Low Threshold Channel Waveguide Laser in a Monocrystalline Nd:(Gd, Lu)$_2$O$_3$ Film

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We report the first waveguide laser based on rare-earth sesquioxides. A structured Nd(0.5%):(Gd, Lu)$_2$O$_3$ film pumped at 820 nm showed lasing at 1.08 µm. The laser threshold was 0.8 mW, the preliminary slope efficiency 0.5 % and the maximum output power 1.8 mW.

OCIS codes: (130.3120) Integrated optics devices; (140.3530) Lasers, neodymium; (140.5680) Rare earth and transition metal solid-state lasers; (230.7380) Waveguides, channeled.

We report the first waveguide laser based on rare-earth (RE) sesquioxides. Due to their relatively low phonon energies, high thermal conductivities and damage thresholds, sesquioxides are very attractive laser host materials. Lattice matched Nd(0.5%):(Gd, Lu)$_2$O$_3$ films have been epitaxially grown on Y$_2$O$_3$ substrates, using pulsed laser deposition. Epitaxial film growth has been verified *in situ* by reflection high energy electron diffraction and atomically smooth terraces have been observed by atomic force microscopy. A room temperature fluorescence lifetime $\tau = 258$ µs has been measured for the $^4F_{3/2}$ (Nd^{3+}) multiplet. The emission cross sections of the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transitions for such a lattice matched Nd:(Gd, Lu)$_2$O$_3$ film have been determined (see Fig. 1) and compared to the ones of a Nd:Y$_2$O$_3$ bulk crystal measured in [1]. While there is a good accordance of the peak positions, the film spectrum shows a slight line broadening in comparison to the bulk crystal, most probably due to the statistical occupation of the cation sites by Gd^{3+} and Lu^{3+}.

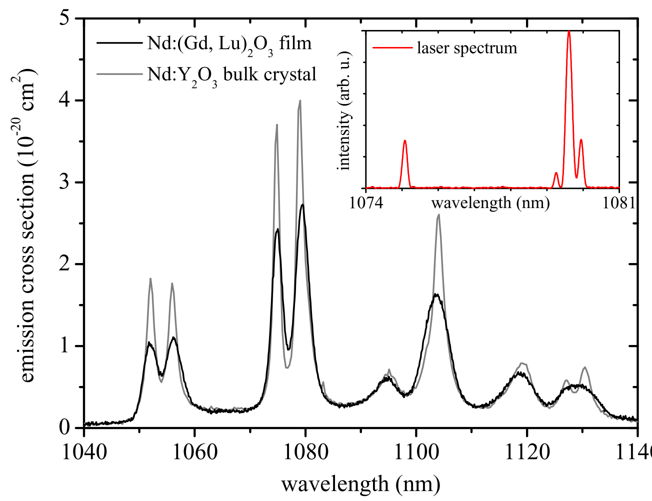

Fig. 1. Emission cross sections of a Nd:(Gd, Lu)$_2$O$_3$ film in comparison with the ones measured in [1] for a Nd:Y$_2$O$_3$ bulk crystal. The film emission cross sections have been determined from the fluorescence spectrum (spectral bandwidth 0.32 nm) with the Füchtbauer-Ladenburg equation. Therein, the radiative lifetime $\tau_{rad} = 410$ µm and branching ratio $\beta = 47\%$ determined in [1] have been used. The inset shows the waveguide laser spectrum.

Laser experiments have been carried out with a 2 µm thick waveguide. It has been structured by reactive ion etching [2], resulting in straight rib channel waveguides with widths ranging from about 2 to 5 µm and an etch depth of 300 nm. The film has been covered by a 1.8 µm thick sputtered amorphous Al$_2$O$_3$ layer and its end-facets have been polished. A highly reflective coating (1000 – 1100 nm) has been applied on the incoupling facet and a coating with 1 – 2 % transmission (1000 – 1100 nm) on the outcoupling facet. A Ti:Al$_2$O$_3$ laser beam at 820 nm has been coupled into a waveguide channel, using a microscope objective with a numerical aperture (NA) of 0.35 (see Fig. 2). The outcoupled light has been collected with another microscope objective (NA = 0.7). Two dichroitic mirrors were used as filters for the pump light.

