Optical gain in erbium-implanted Al2O3 waveguides

OPTICAL GAIN IN ERBIUM-IMPLANTED Al_2O_3 WAVEGUIDES

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Al_2O_3 ridge waveguides implanted with 1.3 at.% Er, pumped with 2.5 mW 1.47 μm light show 4.5 dB/cm enhancement of a 1.53 μm signal beam. The maximum gain is limited by cooperative upconversion effects. Calculations for lower Er concentrations show that 1 dB/cm net optical gain is possible at 10 mW pump power.

I. INTRODUCTION

Since the developement of the erbium-doped fiber amplifier, a lot of work has been aimed at achieving optical gain in Er-doped planar waveguides. Trivalent Er is used as optical dopant because of its intra-4*f* transition around 1.54 μm, coinciding with the low loss telecommunications window of silica fiber. High concentrations of Er ($\sim$ 1 at.%) are needed in order to reach reasonable optical gain on a small length scale. However, at such high Er doping levels, concentration quenching effects come into play, in which interaction between Er^{3+} ions takes place. For example, cooperative upconversion, where two excited Er^{3+} ions exchange energy, can deplete the first excited state of Er^{3+}, making it more difficult to reach population inversion and gain [1, 2]. In spite of these difficulties, several reports have demonstrated optical gain in silica-based planar devices [3, 4].

This study involves optical gain measurements on Er-implanted Al_2O_3 waveguides. Al_2O_3 is an ionic crystal with a structure similar to that of Er_2O_3 [5], enabling high concentrations of optically active Er as a dopant [6], and therefore high optical gain. Ridge waveguides fabricated on silicon substrates show a low optical loss of 0.35 dB/cm [7]. Also, the compact structure of the waveguide and the high index difference between core and cladding, allow for high confinement of the optical mode in the guide, resulting in high intensities for a given pump power, and therefore efficient pumping. Furthermore, the fabrication of the waveguides is compatible with standard silicon processing techniques, and many passive waveguide devices, such as splitters, couplers, and optical phased arrays have been demonstrated in this material [7, 8].

II. EXPERIMENTAL

Al_2O_3 waveguide films, 600 nm thick, were deposited onto thermally oxidized Si (100) substrates by sputter deposition from an Al_2O_3 target, in an oxidizing ambient. The films were implanted with 1.3 MeV Er to a peak concentration of 1.3 at.%, with the samples held at 77 K. Ridges, 0.3 μm deep, were etched into the Al_2O_3 using reactive ion etching, and the waveguide width ranged from 1.0 to 3.5 μm. Subsequently, a top SiO_2 cladding layer was deposited, and the structures were annealed at 825 °C for 1 hr in N_2 in order to achieve low loss [7], anneal out implantation damage, and activate the Er [6]. Using Rutherford backscattering spectrometry a Gaussian Er implantation profile at a depth of 270 nm with a full width at half maximum of 160 nm was measured; the profile is centred in the middle of the waveguide, where the light intensity is highest.

Photoluminescence (PL) spectroscopy was performed using standard equipment [6] with an Ar laser to excite the samples. Optical loss measurements were done using prism coupling. For optical gain measurements the waveguides were pumped with 1.47 μm laser light from an InGaAsP diode pump laser coupled into the waveguides using a tapered optical fiber. A signal beam at 1.53 μm was included using a wavelength division multiplexer. The signal emitted at the other end of the guide was analysed with a monochromator and sensitive Ge-detector employing lock-in techniques.

III. RESULTS AND DISCUSSION

A. Er^{3+} emission and absorption

Figure 1 shows the PL spectrum of an Er-implanted slab waveguide, i.e. without ridges and top SiO_2 cladding layer. The spectrum is typical for the first excited ($^4I_{13/2}$) to ground state ($^4I_{15/2}$) transition in Er^{3+}. The luminescence lifetime for this sample was measured to be 4.5 ms. Figure 1 also shows the absorption spectrum of the slab waveguide (solid line, left axis), after subtraction of 0.4 dB/cm intrinsic waveguide loss. A peak absorption of 8 dB/cm is observed, due to Er^{3+}. Given the implantation profile and optical mode profile of the waveguide, the absorption cross section for Er^{3+} in Al_2O_3 may be derived from the absorption data in Fig. 1. This is shown on the right scale of Fig. 1. From this result, and using the Füchtbauer-Ladenburg equation [9], the emission cross section was derived from the measured PL spectrum (see righthand scale of Fig. 1). As can be seen, both absorption and emission cross section peak at 12×10^{-21} cm^2.

B. Photoluminescence in a waveguide

Figure 2 shows the PL spectrum of a 1.5 μm wide Er-implanted waveguide pumped at 1.48 μm ($\sim$ 4 mW in the waveguide). Several luminescence peaks can be distinguised, each one characteristic of an intra-4f transition in Er^{3+}, as indicated in the figure. Besides the 1.53 μm emission from the first excited state, a number of transitions originating from higher excited states is also observed. In fact, the green emission at 545 nm can be clearly seen by the naked eye. The luminescence at 800 and 980 nm is caused by cooperative upconversion, where two Er^{3+} ions in the first excited state exchange energy [2]. The emission at shorter wavelengths is due to two sequential upconversion steps.

