High-gain spiral amplifiers in a-$Al_2O_3:Er^{3+}$ on a silicon chip

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Abstract: We designed and fabricated integrated optical amplifiers with 20 dB of gain at λ = 1532 nm. Aluminum-oxide films with erbium concentrations of $0.45-3.1\times10^{20}$ cm^{-3} were deposited onto thermally oxidized silicon wafers and microstructured. For a 24.5-cm-long spiral-shaped amplifier with an erbium concentration of 0.95×10^{20} cm^{-3}, a maximum internal net gain of ~20 dB was measured.

Introduction

Rare-earth-doped devices are of great interest for optical amplification due to their weak refractive-index change[1] compared to that typically induced in semiconductor optical amplifiers by electron-hole pairs, their long excited-state lifetimes, their large amplification bandwidth,[2] and the possibility for high-speed amplification.[3] In addition to these properties, giant optical gain of ~1000 dB/cm was measured in a ytterbium-doped crystalline waveguide.[4] Nevertheless, inferior gain performance is commonly observed in amorphous materials due to lower transition cross-sections caused by inhomogeneous broadening, hence only moderate values of gain per unit length have been reported.[5] In this work, we present the design, fabrication, and characterization of erbium-doped amorphous aluminum oxide waveguide amplifiers that exhibit ~20 dB of total internal net gain.

Design and fabrication

The model by Agazzi *et al.*[5] enables a comprehensive study of the spectroscopic characteristics of $Al_2O_3:Er^{3+}$ and, thus, was employed for the design of our waveguide amplifiers. Preliminary simulations employing the model indicated that the doping concentration has to remain below $\sim4\times10^{20}$ cm^{-3} to avoid ETU and fast quenching processes, which were accentuated with the erbium concentration. To ensure that most of the available pump power was absorbed, the amplifier length had to be on the order of tens of centimeters. A spiral-shaped channel waveguide was designed to minimize the footprint of the waveguide. By use of software (*Phoenix B.V.*),[6] mode-field simulations were performed for different ridge channel waveguide cross-sections, and the optimal dimensions were 1 µm height by 1.5 µm width, with a ridge height of 0.35 µm. These waveguide dimensions allowed for good confinement (>80%) of the mode field for both, pump and signal. The targeted maximum bending loss of $\sim10^{-6}$ dB/cm was satisfied in our design for a minimum bending radius of 2 mm.

A ~1-µm-thick layer of $Al_2O_3:Er^{+3}$ was deposited onto a thermally oxidized silicon wafer by RF reactive co-sputtering.[7] The spiral-shaped waveguides were patterned into the $Al_2O_3:Er^{3+}$ film employing common lithographic techniques and reactive ion etching.[8] A protective SiO_2 cladding layer was deposited on top by plasma-enhanced chemical vapor deposition.

Amplifier characterization

Background propagation losses were measured in the spirals using the imaging method.[9] This method consists in analyzing a digital image that records the light scattered from randomly distributed defects within the channel. The light from a fiber-coupled infrared laser (λ = 1320 nm) was butt-coupled to the spiral-shaped waveguide, and the scattered light was captured from the top face of the spiral using an InGaAs camera. Accurate calibration of the images was performed before analysis of the intensity distribution along the channel length in the spiral waveguide. An exponential decay curve as a function of propagation length was fitted to each intensity profile, and background propagation losses were found to be in average (0.2±0.1) dB/cm.

The spiral gain was characterized by employing the pump-probe technique. Pump light from a λ = 976 nm pig-tailed diode laser was combined with signal light from a tunable laser (λ = 1460−1640 nm) using a fiber-based WDM that was butt-coupled to the input of the spiral-shaped waveguides. At the output end of the waveguide, a second WDM was employed to separate the signal from the residual pump. By lock-in amplification the amplified signal was discriminated from the residual pump and the amplified spontaneous emission coupled to the waveguide. Figure 1 shows an image of a pumped $Al_2O_3:Er^{+3}$ spiral-shaped amplifier. The internal total gain measured in spirals of different length for a doping concentration of 0.95×10^{20} cm^{-3} is shown in Fig. 2. A maximum total gain of ~20 dB is achieved for a 24.5-cm-long spiral. Lower performance in longer waveguides is attributed to insufficient pump power at the end of the spiral, causing lower population inversion and, thus, signal re-absorption at the furthermost part of the spiral.

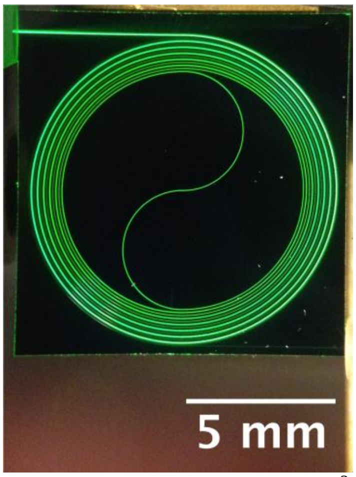

Fig. 1: Spiral-shaped $Al_2O_3:Er^{3+}$ amplifier pumped with a 976 nm pig-tailed diode laser.

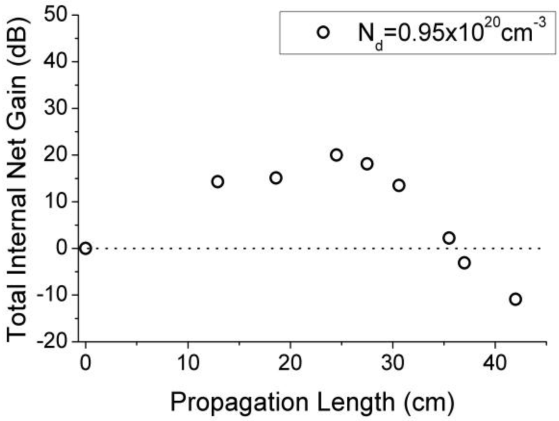

Fig. 2: Maximum total internal gain for different $Al_2O_3:Er^{3+}$ waveguide amplifiers with a doping concentration of 0.95×10^{20} cm^{-3}.

Conclusions

By carefully adjusting the ridge waveguide cross-section, erbium concentration, and waveguide length, we demonstrated 20 dB of internal gain in spiral-shaped $Al_2O_3:Er^{3+}$ waveguide amplifiers on a silicon chip. Further improvement can be expected if the fast quenching process that limits the useful erbium concentration can be diminished.

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