

Fibre-coupled red diode-pumped Alexandrite TEM₀₀ laser with single and double-pass end-pumping

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Abstract

We report the investigation of an Alexandrite laser end-pumped by a fibre-coupled red diode laser module. Power, efficiency, spatial, spectral, and wavelength tuning performance are studied as a function of pump and laser cavity parameters. It is the first demonstration, to our knowledge, of greater than 1W power and also highest laser slope efficiency (44.2%) in a diode-pumped Alexandrite laser with diffraction-limited TEM₀₀ mode operation. Spatial quality was excellent with beam propagation parameter $M^2 \sim 1.05$. Wavelength tuning from 737 – 796nm was demonstrated using an intracavity birefringent tuning filter. Using a novel double pass end-pumping scheme to get efficient absorption of both polarisation states of the scrambled fibre-delivered diode pump, a total output coupled power of 1.66 W is produced in TEM₀₀ mode with 40% slope efficiency.

PACS:

(Some figures may appear in colour only in the online journal)

1. Introduction

The family of Cr³⁺-doped laser materials (e.g. Alexandrite, Cr:LiSAF, Cr:LiCAF, Cr:LiSGaF) are of considerable interest due to their wide wavelength tunability across the important near-IR wavelength region (~700-1100 nm) [1-5]. Their bandwidth permits modelocking to generate femtosecond pulse durations [6-8] and with frequency conversion by harmonic generation, tunable laser sources can be generated across the blue/UV/deep-UV regions, where a quite limited choice of laser sources exists. The other pivotal aspect of the Cr³⁺-doped laser materials is that they have broad absorption bands and can be efficiently pumped by red diode lasers (AlGaInP). Compared to lamp or laser-pumping, the use of direct-diode-pumping provides order-of-magnitude higher efficiency and the scope for much lower-cost and more compact physical formats compared to non-diode pumped solid-state lasers. Of particular further interest is Alexandrite (Cr³⁺-doped Chrysoberyl) since it has a number of superior thermo-mechanical properties amongst the Cr³⁺-doped lasers, favourable for high power operation. Comparing to the ‘industry-standard’ laser crystal Nd:YAG, Alexandrite’s thermal conductivity (23 Wm⁻¹K⁻¹) [5] is almost twice as

high, its fracture resistance is five-times higher [1], and its strong birefringence gives highly linearly-polarised laser emission and minimising depolarisation problems. It has a long upper state lifetime of 260 μ s, almost 100 times longer than Ti:sapphire, which is favourable for good energy storage using diode-pumping for high energy pulse operation. The stimulated emission cross-section for Alexandrite is low (0.7×10^{-20} cm²) at room temperature, favourable for high inversion storage, but can be significantly increased by raising the crystal temperature – a rather unique feature of Alexandrite [1].

Despite the attractive properties of Alexandrite surprisingly limited investigation has been made of its diode-pumped operation and mostly at very moderate sub-W level [9-13], partially due to the immaturity of the red pumping technology. Recent advance in red diode lasers has been driven by the display industry leading to higher powers with shorter red wavelengths (giving higher absorption in Alexandrite) and longer diode lifetime. This offers new opportunities for diode-pumped Alexandrite with higher power operation and has led to the first demonstration of multi-watt diode-pumped slab Alexandrite laser [14] and 26.2 W in an end-pumped Alexandrite rod [15]

both performed in earlier work by our group using free-space diode pumping.

This paper describes the first study of fibre-coupled red diode-pumping of Alexandrite. Fibre-delivered diode pumping is a more power-scalable approach to Alexandrite pumping than in recent studies using near diffraction-limited pump diodes where just 200 mW was achieved [12-13]. Compared to our previous free-space diode format where beam shaping was complex and TEM₀₀ mode laser operation difficult to optimise, fibre-delivery provides a simplified coupling scheme for compact TEM₀₀ operation at high power. In this study fibre-delivered end-pumped operation of Alexandrite is performed. Results are shown of power, efficiency, spatial and spectral performance including wavelength tuning. The first demonstration is made of > 1W power and the highest laser slope efficiency (44.2%) in a diffraction-limited TEM₀₀ spatial quality beam ($M^2 \sim 1.05$), from diode-pumped Alexandrite, to our knowledge. To achieve good absorption efficiency for both polarisation states of the polarised scrambled diode fibre output, we devise a novel double-pass end-pumped scheme with polarisation flipping of the pump on the return pass, and demonstrate 1.66W total output coupled power and 40% laser slope efficiency.

