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Short-Pulse-Width Repetitively Q-Switched ~2.7-µm $Er:Y_2O_3$ Ceramic Laser

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Abstract: A short-pulse-width repetitively Q-switched 2.7-µm $Er:Y_2O_3$ ceramic laser is demonstrated using a specially designed mechanical switch, a metal plate carved with slits of both slit-width and duty-cycle optimized. With a 20% transmission output coupler, stable pulse trains with durations (full-width at half-maximum, FWHM) of 27–38 ns were generated with a repetition rate within the range of 0.26–4 kHz. The peak power at a 0.26 kHz repetition rate was ~3 kW.

Keywords: laser materials; mid-infrared lasers; rare-earth solid-state lasers

1. Introduction

Laser radiation at ~2.7-µm is important for practical applications and scientific research. Being regions of water absorption and molecular fingerprints, laser sources at ~2.7-µm are useful for biomedical therapy [1,2] and atmospheric sensing [3]. In addition, these lasers are utilized for generating 3–5-µm laser emission [4,5], which corresponds to an atmosphere transparent window. Lasers at ~2.7-µm also facilitate studies of laser materials that is suitable to generate deep-infrared lasing [6,7]. Both the applications and research require versatile ~2.7-µm laser sources with short pulse duration and high repetition rate.

A simple approach to generate ~2.7-µm pulses is Q-switching ion-based (as Er^{3+}, Ho^{3+}, Dy^{3+} and Cr^{2+}) lasers. Er-based lasers operating on the transition between $^4I_{11/2}$ and $^4I_{13/2}$ energy levels are most often utilized because of the mature pump sources of flashlamps and ~976-nm laser diodes (LDs). With 50 atom % Er:YAG ($Y_3Al_5O_{12}$), 30 atom % Er:YSGG ($Y_3Sc_2Ga_3O_{12}$), and 15 atom % Er:YLF ($LiYF_4$) laser materials, ~2.7-µm pulses at durations of tens of nanoseconds have been obtained. However, the repetition rates of these lasers are generally limited to several Hertz due to the severely thermal effects generated during laser operations [8–11]. Laser pulses at ~2.7-µm with repetition rates at the kilohertz scale have been generated from Er:ZBLAN (ZrF_4-BaF_2-LaF_3-AlF_3-NaF) fiber lasers, which are more thermally advanced [12,13]. However, the pulse durations are hundreds of nanoseconds because fibers have limited energy storage capability. So far, short pulses at ~2.7-µm with high repetition rates are rare.

The use of Er-based sesquioxides is promising in terms of obtaining ~2.7-µm laser pulses with short pulse durations and high repetition rates. As ~2.7-µm laser oscillation can be realized from Er-based sesquioxides with low doping concentrations (lower than ~7 atom %) [14,15], the thermal effects generated during laser operation are greatly alleviated. In addition, sesquioxides have high thermal conductivity, which decreases slightly with increasing doping concentration [16]. Furthermore, Er-based sesquioxides have long ~2.7-µm fluorescence lifetimes (e.g., an order of magnitude longer than that of Er:YAG), making them beneficial for energy storage [17]. Unfortunately, sesquioxides have extremely high melting points (>2400 °C), imposing serious challenges for traditional single-crystal-growth approach. In this aspect, polycrystalline ceramics are superior to single crystals since they can be sintered at much lower temperatures. Moreover, transparent ceramics have advantages over crystals in terms of their rapid fabrication in large scale and composite structures, flexible doping concentrations, and good thermo-mechanical properties [18]. Recently, sesquioxide ceramics have been successfully fabricated and mainly explored to realize continuous-wave (CW) laser operation at ~2.7-µm. A passively Q-switched ~2.7-µm Er:Y_2O_3 ceramic laser with a pulse duration of 4.47 µs and a pulse repetition rate of 12.6 kHz was realized, aiming to demonstrate the broadband availability of black-phosphorus [19]. For actively Q-switched operation, an acousto-optically Q-switched Er:Y_2O_3 ceramic laser was demonstrated, generating pulses with durations of 41–190 ns in the range of 0.3–10 kHz [20]. Due to the scarcity of ~2.7-µm acousto-optic and electric-optic Q-switches, mechanical Q-switching is commonly used in a wavelength range of ~2.7-µm [21,22], which does not require high voltages or drive power and has avoidable insert losses.

