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RESEARCH ARTICLE

Resonantly pumped 1645 nm Q-switched Er:YAG laser with a ring cavity

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Abstract This paper report an 1645 nm Er:YAG laser resonantly pumped by an Er-fiber laser operating at 1532 nm. 1.78 W continous wave (CW) output power with a slope efficiency of 52% was obtained using a long ring cavity and an 1 at.% doped Er:YAG crystal. In Q-switched mode, the obtained pulse energy was 1.6 mJ at a repetition rate of 500 Hz; for 1 kHz repetition rate, 1.2 mJ output energy was obtained.

Keywords resonantly pumped laser, Er:YAG laser, ring cavity

1 Introduction

Eye-safe laser sources operating at 1.5–1.6 μm have a number of applications in commercial and scientific areas. Recently, the novel fiber-bulk hybrid system concept has got much attention [1–7]. In this approach, high brightness fiber lasers are used as pump sources in resonantly pumped bulk solid state lasers. Resonant pumping facilitates lasing with a small quantum defect, simplifies thermal management, and enables power scaling capabilities.

A 1.645 μm wind lidar transmitter was demonstrated by Stoneman et al. from Coherent Technologies, Inc. in 2005 [8]. Pulses with energy up to 16 mJ in the Q-switched mode were achieved. The highest slope efficiency of the Er:YAG hybrid laser with respect to incident pump power was 81% in continous wave (CW) mode by using a 0.5% doped crystal. This result was reported by Shen et al. from the university of Southampton in 2006 [9]. They also compared the performance of Er:YAG crystals with different Er^{3+} dopant concentrations. A slope efficiency of 19% was obtained by using a 1 at.% doped Er:YAG crystal. The slope efficiency was 34% as a 0.5 at.% doped crystal was used under the same experimental condition [10]. Moskalev et al. from the University of Alabama at Birmingham reported a 0.5 at.% doped Er:YAG laser which out-coupler was a volumetric Bragg grating (VBG) in 2008. In the Q-Switched regime of operation at 10 kHz repetition rate, the laser generated up to 1.1 mJ output energy at 19.5 W pump power with 75% slope- and 59% real-optical efficiencies, respectively [11].

In this paper, we report the experimental results of a single-pass-pumped Er:YAG laser operating in CW and Q-switched modes. By using an Er:YAG rod with erbium concentration of 1 at.%, the corresponding slope efficiency was up to 52%. To our knowledge, this is the highest slope efficiency among those 1 at.% doped Er:YAG lasers.

2 Experimental setup

A schematic diagram of the resonantly pumped Er:YAG ring cavity laser is shown in Fig. 1. A fiber laser was used as the pump source, with a center wavelength of 1532 nm and a linewidth of 0.2 nm (full width at half maximum (FWHM)). The maximum output power of the fiber laser is 20 W. The pump beam was focused into the Er:YAG crystal by a coupling optics including two positive lenses with focal lengths of 500 mm (L_1) and 100 mm (L_2). To prevent shutting down the Er-fiber laser resulted from the feedback of subsequent laser system, the pump power was limited to 10 W.

In Fig. 1, a 1.0 at.% doped Er:YAG rod with a dimension of Φ 5 mm × 15 mm was used. Both end surfaces of the Er:YAG rod were anti-reflection (AR) coated at the pumping and lasing wavelengths. We measured the single-pass absorption of the Er:YAG rod for pump light at 1532 nm, which was about 96% under the lasing condition. The Er:YAG rod was mounted in a copper heat sink maintained at a temperature of 18°C. The heat sink was cooled by a thermal electric cooler (TEC).