2. Experimental arrangement(s) for single-end-pumping of Alexandrite

Fig. 1 shows the single end-pumped Alexandrite laser system with two configurations investigated: a compact cavity design for maximum efficiency and power, and an extended cavity design with a birefringent filter for wavelength tuning of the laser.

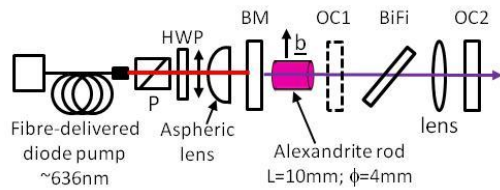


Figure 1. Experimental arrangements for fibre-delivered polarised diode single-end-pumped Alexandrite laser: compact cavity with output coupler OC1; and extended cavity with output coupler OC2, lens and birefringent filter.

The compact cavity (cavity length 15mm) was formed by a dichroic back mirror (BM) which is highly reflecting for the laser wavelength (~755 nm) and highly transmitting for the pump wavelength (~636 nm, nominally), and an output coupler (OC1) with transmission T_{OC} . The extended cavity was formed by the same dichroic back mirror (BM) and an output

coupler (OC2) forming a resonator of length ~100 mm. A spherical lens, with focal length of 100 mm, was positioned in the cavity to match the fundamental mode size to the pump region. Two Alexandrite rods (length 10mm, diameter 4mm, AR-coated end faces at ~760nm) with Cr-doping 0.13 at.% and 0.22 at.% were used in this study. The absorption coefficients (α_p) at the pump wavelength of these two crystals were ~3.5cm⁻¹ and ~6cm⁻¹, respectively.

In both cavity configurations, end-pumping was achieved using a nominally 5 W fibre coupled diode laser operating at a wavelength ~ 636 nm, with a fibre core diameter of 105 μ m and NA = 0.22. The fibre output was collimated using a collimating lens with focal length = 10.99 mm and NA = 0.25. The diode polarisation, which was scrambled by the fibre, was sent through a polariser (P) to obtain linear polarisation and a half-waveplate (HWP) used to match polarisation to the crystal b-axis for maximum absorption in the Alexandrite rods. The available linearly polarised red diode pump power to the laser crystal was ~3 W. The pump beam was measured to have an M^2 beam quality ~ 43. The pump radiation was focused into the Alexandrite rod using an aspheric lens. A selection of aspheric lens with different focal lengths (f) was investigated to optimise the focal spot size (d_f) and its confocal parameter (b) for best laser performance.

3. Compact cavity laser results

A comparative study of the performance of the two Alexandrite rods with different Cr doping density was undertaken using the compact cavity arrangement. Fig. 2 shows the output power versus absorbed pump power obtained using the 0.13 at.% (red line) and 0.22 at.% (black line) Alexandrite rods.

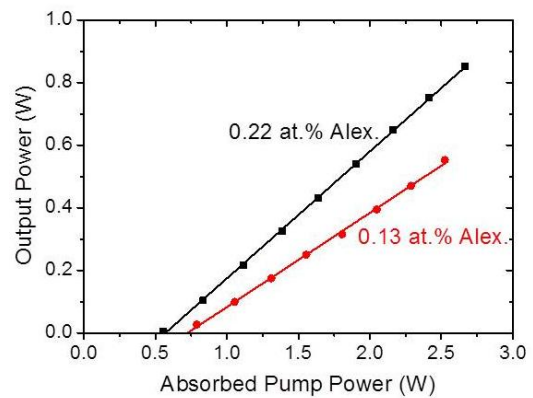


Figure 2. Laser performance of 0.13at.% Alexandrite rod (red line) and 0.22at.% Alexandrite rod (black line) in the compact cavity design ($f=26$ mm, $T_{oc}=0.8\%$, $T_d=15^\circ\text{C}$ and $T_{\text{xtal}}=50^\circ\text{C}$).

