Long Wavelength Laser Operation of $Tm:Sc_2O_3$ at 2116 nm and Beyond

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Abstract: We report on the high power laser operation of $Tm:Sc_2O_3$ with a slope efficiency of 41 % and an output power of 26 W at 2116 nm. A tunability from 1975 nm to 2168 nm is presented.

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1. Introduction

A wide field of applications in medicine, LIDAR-systems, and gas detection causes an increasing interest in 2 µm laser systems. Thulium- and holmium-doped solid state lasers are the most commonly used sources for laser radiation in the 2 µm region. Thulium doped solid state lasers exhibit the great advantage that they can be pumped at wavelengths around 800 nm, where high performance laser diodes are commercially available. Due to an efficient cross relaxation process, 2 µm laser radiation can be generated with a quantum efficiency of up to two. Depending on the host material, the laser wavelength of these systems commonly lies between 1900 nm and 2050 nm (e.g. 1908 nm for YLF and 2013 nm for YAG).

Holmium lasers generally reach longer wavelengths, commonly between 2050 nm (YLF) and 2100 nm (YAG: 2090 nm), which are more suitable for e.g. pumping ZGP (zinc-germanium-phosphide) for the generation of mid-IR radiation via non-linear frequency conversion. However, for pumping Ho-lasers either thulium lasers or high-cost and low-efficiency 1.9 µm laser diodes have to be used. Alternatively co-doped Tm,Ho:solid state lasers can be employed, which however suffer from stronger up-conversion losses and lower efficiency.

A more direct and more efficient way for the generation of long wavelength laser radiation can be achieved by using thulium doped sesquioxides, which show a very strong Stark splitting of the energy levels. This leads to low reabsorption losses on the one and to longer wavelengths on the other hand. Recently laser operation at 2065 nm with output powers above 40 W has been achieved with thulium doped lutetia ($Tm:Lu_2O_3$) [1]. Due to the smaller lattice constant thulium doped scandia ($Tm:Sc_2O_3$) offers an even stronger Stark splitting, leading to even longer wavelengths. So far the output power has been limited to 194 mW in a Ti:sapphire- and to 101 mW in a diode-pumped setup [2]. In this paper we present output powers exceeding 25 W at a wavelength of 2116 nm. The crystal for this experiment was grown by the heat exchanger method [3]. Spectroscopic data on the absorption and gain cross sections and the fluorescence lifetime of the upper laser level are also presented.

2. Spectroscopy

2.1. *Absorption Cross Sections*

The spectrum of the $^3H_6 \rightarrow {}^3H_4$ transition around 800 nm was measured with a Cary 5000 spectrophotometer with a resolution of 0.05 nm and is presented in Fig. 1. A broad spectrum from 760 nm to 820 nm with a strongly pronounced peak at 796 nm with a cross section of $4.5 \cdot 10^{-21}$ cm^2 can be seen. Pumping at this wavelength seems to be the most promising way for efficiently exciting $Tm:Sc_2O_3$.

2.2. *Gain Cross Sections*

The gain cross sections around 2 µm were calculated from the absorption and the emission spectrum. The emission cross sections were determined via the Füchtbauer-Ladenburg equation. As can be seen in Fig. 2, even for low inversions gain is available in the long wavelength region around 2120 nm. For higher inversion densities the maximum gain is found around 1990 nm.

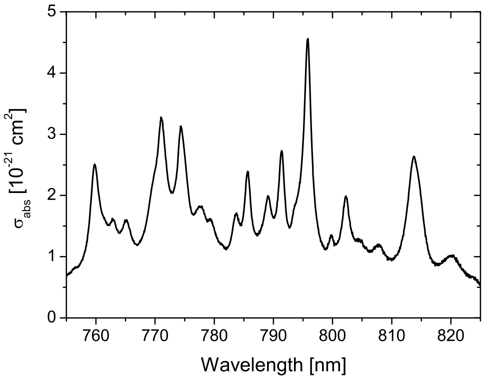

Fig. 1: Absorption spectrum of $Tm:Sc_2O_3$ around 800 nm.

