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146.4 W end-pumped Ho:YAG slab laser with two crystals

X.M. Duan, Y.J. Shen, B.Q. Yao, Y.Z. Wang

Abstract. **We report a high-power two-crystal Ho:YAG slab laser. A maximum cw output power of 146.4 W at a wavelength of 2090.7 nm is achieved, corresponding to a slope efficiency of 66.0% and an optical efficiency of 61.2%. The beam quality factor is measured to be $M^2 < 2.2$ at different output power levels. With an acousto-optic *Q*-switch, a maximum average output power of 141.3, 137.7 and 134.5 W are obtained at pulse repetition rates of 20, 30 and 50 kHz, respectively. Minimum pulse widths of 39 ns, 44 ns and 74 ns are achieved for the above pulse repetition rates.**

Keywords: *solid-state laser, Ho:YAG laser, high power.*

1. Introduction

Two-micron solid-state lasers are important for many applications such as remote sensing [1], medicine [2], materials processing [3], and mid-IR generation via pumping optical parametric oscillators (OPOs) [4]. With the advantage of a low quantum defect, the 1.9 μm in-band pumped Ho-doped laser has a high conversion efficiency and a low thermal load. To date, this is the best 2 μm high-power laser source. Furthermore, Ho^{3+} ions with a long upper laser level lifetime are suitable for *Q*-switched operation. Therefore, the Ho-doped laser is a vital way to achieve 2 μm pulsed lasing with a high output average power.

Up to now, many Ho lasers have been demonstrated in various hosts [5–9]. However, there are scarce data on the Ho laser with a 100 W level output. An output power of 83 W was achieved in a Tm, Ho co-doped fiber laser [10]. A 101 W average output power at a pulse repetition rate of 30 kHz was reported in a *Q*-switched Ho:YAG oscillator with two rods [11].

Among many host crystals, YAG crystal has a high thermal conductivity and great mechanical properties, and good quality YAG crystals are easy to grow. Therefore, the Ho:YAG crystal is very suitable for high-power lasers. In this paper, by using a double-end-pumped structure and two slab crystals, we have demonstrated an output power of as much as 146.4 W at continuous wave (cw) mode from the Ho:YAG laser. With *Q*-switched mode, the average output powers of 141.3, 137.7 and 134.5 W were achieved at pulse repetition rates of 20, 30 and 50 kHz. To the best of our knowledge, this is the highest output power in the cw and *Q*-switched Ho laser at room temperature. The output emitting at 2090.7 nm was observed in both cw and *Q*-switched modes. The beam quality factor was measured to be $M^2 < 2.2$ at different output power levels.

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2. Experimental setup

The experimental setup of the Ho:YAG laser with two slab crystals is schematically shown in Fig. 1. To achieve a high efficiency and a high power, dual end-pumping and a spherical pump beam were employed. We choose four volume-Bragg-grating-locked diode-pumped Tm:YLF lasers at 1908 nm as a pump source, which had a maximum output power of 70 W and a beam quality factor of 2.4. There are two Ho:YAG slab crystals in the Ho cavity. Each Ho crystal was dual-end-pumped by two orthogonally polarised diode-pumped Tm:YLF lasers. One pump laser is s polarised, while the other is p polarised. In order to avoid the pump lasers being influenced by each other, four thin-film polarisers (TFPs) were employed in the experiment. The TFP has high reflection for s-polarised pump and high transmission for p-polarised pump. The pump beam diameter of about 0.8 mm was focused by two lenses with a simple telescopic lens system at a pump power of 50 W.

The Ho:YAG crystal was grown by the Czochralski technique. Both end faces of the crystal were antireflection coated for the laser wavelength and the pump wavelength. The size of the Ho:YAG slab crystal with a doping concentration of 0.8 at % is 5 mm in width, 1.7 mm in thickness, and 50 mm in length. Compared with a rod crystal, the slab crystal (thin and wide) has a larger cooling area, which is essential for reaching a higher pump power. The crystal was wrapped in indium foil and clamped in a copper heatsink held at a temperature of 20 °C with a water-cooler. The folded resonator with a physical length of 295 mm consists of a flat dichroic mirror (M1) perpendicular to the beam axis, two flat dichroic mirrors (M2), and a concave output coupler (M3) with a radius of curvature of 300 mm and transmittance of 70%. All dichroic mirrors provide both high reflection at 2.09 μm and high transmittance at 1.91 μm. Two 0.1-mm-thick YAG Fabry–Perot (FP) etalons were inserted in the cavity. One was utilised as a Brewster plate to hold the s-polarised laser output, the other was used to achieve the single wavelength output. A 50-mm-long acousto-optic modulator (AOM, Gooch & Housego Corp.) was used for *Q*-switched operation. The AOM had a maximum rf power of 100 W.

