

Absorption and emission cross sections of Er^{3+} in Al_2O_3 waveguides

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Al_2O_3 slab waveguide films were doped with erbium using ion implantation to a peak concentration of 1.5 at. %. Prism coupling measurements show absorption caused by $^4I_{15/2} \rightarrow ^4I_{13/2}$ intra-4f transitions in Er^{3+} with a maximum at 1.530 μm of 8 dB/cm. The Er^{3+} absorption cross section is determined as a function of wavelength. We used the McCumber theory to derive the emission cross section spectrum from the absorption results, which we then compared with the Er^{3+} photoluminescence spectrum. The peak absorption and emission cross sections are found to be $6 \times 10^{-21} \text{ cm}^{-2}$. The results are used to predict the optical gain performance of an Er-doped Al_2O_3 optical amplifier that operates around 1.5 μm .
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1. Introduction

Erbium-doped planar waveguides are being studied because of their application as integrated optical amplifiers or lasers that operate at 1.5 μm . The rare-earth-ion Er^{3+} has one of its intra-4f transitions around 1.53 μm ,¹ coinciding with the low-loss window of standard silica optical fiber. Optical amplifiers at this wavelength are necessary to overcome losses in the processing and distribution of optical signals, while maintaining high bandwidth and low cross talk. The use of planar amplifiers offers the important advantage that they can be integrated together with other waveguide devices on a single chip. An integrated optical circuit, the combination of an optical amplifier with a $1 \times N$ beam splitter, has been proposed.²

The performance of an Er-doped amplifier depends on the magnitude and wavelength dependence of the emission and absorption cross sections. Together with the Er concentration profile, the optical intensity profile, and the waveguide loss, knowledge of these parameters enables a first-order estimate of the potential optical gain. Al_2O_3 waveguide films on sil-

icon wafers are interesting as a host material for Er because waveguide fabrication technology is well developed for this material.³ Low-loss, single-mode waveguides can be fabricated using standard photolithographic techniques. The high-index contrast between SiO_2 cladding and the Al_2O_3 core results in a high mode intensity in the waveguides and allows for a small bending radius and thus compact waveguide devices. In addition, our earlier research has shown that high concentrations of optically active Er can be incorporated into this material.⁴ To predict the optical gain in an Er-doped Al_2O_3 waveguide, we determine the absorption and emission cross section for Er^{3+} in such a waveguide. It should be noted that the actual gain performance is also determined by processes such as concentration quenching, cooperative upconversion, and excited-state absorption.⁵

Direct measurement of both emission and absorption cross sections is difficult; in practice it is easier to measure absorption by standard techniques and calculate the emission cross section from absorption results, which is referred to as the McCumber theory or method of reciprocity.⁶⁻⁸ Based on a detailed balance, $\sigma_{ij} = \sigma_{ji}$, where σ_{ij} is the cross section for absorption from sublevel i to sublevel j , and σ_{ji} is the corresponding emission cross section. This also implies that the total emission cross section $\sigma_{\text{em}}(\nu)$ at a frequency ν is related to the absorption cross section $\sigma_{\text{abs}}(\nu)$:

$$\sigma_{\text{em}}(\nu) = \sigma_{\text{abs}}(\nu) \frac{Z_l}{Z_u} \exp[(E_{ZL} - h\nu)/kT], \quad (1)$$

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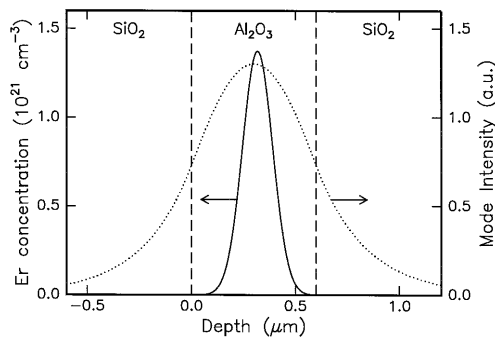


Fig. 1. Depth profile of an Er-implanted Al_2O_3 waveguide showing the Er concentration profile derived from Rutherford backscattering spectrometry (solid curve). The dotted curve shows the calculated optical mode profile at $1.53 \mu\text{m}$.