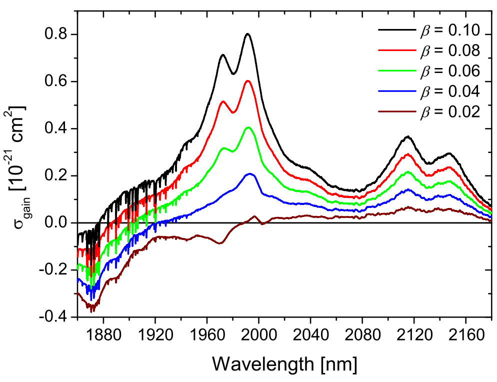

Fig. 2: Gain spectrum of $Tm:Sc_2O_3$ around 2 µm for different inversions β.

2.3. Fluorescence Lifetime

The fluorescence lifetime of the $^3F_4$ level was measured with the pinhole method [4]. This method allows for a destruction-free measurement of the lifetime without reabsorption effects. The polished crystal is placed behind a thin plate with a pinhole, which lowers the excited volume when being adressed by a pulse of an OPO. The lifetime of the $^3F_4$ level of the Tm^{3+} ion is then measured for the initial (2.5 mm) and further, decreasing pinhole diameters. The lifetime without reabsorption effects can then be extrapolated for a pinhole diameter of zero.

For the excitation a 10 ns OPO pulse at a wavelength of 796 nm was used. The 2 µm radiation was separated with a 0.5 m SPEX monochromator and detected with a PbS-diode. The inset of Fig. 3 shows the decay-curves for the different pinhole diameters. As can be seen, the decay shows an exponential characteristic. The measured lifetimes for the different pinhole diameters are displayed in Fig. 3. The extrapolation to zero yields a lifetime of (3441 ± 25) µs. The lifetime is much shorter than the one of Tm:YAG (10.5 ms) and Tm:YLF (15.6 ms) and slightly shorter than the one of $Tm:YAlO_3$ (5 ms). It is also slightly shorter than the lifetime given in [2] for $Tm:Sc_2O_3$ (4.0 ms), which supposably is due to the fact that these measurements suffered from reabsorption effects. Measurements of the lifetime of the here presented crystal without pinholes also yielded 4.0 ms.

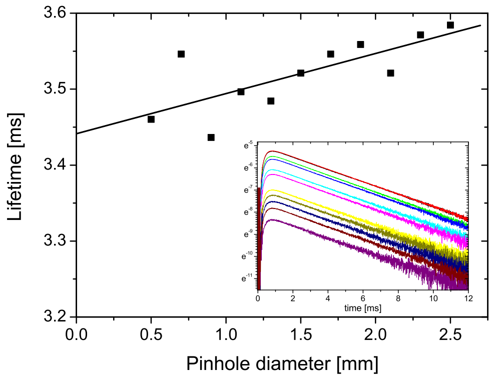

Fig. 3: Extrapolation of the fluorescence lifetime of the $Tm:Sc_2O_3$ $^3F_4$ level. Inset: Decay-curves for different pinhole diameters.

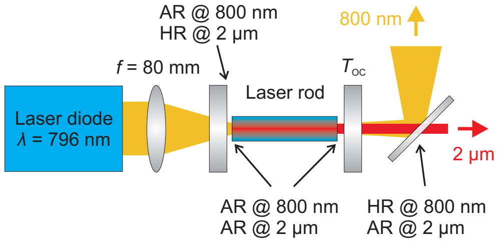

Fig. 4: Setup for the $Tm:Sc_2O_3$ laser experiments with the ∼ 19 mm long plano-plano laser cavity.

