Wavelength Tunable Passively Q-Switched Alexandrite Laser with Direct Diode-Pumping at 635 nm

Ufuk Parali[1,2*], Gabrielle M. Thomas[1], Ara Minassian[3], Xin Sheng[1] and Michael J. Damzen[1]
[1]*Photonics Group, The Blackett Laboratory, Imperial College London, London, SW7 2AZ, U.K.*
[2]*Department of Computer Engineering, Adnan Menderes University, Aydin, 09010, Turkey*
[3]*Unilase Ltd, 1 Filament Walk, Unit G02, London, SW18 4GQ, U.K.*

Keywords: Alexandrite, Passive Q-Switch Lasers, Tunable Lasers, Diode-Pumped Lasers.

Abstract: We report on a wavelength tunable passively Q-switched Alexandrite laser directly red-diode-pumped at 635 nm. Passive Q-switching was achieved with a semiconductor saturable absorber mirror (SESAM) and wavelength tuning with a birefringent tuner. The pulse repetiton rate was variable on the pump power and wavelength and a maximum 27 kHz rate was achieved in fundamental TEM_{00} mode. The maximum average output power obtained was 41 mW. The Q-switched wavelength tuning band was studied between 740 nm and 755 nm. To the best of our knowledge, this is the first time that tunable TEM_{00} passive Q-switched operation of a diode-pumped Alexandrite laser has been achieved. The results obtained in this study can be significantly further optimised for performance. A new cavity configuration for this optimisation is described. Future work is expected to lead to the development of higher power, more efficient tunable passive Q-switched (and potentially passive mode-locked) diode-pumped Alexandrite laser sources in the near-infrared band and also ultraviolet region through frequency conversion.

1 INTRODUCTION

Laser sources possessing broad emission bandwidths can provide wavelength tunable in a wide range with capability of different pulse durations (ns/ps/fs) and capability to potentially offer significantly benefit to many technological and scientific studies. Nonlinear microscopy, optical coherence tomography, frequency conversion, generation of high power ultrashort optical pulses and remote sensing applications can be given as some examples (Damzen, 2014; Teppitaksak, 2014; Koechner, 2003; Ghanbari, 2016;). In air-borne (and also in space-borne) remote sensing with laser-based lidar and altimetry techniques, such as resonant backscatter lidar, ground vegetation bio-mass/bio-health detection etc., such laser sources could provide a powerful tool for 3-D mapping of atmospheric species and physical attributes, spectral indicators of Earth features and high precision ground topography (Damzen, 2014; Eitel, 2011; Lu, 2016; Pelon, 1986; Milton, 1997; Chen, 2014). This would provide a valuable source for understanding the atmospheric science and health of the Earth vegetation and ecological system (Eitel, 2011). However, these remote sensing techniques requires the utilization of cutting-edge laser technologies having space-borne qualification. The exacting requirements for spaceborne operation severely restricts the class of lasers compatible in the space environment. The primary laser system with long space heritage is the diode-pumped Nd:YAG laser (Damzen, 2014; Eitel, 2011). However, this laser system has narrow linewidth and does not allow for wavelength tunability providing only a discrete single frequency at its primary fundamental laser line 1064 nm and its higher harmonics at 532 nm and 355 nm. Thus, accessing other wavelength regions at these systems is only possible by optical parametric conversion methods leading to higher complexity and cost and lower reliability and efficiency (Teppitaksak, 2014; Koechner, 2003; Ghanbari, 2016; Teppitaksak, 2015). An alternative approach for obtaining wavelength tunability and pulse generation capabilities by directly diode laser pumping is the utilization of vibronic solid-state laser materials. Today, the most commonly used vibronic laser systems are Ti:Sapphire solid-state lasers, which have the broadest gain bandwidth permitting direct generation of a few cycle optical

