Directly diode-pumped high-energy Ho:YAG oscillator

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We report on the high-energy laser operation of an Ho:YAG oscillator resonantly pumped by a GaSb-based laser diode stack at 1.9 μm. The output energy was extracted from a compact plano–concave acousto-optically Q-switched resonator optimized for low repetition rates. Operating at 100 Hz, pulse energies exceeding 30 mJ at a wavelength of 2.09 μm were obtained. The corresponding pulse duration at the highest pump power was 100 ns, leading to a maximum peak power above 300 kW. Different pulse repetition rates and output coupling transmissions of the Ho:YAG resonator were studied. In addition, intracavity laser-induced damage threshold measurements are discussed. © 2012 Optical Society of America

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Q-switched high-energy lasers operating in the nominally eye-safe 2 μm wavelength region are vital for applications in medicine, material processing, and lidar systems [1]. Regarding coherent light sources in the mid-IR spectral range, Q-switched 2 μm lasers are of great interest because they can be used to pump optical parametric oscillators (OPOs) based on ZGP or periodically poled GaAs [2], which allow for the generation of wavelengths ranging from 3 to 12 μm. Many of these applications call for wavelengths above 2 μm, e.g., ZGP shows a reduced absorption at 2.09 μm compared to 2 μm, leading to a higher conversion efficiency [2]. Thus, Ho-based lasers are ideally suited for these applications. Primary work was focused on Tm-sensitized Ho crystals (YAG, YLF), which can be diode pumped at ~800 nm. The pump light is absorbed by the Tm ions and then transferred to the Ho ions. When Q-switching such crystals, cooperative upconversion processes have to be taken into account that reduce the laser efficiency and thus the efficient extraction of high-energy laser pulses [2,3]. In recent years, codoped vanadate crystals were used for realizing Q-switched long-wavelength lasers, but these crystals require cryogenic cooling to operate efficiently [4]. These drawbacks can be avoided by in-band pumping of Ho-doped crystals, e.g., Ho:YAG [3]. More recently a high-energy (37 mJ) Ho:LLF laser was demonstrated [5]. Also, high-energy Ho-based master oscillator power amplifier (MOPA) systems delivering up to 330 mJ of pulse energy were reported [6–9].

However, these Ho systems were pumped by diode-pumped Tm-doped bulk or fiber lasers leading to bulky setups and poor overall efficiencies.

Direct in-band pumping with laser diodes around 1.9 μm is therefore an attractive alternative to develop simple and compact Ho:YAG laser systems with high efficiencies. Barnes *et al.* published a Q-switched Ho:YAG laser pumped by a pulsed InGaAs laser diode that was wavelength stabilized at 1.86 μm and cooled to 5 °C [10]. However, the quasi-cw slope efficiency and Q-switched pulse energy did not exceed 24% and 1 mJ, respectively. To date, no data have been published on high-energy and high-peak-power Ho:YAG lasers that are directly diode pumped. In our previous work, the cw operation of a diode pumped Ho:YAG laser was studied in detail. At room temperature, output powers of 55 W and slope efficiencies as high as 62% with respect to the incident pump power were achieved with a very simple and compact plano–plano resonator [11]. The pulse energy of the previous work was limited to a few millijoules due to damage of the optical components.

This work demonstrates damage-free high-energy operation of a diode-pumped Ho:YAG laser. For Q-switched operation, a new plano–concave cavity was designed, which is shown in Fig. 1. A GaSb-based laser diode stack, which was water cooled to 18 °C and delivered a maximum cw output power of 163 W, was used for pumping the Ho:YAG rod. The stack consists of 10 linear bars each with 19 single emitters. The shift of the center wavelength of the pump light spectrum from the threshold to the maximum output power is 45 nm, while the FWHM increases from 9 to 25 nm. Thus, several absorption peaks are addressed by the pump light (see inset of Fig. 2). A more detailed characterization of the pump source can be found in [11]. The pump light was focused onto the water-cooled (15 °C) Ho:YAG rod with an antireflective (AR) coated multilens optic leading to a pump spot that was ~2 mm in diameter. The rod was barrel polished for assuring guiding of the pump light by total internal reflection. Its length was 100 mm, and its diameter was 3 mm. The front and rear facet of the 0.5% Ho-doped rod were AR coated for the pump and laser wavelength. The transmission of

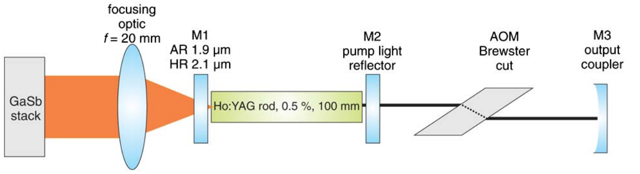

Fig. 1. (Color online) Resonator of the Ho(0.5%):YAG laser formed by mirror M1 and mirror M3 (output coupler). The resonator length was approximately 90 cm.