The absorbed pump power for the 0.13 at.% and 0.22 at.% crystals was 90% and 95% of the incident power, respectively, including unabsorbed pump and surface coating losses of pump lens, back mirror and laser rod. The pump lens had focal length $f = 26$ mm, the output coupler transmission, $T_{OC} = 0.8\%$ ($R_{oc} = 99.2\%$), and the diode and Alexandrite crystal temperatures were $T_d = 15^\circ\text{C}$ and $T_{xtal} = 50^\circ\text{C}$.

The best performance was obtained from the 0.22 at.% rod, which had 851mW of output power at a wavelength of 769nm for 2.7W absorbed pump power. The slope efficiency was 41% and the laser threshold was 0.57 W. The 0.13 at.% rod had lower output power 552 mW at slightly shorter wavelength 765nm, with lower slope efficiency of 29% and higher laser threshold of 0.73 W. The remainder of the work presented in this paper uses the 0.22 at.% rod due to its superior performance.

To investigate the pump focusing for optimising the laser performance, four aspheric lenses with focal lengths (f) of 20 mm, 26 mm, 32 mm, and 40 mm were tested in the compact laser system with 0.22 at.% Alexandrite rod. The pump beam diameter (d_f) at focus (based on the ISO second moment method) and its (free-space) confocal parameter b (equal to twice the Rayleigh length z_R) were measured for each lens case. These results are shown in Table 1 with the corresponding laser performance: laser slope efficiency η_s , threshold pump power P_{th} and laser power P_0 for 3W pump power.

Table 1: Summary of important focal pump beam parameters using different aspheric lenses and performance of the 0.22 at.% Alexandrite compact cavity laser ($T_{oc} = 0.8\%$, $T_d = 15^\circ\text{C}$ and $T_{xtal} = 50^\circ\text{C}$).

f (mm)	d_f (μm)	$b=2z_R$ (mm)	P_{th} (W)	η_s (%)	P_0 (W)
20	150	1.2	0.50	41.2	1.02
26	170	1.7	0.53	42.1	1.03
32	220	2.6	0.59	39.6	0.94
40	270	4.2	0.83	39.2	0.85

The $f = 26\text{mm}$ lens had highest output power and slope efficiency consistent with an optimal combination of small focal spot size and a confocal parameter suitably matching the pump focal region to the absorption depth ~ 1.7 mm of the 0.22 at.% rod ($\alpha_p \sim 6\text{ cm}^{-1}$). This also explains the poorer results with the longer absorption depth $\sim 2.8\text{mm}$ ($\alpha_p \sim 3.5\text{cm}^{-1}$) for the 0.13 at.% crystal. The 26mm aspheric lens was chosen for use in the following Alexandrite laser experiments.

Fig. 3 shows the output power versus absorbed pump power for the compact cavity Alexandrite laser using an optimized set of parameters: Alexandrite laser rod with 0.22 at.% Cr doping; $f = 26$ mm focal length pump lens; $T_{OC} = 0.8\%$ output coupler; diode water temperature $T_d = 12^\circ\text{C}$; and laser crystal temperature $T_{xtal} = 45^\circ\text{C}$. The diode water temperature was the minimum attempted due to the potential for formation of condensation on diode module at lower temperature.

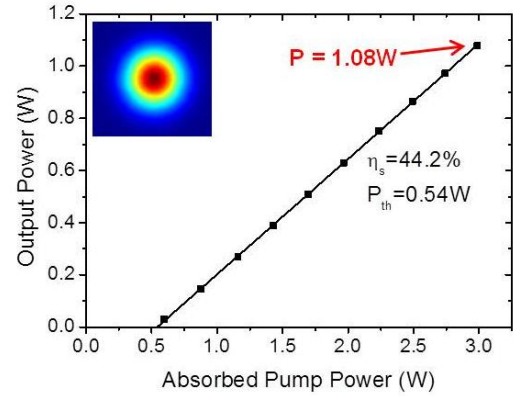


Figure 3. Output power of compact cavity 0.22 at.% Alexandrite laser with $T_{oc} = 0.8\%$ output coupler, $f = 26\text{mm}$ pump focusing lens, $T_d = 12^\circ\text{C}$, and $T_{xtal} = 45^\circ\text{C}$. Inset shows spatial beam profile at maximum power.

