

Diode-pumped Alexandrite lasers in Q-switched and cavity-dumped Q-switched operation

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Abstract: We present the first study of Q-switched Alexandrite lasers under continuous-wave diode-pumping with operation up to 10 kHz repetition rates in TEM₀₀, with spatial quality M² 1.15. With a pulsed-diode dual-end-pumped design, pulse energy is scaled to a record level of 3 mJ. We also demonstrate, for the first time, cavity-dumped Q-switching of diode-pumped Alexandrite lasers under continuous-wave and pulsed diode-pumping, up to 10 kHz. Pulse energy of 510 μJ is demonstrated with 3 ns pulse duration and 170 kW peak power, in TEM₀₀ with M² < 1.2. Second harmonic generation of the cavity-dumped Q-switched pulses was used to generate UV wavelength 379 nm with conversion efficiency of 47%.

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1. Introduction

Alexandrite (Cr³⁺-doped chrysoberyl) is a vibronic solid-state laser material with broadly tunable lasing capability (~ 701 – 858 nm [1,2]) and many superior thermo-mechanical properties including high thermal conductivity, high mechanical strength, and high optical damage threshold that make it suitable for high power operation [1,3]. Alexandrite lasers have been well developed since the 1970s but have largely been lamp-pumped [1–3]. Its broad absorption spectrum in the visible region however means it can be directly diode-pumped using red (AlGaInP) laser diodes, offering the potential of order-of-magnitude higher efficiency. Direct diode-pumping of Alexandrite was first demonstrated by Scheps in 1990 [4] and then in 1993 demonstrating 25 mW with 28% slope efficiency [5]. Red-diode lasers have developed considerably since those first experiments and new demonstrations have been made in recent years at the sub-Watt level [6–8], greater than Watt level with diode array [9], fibre-delivered diode format [10], and diode-stack side-pumped Alexandrite slab geometry [11]. Recently we demonstrated 26.2 W with 49% slope efficiency in end-pumped geometry [12] showing the potential for significant power scaling of diode-pumped Alexandrite with good efficiency.

For many applications (e.g. remote sensing; multi-photon microscopy) it would be desirable to have short pulsed laser operation to provide high peak power and high temporal resolution. Alexandrite has a long upper-state lifetime of 262 μs at room temperature [1] and this is favourable for good energy storage in Q-switched operation under diode-pumping. In our previous work [12] in 2014 we demonstrated the first Q-switched diode-pumped Alexandrite laser producing pulse energy of 0.74 mJ at 1 kHz pulse repetition rate. Munk *et al* subsequently in 2015 also demonstrated Q-switched operation with 0.8 mJ pulse energy but lower 35 Hz pulse rate [13]. The broad emission tuning band also has potential for modelocked ultra-short pulse formation, down to ~ 10 fs, in principle. Sub-picosecond pulses were not achieved in earlier attempts with active modelocking [14] and passive modelocking with saturable absorbers [15] from lamp-pumped Alexandrite systems. Recently, Kerr lens modelocking has produced 170 fs pulses with 780 mW average power from an Alexandrite laser pumped at 532 nm, by a frequency-doubled Nd-laser [16]. These very recent Q-switched and modelocked results show interesting potential for tunable-wavelength, short-pulse operation of Alexandrite lasers.

One of the potential applications of wavelength tunable Alexandrite lasers is for remote sensing based on LIDAR for atmospheric sensing, and also altimetry and vegetation monitoring. If this is performed from a satellite-based platform it can provide global coverage. For atmospheric sensing high pulse energies are normally required (multi-ten mJ class) due to the low signal return, but pulse duration can be long (multi-ten to even 100 ns) and moderate pulse rates (~ 100 Hz) are used due to the large scale sizes of interest. For altimetry and vegetation monitoring, signal return is higher and lower pulse energy (sub-mJ or low mJ class) is possible, but for high spatial height resolution short pulses (ns-class) are required, (e.g. 1 ns of pulse duration corresponds to a round-trip resolution of 15 cm in height profiling), and high pulse rate (multi-kHz) is desirable for good lateral spatial resolution and high sampling rate. The recent Q-switched pulse demonstrations in diode-pumped

Alexandrite [12,13] being only sub-mJ need considerable scaling if they are to address atmospheric LIDAR. Furthermore, the low gain of Alexandrite gives rather long Q-switched pulse duration (~ 50 ns in [12] and 350 ns in [13]), and this lacks the temporal resolution to address altimetry applications.

In this paper, we describe recent developments we have made and results we have demonstrated in Q-switched operation of diode-pumped Alexandrite laser systems. In particular we have been looking towards better addressing the requirements of remote sensing: raising the Q-switched pulse energy; finding an effective approach to generate short (few-ns-class) pulses; and increasing the pulse rates to multi-kHz and beyond.

