplifiers and lasers, which are currently being investigated.

Acknowledgment

The authors thank D. Geskus for help with the gain experiments.

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