Appl. Phys. B (2016) 122:84
DOI 10.1007/s00340-016-6357-4

Applied Physics B
Lasers and Optics

High-energy resonantly diode-pumped Q-switched Er:YAG laser at 1617 nm

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Received: 13 November 2015 / Accepted: 3 February 2016 / Published online: 31 March 2016

Abstract We report high-energy linearly polarized operation of an Er:YAG laser at 1617 nm, resonantly pumped by quasi-continuous-wave 1470-nm laser diodes. A U-shape resonator incorporating two 0.25 at.% Er:YAG rods and an acousto-optic Q-switch was employed. Polarized output with pulse energy of 20.5 mJ and pulse width of 52 ns at a 50 Hz repetition rate was obtained. At the maximum output energy, the output beam quality M^2 was approximately 1.02 and 1.03 in horizontal and vertical directions, respectively. To the best of our knowledge, this polarized pulse energy is the highest ever reported for a directly diode-pumped Q-switched Er:YAG laser operating at 1617 nm.

1 Introduction

Pulsed laser sources with an eyesafe wavelength of 1.5–1.6 µm are useful for a range of applications including active imaging, ranging and remote sensing. Er:YAG lasers at ~1.6 µm directly pumped by an Er:Yb fiber laser [1, 2] or by an InGaAsP/InP laser diode (LD) at 1470 nm [3, 4] or 1532 nm [5, 6] are well suited for such applications. Because of the long storage lifetime of Er:YAG, pulses with high energy can be obtained in Q-switched operation. Er:YAG has emission lines around 1617 and 1645 nm. The former benefits from a higher emission cross-section, but has much more pronounced three-level character. As a consequence, lasing at the 1645-nm line is common. Unfortunately, there exist some atmospheric absorption lines of methane near 1645 nm. The use of 1617-nm line, which is free of absorption, is more efficient in some active imaging and ranging applications. Besides, laser beams with linear polarization are beneficial for the pollutant probing [7, 8].

Er:YAG lasers operating at 1617 nm have been achieved by using intracavity wavelength selective components, operating at cryogenic temperatures or simply by adopting an output coupler with much higher transmission [9–11]. By using 1532-nm Er:Yb fiber laser as a pump source, as much as 30.5 mJ pulse energy with pulse width of 20 ns was obtained at 20 Hz repetition rate [1]. Although the most impressive results so far have been achieved by fiber laser pumping, the whole system was complex due to an intermediate fiber laser stage. Alternatively, direct diode pumping of Er:YAG provides an attractive means. With a 1532-nm fiber-coupled laser diode as the pumping source, pulses with pulse energy of 11.8 mJ at 100 Hz pulse repetition rate were generated [5]. Due to its narrow spectral width, the 1532-nm pumping band is better suited with spectrally narrowed laser diode [12, 13]. Compared with 1532-nm pump source, the shorter wavelength 1.47 µm has several advantages in spite of a higher quantum defect. The absorption bandwidth of Er:YAG near 1.47 µm is relatively broader, which makes the 1.47-µm pumping band less sensitive to spectral shifts [14, 15]. Additionally, the emission cross-section at 1470 nm is much smaller than that at 1532 nm, which would reduce the loss of excited ions by stimulated emission at the pump wavelength [16]. By resonantly pumping with a low diode pump power at 1470 nm, passively Q-switched Er:YAG single-crystal fiber laser was presented, and pulse energy of 220 µJ at 1617 nm was obtained [17]. However, the operation of

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quasi-continuous-wave (QCW) 1470-nm LD pumped Er:YAG lasers at 1617 nm for high-energy output has not been investigated.

In this paper, we describe a linearly polarized Q-switched 1617-nm Er:YAG laser in-band pumped by QCW fiber-coupled LDs at 1470 nm. Two 0.25 at.% Er:YAG rods were adopted for average power scaling. The QCW pumping technique was adopted to reduce the thermal load applied to laser crystals. A maximum polarized pulse energy of 20.5 mJ with a pulse width of 52 ns was achieved at a repetition rate of 50 Hz. The output beam quality was measured to be $M_x^2 = 1.02$ and $M_y^2 = 1.03$, respectively.

