Optical vortex generation from a diode-pumped alexandrite laser

G. M. Thomas\textsuperscript{1}, A. Minassian\textsuperscript{2} and M. J. Damzen\textsuperscript{1}

\textsuperscript{1} Photonics Group, Blackett Laboratory Physics, Imperial College London, Prince Consort Road, London SW7 2AZ, UK
\textsuperscript{2} Unilase Ltd, 1 Filament Walk, Unit G02, London SW18 4GQ, UK

E-mail: gmt03@ic.ac.uk

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Abstract. We present the demonstration of an optical vortex mode directly generated from a diode-pumped alexandrite slab laser, operating in the bounce geometry. This is the first demonstration of an optical vortex mode generated from an alexandrite laser or from any other vibronic laser. An output power of 2 W for a vortex mode with ‘topological charge’ of 1 was achieved and the laser was made to oscillate with both left- and right-handed vorticity. The laser operated at two distinct wavelengths simultaneously, 755 and 759 nm, due to birefringent filtering in the alexandrite gain medium. The result offers the prospect of broadly wavelength tunable vortex generation directly from a laser.

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1. Introduction

Optical vortices possessing annular spatial amplitude profile, and a spiral phase structure with a central phase singularity exhibit a property known as orbital angular momentum [1, 2, 3]. They have recently attracted intense interest due to their application in a broad range of fields, including optical trapping and manipulation [4, 5], optical communications [6, 7], super-resolution microscopy [8, 9, 10], and laser materials processing [11, 12]. An optical vortex can be generated from a laser via means of a spiral phase element [13], a defect on a cavity mirror [14], pumping the laser with an annular beam [15, 16], or by use of a spatial light modulator [17] or holographic plate on the output laser beam [18]. Another method of producing a vortex beam is by exploiting the inherent spherical aberration of a thermally-induced lens in the laser gain medium as a spatial filter to select preferentially the LG_{0m} mode. This method has been demonstrated by Omatsu et al. for Nd-doped gain media operating at 1 µm and 1.3 µm [19, 20] and also in our previous work [21].

For such a broad and ever increasing range of applications for optical vortices, it is equally important for vortex sources to be robust and flexible in terms of output characteristics (e.g. wavelength, power, pulse format, handedness). Optical vortices are externally generated from the output of Ti:sapphire lasers in microscopy to take advantage of its wavelength tunability [22] and there have been some recent reports and investigations into the generation of ultrafast vortices [23, 24, 25] for high-field scientific experiments. Wavelength versatility and handedness control have recently been summarized by Omatsu et al. [26] and Lin et al. [27]. Wavelength conversion has been achieved in a variety of ways: via second harmonic generation [28], optical parametric oscillation [29] and stimulated Raman scattering [30]. All of these experiments have relied upon an active device (like a spatial light modulator or a spiral phase plate), which is typically inefficient, wavelength-sensitive and can have limiting damage thresholds [22].

Wavelength-versatile lasers bring flexibility to many applications, and by far the most commonly used broadly tunable laser is Ti:sapphire. Operating over the extraordinarily large wavelength range ~700 – 1100 nm, Ti:sapphire belongs to a group of laser materials known as vibronic lasers, where photon-phonon interaction in the crystal lattice leads to homogeneous broadening of the lasing transition. One such vibronic laser which has recently generated interest is alexandrite, Cr^{3+}-doped chrysoberyl [31, 32]. Whilst operating over a narrower wavelength range than Ti:sapphire (~700 – 850 nm), it possesses some attractive properties that make it a useful laser source for application-driven research. It has a thermal conductivity of 23 Wm^{-1}K^{-1}, which is around five times that of the Cr^{3+}-doped colquirites (which also belong to the vibronic laser family), and has a fracture resistance of 1 GPa, five times that of Nd:YAG [32].

One key capability, however, is the potential for high-power diode-pumping of alexandrite using commercially available red (AlGaInP) laser diodes. Alexandrite also exhibits a long room-temperature upper state lifetime, ~260 µs, allowing for good energy storage under diode-pumping and is beneficial for Q-switched operation. Direct diode-pumping of Ti:sapphire has recently been demonstrated, but output powers are still fairly modest, and its upper state lifetime is only 3 µs [33, 34].

Despite alexandrite’s attractive and beneficial properties, diode-pumping with significant power has only recently been reported. In our previous work we demonstrated: record continuous-wave (CW) output powers of >26 W from a diode-pumped alexandrite laser, with slope efficiency 49 % [35]; high energy Q-switching and the first ever cavity-dumped Q-switching of a diode-pumped alexandrite laser [36]; and we have reported analytical models that underpin our understanding and alexandrite laser design considerations [37]. There have been further reports of diode-pumping alexandrite lasers, using tapered diodes to in-band pump [38, 39], with broad tunability [37, 40] and alexandrite ring laser development [41]. In all these systems, the alexandrite crystal has been longitudinally pumped. Whilst providing excellent overlap between pump and laser mode, this scheme is inherently limited in terms of power-scaling. We recently aimed to address this in alexandrite using a slab laser geometry known as the bounce geometry [42]. This is a well-established laser geometry, used for power scaling slab lasers, typically those using highly absorbing high gain Nd-doped media [43, 44, 45, 46].