Initially, we present in this study the results of the first Q-switched operation of a continuous-wave (CW) diode-pumped Alexandrite laser. Using a BBO Pockels Cell, Q-switching is demonstrated at repetition rates up to 10 kHz, an order of magnitude higher pulse rate than our prior demonstration [12]. Pulse energy of 195 μJ is achieved at 5 kHz with pulse duration ~ 150 ns. To scale pulse energy an enhanced diode-pumped Alexandrite laser is devised with dual-end-pumped rod and higher energy pulsed diode-pumping. Output pulse energy of 3 mJ is achieved at 500 Hz and pulse duration 70 ns. This is the highest pulse energy to date from a diode-pumped Alexandrite laser system.

The low gain of Alexandrite precludes the standard Q-switching method from achieving few-ns-class pulse durations, such as required for altimetry LIDAR. To this end, we have made a study of a cavity-dumped Q-switching approach. Using cavity-dumped Q-switching of a CW diode-pumped Alexandrite we demonstrate short pulse duration 2.9 ns independent of pulse repetition rate and up to 10 kHz, including 170 μJ pulse energy at 4 kHz. Using a dual-end-pumped Alexandrite laser with pulsed diode-pumping, cavity-dumped pulse energy was scaled to 510 μJ and short 3.0 ns pulse duration at multi-kHz pulse rate, corresponding to peak power 170 kW. Using cavity-dumped Q-switched pulses at 758 nm, demonstration of second harmonic generation (SHG) was used to produce UV radiation at wavelength 379 nm with conversion efficiency of 47%.

2. Q-switched diode-pumped Alexandrite lasers

In this section we investigate Q-switched operation of two types of Alexandrite laser systems. The first is a CW diode-pumped Alexandrite laser with single-end-pumping, as shown schematically in Fig. 1(a). The second is a dual-end-pumped Alexandrite laser with pulsed diode-pumping delivered from the two ends of the rod, as shown in Fig. 1(b), to provide higher energy scaling potential.

2.1 Q-switched CW diode-pumped Alexandrite laser operation

Figure 1(a) is the schematic of the Q-switched CW pumped Alexandrite laser. The gain medium was an Alexandrite rod with 0.22 at.% Cr-doping concentration and dimensions of 4 mm diameter and 10 mm length. The end faces of the rod were plane-parallel and anti-reflection (AR) coated at the lasing wavelength ~ 755 nm. The rod was mounted with its b -axis orientated horizontally in a water-cooled copper heat sink and its temperature maintained at 18°C.

The red diode pump was a multi-bar module, the same as described in [12], operating nominally at 638 nm and capable of producing greater than 60 W power in CW mode. It was spatially redistributed to reduce the high horizontal M^2 at the expense of increasing the vertical M^2 , providing M^2 of 231 in the horizontal (x) and 68 in vertical (y). A combination of cylindrical and spherical lenses was used to bring the asymmetric pump to a focus at the rod, with full-width half-maximum (FWHM) spot size ~ 350 μm (x) by 250 μm (y). A half-wave plate was used to rotate the near-linear polarisation of the pump module parallel to the high absorption b -axis of the Alexandrite rod, and the crystal absorbed 95% of the incident pump.

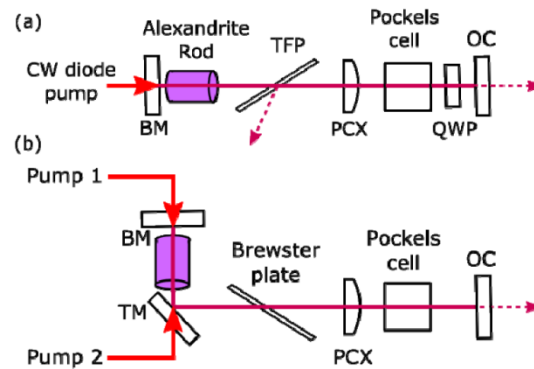


Fig. 1. Schematic of (a) Q-switched CW diode-pumped Alexandrite laser; (b) Q-switched dual-end-pumped Alexandrite laser with pulsed diode-pumping.

The laser cavity was formed of two plane mirrors: a dichroic back mirror (BM) which was highly reflecting (HR) at the laser wavelength (~ 755 nm) and had high transmission (HT) ($T > 95\%$) at the pump wavelength (~ 638 nm) and an output coupler (OC) with nominal reflectivity, $R = 96.5\%$ at the laser wavelength. An intra-cavity plano-convex lens (PCX) of focal length $f = 100$ mm was used to control the size of the laser TEM_{00} mode at the pumped region in the rod and also control cavity stability in the presence of the rod's thermally-induced lensing. The cavity length was approximately 195 mm.

Q-switching was achieved by incorporating a Pockels cell within the laser cavity. The Pockels cell crystal was β -Barium Borate (BBO), chosen as it is a good electro-optic material for high repetition rates with its low piezoelectric ringing and also has high damage threshold. The Pockels cell was operated with a transverse electrode arrangement and had quarter wave voltage ~ 2.2 kV. A quarter-wave plate (QWP) in combination with an intra-cavity thin film polariser (TFP) was also incorporated into the cavity to passively inhibit lasing when no voltage was applied to the Pockels cell. This meant high voltage was only needed to be applied to the Pockels cell for a short period when Q-switching was required, which is desirable for the good operation and lifetime of the cell.

