Resonantly diode-pumped continuous-wave and Q-switched Er:YAG laser at 1645 nm.

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Abstract: We describe an efficient Er:YAG laser that is resonantly pumped using continuous-wave (CW) laser diodes at 1470 nm. For CW lasing, it emits 6.1 W at 1645 nm with a slope efficiency of 36%, the highest efficiency reported for an Er:YAG laser that is pumped in this manner. In Q-switched operation, the laser produces diffraction-limited pulses with an average power of 2.5 W at 2 kHz PRF. To our knowledge this is the first Q-switched Er:YAG laser resonantly pumped by CW laser diodes.

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1. Introduction

Multi-watt lasers with an output wavelength in the eye-safe band are required for many remote sensing applications. Er:YAG lasers at 1617 nm or 1645 nm can potentially satisfy this need. Q-switched lasers at these wavelengths are potential sources for scanning coherent laser radars for time-resolved wind-field velocity mapping. Such profiling is useful for site selection for wind farms and the investigation of atmospheric pollution transport.

Doppler wind-field mapping requires single frequency, diffraction limited pulses at a high pulse repetition frequency (PRF) to provide a spatially dense array of samples, allow signal averaging with minimal loss of temporal resolution and to minimize the time required to scan an extended volume. Pulses with energies > few mJ and pulse durations of > 100 ns are essential for these measurements. Such requirements can be satisfied by CW pumping of a Q-switched free-space laser.

Lasers operating near 1645 nm are also useful for atmospheric trace gas measurements of methane, a critical greenhouse gas [1]. Additionally, high power CW lasers operating in this band are potentially useful for third generation interferometric gravitational wave detectors and range-Doppler imaging of hard targets using pseudo random phase modulation.

The development of reliable, high power Er:YAG lasers is facilitated by the use of resonant pumping. This minimizes the waste heat from the pumping process, reducing thermally induced lensing and birefringence to yield a laser that can operate efficiently at a variety of power levels. Er:YAG lasers can be resonantly pumped at either 1470 nm or 1532 nm, using either laser diodes [2–5] or erbium-doped fiber lasers (EDFL) [6–11].

EDFL pumping allows efficient pump absorption due to its narrow bandwidth and good spatial overlap of the pumped region with the laser mode because of the excellent pump beam quality. High power and good optical efficiency have been achieved using this approach; the highest reported power and slope efficiency are 60 W and 80% respectively [8]. However, this pumping approach adds complexity, weight and volume to the laser system. Additionally, the overall optical efficiency with EDFL pumping is typically only about 28% due to the efficiency of the EDFL [9].

Direct pumping using high power laser diodes is complicated, however, by their low brightness and broad bandwidth. Nevertheless, Eichorn [2] demonstrated that pumping of Er:YAG lasers using fibre-coupled, CW 1535 nm laser diodes that were bandwidth narrowed to 1 nm yielded a multi-mode output power of 7 W at a slope efficiency 54%, neglecting the loss in pump power due to the fibre coupling. Kudryashov *et al* have recently investigated pumping using CW, 1470 nm and 1532 nm laser diodes that were bandwidth narrowed using external volume Bragg gratings [4]. The initial measurement with the broad bandwidth (10-12 nm) diodes obtained a multi-mode slope efficiency of ~20%. Reducing the bandwidth to about 0.6 nm, which is similar to the linewidth of the strongly absorbing transitions within the absorption bands, yielded a slope efficiency for the 1470 nm system of 28% for output powers up to 60 W. Pumping using low power, fibre-coupled broadband 1470 nm diodes to produce a diffraction-limited TEM_{00} output has also been investigated: an output power of 50 mW with a slope of efficiency of 20% was reported [5].

In this paper we report a CW laser that is pumped by a broad bandwidth laser diode at 1470 nm that produces 6.1 W with a slope efficiency of 36%. We also describe Q-switched operation of this laser. To our knowledge, there have been no reports of Q-switched Er:YAG lasers resonantly pumped by a broad bandwidth, CW diode.

2. Description of Laser

A schematic of the laser is shown in Fig. 1. The pump source is a CW, 40 W, fast axis collimated, three bar, laser diode array operating at 1470 nm, with a full-width at half maximum (FWHM) bandwidth of 12 nm. The output of the diode is imaged using a 100 mm focal length lens to produce a 1.3 mm diameter waist with a divergence of 65 mrad inside the slab. The gain medium is a 20 × 3 × 3 mm^3, Er^{3+}(0.5%):YAG slab. The slab face closest to the diode is also the end mirror of the resonator, and is coated for high reflectivity (R > 99.7%) at 1645 nm and high transmission (T > 99.8%) at 1470 nm. The other end is cut at Brewster's angle, thereby providing the polarization discrimination required for electro-optic Q-switching. A Rubidium Titanyle Phosphate (RTP) Pockels cell and an anti-reflection coated (R < 0.5%) quarter-wave plate (QWP) are used as the Q-switch. The output coupler is a flat mirror with 5% transmission and the physical resonator length is ~17 cm.

