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Efficient diode-pumped laser operation of $Tm:Lu_2O_3$ around $2\,\mu m$

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We report on the first diode-pumped laser operation of thulium-doped Lu_2O_3. With a very compact setup an output power of 75 W and slope efficiencies of around 40% with respect to the incident pump power were achieved at room temperature. Free running laser operation was observed at wavelengths of 2065 nm and 1965 nm. With a birefringent filter the wavelength could continuously be tuned from 1922 nm to 2134 nm. The thermal conductivity of $Tm:Lu_2O_3$ was measured for different dopant concentrations and is compared to the one of thulium-doped YAG. © 2011 Optical Society of America

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High-power $2\,\mu m$ lasers are of great interest for a large number of applications, such as medicine, material processing, and LIDAR systems [1]. Commonly, the systems of choice are thulium-doped solid state lasers. They offer the great advantage that they can be pumped at around 800 nm where high performance laser diodes are commercially available while the laser wavelength lies between $1.8\,\mu m$ and $2.1\,\mu m$, depending on the host material. Despite the huge quantum defect, high efficiencies can be reached with these systems as a result of a cross-relaxation process, which leads to a quantum efficiency of up to two [2]. Nevertheless, a large amount of heat is produced in the pumped area and for high-power lasers the heat removal becomes crucial, thus, a high thermal conductivity is needed. The sesquioxides Lu_2O_3, Y_2O_3, and Sc_2O_3 offer high thermal conductivities between $13\,Wm^{-1}K^{-1}$ and $17\,Wm^{-1}K^{-1}$ [3].

Previous laser experiments have shown high slope efficiencies of up to 68% under Ti:sapphire pumping [4]. We now report on the first diode-pumped laser experiments, which were carried out with a $Tm(1\%):Lu_2O_3$ crystal that was grown by the heat exchanger method [5]. An output power of 75 W and slope efficiencies around 40% with respect to the incident pump power were observed.

In general, thulium-doped solid state lasers require relatively high dopant concentrations for assuring an efficient pumping via cross relaxation. The drawback of high dopant concentrations is often a strong decrease of the thermal conductivity, which further increases with the difference of the masses of the dopant ion and the lattice cation [6]. For thulium and lutetium this difference is only about 3%, while the thulium ion mass is about two times the mass of the yttrium ion. Since in Tm:YAG, the most common thulium-doped crystal, the thulium ion occupies an yttrium site, a strong decrease of the thermal conductivity can be expected for this material, in contrast to thulium-doped Lu_2O_3. The expectations could be verified by measurements of the temperature wave propagation [7] with an *ai-Phase Mobile1* on several $Tm:Lu_2O_3$ and Tm:YAG crystals, as can be seen in Fig. 1. For $Tm:Lu_2O_3$ a drop of the thermal conductivity from $12.8\,Wm^{-1}K^{-1}$ to $11.3\,Wm^{-1}K^{-1}$ could be observed for dopant concentrations between 0 and 5 at.%. For Tm:YAG the thermal conductivity decreases from $10\,Wm^{-1}K^{-1}$ to $4.9\,Wm^{-1}K^{-1}$ for increasing dopant concentrations from 0 to 20 at.%.

For the determination of the optimum diode pump wavelength, the absorption spectrum of $Tm:Lu_2O_3$ in the 800 nm region has been folded with a Gauss function with an FWHM of 1.8 nm, which corresponds to the spectrum of the laser diodes to be used. This way an effective absorption spectrum of the laser diode radiation could be determined, as shown in Fig. 2. The peak absorption cross section remains unchanged at 796 nm, between 793 nm and 798 nm the effective absorption cross section is between $2.4 \cdot 10^{-21}\,cm^2$ and $3.1 \cdot 10^{-21}\,cm^2$. Therefore, a relatively homogeneous absorption efficiency is achieved when laser diodes are used for pumping in this region whose wavelength commonly shifts by 3 nm to 4 nm from threshold to maximum power.

