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Efficient high-power Ho:YAG laser directly in-band pumped by a GaSb-based laser diode stack at 1.9 µm

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Abstract An efficient high-power Ho:YAG laser directly in-band pumped by a recently developed GaSb-based laser diode stack at 1.9 µm is demonstrated. At room temperature a maximum continuous wave output power of 55 W at 2.122 µm and a slope efficiency of 62% with respect to the incident pump power were achieved. For narrow linewidth laser operation a volume Bragg grating was used as output coupler. In wavelength stabilized operation a maximum output power of 18 W at 2.096 µm and a slope efficiency of 30% were obtained. In this case the linewidth is reduced from 1.2 nm to below 0.1 nm. Also spectroscopic properties of Ho:YAG crystals at room temperature are presented.

1 Introduction

Lasers operating in the 2-µm wavelength range offer exceptional properties which are exploited in many application fields such as medicine and material processing. These lasers are nominally eye-safe, which is an important condition e.g. for free space applications like sensing of atmospheric gases (H_2O, CO_2, N_2O) [1]. Another promising field is the nonlinear frequency conversion to the 3–12 µm spectral range via optical parametric oscillators (OPOs) based on ZGP. Even though it can be pumped at 2 µm, ZGP shows a reduced absorption at 2.09 µm [2]. Thus, Ho:YAG lasers are attractive candidates for efficiently pumping OPOs based on ZGP which provide very broad wavelength tuning ranges [3]. Recently published results of Tm-doped sequioxides show beneficial high-power laser operation at the exceptionally long wavelengths of 2.07 µm and even 2.12 µm [4, 5]. However, these crystals are not commercially available.

Many of these applications require not only high output powers but also call for spectral stability and narrow linewidth operation to achieve highly reliable systems. Due to the low quantum defect, in-band pumping of Ho:YAG lasers is a promising approach to achieve high output powers and high efficiencies in the 2-µm wavelength range. Very high efficiencies ($\eta_{\text{slope}} = 80\%$) using Tm-doped fiber lasers for in-band pumping of Ho:YAG lasers were reported [6, 7]. Also Tm-doped bulk lasers were used for pumping of the Ho $^5I_7$ manifold [8, 9]. However, these Tm lasers again are diode pumped at ∼800 nm leading to complex and cascaded setups with poor overall efficiencies.

In 1995, Nabors et al. demonstrated a GaInAsSb–InGaAsP–based diode-pumped Ho:YAG laser operating at −53°C with nearly 0.7 W of output power and a slope efficiency of 35% (with respect to the absorbed power) [10]. Laser operation was observed at temperatures of up to 60°C with strongly reduced output powers. Recently published work by Barnes et al. utilizes a volume Bragg grating (VBG) locked InGaAs-based pulsed laser diode which was additionally cooled to 5°C to emit at 1.9 µm for pumping Ho:YAG crystals [11]. However, the slope efficiency of this study was limited to 24%.

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Recently developed GaSb-based laser diode stacks show high output powers at 1.9 µm at room temperature. This feature makes additive wavelength stabilization via VBGs or temperature redundant. Thus, a more powerful and efficient pump process of the holmium ions in YAG is enabled even at room temperature.

In previous conference communications, we reported output powers at 2.1 µm exceeding 40 W with a 60 mm long Ho(0.5%):YAG rod [12, 13]. Here we present the improved results of the system. Optimizing the Ho:YAG crystal length to 52 mm and the dopant concentration to 1%, it was possible to upscale the output power to 55 W. This crystal showed an optimized absorption of the pump light in a double pass configuration. Additionally, wavelength stabilization of the Ho:YAG laser by a VBG leading to narrow linewidth operation is demonstrated.

2 Gain spectra at room temperature

In order to estimate the potential emission wavelengths for different inversions β of the Ho:YAG laser the gain spectra $\sigma_{\text{gain}}(\lambda)$ were calculated on the basis of the emission cross sections $\sigma_{\text{em}}(\lambda)$ and absorption cross sections $\sigma_{\text{abs}}(\lambda)$ (see Fig. 1). The inversion $\beta = \frac{N_2}{N_{\text{tot}}}$ is the number of the excited Ho^{3+}-ions in the $^5\text{I}_7$ manifold divided by the total number of Ho^{3+}-ions.