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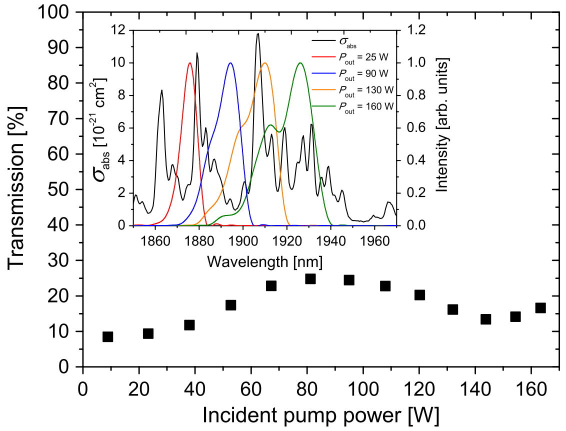

Fig. 2. (Color online) Single pass transmitted pump power. The inset shows the spectrum of the pump diode (colored curves) and the absorption cross section spectrum of Ho:YAG (black curve).

the pump light in the nonlasing condition was measured and is shown in Fig. 2. The relatively high transmission for ~90 W of incident pump power is due to the small overlap of the pump light spectrum with the Ho:YAG absorption spectrum at this pump power level (see inset of Fig. 2). The pump light reflector M2 reflected back the transmitted pump light leading to a double pass and thus a higher exploitation of the diode output. A fused silica Brewster-cut acousto-optic modulator (AOM) was used for Q-switched operation and ensured linear polarization. Its aperture is 5 mm, and the interaction length is 46 mm. The concave output coupling mirror M3 had a radius of curvature of $R = 500$ mm. With this curved mirror, the calculated TEM$_{00}$ laser mode radius was ~800 μm in the Ho:YAG rod. Especially for high-energy lasers, this is a very important aspect to consider in order to decrease the intracavity fluence and attain damage-free operation. Two different output coupling transmissions (41% and 50%) were used. Thanks to the high-emission cross section of Ho:YAG and the long crystal rod, it was possible to use these relatively high transmission rates to further minimize the intracavity fluence. Using the output coupling transmission T_{OC} of 50%, the maximum intracavity fluence was 3.6 J/cm^2. With $T_{OC} = 41\%$, this value reached 3.8 J/cm^2 in a damage-free operation. When exceeding this fluence, damage of the optical coatings was observed.

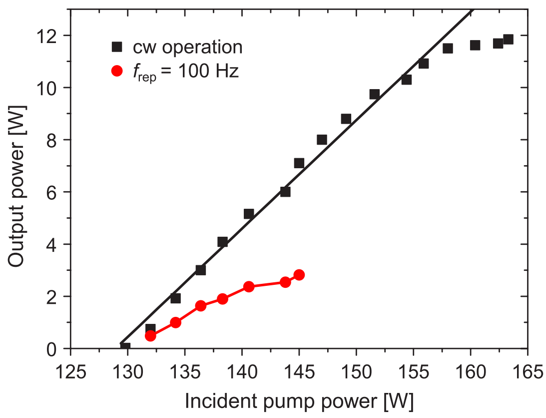

Fig. 3. (Color online) Input–output curves of the Ho(0.5%):YAG laser with $T_{OC} = 41\%$. In Q-switched operation, mirror M2 was damaged at an intracavity fluence of 4 J/cm^2.

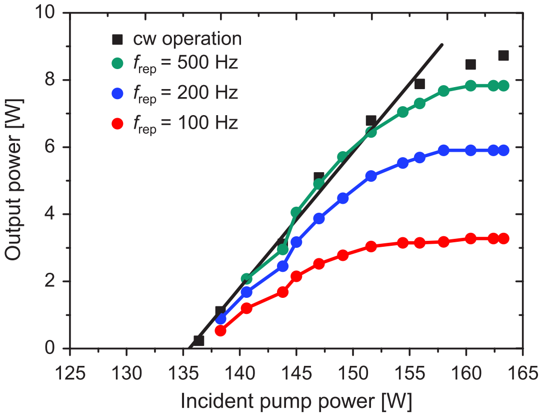

Fig. 4. (Color online) Input–output curves of the Ho(0.5%):YAG laser with $T_{OC} = 50\%$.

