Versatile Sources Based on High Gain Nd:vanadate Amplifiers and Diode-Pumped Alexandrite Lasers for Remote Sensing Applications

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ABSTRACT

This paper presents data on performance capabilities of ultra-high gain Nd:vanadate slab amplifiers with single pass small signal gains in excess of 40-50dB from a single amplifier stage. Micro-watt level pulsed diode with duration of 0.2-1ns at 1064nm and operating at 500kHz have been amplified to tens of watts and subsequently converted to the visible and UV with conversion efficiencies in excess of 60% at 532 and 30% at 355nm. A number of Alexandrite lasers in Q-switched or Cavity-dumped configurations will be presented as well. Under standard Q-switched operating mode mJ-class pulses at hundreds of Hz has been demonstrated. Operating in Cavity-dumped mode multi-kHz short (<1.5ns) pulses with 50-100μJ energies have been demonstrated and deployed in field trials for vegetation LIDAR.

1.0 DIODE PUMPED ALEXANDRITE LASERS FOR REMOTE SENSING

1.1 Introduction

Satellite-based remote sensing is an invaluable tool for global 3-D mapping of atmospheric species (e.g. CO_2, ozone, clouds, aerosols), physical attributes of the atmosphere (e.g. temperature, wind speed), and spectral indicators of Earth features (e.g. vegetation, water). Such data is critical in improving our understanding of climate change, atmospheric science as well as providing more accurate weather prediction. Most space based laser technologies are based on diode-pumped Nd:YAG at 1064nm and its harmonics offering no tunability. Tunable lasers would provide significant scientific and performance benefits that fall outside wavelength regions not covered by fixed wavelength lasers.

The most common and widely used tunable solid state laser is Ti:sapphire (Ti:S). However, Ti:S requires frequency doubled Nd:YAG or Nd:YVO_4 lasers as pump sources making overall system efficiency low and therefore unsuitable for space based applications. As an alternative, Alexandrite (Cr^{3+}:$BeAl_2O_3$) provides broad tunability (700-850 nm) and in combination with high thermal conductivity (23 $W.m^{-1}.K^{-1}$) and long upper state lifetime (~260μs) becomes an attractive candidate for high energy pulsed operation. Alexandrite's broad absorption spectrum in the visible region allows direct diode-pumping using high power red (AlGaInP) laser diodes as shown in Figure 1.

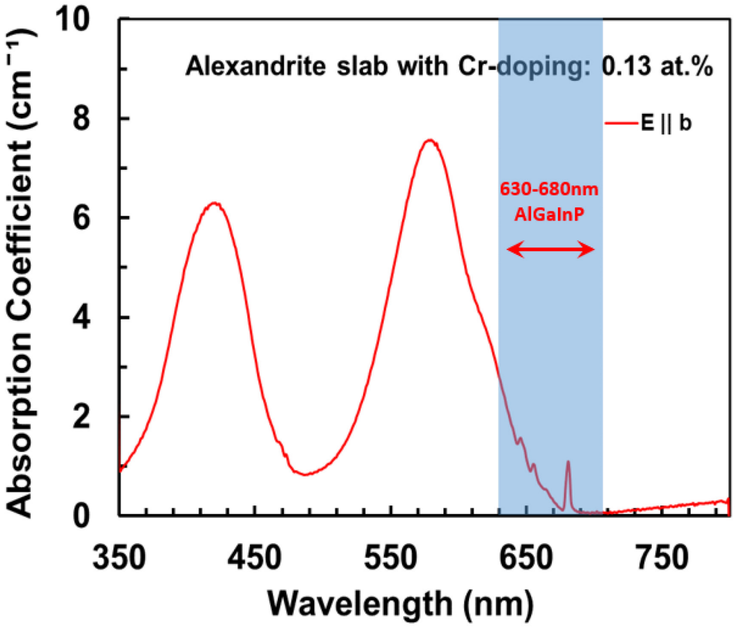


Figure 1: Alexandrite absorption spectrum in the UV-VIS.

In recent years European Space Agency (ESA) has funded development of diode pumped Alexandrite lasers at Imperial College London for future space based remote sensing missions and in particular vegetation LIDAR. Alexandrite's emission bandwidth allows high sensitivity monitoring of bio-mass/bio-health as it overlaps the steep rising transition region between high red absorption and high near–IR reflection commonly known as the "red-edge" of chlorophyll shown in Figure 2.