where Z_u and Z_l are the partition functions of the upper and lower states, respectively, E_{ZL} is the energy difference between the bottom of the upper (excited) state manifold and the bottom of the ground (lower) state manifold (the so-called zero-line energy), T is temperature, and k is Boltzmann's constant. The only assumption in this theory is that the time to establish thermal equilibrium in each manifold is short compared with the lifetime of the manifold, which is the case for the ${}^4I_{13/2} \rightarrow {}^4I_{15/2}$ transitions of Er^{3+} in Al_2O_3 (~ 10 -ms lifetime).⁴

Here we used prism coupling measurements to determine the optical absorption of Er-implanted Al_2O_3 slab waveguides as a function of wavelength. Using the Er implantation depth profile and the calculated optical mode profile, we determined the corresponding absorption cross sections. The emission line shape was measured using photoluminescence spectroscopy. We used the McCumber theory to calculate the emission cross section spectrum. Finally, the determined cross sections are compared to other Er-doped materials.

2. Experimental

Planar single-mode Al_2O_3 waveguides were fabricated by sputter deposition resulting in a $0.6\text{-}\mu\text{m}$ -thick Al_2O_3 layer on a $6\text{-}\mu\text{m}$ -thick thermal oxide on a Si (100) substrate. Er was implanted into the Al_2O_3 film at 1.35 MeV to a fluence of $2.5 \times 10^{16} \text{ Er/cm}^2$, with the sample held at 77 K . Following implantation, the films were annealed at $825 \text{ }^\circ\text{C}$ to minimize the waveguide loss³ and to activate the implanted Er.⁴ Subsequently, a $1.35\text{-}\mu\text{m}$ -thick top SiO_2 cladding was deposited, and the complete structure was annealed at $700 \text{ }^\circ\text{C}$. Figure 1 shows a depth profile of the waveguide indicating the Al_2O_3 layer as well as the optical mode intensity profile in the waveguide (dotted curve). The latter was calculated from the known thickness of the guide and the refractive indices (n) of the Al_2O_3 core ($n = 1.64$) and SiO_2 cladding ($n = 1.44$) layers. The refractive indices of these films were measured using prism coupling. Figure 1 also shows the Gaussian Er implantation profile derived from Rutherford backscattering spectrometry that was measured before

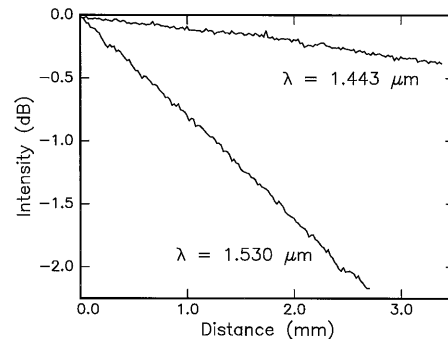


Fig. 2. Prism coupling measurements of the optical loss in an Er-implanted Al_2O_3 waveguide film for two different wavelengths.

deposition of the top cladding (solid curve: 320-nm depth, 170 nm full width at half-maximum). The Er peak concentration is $1.5 \text{ at. } \%$.

Optical absorption measurements were performed by coupling light from a tunable external cavity laser ($1.443\text{--}1.566 \mu\text{m}$) into the Er-implanted Al_2O_3 waveguide film using a high-index prism ($n = 1.7356$) and index-matching fluid. A second prism was employed to couple the light out of the film and onto a Ge detector. By moving the second prism relative to the first, the intensity in the waveguide was probed as a function of distance. Photoluminescence spectroscopy was performed using the 514.5-nm line of an Ar laser as the excitation source and dispersing the luminescence light with a 48-cm single-grating monochromator with a resolution of 3 nm . The light was detected using a liquid-nitrogen-cooled Ge detector and lock-in techniques. Data were corrected for the detection sensitivity so that the relative intensities at different wavelengths could be compared. All the measurements were performed at room temperature.

3. Results and Discussion

Figure 2 shows the light intensity in the Al_2O_3 slab waveguide as a function of distance, as measured using the prism coupling technique. The data are shown on a logarithmic scale for two different wavelengths: 1.443 and $1.530 \mu\text{m}$. The intensities are normalized to 1 (0 dB) at 0 mm . The decay of the intensity with distance is exponential, as indicated by the linear decrease in Fig. 2. From the slope of the data we determined the optical loss. The loss at $1.530 \mu\text{m}$ is 8.4 dB/cm , much higher than the loss of 1.3 dB/cm measured at $1.443 \mu\text{m}$.