Parali U., Thomas G., Minassian A., Sheng X. and Damzen M.
Wavelength Tunable Passively Q-Switched Alexandrite Laser with Direct Diode-Pumping at 635 nm.
DOI: 10.5220/0006155500820089
In *Proceedings of the 5th International Conference on Photonics, Optics and Laser Technology (PHOTOPTICS 2017)*, pages 82-89
ISBN: 978-989-758-223-3

pulses (Teppitaksak, 2014; Koechner, 2003; Ghanbari, 2016; Beyatli, 2013; Demirbas, 2009). However, these lasers usually requires complex pump sources causing disadvantages such as complex system structure, bulky and large physical size, and low efficiency of electrical-optical conversion (Teppitaksak, 2014; Demirbas ,2009). As an alternative class of vibronic laser crystals, there are the well-known Cr-doped colquiriites (Cr:LiSAF, Cr:LiCAF and Cr:LiSGaF) and Cr-doped chrysoberyl (Cr:$BeAl_2O_4$) more commonly known as Alexandrite (Teppitaksak, 2014; Ghanbari, 2016; Beyatli, 2013; Sennaroglu, 1998; Demirbas, 2009; Sennaroglu, 2007). Among these crystals, however there are some performance-limiting disadvantages such as upper-state lifetime quenching at elevated temperatures, poor thermal conductivity and excited state absorption, Cr-doped colquiriite lasers are not attractive alternatives (Koechner, 2003; Ghanbari, 2016). Conversely, Alexandrite has a number of superior optical and thermo-mechanical properties making it an attractive vibronic solid-state laser gain medium. Alexandrite can be direct diode-pumped by red, green and blue laser diodes due to its broad absorption bands in the visible range (Koechner, 2003; Ghanbari, 2016). However for highest efficiency and lowest heating factor the red diodes provide the most favourable pump sources. It has a fracture resistance five-times bigger than that of Nd:YAG. And its thermal conductivity ($23 Wm^{-1}K^{-1}$) (Koechner, 2003) is almost twice that of Nd:YAG and five-times that of the Cr doped colquiriites. The laser emission of the Alexandrite is highly linearly polarized due to the birefringence of the crystall eliminating the depolarization problems (Teppitaksak, 2014; Koechner, 2003). Its relatively longer upper-state lifetime (~260µs) at room-temperature provides a good energy storage potential for Q-switched operation (Teppitaksak, 2014). Moreover, Alexandrite's laser performance is increased at elevated temperatures due to its unique spectroscopic properties (Loiko, 2016). It has a relatively low stimulated emission cross section (0.7×10^{-20} cm^2) requiring intense diode pumping (Koechner, 2003). Historically, it is the first wavelength tunable solid state laser operated at room temperature. Alexandrite has a broad emission wavelength range from ~ 700 nm to 850 nm (Walling, 1985; Sam, 1980). This spectral band is especially important. It is in the biological window for tissue transmission and for remote sensing of vegetation sits across the so-called red-edge band (~700-750nm) of chlorophyll (Eitel, 2011). This band is the steep rising transition band between high red and visible absorption and high near-IR reflection. Changes in this spectral band are well-known as indicators of plant health (Eitel, 2011). It is very interesting for a vegetation lidar to have a laser with emission wavelength range covering this red-edge band range.

Recently, in our prior work at Imperial College, continuous-wave (cw) red diode-pumped Alexandrite laser with 26W of average output power was obtained and the first active Q-swithcing with an electro-optic Pockels cell (Teppitaksak, 2014). Interestingly, the first femtosecond Kerr-lens mode-locked Alexandrite laser was recently reported in (Ghanbari,2016) producing pulses as short as 170 fs.

In this study, we report the first successfully demonstration of a wavelength tunable passive Q-switched Alexandrite laser with semiconductor saturable absorber mirror (SESAM) and using a red diode (AlGaInP) pump laser at 635 nm. For tuning the wavelength, a birefringent filter (BiFi) was used in the cavity. The highest repetiton rate achieved was 27 kHz in fundamental TEM_{00} mode. The maximum average output power obtained was 41 mW. The shortest pulse generated was 550 ns (FWHM). The wavelength tuning band spanned was between 740 nm and 755 nm. To the best of our knowledge, this is the first wavelength tunable TEM_{00} passive Q-switched operation of a red diode-pumped Alexandrite laser. Our results open the way for further development, optimization and power scaling of this new generation passive Q-switched (and also potentially for passive mode-locked) Alexandrite lasers. One interesting application for developing a low-cost, compact and wavelength tunable pulsed laser source is space-borne remote sensing applications, especially for the next generation vegetation lidar systems.