For this purpose the absorption spectrum was measured by a dual beam spectrophotometer (Varian Cary 5000, 0.5 nm resolution) and the emission spectrum was calculated via the McCumber theory [14]. Additionally it was calculated via the Füchtbauer–Ladenburg equation [15]. The required fluorescence spectrum was detected by a Fourier-transform spectrometer (Bruker Equinox 55). The top of Fig. 1 shows the absorption and emission cross sections of the long wavelength region which is relevant for the calculation of the gain cross sections which again can be seen at the bottom of Fig. 1.

For inversions above 10% gain can be found at 2.129 µm. The emission cross sections for this wavelength are 4×10^{-21} cm^2. When the inversion increases to 15% an additional gain peak appears at 2.122 µm where the emission cross section is 6.2×10^{-21} cm^2. At shorter wavelengths gain is expected for inversions of approximately 20%. In this case the gain spectrum shows two peaks with the same gain cross section at 2.09 µm and 2.096 µm. Here, the emission cross sections show the highest values of 12.9×10^{-21} cm^2 and 11.2×10^{-21} cm^2, respectively. Thus, for higher inversions the maximum gain is expected at 2.09 µm.

3 Pumping scheme

A recently developed GaSb-based laser diode stack consisting of 10 linear bars served as the pump source. The single emitters have a stripe width of 150 µm and a pitch of 500 µm. The rear facets are coated with a highly reflective (HR) double-stack of Si and SiO$_2$ films ($R > 95\%$) and the front facets are coated by a single layer of SiN ($R \approx 3\%$). Thanks to the low beam divergence (<45°) the pump light can be collected by state-of-the-art optics. The diameter of the pump spot was 2 mm. The stack was water cooled to 18°C and has a maximum continuous wave (CW) output power of 160 W.

The absorption spectrum of the Ho:YAG crystal shows several peaks in the 1.9 µm range which are addressed by the emission spectra of the diode stack (see Fig. 2). The colored lines show the emission spectra of the pump source for different output powers. The shift of the central wavelengths from the threshold to the maximum output power is 45 nm. At high output powers the FWHM is about 25 nm.

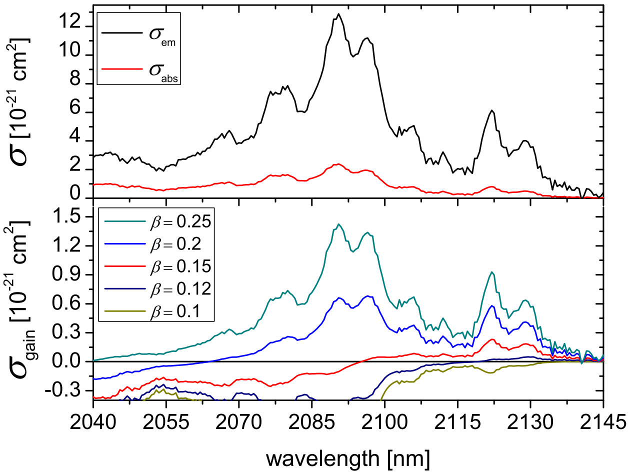

Fig. 1 Calculated gain spectra in the 2-µm region for different inversions β

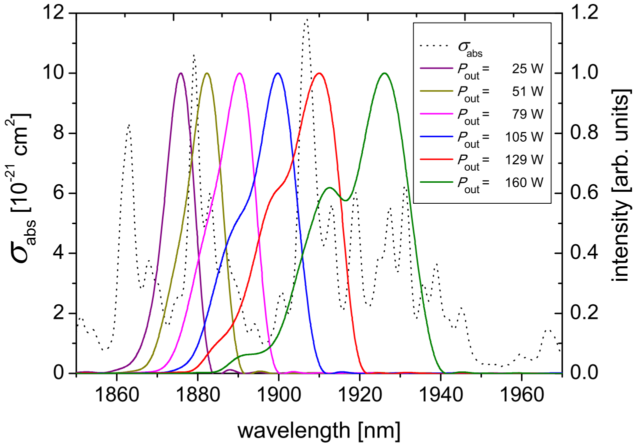

Fig. 2 Room temperature absorption cross sections (*dots*) and the normalized emission spectra (*colored*) of the laser diode stack for different output powers at room temperature