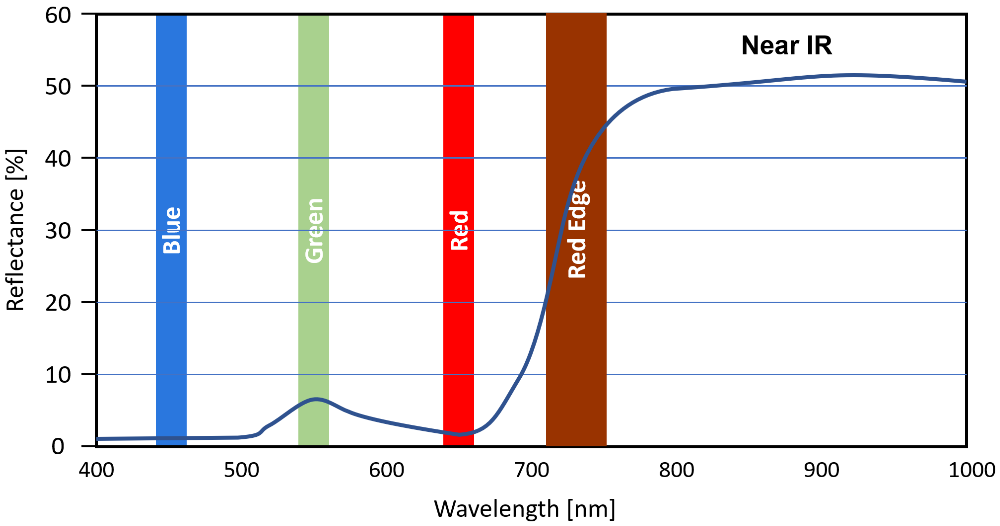
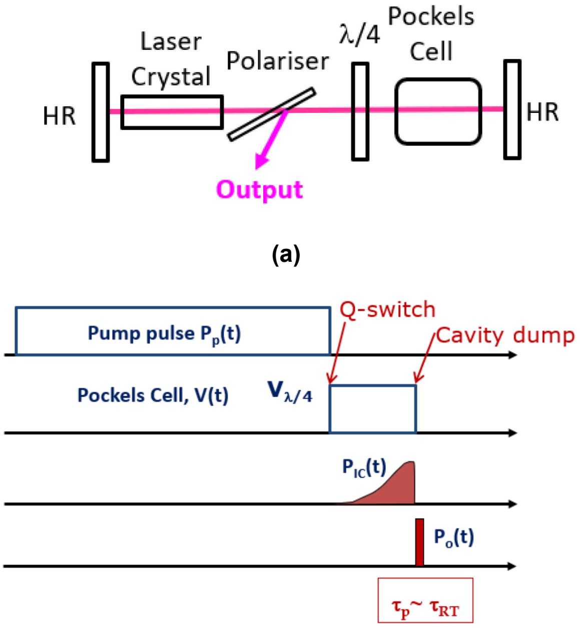


Figure 2: Spectral response of vegetation showing coverage of the "red-edge" by Alexandrite's emission bandwidth.

1.2 Q-switched Cavity-Dumped Alexandrite Laser for Vegetation LIDAR

For vegetation LIDAR the laser is expected to operate with pulse energies in the range tens to hundreds of microjoules running at few kHz repetition rate and produce short pulses with duration under 2ns. Since laser emission cross section is quite low in Alexandrite ($10^{-20}cm^2$) it is not possible to obtain pulses of few ns duration under standard Q-switched mode of operation. Instead, the laser must be configured to operate in what's known as Q-switched Cavity Dumped (QS-CD) regime. Figure 3(a) shows the basic elements of a cavity configured for operation in QS-CD mode. The cavity is formed by two high reflectivity mirrors, laser gain medium, a polarising element where the output coupling takes place and a quarter-wave plate/Pockels cell combination controlling the pulsing action.



(a)

(b)

Figure 3: (a) Basic cavity elements of a Q-switched Cavity-Dumped (QS-CD) laser, (b) timing diagram for QS-CD where P_{IC} is intracavity power, P_O is output power, τ_p is pulse duration and τ_{RT} is cavity round trip time.

The timing diagram for the QS-CD cavity is summarised in Figure 3(b) where at the end of the pump pulse quarter wave voltage is applied to the Pockels Cell thereby changing the cavity Q from low to high. This allows intracavity power to build up and once it reaches an optimum level the Pockels Cell quarter wave voltage is rapidly switched off allowing the intracavity flux to "dump" out of cavity in the form of a short pulse. The duration of the pulse is of the order of the cavity round trip time.