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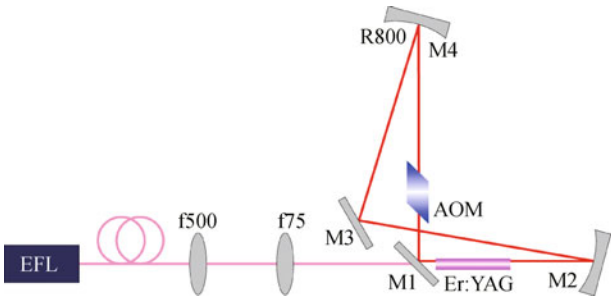

Fig. 1 Schematic of resonantly pumped Er:YAG laser in ring cavity (EFL: Erbium fiber laser; AOM: Acousto-optic modulator)

The pump beam deposited on the active medium through a diachronic flat input coupler (IC) M1 (HT@1532 nm, HR@1645 nm at 45° incident angle). M3 was a dichroic flat mirror coated as M1. M2 was a diachronic concave mirror (HT@1532 nm, HR@1645 nm, at 0° incident angle, for a single-pass-pumped laser) and M4 was an output coupler, both with radii of curvature 1000 mm. The output coupler has a transmissivity of 10% at 1.645 μm. The oscillation beam radius of TEM_{00} mode was calculated for 9.43 W pump power and 2078 mm-length cavity. As shown in Fig. 2, the calculated TEM_{00} beam waist was 0.27 mm, which located in the center of the Er:YAG rod. The red line represented the radius of oscillating beam in the sagittal surface and the blue dashed line shows the beam radius in the meridian plane. A quartz acoustic optical (AO) Q-switcher was used for the Q switching.

3 Experimental results

We studied the CW operation of the Er:YAG laser. The performance of the Er:YAG laser in CW mode was closely related to the mode size of oscillating beam. The slope efficiency changed as the pump power varied. It decreased as the pump power increased. This phenomenon resulted from a change in the TEM_{00} beam size in the Er:YAG rod due to the thermal load.

Figure 3 shows the laser performance as a function of the length of the cavity. The data indicated that when the length of the cavity changed from 1.826 to 2.078 m, the

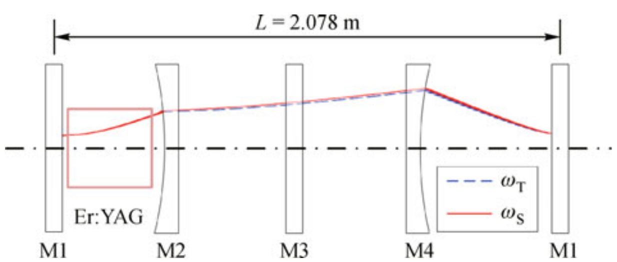

Fig. 2 Evolution of fundamental mode beam radius calculated for structure in Fig. 1 when pump power was 9.43 W

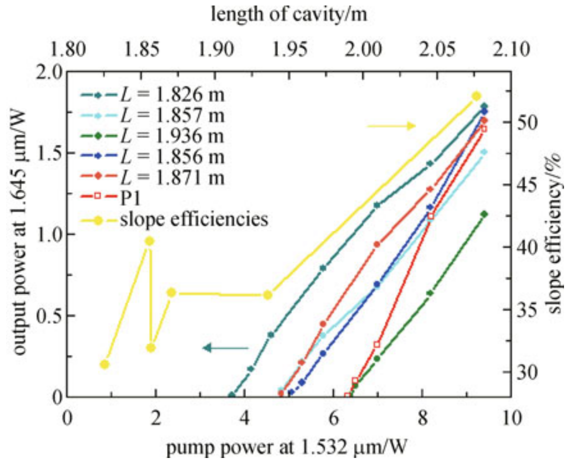

Fig. 3 Influence of length of cavity on performance of Er:YAG laser

threshold pump power changed from 3.7 to 6.4 W, and the total slope efficiency altered from 30% to 52% (the line of P1, L~2.078 m, the variation of spot size is shown in Fig. 2). The highest output power was 1.78 W at 9.43 W incident pump power when the length of the cavity was 1.826 m. If we had increased the pump power to a higher level, the output power of the composition with a 2.078 m cavity length would have surpassed other resonators' for the largest 52% slope efficiency.