The gain spectrum for the $2\,\mu m$ region was calculated from the absorption and emission spectra. The spectrum is shown in Fig. 3 for different inversions between 2% and 14%. The inversion parameter β is the ratio between the total occupation of the upper and the ground state manifold. As can be seen, even for low inversions gain is available in the long-wavelength region around 2090 nm. For somewhat higher inversions the maximum gain is found

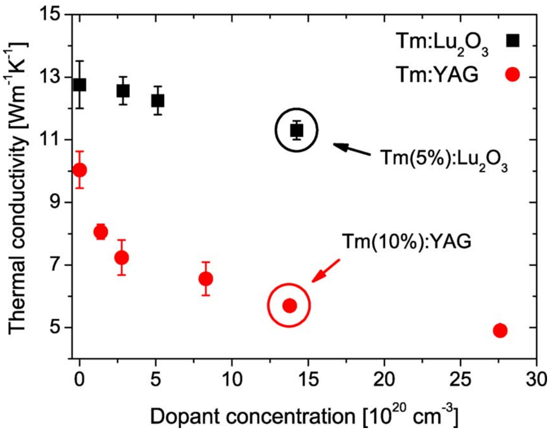

Fig. 1. (Color online) Thermal conductivity of $Tm:Lu_2O_3$ and Tm:YAG for different dopant concentrations. Note that the abscissa is given in $10^{20}\,cm^{-3}$ due to the different cation densities of Lu_2O_3 and YAG.

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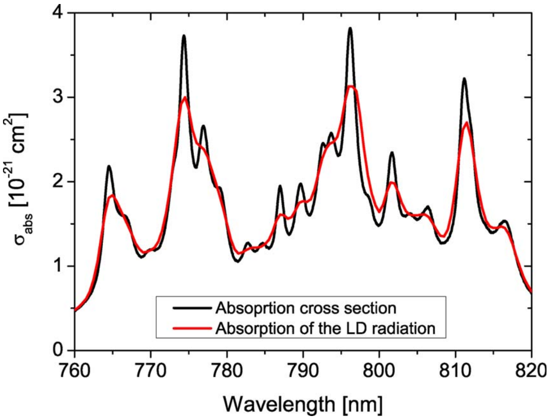

Fig. 2. (Color online) Room temperature absorption spectrum of $Tm:Lu_2O_3$ and calculated effective absorption spectrum of the laser diode radiation.

around 2070 nm. Starting at an inversion of 8%, maximum gain is found at 1965 nm. For inversions above 10%, the gain peak is located at 1942 nm.

The broad gain spectrum makes $Tm:Lu_2O_3$ a promising candidate for the generation of short pulses via mode locking. First results on this system have recently been reported by Schmidt *et al.* [8].

For the laser experiments a very simple and compact setup was chosen, which is depicted in Fig. 4. The fully collimated beam of a laser diode ($\lambda = 796\,\mathrm{nm}$, $P_{\max} = 110\,\mathrm{W}$) was focused directly onto the laser rod. The laser rod had an antireflective (AR) coating for the pump and a highly reflective (HR) coating for the laser wavelength on the incoupling side; therefore, this facet acted as one of the resonator mirrors. The outcoupling side of the laser rod was AR coated for the laser and HR coated for the pump wavelength, leading to a double pass of the pump light. The rods were fabricated from a 1 at.% doped $Tm:Lu_2O_3$ crystal boule that was grown by the heat exchanger method [5]. This relatively low dopant concentration was chosen to minimize the temperature of the incoupling facet. Previous experiments showed an efficiently operating cross relaxation at this dopant concentration [4]. The barrel polished laser rod was water cooled to 19 °C. Its length was 15 mm and three different diameters of 2 mm, 2.5 mm, and 3 mm were available. The plane output coupling mirror was placed as close to the laser rod as possible, leading to a resonator length of 17 mm. Thus, the cavity was stabilized by the thermal lens of the laser rod. Different output coupling transmissions T_{OC} between 0.8% and 23% were available.