3. Laser Experiments

The laser experiments were carried out with a very simple and compact setup. As can be seen in Fig. 4, the collimated beam of a laser diode ($\lambda = 796$ nm, $P_{max} = 100$ W) was focused into the laser rod with an $f = 80$ mm lens. The laser rod was a $Tm(1\%):Sc_2O_3$ crystal which was 15 mm in length and 3 mm in diameter. It was barrel polished and water cooled to 20 °C. Both endfacets were AR-coated for the pump and the laser wavelengths. The plane incoupling mirror was AR-coated for the pump wavelength and had a broadband HR-coating for the 2 µm region. The plane outcoupling mirrors were placed as close to the crystal as possible, giving the cavity a total length of approximately 19 mm. They transmitted more than 90 % of the pump light, making it possible to determine the transmitted pump power after seperating the pump from the 2 µm radiation with a dichroic plate.

The resulting input-output curves are shown in Fig. 5. A maximum slope efficiency of 41 % could be achieved with 3 % of output coupling, the maximum output power was 26.2 W. For low output coupling rates the laser thresholds were well below 3 W, for 12 % of output coupling it was still below 6 W. The free running laser wavelength was 2116 nm for all except for the 12 % output coupler. Here it changed to 1996 nm, which is the gain maximum for higher inversion densities, see Fig. 2.

The here presented output powers strongly exceed the so far reached values in the area of 0.1 W to 0.2 W [2]. Furthermore, the output power is only limited by the available pump power and therefore even higher powers can be expected.

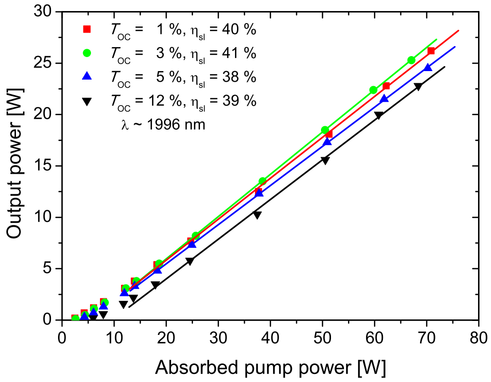

Fig. 5: Input-output curves of the $Tm(1\%):Sc_2O_3$ laser for different output couplings.

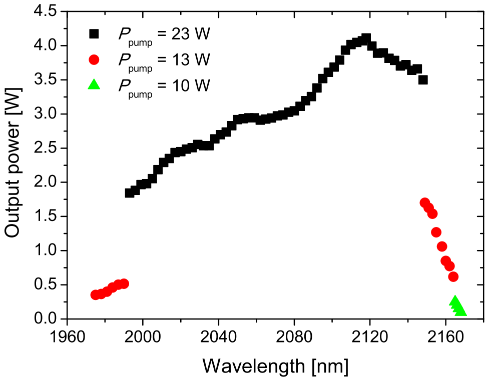

Fig. 6: Tuning curve of the $Tm(1\%):Sc_2O_3$ laser. For lower pump powers an expansion of the tuning range can be observed.

For tuning the wavelength of the laser, the output coupler was replaced by a curved mirror with $R = 100$ mm and $T_{OC} = 1$ %, which was placed 65 mm behind the crystal. In between a 1 mm quartz plate was introduced into the resonator which served as a birefringent filter. For the tuning experiments the pump power was set to 23 W. With this setup continuous tuning from 1993 nm to 2148 nm could be achieved, as can be seen in Fig. 6. At the ends of this tuning curve the power did not drop to zero, the laser jumped to 1996 nm and 2116 nm instead, where more gain was available. For lower pump powers of 13 W and 10 W, respectively, it was possible to extend the tuning range to 1975 nm to 2168 nm, however with much lower output powers.

4. Summary and Outlook

We reported on the high power laser operation of $Tm:Sc_2O_3$ with a slope efficiency of 41 % and an output power of 26 W at 2116 nm. A tunability from 1975 nm to 2168 nm was presented. Absorption and gain spectra were shown and a lifetime of the upper laser level of 3.4 ms has been determined with the pinhole method. In the future further scaling of the output power by the use of higher dopant concentrations and experiments in the q-switched regime are planed.

References

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