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Resonantly pumped high power acousto-optical Q-switched Ho:YAG ceramic laser

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ABSTRACT

We demonstrated a high power acousto-optical Q-switched Ho:YAG ceramic laser operating at 2090.5 nm that was pumped at 1908 nm by a Tm:YLF laser. A maximum continuous wave power of 22.6 W was obtained, which corresponds to a slope efficiency of 50.6% and an optical-to-optical efficiency of 47.6% with respect to the absorbed pump power. For the Q-switched mode, to our best knowledge, the maximum average output power of 21.2 W was achieved with a minimum pulse width of 20 ns at a pulse repetition frequency of 10 kHz, corresponding to an energy of 2.12 mJ per pulse and a peak power of 106 kW.

1. Introduction

Solid-state lasers based on Ho^{3+} ions operating in the 2 μm eye-safe spectral region are of great interest for applications in spectroscopy, medicine, wind lidar, remote sensing [1,2]. In particular, high power 2 μm Q-switched lasers play an important role for the purpose to pump the optical parametric oscillators (OPOs) to obtain the high power mid-IR lasers [3,4]. In recent years, polycrystalline ceramics as new laser gain media have drawn much attention due to a variety of important advantages over single crystals, such as low cost, extreme flexibility in doping concentration profile, ease of fabrication and conveniently in large volume [5–7]. With the progress in fabricated technology, scattering losses of the ceramics are not significantly larger than that of single crystals so that ceramics are comparable to the corresponding single crystals for producing lasers. Efficient laser oscillation operating at 1 μm wavelength region, which was produced by the Nd-doped [8,9] and Yb-doped YAG ceramics [10,11] have been widely investigated. As for ceramic lasers emitting at 2 μm, Tm^{3+},Ho^{3+} codoped polycrystalline YAG ceramics and Ho^{3+} doped ceramics have been used as the gain media. A maximum output energy of 40 mJ was obtained from the Tm,Ho:YAG ceramic that was pumped by diode lasers at 787 nm, corresponding to a pulse width of 150 ns and a pulse repetition rate (PRF) of 10 Hz [12]. Ho:Y_2O_3 ceramic laser with a maximum output power of 2.5 W was demonstrated in the continuous wave (CW) regime, and a slope efficiency of 35% with respect to absorbed power was obtained [13]. Ho:YAG ceramic as a promising candidates for producing 2 μm wavelength have also been widely studied in CW and Q-switched regimes. 21.4 W CW output power at 2097 nm was achieved under the maximum incident pump power of 35 W that was pumped at 1907 nm by a Tm:fiber laser, and the slope efficiency was 63.6% with respect the incident pump power [14]. A tunable active Q-switched Ho:YAG ceramic laser at 2097 nm pumped by a Tm:YLF laser at 1908 nm was demonstrated [15]. A maximum pulse energy of 10.2 mJ was achieved at a PRF of 100 Hz, and the maximum average power of 1.9 W was obtained at a PRF of 200 Hz. As for passive Q-switching, a Ho:YAG ceramic laser with a grapheme saturable absorber was demonstrated [16]. With this grapheme saturable absorber, a maximum average output power of 264 mW at the maximum PRF of 64 kHz was obtained under 3.27 W pump power, corresponding to a 9.3 μJ pulse energy and a minimum pulse width of 2.6 μs.

Compared to the results obtained in [15] and [16], to our best knowledge, we realized a maximum average output power Q-switched Ho:YAG ceramic laser in this paper. Up to 21.2 W average output power was achieved at a PRF of 10 kHz with a pulse width of 20 ns, corresponding to a pulse energy of 2.12 mJ and a peak power of 106 kW.

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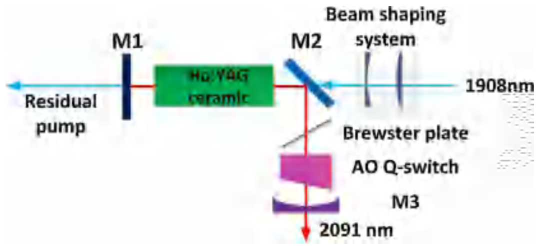

Fig. 1. Experimental setup of the Q-switched Ho:YAG ceramic laser.

