

# Holmium-Doped Lutetia: A Novel Diode Pumped Laser at 2124 nm

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**Abstract:** We present the first 1.9  $\mu\text{m}$  diode pumped Ho:Lu<sub>2</sub>O<sub>3</sub> laser at room temperature with an output power of 15 W and an estimated optical-to-optical efficiency with respect to the absorbed power exceeding 50 %.

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## 1. Introduction

Laser systems with wavelengths in the spectral region around 2  $\mu\text{m}$  have a large field of applications in medicine, gas detection, LIDAR systems, and pumping of OPOs for the conversion into the mid-infrared spectral region [1]. This wavelength range is covered by thulium- and holmium-based lasers, while the wavelengths of most Tm<sup>3+</sup>-lasers are below and the wavelengths of Ho<sup>3+</sup>-lasers are above 2  $\mu\text{m}$ . Ho<sup>3+</sup>-ions exhibit the advantage of longer lifetimes and higher emission cross sections. Furthermore, around 2.1  $\mu\text{m}$  the absorption of water vapor is strongly reduced. Ho<sup>3+</sup>-ions can be inband pumped at around 1.9  $\mu\text{m}$ . Commonly thulium-lasers are applied as pump sources but direct diode pumping is desirable and recent development of laser diodes with wavelengths in the 1.9  $\mu\text{m}$  region makes this possible. The first diode-pumped Ho<sup>3+</sup>-laser was set up by Nabors et al., achieving a slope efficiency of 35 % and an output power of 0.7 W at a temperature of the Ho:YAG crystal of -53 °C [2].

Recently up to 55 W of output power were achieved with a diode pumped Ho:YAG laser. The slope efficiency with respect to the incident pump power was 62 % [3].

Due to their favorable thermal and spectroscopic properties, Yb- and Tm-doped sesquioxides have shown very efficient laser operation [4, 5] in recent years. However, due to their limited availability, little research has been performed on holmium-doped sesquioxides. Some spectroscopic data on Ho:Sc<sub>2</sub>O<sub>3</sub> and Ho:Y<sub>2</sub>O<sub>3</sub> are presented in [6].

First diode pumped laser experiments of holmium-doped Y<sub>2</sub>O<sub>3</sub> ceramics were carried out recently [7]. An output power of 2.5 W and a slope efficiency of 35 % were obtained at cryogenic temperatures.

Here we present first diode pumped laser operation of Ho:Lu<sub>3</sub>O<sub>3</sub> with a 0.3 % doped crystal which was grown by the Heat-Exchanger Method (HEM) [8]. An output power of 15 W was obtained at 2124 nm at an incident pump power of 150 W. Due to a low absorption efficiency the slope and the optical-to-optical efficiency with respect to the absorbed pump power are estimated to exceed 50 %.

## 2. Laser Setup

For the laser experiments a GaSb-based laser diode stack served as the pump source. It was not designed for the experiments presented here but for the Ho:YAG experiments described in [3].

The laser diode stack consisted of ten linear bars and delivered a pump power of up to 150 W. While the central wavelength of the diode spectrum shifted from 1890 nm at threshold to 1935 nm at maximum power its spectral bandwidth (FWHM) increased from 10 nm to 30 nm (see Fig. 1).

As shown in Fig. 2, the pump light was focused onto a Ho(0.3%):Lu<sub>2</sub>O<sub>3</sub> laser rod using an anti-reflective (AR) coated multi-lens focusing optic with  $f_{\text{tot}} = 20$  mm, creating a pump spot diameter of  $\sim 2$  mm. The laser rod was 2.5 mm in diameter and 20 mm in length. It was barrel polished to assure guiding of the pump light. Both facets were AR coated for pump and laser wavelength and it was water cooled to 18 °C. The resonator was formed by two plane mirrors, with the incoupling mirror placed as close to the laser rod as possible and the output coupling mirror 15 mm behind the

crystal's rear facet, leading to a resonator length of 37 mm. The resonator was stabilized by the thermal lens inside the crystal. Between the laser rod and the output coupling mirror a water cooled pinhole ( $\varnothing = 3$  mm) was placed which protected the mirror mount from heating up strongly, as it otherwise would have been irradiated by the non-absorbed pump light.

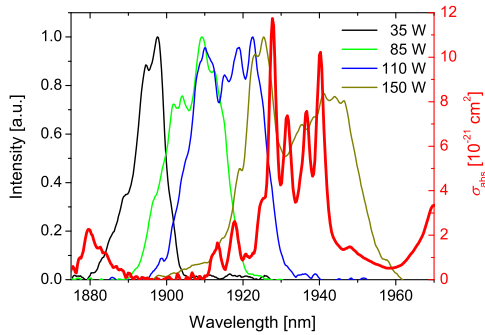


Fig. 1: Absorption spectrum of Ho:Lu<sub>2</sub>O<sub>3</sub> (red, thick) and emission spectra of the laser diode for different pump powers

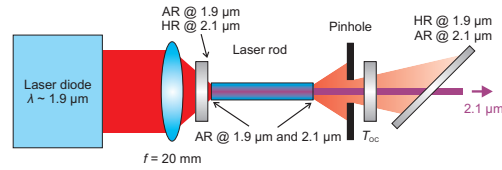


Fig. 2: Resonator setup for the diode pumped laser experiments. The water cooled pinhole prevents the mirror mount from heating up strongly.