Output power of 1.08 W was obtained at 3 W absorbed pump power, corresponding to optical-to-optical efficiency of 36%. The laser slope efficiency was 44.2% and the laser threshold was 0.54 W. The lasing wavelength was 769.3 nm with a FWHM bandwidth of 4nm. The spatial profile of the Alexandrite beam, shown inset in Fig. 3, was TEM_{00} , with measured beam propagation parameter values of $M_x^2 = 1.06$ and $M_y^2 = 1.05$ at maximum output power.

The effect of varying the output coupler transmission T_{OC} on the Alexandrite compact cavity laser output was investigated and the results shown in Fig. 4. Fig. 4(a) shows power curves obtained with each of the seven different output couplers used. Fig. 4(b) is a composite plot showing the slope efficiency, η_s , and threshold pump power, P_{th} , plotted against output coupler transmission, T_{OC} . The slope efficiency shows a maximum value near the output coupling $T_{OC} \sim 1\%$ and the pump threshold increases with a near linear dependence with output coupling.

It is interesting to analyse this data-set of laser performance. According to four-level laser theory the pump threshold P_{th} and laser slope efficiency η_s should have a dependence on the output coupling T_{oc} and roundtrip intracavity loss L with the form:

$$P_{th} = a(T_{OC} + L) \quad (1)$$

$$\eta_s = \eta_i \left(\frac{T_{OC}}{T_{OC} + L} \right) \quad (2)$$

where a is a constant including laser saturation intensity and beam area, and η_i includes other efficiency factors such as Stokes and pump quantum efficiencies and laser mode fill factor. We have approximated for low output coupling and intracavity loss; for higher values output coupling T_{OC} and intracavity loss L should be replaced by logarithmic factors: $-\ln(1-T_{OC})$ and $-\ln(1-L)$, respectively.

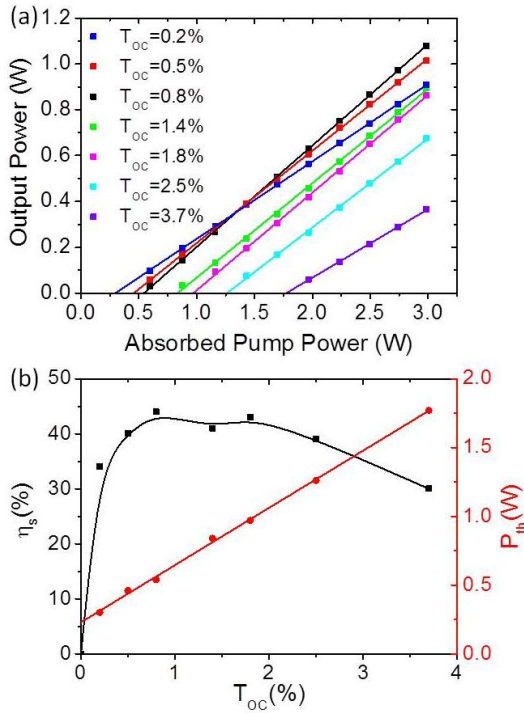


Figure 4. (a) Output power performance and (b) slope efficiency and pump threshold power of compact cavity 0.22 at.% Alexandrite laser with different output coupling transmissions, T_{OC} , at $T_d = 12^\circ\text{C}$ and with $f = 26\text{mm}$.