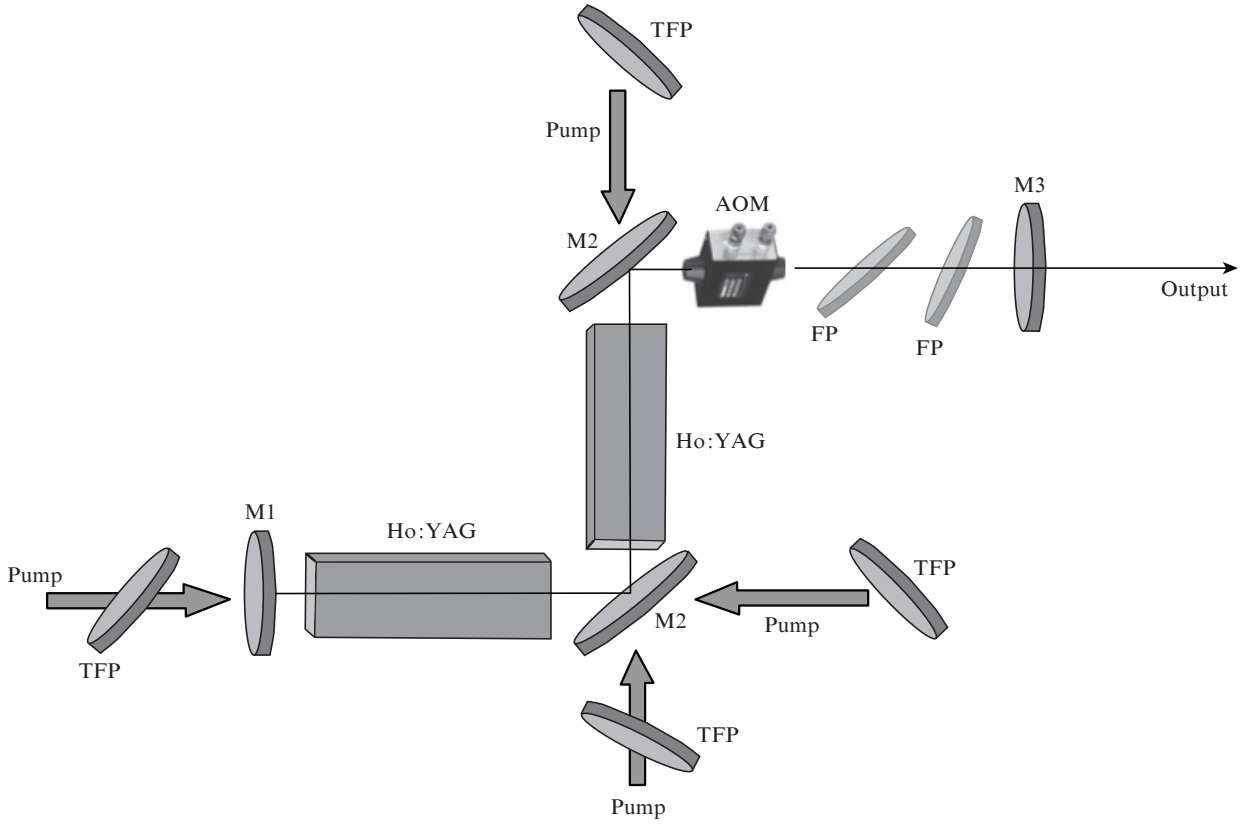

Figure 1. Schematic of the experimental setup.

3. Experimental results

A Coherent PM150 power meter was used to measure the output power of the Ho:YAG laser in this experiment. Firstly, with the AOM switched off, the Ho:YAG laser operates in cw mode, and a maximum output power of 146.4 W is obtained with an incident pump power of 239.3 W. The slope efficiency and optical efficiency were 66.0% and 61.2%, respectively. Next, with the AOM switched on, we measured the performance of the *Q*-switched Ho:YAG laser. At a pulse repetition rate of 50 kHz, a maximum average output power of 141.3 W was achieved with a slope efficiency of 63.9%. At a pulse repetition rate of 30 kHz, the Ho:YAG laser produces 137.7 W of average output power and 62.3% of slope efficiency. At a pulse repetition rate of 20 kHz, a maximum average output power of 134.5 W was obtained with a slope efficiency of 60.8%. The results obtained are shown in Fig. 2. As far as we know, this is the highest output power ever achieved in the cw and *Q*-switched Ho:YAG laser at room temperature.