2 EXPERIMENTAL SETUP

A simple linear cavity was designed to study the wavelength tunable passive Q-switching operation mode of the direct diode-pumped Alexandrite laser. Two experimental systems are described. The first is a wavelength tunable cw setup shown in Figure 1 as a precursor study. The second setup was a wavelength tunable passive Q-switched using a semiconductor saturable absorber mirror (SESAM) as shown in Figure 2.

The wavelength tunable cw laser had a plane-plane mirror cavity. The Alexandrite gain medium was a 10 mm-long and 4 mm-diameter Alexandrite rod crystal doped with 0.22% of Cr^{3+} and c-axis cut. The

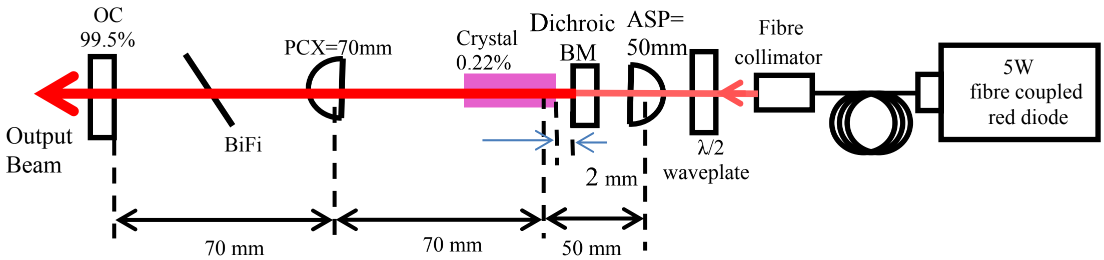

Figure 1: Schematic layout of the plane-plane mirror cavity wavelength tunable continuous-wave direct red diode-pumped Alexandrite laser operating in fundamental TEM_{00} mode.

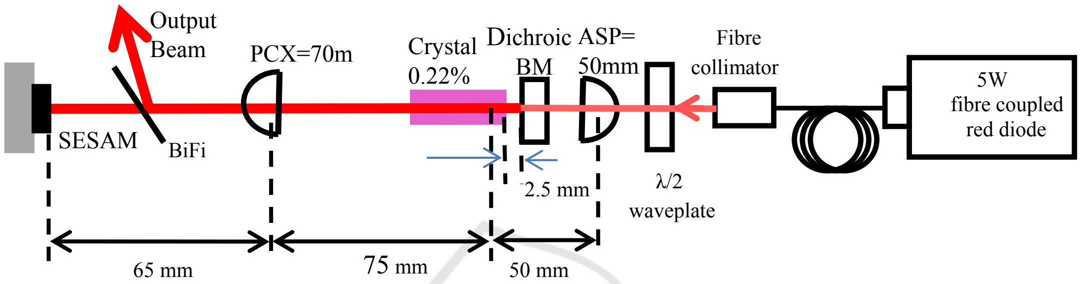

Figure 2: Schematic layout of the wavelength tunable passive Q-switched direct red diode-pumped Alexandrite laser. Here, OC in Figure 1 is replaced with SESAM. The output coupling is provided from the reflection of the BiFi in the cavity.

end faces of the rod were plane-parallel and anti-reflection coated at the Alexandrite wavelength (~755 nm). The rod was mounted in water-cooled copper heat-sink and an indium foil interface used for enhanced thermal contacting to the copper.

The cavity length ~142 mm including an intracavity plano-convex lens (PCX, f=70 mm). The intracavity lens design was chosen to form a stable cavity configuration and to optimise for TEM_{00} operation. A dichroic back mirror (BM) was highly-reflecting (R>99.9%) at laser wavelength (~755nm) and highly-transmitting (R<0.2%) for pump diode laser (~635 nm). Both the temperature of the crystal and pump laser diode were cooled to 16 °C using a single water chiller in the experiments.

