Understanding $Al_2O_3:Er^{3+}$ device performance

L. Agazzi, J.D.B. Bradley, F. Ay, K. Wörhoff, and M. Pollnau

Integrated Optical MicroSystems Group, MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

$Al_2O_3:Er^{3+}$ thin films were deposited on Si wafers and subsequently structured. On-chip devices such as amplifiers, ring lasers and a loss-less splitter were fabricated; data transmission at 170 Gbits/s and monolithic integration with SOI waveguides were demonstrated. The discrepancy between device performance and predictions deriving from the analysis of spectroscopic data prompted us to develop an Er^{3+} rate-equation model that, besides accounting for "slow" energy-transfer and upconversion processes, also considered the presence of luminescence quenching mechanisms occurring at significantly shorter time scales.

Introduction

$Al_2O_3:Er^{3+}$ is interesting as gain material due to its broad emission spectrum, high Er solubility and higher refractive index compared to other typical glass hosts, which allows higher integration density. Our growth method enables straightforward deposition on silicon [1], resulting in low background losses (typically 0.1-0.2 dB/cm).
Here we report various applications of $Al_2O_3:Er^{3+}$. We have fabricated waveguide amplifiers with a peak gain of 2.0 dB/cm in combination with a broadband gain over a wavelength range of 80 nm [2]. As a result, a number of on-chip integrated active devices has been realized, such a ring laser, a zero-loss power splitter operating over the entire C-band (1525-1565 nm), and a high-speed amplifier operated at 170 GBit/s. In addition, wafer-scale monolithic integration of active Er-doped Al_2O_3 waveguides with passive SOI waveguides has been demonstrated.
Finally we discuss an Er^{3+} rate-equation model that, unlike most models present in the literature, accounts for fast, detrimental luminescence quenching effects occurring in the Er^{3+} system and allows us to achieve a better understanding of our devices performance.

Applications

1-µm-thick $Al_2O_3:Er^{3+}$ layers were deposited on thermally oxidized silicon substrates by reactive co-sputtering [1]. 4.0-µm-wide ridge waveguides were defined by reactive ion etching to a depth of 50 nm [3]. The Er concentration varied from 0.27 to 3.66×10^{20} cm^{-3}. Gain measurements were carried out by launching simultaneously 977-nm pump light from a Ti:Sapphire pump source and modulated signal light from a tunable laser (1500-1580 nm) into the channel waveguides using a lens-coupling setup. The output signal was coupled to a detector followed by a lock-in amplifier to eliminate residual pump light and amplified spontaneous emission. Internal net gain of up to 2.0 dB/cm was obtained for an Er concentration of 2.12×10^{20} cm^{-3}. Furthermore, net gain was obtained over a wavelength range of 80 nm with a peak gain of 9.3 dB at 1533 nm, for an amplifier length of 5.4 cm and an Er concentration of 1.17×10^{20} cm^{-3}.
For the ring laser, a ~500-nm-thick $Al_2O_3:Er^{3+}$ film was deposited and subsequently structured according to the design of Fig. 1a [4]. The waveguides had a width of 1.5 µm and were cladded by a 5-µm-thick SiO_2 layer deposited by plasma-enhanced chemical

vapour deposition. Coupler 1 was designed such that strong coupling at the signal wavelength around 1550 nm of > 95 % and weak coupling of <10% at the pump wavelength of 980 nm was achieved. The coupler lengths were varied from 350 to 600 μm, while the resonator length was varied from 2.0 to 5.5 cm. Pump light from a 980-nm diode laser was coupled to the chip and the output signal was collected. The laser power and spectra were measured using a lightwave multimeter and a spectrometer, respectively. Devices with coupling lengths ranging from 400 to 550 μm were observed to lase, at wavelengths ranging from 1530 to 1557 nm. The maximum output power was 9.5 μW at 19 mW of launched pump power, with a slope efficiency of 0.11% observed in a 5.5-cm-long device. The threshold pump power varied from 6.4 to 15.5 mW. The spectra were multimode, due to the long resonator length, which results in a free spectral range of 0.3 to 0.8 pm.

A lossless splitter with the same waveguide dimensions as described for the ring laser was fabricated [5]. The 8.6-cm-long device, fold to fit an area of 4.2 × 30 mm, had two pump inputs in order to ensure sufficient pump power excitation. Gain was measured with a method similar to that used for the $Al_2O_3:Er^{3+}$ waveguide amplifiers, with the help of fiber-array units to couple pump and signal light to and from the chip. Net internal gain per output branch of up to 9.0 dB and over a wavelength range of 1525 to 1565 nm, covering the entire C-band, was achieved.