Here we report a short-pulse-width repetitively Q-switched Er:Y_2O_3 ceramic laser at ~2.7-µm using a specially designed mechanical switch, a metal plate carved with slits of both slit-width and duty-cycle optimized. The laser performances with output couplers (OCs) of 5%, 8% and 20% transmissions are compared in both CW and Q-switched operation modes. In the CW operation mode, the 8% transmission OC yields an output power of over 1.8 W. In the Q-switched operation mode, the 20% transmission OC yields pulse trains with durations (FWHM) of 27–38 ns and energies of 80.8–27.5 µJ with repetition rates in the range of 0.26–4 kHz. The corresponding peak power at the 0.26 kHz repetition rate is ~3 kW. To the best of our knowledge, the laser offers the shortest pulse durations among ~2.7-µm Q-switched lasers with pulse repetition frequency (PRF) above several Hertz.

2. Experimental Details

Figure 1 shows the schematic layout of the pulsed Er:Y_2O_3 ceramic laser. A pig-tailed ~976-nm LD with a fiber core diameter of 105-µm and a numerical aperture (NA) of less than 0.15 was used to pump the Er:Y_2O_3 ceramic. The pump light was focused into the Er:Y_2O_3 sample with a ~420-µm spot diameter through a 25-mm-focal-length lens F1 and a 100-mm-focal-length lens F2. The confocal parameter was estimated to be ~26 mm. The physical length of the plane–plane cavity was 28 mm. The input coupler (IC) was high-transmission coated at ~976 nm (T > 98%) and high-reflectivity coated at ~2.7-µm (R > 99.8%). Three flat mirrors with transmissions of 5%, 8%, and 20% at ~2.7-µm and high transmissions at ~976 nm were employed as OCs. The Er:Y_2O_3 ceramic (developed at Jiangsu Normal university) was synthesized by the solid-state reaction method and vacuum sintering followed by hot isostatic pressing [14]. The ceramic sample had a dimension of 2 × 3 × 12 mm and an Er-ion concentration of 7 atom % and was uncoated. It was mounted in a copper block that was cooled by water at ~13 °C to allow for effective heat removal. A dichroic mirror (DM) coated with high reflectivity at the laser wavelength and high transmission at the pump wavelength was placed between the OC and the detector to filter out the unabsorbed pump power.

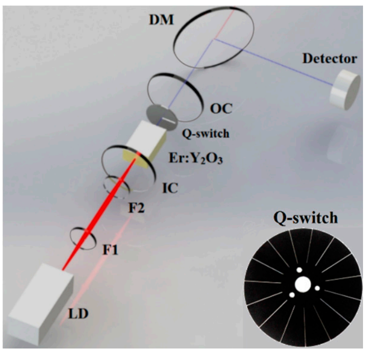

Figure 1. Schematic setup of the Q-switched Er:Y_2O_3 ceramic laser. LD: laser diode; IC: input coupler; OC: output coupler; DM: dichroic mirror.

The mechanical Q-switch was a 1-mm-thick rotating metal plate carved with sagittal rectangular slits (see the inset of Figure 1), of which the rotating speed and slit number were variable from 1 to 134 rounds per second and 1 to 30, respectively. It was placed close to the ceramic sample, where the diameter of the laser mode was calculated to be ~470-µm. The modulation frequency was adjusted by changing the slit number or (and) the rotating speed. The slit width was optimized to be 0.6 mm. The duty ratio of the Q-switch was continually tunable by moving the plate along its radial direction. Using such a mechanical Q-switch considerably increased the time for the inversion population to accumulate.

3. Results

A comparison of CW laser performances with 5%, 8% and 20% transmissions OCs of the Er:Y_2O_3 medium was first made. Figure 2 shows dependences of output powers on the absorbed pump power. The absorbed pump power was calculated by multiplying the incident pump power by the absorption efficiency, which was measured under non-lasing condition (without existence of the laser resonator) to be ~90%. The threshold pump powers for the 5%, 8% and 20% transmission OCs were ~1.1 W, ~1.4 W, and ~3 W, respectively. At pump powers of less than 14 W, the output powers increased linearly with the pump power for all three OCs, and the 8% OC yielded the highest slope efficiency of 10.2% with respect to absorbed pump power. When the pump power was above 14 W, the laser became slightly less efficient due to the increased thermally induced losses. Nevertheless, an output power of over 1.8 W was obtained at 19 W of pump power with the 8% transmission OC. According to the laser properties with different output couplers, the distributed cavity losses (excluding the output coupling loss) were calculated to be ~1.67% cm^{-1} using the well-known Findlay–Clay method, comprising the thermally induced losses and the losses of the cavity mirrors and ceramic sample (~1.2% cm^{-1} estimated though the in-line transmission spectrum of a 1.3-mm-long Er:Y_2O_3 sample). The attainable output power should be readily increased by improving the cooling system and reducing passive losses of the ceramic sample.