The small-signal absorption coefficient (α) of the crystal measured ~6cm^{-1} with a He-Ne laser at 633 nm for light polarized parallel to the b-axis of Alexandrite crystal. The crystal was pumped by a red diode module, operating nominally at central wavelength 635nm with bandwidth (FWHM) of ~ 1.5nm and capable of providing max ~5W (5180 mW full power) in cw mode. The diode module is fibre coupled in a multi-mode fiber with core diameter of 105 µm and numerical aperture of 0.22. An aspheric fiber collimator with 35mm of focal length was used for collimating the pump beam output from the fiber. The circularized pump beam was focused into a ~120 µm spot size diameter inside the crystal by an aspheric pump lens (ASP) of 50 mm focal length.

The output of the fibre was not a pure polarisation but > 60% was in the highly absorbing b-axis direction of the Alexandrite crystal. About 83% of the pump power was absorbed in the crystal. The confocal parameter of the b-axis component of the pump (~4 mm) was sufficiently longer than the absorption depth of the crystal to allow good laser mode overlap with the pump. The overlap of the laser mode to the other polarisation however would be poor.

The wavelength tuning of the laser is provided by using a quartz plate with a thickness of 0.5 mm acting a birefringent filter (BiFi) tuner. The BiFi sits at Brewster angle (to minimize insertion losses) and wavelength tuned by rotation of the BiFi in the plane of the plate using a goniometer to alter the birefringence of the plate. In this way it was simple to tune the wavelength of the laser output of both cavities (Figures 1 and 2) working in cw and passive Q-switched mode.

For optimizing the laser cavity and as a reference, we first obtained the cw mode of operation by using an output coupler (OC) with 99.5% reflectivity (Figure 1). The output of the wavelength tunable cavity working in cw mode is obtained through the

OC. Once the cavity was optimized in cw mode, we replaced the OC with a SESAM to obtain passive Q-switching mode (Figure 2). The output beam was obtained from the BiFi since the SESAM was used as the end mirror in the cavity and was non-transmitting as it was attached on an aluminium disc using thermal adhesive. This helped to increase the heat transfer between SESAM and the aluminum. The beam spot size diameter on the SESAM was calculated about to be ~250 µm. The SESAM had a saturable absorption with modulation depth ~ 0.5% and had also some nonsaturable loss (~1%). Both the nonsaturable loss and modulation depth depends on wavelength. The SESAM structure had a ~60 nm reflectivity bandwidth centered around 740 nm (R=~99%) and a ~10 nm (FWHM) photoluminescence band centered around ~736 nm. The dynamic response (absorption recovery) of the SESAM was biexponential with <0.5 ps for fast component and ~300 ps for slow component. The saturation intensity was around ~30 µJ/cm^2.

3 RESULTS AND DISCUSSION

In the initial experiments, we investigated the variation of the cw output power as a function of emission wavelength. The wavelength of the Alexandrite laser with the 99.5% reflectivity output coupler was tuned in the range extended from 730 nm to 790 nm and the output power shown in Figure 3. Maximum output power was obtained at 740 nm lasing wavelength at full pump power ~5W (5180 mW) at 635 nm. It can be seen from Fig.3 that a much wider tuning range was possible, however the main focus of this study was operation around the wavelength band of the SESAM device.

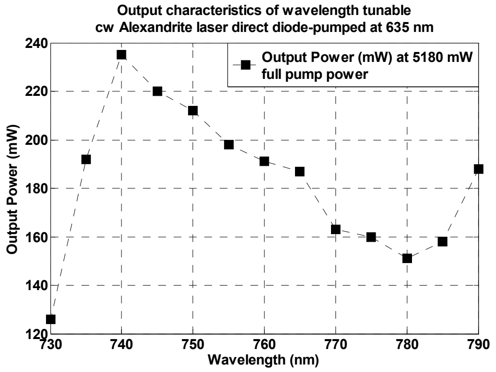

Figure 3: Tuning curve for the cw Alexandrite laser with 0.5 mm BiFi tuner plate. Alexandrite crystal temperature was 16 ºC, output coupler was 0.5% transmitting, and incident pump power was 5180 mW.

