Net optical gain at 1.53 μm in Er-doped Al_2O_3 waveguides on silicon

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A 4 cm long Er-doped Al_2O_3 spiral waveguide amplifier was fabricated on a Si substrate, and integrated with wavelength division multiplexers within a total area of 15 mm^2. When pumped with 9 mW 1.48 μm light from a laser diode, the amplifier shows 2.3 dB net optical gain at 1.53 μm. The gain threshold was 3 mW. The amplifier was doped with Er by ion implantation to a concentration of 2.7×10^{20} cm^{-3}. The data agree well with calculations based on a model which includes the effects of cooperative upconversion and excited state absorption. For an optimized amplifier, net optical gain of 20 dB is predicted. © *1996 American Institute of Physics.* [S0003-6951(96)01514-0]

Planar waveguide amplifiers are one of the key components of integrated optic devices. The integration of amplifiers together with other optical components such as splitters, couplers, and wavelength division multiplexers, enables many optical functions to work together on a single chip without optical losses. Erbium is used as an optically active element in waveguide amplifiers because of its intra-4*f* transition around 1.54 μm, a standard telecommunications wavelength. Advantages of erbium-doped amplifiers are the linear gain response, temperature and polarization insensitivity, and low noise.[1] In order to achieve high gain values on the centimeter length scale of an optoelectronic integrated circuit, Er concentrations in the atomic percent range are needed. At such high Er doping levels, concentration quenching effects, such as cooperative upconversion, can affect the gain performance of the amplifier. By using relatively low Er concentrations in long waveguides (up to 50 cm), optical gain has been obtained in silica-based planar devices.[2–5] However, because of the large optical mode dimensions of these devices, high pump powers (~100 mW) are necessary to reach net gain. In addition, due to their large waveguide bending radius (~cm) these amplifiers take up a large area on a planar substrate.

This study is aimed at the achievement of net optical gain at low pump powers in compact (mm^2) waveguide devices. Al_2O_3 is chosen as host material for the Er because its crystal structure enables the incorporation of high concentrations of optically active Er as a dopant.[6,7] Single mode Al_2O_3 ridge waveguides with a low optical loss (0.35 dB/cm) are readily fabricated on silicon substrates.[8,9] The high index contrast between core and cladding results in high confinement of the optical mode in the guide, leading to efficient pumping and amplification. In addition, the high index contrast allows for the use of small waveguide bending radii (<100 μm),[10] making compact waveguide devices possible.

Waveguides were fabricated by sputter deposition of Al_2O_3 onto a oxidized silicon (100) substrate (oxide thickness 5 μm). The Al_2O_3 layer thickness was 600 nm. Using a Van de Graaff accelerator, Er was implanted into the Al_2O_3 film at energies ranging from 100 keV to 1.5 MeV in order to obtain a flat Er concentration profile from 25 to 450 nm under the surface. The total Er fluence was 1.2×10^{16} ions/cm^2, corresponding to a concentration of 2.7×10^{20} Er/cm^3 (0.28 at.%). On the basis of our previous work, this Er concentration was calculated to be the optimum concentration (at higher concentrations cooperative upconversion effects would reduce the gain).[11] After implantation, the films were annealed at 775 °C, in order to achieve low loss,[9] anneal out implantation damage, and activate the Er.[6] Using photolithography, 2 μm wide waveguides were defined. Subsequently, an Ar atom beam was used to etch away 300 nm of the Al_2O_3 film, resulting in ridge waveguides under the previously defined area. A 1.3 μm thick SiO_2 cladding was deposited on top in order to reduce scattering losses, and the complete structure was annealed at 700 °C for 30 min in N_2. Lastly, the end faces of the sample were mechanically polished to obtain efficient coupling of light into the waveguide. A cross section through the waveguide is indicated in Fig. 1.