Figure 4 shows the practical implementation of a QS-CD Alexandrite laser developed for ESA for vegetation LIDAR. The cavity is folded into a "U"-shaped layout. The pump is a 15W fibre coupled diode at 640nm (200µm/0.22NA) and after going through collimating and focussing optics is it delivered through the back mirror of the cavity and incident onto the Alexandrite crystal. The crystal is a 0.22% at. and 4x4x6mm in size. Any unabsorbed pump is reflected back onto the crystal for a second pass by the Pump Recycling Optics maximising complete absorption of available pump power. A Birefringent (BiFi) plate controls the operating wavelength of the cavity. The Thin Film Polariser (TFP) is designed to operate at 45° angle on incidence and acts as the output coupler for the cavity. A BBO (β-barium borate) Pockels Cell and a Quarter Wave Plate (QWP) control the pulsing of the cavity.

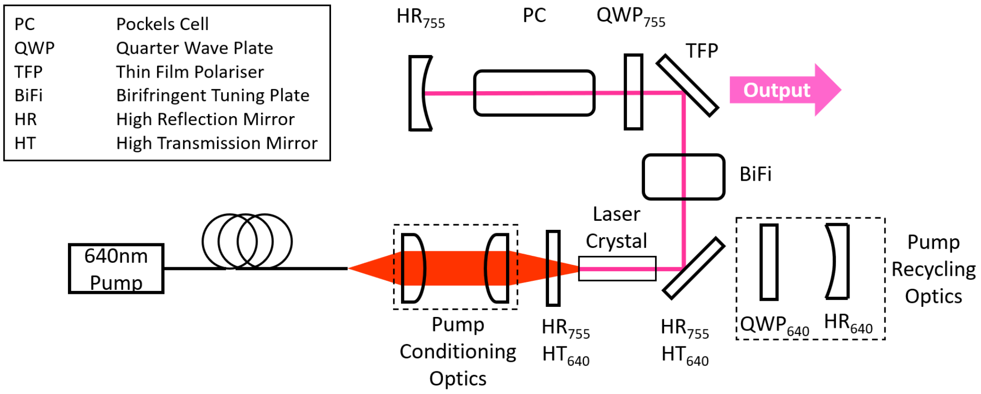


Figure 4: Experimental implementation of a diode pumped Alexandrite laser for vegetation LIDAR for ESA.

A manufactured and packaged version of the laser is shown Figure 5 occupying a 260x162x100 mm (LxWxH) footprint.

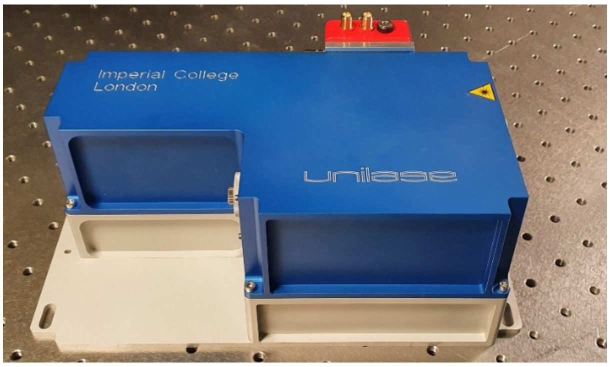
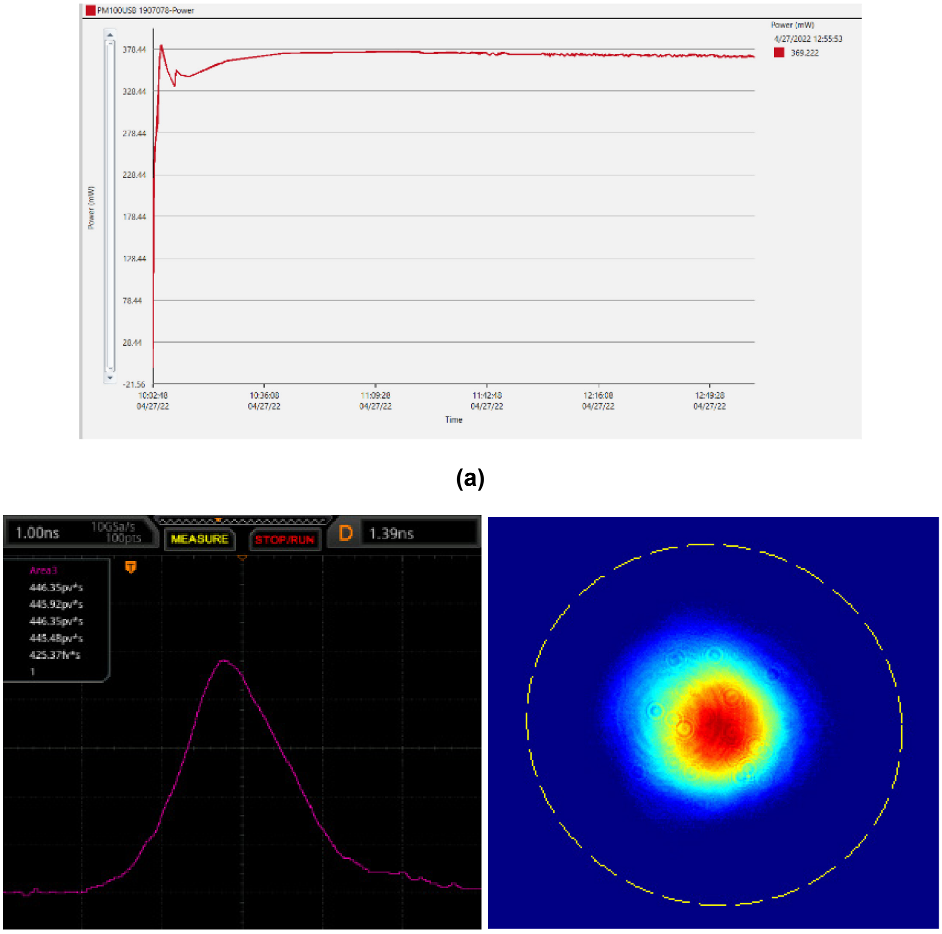