Figure 3 shows the optical loss (filled circles) measured by prism coupling for several different wavelengths in the $1.443\text{--}1.566\text{-}\mu\text{m}$ range. The loss spectrum peaks at $1.530 \mu\text{m}$ and corresponds to ${}^4I_{15/2} \rightarrow {}^4I_{13/2}$ (ground state \rightarrow first excited state) transitions in Er^{3+} .¹ Note that the light intensity was low enough to ensure that no significant population build up of excited Er^{3+} could take place. Note further that the measured loss spectrum also contains contributions that are due to scattering and absorption by the waveguide itself. In undoped waveguides this loss amounts to 0.35 dB/cm .³ For implanted

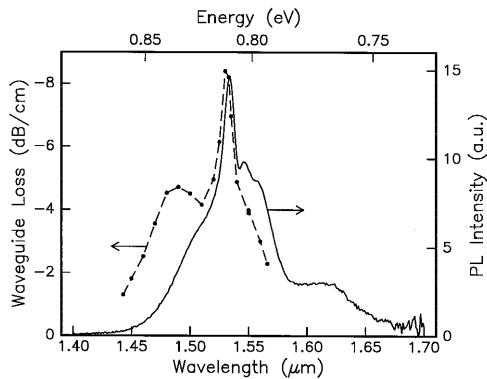


Fig. 3. Optical loss (filled circles and dashed curve, left scale) as a function of wavelength for an Er-implanted Al_2O_3 waveguide film. For comparison, the photoluminescence emission spectrum of the same sample is shown (solid curve, right scale).

waveguides we assume the same amount of intrinsic waveguide loss; the measured loss data in Fig. 3 show that, at the edge of the Er absorption spectrum ($\lambda = 1.44 \mu\text{m}$), the total (Er and intrinsic) waveguide loss is approximately 1 dB/cm and continues to decrease. Figure 3 also shows the photoluminescence spectrum measured on the same sample (solid curve, right axis). As no absolute intensities were measured, the spectrum is plotted in arbitrary units. The shape of the spectrum is again characteristic of Er^{3+} and corresponds to ${}^4I_{13/2} \rightarrow {}^4I_{15/2}$ (first excited state to ground state) transitions.¹

The measured absorption and emission spectra shown in Fig. 3 can be used to derive the corresponding absorption and emission cross sections. The loss of light power $P(z)$ as a function of distance z along the waveguide is

$$\frac{dP(z)}{dz} = -\sigma_{\text{abs}}(\lambda) \int N(y)I(y)dyP(z), \quad (2)$$

where $N(y)$ is the Er concentration depth profile and $I(y)$ is the optical mode profile of light in the waveguide, with y being the depth coordinate. $\sigma_{\text{abs}}(\lambda)$ is the cross section for absorption that depends on wavelength λ . The integral $\int N(y)I(y)dy$ can be evaluated using the Er implantation and optical mode profiles given in Fig. 1 and amounts to $3.15 \times 10^{20} \text{ cm}^{-3}$. Equation (2) now gives a linear relation between the measured waveguide loss and the absorption cross section of Er^{3+} . Note that, in the horizontal x direction, the slab waveguide has no boundaries, which means that the 1-mm-wide collimated laser beam is not confined in this direction and is collected completely by the second prism.

Figure 4(a) shows the absorption cross section of Er^{3+} in Al_2O_3 , as determined when we used Eq. (2) from the optical loss spectrum shown in Fig. 3, after subtraction of the intrinsic waveguide loss. It is assumed that all the implanted Er is optically active. This assumption is supported by previous measurements of the Er concentration dependence of the photoluminescence.⁴ The peak cross section