Figure 1 also shows the layout of the complete Er-doped waveguide amplifier, in which several optical functions are integrated. Pump and signal beams are coupled into separate waveguides indicated by P and S, respectively. Pump and signal are then combined into a single waveguide using a wavelength division multiplexer (WDM). The amplifying section consists of a 4 cm long waveguide, rolled up to fit onto a small area. After amplification, two WDM structures are used to separate pump and signal beams. The WDMs operate on the multimode interference principle; their design

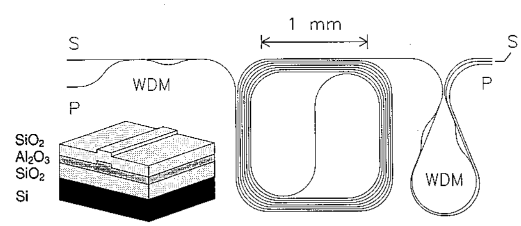

FIG. 1. Layout of a 4 cm long Er-doped spiral ridge waveguide amplifier integrated with WDM. P and S indicate the pump and signal input and output. In the actual amplifier, the waveguide section between the spiral and the output WDM is longer then drawn here. The inset shows a cross section through the waveguide. The Al_2O_3 core dimensions are 0.6 μm$\times$2 μm.

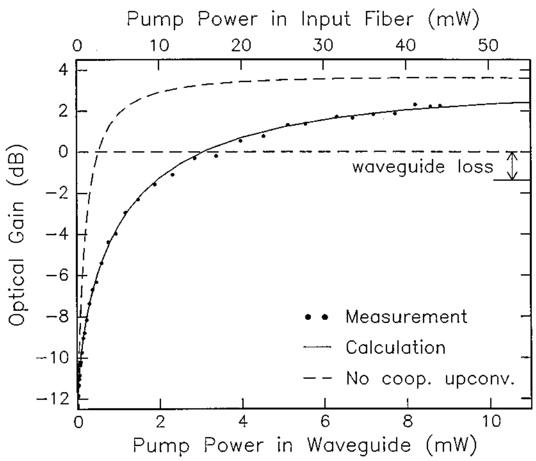

FIG. 2. Measurements of the (small-signal) optical gain at 1.53 μm in a 4 cm long Er-doped (2.7×10^{20} Er/cm^2) waveguide amplifier as a function of 1.48 μm pump power. Calculations are included for two cases; with and without cooperative upconversion.

is discussed elsewhere.[12,13] The complete device fits within an area of 1.5 mm$\times$9.5 mm.

The amplifier was pumped with 1.48 μm light from a Philips InGaAsP diode laser. The light was coupled into the waveguide with a tapered optical fiber, which was aligned to the pump input by means of piezoactuators. Similarly, signal light ($1.50<\lambda<1.55$ μm) chopped at 317 Hz from a tunable laser (HP 8168A) was coupled into the signal input waveguide. The signal power was below -40 dBm (0.1 μW). Pump and signal light were coupled out on the other side of the amplifier with a microscope objective, and detected using a liquid-nitrogen-cooled Ge-detector employing lock-in techniques.

Figure 2 shows the measured enhancement of the 1.53 μm optical signal intensity as a function of pump power in the 4 cm long waveguide amplifier described above. The pump power in the waveguide was derived from the measured pump power in the input fiber using a fiber-to-chip coupling loss of 7 dB, as will be discussed below. The relative gain measurement was converted to an absolute scale by setting the intensity at 0 pump power equal to the calculated waveguide absorption due to Er^{3+} (11.1 dB) added to the known waveguide loss (1.4 dB). The calculation of the absorption is based on known measured values for the Er cross sections,[14] the measured Er concentration profile, and the calculated optical mode profile. Figure 2 shows that as the pump power is increased the signal rapidly increases; net optical gain is reached at a pump power of 3 mW in the waveguide. For higher pump powers, saturation of the gain is observed; at 9 mW a net (small-signal) gain of 2.3 dB is achieved.

Calculations of the optical gain were performed, based on a rate equation model for the Er^{3+} ions. The parameters used in the calculation are shown in Table I. In the model, described in detail in Ref. 11, cooperative upconversion due to an interaction of two Er^{3+} ions in the first excited state ($^4I_{13/2}$) is taken into account, as well as excited state absorption (ESA) from the $^4I_{13/2}$ state to the $^4I_{9/2}$ state. The coefficients for these processes were determined experimentally.[11] All calculations include a waveguide loss of 0.35 dB/cm.[9] In the calculation, the Er^{3+} population in the ground state, and first and second excited states are considered, and effects of pump and signal emission and absorption (also through ESA) are taken into account. The changes in pump and signal intensities are integrated numerically along the length of the waveguide.