The absorption of two different lengths (3 mm diameter), 42 mm and 52 mm, of the anti reflective (AR) coated Ho(1%):YAG rods was studied. The rods were barrel polished for assuring guiding of the pump light by total internal reflection. Figure 3 shows the percentage of the single pass transmitted pump power for the different lengths. The 52-mm long rod transmits about 17% of the incident pump power for low pump powers and about 25% for high pump powers. The shorter rod transmits 25% for low and 32% for high pump powers. Both curves show a maximum at a pump power of 90 W where the transmission increases to 33% and 39%, respectively. Besides absorption, unknown guiding losses and in-coupling losses have to be taken into account which further reduce the transmitted pump power.

For a better insight on the absorption process the effective absorption coefficients α_{eff} were calculated on the basis of the overlap integrals of the diode output and Ho:YAG absorption spectra for different pump powers. The blue dots in Fig. 3 show the calculated absorption coefficient. For increasing pump powers the absorption coefficient decreases from $\sim 0.54\ \mathrm{cm}^{-1}$ to $\sim 0.25\ \mathrm{cm}^{-1}$ at 90 W of incident pump power because the diode shifts into a minimum of the Ho:YAG absorption at around 1.895 µm (see Fig. 2). If one assumed that these absorption coefficients represented the actual absorption the transmitted pump power could be calculated via the Lambert–Beer relation. However, the calculated values are lower than the measured percentages. This is not surprising since the calculated overlap integral is only true at the in-coupling facet. Due to the stronger absorption at the absorption peaks the pump spectrum changes while the pump beam propagates through the crystal and therefore the effective absorption coefficient decreases. Thus, guiding losses and in-coupling losses could not be determined.

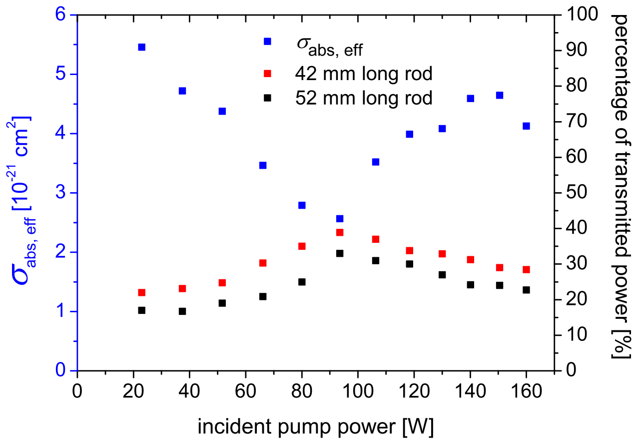

Fig. 3 Single pass transmitted pump power (*red*, *black*) and calculated effective absorption cross sections (*blue*)

When comparing the measured transmitted pump power for equal values of the calculated absorption coefficient at low and high pump power levels, a slight increase of the transmitted pump power can be found for high pump powers, which can be attributed to bleaching effects.

4 Laser experiments

The experimental setup of the Ho:YAG oscillator is shown in Fig. 4. For laser operation a compact plano–plano resonator was built up. The resonator mirrors were positioned as close as possible to the facets of the rods leading to a resonator length which is 3 mm longer than the rods. The pump light was focused onto the crystal surface with an AR coated optic leading to a pump spot diameter of 2 mm. The front and the rear facet of the rods were AR coated for the pump and laser wavelength. Both rods were water cooled to 18°C. The plane mirror M1 was AR coated for the pump wavelength and HR coated for the laser wavelength. The mirror M2 was also plane and served as the output coupling element. The transmitted pump light was extracted with the dichroic mirror M3. Five different transmission rates T_{oc} (5%, 7%, 10%, 18%, 33%,) were investigated (see Fig. 5). With 5% of output coupling 55 W of output power were achieved which is to our knowledge the highest CW output power of a Ho:YAG oscillator. The optical-to-optical efficiency was 34% and the corresponding slope efficiency was 62% with respect to the incident pump power. The slope efficiency decreased with higher output coupling rates because higher inversions were required for laser operation leading to higher up-conversion losses and a reduced absorption efficiency. Also the transmission rates of the output couplers at the pump wavelength increased with the output coupling rate from 3.5% to 60%. Thus, smaller fractions of the transmitted pump light are reflected back into the crystal for a second