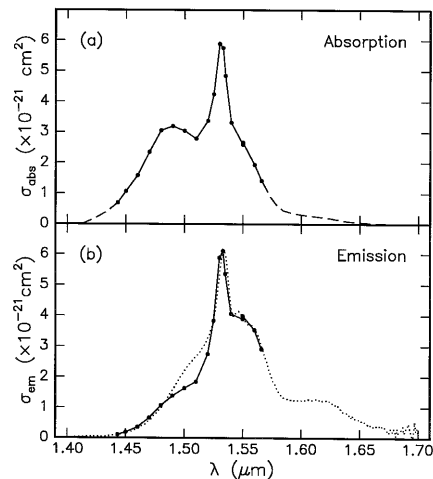


Fig. 4. Cross section spectra for the ${}^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition in Er-implanted Al_2O_3 : (a) absorption as determined from prism coupling measurements (circles and solid curve), the dashed curve is an extrapolation; (b) emission calculated from the absorption data with the McCumber theory (circles and solid curve) and the measured photoluminescence spectrum (dotted curve) scaled to overlay the calculated spectrum.

for absorption is found to be $5.9 \times 10^{-21} \text{ cm}^2$ at $1.530 \mu\text{m}$. At the commonly used $1.48\text{-}\mu\text{m}$ pump wavelength for Er-doped amplifiers, the absorption cross section is $3.0 \times 10^{-21} \text{ cm}^2$.

By applying the McCumber theory [Eq. (1)], the emission cross section spectrum can be calculated from the absorption spectrum in Fig. 4(a). The result is shown as circles in Fig. 4(b). We have assumed here that the ratio of the partition functions, z_l/z_u in Eq. (1), equals unity. This assumption is supported by measurements on two other materials with a crystal structure similar to that of Al_2O_3 : Er_2O_3 (Ref. 9) and Y_2O_3 (Ref. 10) both show a partition function ratio close to 1. In general, for Er^{3+} the different manifolds all have similar energy spacing between the sublevels, leading to a partition function ratio that is always close to unity.

Figure 4(b) also shows the shape of the emission curve measured by photoluminescence spectroscopy (dotted curve). The spectrum is scaled to overlay the absolute emission cross section spectrum calculated by the McCumber theory (circles). Good agreement between photoluminescence and the McCumber data is observed. Because the absorption spectrum of Fig. 4(a) and the corresponding McCumber emission spectrum could be determined only between 1.443 and $1.566 \mu\text{m}$, we used the photoluminescence spectrum to determine the emission cross section outside this range. Applying Eq. (1) to this result also gives values for the absorption cross sections outside the initially measured range [dashed curve in Fig. 4(a)].

The determined cross sections compare well with those measured for Er^{3+} in other waveguide host materials. For example, the peak emission cross section for Er^{3+} in Al_2O_3 codoped silica glass fiber is $4.4 \times 10^{-21} \text{ cm}^2$,¹¹ compared with $6.1 \times 10^{-21} \text{ cm}^2$

found here for Al_2O_3 . Knowledge of the cross sections enables one to obtain a first-order estimate of the optical gain at $1.5\ \mu\text{m}$, which is attainable in an Er-doped Al_2O_3 single-mode ridge waveguide. In principle, one can achieve a net optical gain of 3 dB/cm in a waveguide doped with $5 \times 10^{20}\ \text{Er}/\text{cm}^3$ (≈ 0.5 at. %) in the core and using a pump wavelength of $1.475\ \mu\text{m}$. Note that concentration quenching effects such as cooperative upconversion need to be taken into account for a realistic prediction of the optical gain.^{12,13} The effect of upconversion in Er-doped planar waveguides has been presented in another study.⁵ Recent measurements on Er-implanted Al_2O_3 waveguides with a lower Er concentration (~ 0.2 at. %) have demonstrated 2.3-dB/cm net optical gain for a pump power of only 9 mW.¹⁴

4. Conclusions

In conclusion, the emission and absorption cross sections of Er^{3+} in an Er-implanted Al_2O_3 slab waveguide have been determined. Using prism coupling measurements we determined the absorption spectrum that could be converted to the absorption cross section spectrum through knowledge of the Er concentration and optical mode profiles. McCumber theory was used to derive the emission cross section spectrum from the absorption data. The calculated emission spectrum is in good agreement with the measured photoluminescence spectrum. The cross sections for Er^{3+} in Al_2O_3 compare well with those of Er^{3+} in other waveguide host materials. The results can be used to predict the performance of Er-doped Al_2O_3 amplifiers and lasers that operate in the $1.5\text{-}\mu\text{m}$ window.

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