The pulse repetition frequency (PRF) in this current study was varied between 1 and 10 kHz to demonstrate high (multi-kHz) pulse rate operation, with the upper PRF limited only by the driver electronics of our Pockels cell. Stable and clean Q-switched pulses were obtained throughout this repetition range. This is the first demonstration of Q-switching with a CW diode-pumped Alexandrite laser, to date, as previous demonstrations [12,13] used pulsed diode-pumping at lower repetition rates.

The variation of pulse energy with CW diode pump power is shown in Fig. 2, for two repetition rates of 5 kHz and 10 kHz. At 5 kHz, pulse energy 195 μ J and 150 ns pulse duration at wavelength 759 nm is obtained at about 25 W of CW diode pump power. The slope efficiency was $\sim 6\%$. At 10 kHz the corresponding pulse energy is 150 μ J. Although slightly lower in pulse energy at twice the repetition rate this corresponds to a higher slope efficiency of $\sim 9\%$. The higher slope efficiency at 10 kHz is consistent with the shorter interval between pulses (t_p) compared to the upper-state lifetime for Alexandrite ($\tau = 260$ μ s) [1], leading to a lower spontaneous loss factor, $\eta_{sp} = \tau/t_p(1 - \exp[-t_p/\tau])$. For 10 kHz and 5 kHz the spontaneous loss factor is 56% and 36%, respectively, similar to the ratio between the slope efficiencies. For this system, the intracavity loss, L , is also estimated to be $\sim 4\%$, so the output coupling, $T = 3.5\%$, is non-optimal ($= T/(T + L) = 47\%$). The beam overlap factor between the laser and pump mode is estimated to be $\sim 50\%$ so there is considerable scope for improving efficiency with reduced cavity loss, optimised output coupling and cavity mode design.

The spatial beam quality M^2 parameter for the Q-switched output mode was measured using the second moment beam size through the focused caustic as shown in Fig. 3 for the case at 5 kHz and maximum pump power. The measured M^2 gives a value of 1.15 in both x and y dimensions, showing the beam to be a near diffraction-limited TEM₀₀ mode, but with some astigmatism due to the asymmetric pump size.

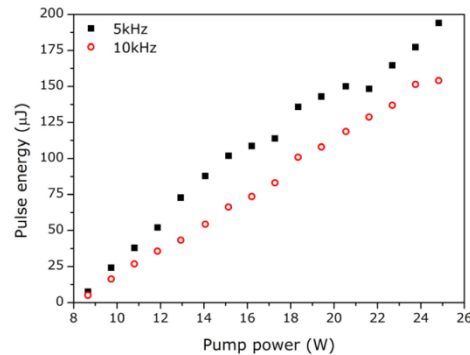


Fig. 2. Variation of Q-switched pulse energy as function of CW diode pump power, at 5 kHz and 10 kHz repetition rate.

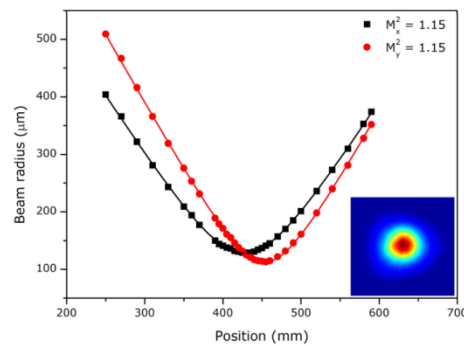


Fig. 3. M^2 caustic fit for Q-switched output at 5 kHz and 25 W pump power. Inset: screenshot of spatial profile at 5 kHz, 195 μ J pulse energy.

2.2 Q-switched dual-end-pumped Alexandrite laser operation

To investigate scaling the pulse energy, an enhanced diode-pumped Alexandrite laser was configured as shown in Fig. 1(b). Instead of single-end-pumping as performed in the CW pumped system and in prior Q-switched Alexandrite work [12,13], dual-end-pumping was employed, with a second identical pump module pumping the other end of the rod and operated in pulsed, rather than CW, mode. As well as doubling the potential pump power, dual-end-pumping provides twice the active Cr-ions in the absorption depth (~ 1.7 mm, in 0.22 at.% Cr-doped Alexandrite) at the two rod ends. In addition, since pump excited state absorption (ESA) is present in Alexandrite [17] and its strength is inversion dependent, distributing the inversion at the two rod ends, rather than all at one end, is favourable for decreasing this loss mechanism and this is predicted to enhance laser efficiency [18]. Running in pulsed mode allows operation at higher peak power whilst negating the impact of thermal lensing by operating at suitably low duty cycle to reduce average pump power and hence thermally-induced lensing in the rod.