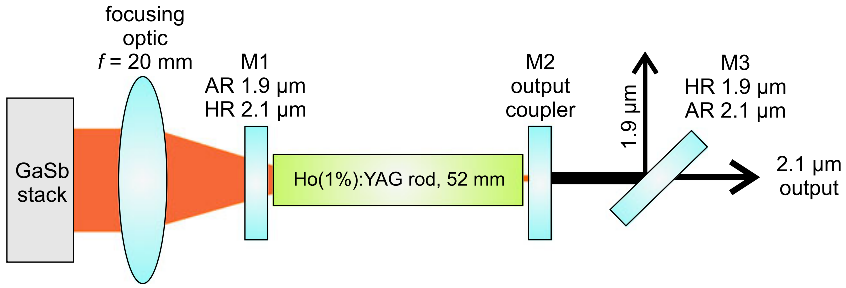

Fig. 4 Compact resonator formed by mirror $M1$ and mirror $M2$ (output coupler)

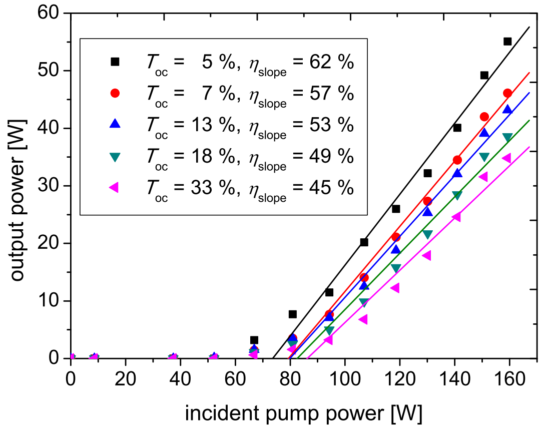

Fig. 5 CW laser performance of the 52-mm long Ho(1%):YAG rod at room temperature

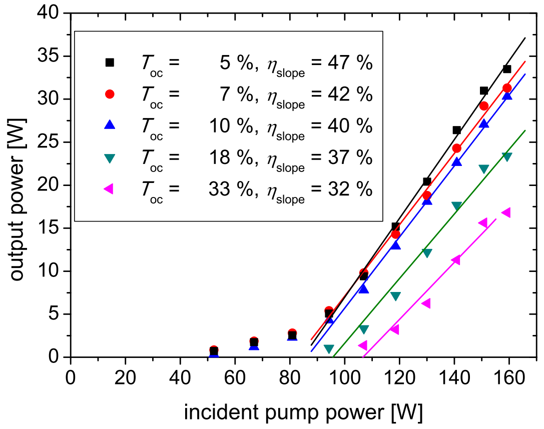

Fig. 6 CW laser performance of the 52-mm long Ho(0.5%):YAG rod at room temperature

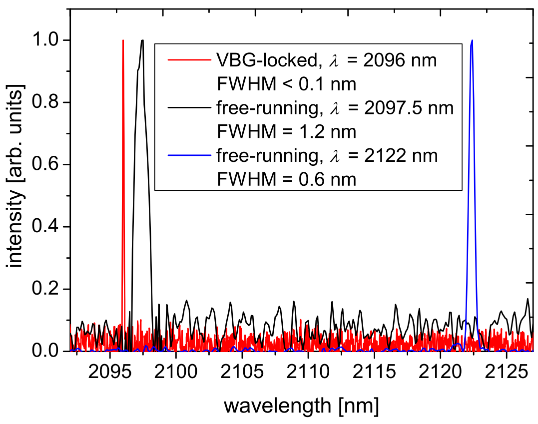

Fig. 7 Emission spectra of the Ho:YAG laser (52-mm long rod) at the highest output powers in free-running and VBG-locked operation

pass for higher output coupling rates. Nevertheless efficient laser operation was achieved with 33% of output coupling (see Fig. 5). This is extremely important for q-switched operation because the high output coupling rate minimizes the intracavity fluence on the surfaces of the optical components and thus avoids damage.