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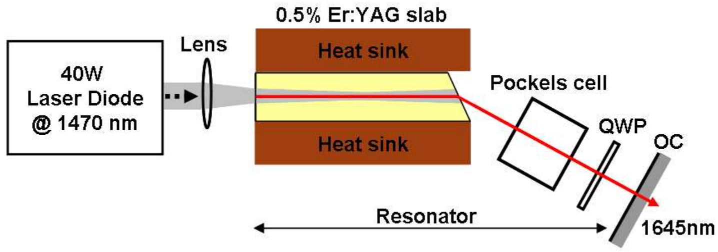

Fig. 1. Schematic of the Q-switched Er:YAG laser. Abbreviations: QWP, quarter wave plate; OC, output coupler.

3. Results

For initial testing, the Pockels cell and QWP were removed and the resonator length reduced to 7 cm. The multi-mode output power of this CW laser as a function of the incident pump power is plotted in Fig. 2. This laser had a slope efficiency of 36% which, to the best of our knowledge, is the highest efficiency reported for an Er:YAG laser that is pumped by broadband diodes at 1470 nm. Since only 55% of the pump power is absorbed, the slope efficiency with respect to the absorbed power is ~60%.

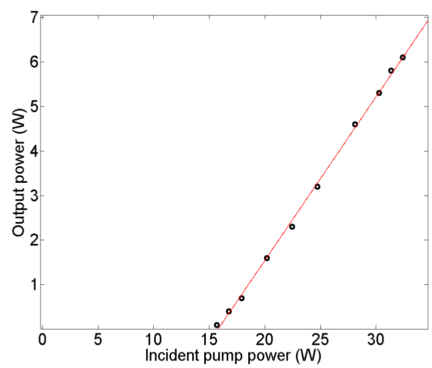

Fig. 2. Plot of multi-mode CW output power versus incident pump power for the reduced-length laser.

The spectral content of the laser output was measured using an optical spectrum analyser, which showed that the laser oscillated at 1645 nm only. Lasing at another emission peak around 1617 nm is also possible. However, it generally has a higher lasing threshold because it requires more excited Er ions (~14.6%) in the upper laser level manifold to reach transparency. Therefore, to lase at 1617 nm, additional wavelength discrimination in the resonator would be required to suppress the 1645 nm emission.

Figure 3 shows the average output power of the Q-switched laser for both CW and pulsed operation. As expected, the additional intra-cavity components result in an increased threshold compared to CW lasing of the reduced-length laser, shown in Fig. 2. The similarity between the average output power in CW and Q-switched lasing indicates that there was no increase in losses due to up-conversion or amplified stimulated emission (ASE) when Q-switching at 2 kHz PRF with incident pump powers up to 30.6 W.

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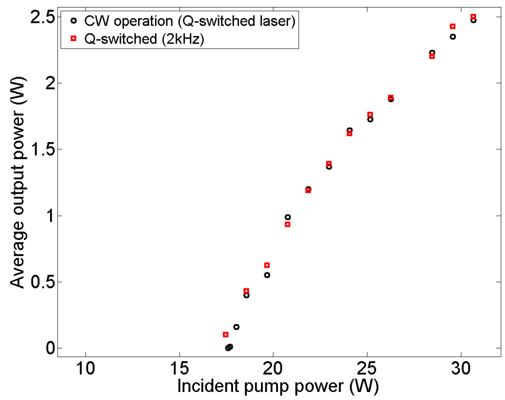

Fig. 3. Plot of the average output power versus incident pump power for CW and Q-switched (2kHz) operation of the laser shown in Fig. 1.

The intensity profile of the output of the Q-switched laser at an average output power of 2.5 W, and a plot of the measured beam size as it passes through a waist are shown in Fig. 4. The curve of best fit, for which $M^2 = 1.04$, is also plotted. This indicates that the laser output is near diffraction-limited.

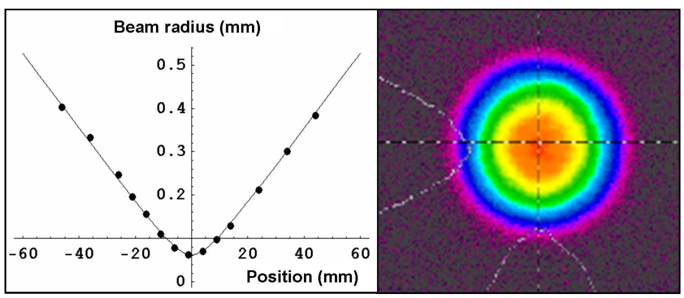

Fig. 4. (Left) Plot of the measured beam size of the output of the Q-switched laser at an average output power of 2.5 W (dots), and the $M^2 = 1.04$ curve of best fit. (Right) Intensity profile of the laser output.

The dependence of the average output power on PRF is shown in Fig. 5. The laser could not be operated at low PRFs and high pump power due to damage of the (low quality) optical coatings caused by the increased intra-cavity peak power (~45 MW/cm^2) of the pulses. The highest measured pulse energy was 2.3 mJ with a pulse duration of ~100 ns at 250 Hz PRF for an incident pump power of 23.5 W. The dependence of pulse energy on PRF at this pump power is plotted in Fig. 6.

