Gain simulation of erbium-doped Al_2O_3 waveguide amplifiers for LiDAR applications

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Photonic integrated circuits (PIC) based laser sources are of great interest for LiDAR applications. PICs play a crucial role for the fabrication of high performance, low cost and low size LiDAR tools. In the Ophellia project (On-chip Photonics Erbium-doped Laser for Lidar Applications) the development of Er^{3+}:Al2O3 waveguides with low background loss and high gain per unit length is proposed to fabricate on-chip amplifiers. In this work, a three-level rate-equation model, which incorporates the quenching effects of the Er3+ ions, is used to calculate the optical gain of the integrated amplifiers. The gain for three different waveguide cross-sections, namely, fully etched, ridge, and inverted strip loaded are compared. Simulation results show >25 dB gain for a fully-etched waveguide with cross-section of 800 nm x 1200 nm.

Introduction

High-performance lightweight laser scanners would enable the extensive use of professional Light Detection and Ranging (LiDAR) systems in complex environments. Applications can be found in areas like archaeology [1], autonomous vehicles and traffic observation [2]. Currently, there are limited laser light sources available that could provide the necessary performance to achieve the required distance range, distance resolution and velocity accuracy. Besides, the existing sources, i.e. single mode or multimode laser diodes and fiber laser sources, are either very costly, delicate or bulky [3].

The Integrated Photonics Systems Roadmap (IPSR) has identified integrated photonics as a key enabling technology for LiDAR, allowing to achieve simultaneously high performance (in terms of range, distance and velocity resolution), and low cost [4].

In the Ophellia project (On-chip Photonics Erbium-doped Laser for Lidar Applications), on-chip erbium-doped waveguide amplifiers (EDWAs) are proposed as building blocks for laser sources for LiDAR applications. Erbium-doped Al_2O_3 is a promising candidate for on-chip amplifiers due to the excellent optical properties of Al_2O_3, such as a wide transparency window (150-5500 nm), low propagation losses and high solubility for rare-earth ions with limited quenching [5].

In this work, the optical gain of Er^{3+} doped Al_2O_3 waveguides are simulated for three proposed cross-sections, namely fully-etched (FE), ridge (R), and inverted strip loaded (ISL). The influence of the Er^{3+} ion concentration and input signal power in the optical gain is also investigated.

Amplifier model

In order to calculate the optical gain for an Er-doped waveguide amplifier, a three-level rate-equation model is spatially resolved as described in Ref. [6]. A pump wavelength of 980 nm and forward propagation are considered. Furthermore, the spectroscopic parameters used in the simulations are taken from [7]–[9].

The mode profiles at the cross-section of the Er-doped Al_2O_3 waveguides, for the pump and signal wavelength, are calculated using the Finite-Difference Eigenmode (FDE) solver from the commercial software Lumerical.

Results

Cross-section designs

A schematic of the cross-sections is presented in Fig. 1. Where *W* is the core width, *H* is the growth thickness, *h* is the etched thickness for the ridge configuration, and α_1 is the etching angle for Al_2O_3. For the case of the inverted strip loaded waveguide, a Si_3N_4 asymmetric double stripe [10] is under the Al_2O_3 layer. The width of the Si_3N_4 (W_{SiN}) waveguide is 300 nm and the SiO_2 buffer layer between the top Si_3N_4 stripe and the Al_2O_3 layer has a thickness (t_{buffer}) of 100 nm.

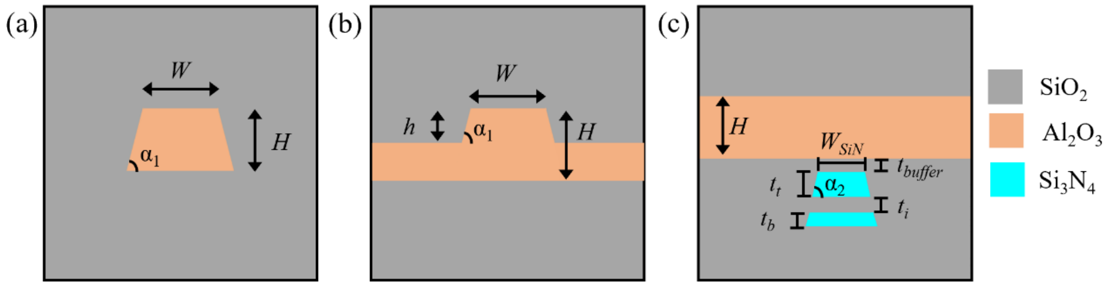

Fig. 1. Schematic of the waveguide cross-section. (a) Fully-etched. (b) Ridge. (c) Inverted strip loaded.