With an AO Q-switch in the cavity and a slightly lengthened resonator, pulsed operation of the ring cavity was achieved. During the whole pulsed operating regime, the output beam contained only TEM_{00} mode. The highest output power was 1.7 W without the Q-switch, and it decreased to 1.5 W when inserting the Q-switch. Figure 4 shows the average output power and the figure of merit (FOM, defined as the average output power divided by the square root of pulse repetition rate (PRF), is an indicator of the range capability of the lidar.) versus PRF during the pulsed operation. The highest average power was 1.5 W at

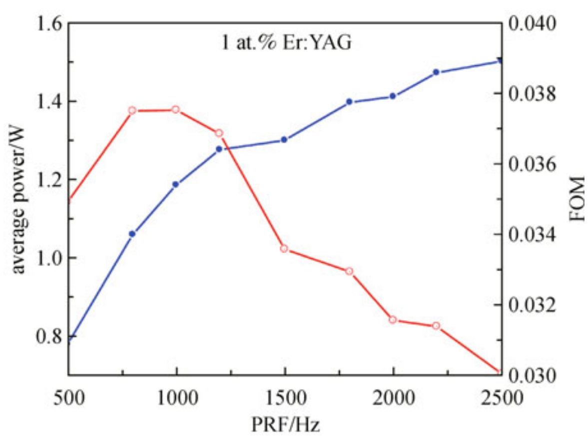

Fig. 4 Q-switched average power and value of FOM versus PRF when pump power was 9.43 W

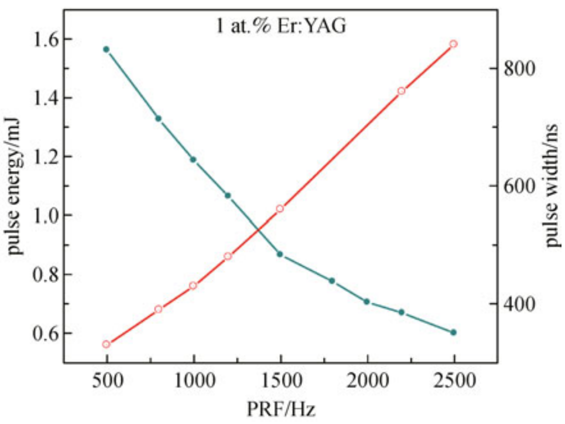

Fig. 5 Q-switched pulse energy and pulse width versus PRF when pump power was 9.43 W

a PRF of 2.5 kHz. The extraction efficiency, defined as average power divided by CW output power at the same pump power, was about 98%.

The best PRF was 800 Hz and 1 kHz derived from the maximum values of FOM. The lidar FOM is maximum at approximately the effective energy storage lifetime of the laser material. So in our experiments, the effective energy storage lifetime of Er:YAG was about 1 ms, estimated from the data. It was much shorter than 3.8 ms in Ref. [9]. Several mechanisms have been proposed to explain this reduction, including up-conversion and amplified spontaneous emission (ASE). Such mechanisms would result in an upper state lifetime reduction that is dependent on the population of the upper state [12]. The amount of energy altered inconspicuously as PRF varied.

Figure 5 shows the dependence of pulse energy and pulse width on PRF when the incident pump power was 9.43 W. As illustrated in the figure, we obtained 1.2 mJ, 430 ns pulses at a PRF of 1 kHz. At a lower PRF of 500 Hz, 1.6 mJ, 330 ns pulses were generated.

4 Conclusions

In conclusion, we have demonstrated a resonantly pumped Er:YAG laser using a ring cavity. With this architecture, we obtained a CW output power of 1.8 W and 1.2 mJ pulses at a PRF of 1.0 kHz in Q-switched mode. The best total slope efficiency was about 52%.

The threshold pump power was higher than those already reported. This might be attributed to the reflectivity loss of the input coupler and reflective mirrors due to the angled reflection. The results in this paper will be enlightening to our future work about Er:YAG lasers with lower concentration.

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