Investigation of Optical Gain in Al_2O_3:Er Channel Waveguide Amplifiers

J. D. B. Bradley, L. Agazzi, D. Geskus, T. Blauwendraat, F. Ay, K. Wörhoff, and M. Pollnau
Integrated Optical MicroSystems Group, MESA+ Research Institute, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands
Author e-mail address: j.d.b.bradley@ewi.utwente.nl

Abstract: Reactively co-sputtered aluminum oxide layers with low background loss and varying Er concentrations have been deposited. Net optical gain of 0.76 dB/cm was obtained for an Er concentration of 0.9×10^{20} cm^{-3} in a channel waveguide.

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

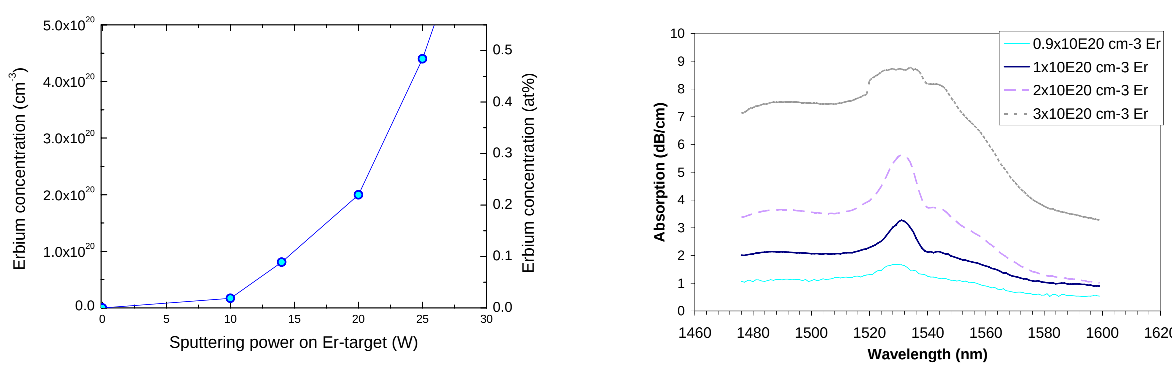
1. Introduction

Erbium-doped aluminum oxide (Al_2O_3:Er) is known to be an excellent material for active integrated optics applications [1,2]. Previously, fabrication complexity limited the potential of this material. The deposition process required additional ion implantation steps and further annealing to reduce background losses, and etching of channel waveguides in the layers was limited to physical sputtering or wet chemical etching. To address these drawbacks, we have recently developed a well-controlled, repeatable deposition process for low-loss as-deposited Al_2O_3 layers [3], and an optimized reactive ion etching (RIE) process for fabrication of high-resolution, high-optical-quality channel waveguides in the Al_2O_3 layers [4]. In this paper, the potential for active devices such as integrated lasers and amplifiers is investigated by comparing the gain characteristics of Al_2O_3 waveguides with different Er concentration fabricated using the optimized processes. Net optical gain is demonstrated.

2. Experimental

Al_2O_3:Er layers of 707 to 956 nm thickness were reactively co-sputtered on thermally oxidized Si <100> substrates using an AJA ATC 1500 system. The deposition process was optimized for uniform, amorphous Al_2O_3 waveguides and simultaneously sputtering from metallic Al and Er targets. The Er concentration in the layers was adjusted to the desired value by altering the RF power applied to the Er and Al targets during deposition, while keeping the substrate temperature (550 °C) and other deposition parameters constant. In order to ensure optimum overlap at both the pump and signal wavelengths of 980 and 1480-1600 nm, respectively, straight channel waveguides approximately 6 cm-long were etched to a depth of ≤ 50 nm with varying widths of up to 8.0 µm. Both processes (deposition and waveguide etching) have been shown to result in channel waveguides with propagation losses as low as 0.21 dB/cm in undoped Al_2O_3 layers [4].

3. Results and Discussion



(a) (b)

Fig. 1 (a) Erbium concentration as a function of sputtering power applied to the Er target and (b) absorption spectra for samples with varying erbium concentration.

The Er concentration variation as a function of RF power applied to the Er target during sputtering is shown in Fig. 1 (a). The lifetime of the Er $^4I_{13/2}$ level was measured to be 7 ms at the lowest and decreased to 2 ms at the highest concentration considered for this investigation, which compares favourably with previous results [1]. Based on these lifetime data, the layer concentrations of the samples to be characterized were selected to be approximately 0.9-, 1-, 2- and 3×10^{20} cm^{-3}, respectively.

The absorption spectra of the layers were measured using the prism coupling technique applying a 1320-nm and a 1480-nm diode laser and Ge detector to determine the background losses and either a supercontinuum white light source and spectrum analyzer or fiber butt-coupling setup with a tuneable laser source to obtain the spectral shape of the Er absorption. The absorption measured in the range of 1480 to 1600 nm is shown for each sample in Fig. 1 (b). The typical Er absorption peak around 1550 nm increases with increasing Er concentration as expected.