Gain simulations

The optical gain as a function of the gain medium length is studied for different Er^{3+} ion concentrations. The pump and signal wavelengths are 980 nm and 1550 nm, respectively. The propagation losses are set to 0.25 dB/cm for both wavelengths.

The simulation results for the three waveguide cross-sections are shown in Fig. 2. For the case of the fully-etched waveguide amplifier, the core is 800 nm thick and 1200 nm wide. The ridge waveguide has a growth thickness of 800 nm, an etch thickness of 350 nm and a width of 1200 nm. For the inverted strip loaded configuration, the thickness of the Al_2O_3 layer is 800 nm. For a frequency-modulated continuous-wave (FMCW) source demonstrator, a signal output power of 100 mW is required. Therefore, a pump power of 300 mW that reaches gain saturation and signal power of 1 mw are considered for the simulation.

Then, the optical gain as a function of the input signal power is presented in Fig. 3. The optimum ion concentrations for each cross-section for a length of 5 cm and the optimum length, i.e. length for which the gain is higher, are extracted from Fig. 2. For the 5 cm long amplifier, a concentration of 30×10^{25} ion/m^3 is used for all the cross-sections. For

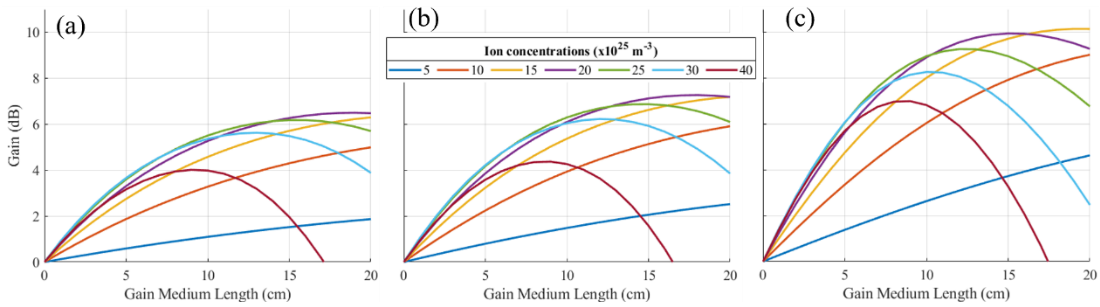

Fig. 2 Optical gain as a function of the gain medium length for various Er^{3+} ion concentration for the three different cross-sections: (a) FE. (b) R. (c) ISL. The pump and signal power are set to 300 mW and 1 mW, respectively.

the optimum length, a concentration of 20x10^{25} ion/m^3 is used for the FE and R cross-sections while for the ISL cross-section, a concentration of 15x10^{25} ion/m^3 is chosen.

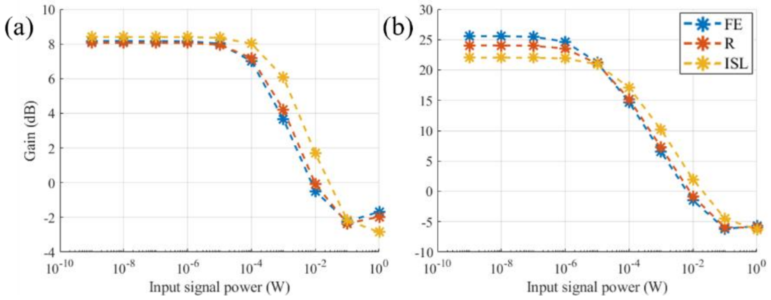

Fig. 3. Optical gain as a function of the input signal power for the optimum concentration for amplifier lengths of: (a) 5 cm, 30x10^{25} ion/m^3 for the 3 cross-sections. (b) Optimum length: FE = 19 cm, 20x10^{25} ion/m^3; R = 18 cm, 20x10^{25} ion/m^3; IS = 19 cm, 15x10^{25} ion/m^3. Pump power of 300 mW is considered.