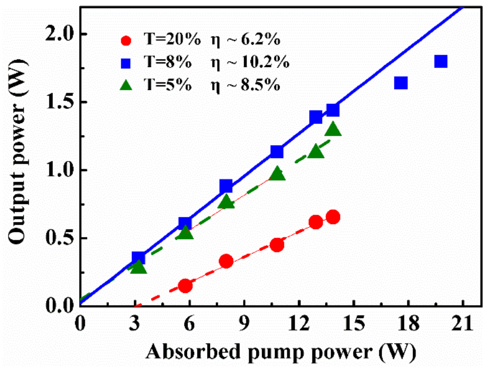

Figure 2. Continuous-wave (CW) output power vs. absorbed pump power with different output couplers.

The Q-switched operation performances were studied with the same output couplers. An HgCdTe detector (PVM-10.6, VigoSystem S. A) with a rise time of 1.5 ns and an oscilloscope (DSO104A, Keysight) with a bandwidth of 1 GHz were utilized to measure the pulse characters. The threshold for Q-switched operation was the same as that for the CW operation. Not too far above the threshold, stable pulse trains were observed for all three OCs. The pulse characters were then optimized by changing the distance between the center of the mechanical switch and the optical axes of the cavity, and the optimal distance was found to be ~50 mm. The pulse duration and pulse energy as functions of the pulse repetition frequency for all three OCs are shown in Figures 3 and 4. With the 5% and 8% transmission OCs, single pulses with 40 ns duration and 30.8 µJ energy, and 37 ns duration and 46.1 µJ energy were obtained at a 0.26 kHz pulse repetition frequency (corresponding to the rotating speed of

130 rounds per seconds and a slit number of 2) under a pump power of 3.2 W. With the increase in repetition frequency, the pulse duration increased while the pulse energy decreased. Nevertheless, pulse durations of less than 50 ns were obtained in the range of 0.26–4 kHz with both OCs. When further increasing the pump power, multi-pulse operation occurred. With the 20% transmission OC, shorter pulse duration and larger pulse energy were achieved. This is because a higher output coupling can delay the occurrence of multi-pulse operation in mechanically Q-switched lasers. In this case, multi-pulse operation occurred when the pump power was above 10 W. Under 10 W of pump power, the pulse duration increased from 27 to 38 ns, whereas the pulse energy decreased from 80.8 to 27.5 μJ with increasing the repetition frequency from 0.26 to 4 kHz, corresponding to ~3 kW peak power at 0.26 kHz repetition frequency. The optical–optical conversion efficiencies in the Q-switched mode could be effectively improved using a larger plate carved with more slits but the same turn-off area and/or a motor with higher rotating speed to make the laser operate at a higher repetition rate. Improvement in the Q-switched efficiencies is also achievable through optimizing the pump wavelength to avoid the excited state absorption of the upper laser level during the pumping process. The short pulse durations achieved in our experiment are a consequence of the good energy storage of $Er:Y_2O_3$, in which losses of excited ions on the upper laser level caused by multiphonon relaxation and spontaneous emission are small.

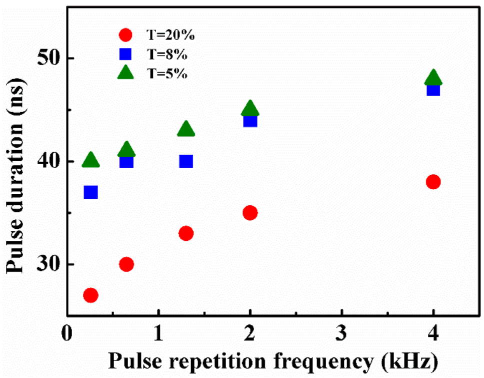

Figure 3. Pulse duration vs. pulse repetition frequency with different output couplers.