Signal transmission experiments at 170 Gbit/s in an integrated $Al_2O_3:Er^{3+}$ waveguide amplifier were performed in collaboration with the University of Rennes, France, to investigate $Al_2O_3:Er^{3+}$ potential application in high-speed photonic integrated circuits [6]. Fig. 1b shows typical eye diagrams measured without and with the EDWA included in the experimental transmission setup. In the latter case, 1480-nm pump light from a Raman laser and optical time division multiplexed signal light modulated at 170 Gbit/s were launched into the device. The eye pattern is open and the pulse FWHM is 2 ps in both cases. Bit error rate (BER) measurements were also performed with and without the device in the setup. Identical bit error rate vs. received optical power curves were obtained in the two cases, verifying that noise added by the amplifier is negligible.

In collaboration with colleagues from Ghent University, Belgium, $Al_2O_3:Er^{3+}$ waveguide amplifiers were integrated with Silicon-on-insulator (SOI) passive waveguides [7]. SOI rib waveguides with a cross section of 450 nm × 220 nm were defined by deep UV lithography. A 1-μm-thick $Al_2O_3:Er^{3+}$ layer was grown directly on top by reactive co-sputtering [1] and 2.0-μm-wide ridge waveguides were defined by reactive ion etching to a depth of 270 nm [3]. The Er concentration was 2.7×10^{20} cm^{-3}. The Si waveguides were tapered down to 100 nm over a length of 400 μm to adiabatically transform the silicon waveguide mode to that of the $Al_2O_3:Er^{3+}$ waveguide and ensure efficient coupling (see Fig. 1c). Losses in such couplers were measured by comparing the transmission of 1533-nm light in $Al_2O_3:Er^{3+}$ waveguides both with and without Si-taper couplers, resulting in a value of 2.5 dB per coupler. This loss is expected to be reduced to 0.5 dB by making some design modification. Signal enhancement measurements were performed in an $Al_2O_3:Er^{3+}$-Si-$Al_2O_3:Er^{3+}$ structure, with a method similar to that described for the gain measurements, but with a pump wavelength of 1480 nm. The two $Al_2O_3:Er^{3+}$ sections had a total length of 9.5 mm, while the Si waveguide was 4 mm long, including the tapers. A peak signal enhancement of 7.2 dB was measured for 50 mW of launched pump power.

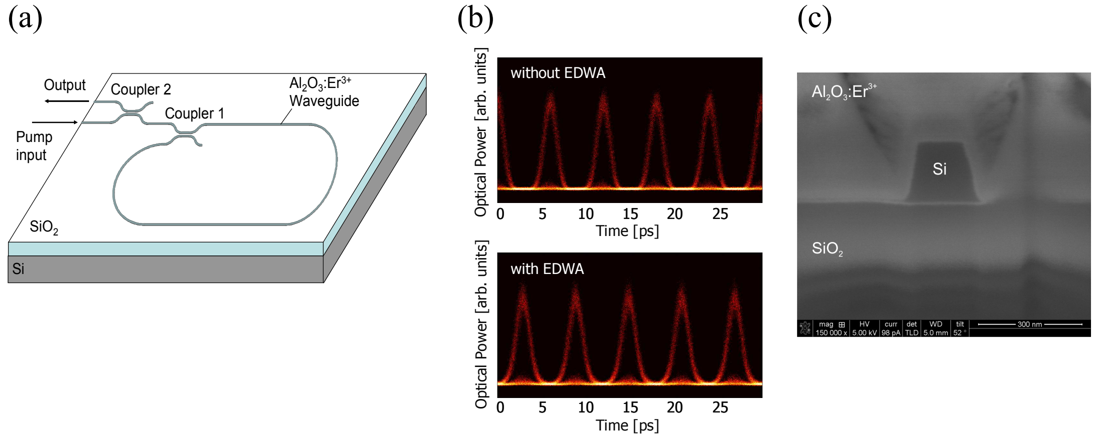

Fig. 1 – (a) Schematic of Al_2O_3:Er^{3+} ring laser [4]; (b) eye diagram for system transmission at 170 Gbit/s with and without the Er-doped waveguide amplifier [6]; (c) SEM picture of a tapered Si waveguide covered by an Al_2O_3:Er^{3+} overlay [7]