Fig. 1 shows the Ho:Lu<sub>2</sub>O<sub>3</sub> absorption spectrum and the diode spectra for different pump powers. Because of the evident change of the overlap for different pump powers, the absorption efficiency was estimated in two different ways.

For calculating the absorption efficiency, the Lambert-Beer law was applied for every wavelength and the transmitted spectrum was determined theoretically. Saturation effects were not taken into account. By comparing the area of the input and the output spectrum the fraction of absorbed power was determined. The results of this calculation are shown in black squares in Fig. 3. It can be seen that with the described pump diode moderate absorption efficiencies can only be expected at high pump powers.

For another estimation of the absorption efficiency, the transmitted pump power was measured with removed output coupler for different pump power levels without lasing. The relative transmission is shown in blue circles in Fig. 3. For the regions of a small overlap of the absorption and the diode spectra a transmission of nearly 100 % is found. This indicates very small incoupling and guiding losses.

In Fig. 3 a strong deviation of the calculated and the measured transmission is found for high pump powers. While theoretically, according to the ground-state absorption cross sections, a relative transmission of less than 60 % is expected, due to strong bleaching effects a relative transmission of more than 80 % is measured.

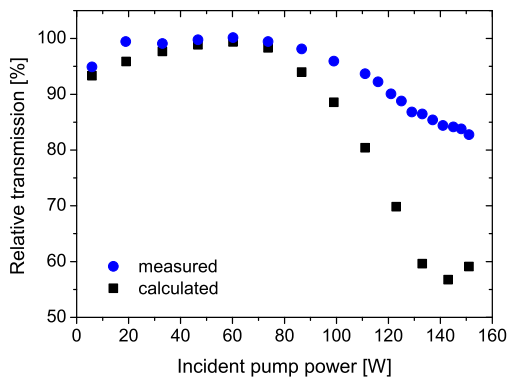


Fig. 3: Measured (blue circles) and calculated (black squares) relative transmission of the Ho:Lu<sub>2</sub>O<sub>3</sub> rod

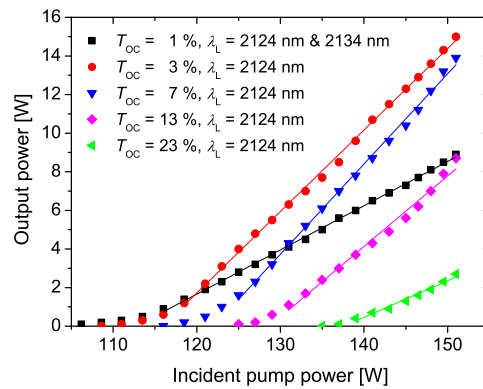


Fig. 4: Input output curves of the diode pumped Ho:Lu<sub>2</sub>O<sub>3</sub> laser

### 3. Results

Output coupling transmissions  $T_{OC}$  between 1 % and 23 % were chosen. The input output curves versus the incident pump power are shown in Fig. 4. At a maximum incident pump power of 150 W a maximum output power of 15 W was obtained with  $T_{OC} = 3\%$ . Due to the shift of the diode spectrum, the laser threshold is about 110 W of incident pump power. With respect to the measured single pass absorbed power the threshold pump powers were between 5.8 W ( $T_{OC} = 1\%$ ) and 19 W ( $T_{OC} = 23\%$ ). Only a rough estimation can be made for the absorbed pump power during laser operation. From Fig. 3 one can derive the fraction of absorbed pump power to be between 40 % (calculated, neglecting thermal and bleaching effects) and 17 % (measured without lasing, thus overestimating thermal and bleaching effects), leading to an optical-to-optical efficiency with respect to the absorbed pump power between 25 % and 59 %. Considering the strong deviation between calculated and measured absorption already at the threshold pump power levels apparent in Fig. 3, one can conclude that bleaching effects are strong. Consequently, the real optical-to-optical efficiency should be in the upper range of the estimated span. Using similar assumptions, the slope efficiency with respect to the absorbed pump power is estimated to be higher than 50 %. However, it should be noted that the curves in Fig. 4 are also affected by the strong change in absorption efficiency with increasing pump power. The laser wavelength was 2124 nm for all output coupling rates exceeding 1 %. At  $T_{OC} = 1\%$  the laser emitted at 2124 nm and 2134 nm simultaneously, with a higher intensity of the 2134 nm transition.

### 4. Conclusion

We grew a Ho(0.3%):Lu<sub>2</sub>O<sub>3</sub> crystal with the Heat-Exchanger Method. Using a 1.9 μm diode stack with 150 W of output power, the first diode pumped Ho:Lu<sub>2</sub>O<sub>3</sub> laser could be set up. At a wavelength of 2124 nm an output power of 15 W was obtained at room temperature. The optical-to-optical efficiency with respect to the absorbed pump power is estimated to be above 50 %.

Recent development of spectrally narrow laser diodes in the 1.9 μm range gives prospect to diode pumped Ho:s sesquioxide lasers with strongly enhanced absorption efficiencies in the near future.

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