In-band Pumping of Epitaxially Grown Er:(Gd, Lu)$_2$O$_3$ Waveguides for Active Integrated Optical Devices

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For the realization of lasers with high frequency stability, crystalline host materials with small emission linewidths are beneficial. Especially rare-earth (RE) doped dielectric oxides with their sharp emission peaks, featuring high cross sections, are well established for such applications. The miniaturization of those devices is very promising, particularly for space applications where size and weight are critical. Therefore, our aim is the fabrication of active integrated optical devices in crystalline rare-earth doped oxides. For this purpose mono-crystalline lattice matched Er(0.6%):(Gd, Lu)$_2$O$_3$ films with thicknesses up to 3 µm and nearly atomically flat surfaces have been deposited on Y$_2$O$_3$ substrates by Pulsed Laser Deposition (PLD). The epitaxial growth has been verified *in-situ* by Reflection High Energy Electron Diffraction (RHEED). As first test structures channel waveguides with widths ranging from 2 to 5 µm and heights from 400 to 700 nm have been fabricated by Reactive Ion Etching and finally covered by about 1.5 µm thick a-Al$_2$O$_3$ top claddings to reduce scattering losses at the surface. Due to the refractive index difference between film and substrate ($\Delta n \approx 0.03$ at 1.55 µm) rib waveguiding could be demonstrated (see Fig. 1a).

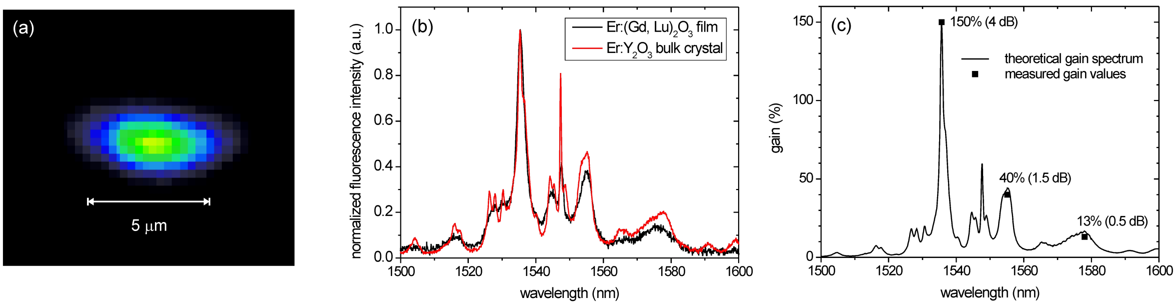

Fig. 1 (a) Intensity distribution of the outcoupled mode of 1 µm light in one of the rib waveguides of a 3.1 µm thick lattice matched Er(0.6%):(Gd, Lu)$_2$O$_3$ film deposited on {100}-oriented Y$_2$O$_3$ and covered by a 1.7 µm thick a-Al$_2$O$_3$ layer **(b)** Normalized fluorescence spectrum of the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ (Er^{3+}) transitions of a mono-crystalline Er:(Gd, Lu)$_2$O$_3$ film compared with the one of an Er:Y$_2$O$_3$ bulk crystal **(c)** Theoretical gain spectrum of a 7 mm long Er(0.6%):Y$_2$O$_3$ waveguide bleached at 1480 nm in comparison with the gain measurements performed with Er(0.6%):(Gd, Lu)$_2$O$_3$ at three different wavelengths

The fluorescence spectra of the films are comparable with those of Er:Y$_2$O$_3$ bulk crystals (see Fig. 1b). Therefore, a theoretical gain spectrum (see Fig. 1c) could be calculated from the absorption and emission spectra of Er:Y$_2$O$_3$. Bleaching at the pump wavelength of 1480 nm results in an inversion ratio $\beta \approx 0.75$ between the $^4I_{13/2}$ and $^4I_{15/2}$ multiplet of Er^{3+} and thus to a theoretical gain of 260% at 1535 nm for a 7 mm long waveguide. Gain measurements using a tunable diode laser (1530 nm to 1583 nm) as signal and a pump diode at 1480 nm have been performed. Both sources have been combined in a single mode fiber and then coupled into the waveguide. Using the lock-in technique and a monochromator, the signal intensity I of the outcoupled light could be measured in dependance of the pump power (up to 100 mW before coupling into the waveguide) and the gain determined as $(I_{pumped} - I_{unpumped}) / I_{unpumped}$. Calculations show that the small waveguide dimensions allow bleaching with absorbed powers well below 1 mW. It has been experimentally verified that the incident signal of 0.5 mW was sufficient to already bleach the waveguide in the unpumped case. Therefore, the reduction of signal absorption in the pumped case can be neglected and does not falsify our measured gain. At 1535 nm a maximum gain of 150% (4 dB) could be measured for the 7 mm long sample, resulting in a gain of 5.7 dB/cm. The measured gain is lower than the theoretically expected, because the intensity distribution of the guided mode is not limited to the doped regions. Taking this into account by normalizing the theoretical gain spectrum to the maximum measured gain of 150% results in a good accordance of the experimentally determined gain at various wavelengths with the theoretical spectrum (see Fig. 1c). The high gain obtainable due to bleaching in the small waveguiding structures combined with the relative high peak cross sections of crystalline RE doped (Gd, Lu)$_2$O$_3$ makes these waveguides promising for the development of compact lasers with low lasing threshold and high frequency stability. Laser experiments with Nd^{3+} and Er^{3+} doped waveguides are therefore in progress.