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Continuous-wave and actively *Q*-switched resonantly dual-end-pumped Er : YAG ceramic laser emitting at 1.6 μm

T.Y. Dai, Y. Deng, Y.L. Ju, B.Q. Yao, X.M. Duan, Y.Z. Wang

Abstract. **We demonstrate a continuous-wave (cw) and actively *Q*-switched Er : YAG ceramic laser resonantly dual-end-pumped by a 1532 nm fibre-coupled laser diode. A maximum cw output power of 1.48 W at 1645.3 nm is obtained at an absorbed pump power of 12.72 W, corresponding to a slope efficiency of 19.2 %. In the *Q*-switched regime the maximum pulse energy of 0.84 mJ is reached at a pulse repetition rate of 100 Hz, pulse duration of 48.03 ns and absorbed pump power of 10.51 W.**

Keywords: *diode-pumped laser, Er : YAG ceramic laser, Q-switching.*

Laser sources with a wavelength in the eye-safe region near 1.6 μm have a lot of applications in lidar and remote monitoring. They include solid-state lasers based on Er^{3+}-doped gain media. Furthermore, actively *Q*-switched lasers based on Er^{3+} ions are also promising for remote sensing, ranging and free-space communications. In the past few years, the Er : YAG single crystal is one of the most attractive laser materials for ~1.6 μm cw and repetitively pulsed lasers due to its robust thermo-mechanical properties and long upper-state lifetime (about 6.5 ms) of $^4I_{13/2}$ [1].

However, compared to the Er : YAG single crystal, polycrystalline Er : YAG ceramics have numerous advantages, such as rapid and large volume fabrication, flexibility in doping concentration, low cost, etc. [2 – 4]. Of importance is also the fact that Er : YAG ceramics have been demonstrated to have spectroscopic parameters and lasing efficiency similar to those of single crystals. Thus, highly transparent polycrystalline Er : YAG ceramic crystals have emerged as a promising candidate for a laser gain host with the improvement in fabrication technologies. Recently, numerous works have been published to demonstrate polycrystalline Er : YAG ceramics operating at 1.6 μm. A maximum cw output power of 13.8 W and 14 W with slope efficiencies of 54.5 % and 51.7 % have been obtained at 1645 nm and 1617 nm, respectively [5, 6]. Passively *Q*-switched operation of polycrystalline Er : YAG ceramic lasers have been demonstrated at 1645 nm or 1617 nm using a graphene saturable absorber. An efficient passively *Q*-switched polycrystalline Er : YAG ceramic laser oscillating at 1645 nm with a pulse energy and pulse repetition rate being 7.08 μJ and 74.6 kHz, respectively, was implemented in 2013 [7]. Xiaoqi Zhang [8] reported a passively *Q*-switched Er : YAG ceramic laser at 1617 nm with a pulse energy of 12.2 μJ and a pulse repetition rate of 54.4 kHz, and Yong Wang [9] demonstrated a high-power cw and graphene *Q*-switched Er : YAG ceramic lasers with pulse durations of 1.5 – 6.4 μs. Compared to passively *Q*-switched lasers, actively *Q*-switched lasers have a higher single pulse energy and a shorter pulse duration, which can meet the requirement of scanning coherent laser radars. As far as we know, there are no reports on actively *Q*-switched operation of an Er : YAG ceramic laser.

In this paper, we report a cw Er : YAG ceramic laser which is resonantly dual-end-pumped by laser diodes. This laser in question produces a maximum output power of 1.48 W at 1645.3 nm with a slope efficiency of 19.2 %. We also describe the acousto-optic *Q*-switched operation of this laser which demonstrates a highest single pulse energy of 0.84 mJ at a pulse duration of 48.03 ns, repetition rate of 100 Hz and absorbed pump power of 10.51 W.

The scheme of the dual-end-pumped Er : YAG ceramic laser is shown in Fig. 1. A simple three-mirror L-type configuration is used to ensure cw and *Q*-switched operation of the polycrystalline Er:YAG ceramic laser. It consists of plane input couplers M1 and M2. Both mirrors have a high transmission (> 98 %) at a pump wavelength of 1532 nm and a high reflectivity (> 99 %) at a lasing wavelength of 1.6 μm. A concave output coupler (M3) with a 200 mm radius of curvature has a transmission of 3.5 % at the lasing wavelength and a high reflectivity at the pump wavelength. The physical length of the resonator is 130 mm. The pumping is performed by two fibre-coupled laser diodes with a 200 μm core diameter and a numerical aperture (NA) of 0.22. The maximum output power of the laser diode is 15 W, and the wavelength can be tuned by changing its working temperature. The pump beams are focused into the middle of the polycrystalline Er : YAG ceramic by a coupling system consisting of two lenses with focal lengths of 20 mm and 60 mm. The 0.5 at % polycrystalline Er : YAG ceramic was cut and polished to measure

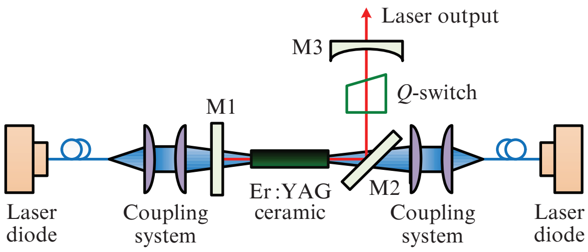

Figure 1. Schematic of the dual-end-pumped Er : YAG ceramic laser.