2. Experiment setup

Fig. 1 shows the experimental configuration. A Tm:YLF laser operating at 1908 nm was used as the pump source. The incident pump was focused to a 0.34 mm spot diameter on the center of the Ho:YAG ceramic with −195 mm and 75 mm optical lenses. The maximum pump power incident on the Ho:YAG ceramic media was 64 W. Ho:YAG ceramic of 1% Ho^{3+}-doping with dimensions of 1.5 mm × 3 mm × 16 mm was used in our experiment. The two end surfaces of the Ho:YAG ceramic were anti-reflection coated at both 1900 nm and 2100 nm. The Ho:YAG ceramic was wrapped with indium foil and mounted in a copper heat sink with circulating water. The temperature of the Ho:YAG ceramic was controlled at 15 °C for efficient heat removal.

An L-shaped plano-concave cavity was employed in the experiment. The plane mirror M1, was antireflection (AR) coated (T > 99.7%) for the pump laser, and highly reflective (HR) for the 2 μm laser (R > 99.8%). The 45° flat dichroic mirror M2 was HR for the 2 μm laser (R > 99.8%) and AR-coated (R > 98%) for the pump radiation. M3 was the output coupler, and the laser performance with different transmissions (100 mm radius of curvature) was investigated. The total physical length of the resonant cavity was 142 mm. For the Q-switched operation, an acousto-optic modulator (AOM) (QS041-10M-HI8, Gooch & Housego) was employed inside the resonator. The radio frequency (RF) was 41 MHz, and the RF power was 28 W. A 0.05 mm thick uncoated YAG etalon was utilized as a Brewster plate to achieve a polarized output to match the polarized requirement for the AOM.

3. Experiment results and discussion

The CW output power and average power at a PRF of 10 kHz using different transmission of output couplers were investigated. During laser emission, the single-pass absorption of Ho:YAG ceramic at the pump wavelength was measured about 0.74. Fig. 2(a) shows the CW output power as functions of absorbed pump power with different output couplers. We can conclude that the best result

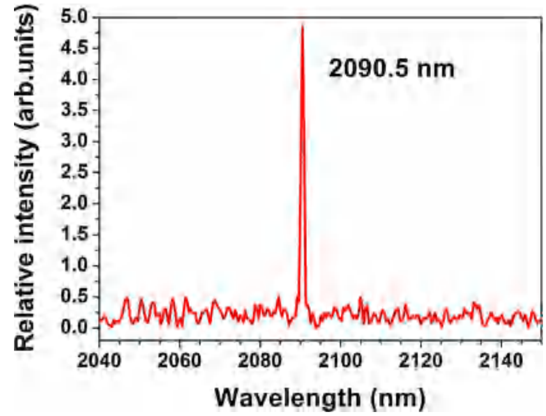

Fig. 3. Output spectrum of the Ho:YAG ceramic laser in CW operation.

was obtained with the output coupler of 50% transmission. The maximum CW output power was 22.6 W, corresponding to a slope efficiency of 50.7%, an optical to optical efficiency of 47.6% with respect to the absorbed pump power. With the output couplers of 30% and 40% transmission, the maximum CW output power were 19.7 W and 18 W, with slope efficiencies of 42.0% and 43.8%, and optical to optical efficiencies of 38.9% and 40.4%, respectively.

Fig. 2(b) shows the laser performance achieved during a Q-switched operation at a PRF of 10 kHz. A maximum average output power of 21.2 W and a slope efficiency of 49.6% were achieved with the output coupler of 50% transmission. With the output couplers of 30% and 40% transmission, the maximum average output power were 18.7 W and 16.9 W, corresponding to the slope efficiencies of 41.1% and 42.4%, respectively.

Output spectrum with the output coupler of 50% transmission is shown in Fig. 3. The spectrum was recorded by a Bristol 721A IR spectrum analyzer. The laser wavelength was centered at 2090.5 nm with a FWHM (full width at half maximum) of about 0.9 nm.