Figure 5: Photograph of fully packaged diode-pumped Alexandrite laser.

The specifications for the QS-CD laser as specified by ESA and the delivered specs by Imperial College London are listed in Table 1. Typical examples of output power stability, pulse duration and spatial profile of the laser are shown in Figure 6.

Table 1: ESA target specifications for Diode Pumped Alexandrite Laser for Vegetation LIDAR.

Laser Parameter	Target Spec	Delivered Spec
Wavelength [nm]	~757	757.7
Rep. Rate [kHz]	5.0	5.0
Pulse Energy [μJ]	20	>60
Pulse Duration [ns]	<2	~1.5
Spatial Mode [M^2]	<1.5	<1.4



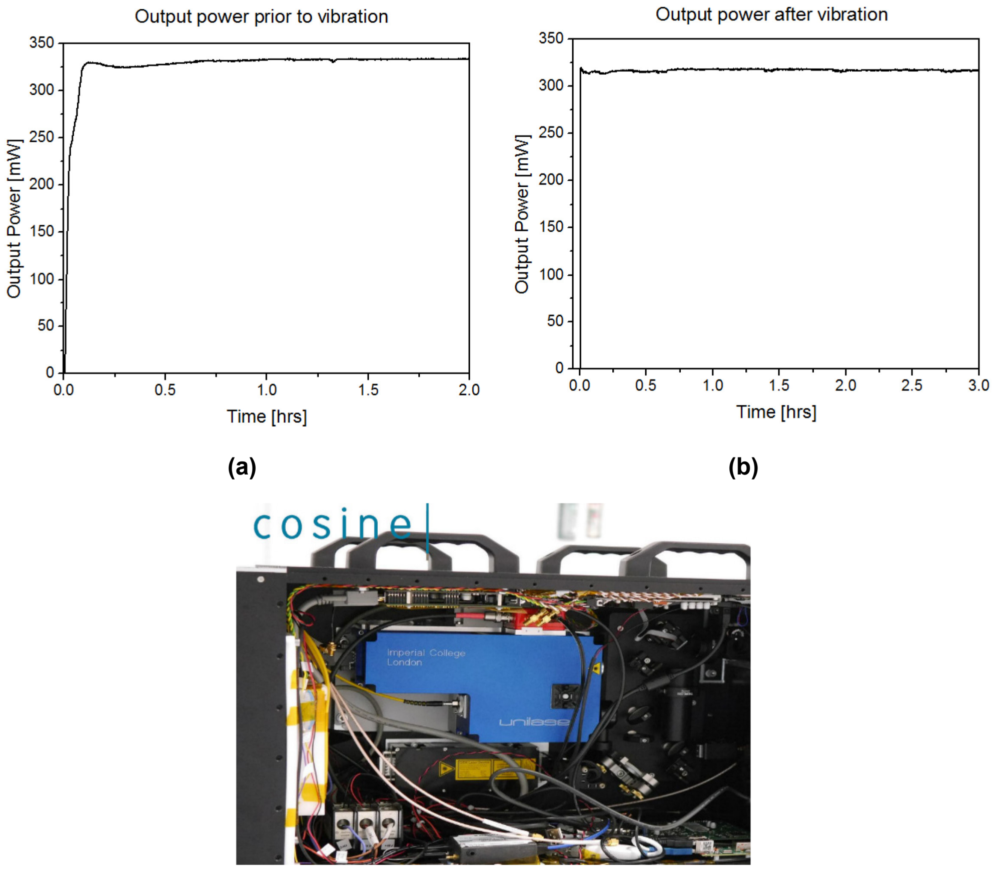
(a)