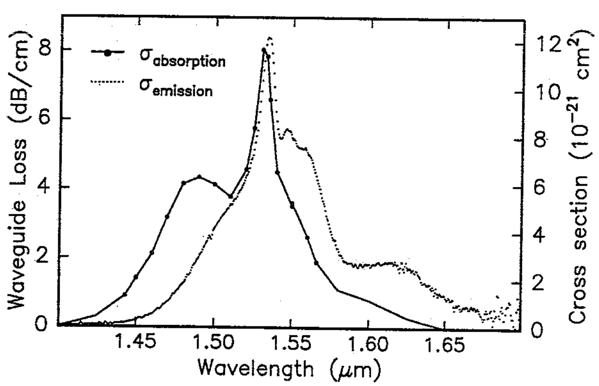

FIG. 1 *Room temperature PL spectrum (dotted line) and absorption spectrum (solid line) of an Er-implanted Al_2O_3 ridge waveguide. From these data the emission and absorption cross sections were determined as shown on the right axis.*

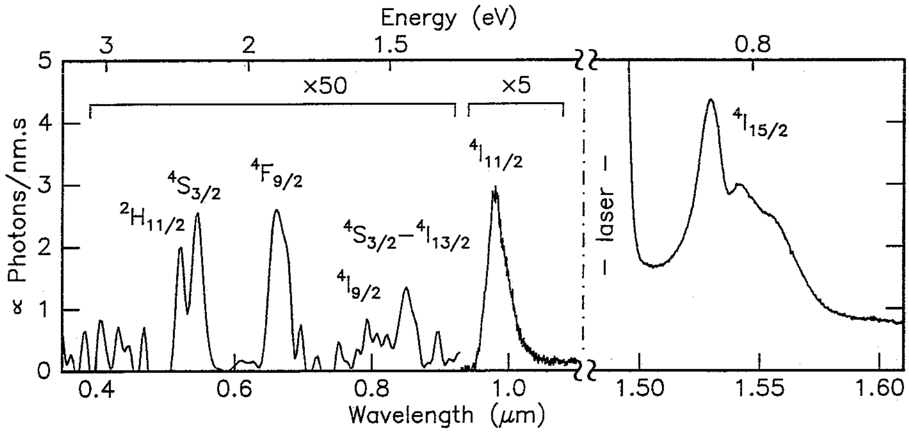

FIG. 2 *Photoluminescence spectrum of an Er-implanted Al_2O_3 ridge waveguide pumped at 1.48 μm. The pump power in the waveguide is ~ 4 mW.*

C. Optical gain

Figure 3 shows the evolution of the 1.53 μm signal intensity versus pump power, measured on a 1.5 μm wide and 9 mm long Er-implanted Al_2O_3 ridge waveguide (Er peak concentration: 1.3 at.%). At low pump powers the peak absorption due to Er^{3+} is 6 dB. The difference with the peak absortion in Fig.1 is because of the lower overlap between Er and mode profiles in the ridge waveguide compared to the slab waveguide of Fig. 1. A maximum transmission change of 4.5 dB is observed after pumping with 4 dBm (2.5 mW) 1.47 μm light. Also shown in the figure are two calculations, using the emission and absorption cross sections derived above. The dashed line is based on a simple 2-level system including stimulated emission of pump and signal beams, excluding upconversion. The solid line is calculated by including cooperative upconversion, and taking the population of Er^{3+} in the second excited state ($^4I_{11/2}$) into account. The population in this level does not contribute to the optical gain, and therefore the maximum achievable gain is lower than in the case without upconversion. Also, the curve shifts to higher pump powers. The calculation fits the data for an upconversion coefficient of 8×10^{-18} cm^3/s. Clearly, cooperative upconversion dominates the behavior of the signal at higher pump powers.

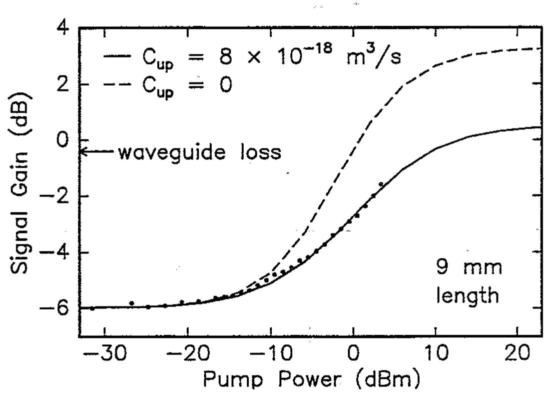

FIG. 3 *Measured transmission change of a 1.53 μm signal versus pump power at 1.47 μm (dots). Also shown are calculations showing the best fit for the case without upconversion (dashed line), and for a model including cooperative upconversion (solid line).*

In order to reduce the effects of upconversion, the Er concentration must be reduced. This may be done without reducing the potential optical gain by redistributing the Er over a larger depth in the waveguide, resulting in a lower peak concentration. Simulations of the signal evolution for such a waveguide with 0.4 at.% Er show that 1 dB/cm net optical gain is possible with a very modest pump power of 10 mW. Experiments are underway to achieve this result.

V. CONCLUSIONS

In conclusion, Er-implanted Al_2O_3 ridge waveguides show high emission and absorption cross sections at 1.5 μm, making high optical gain possible. Experiments show 4.5 dB signal enhancement for a waveguide doped with 1.3 at.% Er. Realistic simulations including effects of cooperative upconversion show that 1 dB/cm net optical gain is possible for only 10 mW pump power at 1.47 μm.

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