2.0 dB/cm gain in an $Al_2O_3:Er^{3+}$ waveguide on silicon

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Abstract: Er concentration, energy-transfer upconversion and gain were investigated in Er-doped aluminum oxide channel waveguides. Net gain of up to 2.0 dB/cm was measured, demonstrating this material to provide a competitive active integrated optics technology.

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

1. Introduction

Recently there has been significant interest in integrated rare-earth-ion doped lasers and amplifiers due to the availability of low-cost diode-laser pump sources. For applications requiring wavelengths around 1.53 µm, Er-doped phosphate glass is currently the material of choice due to its high Er solubility without introducing strong quenching effects and typically high net gain per unit length of ~3 dB/cm [1,2]. In the past, $Al_2O_3:Er^{3+}$ has also been investigated for integrated amplifier applications. This material offers several advantages, including a broad emission spectrum for wavelength tunability, a higher refractive index contrast allowing more compact integrated optical devices, low background losses and a straightforward fabrication process allowing deposition on a variety of substrates such as silicon. However, previously only relatively low net gain of 0.58 dB/cm was measured in an $Al_2O_3:Er^{3+}$ waveguide, even though much higher gain was predicted [3]. The lower observed net gain was attributed to depletion of the $^4I_{13/2}$ Er level by energy-transfer upconversion (ETU). In this paper we present results based on an alternative deposition process which yields high-quality $Al_2O_3:Er^{3+}$ layers and reduced ETU from the $^4I_{13/2}$ level. We demonstrate internal net gain of up to 2.0 dB/cm and a total gain of 9.2 dB in a 5.4-cm-long amplifier at 1533 nm, confirming $Al_2O_3:Er^{3+}$ as an attractive alternative gain material for integrated optics applications.

2. Experimental

$Al_2O_3:Er^{3+}$ layers with a thickness of approximately 1.0 µm were deposited on thermally oxidized silicon substrates using an optimized sputtering technique [4]. The Er concentration, measured using Rutherford backscattering spectrometry, was uniform throughout the layer and varied from 0.27 to 3.66×10^{20} cm^{-3}. Ridge waveguides with a width of 4.0 µm were defined using reactive ion etching and end facets were prepared by cleaving.

Luminescence decay measurements were performed after exciting the channel waveguides with 976-nm pump light from a diode laser modulated by a square-pulse generator. The pulse had duration of 40 ms, allowing the Er^{3+} population to reach steady state before the pump was switched off. The light at 1530 nm from the luminescent decay was collected using a high N.A. liquid fiber mounted normal to the sample surface and the resulting signal was acquired with a digital oscilloscope.

The propagation losses at 633 nm, 977 nm, 1320 nm and 1533 nm were measured using the prism coupling method to determine absorption at the pump and signal wavelengths and the background propagation loss. Gain measurements were carried out by simultaneously launching 977-nm pump light from a Ti:Sapphire pump source and 1533-nm signal light from a tunable laser into the channel waveguide using a lens coupling setup. The signal light coupled out of the channel waveguide was isolated from transmitted pump light and spontaneous emission using a silicon filter and a lock-in amplifier, respectively.

3. Results

A consistently high $^4I_{13/2}$ lifetime ranging from 7.5 ms at the lowest concentration to 6.1 ms at the highest concentration was measured. The ETU parameter W_{11} was obtained from the luminescence decay curves following the method described in Ref. [5]. Figure 1 (a) shows the ETU parameter W_{11} as a function of Er concentration. The values reported here are approximately one order of magnitude lower than that reported previously in a similar material for an Er concentration of approximately 1.1×10^{20} cm^{-3} [6], indicating that Er ion clustering and gain-quenching effects are significantly reduced in our material. Figure 1 (b) shows the maximum small-signal internal net gain per unit length at 1533 nm as a function of Er concentration. The waveguide lengths varied from 1.0 to 6.4 cm depending on Er concentration, in order to optimize absorption of the 977-nm pump light but simultaneously avoid reabsorption of the signal light. A maximum internal net gain per unit length of 2.0 dB/cm was demonstrated for a waveguide length of 2.1 cm and Er concentration of 2.12×10^{20} cm^{-3}. Relatively high gain is measured even at high Er concentrations, which is supported by the consistently low ETU parameter.

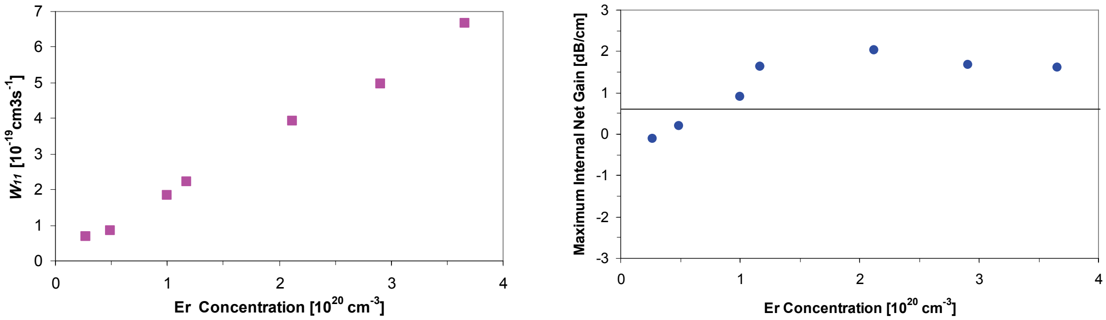

Fig. 1. (a) ETU parameter, W_{11}, as a function of Er concentration; (b) maximum small-signal internal net gain per unit length at each Er concentration for the optimized sample length and pump power

In order to achieve high overall gain a longer amplifier is required, and the Er concentration should be optimized dependant on the available pump power. Figure 2 shows the small signal gain for a 5.4-cm-long amplifier with a concentration of 1.17×10^{20} cm^{-3}. Up to 9.2 dB internal net gain was measured for a launched pump power of 95 mW. A simulation program based on a rate-equation model was used to verify the experimentally determined gain, the results of which are also shown in Fig. 2. The model takes into account the waveguide geometry and signal and pump confinement within the waveguide, ETU from the first excited state, the lifetimes and branching ratios of the relevant Er levels, and the pump and signal absorption and emission cross-sections, which were determined from the propagation loss measurements and photoluminescence spectra. A reasonable agreement was found with the measured data, indicating the model can be reliably used for the design of active devices.

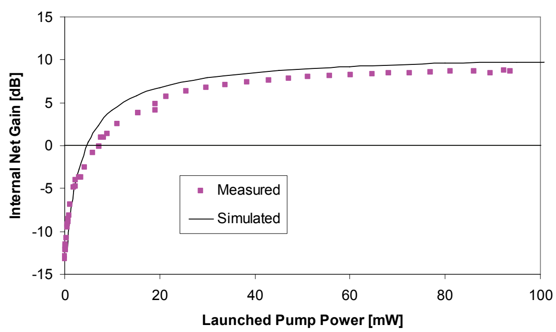

Fig. 2. Measured and simulated internal net gain vs. launched pump power for an Al_2O_3:Er^{3+} amplifier with a concentration of 1.17×10^{20} cm^{-3}

4. Summary

Due to low ETU parameters, internal net gain of up to 9.2 dB and gain per unit length of 2.0 dB/cm were demonstrated in Al_2O_3:Er^{3+} amplifiers.

5. Acknowledgment

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6. References

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