By fixing the angle of the BiFi so that the laser output wavelength is constant at 740 nm, the measured cw output power versus the pump power curve of the cavity is depicted in Figure 4. The slope efficiency was ~14% and shows no sign of decreasing at the highest output power. This suggests that thermal lensing effects did not limit the output power. As can be further seen in Figure 4, the slope efficiency and output power is increasing with the available pump power, suggesting that the power performance can be further improved with more powerful pump lasers. The optical-to-optical efficiency with respect to incident pump power can also be expected to be considerably increased by optimising output coupling, reducing intracavity loss and attention to spectral profile of coated cavity optics.

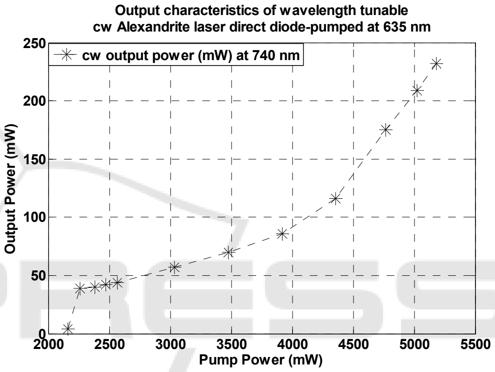

Figure 4: Output power vs Pump power curve of cw Alexandrite laser cavity at constant wavelength of λ=740 nm. Laser crystal is at 16 ºC and 0.5% transmitting output coupler.

After the characterisation of the wavelength tunable cw laser cavity, the OC mirror was replaced with the SESAM for passively Q-switching the Alexandrite laser. The output of the laser was provided by a reflection loss from the BiFi plate. With the dimensions of the cavity as shown in Figure 2, the system started working in a self-Q-switched mode. In particular, after the alignment of the cavity was optimized, the output power showed a strong dependence on the position of the intracavity lens that might be to do the spot size on the SESAM.

For constant wavelength λ=747 nm (by fixing the BiFi at appropriate angle), the evolution of the output power, pulse width and the repetiton rate with respect to the pump power are given in Figure 5. It is noted that the cavity has a higher threshold due to the larger losses incurred by insertion of the SESAM. As the available pump power increases above threshold, shorter pulses with higher repetition rate were obtained.

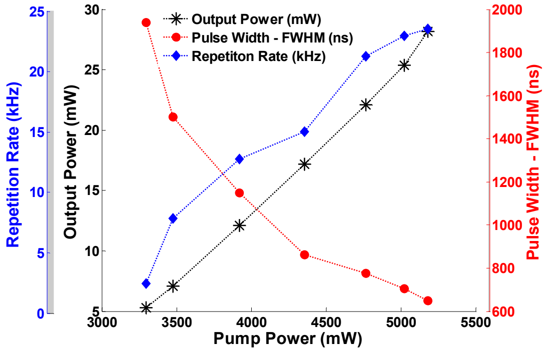

Figure 5: For constant wavelength λ=747 nm, the evolution of the output power, pulse width and the repetiton rate of the passive Q-switched diode-pumped Alexandrite laser with respect to the 635 nm pump power.

The slope efficiency was limited by the intracavity losses and can be improved by careful intracavity loss management. Moreover, the output is obtained from the BiFi in the cavity meaning that the actual power generated by the cavity is higher than the measured value. Although this is not the best configuration for obtaining the output pulse from a laser cavity, we preferred to use this cavity configuration as shown in Figure 2. Our objective in choosing this setup was to make the system as simpler as possible in order to just show experimentally for the first time that the diode-pumped Alexandrite crystal can be passively Q-switched. In our future studies, we are planning to use an X-Cavity (as described in Section 4) and/or L-cavity configurations with higher crystal temperature to obtain higher efficiency and higher pump power to provide higher output power in passive Q-switching of diode-pumped Alexandrite laser.

In the tunable passive Q-switching experiments, the BiFi was again used to tune the wavelength but was also restricted by the limited reflectivity band of the SESAM and range over which Q-switching could be accomplished. The tuning bandwidth achieved was between 740 nm and 755 nm (Figure 6). Compared with the cw tuning range shown in Figure 3, Q-switching tuning bandwidth is narrower. Figure 6 shows the evolution of the output power, pulse width, repetition rate and spectral width of the pulses obtained from the passive Q-switched diode-pumped Alexandrite laser in the wavelength tunability range for full pump power.