The extrapolation of the pump threshold power curve in Fig. 4(b), and using Eq. (1), is equivalent to the Findlay-Clay analysis and gives an intracavity loss factor $L = 0.53\%$. The form of Eq. (2) shows that the laser slope efficiency should be increasing with output coupling to an asymptotic limit: $\eta_s = \eta_i$. Fig. 4(b) shows, however, a decreasing slope efficiency at values of output coupling, T_{OC} , greater than $\sim 1\%$. This discrepancy suggests an inversion dependent loss mechanism is acting at higher output coupling T_{OC} to decrease the slope efficiency. No energy transfer upconversion (ETU) processes have been identified in Alexandrite but excited state

absorption (ESA) at the pump wavelength has been noted [16]. Pump ESA decreases the pump quantum efficiency since some fraction of the pump absorption is not used in the inversion creation process.

4. Extended laser cavity and wavelength tuning using a birefringent filter

The extended laser cavity was arranged as shown in Fig. 1. Wavelength tuning of the end pumped Alexandrite laser was achieved using a quartz birefringent filter plate (BiFi) using the $T_{OC} = 0.8\%$ output coupler at $T_d = 12^\circ\text{C}$, $T_{xtal} = 40^\circ\text{C}$. Fig. 5(a) shows the output power versus absorbed pump power from the extended cavity arrangement without the BiFi in the resonator. The maximum output power from this cavity was 0.75 W, in TEM_{00} mode with $M^2 < 1.1$. Fig. 5(b) shows the wavelength tuning curve obtained using a 1mm thick BiFi in the cavity at maximum pumping ($P_{abs} = 3\text{W}$). The maximum output power was 0.64W, at a wavelength of 760 nm. The Alexandrite laser tuned from 737 nm to 796 nm, and was limited by the free spectral range of the BiFi. The short wavelength cut-off was partially limited by a rapid spectral decrease of the output coupler reflectivity at short wavelengths.

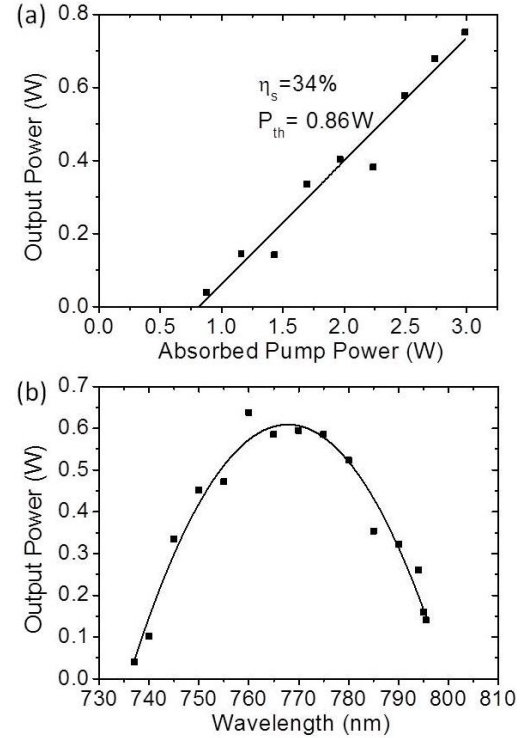


Figure 5. Output power from 0.22 at.% Alexandrite extended cavity (a) without BiFi and (b) with BiFi showing wavelength tuning. All data with $T_{OC} = 0.8\%$, $f = 26\text{mm}$ pump focusing lens, $T_d = 12^\circ\text{C}$, $T_{xtal} = 40^\circ\text{C}$.

5. Double-pass end pumped Alexandrite laser with polarization flipping of pump radiation

In the previous investigations, the fibre-delivery of the pump diode leads to its polarisation being scrambled and it was polarized before pumping thereby losing near to half the available pump power. The reason for using a polarised pump is that only the b-axis is highly absorbing. The orthogonal polarisation has an order of magnitude smaller absorption cross-section and is poorly absorbed in the focal region of the pump.

To utilize the fuller pumping power we devised the laser arrangement shown in Fig. 6. The full near-unpolarised output of the fibre-delivered pump (5.4 W) was focused as before to end-pump the laser rod. There was considerable unabsorbed pump power orthogonal to the b-axis that emerged from the rod (1.64 W). This light was retro-reflected with a high reflectivity (HR @ 636nm) mirror and refocused to the output face of the Alexandrite rod by double-passing a spherical lens ($f = 50$ mm) and with 90° polarisation rotation by double-passing a quarter-waveplate (QWP) to bring the unabsorbed pump to be parallel to the b-axis orientation.

