Mono-crystalline Rare Earth Doped (Gd, Lu)$_2$O$_3$ Waveguiding Films Produced by Pulsed Laser Deposition and Structured by Reactive Ion Etching

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Epitaxially grown Nd(0.5%):(Gd, Lu)$_2$O$_3$ and Er(0.6%):(Gd, Lu)$_2$O$_3$ waveguides deposited on Y_2O_3 by Pulsed Laser Deposition, providing peak emission cross sections comparable with those of Lu_2O_3 bulk crystals, have been fabricated and structured. Rib waveguiding has been shown.

OCIS codes: (140.3380) Laser materials; (230.7380) Waveguides, channeled; (310.1860) Deposition and fabrication

While the waveguide geometry is already well established for semiconductor lasers, it is also promising for another attractive class of solid state laser media, the rare-earth (RE) doped dielectric oxides. Especially the sesquioxides with their relatively low phonon energies, high thermal conductivities and damage thresholds are attractive host materials for optically active RE ions. Therefore, our aim was the fabrication of RE doped sesquioxide waveguiding films with high peak cross sections and low propagation losses. As high peak cross sections can rather be obtained in crystalline than amorphous materials, and crystals usually offer other advantages like a better thermal conductivity and mechanical stability as well, the production of highly crystalline films was desired. Due to its flexibility regarding different material systems, the possibility of stoichiometric material transfer, and the high particle energies obtainable, Pulsed Laser Deposition has been chosen for the fabrication of these films. To achieve a high crystallinity and to prevent lattice stress, the lattice mismatch between the deposited film and substrate should be as low as possible. Even though highly textured RE doped Y_2O_3 on α-Al_2O_3, Sc_2O_3 on α-Al_2O_3 and Sc_2O_3 on Y_2O_3 films featuring emission cross sections comparable with bulk crystals have been deposited successfully, the high lattice mismatch of 4.8 %, -2.6 %, and -7.7 %, respectively, prevented the fabrication of mono-crystalline films with thicknesses in the micrometer range. It is very likely that scattering due to small crystallites, especially at the surface, contributes highly to the parasitic losses in the waveguide. Therefore the scattering losses, which have been determined to be about 4 dB/cm (at 800 nm) for a 1 μm thick Er(1%):Y_2O_3 planar waveguide on α-Al_2O_3, might be significantly reduced in a mono-crystalline one. While epitaxial growth has already been shown for homoepitaxial sesquioxide systems [1], we have recently fabricated 1 μm thick mono-crystalline (Gd, Lu)$_2$O$_3$ films on Y_2O_3 and thus realized a system which provides a positive refractive index difference between film and substrate and therefore allows waveguiding.

A 0.5 at% Nd-doped (Gd, Lu)$_2$O$_3$ film has been deposited on a mono-crystalline and epitaxial grade polished Y_2O_3 substrate, oriented in {100} direction. The growth has been monitored *in situ* by Reflection High Energy Electron Diffraction. The intensity oscillations of the specularly reflected electron beam indicating a layer-by-layer growth could be seen up to film thicknesses of 100 nm. After that the growth mode was passing into step-flow-growth until the end of deposition at about 1 μm film thickness. The crystalline growth in {100} direction has been verified by *ex situ* X-Ray Diffraction and the surface investigated by Atomic Force Microscopy (AFM), showing atomic steps confirming the 2D-growth mode (see figure 1a). The fluorescence decay lifetime of the $^4F_{3/2}(Nd^{3+})$ multiplet was measured to be 188 μs at room temperature and the emission cross sections of the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transitions have been determined from the fluorescence spectrum using the Füchtbauer-Ladenburg equation (see figure 1b). For the cross section determination the measured lifetime was assumed to be the radiative one. The peak positions can be found approximately at the same wavelengths where the maxima for Nd:Y_2O_3 would be situated and the maximum emission cross section of 5.5×10^{-20} cm^2 at 1079 nm is about the same magnitude as the corresponding peak cross sections of Nd-doped Y_2O_3 and Lu_2O_3 bulk crystals.