A further modification of this system compared with the singly-end-pumped system described in Section 2.1 and our prior work [12] was the use of a thermo-electric (Peltier) controlled Alexandrite crystal oven, for rapid and wider tuning range control of the

temperature of the Alexandrite rod (from 25 to 125°C). This was to investigate the effect of crystal temperature on the performance of the Alexandrite laser, since in contrast to most laser materials, Alexandrite experiences enhanced gain at higher temperatures [1].

The schematic of the dual-end-pumped Alexandrite laser system is shown in Fig. 1(b). The output beams from the pump modules were brought to a focus at each end of the rod using a combination of cylindrical lenses providing near-circularised pump beams $\sim 300\ \mu\text{m}$ FWHM. The Alexandrite rod was 4 mm diameter and 10 mm length as before. The laser had an 'L'-shaped cavity formed by the same dichroic BM described in Section 2.1, a 45° incidence turning mirror (TM) and an OC with reflectivity $R = 95\%$. The turning mirror (TM) was HR for the laser wavelength and HT for the pump wavelength to allow access for the second pump beam.

Prior to configuring the cavity for Q-switched operation, the performance of the cavity formed simply of the BM, TM and OC in a compact L-shaped configuration (cavity length $\sim 40\ \text{mm}$) was tested in free-running mode to assess the benefit of dual-end-pumping compared to single-end-pumping. Figure 4 shows the free-running energy curves for the compact L-shaped Alexandrite laser cavity for three cases: single-end-pumping through BM; single-end-pumping through TM; and dual-end-pumping when both pump beams are simultaneously present. In all cases the pump duration was 250 μs and PRF was 500 Hz. The crystal temperature was kept at 40°C

For single-end-pumped operation with pumping only through BM (open black squares) a free running energy of $\sim 5.3\ \text{mJ}$ was measured at a pump energy of 21.8 mJ with slope efficiency 30.1%. For the case where single-end-pumping was through TM (filled black squares), the energy obtained was 4.9 mJ at pump energy 22.4 mJ with slightly poorer slope efficiency of 28.8%. When both pump modules were operated for dual-end-pumping (red circles), the slope efficiency of the system increased to 38.5%, and the maximum energy was 14.8 mJ, for combined pump energy of 44.2 mJ. The results therefore show an enhancement of slope efficiency when dual-end-pumping for the free-running case.

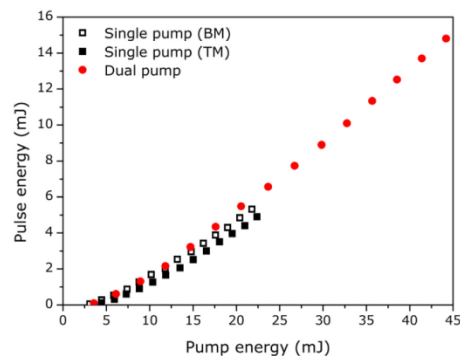


Fig. 4. Comparison of single- and dual-end-pumped Alexandrite laser output energy under free-running conditions.

For Q-switching, the cavity was extended as shown in Fig. 1(b) with inclusion of a BBO Pockels Cell, a Brewster plate to provide polarisation loss for lasing hold-off with voltage on the Pockels cell, and a PCX lens of focal length 100 mm whose location was chosen to help optimise the laser spatial mode to the pumped gain region in the rod and maintain stable operation of laser cavity. No QWP was used in this system as only low duty cycle operation was used.

It was possible to Q-switch with, or without inclusion of the Brewster plate as a polarisation loss element. Without the Brewster plate, Q-switching was achieved by using the polarisation gain switching approach [12,15] that can be applied to Alexandrite lasers because it experiences gain almost exclusively for polarisation parallel to the crystal *b*-axis. By

running the Pockels cell at its quarter wave voltage, with 90° polarisation rotation occurring on its double-pass, the cavity flux experiences double-pass gain in the gain medium on average only every second round-trip, but sees the full cavity losses in each round-trip. In this way the Pockels cell can inhibit lasing up to twice the threshold pumping compared to when no voltage is applied to the Pockels cell.

Figure 5 shows results of polarisation gain-Q-switched pulse energy as function of pump energy without Brewster plate, for pump duration 100 μ s and 500 Hz pulse rate. Pump threshold is approximately 4 mJ and clean Q-switching is observed up to 8.14 mJ, where Q-switched pulse energy is 0.62 mJ. This corresponds to optical-to-optical efficiency 7.4% and laser slope efficiency 14.5%. Pulse duration was ~ 200 ns, spatial quality M^2 parameter was 1.3 and wavelength was 757 nm with a bandwidth of 0.8 nm. When pumping above 8.14 mJ (approximately twice threshold), pre-pulse breakthrough laser emission occurred, as expected, prior to Pockels cell Q-switching at the end of the pump pulse. Since this limits the pulse energy scaling, in the following results the intra-cavity Brewster plate was incorporated.