(b)

(c)

Figure 6: Examples of output from diode-pumped QS-CD Alexandrite lasers showing (a) output power stability over 3 hours, (b) 1.39ns pulse duration and (c) TEM$_{00}$ beam quality with M^2~1.3.

QS-CD Alexandrite laser was developed for integration and field testing in a single-photon LIDAR instrument. Prior to shipment the laser was subjected to vibration testing to ensure it would operate as per final settings tested at Imperial College London. Figure 7 shows the results of the output power stability before and after the vibration testing and final integration inside the single-photon LIDAR instrument.



(a) **(b)**

(c)

Figure 7: Output power stability of the packaged Alexandrite laser (a) prior and (b) after vibration tests. (c) Alexandrite laser integrated in single-photon LIDAR instrument prior to filed testing.

1.3 Acousto-Optic Q-switched Alexandrite Laser

Q-switched Cavity-Dumped laser described in the previous section required a BBO Pockels Cell for switching large voltages (up to 2kV) using very fast drive electronics (~ns rise/fall times) for modulating cavity losses to produce short pulse output. Switching high voltages at very high speed is quite challenging and for many applications pulsed output with tens of nanosecond durations is sufficient. In such cases one can achieve pulsed output by using an Acousto-Optic (AO) modulator where the AO cell produces a periodic deflection of the cavity mode by diffraction by application of RF power to produce pulsed output.

Here we present what we believe to be the world first demonstration of pulsed output from a diode-pumped Alexandrite laser using an AO Q-switch. The AO switch operates at 80MHz RF frequency and 15W of RF power. The basic cavity layout is shown in Figure 8 which comprises of a High Reflectivity back mirror, Alexandrite laser crystal, the AO-QS and the Output Coupler. Total cavity length is ~50mm.

The laser was operated under pulse pumping where the pump diode was operated at 350µs duration at 200Hz with Q-switch driver synchronised to open the cavity at the end of the pump pulse. It was also tested when pumped continuously (cw) and Q-switched at repetition rates 1kHz and higher. Figure 9 summarises preliminary results of AO-QS Alexandrite laser under pulsed- and CW pumping conditions. It can be seen that under pulse pumping over 700µJ has been achieved with pulse duration of ~40ns. Under CW pumping over 500µJ at 5kHz and over 700µJ at 1kHz is achieved. Pulse durations are ~100ns for both cases at maximum pumping powers. Spatial output from the laser is also in the form of a TEM_{00} beam with $M^2<1.1$.

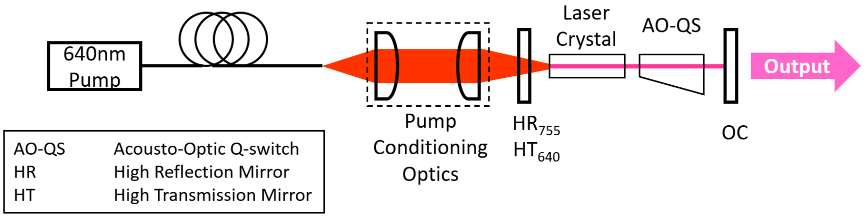


Figure 8: Acousto-Optic Q-switched Alexandrite Laser Cavity.