Discussion

With the fully-etched cross-section a signal output power of ~ 45 mW can be achieved, considering an input power of 1 mW and an amplifier length of 19 cm with an optimum Er^{3+} ion concentration of 20x10^{25} ion/m^3. In Fig. 3, it is observed that for higher input signal powers the gain is drastically reduced. This is due to the saturation of the ion population in level $^4I_{13/2}$ (where stimulated emission takes place), quenching, and energy transfer up-conversion (ETU) [8], [11].

The impact of the excited-state absorption (ESA), quenched ions, and core dimensions on the gain of an EDWA with FE cross-section are shown in Fig. 4a. It is observed that ion quenching has the most detrimental impact on the optical gain compared to ESA. Scaling of the waveguide core cross-section by a factor 3 has almost the same effect on the optical gain as removing the pair induced ion quenching for the range where 1 mW $\geq$ input signal power $\geq$ 1 μW. Increasing the core waveguide dimensions allows reaching higher output powers. However, waveguides with such large cross-sections are multimode leading to bad beam quality (M^2>1). Fig. 4b shows that increasing the pump power is inefficient because ETU and quenching among Er^{3+} increase with pump power. A significant amount of absorption is non-saturable at the applied pump powers. Moreover, the applied pump power is limited by the available single-mode laser diode at 980 nm (~600 mW) and the coupling efficiency between the diode and the EDWA.

In practice, for an amplifier with a spiral configuration, a fully-etched cross-section would be preferred for longer amplifier lengths. This is because the mode is more confined to the core and therefore the minimum bending radius, to have negligible losses, is reduced compared to the ridge and inverted strip loaded cross-sections. On the other hand, for

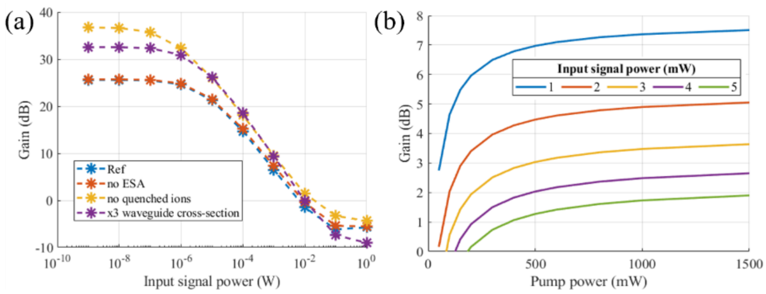

Fig. 4. (a) Influence of ESA, quenched ions and waveguide core dimensions on the optical gain for a FE cross-section. Blue dashed line corresponds to the results presented in Fig. 3. Pump power is set to 300 mW. (b) Optical gain as a function of pump power for the FE cross-section.

short amplifiers, the inverted strip loaded design has the advantage of a less complex fabrication process since the patterning of Al_2O_3 is not needed. Although to achieve compact devices, the fully-etched waveguide is still the preferred option.

Conclusion

The optical gain for three different Er^{3+}:Al_2O_3 waveguide cross-sections was studied. The simulation results showed that the fully-etched cross-section is more suitable for the FMCW soured requirements. The fully-etched amplifier design could reach an optical gain of 6.5 dB, i.e. 45mW output power, for an input pump and signal power of 300 mW and 1 mW, accordingly. Nevertheless, the optical gain is limited by different factors such as ETU, ESA, and quenching effects. Alternative pumping schemes such as bi-directional pumping and 1480 nm pumping could be used to circumvent the ETU and ESA limitation. Furthermore, the spectroscopic parameters used for the simulations were taken from literature and therefore these parameters have to be measured for the optimized material that has been developed in the research group [12].

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