More laser performance details with the output coupler of 50% transmission in the Q-switched regime was researched in this paper. The output pulse energies and pulse widths of the Q-switched Ho:YAG ceramic laser are shown in Fig. 4. The Q-switched laser pulses versus the absorbed pump power at PRFs of 10, 20 and 30 kHz were measured by an InGaAs photodiode. At a PRF of 10 kHz, we achieved a maximum output energy of 2.12 mJ. The pulse duration demonstrates a steady decrease with the absorbed pump power up to values of 20 W, ending around 20 ns. The pulse energy keeps increasing with the increase of the absorbed pump power.

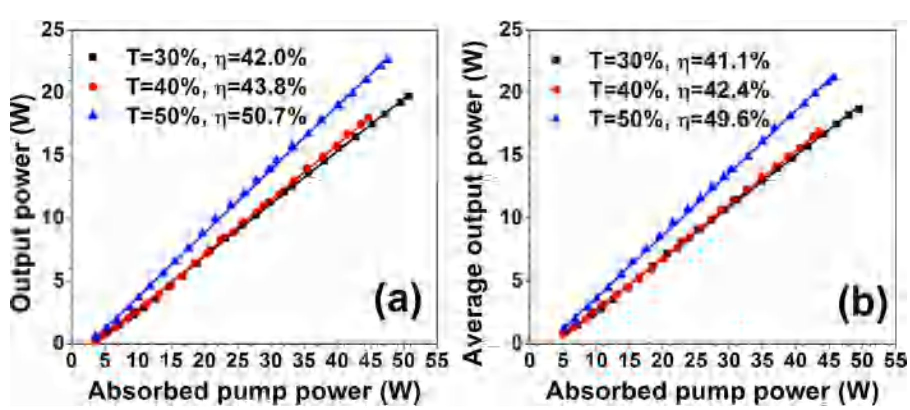

Fig. 2. Output power of (a) CW and (b) Q-switched Ho:YAG ceramic laser.

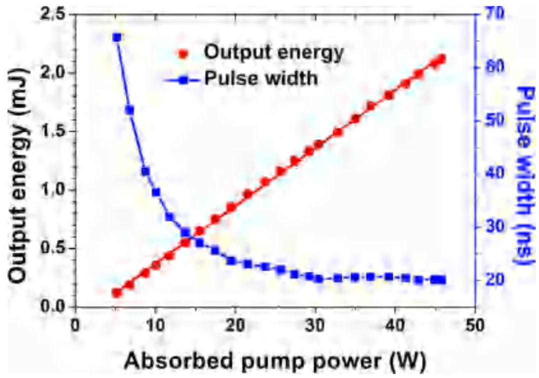

Fig. 4. Pulse widths and pulse energies at a PRF of 10 kHz.

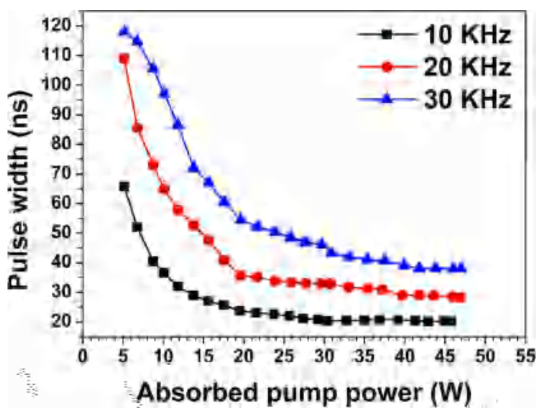

Fig. 5. Pulse widths versus the absorbed pump power.