2 Experimental setup

The schematic diagram of the Er:YAG laser in our experiment is shown in Fig. 1. A U-shape plano-concave resonator with a cavity length of ~470 mm was employed. The rear flat mirror M1 was high-reflection coated (>99.5 %) at the lasing wavelength (1600–1700 nm) and antireflection (AR)-coated (>95 %) at the pump wavelength (1470 nm). A plane dichroic mirror M2 with high reflectivity (>98 %) for the s-polarized light at the lasing wavelength and high transmission (>90 %) at the 1470-nm pump wavelength was used as one of the folding mirrors. The other folding mirror M3 was plane and high-reflection coated (>99.5 %) at the lasing wavelength. A concave mirror M4 with 1000-mm curvature was used as the output coupler, with transmission of 50 % at the lasing wavelength. A 0.1-mm-thick uncoated fused-silica etalon was adopted to provide the wavelength discrimination (when necessary) to ensure lasing on the 1617-nm line.

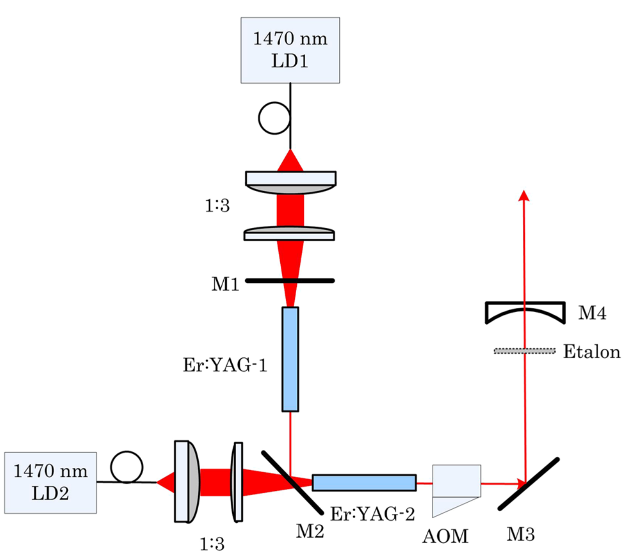

Fig. 1 Schematic diagram of the Q-switched Er:YAG laser

The laser crystals were two identical Er:YAG rods (marked as Er:YAG-1 and Er:YAG-2) with low erbium doping concentration of 0.25 at.%, thus minimizing energy transfer upconversion (ETU) and reabsorption at 1617 nm. The Er:YAG rods were 40 mm long and 4 mm in diameter. End surfaces of the rods were polished and AR coated at both the lasing and pump wavelengths. An estimation of the amount of thermal lensing in each laser rod showed that the effective focal length was about 2 m for Er:YAG crystals at the highest incident pump energy. Taking account of the thermal lens effect, the beam radius of the laser TEM_{00} mode was calculated by using ABCD matrix method. The beam radii at the center of Er:YAG-1 and Er:YAG-2 were about 483 and 475 μm, respectively. The Er:YAG rods were wrapped with indium foil and tightly mounted in a water-cooled copper heat sink maintained at ~15 °C. The pump source was two fiber-coupled laser diodes from QPC with a core diameter of 400 μm and a numerical aperture (NA) of 0.22. Each LD generated up to 100 W (QCW) at a wavelength of 1470 nm with ~10 nm full-width at half-maximum (FWHM) spectral width. The output from the pump fiber was imaged in the crystal using 1:3 telescopes with a radius of 600 μm in each crystal. To provide a modulation of the cavity Q-factor, a fused-silica, Brewster-cut, acousto-optic modulator (AOM) was adopted and placed close to Er:YAG-2.

3 Results and discussions

During the experiment, a pulsed pumping technique was employed to reduce the thermal load applied to laser crystals. The laser diodes were driven at a fixed repetition rate of 50 Hz and water-cooled at 22.5 °C, at which a pump wavelength in the vicinity of 1470 nm and thus efficient absorption at higher incident pump energy could be obtained. The fluorescence lifetime of Er:YAG was about 7 ms, but reduced upper-level lifetime for Q-switched Er:YAG lasers and the mechanisms for reduced upper state lifetime have been reported [4, 5, 18]. Based on previous results, the pumping pulse duration of 4–5.5 ms was adopted for high-energy pulse generation.