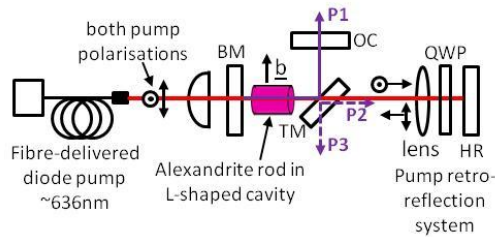


Figure 6. Experimental arrangement for double-pass end pumping of Alexandrite laser rod with an unpolarised fibre-delivered diode pump and with pump retroreflecting and polarisation rotating optics for the double-pass pumping.

To decouple the Alexandrite laser from this double-pass pumping system, an L-shaped laser cavity was formed with a turning mirror (TM) and the output coupler mirror (OC) placed as shown in Fig. 6 to give the laser output (P1). The turning mirror was high reflectivity (HR) at laser wavelength and high-transmitting (HT) for the red pump. It was found under lasing conditions when using the output coupler with $T_{OC} = 0.8\%$ that there was a considerable laser power output from the two directions from the turning mirror TM (see dashed arrows in Fig. 6) from which we calculate it had a transmission of 0.15% at the laser wavelength. The net total output power was 1.38 times the laser output (P1) from the output coupler.

Fig. 7 shows the output power (P1) and total output power ($P1+P2+P3$) versus incident diode

pump power for the double-pass pumping arrangement. A total output coupled power of 1.66 W ($P1 = 1.2$ W and $P1+P2 = 0.46$ W) was produced for 5.4 W of incident pump power. The laser slope efficiency was 40% with respect to incident pump (rather than absorbed pump). The spatial output was TEM_{00} mode ($M^2 < 1.1$)

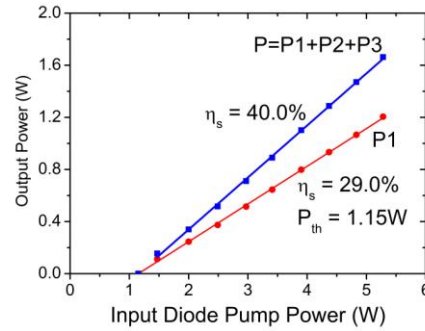


Figure 7. Total output power of double-pass end-pumped Alexandrite laser with $T = 0.8\%$ output coupler, $f = 26$ mm pump focusing lens, $T_d = 12^\circ\text{C}$, and $T_{\text{xtal}} = 50^\circ\text{C}$.

From pump power measurements in the system, we estimate that about 25% of the orthogonal to b-axis incident pump polarisation is absorbed over the 10mm length of the rod. Much of this absorbed orthogonal pump component will not overlap well with the laser mode except in the first few mm of the rod in the input pump focal region, and is an effective loss to the efficiency. A further few percent of the single-pass transmitted pump is lost in surface reflections before it is re-absorbed on the second pass of the rod. These combined pump losses account for the higher pump threshold (1.15 W) of this double-pass pump case compared to the absorbed pump threshold (0.54 W) for the polarised single end-pump case in Fig. 3. With lower losses for the orthogonal pump polarisation by using a slightly shorter crystal length and using lower loss retro-reflecting optics, the power performance can be expected to be further improved in this double-pass pumping arrangement.

6. Conclusion

This work presents the first demonstration of > 1 W diffraction limited output power from a diode-pumped Alexandrite laser and its first fibre-coupled diode pumping. We believe we have also obtained the highest slope efficiency (44.2%) to date from such a system with TEM_{00} mode and excellent beam quality $M^2 \sim 1.05$. Alexandrite laser performance was investigated as function of pump and laser cavity parameters including testing different pump focusing

lenses, output coupler transmissions, and diode temperature tuning. From the laser performance (slope efficiency, laser threshold) with different output couplers we conclude that ESA at the pump wavelength plays an important role in the diode-pumped Alexandrite laser [16]. Wavelength tuning of the diode-pumped Alexandrite laser from 737 – 796nm was demonstrated using an intra-cavity birefringent filter (BiFi) as the tuning element. The tuning was limited by the BiFi free-spectral range and spectral shape of the coatings of the cavity optics which were optimised for $\sim 760\text{nm}$. Better optimisation would lead to extended tuning range and power.

