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Optics Letters, 2016; 41(18):4309-4311

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Published version: http://dx.doi.org/10.1364/OL.41.004309

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7 September 2017

http://hdl.handle.net/2440/102771

A compact cavity-dumped Q-switched Er:YAG laser

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Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

We report a compact cavity-dumped Q-switched Er:YAG laser that produces pulses with 4.5 ns full-width-half-maximum duration and 10 mJ energy. The resulting 2 MW peak power is the highest reported to date from a 1645 nm Er:YAG laser.

OCIS codes: *(140.3500) Lasers, erbium; (140.3480) Lasers, diode-pumped; (140.3538) Lasers, pulsed*

http://dx.doi.org/10.1364/OL.99.099999

High peak power lasers that emit in the ‘eye-safe’ wavelength band (1.4 to 1.8 μm) are required for a variety of remote sensing applications. For example, high precision, long-distance range-finding applications demand pulses with high peak power and short duration. Practical considerations in the detection system often mean that it is not possible to benefit from the increase in peak power achieved when pulse durations are reduced below a few nanoseconds. Thus, high energy pulses are also required. Currently, eye-safe range-finders use pulses produced by frequency-shifting the 1064 nm output of a Q-switched Nd:YAG laser using an optical parametric oscillator.

Er:YAG lasers, by contrast, can emit directly at 1617 nm or 1645 nm. However, it is difficult to achieve short duration pulses because Er:YAG is an inherently low gain system: Stark splitting of the upper lasing level means that only 21% of its population is available at any time which limits the gain. Further, ground state absorption means that a significant upper level population density is required. This is made more challenging because energy transfer up-conversion (ETU) processes remove ions from the upper lasing level [1].

These limitations are particularly important when trying to achieve short duration pulses using Q-switching [2]. The shortest duration pulses from a passively Q-switched Er:YAG laser were 7 ns with a peak power of only 35 kW [3], while the shortest actively Q-switched Er:YAG lasers pulses that have durations of 14 ns and <20 ns [4,5] with peak powers of 400 kW and 1.5 MW respectively.

The laser reported in [4] used a compact resonator and a Co-Planar Folded zigzag Slab (CPFS) gain medium [6], as it provides the highest gain-length product for a given absorbed pump power and thus enabled the production of short-duration Q-switched pulses. Additionally, [4] showed that the pulse duration is inversely proportional to the pulse energy in a laser optimized for the production of short duration pulses. Thus, shorter duration pulses will necessarily have higher energy. Unfortunately, the surfaces of the CPFS gain medium at which the lasing mode is reflected via total internal reflection proved to be vulnerable to very high intra-cavity peak powers. This necessitated a change of approach to cavity-dumped Q-switched lasers.

Cavity-dumped Q-switched lasers are less common than Q-switched lasers but have three important advantages. Firstly, the lasing threshold is reduced since there is no output coupling during the growth of the giant pulse within the resonator. Secondly, the pulse duration can be as short as the round trip time of the resonator, relaxing the requirement on the length of the resonator and the round-trip gain. Finally, the intra-cavity peak power is no greater than the output peak power because the entire pulse is switched out rather than being the result of transmission through a partially reflecting mirror. The main drawbacks of cavity dumping are the need for an additional intra-resonator polarizer and the need for a higher speed control of the high voltage required for the Pockels cell Q-switch.

Cavity-dumped lasers have been used to produce short duration pulses from a variety of gain media using both electro-optic Pockels cell [7,8] and acousto-optic-modulator switches (AOM) [9]. The latter is limited by the rise-time of the AOM due to the speed of sound in the crystal. Hence electro-optical switches are used to produce the shortest pulses. The shortest duration, high peak power pulses reported to date from an Er:YAG laser had a pulse duration of 1.1 ns and a peak power of 1.5 MW [8]. These pulses were produced by cavity-dumping a partially evolved Q-switched pulse from an injection-seeded fibre-laser-pumped Er:YAG ring oscillator, yielding pulses with an energy of 0.22 mJ. These pulses were subsequently amplified to 1.6 mJ using a double-pass amplifier.