By regulating the peak drive current (50–75 A), the absorption efficiency as a function of the incident pump energy was measured for different pulse durations (4.0, 4.4, 4.8, 5.0, 5.2 and 5.5 ms). The absorbed pump energy was the difference between the incident and transmitted pump energy. However, the transmitted energy of the Er:YAG crystal included not only the unabsorbed pump energy, but also the fluorescence from $^4I_{13/2}$ and higher energy levels, which made the measurement of the actual absorbed pump energy difficult. On the other hand, the fluorescence was believed to be insignificant, and the calculated absorption

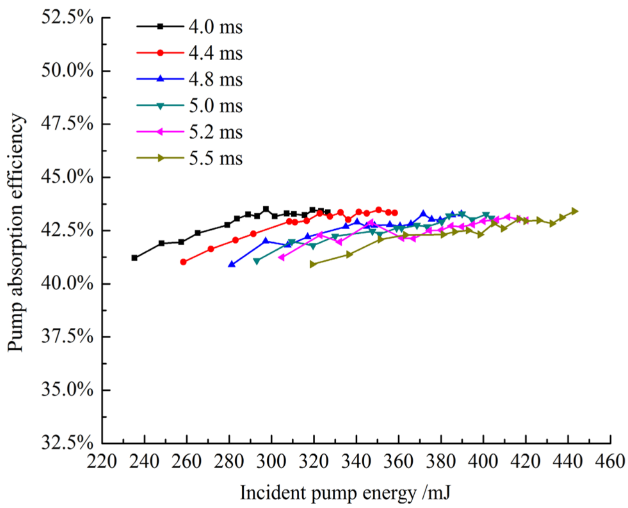

Fig. 2 Pump absorption efficiency versus incident pump energy of laser diode LD1 for different pump durations

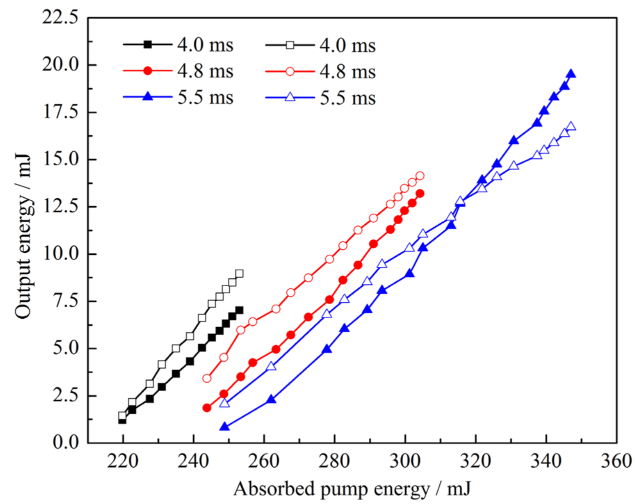

Fig. 3 Free-running (*closed points*) and Q-switched (*open points*) output for various pump durations (with etalon)

efficiency was still useful. Figure 2 shows the results for the absorption efficiency as a function of incident pump energy of laser diode LD1 for different pump durations. It can be seen that the absorption efficiency changed slowly as the incident pump energy increased at different pump durations. At pump duration of 5.5 ms, the absorption efficiency varied slightly from 40.9 to 43.4 % as the incident pump energy increased from 320 to 443 mJ. Besides, for a certain peak current, there was little variation in the absorption efficiency as the pump duration increased from 4.0 to 5.5 ms.

The output spectrum of the Er:YAG laser was investigated both in free-running and Q-switched modes. In free-running mode, without any selective element in the cavity, it was found that the laser spectrum consisted of two lines at 1617 and 1645 nm, and that the 1617-nm emission line dominated as the incident pump energy increased. By using the intracavity etalon, the lasing at 1645 nm was suppressed. The obtained spectrum characteristic was different from previous studies [1, 10, 18]; the etalon was used to suppress lasing at 1645 nm even with a 50 % transmission output coupler in free-running operation. This indicated that the inversion density was not large enough to provide a larger gain at 1617 nm than that at 1645 nm [10, 14]. On the other hand, for Q-switched operation and without the intracavity etalon, the measured emission wavelength was always 1617 nm. This can be ascribed to a much higher gain cross-section at 1617 nm than that at 1645 nm in Q-switch mode [10, 14]. The measured spectral width was about 0.2 nm.