Quenched-ion model

By fitting the gain measurements of Al_2O_3:Er^{3+} waveguide amplifiers mentioned above with the simple Er^{3+} rate-equation model described in [2] it was possible to extract the coefficient W_{ETU} of energy-transfer upconversion (ETU), an interaction process between Er^{3+} ions with detrimental effects on the devices performance. The results obtained with this procedure showed a discrepancy of about one order of magnitude with the values directly obtained from luminescence decay measurements [8]. The origin of the discrepancy laid in the fact that the simple rate-equation model assumed that all the Er^{3+} ions are active, while in general a fraction of Er^{3+} ions is present in ion pairs and clusters, or interacts with impurities and defects in the host material. The luminescence of such ions is quickly quenched, with a characteristic time τ_1^* in the order of 1-10 μs [9], and significant decrease in the optical gain occurs. We propose a simple yet comprehensive “quenched-ion model” that generalizes the ion-pair scheme of [9] and combines all the fast quenching mechanisms mentioned above in one term. The Er^{3+} ions were split into two classes. The first class consists of active ions, uniformly dispersed in the host, which exhibit a long luminescence lifetime τ_1 of 7.6 ms and play an effective role in the amplification process. They can interact through “slow”, homogeneous energy transfer and upconversion processes. The second class consists of the quenched ions, which do not take part in the amplification process. Gain and luminescence decay measurements were re-analyzed with the new model to extract the fraction of quenched ions f_a and the ultimate W_{ETU} values. f_a decreased from 90% down to 67% with Er^{3+} concentration increasing from 1.17 to 3.66 × 10^{20} cm^{-3}, due to the higher probability of Er^{3+} pairs/clusters formation and of interaction with defects and impurities with increasing concentration. The new W_{ETU} coefficients were in reasonable agreement with those determined via luminescence decay measurements. These results were afterward confirmed by nonsaturable absorption experiments. 1480-nm pump light was launched into the waveguide, and the transmission as a function of launched power was recorded. The transmission is strongly dependent on the amount of quenched ions, and our new model could fit the results with good accuracy.

Conclusions

Various active devices applying $Al_2O_3:Er^{3+}$ have been demonstrated, including an integrated ring laser, a zero-loss power splitter and a high-bit-rate amplifier. In addition active $Al_2O_3:Er^{3+}$ waveguides were monolithically integrated with passive SOI waveguides. An Er^{3+}-rate-equation model that considers the presence of fast luminescence quenching mechanisms was developed. The proposed model is helpful for the performance optimization of our devices.

Acknowledgements

This work was financially supported by the European Union's Sixth Framework Programme (Specific Targeted Research Project "PI-OXIDE", contract no. 017501) and by the Smartmix Memphis programme of the Dutch Ministry of Economic Affairs. The authors thank the members of the CNRS FOTON Laboratory, PERSYST Platform, University of Rennes for help with the high bit rate amplification measurements as well as G. Roelkens and R. Baets from the Photonics Research Group, Ghent University for preparing the SOI chip.

References

[1] K. Wörhoff, J. D. B. Bradley, F. Ay, D. Geskus, T. P. Blauwendraat, and M. Pollnau, "Reliable low-cost fabrication of low-loss $Al_2O_3:Er^{3+}$ waveguides with 5.4-dB optical gain," IEEE J. Quantum Electron. **45**, 454-461 (2009).

[2] J. D. B. Bradley, L. Agazzi, D. Geskus, F. Ay, K. Wörhoff, and M. Pollnau, "Gain bandwidth of 80 nm and 2 dB/cm peak gain in $Al_2O_3:Er^{3+}$ optical amplifiers on silicon," J. Opt. Soc. Am. B **27**, 187-196 (2010).

[3] J. D. B. Bradley, F. Ay, K. Wörhoff, and M. Pollnau, "Fabrication of low-loss channel waveguides in Al_2O_3 and Y_2O_3 layers by inductively coupled plasma reactive ion etching", Appl. Phys. B **89**, 311-318 (2007).

[4] J. D. B. Bradley, R. Stoffer, L. Agazzi, F. Ay, K. Wörhoff, and M. Pollnau, "Integrated $Al_2O_3:Er^{3+}$ ring laser on silicon with wide wavelength selectivity," Opt. Lett. **35**, 73-75 (2010).

[5] J. D. B. Bradley, R. Stoffer, A. Bakker, L. Agazzi, F. Ay, K. Wörhoff, and M. Pollnau, "Integrated $Al_2O_3:Er^{3+}$ zero-loss optical amplifier and power splitter with 40 nm bandwidth," IEEE Photon. Technol. Lett. **22**, 278-280 (2010).

[6] J. D. B. Bradley, M. Costa e Silva, M. Gay, L. Bramerie, A. Driessen, K. Wörhoff, J. Simon, and M. Pollnau, "170 Gbit/s transmission in an erbium-doped waveguide amplifier on silicon," Opt. Express **17**, 22201-22208 (2009).

[7] L. Agazzi, J. D. B. Bradley, M. Dijkstra, F. Ay, G. Roelkens, R. Baets, K. Wörhoff, and M. Pollnau, "Monolithic integration of erbium-doped amplifiers with silicon-on-insulator waveguides," submitted.

[8] L. Agazzi, K. Wörhoff, A. Kahn, H. Scheife, G. Huber, and M. Pollnau, "Microscopic treatment of energy-transfer upconversion and additional quenching mechanisms in rare-earth-ion-doped materials," in preparation.

[9] E. Delevaque, T. Georges, M. Monerie, P. Lamouler, and J.-F. Bayon, "Modeling of pair-induced quenching in erbium-doped silicate fibers," IEEE Photon. Technol. Lett. **5**, 73-75 (1993).