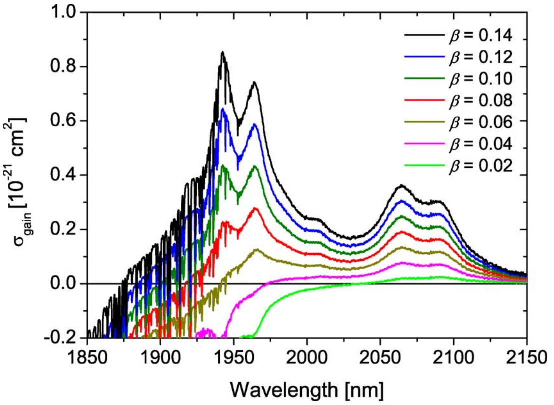

Fig. 3. (Color online) Gain spectrum of $Tm:Lu_2O_3$ for different inversions β.

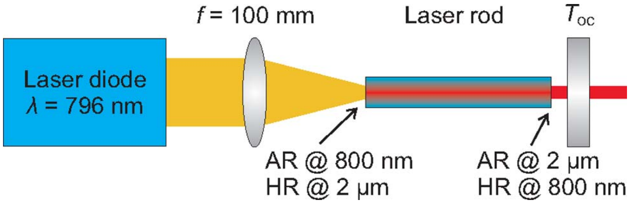

Fig. 4. (Color online) Resonator setup of the $Tm(1\%):Lu_2O_3$ laser. The resonator length was 17 mm.

The input–output curves for the 2.5 mm laser rod are shown in Fig. 5. As can be seen, the laser threshold is as low as 4 W, the maximum multimode output power is 41 W, and at 3.8% of output coupling the maximum slope efficiency is 42% with respect to the incident pump power. Since the crystal absorbed approximately 90% of the pump light, the slope efficiency with respect to the absorbed pump power is about 46%. For higher values of T_{OC} the slope efficiency decreases due to the increasing inversion and, therefore, increasing upconversion losses. The increasing inversion also leads to another effect: for low values of T_{OC} the laser wavelength is 2065 nm, for high values of T_{OC} the wavelength is 1965 nm. This is consistent with the expectations derived from the gain spectrum (Fig. 3).

The results achieved with the laser rod, which was 2 mm in diameter, were slightly inferior to those achieved with the 2.5 mm rod ($\eta_{\mathrm{sl,max}} = 41\%$, $P_{\max} = 39\,\mathrm{W}$).

For pumping the rod with $\varnothing = 3\,\mathrm{mm}$ in diameter two polarization-coupled laser diodes were used for achieving higher pump powers. The input–output curve for this setup with $T_{OC} = 7\%$ is shown in Fig. 6. As can be seen, a maximum output power of 75 W and a slope efficiency of 39% were achieved, but for a pump power of 220 W a thermal rollover was observed. Higher pump powers led to the destruction of the crystal.

For tuning the laser wavelength a 1 mm thick quartz plate was introduced into the resonator at Brewster's angle. Furthermore, the output coupling mirror was replaced by a curved mirror with a radius of curvature of 100 mm, which was placed 65 mm behind the crystal. An output coupling transmission of 0.8% was chosen. For

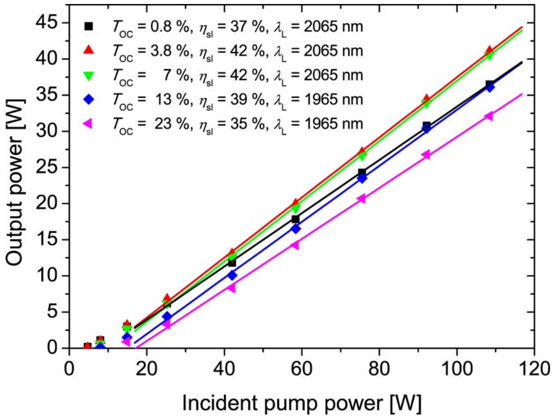

Fig. 5. (Color online) Input–output curves of the $Tm(1\%):Lu_2O_3$ laser ($\varnothing = 2.5\,\mathrm{mm}$) for different output coupling transmissions.

