A 52-mJ Ho:YAG Master Oscillator and Power Amplifier with Kilohertz Pulse Repetition Frequency *

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(Received 17 June 2014)

We report on a high energy, high repetition rate Ho:YAG master oscillator and power amplifier (MOPA), resonantly dual-end-pumped by Tm:YLF lasers at room temperature. At the pulse repetition frequency of 1 kHz, we demonstrate a maximum energy of 30 mJ per pulse with a 28.2 ns pulse width in a Ho:YAG oscillator system resonantly double-end-pumped by Tm:YLF lasers. A maximum energy of 52 mJ per pulse with a 30.5 ns pulse width is achieved in the Ho:YAG amplifier, corresponding to a peak power of approximately 1.7 MW. The output wavelength is at 2090.6 nm and 2096.9 nm, and a beam quality factor of M^2~2.1 is achieved.

PACS: 42.60.Da, 42.60.Gd, 42.55.Xi DOI: 10.1088/0256-307X/31/9/094201

Solid state lasers operating in the nominally eye-safe 2 μm wavelength region are vital for applications in medicine, material processing, lidar systems,[1,2] and mid-infrared radiation with the structure of optical parametric oscillators (OPOs) based on ZGP or periodically poled GaAs.[3] 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 conversation efficiency.[3] Thus it is quite acceptable to use Ho-doped lasers in these applications.[4−6] With the Ho ions directly pumped, there are a lot of advantages, such as decreased gain sensitivity with temperature, reduced upconversion losses, reduced number of quantum defects, elevated shortpulse light efficiency, and elimination of energy transfer. Solid state lasers doped with Ho ions are especially suitable for Q-switched working, due to the fact that the upper laser level lifetime is relatively long.[7] Due to these advantages, Ho-doped lasers with high energy and high average power output are achievable.

For high energy output, through a master oscillator and power amplifier (MOPA) system at 100 Hz, Schmidt *et al.* achieved 125 mJ with a gain medium of Ho:YAG.[8] Dergachev *et al.* used a Ho:YLF laser operating at 100 Hz with the structure of the MOPA system, and obtained a 170 mJ pulse energy.[9] Schellhorn *et al.* acquired a 103.6 mJ pulse energy at a repetition rate of 100 Hz through a Ho:LLF MOPA.[10] As the laser host, YLF and YAG both are commonly used. Unlike YLF, there are many advantages of YAG crystal, such as better mechanical properties and higher thermal conductivity. What is more, good quality YAG crystals grow easily.[3] Thus we choose Ho:YAG as the working medium in our experiment. For high repetition output, through a Ho:YAG oscillator, Shen *et al.* have obtained a 101 W average output power at 30 kHz.[11] However, to achieve an output with both high repetition rate and high energy is rather difficult. Using the MOPA structure in Ho:YAG laser, Yu *et al.* have demonstrated 30 mJ output energy at 1 kHz.[12] A higher energy output at a high repetition rate is still needed for pumping the ZGP OPO. However, a higher energy output in Ho:YAG laser at the pulse repetition frequency (PRF) of 1 kHz has not been reported.

In this work, we demonstrate a maximum energy of 52 mJ per pulse with a 30.5 ns pulse width at 1 kHz in a Ho:YAG MOPA system resonantly double-end-pumped by Tm:YLF lasers at room temperature. The output wavelength is at 2090.6 and 2096.9 nm, and peak power reaches approximately 1.7 MW corresponding to a beam quality of M^2~2.1. To our knowledge, this is the highest energy result at the PRF of 1 kHz from a Ho:YAG laser.

The schematic diagram of the MOPA system is shown in Fig. 1. The first part is an oscillator. Two identical diode-pumped Tm:YLF lasers with an emission wavelength of 1.91 μm and a maximum output power of 93.9 W were utilized as the pump source, which had a beam quality of M^2~1.8. For the two pumps, one is s-polarized while the other is p-polarized. The thin-film polarizer (TFP) is HR for the s-polarized pump and HT for the p-polarized pump. Two TFPs were employed in the amplifier to avoid the Tm:YLF lasers being influenced by each other. The Tm pump beam radiation was focused by a telescopic lens system to a $1/e^2$ diameter of 1.2 mm inside the Ho:YAG rod. Ho:YAG crystal was obtained by the

*Supported by the National Natural Science Foundation of China under Grant No 61308009, the China Postdoctoral Science Foundation under Grant No 2013M540288, and the Fundamental Research Funds for the Central Universities under Grant No HIT.NSRIF.2014044.