We report the development of a compact cavity-dumped Q-switched Er:YAG laser that is pumped by an inexpensive, broadband 1.47 μm laser diode array and produces pulses with an energy of 10 mJ per and duration of 4.5 ns at 1645 nm from a single oscillator To our knowledge, this is the highest peak power reported at this wavelength.

A schematic of the cavity-dumped Q-switched laser is shown in Fig. 1. A CPFS gain medium [6] was used as it does not require any optical coatings because the lasing mode enters and exits the slab at

Brewster's angle and it can be confined within the slab by total-internal-reflection at the side and end surfaces if the slab is cooled through the top and bottom surfaces. Additionally, it can provide a long pump absorption length if end-pumped, as shown, thus allowing the use of broadband low-brightness pump sources and low-concentration Er dopings.

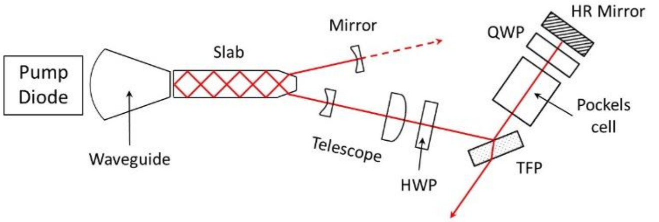

Fig. 1. A schematic of the cavity-dumped Q-switched Er:YAG laser. The red line represents the path of the laser mode. Abbreviations: HWP is a half-wave plate, TFP is a thin-film polarizer, QWP is a quarter-wave plate, HR is high reflectance. The Mirror was slightly transmitting to allow convenient diagnostics of the stored energy evolution using the dashed beam.

The gain medium is end-pumped by a fast-axis-collimated broadband 1.47 μm InGaAsP laser diode that is mounted on a water-cooled copper block. The diode produces 10 ms duration pulses with peak power of up to 60 W at a 12 Hz pulse repetition frequency. A glass lens duct was used to guide the pump light into the slab. In the fast-axis (vertical) direction, the height of the pumped region was 0.7mm. In the slow axis (horizontal) direction, the rapidly diverging pump light is trapped within the slab by total internal reflection at the slab surfaces.

Initial tests used the 0.5 at. % Er-doped slab used for the earlier Q-switched laser development [4]. However, the high threshold pump density and the small size of the laser mode limited the pulse energy to a few millijoules before laser-induced damage occurred.

The results presented here were obtained using a 0.25 at. % doped slab, which reduced losses due to ETU and allowed a larger lasing mode but also required the use of a longer slab. The Er:YAG slab that was 67.2 mm long, 4.0 mm wide and 4.0 mm high. It was mounted in a laser head consisting of two water-cooled copper blocks that were mounted to the top and bottom surfaces. Stress relief and excellent thermal contact was achieved by placing indium sheets between the Er:YAG slab and the copper blocks.

The resonator incorporates a telescope to reduce the fluence incident upon the half-wave plate (HWP), thin-film polarizer (TFP), rubidium-titanyl-phosphate Pockels' cell (PC) and quarter-wave plate (QWP) to minimize the possibility of laser induced damage. All of these components were anti-reflection coated.

The HWP is used to rotate the polarization of the lasing mode from π polarization in the gain medium to σ polarization at the TFP, where it is reflected. This configuration maximizes the efficiency of the Q-switched laser as TFPs generally are more efficient at reflecting σ polarization than transmitting π polarization.

The combination of the TFP, PC and QWP enables both the Q-switching and the cavity dumping. The orientation of the QWP was adjusted to provide high output coupling during pumping without any voltage applied to the PC. The high output coupling during pumping prevents lasing and allows the build-up of a significant population inversion. Once pumping is complete, the cavity is Q-switched to low loss mode by applying a quarter wave voltage (1.1 kV here) to the Pockels cell. This reduces the output coupling to zero and allows the rapid buildup of the intra-resonator energy, limited only by the losses in the cavity. Once the desired stored laser mode energy is achieved, it is "dumped" (out-coupled) through the TFP by rapidly removing the voltage applied to the Pockels cell.