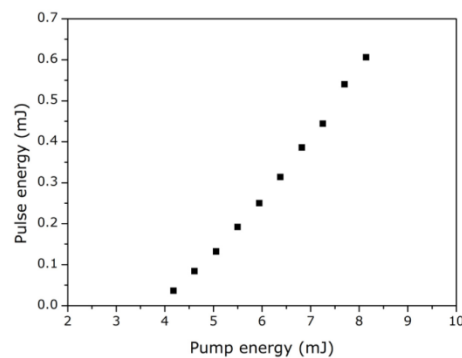


Fig. 5. Variation of Q-switched output energy with pump energy, using polarisation-gain switching with no Brewster plate in cavity.

With the Brewster plate incorporated, Q-switching of the dual-end-pumping Alexandrite rod was operated with longer pump pulse duration 200 μ s and pulse rate 500 Hz, and providing up to a maximum combined dual-end-pump energy of 30 mJ. The crystal temperature was 40°C , found to be optimal for this pump duration in a temperature tuning measurement.

Figure 6 displays the Q-switched pulse energy and corresponding pulse duration with pump energy for this dual-end-pumped configuration. At 30 mJ pump energy, 3 mJ Q-switched pulse energy was obtained, corresponding to an optical-to-optical conversion efficiency of 10%. The resulting slope efficiency was $\sim 14.2\%$. The 3 mJ result is the highest Q-switched pulse energy from a diode-pumped Alexandrite laser, a 4-times increase on our previous work [12]. The pulse duration at maximum output pulse energy was 70 ns. The wavelength was centred at 753 nm and had a bandwidth ~ 7 nm (FWHM) and exhibited modulation with a periodicity ~ 4.8 nm. This modulation is consistent with a birefringent filtering effect in the Alexandrite crystal when lasing polarisation is not completely parallel to the b -axis. We believe the effect was caused (or enhanced) by misalignment of the vertical orientation of the intra-cavity Brewster plate, evidence by a measured sizeable ejected power $\sim 4\%$ compared to the power from the main output coupler.

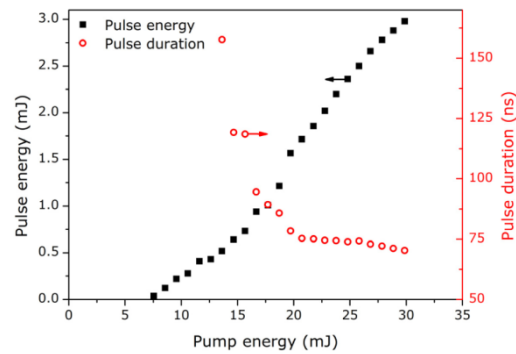


Fig. 6. Q-switched pulse energy (black squares) and pulse duration (open red circles) for the dual-end-pumped Alexandrite laser.

A further investigation was made of the spectral tuning of the Q-switched dual-end-pumped laser. In this study, the laser cavity had been modified by extending the cavity length and produced a doughnut-shaped (LG_{01}) mode. The formation of a doughnut mode has been generated in the past by operating near the edge of cavity stability and using the spherical aberration in the thermally-induced lens of the laser rod as a spatial filter [19,20]. The measured spatial M^2 parameter was 2.6 in the horizontal and 2.2 in the vertical. For a perfect doughnut-mode (the superposition of a TEM_{01} and TEM_{10} mode) the expected M^2 parameter is 2.0, suggesting the presence of higher order components in our doughnut mode.

The Q-switched pulse energy was 1.68 mJ for 20 mJ pump energy. With this system, the Brewster plate was replaced by a 0.5 mm thick quartz plate acting both as the polarisation loss element for Q-switching and simultaneously as a birefringent filter (BiFi) used for wavelength tuning. Figure 7 shows results of Q-switched pulse energy and pulse duration as a function of laser wavelength. Tuning was achieved between 723 nm to 784 nm (61 nm tuning range). The maximum pulse energy was 1.6 mJ at 757 nm, with pulse duration of 88 ns. It is noted that the lasing tuning range would have been partially limited by the spectral coatings (AR/HR) of the cavity optics, including the Alexandrite rod and Pockels cell which were selected for optimised operation near 760 nm, rather than across the fuller tuning band of Alexandrite.

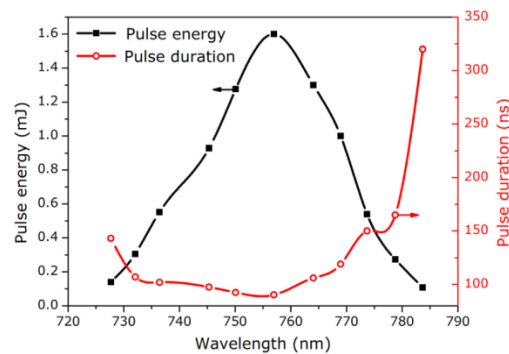


Fig. 7. Wavelength tuning of Q-switched dual-end-pumped Alexandrite doughnut-mode laser with intra-cavity BiFi tuning element.