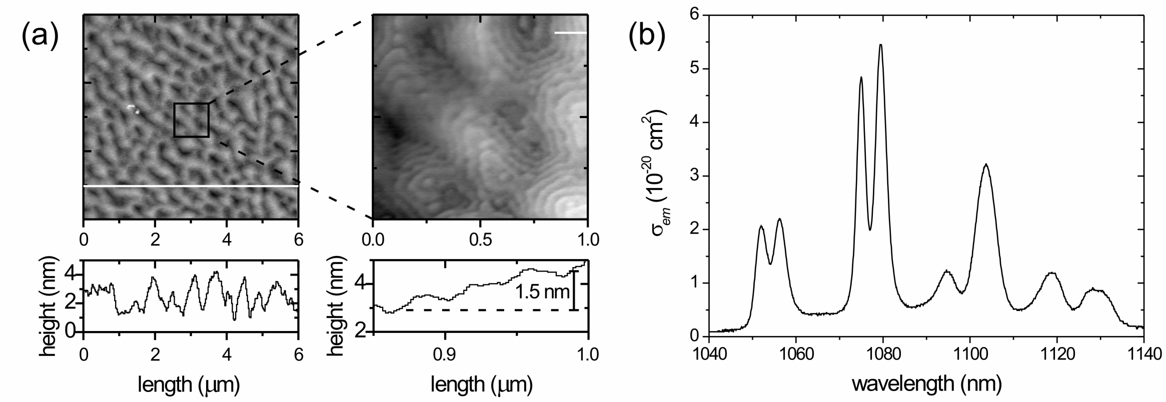

Fig.1. (a) AFM images of a 1 µm thick lattice matched Nd(0.5%):(Gd, Lu)$_2$O$_3$ film deposited on {100}-oriented Y_2O_3. The height profiles were taken along the white lines indicated in the image. (b) Emission cross sections σ_{em} of the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ (Nd^{3+}) transitions of the same film.

Another promising application of RE doped waveguiding films is the realization of active integrated optical devices, especially with Er-doping. For this, a 1 µm thick mono-crystalline Er(0.6%):(Gd, Lu)$_2$O$_3$ film has been deposited on a {111}-oriented Y_2O_3 substrate and structured by Reactive Ion Etching, resulting in approximately 30 channel waveguides with top widths ranging from 2 to 5 µm and heights of about 400 nm. To reduce scattering losses at the surface the waveguide has then been covered by an approximately 1.5 µm thick a-Al_2O_3 top cladding. The Cauchy parameters describing the refractive index of the waveguiding film have been measured through spectroscopic ellipsometry and the refractive index n at 1.55 µm has been determined to be 1.91. Due to the lower refractive index of the substrate (n_{Y2O3} = 1.88 at 1.55 µm) light confinement is possible and has been verified in first waveguiding experiments at 670 nm (see figure 2).

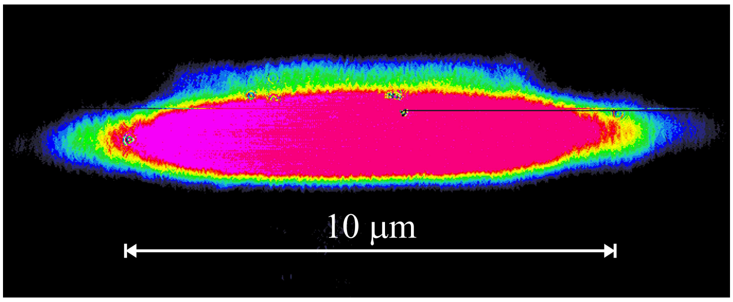

Fig. 2. Intensity distribution of the outcoupled mode of 670 nm light in one of the rib waveguides of a 1 µm thick lattice matched Er(0.6%):(Gd, Lu)$_2$O$_3$ film deposited on {111}-oriented Y_2O_3 and covered by a 1.5 µm thick a-Al_2O_3 layer after structuring.

Given the good spectroscopic properties obtained in the Nd-doped system, which are expected for Er-doping as well, and the possibility of light confinement, lattice matched RE-doped (Gd, Lu)$_2$O$_3$ on Y_2O_3 is a promising system for the realization of active waveguiding devices. Upcoming propagation loss measurements will show whether those mono-crystalline waveguides provide significant lower scattering losses than their polycrystalline counterparts. Furthermore, laser and gain experiments are in progress. We acknowledge the support of the European Commission within the STREP project PI-OXIDE (017 501).

[1] T. Gün, Y. Kuzminykh, K. Petermann, H. Scheife, and G. Huber, "Epitaxial growth by pulsed laser deposition of Er-doped Sc_2O_3 films on sesquioxides monitored in situ by reflection high energy electron diffraction," Appl. Phys. Lett. **91**, 083103 (2007).