Photoluminescence and attenuation of spray-pyrolysis-deposited erbium-doped Y_2O_3 planar optical waveguides

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Erbium-doped Y_2O_3 planar optical waveguides have been fabricated by spray-pyrolysis deposition. The attenuation spectrum of the waveguide shows peaks that are due to absorption of the erbium ions. The as-deposited layers also show photoluminescence sharply peaking at 1540 nm with additional Stark splitting. The thin layers of Er^{3+}:Y_2O_3 obtained are promising for the realization of integrated-optic amplifiers and lasers.

In optical telecommunications there is a need for optical amplifying and lasing in the third window near 1.5 μm. These functions can be realized by using erbium-doped materials as demonstrated by erbium-doped fiber amplifiers.[1] An alternative to the erbium-doped fiber amplifier is the incorporation of the amplifying function in the integrated optical circuit, which is designed for routing and switching of optical signals. Combining the integrated-optic amplifier with a resonator results in an integrated-optic laser for use in coherent detection schemes. The use of electro-optic materials in the resonator may make possible an integrated-optic tunable laser,[2] which is needed for wavelength-division multiplexing. The incorporation of erbium into the optical waveguiding circuit can be done by either locally doping the circuit with erbium or by adding an erbium-doped waveguiding layer to the circuit. Local doping of an optical waveguide can be carried out by erbium diffusion[3] or ion implantation.[4,5] The only example known of deposition of erbium-doped waveguides is a multistep flame hydrolysis process.[6]

In this Letter we report on spray-pyrolysis-deposited Er^{3+}:Y_2O_3 planar optical waveguides. To our knowledge these are the first erbium-doped waveguides prepared by a single-step deposition process. Erbium ions in Y_2O_3 crystals are known to be active.[7] Furthermore Y_2O_3 can be deposited in thin transparent films by various techniques, such as vacuum evaporation,[8] sputtering,[9] and spraying.[10] We use the spraying technique because it is flexible and cheap. Results are presented on the optical properties of such sprayed Er^{3+}:Y_2O_3 optical waveguides, especially the waveguide attenuation and luminescence spectra.

Steam oxidized silicon wafers are used as substrates. The SiO_2 layers are 2.8 μm thick and have refractive indices of 1.457 at 633 nm and 1.444 at 1522 nm. The Er^{3+}:Y_2O_3 layers are deposited onto the substates by spray-pyrolysis deposition, also known as the chemical aerosol-deposition technique.[11] As precursors we use 2% yttrium 2,2,6,6-tetramethyl-3,5-heptanedionate (98+% pure) and 0.06% erbium acetylacetonate (99.9% pure) dissolved in *n*-butyl acetate. An aerosol is created by ultrasonically nebulizing this solution. A carrier gas (80% N_2 and 20% O_2) leads the aerosol to the nozzle, where it is sprayed onto the substrate, which has a temperature of 500°C. Scanning electron microscopy shows a smooth, crack-free surface and a uniform cross section with fine grains (<20 nm). The ratio of metal to oxygen is determined by energy dispersive x-ray analysis and is found to be 35:65 by using bulk Y_2O_3 and erbium metal references. From this analysis we determine an erbium concentration in the layer of 2 at. % and no detectable impurities. The x-ray diffraction spectra of the Er^{3+}:Y_2O_3 layers show clear reflection peaks from the 222 and 440 planes. This indicates that the polycrystalline layers grow in the body-centered cubic (bixbyite) phase. However, the peak intensity is rather low, so short-range order polycrystallinity or even amorphous parts may be present in the layers.

The experimental setup used for recording waveguide transmission spectra is shown in Fig. 1. A tungsten lamp with a collimator is used as a light source. The converging polarized polychromatic light beam is coupled by a prism to the propagating fundamental TE mode of the waveguide. Mode selection is done by adjusting the central coupling angle and the cone angle of the polychromatic beam. The mode is coupled out by a second prism, and the transmitted spectrum is analyzed with a spectrometer. The spectral attenuation $\alpha(\lambda)$ of the waveguide can be calculated by a logarithmic fit of the data from transmission spectra recorded for various prism separations. The attenuation spectrum determined in this way accounts only for the waveguide attenuation because spectral-dependent properties of the lamp, the coupling, and the detection system are eliminated if the coupling efficiency is kept constant during a measurement series. This could be achieved by using a well-designed rigid prism coupler in which the smoothness of the waveguides' surfaces has been shown to be advantageous. Luminescence spectra are also recorded with the experimental arrangement of Fig. 1, but now with a 30-mW cw dye laser tuned at 666 nm as the light source for exciting the erbium ions by a guided fundamental TE

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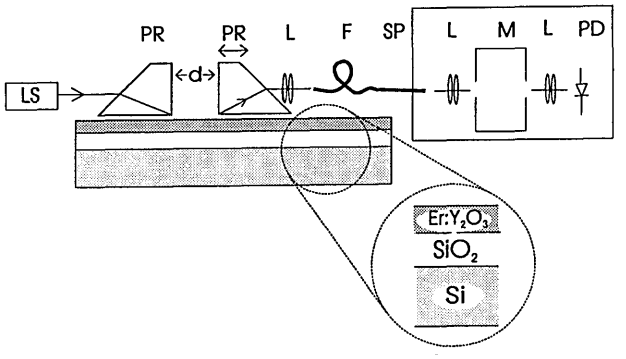

Fig. 1. Experimental setup for attuenuation and luminescence measurements. LS, light source; PR's, prisms; L's, lenses; F, fiber; SP, spectrometer [consisting of a monochromator (M) and a photodiode (PD)].