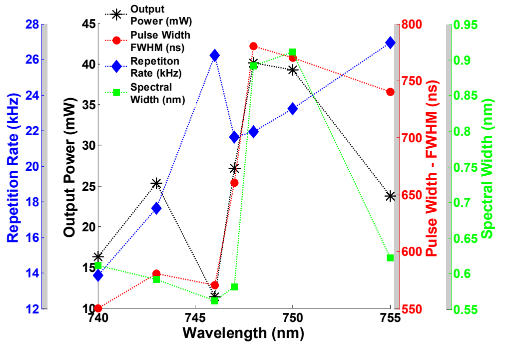

Figure 6: The output power, pulse width, repetition rate and spectral width of the pulses obtained in the wavelength tunability range from the passive Q-switched Alexandrite laser.

The highest pulse repetition rate was 27 kHz at 755 nm and the shortest pulse width was 550 ns at 740 nm. The observed spectral width was <1 nm for the tuning range of the passive Q-switch mode. Figure 7 compares the pulse widths and spatial profiles obtained at the wavelengths 743 nm and 750 nm for full pump power. The laser output beams for both wavelengths had TEM_{00} beam profile with M^2 values <1.7 and <1.9 for 743 nm and 750 nm, respectively. The M^2 beam quality was determined using the ISO 11146-1 method, based on the second moment beam size. When the mode of the beam profile was adjusted to higher spatial modes, higher output power was achieved due to the increased mode-gain overlap in the cavity.

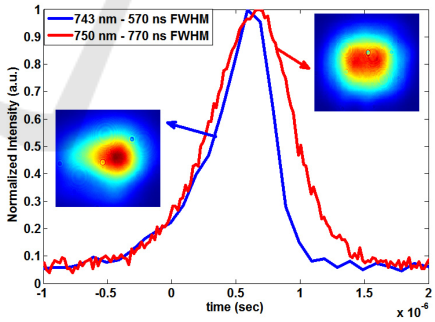

Figure 7: Pulse profiles and spatial profiles obtained at 743 nm and 750 nm from the tunable passive Q-switched Alexandrite laser.

Figure 8 shows the pulse train and the repetition rates obtained at the wavelengths 743 nm and 750 nm for full pump power. At 743 nm a pulse repetition rate of 14 kHz was obtained, whilst at 750 nm the repetition rate was higher at 23 kHz.

A photograph of the developed laser is shown in Figure 9 below (see Figure 2 for dimensions and schematic layout). We noted that in order to demonstrate this wavelength tunable passive Q-switched direct diode-pumped Alexandrite laser experimentally for the first time in the literature, we choice to utilize this very simple cavity configuration. However this linear cavity configuration we used has some disadvantages especially in the means of achieving relatively higher output power and higher efficiency. In particular, the use the beam coming from the BiFi was not ideal. This caused lower output power values to be detected in the measurements. In order to overcome this issue, we developed an X-cavity setup for our future studies as explained in the next section.

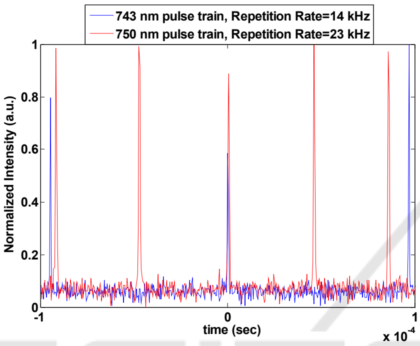

Figure 8: Pulse train observed from passively Q-switched Alexandrite at 743 nm and 750 nm with repetition rates 14 kHz and 23 kHz, respectively.