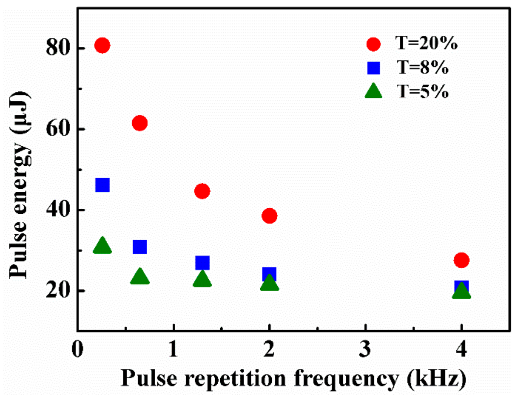

Figure 4. Pulse energy vs. pulse repetition frequency with different output couplers.

Figures 5 and 6 show the typical single pulse profile and pulse train recorded at 0.26 kHz repetition rate with the 20% transmission OC under 10 W of pump power. The pulse profile shows a fairly symmetric shape and the time spacing between two adjacent pulses remains nearly fixed for the given repetition rate with no noticeable timing jitter. The amplitude fluctuations were estimated to be less than 10%.

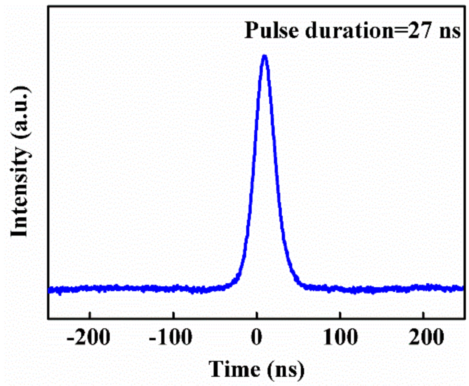

Figure 5. Typical pulse profile recorded at 0.26 kHz pulse repetition frequency (PRF) under 10 W of absorbed pump power.

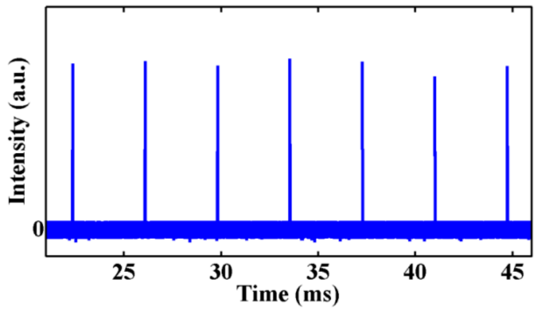

Figure 6. Pulse train recorded at 0.26 kHz PRF under 10 W of absorbed pump power.

The optical spectrum of the Q-switched Er:Y_2O_3 ceramic laser with the 20% transmission OC was found to vary slightly with the repetition rate or pump level. Figure 7 shows the typical emission wavelength measured by a Fourier transform spectrum analyzer with a resolution of 7.5 GHz (OSA205, Thorlabs, Newton, NJ, USA). It was centered at 2716.5 nm with a linewidth of 0.12 nm.

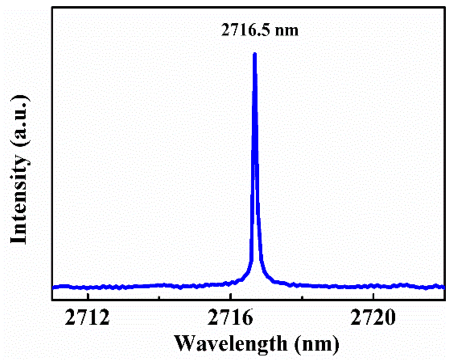

Figure 7. Spectrum of the Q-switched Er:Y_2O_3 laser.

4. Conclusions

In summary, we demonstrated a short-pulse-width repetitively Q-switched Er:Y_2O_3 ceramic laser at ~2.7-µm using a specially designed mechanical switch. Stable pulse trains with 27–38 ns durations and energies of 80.8–27.5 µJ were obtained with a pulse repetition frequency within a range of 0.26 to 4 kHz. A peak power of ~3 kW was realized at 0.26 kHz. The results presented here reveal the potential of Er-doped sesquioxide ceramics in generating short pulses at ~2.7-µm. Improvements in terms of pulse energy should be possible by further optimizing the transmission of the output coupler.

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Author Contributions: Jian Zhang, Dingyuan Tang and Deyuan Shen conceived and designed the experiments; Xiaojing Ren and Yong Wang performed the experiments, analyzed the data, and wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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