The input–output curves with $T_{OC} = 41\%$ are shown in Fig. 3. Both the cw operation output power and the measured average power in Q-switched operation can be seen. A maximum output power of 11.8 W and a slope efficiency of 42% were achieved. The small spectral overlap at moderate pump intensities and the voluminous Ho:YAG rod to be inverted led to a relatively high laser threshold [11]. For high pump powers ($P > 155$ W), a decreasing slope efficiency can be seen. This effect can probably be explained by the wavelength shift of the pump source (see inset, Fig. 2) and a decreasing resonator stability due to thermal lensing for high pump powers. For Q-switched operation, the AOM was activated and three different pulse repetition rates (500, 200, 100 Hz) were studied. Here, the pulse energy was limited by damage on the surface of mirror M2 at an intracavity fluence of 4 J/cm^2. At the 100 Hz pulse repetition rate, the maximum measured pulse energy was 28.2 mJ with a pulse duration of 100 ns. In this case the optical-to-optical efficiency was nearly 2%.

Figure 4 shows the cw operation output power and the measured average power in Q-switched operation with $T_{OC} = 50\%$. Increasing the output coupling transmission to 50% led to a maximum cw output power of 8.7 W and a slope efficiency of 36%. In addition, the threshold

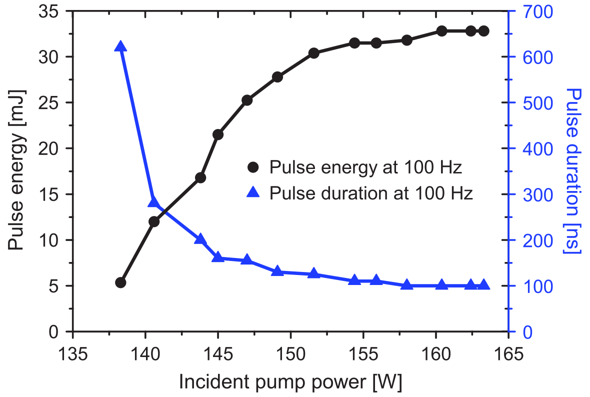

Fig. 5. (Color online) Pulse energy and corresponding pulse duration of the Ho:YAG oscillator at 100 Hz.

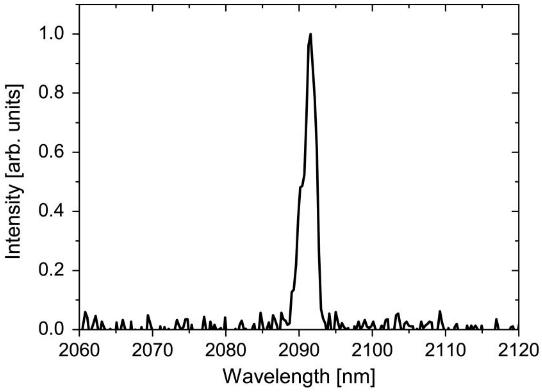

Fig. 6. Laser wavelength of the *Q*-switched Ho:YAG laser.

increased from 130 to 135 W due to higher cavity losses, which again result in higher inversions that are required for the laser operation.

Using the higher T_{OC}, damage-free high-energy operation was achieved. At the maximum pump power, pulse energies of 15.7, 29.5, and 33 mJ were achieved when the pulse repetition rate was 500, 200, and 100 Hz, respectively. Pulse durations of 200, 125, and 100 ns were obtained. For repetition rates of ~750 Hz the average output power was approximately as high as the cw output power. The optical-to-optical efficiency was 4.8%, 3.6%, and 2% with decreasing pulse repetition rates. Further, a strong decrease of the average power can be seen in Fig. 4 for repetition rates below 500 Hz. This effect can be attributed to bleaching effects of the crystal, which result in a reduced pump light absorption. Another reason for the decrease is the limited lifetime of the $^5I_7$ manifold of ~8 ms. Figure 5 shows the pulse energy and the pulse duration at 100 Hz.

The laser wavelength, which is centered at 2.09 μm with a FWHM of 2 nm, is depicted in Fig. 6. This laser wavelength did not change when the lower output coupling transmission was used.

In this Letter, a high-energy acousto-optically *Q*-switched Ho:YAG oscillator in-band pumped by a GaSb-based laser diode stack was demonstrated. With 50% of output coupling, pulse energies of 33, 29.5, and 15.7 mJ were achieved at 100, 200, and 500 Hz pulse repetition rates, respectively. The shortest pulse durations for each repetition rate were 100, 125, and 200 ns. The laser wavelength was centered at 2.09 μm, and the FWHM was 2 nm. The intracavity damage threshold was measured to be 4 $\mathrm{J/cm^2}$. Damage-free operation was possible up to 3.8 $\mathrm{J/cm^2}$ of intracavity energy fluence. For high-energy and high-peak-power applications, the demonstrated diode-pumped Ho:YAG laser is a promising attractive compact alternative to Ho:YAG lasers pumped by diode-pumped Tm-based lasers.

Future work will be focused on the development of a compact diode-pumped Ho:YAG MOPA system.

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