With the etalon inserted in the cavity, the performances of the Er:YAG laser in free-running and Q-switched modes at various pump durations were studied. Figure 3 shows

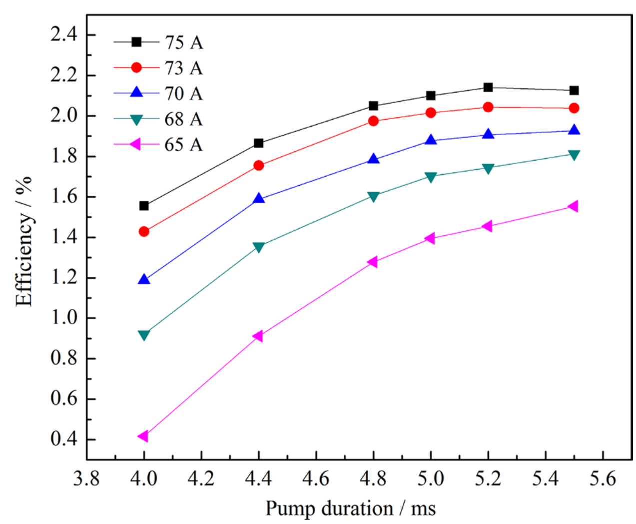

Fig. 4 Conversion efficiency versus pump duration for different peak drive currents

free-running output energy by solid points and Q-switched energy by open points as a function of absorbed pump energy for 4.0, 4.8 and 5.5-ms pump durations. For 5.5-ms pump duration, 19.5-mJ long-pulse energy was obtained at 347 mJ absorbed pump energy; in Q-switched mode, the highest pulse energy of 16.7 mJ was obtained, with a pulse width of ~56 ns. The linear output characteristics indicated that the thermal effects were weak up to the maximum absorbed pump energy, which can be beneficial to further average power scaling. On the other hand, less of the long-pulse energy was extracted as the pump duration increased in Q-switched mode. At the highest output energy, the extraction efficiency, which is a ratio of Q-switched to

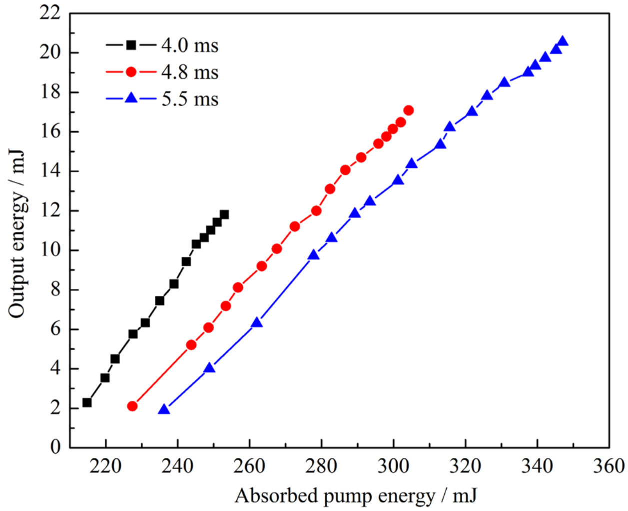

Fig. 5 Output pulse energy versus absorbed pump energy in Q-switched operation for various pump durations (without etalon)

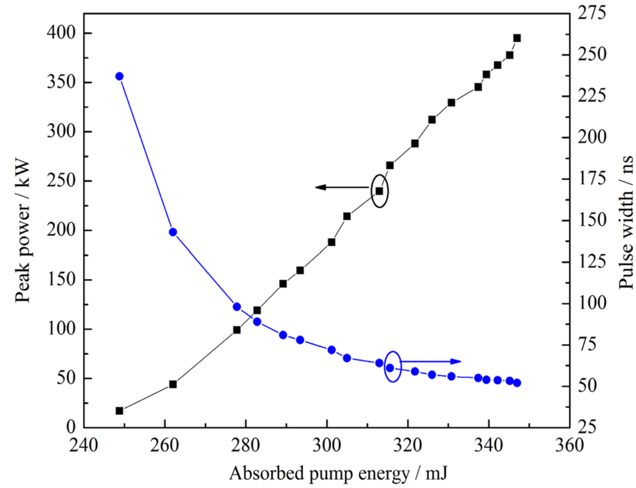

Fig. 6 Peak power and pulse width versus absorbed pump energy in Q-switched operation at 5.5-ms pump duration