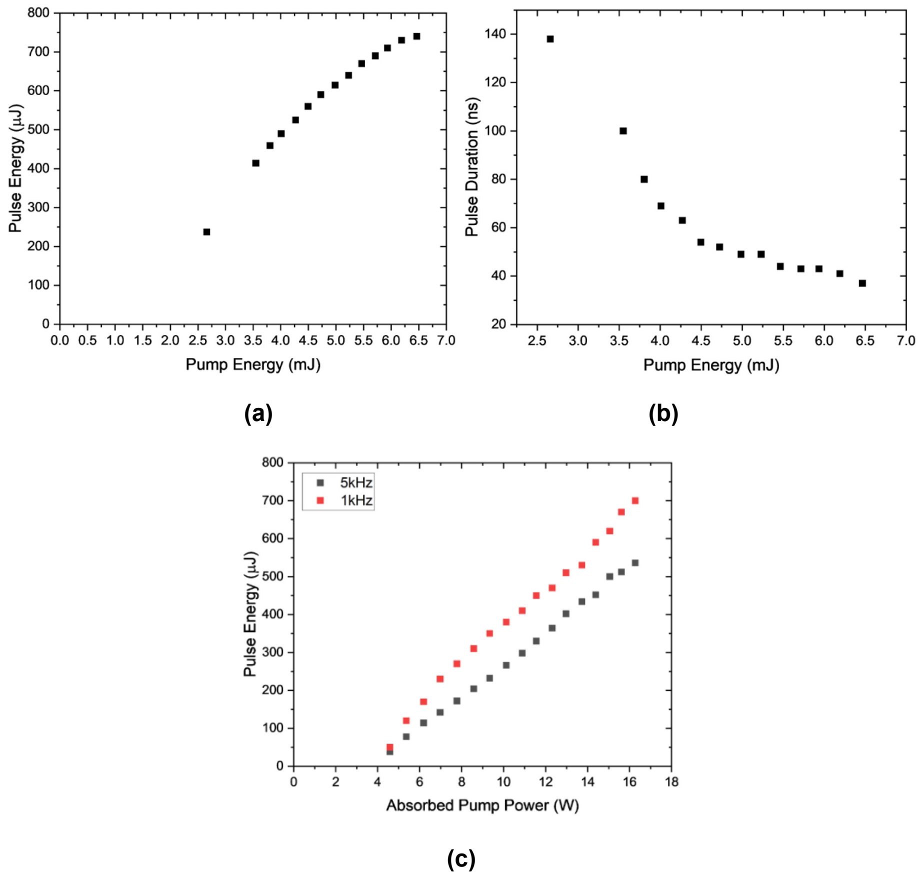


Figure 9: Laser performance from Acousto-Optic Q-switched Alexandrite Laser. (a) & (b) showing output pulse energy and pulse duration under pulse pumping at 200Hz and (c) showing pulse energies at 1 and 5kHz when pumped in CW regime.

2.0 DIODE PUMPED ND:VANADATE LASERS AND AMPLIFIERS

Unilase has been developing a range of high performance amplifiers based on side-pumped slab geometry as shown in Figure 10. This geometry matches perfectly to the output of high power diode arrays where the output from the diode is coupled into the laser crystal using a simple cylindrical lens. Material of choice for this geometry is Nd:$YV0_4$ due to its high pump absorption creating a shallow region (<0.5mm) of inversion just inside the pump face. By directing the laser mode towards the pump face at a grazing incidence it can experience total internal reflection and due to the small incidence angle fully overlap with the deposited pump. The reflection at the pump face provides considerable spatial averaging of gain nonuniformities and help to preserve the beam quality of seed sources. The geometry is readily scalable and provides exceptionally high gain without requiring complex multi-pass or regenerative schemes. Finally, since it is based on bulk technology it is ideal for amplification of nanosecond or picosecond pulses with no issues with onset of nonlinearities.