The poor spectral overlap at moderate pump intensities (see Fig. 2) leads to a relatively high laser threshold. At 67 W of pump power 3.2 W of output power were obtained which indicates a laser threshold well below this pump power.

Figure 6 shows the input-output curves of the 52-mm long Ho(0.5%):YAG rod at room temperature. Compared to the higher-doped rods the laser threshold is reduced to below 52 W of incident pump power. The maximum slope efficiency was 47% for 5% of output coupling. More than 33 W of output power were obtained. The lower slope efficiencies compared to the higher-doped crystal are due to the lower absorption in this rod. In non-lasing condition the transmitted pump power ranged from 35% to 55%. The higher output coupling rates of 18% and 33% showed a higher threshold of up to 100 W.

A 10-mm longer rod showed with the same dopant concentration a maximum output power of 41 W and a maximum slope efficiency of 55% while the threshold was slightly higher (57 W).

Laser experiments with the 42-mm long Ho(1%):YAG rod show a maximum output power of 40 W and a maximum slope efficiency of 45% while the laser threshold did not change significantly compared to the 52 mm long Ho(1%):YAG rod.

Recently published Tm:YLF laser-pumped Ho:YAG lasers show the same slope efficiencies but much more complex and cascaded experimental setups [8]. The high beam quality of their pump laser allowed a mode-matched pumping scheme even with long crystals, resulting in high beam quality ($M^2 \leq 1.2$). In this work we did not make any attempt to optimize the beam quality; ongoing work will address this matter. Currently we observe a highly multimode beam explained by the calculated Fresnel number of approximately 19 in our resonator configuration.

Figure 7 shows the emission spectra of the free-running Ho:YAG laser. When the transmission rates were 5%, 7%, 10% or 18% the wavelength was 2.122 μm (0.6 nm FWHM), which corresponds to the long wavelength region of the calculated gain spectra (see Fig. 1). For 33% of output coupling the wavelength was 2.097 μm (1.2 nm FWHM) which is also in accordance with the expectation made from Fig. 1.

For narrow linewidth operation a volume Bragg grating (OptiGrate, $8 \times 8 \times 5.5$ mm^3) was used as the output coupler and wavelength stabilization. Its reflectivity was 98% at 2.096 μm and it was AR coated for the pump and laser wavelength. In that configuration 18 W of output power and a slope efficiency of 30% were achieved. The threshold increased to 90 W because no pump light was reflected back into the crystal and high inversions are required. The emission wavelength in VBG-locked operation was 2.096 μm and the FWHM was significantly reduced to below 0.1 nm, limited by the resolution of the spectrometer (see Fig. 7, red line).

5 Summary

In conclusion, an efficient room temperature high-power Ho:YAG laser directly in-band pumped by a GaSb-based laser diode stack has been demonstrated. With 5% of output coupling 55 W of output power, limited by the available pump power, and a slope efficiency of 62% with respect to the incident pump power have been obtained with a 52-mm long Ho(1%):YAG rod. Different lengths (42 mm, 52 mm, 62 mm) and different dopant concentrations (0.5%, 1%) have been investigated.

For transmission rates above 30% the laser wavelength switched from 2.122 μm to 2.097 μm, which is in accordance with the calculations of the gain cross sections. Here, the maximum output power was 35 W and the slope efficiency decreased to 45% with the 52-mm long Ho(1%):YAG rod.

In VBG-locked operation at 2.096 μm 18 W of output power and a slope efficiency of 30% have been achieved. The FWHM was significantly reduced from 1.2 nm to below 0.1 nm.

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