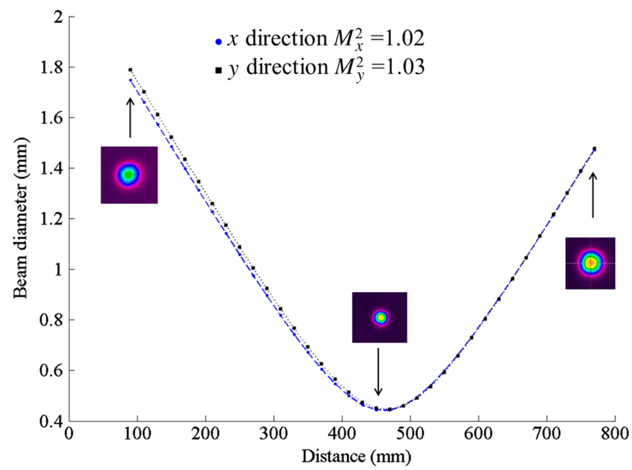

Fig. 7 Beam characterization at the maximum output energy of 20.5 mJ

free-running energy, was about 127 % after 4.0-ms pump duration, about 107 % after 4.8 ms, about 97 % after 5.2 ms (not shown in Fig. 3) and ~86 % after 5.5 ms. The reduced extraction efficiency can be attributed to a decrease in the storage lifetime at high excitation densities. Taking into account effects such as bleaching, one practical definition of storage lifetime is the pump duration at which conversion efficiency is maximum [14]. Figure 4 shows the conversion efficiency versus pump duration for peak drive current between 65 and 75 A. For low pump peak power (65 A), no roll-over was observed in conversion efficiency up to 5.5-ms pump duration. For the highest pump peak power, a maximum optical conversion efficiency of 2.14 % occurred at 5.2 ms.

For Q-switched operation, laser performances were investigated without the intracavity etalon. The dependence of Q-switched pulse energy on the absorbed pump energy for various pump durations was shown in Fig. 5. At 4.0-ms pump duration, a maximum pulse energy of 11.8 mJ (72 ns pulse width) was produced, and linear fitting to the data yielded a slope efficiency of 25.2 %. At 4.8-ms pump duration, a maximum pulse energy of 17.1 mJ (59 ns pulse width) was measured, and the slope efficiency was 19.5 %. At 5.5-ms pump duration, the slope efficiency dropped to 16.45 %, but a maximum output pulse energy of 20.5 mJ was obtained. The pulse duration was measured to be 52 ns; thus the corresponding highest peak power was about 394 kW, as shown in Fig. 6. In case of the occurrence of optical damage, the output pulse energy was not scaled further. With a combination of a half-wave plate and a polarizer, the polarization of the output beam was measured. The used polarizer had an extinction ratio larger than 1000:1, and the maximum degree of extinction of the measurement system was estimated to be better than 30 dB. By rotating the half-wave plate and measuring the maximum and minimum laser energy through the polarizer, the degree of linear polarization of the emitted beam was calculated to be ~ 24 dB, which was within the limits of the measurement system.

Finally, at the maximum output energy of 20.5 mJ, the beam profiles were measured by using an InGaAs camera (XEVA, Ophir). The beam sizes and the beam propagation factor (M^2) were calculated from these images with the second momentum technique, as described in the ISO 11146 norm. The generated beam was diffraction limited ($M_x^2 = 1.02$ and $M_y^2 = 1.03$), as shown in Fig. 7. It is worthy to mention that the output beam quality was mainly determined by the resonator, where a large fundamental mode size was designed and then the pump beam size was optimized to match the laser beam. Besides, the QCW pumping approach and the low Er^{3+} doping concentration were adopted to minimize the thermal effects, thus benefiting the generation of a good beam quality.

4 Conclusion

In summary, we have demonstrated an actively Q-switched 1617-nm Er:YAG laser. QCW fiber-coupled laser diodes at 1470 nm were employed for resonant pumping. At a repetition rate of 50 Hz, polarized output with pulse energy of 20.5 mJ and pulse duration of ~52 ns was generated, corresponding to a peak power of 394 kW. To the best of knowledge, this is the highest pulse energy ever reported for a directly diode-pumped Q-switched 1617-nm Er:YAG laser. Beam quality parameters for the output beam were $M_x^2 = 1.02$ and $M_y^2 = 1.03$.

Acknowledgments This work is supported by the National Natural Science Foundation of China (NSFC) under Grant Number 61405213.

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