The temporal variation in the energy stored in the resonator, as observed through the Mirror, is plotted in Fig 2. The asymmetry in this pulse shape is due to low output coupling which leads to a rapid rise time and a slower fall time.

The maximum pulse energy and peak power will occur if the cavity is dumped near the peak. However, the stored energy can also be dumped before the peak is reached, to yield a so-called partially evolved Q-switched pulse. This results in a small reduction in output energy but significantly reduces the fluence to which the laser components are exposed and thus reduce the likelihood of laser induced damage. Note, Fig 2 shows the case in which 52 W peak pump power was used as this plot cannot be obtained when the maximum pump power (57 W) is used since laser induced damage will result.

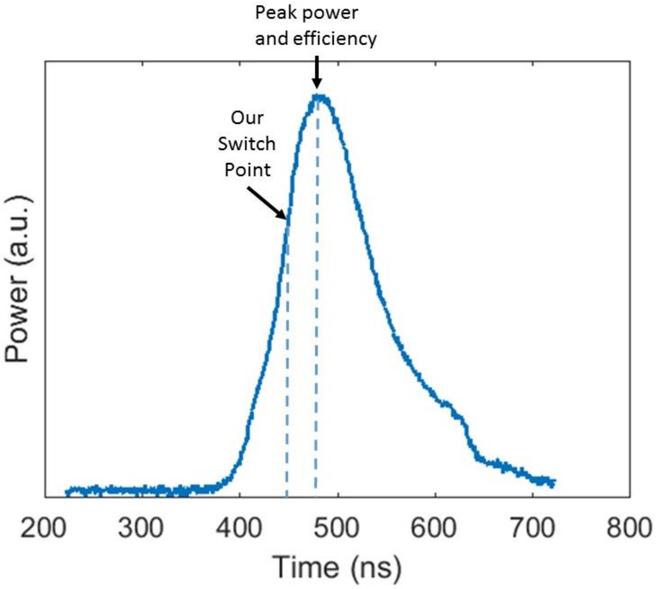

Fig. 2. A plot of evolution of the energy stored in the cavity laser mode, as observed through the partially transmitting mirror when 52 W of pump power is used and the intracavity mode is not dumped out the output port.

Effective operation of a cavity-dumped laser requires electronics that can rapidly switch the high voltage on the Pockels cell. In particular, it must be capable of a switch-off time much less than the resonator round trip time, in this case 4.5 ns. We used a custom Starfire HV Pulser from Quantum Technology. A typical cavity-dumped pulse is plotted in Fig. 3. We attribute the slight plateau and oscillation at the end of the pulse to ringing in the photodetector.

The threshold peak pump power for cavity-dumped Q-switched operation was approximately 34 W, corresponding to a pump-pulse energy of 340 mJ. The energy of the laser pulses is plotted as a function of time delay after Q-switching for several pump pulse energies in Fig. 4. As would be expected, increasing the pump pulse energy decreases the pulse build-up time. All of the pulses had a wavelength of 1645 nm.

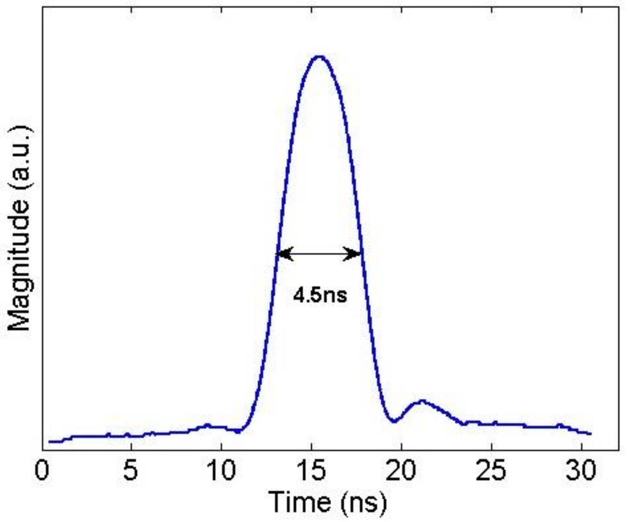

Fig. 3. A plot of a typical cavity-dumped pulse with 4.5 ns FWHM duration. The detector used had a rise time of 180ps and the oscilloscope had a bandwidth of 200 MHz with a sample rate of 2 Gs/s.

