$\text{Al}_2\text{O}_3:\text{Er}^{3+}$ as a New Platform for Active Integrated Optics

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ABSTRACT

Recently, we have demonstrated internal net gain with a bandwidth of 80 nm (1500 – 1580 nm) and 1533 nm peak gain of 2.0 dB/cm in $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ channel waveguides which were sputtered on silicon substrates and subsequently reactive ion etched. Based on measured spectroscopic parameters, rate-equation simulations predict gain of > 20 dB throughout the entire telecom C-band for optimized waveguide lengths. Data transmission of 40 Gbit/s has been obtained. Grating structures for on-chip integrated cavities and distributed-feedback lasers have been fabricated in this material and are currently under investigation.

Keywords: aluminum oxide, erbium-doped materials, optical amplifier, channel waveguide, Bragg grating, Integrated optics.

1. INTRODUCTION

In integrated optics the search continues for active materials which can be integrated with passive materials in a straightforward and low-cost manner. Dielectric Er^{3+} -doped planar glass waveguiding materials offer broad gain around the critical 1550-nm wavelength range, and the potential for integrated on-chip tunable or short-pulse laser sources. Compared to other such glass materials, $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ has distinct advantages. It possesses a highly broadened emission spectrum for gain over a wider wavelength range. It has a higher refractive index contrast which allows tighter bend radii and more compact devices. Furthermore, it can be deposited on a number of common substrates, including thermally-oxidized Si wafers. This opens the possibility for integration of $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ directly with photonic materials such as Si which are optimized for passive waveguiding functions.

2. OPTICAL GAIN IN $\text{Al}_2\text{O}_3:\text{Er}^{3+}$

Deposition of $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ is carried out by applying a low-cost and straightforward reactive co-sputtering approach [1] and channel waveguides are prepared by reactive ion etching [2]. $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ amplifiers with different Er^{3+} concentrations have been investigated. Up to 2.0 dB/cm net gain was demonstrated at 1533 nm for an Er^{3+} concentration of $2 \times 10^{20} \text{ cm}^{-3}$ when pumping at 977 nm [3], see Fig. 1. Peak total gain of 9.3 dB was demonstrated in a 5.4-cm amplifier and positive gain was achieved over an 80-nm bandwidth [3]. Using a rate-equation model, up to 33 dB at the peak and > 20 dB between 1525 – 1565 nm is predicted in a 24-cm-long amplifier for a pump power of 100 mW [3], see Fig. 2. In Er^{3+} -doped fiber amplifiers, the long excited-state lifetime means transmission at bit rates around 40 Gbit/s is possible. We recently showed open-eye diagrams and only a small power penalty of 1 dB in bit-error-rate measurements for on-chip 40 Gbit/s signal transmission in an integrated $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ amplifier [4].

3. ON-CHIP INTEGRATED RESONANT STRUCTURES

We employed an optimized approach of focused ion beam (FIB) nano-structuring, which enabled patterning of distributed Bragg reflector (DBR) gratings on Al_2O_3 channel waveguides with smooth and uniform sidewalls and investigated the optical performance and limits of FIB-patterned integrated waveguide Fabry-Perot microcavities formed by two 520-nm-period surface-relief DBR gratings on dielectric channel waveguides, see Fig. 3. The grating structures were milled by 200 nm and the length of each grating was $\sim 47.5 \mu\text{m}$. The cavity length was varied between 100 – 450 μm . Measured Fabry-Perot resonances in the 1540-1577-nm wavelength range before and after annealing the sample at 600 °C for 17 hrs in N_2 atmosphere are plotted in Fig. 4, together with calculated transmission spectra of the annealed Fabry-Perot cavity. Values for the annealed Fabry-Perot cavity are a free spectral range of 7.5 nm, finesse of 3.1, reflectivity of 40%, and total resonator losses of 2.8 dB [5]. Based on these results we are currently investigating channel waveguide lasers based on DBR gratings as well as distributed feedback lasers in $\text{Al}_2\text{O}_3:\text{Er}^{3+}$. Furthermore, we are working on integrated ring lasers based on this material.

Figure 1. Net internal gain vs. 977-nm pump power in a 2.1-cm-long $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ amplifier, demonstrating up to 2.0 dB/cm gain. Figure taken from [3].

Figure 2. Predicted total gain vs. length at 1525, 1533, and 1565 nm in compact spiral amplifiers with an Er^{3+} concentration of $2 \times 10^{20} \text{ cm}^{-3}$ for 100 mW pump power. Figure taken from [3].

Figure 3. Scanning electron micrograph of a sample grating device realized on a waveguide.
Figure taken from [5].

Figure 4. Experimental and calculated Fabry-Perot transmission resonances for TE polarization of the as-milled and annealed cavity. Figure taken from [5].

4. CONCLUSIONS

The high net gain per unit length, large gain bandwidth, and high predicted total gain for low launched pump power demonstrate that $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ qualifies as a competitive material for active integrated optical devices, thus opening perspectives for amplifiers as well as widely tunable and ultrashort-pulse lasers in a material which can be integrated with silicon photonics. Rather than operating as a stand-alone device, which would give rise to significant coupling losses between the individual components and also have to compete with existing, high-performance, but non-integrable fiber-based solutions for amplifiers and lasers, we envisage the technology presented in this work primarily as applying to on-chip amplification and lasing within an integrated circuit, thereby exploiting its full integration and miniaturization potential.

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