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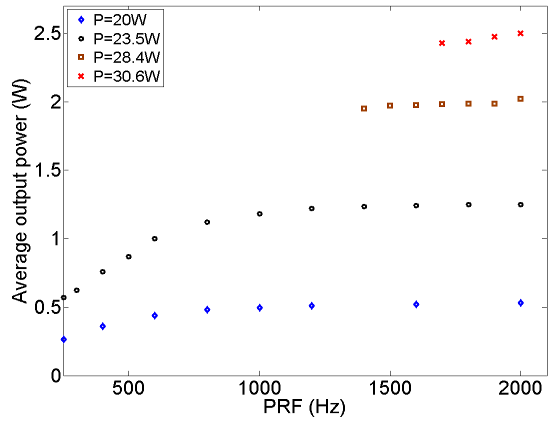

Fig. 5. Plot of the dependence of average output power on PRF for various incident pump power values.

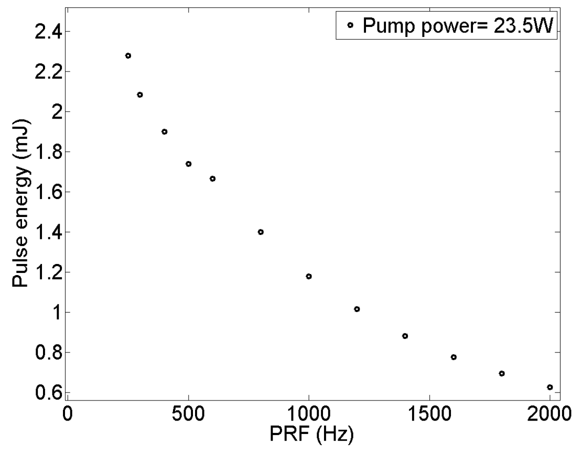

Fig. 6. Plot of the dependence of pulse energy on PRF for an incident pump power = 23.5 W.

The expected dependence of the average power on PRF for a CW pumped Q-switched laser is given by

$$P_{av}(\mathrm{PRF}) = P_{av}(\mathrm{CW})\ [1 - \exp(-t_q/t_s)]$$

where P_{av}(CW) is the average power in CW operation, t_s is the effective lifetime of the upper state and t_q = 1 / PRF [12]. Since Fig. 3 shows that the average power for both CW and PRF = 2 kHz lasing are identical at these pump powers, we plot in Fig. 7 the measured P_{av}(PRF) / P_{av}(PRF = 2 kHz) ratio and the ratio expected assuming that (a) t_s = 6.9 ms, (the fluorescent lifetime of the upper lasing state [13]), and (b) t_s = 2.3 ms (a lifetime estimated from the data recorded at low PRF).

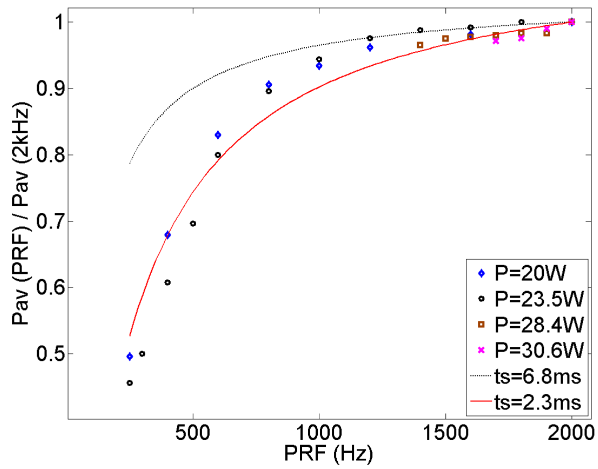

Fig. 7. Measured (symbols) and expected (solid lines) ratio of average power at different PRF.

It is clear that the decrease in average power at low PRF is not consistent with the assumption that the effective lifetime is 6.8 ms at low PRF. Another loss mechanism must therefore be decreasing the lifetime of the upper lasing state. Reduced upper state lifetimes for Q-switched Er:YAG lasers pumped by EDFLs have been reported by a number of authors [10,11,14]. Several mechanisms have been proposed to explain this reduction, including up-conversion [11,14] and ASE [10]. Such mechanisms would result in an upper state lifetime reduction that is dependent on the population of the upper state, which is consistent with the result shown in Fig. 7.

We are currently investigating the cause of the lifetime reduction in 1470 nm diode-pumped Er:YAG lasers using spectroscopic techniques. Initial measurements show both up-conversion and excited state absorption but negligible ASE. We expect to report a more detailed analysis in a later paper.

4. Summary

We have demonstrated an efficient Er:YAG laser that is resonantly pumped using CW diodes at 1470 nm. Using a reduced-length resonator, CW output powers up to 6.1 W at 1645 nm have been obtained with a multi-mode slope efficiency of 36%. In pulsed operation, the laser is Q-switched at 2 kHz PRF to yield diffraction-limited pulses with an average power of 2.5 W. The highest single pulse energy obtained was 2.3 mJ with a pulse duration of 100 ns at 250 Hz PRF. Higher pulse energy should be achieved by employing a more-robust high reflection coating on the Er:YAG slab.

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