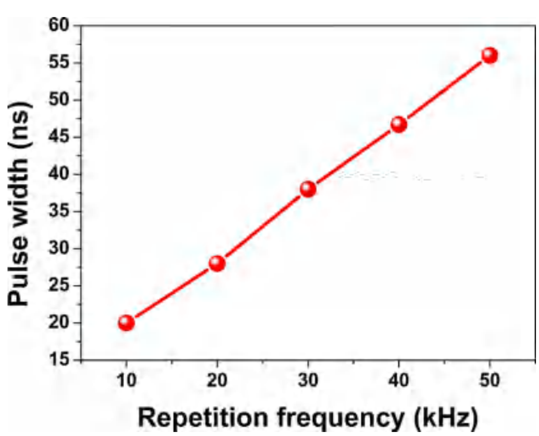

Fig. 6. Pulse widths versus the PRF.

The dependence of the laser pulse widths on the absorbed pump power between PRFs of 10, 20 and 30 kHz are compared and shown in Fig. 5. The pulse width shortens sharply as the absorbed pump power increases. As a result, when the absorbed pump power was over 40 W, minimum pulse widths of 20, 28 and 38 ns were obtained at the PRFs of 10, 20, and 30 kHz, respectively.

The pulse widths of 40 and 50 kHz were also recorded at the maximum incident pump power of 64 W, corresponding to the pulse widths of 46.7 and 56 ns, respectively. Fig. 6 shows the relationship between the minimum pulse widths and the PRF at the maximum incident pump power of 64 W. We can conclude that the minimum pulse width is almost linear with the increase of the PRF in the Q-switched mode.

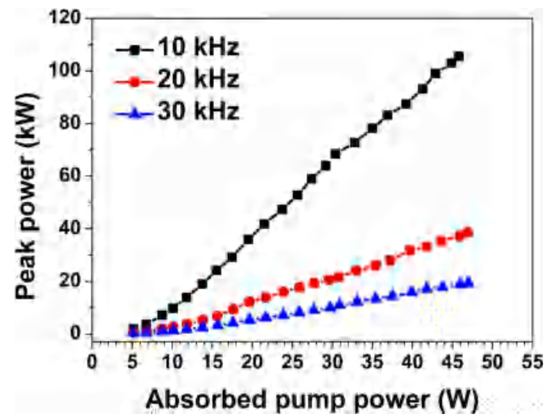

Fig. 7. Peak power versus the absorbed pump power.

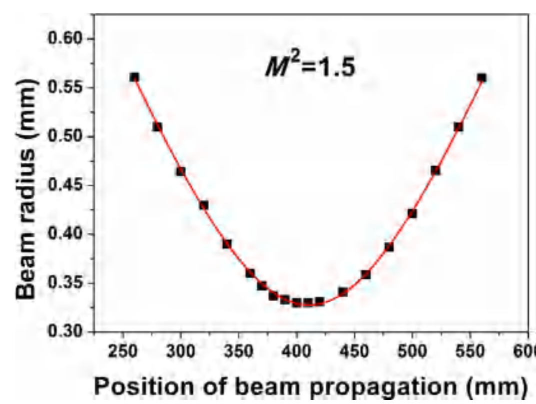

Fig. 8. Beam propagation of Q-switched Ho:YAG ceramic laser.

The peak powers of the Q-switched Ho:YAG ceramic laser obtained in the PRFs of 10, 20 and 30 kHz are compared and shown in Fig. 7. The peak power increased linearly with the increase of the absorbed pump power. The maximum peak powers of 106, 38.5 and 19.2 kW were achieved at the PRFs of 10, 20 and 30 kHz, respectively.

The output beam radius at 22.6 W as a function of distance behind a focusing lens of 150 mm was measured with knife edge method. Fig. 8 shows the measured beam radii along the beam propagation and the beam quality was estimated to be $M^2 = 1.5$.

4. Conclusion

In summary, we have demonstrated a high pulse repetition frequency Q-switched Ho:YAG ceramic laser in band pumped by a Tm:YLF laser. We achieved an average power of 21.2 W with a minimum pulse width of 20 ns at a pulse repetition frequency of 10 kHz, corresponding to an energy of 2.12 mJ and a peak power of 106 kW. The maximum output power of continuous wave was 22.6 W with a slope efficiency of 50.6% and an optical to optical efficiency of 47.6% with respect to the absorbed pump power. The beam quality factor of $M^2 = 1.5$ was obtained with the knife-edge method.

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