The solid line in Fig. 2 is a calculation of the optical gain as a function of pump power for this particular amplifier. In order for the calculation to fit the data, the pump power measured in the input fiber was scaled by 7 dB in order to obtain the power in the waveguide. The scaling factor arises from the fiber-chip coupling loss. Also shown in Fig. 2 is a calculation in which the effects of cooperative upconversion are set to zero (dashed line). In this case, net gain would be achieved at 0.5 mW, and a higher saturation value would be reached. This shows that cooperative upconversion is one of

TABLE I. Parameters of the spiral waveguide amplifier used in the calculations.

Parameter		Quantity	Reference
Er concentration	ρ_{Er}	2.7×10^{20} cm^{-3}	
Pump absorption cross section (1.48 μm)	σ_p^a	2.7×10^{-21} cm^2	14
Pump emission cross section (1.48 μm)	σ_p^e	0.77×10^{-21} cm^2	14
Signal absorption cross section (1.53 μm)	σ_e^a	5.8×10^{-21} cm^2	14
Signal emission cross section (1.53 μm)	σ_s^e	6.1×10^{-21} cm^2	14
Excited state absorption cross section ($^4I_{13/2}$+1.48 μm pump photon $\rightarrow {}^4I_{9/2}$)	σ_{ESA}	0.85×10^{-21} cm^2	11
Er^{3+} first excited state lifetime ($^4I_{13/2}$)	τ_2	7.8 ms	11
Er^{3+} second excited state lifetime ($^4I_{11/2}$)	τ_3	30 μs	11
Upconversion coefficient ($^4I_{13/2}+{}^4I_{13/2}\rightarrow{}^4I_{9/2}+{}^4I_{15/2}$)	C_{up}	4.1×10^{-18} cm^3/s	11
Waveguide length		4 cm	
Waveguide loss	α	0.35 dB/cm	9
Optical mode size		0.6×2 μm^2	
Overlap mode intensity with Er profile		36%	

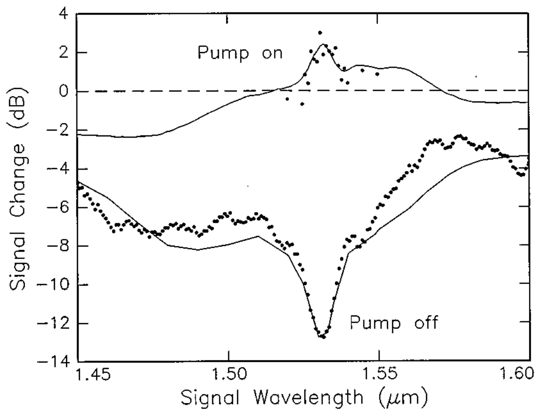

FIG. 3. Optical gain (9 mW 1.48 μm pump on) and loss (pump off) spectra of a 4 cm long Er-doped waveguide amplifier (dots). Calculations of the spectra based on previously measured parameters (see Table I) are included as the solid lines.

the main limiting factors in the performance of Er-doped waveguide amplifiers. Note that the saturation gain is determined by the maximum degree of inversion that is achievable using a pump wavelength of 1.48 μm: 78%.

Figure 3 shows the measured gain (pump on) and loss (pump off) data versus signal wavelength together with calculations of these spectra based on the measured parameters listed in Table I. The gain data were determined as above by measuring the total signal change when switching on the 9 mW pump. The data compare reasonably well with the calculation of the net gain. Note that the gain spectrum (net gain >0 dB) extends from 1.52 to 1.57 μm, approximately 50 nm wide. Loss data were measured by coupling light from a white light source into a 0.95 cm long straight waveguide on the same chip as the amplifier. Figure 3 shows this data (pump off) corrected to correspond to the 4 cm long waveguide amplifier. The data agree well with the calculation of the loss spectrum based on the measured Er cross sections in the region around 1.53 μm. Outside this region discrepancies are observed, possibly due to wavelength dependent coupling efficiencies in the setup.

Several improvements are possible in the waveguide design. Figure 4 shows a calculation of the small-signal optical gain of an optimized Er-doped Al_2O_3 waveguide amplifier, based on the experimental results of this study. In this calculation, the Er has been distributed throughout the complete core of the waveguide. This may be achieved by cosputtering of Er and Al_2O_3 during the fabrication of the waveguide films, rather than using ion implantation. The waveguide is chosen to be 15 cm long, and the Er concentration is the same as above (2.7×10^{20} cm^{-3}). A net optical gain of nearly 20 dB is possible at a pump power of 50 mW. The proposed 15 cm long spiral amplifier can fit within the same area (1.5×9.5 mm^2) as the 4 cm amplifier fabricated here. In Fig. 4, the effect of excited state absorption is also apparent: for pump powers above 50 mW the gain decreases because ESA depletes the population of the $^4I_{13/2}$ level. The saturation signal output power is calculated to be 7 dBm (5 mW).