In this paper, we explore a vortex laser mode directly generated from a vibronic laser. Using a diode-pumped alexandrite slab laser operating in the bounce geometry, a vortex whose handedness can be controlled by pumping conditions was generated, due to mode selection arising from spherical aberration of the thermally-induced lens of the alexandrite gain medium. Continuous-wave output power of 2 W was achieved, with a clear annular spatial profile, and measured M^2 beam quality factor 2.29 in the horizontal and 2.44 in the vertical dimensions. Interferometric measurements determined that the vortex had topological charge of 1. These results show promise for broadly tunable optical vortices with flexible pulsing capabilities.
2. Experimental alexandrite vortex laser

The laser system of interest was an alexandrite slab laser, operated in the bounce geometry [43, 44, 45, 46]. Figure 1 shows the experimental cavity configuration for the generation of a vortex mode from the alexandrite bounce geometry laser. The slab was of dimensions 20 × 4 × 2 mm and 0.22 at.% Cr-doping concentration, with the b-axis of alexandrite oriented as indicated in Fig. 1. The slab was mounted on a water-cooled aluminum heat sink, with enhanced thermal contacting of one of the 20 × 2 mm faces achieved with an indium foil interface.

![Figure 1. Experimental alexandrite vortex laser schematic.](image1)

The slab was pumped using a red diode module operating ~ 638 nm, with polarization parallel to the b-axis of alexandrite, and is described in detail in Teppitaksak et al.[35]. The output of this module was brought to a line focus on one of the 20 × 2 mm faces using a vertical cylindrical lens (VCL) of focal length f = 50 mm to produce a region of high inversion near the pump face. The pump face was not anti-reflection (AR) coated so the pump beam experienced Fresnel reflection loss at this input face (~ 7.4 %). Using this configuration, approximately 90 % of the remaining pump was absorbed through the 4 mm crystal width.

The cavity was formed of two plane mirrors: a back mirror highly reflecting (HR) at the laser wavelength of ~ 755 nm, placed at distance L₁ = 170 mm from the center of the laser crystal, and an output coupler (OC) with reflectivity, R = 98 % placed at distance L₂ = 330 mm. Two intra-cavity vertical cylindrical lenses (VCL₁ and VCL₂) of focal length f = 60 mm were incorporated, approximately at their focal length away from the center of the crystal, to match the laser mode size in the vertical dimension to that of the narrow gain region. Lasing was via the two 4 × 2 mm faces, which were AR coated for the lasing wavelength. The bounce angle θ_B was approximately 10°.

3. Alexandrite vortex laser results

Initially, the cavity was aligned for HG₀₀ (TEM₀₀) operation at high pump power by optimizing the arm lengths L₁ and L₂ in the presence of the pump-dependent thermally-induced lens in the laser amplifier. By making adjustments to the pumping conditions (and hence the strength of the thermal lens, which acts as a limiting aperture) by means of adjusting the position of the VCL_D with respect to the pump face, the cavity was made to oscillate on a superposition of Hermite-Gaussian modes HG₁₀ (TEM₁₀) and HG₁₀ (TEM₁₀) in phase quadrature (i.e. with π/2 phase difference between them), resulting in Laguerre-Gaussian LG₀₁ mode with annular spatial profile. This method is further described by Okida et al. [19, 20] and Chard et al. [21]. A single plano-convex (PCX) lens was used to image the output of the vortex laser onto a CCD camera, to visualize the spatial profile. Figure 2, shows the spatial profile of the vortex beam at the focus of the PCX lens. It displays a clear zero in intensity at the center of the beam, and double-lobed cross-section in both horizontal and vertical dimensions.

![Figure 2. Spatial profile of the vortex laser output, with distinct zero in intensity at the center.](image2)

The output power of the alexandrite vortex laser was measured with respect to absorbed pump power, and the results are shown in Fig. 3. The figure shows three distinct regions of operation. Near threshold, the cavity oscillated on HG₀₀ (TEM₀₀) mode, until around 30 W absorbed pump power where it flipped between HG₁₀, (TEM₁₀) and HG₀₁ (TEM₀₁). As the absorbed pump power approached ~ 37 W, the cavity began to oscillate on the LG₀₁, or vortex mode. The power increases linearly, without any decrease in output power during vortex operation, likely due to improved pump-laser mode overlap, an intricacy that has been previously reported by Okida et al. [20]. The cavity continued to
support the vortex mode until \( \sim 47 \) W absorbed pump power and above this the cavity became unstable. Based on our previous work \[21\] and the power-dependent spatial behavior of this system, it is clear that the vortex mode is preferentially allowed to lase due to cavity stability requirements. Above 30 W pumping, stable TEM\(_{00}\) (or HG\(_{00}\)) operation is not supported as the power-dependent thermal lens becomes too strong and its spherical aberration acts as a limiting aperture \[21\].