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1.2×3×16 mm. The gain media was wrapped with indium foil and mounted on a water-cooled copper heat sink. A 30-mm-long acousto-optic Q-switch with a low insertion loss was used to ensure Q-switched operation. Its maximum RF power was 25 W and its intrinsic diffraction loss was 62.5%, which was adequate to prevent lasing.

First, we compared a cw Er:YAG ceramic laser having two output couplers with transmission coefficients T = 3.5% and 10%. Figure 2 shows the output power of the cw Er:YAG ceramic laser as a function of absorbed pump power for output couplers with T = 3.5% and 10%. For the 3.5% output coupler, a maximum cw output power of 1.48 W with a slope efficiency of 19.2% under the absorbed pump power of 12.72 W was achieved. The Er:YAG ceramic laser fitted threshold was 4.7 W. One can see that the output power still has a room to increase with increasing pump power. The low efficiency can possibly be attributed to the mismatch of the pump laser wavelength of the laser diode with the absorption peak of the polycrystalline Er:YAG ceramic. The absorption peak of the polycrystalline Er:YAG ceramic near 1532 nm is narrow, and the pump laser wavelength of laser diode drifts as the output power of laser diode increases. The output laser spectrum of the cw Er:YAG ceramic laser was recorded with a Bristol 721A IR spectrum analyser. For the 3.5% output coupler, the spectrum is shown in Fig. 3a. The emission line was located at λ = 1645.3 nm.

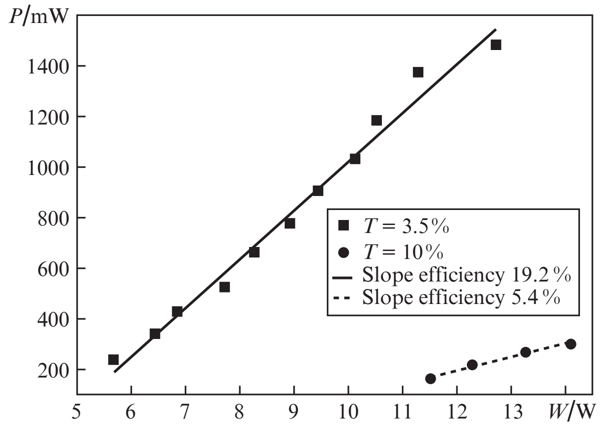

Figure 2. Output power P vs. absorbed pump power W for the cw Er:YAG ceramic laser at different output coupler transmissions.

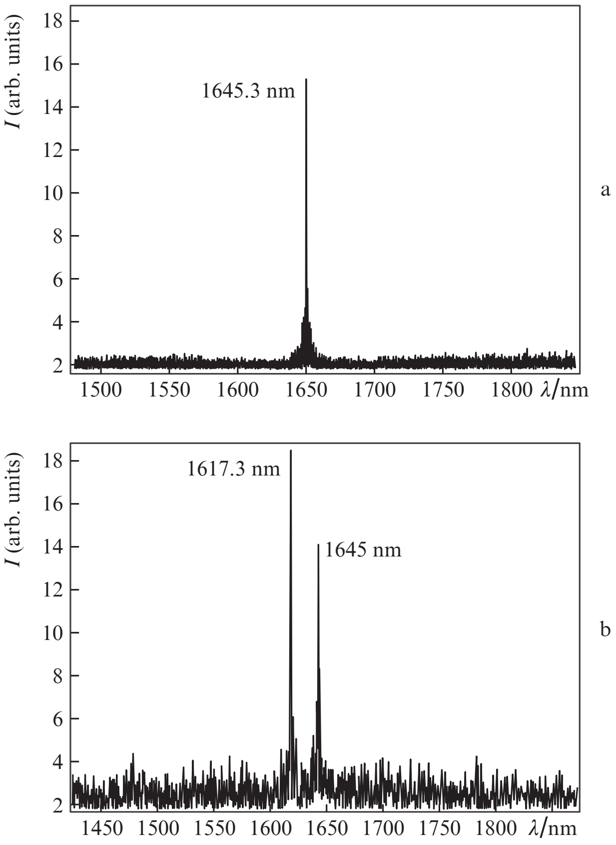

Figure 3. Output spectrum of the cw Er:YAG ceramic laser at different output coupler transmissions T = (a) 3.5% and (b) 10%.