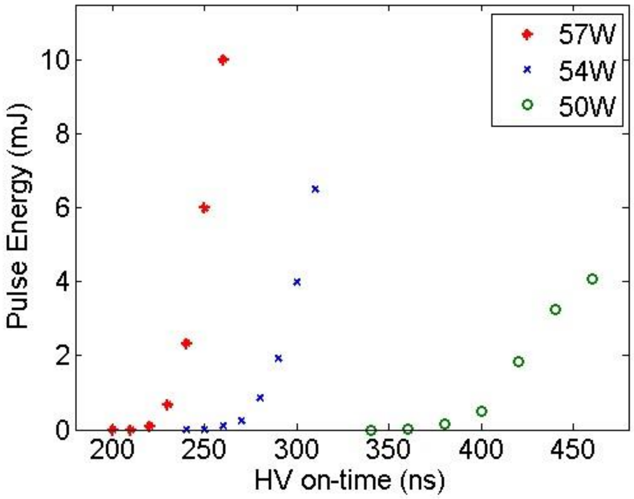

Fig. 4. Plot of pulse energy as a function of time delay after Q-switching for several pump powers.

The maximum output pulse energy was a 10 mJ, with a 4.5 ns full-width-half-maximum duration, corresponding to a peak power of 2.0 MW. A typical beam profile with fits to a TEM_{00} Gaussian is shown as Fig. 5. The ellipticity of the laser mode is due to the asymmetry of the laser slab geometry.

In summary, we have demonstrated a compact cavity-dumped Q-switched Er:YAG laser that can produce pulsed TEM_{00} beams at 1645 nm with 10 mJ pulse energy and 4.5 ns duration. The 2.0 MW peak power is the highest reported for an Er:YAG laser at 1645 nm. Additionally, the peak power could be doubled simply by polarization combining an additional laser diode array and increasing the area of the pumped gain volume. This system would thus be competitive with the OPO-shifted Q-switched Nd:YAG systems currently used in range-finder lidar systems.

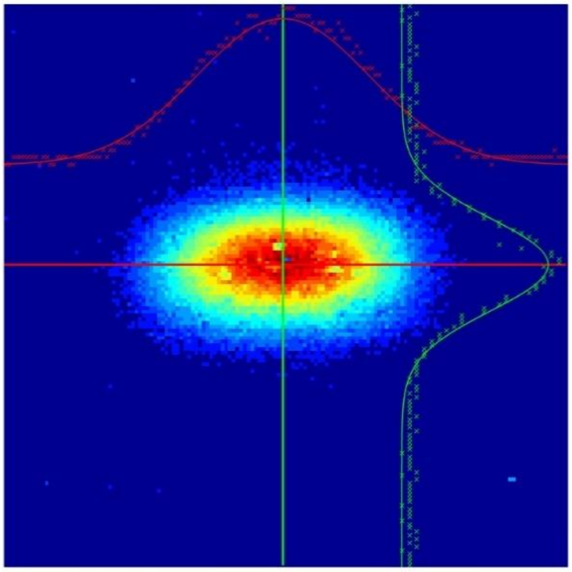

Fig. 5. A typical beam profile of the output of the cavity-dumped laser output showing fits to Gaussian.

Funding.
This work was financially supported by the Australian Research Council under ARC Linkage Grant LP110200734. In-kind and funding support was also provided by BAE Systems Australia (Holden Hill).

Acknowledgment. The authors acknowledge Martin O'Connor and Gerry Smith from BAE Systems Australia (Holden Hill) for useful discussions. We also acknowledge technical support from Bob Chivell from the University of Adelaide, School of Physical Sciences workshop.

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