Figure 3. Power curve for the alexandrite vortex cavity, indicating the different regions of operation.

Figure 3 shows that the output power of the alexandrite vortex laser increased linearly with pump power, up to a maximum output power of 2 W, from \( \sim 47 \) W pump power. The slope efficiency was \( \sim 9.5 \% \) and the optical-to-optical conversion efficiency was \( \sim 4.3 \% \). The low efficiency is likely due to poor mode-matching between the pumped region and laser mode and would certainly be improved by better laser cavity design, but this was not implemented during the course of this study.

To verify that the annular beam had angular momentum (and hence was a true vortex beam) and to determine how many times the phase traverses \( 2\pi \) (referred to as the ‘topological charge’), the beam was self-interfered in a Mach-Zehnder interferometer. The wavefront of the laser beam was interfered with a magnified version of itself. The self-interference fringes obtained by this process are seen in Fig. 4(c). Although the quality of the interferograms is not ideal, likely due to poor quality optical elements used in the measurement, the single fork, clearly visible in the center of the interferogram, shows the phase singularity and indicates a topological charge of 1.

The handedness of the vortex depends on the sign of the relative phase difference between HG\(_{01}\) and HG\(_{10}\). It can be either \( +\pi/2 \) or \( -\pi/2 \), corresponding to a left- or right-handed vortex, respectively \[47\]. By making minor adjustments to the position of the pump VCL\(_D\) with respect to the crystal (i.e. changing the pumping conditions), the laser could be made to change between left- and right-handed vortices, a method of handedness control described by Omatsu \textit{et al.} \[26\], and references within. This was observed via the introduction of a spherical wavefront to one arm of the interferometer, resulting in a spiral interference pattern. Figure 4 shows both (a) left- and (b) right-handed spiral interference patterns obtained, indicating that the cavity can produce left- and right-handed single vortices.

The beam quality factor, \( M^2 \), of the vortex mode was measured. The resultant caustic fit is shown in Fig. 5, indicating low astigmatism with \( M^2_x = 2.29 \) and \( M^2_y = 2.44 \). A perfect LG\(_{01}\) mode would have \( M^2 = 2 \), suggesting that in our vortex laser some higher order modes are present. Typically in the bounce geometry, the beam quality in the vertical dimension is better than the horizontal dimension due to mode-matching provided by the intra-cavity VCL’s \[43\]. In this case the opposite is true. This may be due to non-optimized positioning of the intra-cavity VCL’s and the action of altering the pumping conditions by adjusting the VCL\(_D\), and would be the subject of future investigation. Spatial profiles of the vortex beam at a focus and in the far-field are shown inset on Fig. 5, demonstrating that the vortex is preserved.
Optical vortex generation from a diode-pumped alexandrite laser throughout.

Figure 5. $M^2$ caustic fit for the alexandrite vortex laser. The spatial profile at the focus and far-field are also shown (inset).

The spectrum of the vortex laser was measured using a Czerny-Turner spectrometer and is shown in Fig. 6. The laser appeared to oscillate at two wavelengths simultaneously: with peaks near 755 nm and 759 nm, separated by a sharp minimum. This behavior is thought to be due to a birefringence filtering effect of the alexandrite slab, which we and others have noted in previous work [36, 39], and results in a periodic wavelength-dependent loss modulation that results in an optimum wavelength for oscillation and intermediate wavelengths with maximum loss that are less strongly able to oscillate.

Figure 6. Lasing spectrum of the alexandrite vortex laser.

Future work will aim to explore wavelength tunability and frequency conversion of the alexandrite vortex laser, with a view to providing wavelength flexibility for subsequent application. Power scaling of this preliminary laser system will also be addressed by optimizing the laser cavity design. Additionally, pulsing capabilities of the alexandrite vortex laser would be interesting to investigate, including Q-switching and modelocking. Such lasers could be of significant interest in fields as diverse as biomedical imaging, material processing and high field physics.

4. Conclusions

We have presented demonstration of an optical vortex directly generated from a diode-pumped alexandrite laser, and the first from any vibronic laser system. By exploiting the power-dependent thermal lens of a diode-pumped alexandrite laser in the bounce geometry, and its behavior as a selecting aperture, an optical vortex with topological charge of 1 was generated directly from the laser itself, with no introduction of any spatial or phase optical elements. An optical vortex with an output power of 2 W was reliably generated and whose handedness could be controlled by minor adjustments to the pump focusing lens.

These results show promise for future optical vortex applications that require a flexible laser with minimal components. Future experiments would aim to increase the efficiency of the alexandrite vortex laser, by improved laser cavity design. Wavelength tuning and conversion, as well as different pulsing capabilities, would also be of interest to study, as many applications benefit from such wavelength and pulse flexibility.

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5. References

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