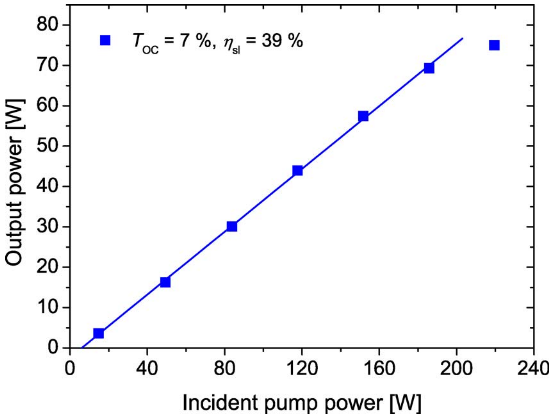

Fig. 6. (Color online) Input–output curve of the Tm(1%):Lu_2O_3 laser ($\varnothing = 3\,mm$) with $T_{OC} = 7\%$ and two polarization-coupled laser diodes as the pump source.

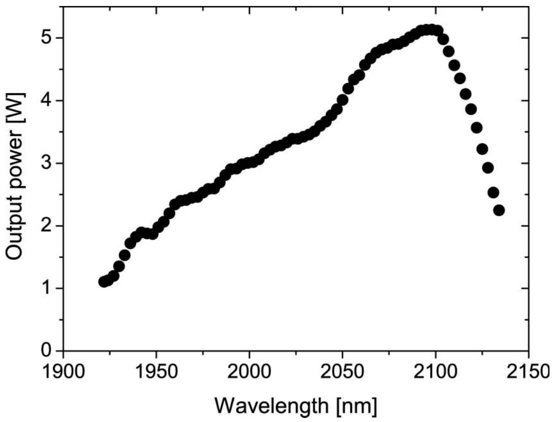

Fig. 7. Tuning curve of the Tm(1%):Lu_2O_3 laser for $T_{OC} = 0.8\%$.

this experiment the pump power was set to 23 W, since for higher pump powers an increase of the power, which was coupled out by the birefringent filter, could be observed. This is due to depolarization inside the laser crystal, which increases with increasing pump power. By turning the birefringent plate around its surface normal a continuous tuning range from 1922 nm to 2134 nm could be achieved with an output power of more than 1 W for the whole range, as shown in Fig. 7. At the ends of this curve the power does not drop to zero, but the laser starts oscillating at 1965 nm instead, with high output coupling losses at the birefringent filter. Here, the losses introduced by the birefringent filter are still too low to compensate for the high gain at 1965 nm. Therefore, with a different setup an even broader tuning range can be expected. In Ti:sapphire-pumped experiments a tunability down to 1900 nm has previously been shown [4].

In this work, the thermal conductivities of thulium-doped Lu_2O_3 and YAG were compared for different dopant concentrations. Furthermore, the effective absorption spectrum of a 1.8 nm FWHM laser diode and the gain spectrum of Tm:Lu_2O_3 were presented. In diode-pumped laser experiments a maximum output power of 75 W and a maximum slope efficiency of 42% with respect to the incident pump power were achieved. Depending on the output coupling, free running laser operation was observed at 2065 nm and 1965 nm, respectively. A tunability of the laser wavelength from 1922 nm to 2134 nm with an output power of more than 1 W for the whole range could be demonstrated.

In the future, laser experiments using Tm:Lu_2O_3 with higher dopant concentrations and other thulium-doped sesquioxides are planned.

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