Erbium-doped dielectric waveguide amplifiers working in the telecom C-band

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Spiral-shaped waveguide amplifiers in erbium-doped amorphous aluminum oxide were fabricated and characterized. The gain characteristics versus waveguide length and doping concentration was studied. A maximum internal net gain of 20 dB was measured in a 24.4-cm-long spiral with a doping concentration of 0.95×10^{20} cm^{-3}. Experimental results were compared with a rate-equation model and good agreement was found when considering a fast quenching process.

Introduction

Erbium-doped materials are of great interest for laser sources and amplifiers in the telecom C-band [1]. Compared to semiconductor optical amplifiers, erbium-doped amplifiers have longer excited-state lifetimes (~ms), undergo smaller refractive-index changes [2] induced by rare-earth-ion excitation ($\Delta n \sim 10^{-6}$), and experience a weak temperature dependence on gain performance [3], which provide temporally and spatially stable gain. Among erbium-doped host materials, aluminum oxide has demonstrated to be a suitable candidate for integrated ultranarrow-linewidth waveguide lasers [4] and amplifiers [5–7]. $Al_2O_3:Er^{3+}$ integrated circuits exhibit low propagation loss [8,5], broadband amplification in the telecom C-band [6], gain per unit length of up to 2 dB/cm [6], and high-speed amplification [7]. Among the relevant characteristics that make $Al_2O_3:Er^{3+}$ a suitable platform for integrated optics are: its relatively high refractive index of n ~ 1.65 at 1.5 μm, which simplifies the integration and miniaturization of optical circuits, the ease of deposition via reactive co-sputtering [5], together with a chlorine-based reactive ion etching process for the definition of channel waveguides [8], and its compatibility with other platforms such as silicon-on-insulator (SOI) [9], polymer-based waveguides [10], and Si_3N_4 waveguides [11].

The amorphous nature of the host material broadens the erbium emission around 1532 nm, which supports signal amplification in wavelength division multiplexing (WDM) systems. On the other hand, the broadband emission penalizes the achievable gain by reducing the transition cross sections. This necessitates higher doping concentrations, which introduce energy transfer upconversion (ETU) and, more importantly, a fast quenching process [12] that escalates with increasing doping concentration, thereby affecting the amplifier performance and, thus, limiting the doping concentration. Consequently, a correct interpretation of the spectroscopic processes complemented by a waveguide geometry that optimizes the interaction of the dopant ions with the pump and signal light is essential for the optimization of an erbium-doped waveguide amplifier.

We present the design, fabrication, and characterization of erbium-doped waveguide amplifiers. A total gain of 20 dB was experimentally determined for a sample with a doping concentration of 0.95×10^{20} cm^{-3} and a waveguide length of 24.45 cm.

Design and Fabrication

Recently, two quenching mechanisms were identified to strongly affect the amplifier performance [12]. ETU, in which one ion in the first excited state ($^4I_{13/2}$) decays to the ground state ($^4I_{15/2}$) and transfers its energy to another ion in the same excited state, promoting it to the third excited state ($^4I_{9/2}$). Due to the large phonon energy of the host material, ions in higher excited energy levels mostly decay non-radiatively to the $^4I_{13/2}$ level [13], which results in a single ion in the first excited state ($^4I_{13/2}$). The second mechanism is a fast quenching process which is attributed to either energy transfer to an impurity in the material, a color center, or pair-induced static ETU [12]. Both quenching mechanisms intensify with increasing doping concentration, therefore the useful doping concentration is limited to $N_d < 3 \times 10^{20}$ cm^{-3}. To compensate this limitation and still benefit from the available pump power, interaction lengths on the order of 10 cm are required. Spiral-shaped waveguide amplifiers (Fig. 1a) were designed to reduce the device foot-print. Mode-field simulations using the FieldDesigner software [14] were performed to estimate the bend loss and the light confinement within the doped region. For a ridge channel waveguide (Fig. 1b) with a bending radius of 2 mm, losses of 10^{-6} dB/cm were estimated. Simulations determined a mode-field confinement of signal light at 1532 nm and pump light at 976 nm within the ridge channel above 80%.