We further demonstrated a novel double-pass pump system that allows the use of an unpolarised pump beam to be efficiently absorbed in the Alexandrite despite the crystal only having strong absorption in one axis (crystal b-axis). A combined optical output coupled power of 1.66 W is demonstrated with 40% slope efficiency with respect to incident (rather than absorbed) pump. It is noted that there were some significant losses for the input pump component orthogonal to the crystal b-axis due to its absorption in the crystal outside the pump focal region and due to the surface reflection losses of the double-pass retro-reflecting optics. By eliminating these losses this system should be able to be further improved in efficiency and power.

We finally conclude that even with pump diodes with far from diffraction-limited beam quality, high efficiency and high beam quality Alexandrite laser operation can be obtained. With further optimisation, including management of pump ESA and minimisation of other passive losses even higher efficiency should be possible to obtain. With fibre-delivery we have the ability to develop compact and high power diode-pumped Alexandrite laser technology, with the future development of

wavelength-tunable CW and Q-switched nanosecond operation and bandwidth potential for modelocked picosecond / femtosecond systems at multi-Watt to multi-ten Watt average power levels.

References

- [1] Walling J, Peterson O G, Jenssen H, Morris R and O'Dell E W 1980 *IEEE J. Quantum Electron.* **16** 1302-1315
- [2] Demirbas U, Li D, Birge J R, Sennaroglu A, Petrich G S, Kolodziejski L A, Kärtner F X and Fujimoto J G 2009 *Opt. Express* **17** 14374-14388
- [3] Kuper J W, Chin T and Aschoff H E 1990 *Proc. Advanced Solid State Lasers (OSA)* **6**, paper CL3
- [4] Walling J C, Peterson O G and Morris R C 1980 *IEEE J. Quantum. Electron.* **16** 120-121
- [5] Walling J, Heller D F, Samelson H, Harter D J, Pete J and Morris R C 1985 *IEEE J. Quantum Electron.* **21** 1568-1581
- [6] Demirbas U, Petrich G S, Li D, Sennaroglu A, Kolodziejski L A, Kärtner F X and J. G. Fujimoto 2011 *J. Opt. Soc. Am. B* **28** 986-993
- [7] Hopkins J, Valentine G J, Agate B, Kemp A J and Keller U 2002 *IEEE J. Quantum Electron.* **38** 360-368
- [8] Demirbas U, Schmalz M, Sumpf B, Erbert G, Petrich G S, Kolodziejski L A, Fujimoto J G, Kärtner F X and Leitenstorfer A 2011 *Opt. Express* **19** 20444-20461
- [9] Scheps R, Gately B M, Myers J F, Krasinski J S and D. F. Heller 1990 *Appl. Phys. Letters* **56** 2288-2290
- [10] Scheps R, Myers J F, Glesne T R and Serreze H B 1993 *Opt. Comm.* **97** 363-366
- [11] Peng X, Marrakchi A, Walling J C and Heller D F 2005 in Conference on Lasers and Electro-Optics. Paper CMAA5, OSA
- [12] Beyatli E, Baali I, Sumpf B, Erbert G, Leitenstorfer A, Sennaroglu A and Demirbas U 2013 *J. Opt. Soc. Am. B* **30** 3184-3192
- [13] Yorulmaz I, Beyalti E, Kurt A, Sennaroglu A and Demirbas U, 2014 *Opt. Mat. Express.* **4**, 776-789
- [14] Damzen M J, Thomas G M and Minassian A 2013 *CLEO Europe*, Paper CA-2.6 SUN
- [15] Teppitaksak A, Minassian A, Thomas G M and Damzen M 2014 *Opt. Express* **22** 16386-16392
- [16] Shand M L, Walling J C and Morris R C 1981 *J. Appl. Phys.* **52** 953-955