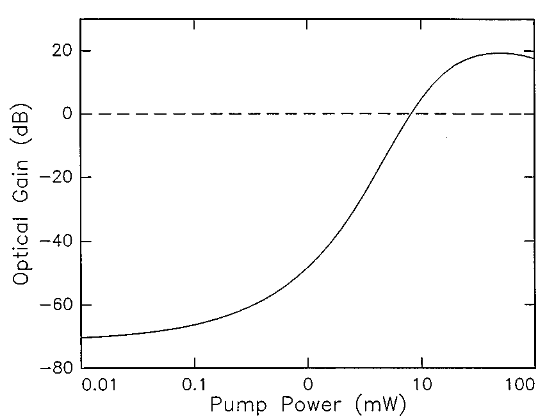

FIG. 4. Calculations of the optical gain at 1.53 μm as a function of 1.48 μm pump power in a 15 cm long waveguide amplifier doped with 2.7×10^{20} Er/cm^3 throughout the core of the waveguide.

In conclusion, 2.3 dB net optical amplification at 1.53 μm has been measured in a 4 cm long Al_2O_3 waveguide amplifier doped with 2.7×10^{20} Er/cm^3 and pumped with 9 mW at 1.48 μm. The amplifier is integrated with wavelength division multiplexers to combine and separate pump and signal beams. The complete device fits within an area of 15 mm^2. The measured gain data agree well with calculations including the effects of cooperative upconversion and excited state absorption. In an optimized waveguide an optical gain of nearly 20 dB should be possible. The study shows the feasibility of compact, low power consuming waveguide amplifiers which can be integrated with other waveguide devices such as optical splitters.

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[1] E. Desurvire, Phys. Today **47**, 20 (1994).
[2] G. Nykolak, M. Haner, P. C. Becker, J. Shmulovich, and Y. H. Wong, IEEE Photonics Technol. Lett. **5**, 1185 (1993).
[3] K. Hattori, T. Kitagawa, M. Oguma, Y. Ohmori, and M. Horiguchi, Electron. Lett. **30**, 856 (1994).
[4] M. Hempstead, J. E. Román, C. C. Ye, J. S. Wilkinson, P. Camy, P. Laborde, and C. Lerminiaux, in Proceedings of the 7th European Conference on Integrated Optics, Delft, 3–6 April 1995 (unpublished), p. 233.
[5] D. Barbier, P. Gastaldo, B. Hyde, J. M. Jouanno, and A. Kevorkian, in Proceedings of the 7th European Conference on Integrated Optics, Delft, 3–6 April 1995 (unpublished), p. 241.
[6] G. N. van den Hoven, E. Snoeks, A. Polman, J. W. M. van Uffelen, Y. S. Oei, and M. K. Smit, Appl. Phys. Lett. **62**, 3065 (1993).
[7] G. N. van den Hoven, A. Polman, E. Alves, M. F. da Silva, A. A. Melo, and J. C. Soares (unpublished).
[8] M. K. Smit, G. A. Acket, and C. J. van der Laan, Thin Solid Films, Electron. Opt. **138**, 171 (1986).
[9] M. K. Smit, Ph.D. thesis, Optics Laboratory, Dept. of Applied Physics, Delft University of Technology, 1991.
[10] E. C. M. Pennings, G. H. Manhoudt, and M. K. Smit, Electron. Lett. **24**, 998 (1988).
[11] G. N. van den Hoven, E. Snoeks, A. Polman, C. van Dam, J. W. M. van Uffelen, and M. K. Smit, J. Appl. Phys. **79**, 1258 (1996).
[12] L. B. Soldano and E. C. M. Pennings, J. Lightwave Technol. **13**, 615 (1995), and references therein.
[13] G. N. van den Hoven, A. Polman, C. van Dam, J. W. M. van Uffelen, and M. K. Smit, Opt. Lett. (to be published).
[14] G. N. van den Hoven, J. A. van der Elsken, A. Polman, C. van Dam, J. W. M. van Uffelen, and M. K. Smit (unpublished).