With the 10% output coupler, the maximum output power and the slope efficiency of the cw Er:YAG ceramic laser sharply decreased and amounted to 302 mW and 5.4%, respectively, the Er:YAG ceramic laser fitted threshold increased to 8.43 W. The output spectrum of the cw Er:YAG ceramic laser with an output coupler having T = 10% is shown in Fig. 3b. The laser oscillated at 1617.3 nm; however, lasing at another emission peak around 1645 nm is also possible. The laser operating at 1617 nm clearly has a higher lasing threshold because in this case, more excited Er^{3+} ions (∼14%) in the upper laser level are required to reach transparency and a lower slope efficiency is needed. To obtain lasing at λ = 1617 nm only, at least 35% of the Er ion population inversion is required [10].

The output characteristics of the Q-switched Er:YAG ceramic laser were studied using an output coupler with T = 3.5%. Figure 4 shows the measured pulse energy of the Q-switched Er:YAG ceramic laser at different repetition rates as a function of the absorbed pump power. One can clearly see from Fig. 4 that the single pulse energy increases with increasing absorbed pump power, and this energy at a smaller repetition rate is greater than that at a higher repetition rate. A maximum pulse energy of 0.84 mJ was obtained at a repetition rate of 100 Hz and absorbed pump power of 10.51 W. Figure 5 shows the measured pulse duration of the Er:YAG ceramic laser versus the absorbed pump power at different pulse repetition rates. One can see that the pulse duration decreases with increasing absorbed pump power,

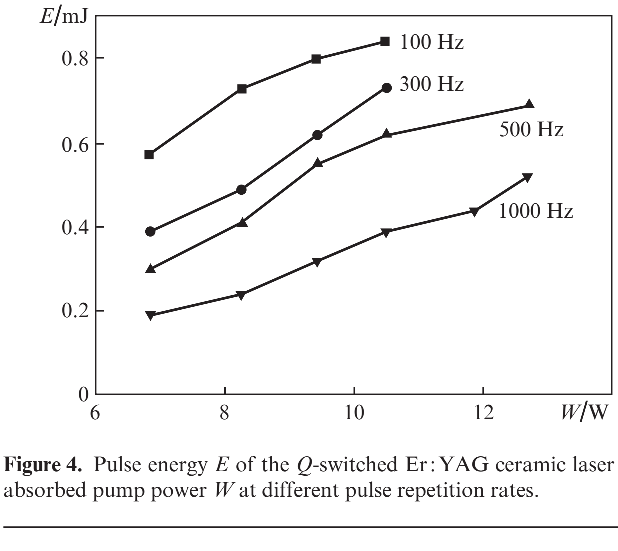

Figure 4. Pulse energy E of the Q-switched Er:YAG ceramic laser vs. absorbed pump power W at different pulse repetition rates.

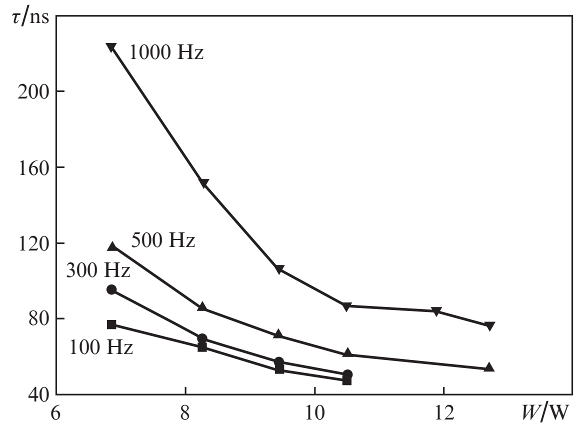

Figure 5. Pulse duration τ of the Q-switched Er:YAG ceramic laser vs. absorbed pump power W at different pulse repetition rates.

and under the same absorbed pump power the pulse duration becomes shorter when the repetition rate decreases. A minimum pulse duration of 48.03 ns was achieved at a repetition rate of 100 Hz and absorbed pump power of 10.51 W (Fig. 6).

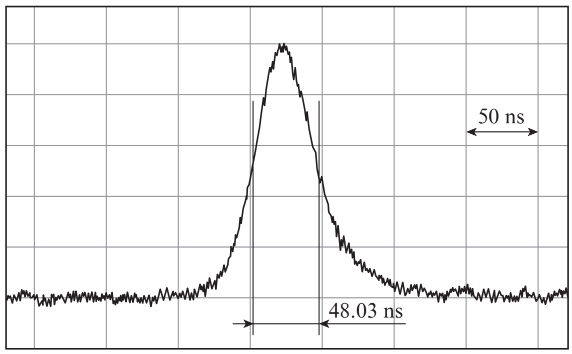

Figure 6. Minimum pulse duration of the Er:YAG ceramic laser.

Thus, we have described a 1.6 μm cw and actively Q-switched Er:YAG ceramic laser resonantly dual-end-pumped by two 1532 nm fibre-coupled laser diodes. A maximum cw output power of 1.48 W with a slope efficiency of 19.2% at 1645.3 nm was obtained under the absorbed pump power of 12.72 W. For the Q-switched operation, a maximum single pulse energy of 0.84 mJ was generated at a repetition rate 100 Hz and absorbed pump power of 10.51 W, corresponding to a pulse duration of 48.03 ns. Future work will be focused on optimising the crystal length, doping concentration and resonator parameters.

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