Then, we have studied the beam quality factor and output spectrum of the cw Ho:YAG laser. At different output powers, the output beam radius of the Ho:YAG laser is measured by a 90/10 knife-edge technique at several positions through a

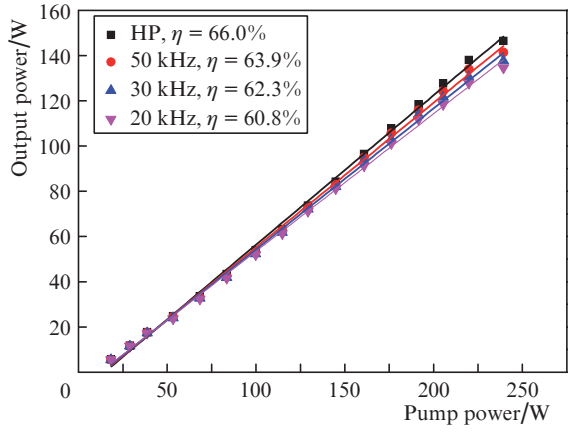

Figure 2. (Colour online) Output power of the Ho:YAG laser under cw and *Q*-switched modes vs. pump power.

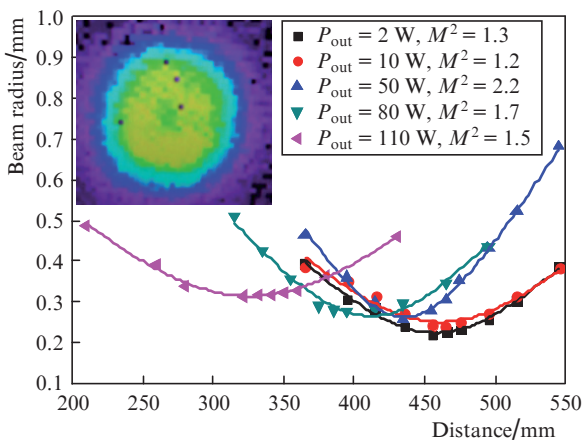

Figure 3. M^2 measurement of the cw Ho:YAG laser at different output levels. The inset shows a 2D beam profile of the Ho:YAG laser.

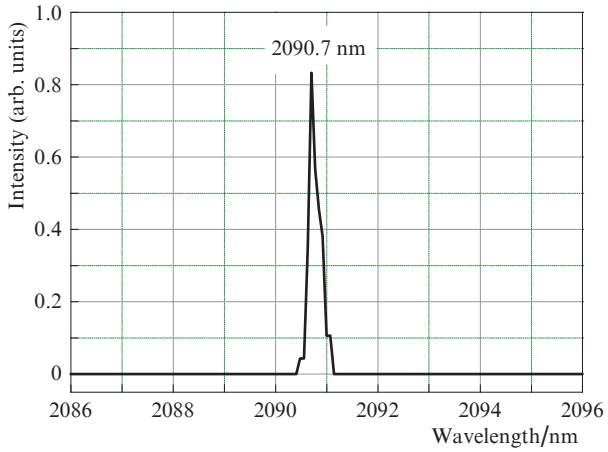

Figure 4. Output spectrum of the cw Ho : YAG laser.

waist formed by a lens with a focus length of 100 mm, as shown in Fig. 3. By fitting the Gaussian beam standard expression to these data, we estimate the beam quality to be M^2 = 1.3, 1.2, 2.2, 1.7 and 1.5 under output powers of 2, 10, 50, 80 and 110 W, respectively. The beam profile of the Ho laser at an output power of 110 W was recorded with a Spricon I, as shown in insert of Fig.3. It indicates that the beam propagates in TEM_{00}. The output spectrum of the cw Ho : YAG laser was recorded by a Bristol 721A wavemeter. At an output power of 10.0 W, the centre wavelength of the Ho : YAG laser was 2090.7 nm, and the full width at half maximum (FWHM) linewidth was 0.3 nm, as shown in Fig.4.

The *Q*-switched laser pulse profiles were recorded by a digital oscilloscope (Wavesurfer 64 Xs, Lecroy) with an InGaAs detector. At an incident pump power of 239.3 W, the minimum pulses with widths of 39, 44 and 74 ns were obtained for the pulse repetition rates of 20, 30 and 50 kHz, respectively. The maximum single pulse energies for these repetition rates of the pulses were 6.7, 4.6, and 2.8 mJ, respectively, corresponding to the maximum calculated peak powers of approximately 172.4, 104.3 and 38.2 kW. In addition, the pulse profiles of minimum pulse widths at the maximum incident pump power are shown in Fig. 6. According to the signal intensity in Fig.6, we calculated that the pulse contrasts of laser oscillations are 39, 25, and 24 dB, respectively.

The output spectrum of the *Q*-switched Ho : YAG laser was recorded with a grating monochromator (300 lines mm^{-1}). At an average output power of 10 W and a pulse repetition rate of 20 kHz, the output wavelength is centred at 2090.7 nm with a FWHM linewidth of 1.6 nm as shown in Fig.7.