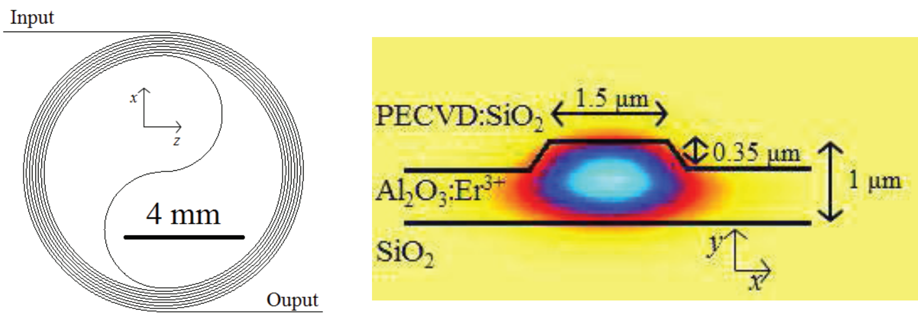

Figure. 1 a) Spiral waveguide design and b) waveguide cross-section and signal mode-field profile.

$Al_2O_3:Er^{3+}$ films were deposited on a thermally oxidized silicon substrate by reactive co-sputtering [5], and channel waveguides were patterned using standard UV lithographic techniques and chlorine-based reactive ion etching [8]. End facets were prepared by dicing.

Characterization

Propagation loss measurements of spiral waveguides were performed via the imaging method presented by Okamura et al. [15]. In average, 0.2 dB/cm loss was determined in the samples.

The pump-probe method was applied to measure the signal enhancement. The experimental setup is depicted in Fig. 2. Fiber-coupled 976 nm and 1532 nm diode lasers were used as a pump and signal sources, respectively. Both were combined into a single fiber by use of a fiber-based WDM. Signal and pump were launched into the waveguide end facet via a butt-coupled single-mode fiber (SMF). The amplified signal and the residual pump were collected and split using a similar WDM for detection. Lock-in amplification was applied for signal detection. The signal power was measured with the pump source on and off, $I_p(\lambda)$ and $I_u(\lambda)$, respectively.

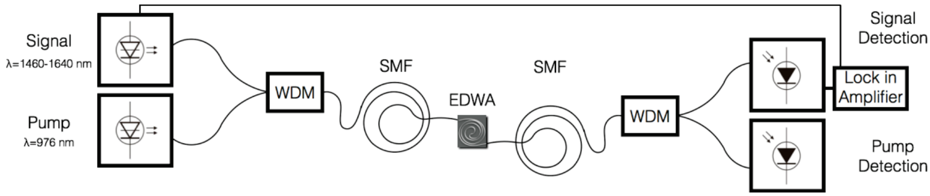

Figure 2. Pump-probe experimental setup for the measurement of signal enhancement.

The total internal net gain G was determined with the signal enhancement and the propagation loss for each sample by

$$G(\lambda)=10\log_{10}\left[I_p(\lambda)/I_u(\lambda)\right]-\alpha_{abs}(\lambda)\ell-\alpha_{loss}(\lambda)\ell\,, \qquad (1)$$

where α_{abs} and α_{loss} are the propagation loss due to erbium absorption and the background propagation loss at the signal wavelength, respectively, and ℓ is the propagation or spiral length.

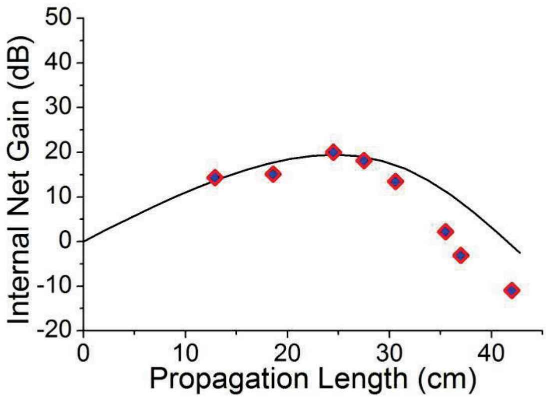

Figure 3. Total internal net gain at 1532 nm for different spiral amplifiers with $N_d = 0.95\times10^{20}$ cm^{-3}, experimental (symbols) and simulation results (line).

Figure 3 presents the total internal net gain as a function of propagation length; symbols display the experimental results, while the line shows the simulation results. A maximum total internal gain of 20 dB was determined for a 24.45-cm-long sample. The rate-equation model presented in [12] was applied for the simulation.

Summary
$Al_2O_3:Er^{3+}$ channel waveguide amplifiers were designed, fabricated, and characterized. Mode-field simulations helped to determine the optimum waveguide cross-sections for a spiral-waveguide design. A maximum internal gain of 20 dB was determined for a 24.4-cm-long spiral. Simulation and experimental results agree with good accuracy.

Acknowledgements
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