3. Cavity-dumped Q-switched Alexandrite lasers

Q-switched pulse durations are dependent on the gain dynamics of the laser material and it is well known that high pulse repetition rates and low-gain lasers produce long pulse durations when Q-switched. The Q-switched results for Alexandrite in this study have so far yielded

pulse durations ≥ 70 ns. Some applications require or would benefit from shorter pulse durations. For instance, altimetry requires short pulses to provide high resolution time-of-flight distance measurements. Short duration pulses also possess higher peak power for a given pulse energy and this is useful for enhancing the efficiency of nonlinear optical processes, including frequency conversion or for material processing. Since the low gain cross-section of Alexandrite effectively precludes very short Q-switch pulse formation we have taken a cavity-dumped Q-switched approach [21,22] to generate few nanosecond-class pulses.

In this section we study two cavity-dumped Q-switched Alexandrite laser systems: one with CW diode-pumping and the second with dual-end pulsed-pumping to provide pulse energy scaling. These two systems are shown schematically in Fig. 8(a) and 8(b), respectively. They are modified versions of the standard CW-pumped Q-switched and dual-end-pumped systems previously described in Sections 2.1 and 2.2, and use the same nomenclature. In each of these systems the OC is now replaced by a HR mirror. The Q-switching is performed by switching on the quarter-wave voltage to the BBO Pockels cell in combination with a QWP. Cavity Q is made maximal and the cavity flux builds up but is not released since there is no output coupling (just residual passive intra-cavity losses). Output coupling is provided by cavity-dumping from the intra-cavity TFP by rapidly switching off the voltage to the Pockels cell, ideally when the cavity flux has its maximum value. If the switch is fast enough the cavity radiation is extracted in a single round-trip. In practice, the pulse duration is a combination of round-trip time and Pockels cell switching speed. This is notably distinct from “standard” Q-switching where the output pulse is a partial leakage of the intra-cavity flux and has the same duration as the intra-cavity flux build-up time. This can be slow and also varies in time-scale with dynamics of the gain medium. In cavity-dumped Q-switching the flux is stored in the cavity and output pulse duration is independent of gain dynamics or PRF and just depends on round-trip time and switching speed. This can be just a few nanoseconds, and in principle much shorter.

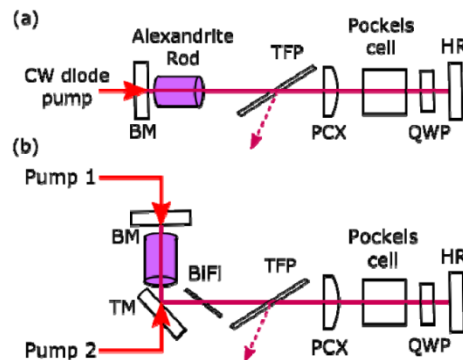


Fig. 8. Schematic of (a) cavity-dumped Q-switched CW diode-pumped Alexandrite laser; (b) cavity-dumping Q-switched dual-end-pumped Alexandrite laser with pulsed diode-pumping.

3.1 Cavity-dumped Q-switching of CW diode-pumped Alexandrite laser

The configuration used for cavity-dumped Q-switching of the CW diode-pumped Alexandrite laser is shown in Fig. 8(a). The single-end-pumped Alexandrite rod with diameter 4 mm and length 10 mm was maintained at 18°C. The intra-cavity PCX lens had focal length 100 mm. The physical cavity length was 190 mm, which includes refractive indices of cavity elements, corresponding to a round-trip cavity time ~ 1.4 ns. The rise and fall time (20% to 80% points) of the quarter-wave voltage to the BBO Pockels cell was measured to be 1.7 ns and 2.4 ns, respectively. The delay between high voltage switching on the Pockels cell and switching off was optimised to maximise cavity-dumped output pulse energy from the TFP. This delay was

varied for different pump power and PRF as it represented the build-up time to reach the maximum intra-cavity flux.

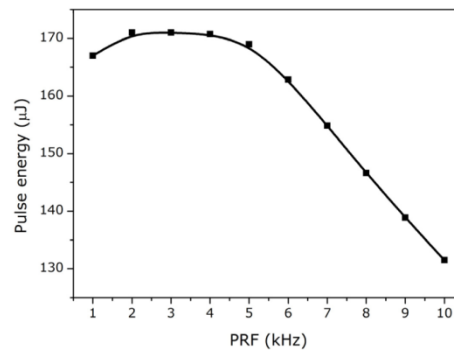


Fig. 9. Variation of cavity-dumped Q-switched pulse energy with pulse repetition rate for CW diode-pumping.

Figure 9 depicts the variation of cavity-dumped Q-switched pulse energy with repetition rate from 1 to 10 kHz for a constant CW pump power of 17 W. The pulse duration was approximately 2.9 ns, measured with a fast 70 ps rise-time photodetector, for all repetition rates. Pulse energy was approximately constant at 170 μJ up to PRF 4–5 kHz. Above this pulse rate, which is approximately the inverse upper state lifetime of Alexandrite ($\sim 260 \mu\text{s}$), the pulse energy decreased nearly linearly with repetition rate, as expected. At 10 kHz the pulse energy was 130 μJ . This is the first time that cavity-dumped Q-switching of diode-pumped Alexandrite laser has been demonstrated.