To measure the small-signal gain in the channel waveguides, 980-nm pump light from a Ti:Sapphire laser and signal light modulated at 331 Hz from a tuneable laser (1480–1600 nm) were in-coupled and out-coupled from the waveguides simultaneously via lenses. The signal intensity was monitored by filtering the out-coupled pump light and using lock-in detection. The resulting net gain was determined by subtracting the known absorption in the layer and taking into account the small additional loss introduced by the channel waveguide etching (~0.1 dB/cm) [4]. The pump power coupled into the waveguide was determined by measuring the output power from the lens at the focal length and calculating the overlap of the minimum beam spot with the simulated optical mode profile expected in the waveguide. Fig. 2 (a) shows the maximum net gain for the three lowest concentration Al_2O_3:Er waveguides across the signal wavelength range. For the higher Er concentration samples, the high absorption of both pump and signal in the layer severely limits the overall achievable gain, while net gain was observed in the two lowest concentration samples. A maximum net gain of 4.9 dB over 6.4 cm length, equivalent to 0.76 dB/cm, was observed for a concentration of 0.9×10^{20} cm^{-3} at a wavelength of 1533 nm. Fig. 2 (b) shows the gain as a function of pump power coupled into the waveguide at 1533 nm, also for the three lowest concentration samples, indicating saturation of the gain at around 70 mW of input power.

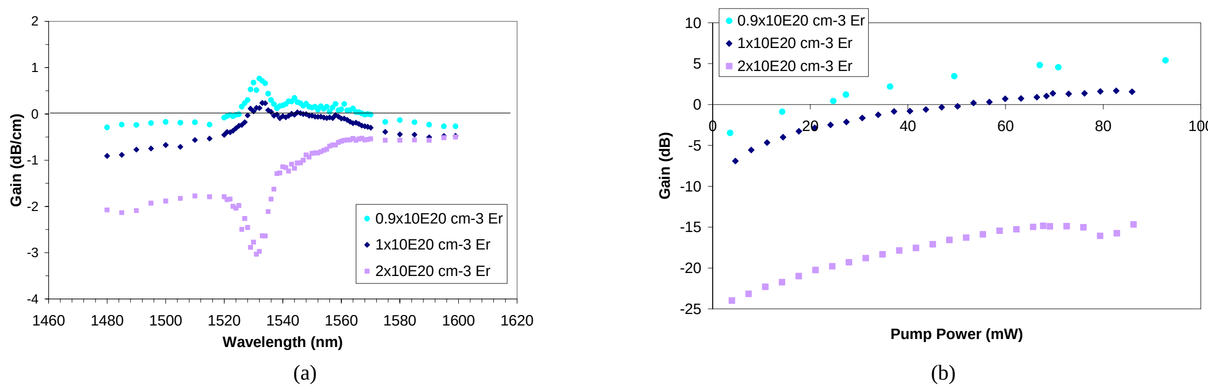


Fig. 2. (a) Gain (dB/cm) as a function of wavelength at 70 mW pump power and (b) total gain (dB) at 1533 nm as a function of pump power in the waveguide for Al_2O_3:Er samples with varying Er concentration.

4. Conclusions

The absorption and gain characteristics have been compared in as-deposited reactively co-sputtered Al_2O_3:Er layers with varying Er concentration. A net optical gain of up to 0.76 dB/cm was demonstrated for an approximate Er concentration of 0.9×10^{20} cm^{-3}, over a wavelength range of 1526-1564 nm. It is expected that the gain can be further increased at lower Erbium concentrations and this study is currently on-going. The optimized layers are very promising for active integrated optical functions such as lasers and amplifiers in silicon-based technology.

5. Acknowledgment

This work was supported by the European Commission within the STREP project PI-OXIDE (017 501).

6. References

[1] G. N. van den Hoven, R. J. I. M. Koper, A. Polman, C. van Dam, J. W. M. van Uffelen, and M. K. Smit, “Net optical gain at 1.53 µm in Er-doped Al_2O_3 waveguides on silicon,” Appl. Phys. Lett. **68,** 1886-1888 (1996).
[2] C. E. Chryssou and C. W. Pitt, “Er^{3+}-doped Al_2O_3 thin films by plasma-enhanced chemical vapor deposition (PECVD) exhibiting a 55-nm optical bandwidth”, IEEE J. Quantum Electron. **34**, 282-285 (1998).
[3] K. Wörhoff, F. Ay, and M. Pollnau, “Optimization of low-loss Al_2O_3 waveguide fabrication for application in active integrated optical devices”, ECS Transactions **3**, 17-26 (2006).
[4] J. D. B. Bradley, F. Ay, K. Wörhoff, and M. Pollnau, “Fabrication of low-loss channel waveguides in Al_2O_3 and Y_2O_3 layers by inductively coupled plasma reactive ion etching”, Appl. Phys. B **89**, 311-318 (2007).