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Czochralski technique. It was 45 mm in length, 5 mm in diameter, and 0.8 at% in Ho^{3+} concentration, whose two end faces were a dual wavelength anti-reflection coating for the laser wavelength around 1.9 μm and 2.1 μm. The absorption coefficient of the Ho:YAG crystal was about 0.56 cm^{-1} at 1.91 μm, which means that nearly 92% of the pump laser was absorbed by the crystal. The crystal was wrapped in indium foil and clamped in a copper heatsink held at a temperature of 18℃ with a thermoelectric cooler (TEC). The physical cavity length of the Ho:YAG oscillator was 260 mm, and the focal length of crystal thermal lens was 580 mm; the TEM00 beam diameter in the crystal was calculated to be 1.0 mm. In our experiment, the plane mirror (M1) was HT ($T > 99.8\%$) at 1.9 μm and HR ($R > 99.5\%$) at 2.1 μm. The 45° dichroic mirror (M2) was HT ($T > 99.6\%$) at 1.9 μm and HR ($R > 99.7\%$) at 2.1 μm. The output coupler (M3) had a 5000 mm curvature radius with a transmission of 68% at 2.09 μm. For a polarized output, we used a Brewster plate, which was achieved by the F–P etalon. The laser was Q-switched by a 50-mm-long fused silica acousto-optical (A-O) modulator (MQH041-100DM-A05, Gooch & Housego) whose maximum rf power was 100 W and the frequency range was from 100 Hz to 50 kHz. The output of the oscillator served as the signal of the amplifier.

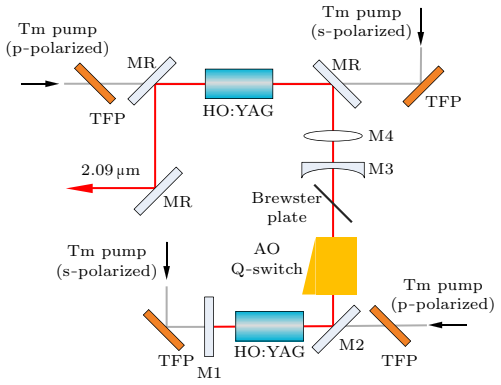


Fig. 1. Structure of the experimental setup for Ho:YAG MOPA.

The second part is an amplifier. Two identical Tm:YLF lasers were employed as the pump source with emission wavelengths of 1.91 μm and total maximum output powers of 79.7 W. Like the pumping structure of the oscillator, two TFPs were used to avoid the two Tm:YLF lasers being influenced by each other. Ho:YAG crystal in the amplifier was a 60-mm-long composite rod with two 5-mm-long undoped ends and 5 mm in diameter with 0.5 at% concentration. The absorption coefficient of Ho:YAG in the amplifier was about 0.41 cm^{-1}, implying nearly 87.2% pump absorption. The crystal was wrapped in indium foil and clamped in a copper heatsink held at a temperature of 18℃ by a TEC. The shifted diameters of the pumps and the signal were all 1.2 mm in the amplifier crystal.

The output power of Ho:YAG oscillator is shown in Fig. 2. Under continuous wave (cw) mode, the maximum output power of 32.9 W was achieved under the incident pump power of 93.9 W, corresponding to an optical-to-optical efficiency of 35% and a slope efficiency of 52.26%. Under the Q-switched operating mode, at 1 kHz of the pulsed repetition frequency, we obtained as much as 30 W for the average output power versus the incident total pump power of 93.9 W, which means that the maximum pulse energy was 30 mJ. After operation for a few minutes, the output energy was still stable and optical damage was not observed. At the limit of the total pump power, a higher output energy was not achieved. Though the optical damage occurs at even a slightly higher output energy, it can still be avoided, in the future, at higher output energy through optimizing the laser radius in the cavity and the pump beam radius at higher total pump power.