3.2 Cavity-dumped Q-switching of dual-end-pumped Alexandrite laser

The L-shaped cavity configuration for the dual-end-pumped Alexandrite laser is shown in Fig. 8(b). The crystal temperature was 60°C. The cavity round-trip time was approximately 1.9 ns. In addition to the cavity-dumped Q-switching elements (Pockels cell, QWP, TFP) a birefringent filter (BiFi) was additionally included for wavelength control. It also provided the spectral narrowing required for efficient phase-matched second harmonic generation (SHG), as described later. In this configuration, cavity-dumped Q-switching was once again realised in the manner described for the CW diode-pumping, but in this case under pulsed-pumping conditions.

Cavity-dumped Q-switching was demonstrated for pulse repetition rates between 1 and 4 kHz. Pulse energy of 0.51 mJ was achieved at 1–3 kHz, and 0.41 mJ at 4 kHz. The laser pulse duration was measured to be 3.0 ns at all repetition rates, and the temporal profile is shown in Fig. 10. The results of cavity-dumped pulse energy as function of pump energy for the case of 1 kHz pulse rate is shown in Fig. 11, for three different pump pulse durations (200, 150 and 100 μs). Laser slope efficiency is seen to improve for shorter pump pulses due to the reduction in losses from spontaneous emission.

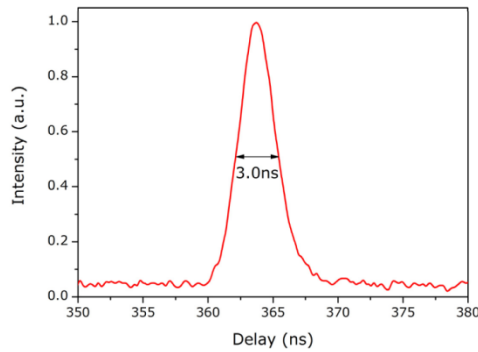


Fig. 10. Temporal profile of the cavity-dumped Q-switched output.

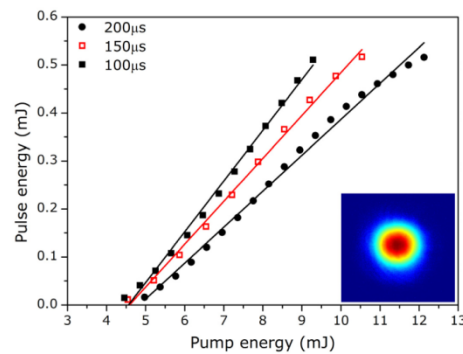


Fig. 11. Pulse energy of cavity-dumped Q-switched Alexandrite laser as function of pump energy for different pump durations, at PRF 1 kHz. Inset: screenshot of spatial profile for 200 μ s pump pulse.

In each case pumping was increased to reach just above 0.5 mJ. This limit was set as a safeguard in case laser-induced damage might occur for higher pulse energy, and would have curtailed the study. No damage was observed during this study, which is promising as it shows further energy scaling should be possible.

For the 1–3 kHz pulse energies of 0.51 mJ and 3.0 ns duration, this corresponds to a peak power of 170 kW. Compared to the best standard Q-switching case of 3 mJ and 70 ns pulse duration (peak power $\sim$ 43 kW), this is 4-times higher peak power. The wavelength was 758 nm and the spatial profile, shown in the inset to Fig. 11, was TEM₀₀ mode with caustic M^2 measurement giving $M^2_x = 1.18$ and $M^2_y = 1.24$.

3.3 Second harmonic generation of the cavity-dumped Q-switched Alexandrite laser

Another key benefit of short cavity-dumped Q-switched pulses is their high peak power and capability to enhance nonlinear frequency conversion. To investigate this, the output of the dual-end-pumped, cavity-dumped Q-switched Alexandrite laser at 1 kHz was brought to a focus at a 4 x 4 x 10 mm BBO nonlinear crystal with a 100 mm focal length lens. With the wavelength of the Alexandrite laser at 758 nm, second harmonic UV light was generated at 379 nm, and the measured spectrum of both is shown in Fig. 12.

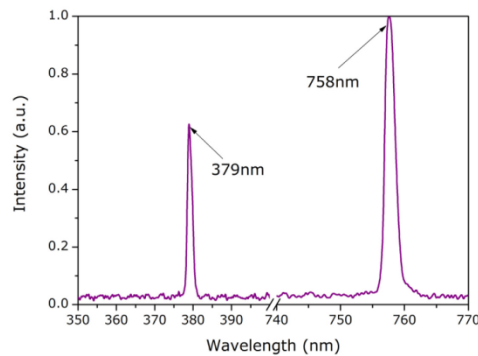


Fig. 12. Lasing spectrum of dual-end-pumped, cavity-dumped Q-switched Alexandrite laser (758 nm) and second harmonic (379 nm).