4 FUTURE STUDY

We established an astigmatically compensated 4-mirror X-cavity direct diode-pumped Alexandrite laser for cw experiments shown in Figure 10. The intention of this configuration was for obtaining higher output power from the wavelength tunable passive Q-switched Alexandrite laser in our future studies. It is important to have an optimized cw cavity to obtain passive Q-switching or passive mode-locking. As we have done previously in Figure 1, as a preliminary to Q-switching we first developed a stable X-cavity cw Alexandrite laser operating in fundamental TEM$_{00}$ mode. The cavity consisted of Brewster angle cut Alexandrite crystal, two curved mirrors (each with a radius of curvature of 75 mm), a highly reflecting flat back mirror (BM) and an output coupler mirror with reflection 99.5%. We used the same diode pump source as in Figure 1. Moreover, as we have done previously, we kept the crystal and pump diode temperature equal and constant at 16°C using the same single water cooling system.

Two different cavity configurations were investigated. In the 1st setup, the internal cavity dimensions are arranged as: L$_1$=37.5 mm, L$_2$=35 mm, L$_3$=62 mm and L$_4$=55 mm. The beam quality of the laser output is measured (with ISO 11146-1 method) as $M_x^2 = 9.6$ and $M_y^2 = 10.4$. Since these beam quality factors are not satisfactory, we tried to re-optimize the X-cavity with new lengths. In this 2nd configuration: L$_1$=53 mm, L$_2$=44 mm, L$_3$=135 mm and L$_4$=96 mm. For this configuration, the laser output beam had a TEM$_{00}$ beam quality and its beam propagation factor was measured as $M_x^2 = 1.34$ and $M_y^2 = 1.17$ which are far better than the results found for the 1st setup. The free running laser wavelength was around ~755 nm in both cavities.

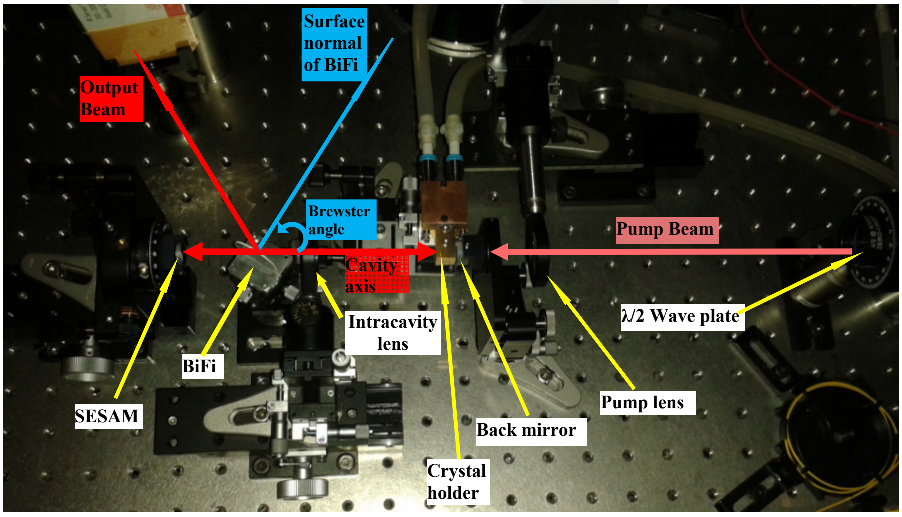

Figure 9: Annotated photograph of the wavelength-tunable passive Q-switched direct diode-pumped Alexandrite laser.