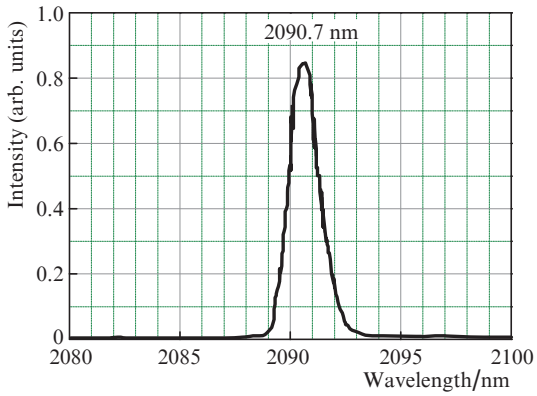

Figure 7. Output spectrum of the *Q*-switched Ho:YAG laser.

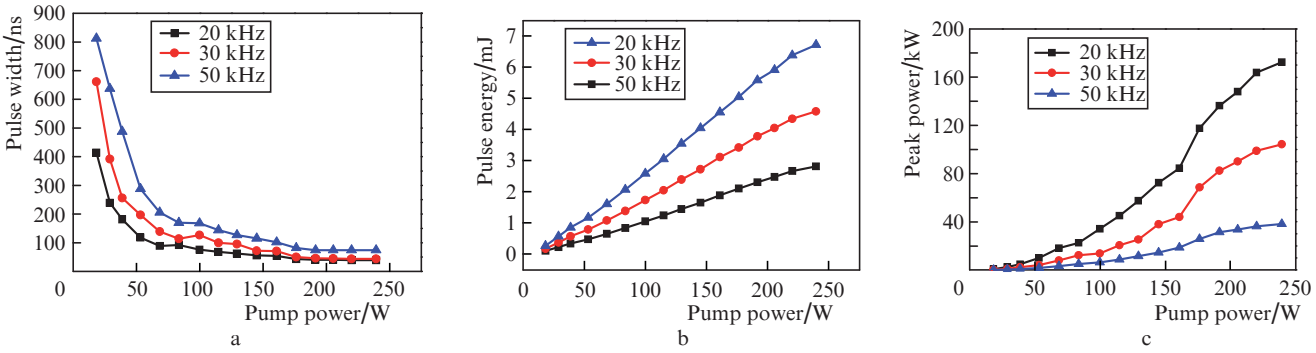

Figure 5. Dependences of (a) pulse widths, (b) pulse energies and (c) peak powers on the pump power at pulse repetition rates of 20, 30 and 50 kHz.

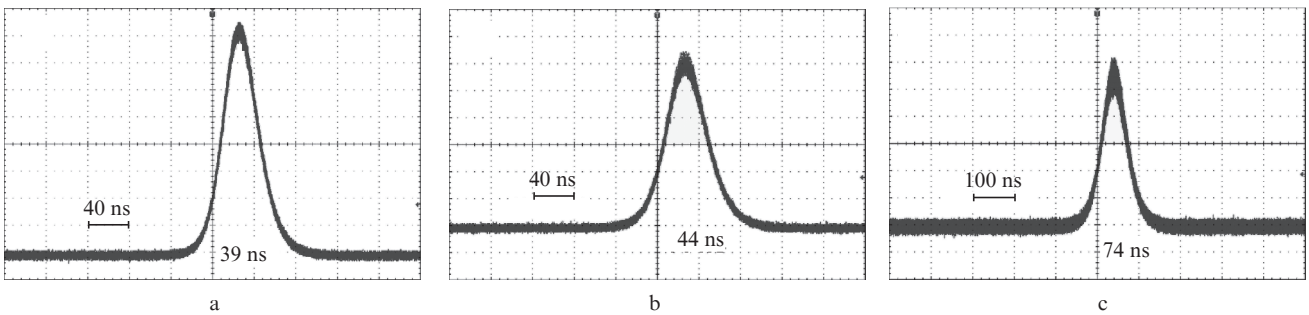

Figure 6. Pulse profiles of the Ho : YAG laser at pulse repetition rates (a) 20, (b) 30 and (c) 50 kHz.

4. Conclusions

We present a high-power and highly efficient cw and *Q*-switched Ho:YAG slab laser. When the incident pump power was 239.3 W, a maximum cw output power of 146.4 W was obtained, corresponding to a slope efficiency of 66.0% and an optical-to-optical efficiency of 61.2 %. The beam quality factor was measured to be $M^2 < 2.2$ under different output power levels. When the Ho:YAG laser operates in *Q*-switched mode, a maximum average output power of 141.3, 137.7 and 134.5 W were achieved with a pulse repetition rate of 20, 30 and 50 kHz, respectively. Minimum pulse widths of 39, 44 and 74 ns were obtained for the same pulse repetition rates. This Ho:YAG laser is suitable for pumping of mid-IR optical parametric oscillators.

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