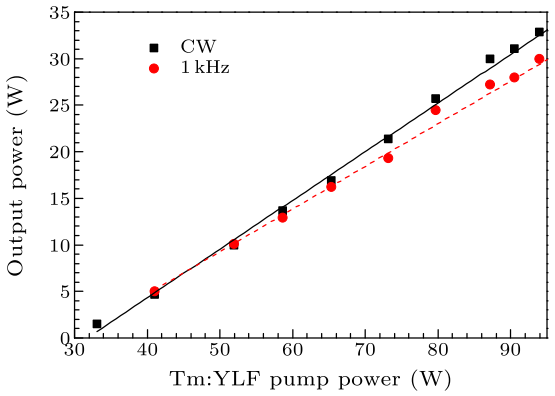


Fig. 2. The average output power of the oscillator.

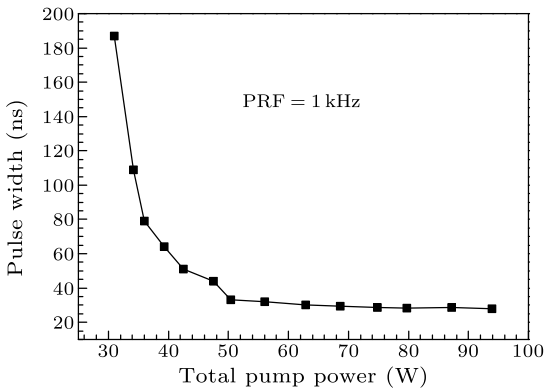


Fig. 3. The pulse width versus the total incident pump power.

An InGaAs detector connected to a digital oscilloscope (Lecroy Wavesurfer 64 Xs) was employed in our experiment for signal detection. Figure 3 shows the pulse duration and demonstrates a steady reduction with the incident total pump power up to 50 W as well as a nearly constant value of about 30 ns with the total pump power ranging from 50 W to 93.9 W.

At the PRF of 1 kHz, we obtained the minimum pulse width of 28.2 ns, and the peak power was 1.06 MW when the total pump power was 93.9 W. For the output energy, the stability was recorded over 60 min at an average energy of 28 mJ, as shown in Fig. 4, and a fluctuation of ±2.25 mJ was achieved, corresponding to a stability of 8%.

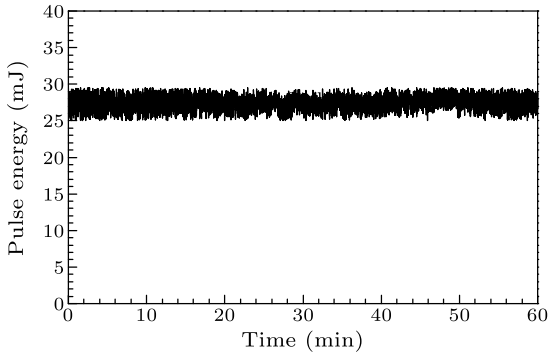


Fig. 4. Pulse stability of the output energy.

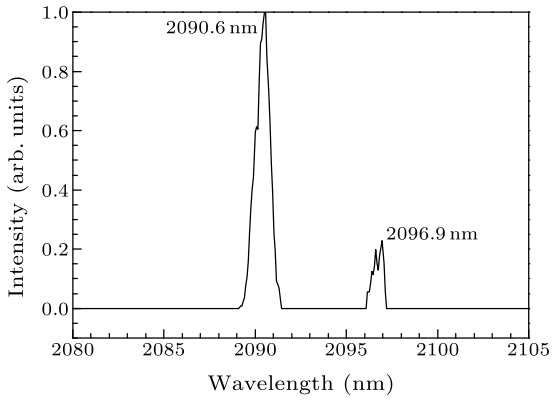


Fig. 5. Wavelength profile of the Ho:YAG oscillator.