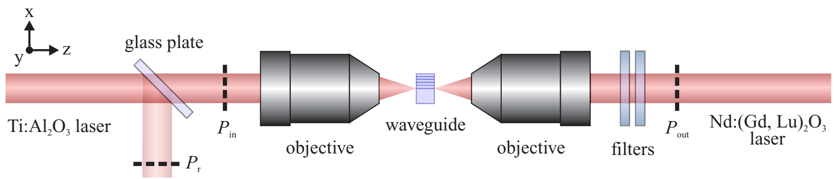

Fig. 2. Waveguide laser setup. Excitation occurred at 820 nm with a Ti:Al_2O_3 laser beam, coupled into a waveguide channel. Two dichroitic mirrors served as filters for the pump light. The input power could be measured simultaneously with the output power P_{out}, by measuring the power P_r reflected from a glass plate.

Three laser wavelengths near 1079 nm and one at 1075 nm have been observed simultaneously (see Fig. 1), as well as heavily damped relaxation oscillations for about 300 µs. The intensity distribution of the outcoupled laser light is displayed in Fig. 3a, while Fig. 3b shows the output power P_{out} of the waveguide laser for various incident pump powers P_{in}.

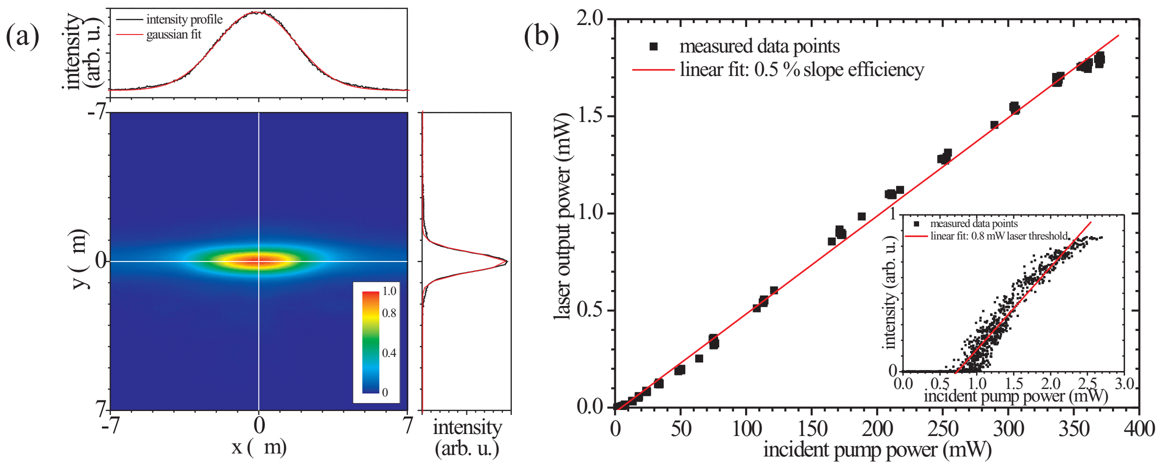

Fig. 3. **(a)** intensity distribution of the outcoupled laser light and the corresponding intensity profiles with gaussian fit functions **(b)** input-output curve for the waveguide laser and measurement results for the determination of the laser threshold (inset)

Using a thin glass plate serving as beam splitter, P_{out} and P_{in} have been measured simultaneously. P_{in} has been corrected by considering the transmittance of the incoupling objective and reflectivity of the incoupling mirror. Additional coupling losses have not been considered. The transmittance of the outcoupling objective and dichroitic mirrors has been taken into account for the determination of P_{out}. Fitting the measured data points with a linear function, a slope efficiency of 0.5% with respect to the incident pump power has been determined. The slope efficiency with respect to the absorbed pump power is most likely significantly higher. P_{out} = 1.8 mW maximum output power has been obtained for P_{in} = 370 mW. Higher output powers can most likely be realized with an increased output coupling. The laser threshold has been determined to be 0.8 mW (see inset of Fig. 3b) by applying the lock-in technique and recording the laser intensity with a photodiode. Due to the light confinement in the small waveguide dimensions, the threshold is very low.

The channel waveguide laser shows that active integrated optics based on such films is possible and that Nd:(Gd, Lu)$_2$O$_3$ is a promising candidate for the realization of more complex integrated optical devices, possibly leading to the implementation of multiple active and and passive elements on a small chip. We acknowledge the support of the European Commission within the specific targeted research project PI-OXIDE (017501).

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