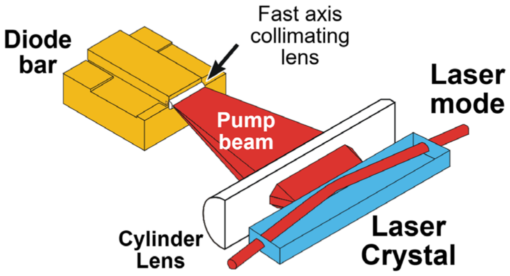
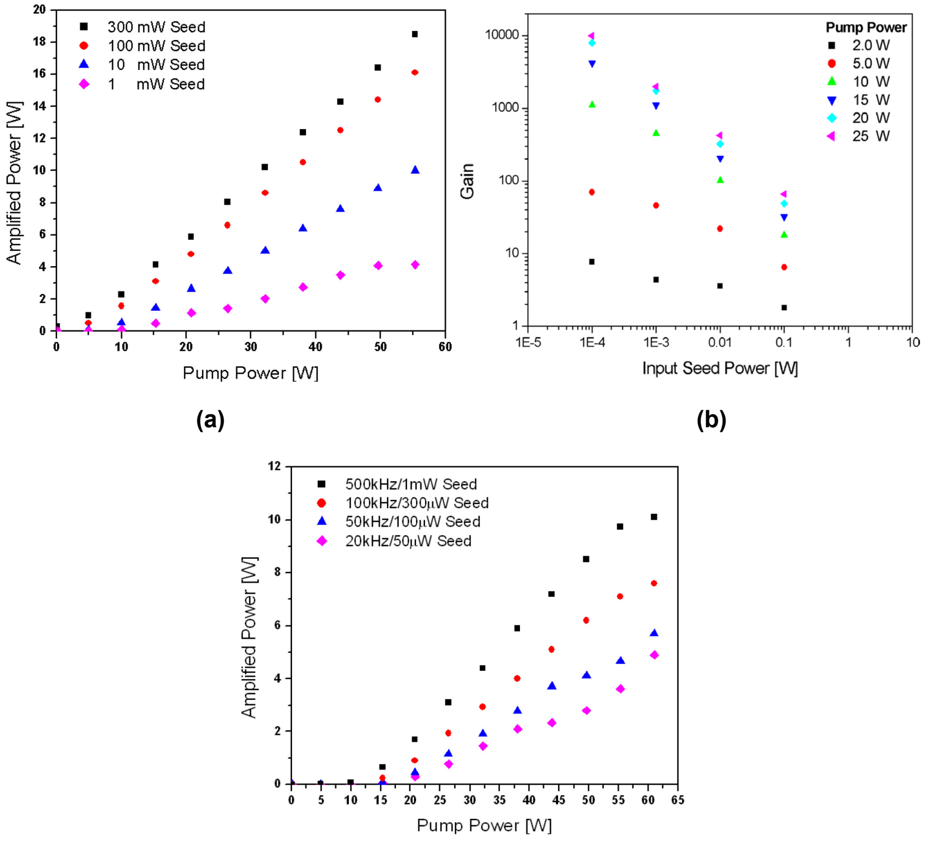


Figure 10: Side-pumped slab technology.

Figure 11 shows typical performance capabilities of the amplifier when seeded with a CW or pulsed lasers. It can be seen in Figure 11(a) that milliwatt level seed beams can experience 30dB or greater gain and be amplified to over 10 watts while maintain very good beam quality. Similar performance gains are maintained when seeded with pulsed sources taking μW level nanosecond sources to several watts as shown in Figure 11(c).



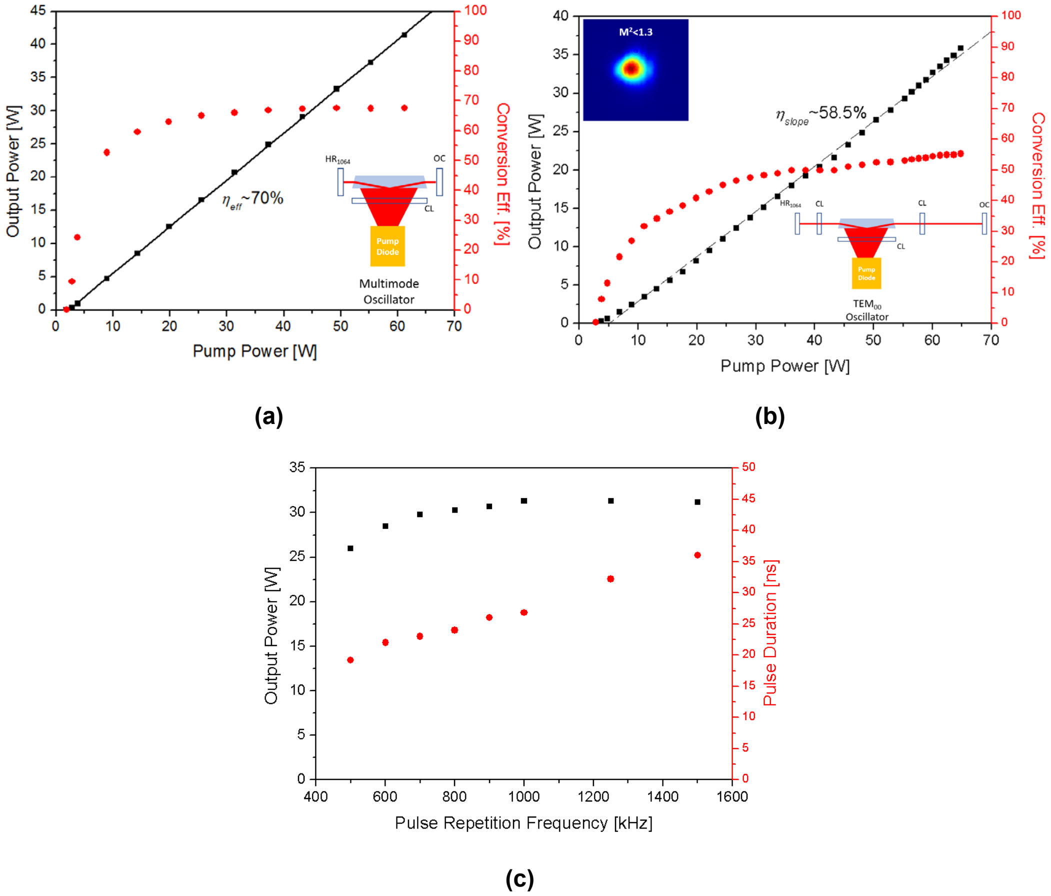
(a)