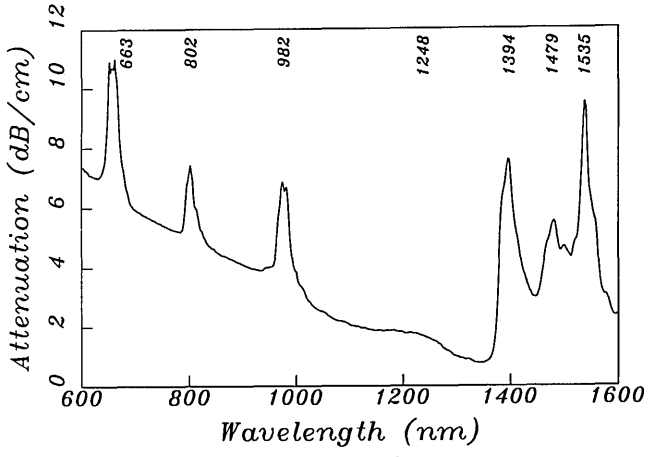

Fig. 2. Waveguide attuation spectrum.

mode. The resulting luminescence is partly collected in a waveguide mode[12] that is coupled out by the second prism and then completely coupled into the multimode input fiber of the spectrometer by collecting and refocusing optics. Luminescence decay measurements were performed by chopping the pump light (30-s period, 30-μs fall time) and connecting the spectrometer with a digitizing oscilloscope. All luminescence measurements are done at room temperature.

The refractive index and thickness of the Er^{3+}:Y_2O_3 waveguides are determined by prism coupling[13] and found to be 1.750 at 633 nm and 1.714 at 1522 nm, where the thickness of the waveguides is near 0.4 μm. With this thickness and refractive index, the waveguides are monomode in the 600–1600-nm wavelength range and the mode field is satisfactory confined to prevent leakage to the silicon wafer. A typical waveguide attenuation spectrum of the fundamental TE mode is shown in Fig. 2. The determination of the attenuation is shown in representative examples in Fig. 3. The attenuation peaks at 1248 and 1394 nm can be explained by stretching vibrations of OH groups. The tails of these absorptions give rise to residual attenuation near 1.5 μm, which may be reduced by thermal annealing. The other peaks in Fig. 2 are caused by absorption of erbium ions and correspond to literature values for Er^{3+}:Y_2O_3 single-crystal energy levels.[14] The absorption peaks at 1479 and 1535 nm are due to Stark splitting of the $^4I_{13/2}$ manifold. Comparable absorption spectra are recorded for TM modes as is expected for isotropic polycrystalline layers. The luminescence spectrum of the waveguide that is due to the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition is shown in Fig. 4. The maximum is at 1540 nm with a FWHM of 5 nm. In addition to this maximum the spectrum shows several Stark components. Comparison of these wavelengths with literature values[14] indicates that both $^4I_{13/2}$ and $^4I_{15/2}$ Stark levels may be involved. Further research is necessary for identification of the Stark transitions. The Stark splitting provides emission over a relatively large wavelength range, which is important for application as a broadband optical amplifier. The fast exponential component of the luminescence decay at 1540 nm corresponds to a lifetime of 1 ms of the $^4I_{13/2}$ level. Comparison with a lifetime of 8 ms in 0.04 at.% erbium-doped Y_2O_3 (Ref. 15) indicates the appearance of ion–ion interactions. However, regarding the high erbium concentrations of our samples, the measured lifetime is acceptable and predicts laser action.

In conclusion, we have demonstrated that Er^{3+}:Y_2O_3 planar optical waveguides can be realized by spray-pyrolysis deposition, which is a straightforward and low-cost process. The waveguides show an attenuation peak at 1535 nm and room-temperature luminescence peaking at 1540 nm. All measurements were performed with as-deposited

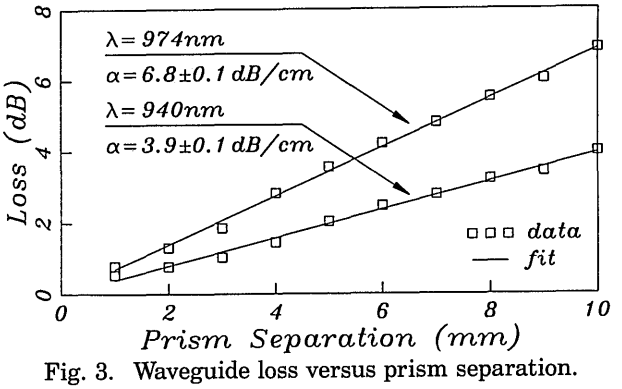

Fig. 3. Waveguide loss versus prism separation.

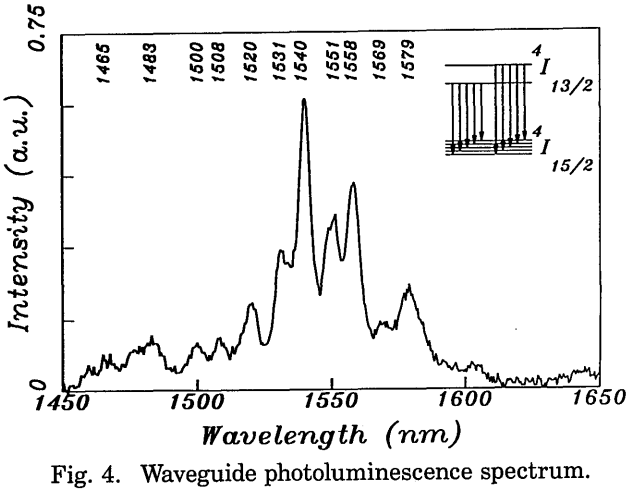

Fig. 4. Waveguide photoluminescence spectrum.

films, so further improvement may be possible. Er^{3+}:Y_2O_3 is therefore a promising material for integrated-optic amplifiers and lasers.

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