Figure 13 shows the variation of pulse energy of both the fundamental (filled black squares) and second harmonic radiation (open purple squares), along with conversion efficiency (red circles). For a fundamental pulse energy of 395 μJ , 184 μJ of second harmonic was produced, corresponding to a conversion efficiency of $\sim 47\%$. This shows excellent promise for efficiently generating tunable UV radiation, using Alexandrite lasers.

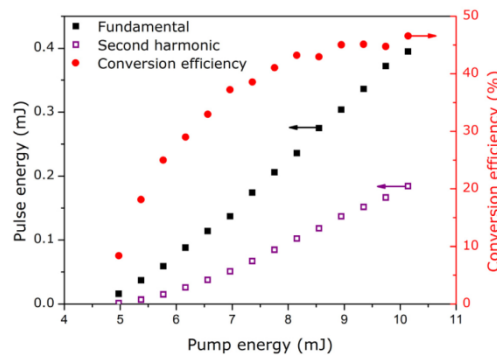


Fig. 13. Pulse energy of fundamental (filled black squares) incident on, and second harmonic (open purple squares) generated by BBO nonlinear crystal, along with conversion efficiency (red circles).

4. Conclusions

We have reported the first demonstration of Q-switching a CW diode-pumped Alexandrite laser. We have demonstrated Q-switching in the multi-kHz PRF range, 1–10 kHz, with upper rate limited only by our Pockels cell driver electronics. At the maximum pulse rate of 10 kHz, pulse energy of 150 μJ was produced at wavelength 759 nm and high spatial quality TEM_{00} mode, with $M^2 = 1.15$ in both horizontal and vertical dimensions. This is the highest Q-switched pulse rate in Alexandrite to our knowledge and order of magnitude higher than our prior diode-pumped Alexandrite work [12].

Pulse energy was scaled by employing a dual-end-pumped laser configuration with pulsed diode-pumping. We showed the improvement in free-running mode of laser slope efficiency of dual-end-pumping compared to single-end-pumping. In Q-switched operation, we demonstrated 3 mJ pulse energy with 70 ns pulse duration at 500 Hz. This is the highest pulse energy to date from a Q-switched diode-pumped Alexandrite laser. The laser spectrum was broad, centred at 753 nm, and modulated with a periodicity ~ 4.8 nm. This is consistent with a birefringent filtering effect in the Alexandrite laser rod believed to be caused, at least in part, by vertical misalignment of the intra-cavity Brewster plate with the crystal *b*-axis. In a further

study, an adapted version of the dual-end-pumped Alexandrite laser generated a doughnut-shaped mode, and with the addition of an intra-cavity BiFi wavelength tuning was achieved from 723 to 784 nm (61 nm tuning range) in Q-switched operation with maximum pulse energy 1.6 mJ at 757 nm.

We also demonstrate, for the first time, cavity-dumped Q-switching of a diode-pumped Alexandrite laser to generate short (few-ns) pulse duration with high peak power, as might be required for altimetry LIDAR applications. Under cavity-dumped Q-switched operation with CW diode-pumping we demonstrate pulse duration 2.9 ns, independent of PRF and up to 10 kHz. Pulse energy of 170 μ J was produced at 4 kHz. Using a dual-end-pumped Alexandrite laser with pulsed diode-pumping, cavity-dumped pulse energy is scaled to 510 μ J at 3 kHz with 3.0 ns pulse duration, corresponding to 170 kW peak power. Spatial beam quality was TEM₀₀ with $M^2 < 1.2$. SHG of the cavity-dumped Q-switched pulses was used to generate UV wavelength 379 nm with conversion efficiency of 47%.

These results show promise for Q-switched diode-pumped Alexandrite lasers as a wavelength tunable source in the near-IR and, with harmonic generation, in the UV. This first successful demonstration of cavity-dumped Q-switching of a diode-pumped Alexandrite laser provides a significant step-change for generating short pulse durations, high peak powers, at high (multi-kHz) PRF, despite the low gain of Alexandrite. As pulse duration is maintained across PRF, it opens up the range of applications for example in high resolution time-of-flight measurements such as altimetry LIDAR.

It is noted that the investigations performed in this work were not fully optimised for efficiency. Several sources of insertion loss were present from multiple intra-cavity elements. Due to the low gain and low output coupling, reduction of these passive round-trip losses can raise the efficiency by at least a factor of two or more. The brightness of the current red pump modules is poor and highly astigmatic, leading to asymmetric and inhomogeneous pumping, with short Rayleigh length in the laser rod, which is unfavourable for optimum pump-to-laser mode beam-overlap efficiency. Improved pump sources would enable both higher power scaling and higher efficiency. Fuller understanding and reduction of other loss mechanisms, such as pump ESA, can also play a role in efficiency enhancement [18].

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