(b)

(c)

Figure 11: Amplification performance figures from side-pumped Nd:YVO_4 slab for (a) & (b) CW input seed source and (c) for pulsed seed source with 10ns duration.

Such high gains leads to exceptionally high efficiency laser oscillators. Figure 12(a) shows example of a compact multimode cavity producing 40W CW output at 1064nm from 60W of diode power corresponding to over 65% optical-to-optical and 70% slope efficiency. The ultrahigh gain of this amplifier technology also translates to unrivalled performance under AO Q-switching as shown in Figure 11(c) where pulse rates from 500-1500kHz can be achieved while maintain short pulses in the rang 20-35ns.



(a)

(b)

(c)

Figure 12: High efficiency side-pumped Nd:YVO$_4$ lasers in (a) compact multimode and (b) extended TEM$_{00}$ mode and (c) high rep rate AO Q-switched output with short pulses.

Recently Unilase has developed Master Oscillator Power Amplifier (MOPA) technologies by combining the high gain amplifiers with versatile commercial off-the-shelf pulsed diodes that are capable of producing 100ps or longer pulses at virtually any pulse rates. Output of such diode lasers can be amplified towards tens of kW peak powers for very efficient wavelength conversion.

Figure 13 shows an example of a pulsed DFB diode producing pulses with 1ns in duration and operating at 500kHz. Microwatt level output of the diode is amplified to over 25W at 1064nm. With a peak power of 50kW it is possible to generate over 18W of 532nm and 10W of 355nm beams from two LBO crystals in series corresponding to conversion efficiencies of >60 and >30% at 532 and 355nm respectively.

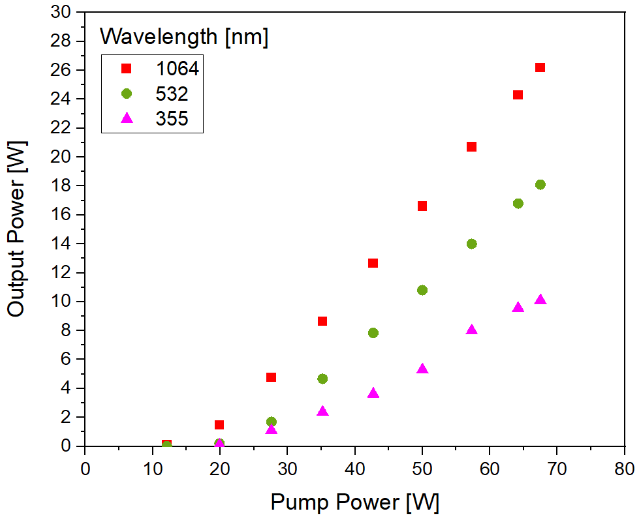


Figure 13: Efficient amplification of pulsed DFB diode (1ns@500kHz) and subsequent harmonic conversion of amplified output to 532 and 355.

3.0 CONCLUSION

In summary we have shown world class diode pumped Alexandrite lasers developed at Imperial College London for ESA for Vegetation LIDAR producing over 60µJ with short 1.5ns pulses at 5kHz. Furthermore, we have presented AO Q-switched operation of Alexandrite laser in a world first in both pulse and cw pumping conditions. From this pulsing technology mJ-class 40ns pulses has been obtained near diffraction limited beam quality.

Finally, we have presented a broad overview of side pumped slab technology at Unilase and demonstrated high gain amplifiers and oscillators with exceptionally high performance capabilities.