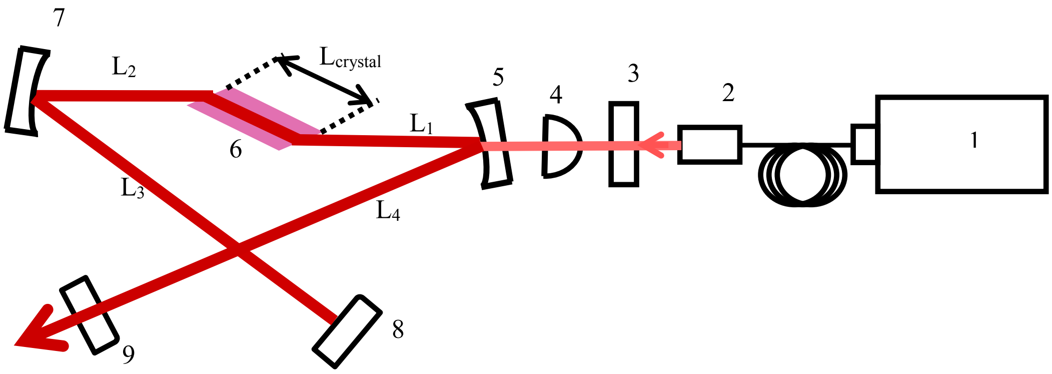

Figure 10: X-cavity cw Alexandrite laser setup with Brewster angle cut crystal: 5W fibre coupled red diode laser module (1), Fibre collimator (2), λ/2 wave plate (3), Plano convex pump lens (PCX) with f=75 mm (4), curved dichroic mirror HT at 635 nm and HR at 755 nm with radius of curvature (ROC) 75 mm (5 and 7), Brewster angle cut Alexandrite rod with $L_{crystal}$ = 8 mm length doped with 0.22% of Cr^{3+} (6), back mirror – BM (8), Output coupler OC with reflection 99.5% (9).

Figure 11 given below shows the cw output power of the X-cavity for the two different setups.

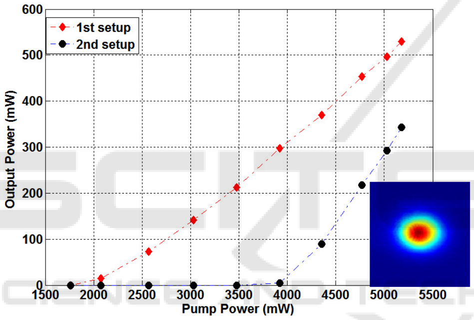

Figure 11: Output power vs Pump power curve of cw X-cavity Alexandrite laser at free running laser wavelength around ~755 nm in the two cavity setups. The crystal temperature was 16 ºC in the experiments and output coupling was 0.5%.

As can be seen in Figure 11, the oscillation threshold of the 2nd setup is much higher than the 1st setup. On the other hand, as can be further seen its slope efficiency (~30%) is higher than the slope efficiency of the 1st setup and output power is increasing with the available pump power. This suggests that the power performance and slope efficiency of the 2nd setup can be further improved with more optimization, adjustment and by utilizing more powerful pump lasers with higher crystal temperatures. After having completed this step, we will plan to replace the back mirror with the SESAM we used in Figure 2, but can now utilise and optimise the output coupler mirror to obtain more efficient passive Q-switched (or potentially passive mode-locked) diode-pumped Alexandrite laser in our future studies.

5 CONCLUSIONS

This work demonstrated experimentally for the first time that a wavelength tunable passive Q-switched TEM_{00} operation of Alexandrite laser can be achieved with direct red diode-pumping. The shortest pulse generated was 550 ns (FWHM) and the highest repetiton rate achieved was 27 kHz in fundamental TEM_{00} mode. The maximum average output power obtained was 41 mW and 0.56 nm was measured as the shortest spectral width. The wavelength tuning band spanned was between 740 nm and 755 nm. The results obtained in this study pave the way for further development, optimization and power scaling of this new generation tunable diode-pumped passive Q-switched (and also potentially for passive mode-locked) Alexandrite laser. In our future studies; higher crystal temperature, higher pump power, higher doping concentration, longer gain medium, optimized (reduced) output coupler reflectivity, enhanced cavity design (X-cavity) and careful intracavity loss management will provide us to obtain better performance in tunable Q-switched operation of diode-pumped Alexandrite laser. Due to the superior optical and thermo-mechanical properties comparing with its counterparts, this new generation direct diode-pumped wavelength tunable, compact, low-cost and efficient passive Q-switched (and also passive mode-locked) Alexandrite laser has the potential to become an attractive source for addressing the requirements of many near-future crucial scientific, medical and game-changing industrial applications such as next generation space-borne vegetation lidar systems.

ACKNOWLEDGEMENTS

We would like to acknowledge support from the British Council and Newton Fund under Project No. 215277462. U.P. would like to acknowledge support from TÜBİTAK (The Scientific and Technological Research Council of Turkey) for his visit to Imperial College London. The authors thank Dr Arkady Major from the University of Manitoba for providing the SESAM that was used in this study.

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