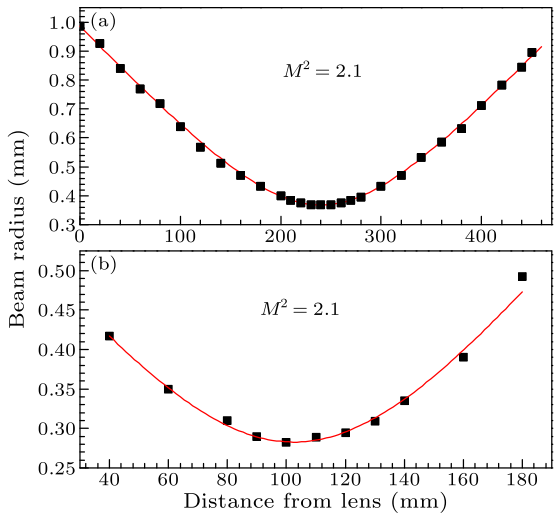


Fig. 6. (a) Beam quality profile of the Ho:YAG oscillator, and (b) beam quality profile of the Ho:YAG amplifier.

Using a single-grating monochromator (WDM1-3, BOIF) to scan the output wavelength of the Ho:YAG oscillator, the laser signal was recorded by an InGaAs detector and processed by an SRS-830 lock-in amplifier. As illustrated in Fig. 5, the Ho laser in Q-switched operation reveals two simultaneously lasing emissions, 2090.6 nm and 2096.9 nm. The intensity was mainly concentrated at 2090.6 nm. We measured the output beam propagation by measuring the beam radius with a 90/10 knife-edge technique at several positions through a 150 mm focal length lens as shown in Fig. 6(a). By fitting the Gaussian beam standard expression to these data, the fit yields $M^2 = 2.1$.

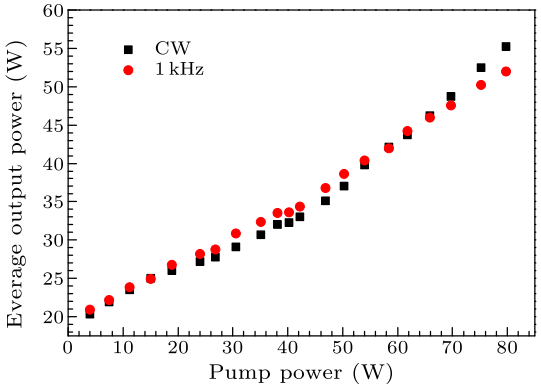


Fig. 7. The average output power of the amplifier.

For a Ho:YAG amplifier, the output energy as a function of the 1.91 μm pump power with the 2.09 μm signal energy fixed at 30 mJ is illustrated in Fig. 7. Under cw operation, the maximum output power of 55.2 W was achieved under a total incident pump power of 79.7 W. Under the Q-switched operating mode, at the PRF of 1 kHz, we obtained as much as 52 W for the average output power versus the incident total pump power of 79.7 W, which means that the maximum pulse energy was 52 mJ, and the beam quality was calculated to be $M^2 \sim 2.1$. As we can see, the slope efficiency during the earlier half of the total pump power was lower than the slope efficiency during the latter half. This can be explained by the pump strategy during the operation. During the earlier 40 W, the increased pump power was contributed by only one Tm:YLF laser injected from one side of the amplifier. During the latter 40 W, the increased pump power was contributed to by the other Tm:YLF laser injected from the other side. Compared with the earlier 40 W pump power equivalent to single-end-pumping, the latter 40 W pump power was equivalent to a double-end-pumping structure, which caused more a balanced thermal distribution in the Ho:YAG crystal of the amplifier. The more balanced thermal distribution contributed to the higher slope efficiency during the latter pump power.

To obtain higher energies in the future, we plan to change the structure of the Ho:YAG oscillator from

a plane–concave cavity to a concave–convex cavity so that the distribution of the beam diameter in the oscillator could be more reasonable, and the damage threshold of the Ho:YAG oscillator could be improved with a larger beam radius distribution. To improve the output performance of the Ho:YAG amplifier, we plan to change the crystal length and doping concentration of the Ho:YAG crystal.

In conclusion, we have reported a high energy and high repetition rate Ho:YAG MOPA system resonantly double-end-pumped by two Tm:YLF lasers at room temperature. During Q-switched operation at 1 kHz, we obtain a 52 mJ output energy, and the Ho laser shows two simultaneously lasing emissions at 2090.6 nm and 2096.9 nm. The minimum pulse width is 30.5 ns with a peak power of 1.7 MW, corresponding to a beam quality of $M^2 \sim 2.1$, which is measured by a 90/10 knife-edge method.

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