Vortex laser from anti-resonant ring coupled cavities

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Abstract: Optical vortex Laguerre-Gaussian (LG_{0l}) modes have wide-ranging applications due to their annular spatial form and orbital angular momentum. Their direct generation from a laser is attractive, due to the pure and high-power modes possible; however, previous demonstrations have had limited ranges of applicability. Here, we propose and implement direct LG_{0l} vortex mode generation with an anti-resonant ring (ARR) coupled laser cavity geometry, where the gain medium inside the ARR is shared between two laser cavities. This generation uses standard wavelength-insensitive optical components, is suitable for high peak and average power levels, and could be applied to any bulk gain medium in pulsed or continuous wave regimes. This work demonstrates the technique with a diode end-pumped Nd:YVO_4 gain medium. From 24 W of pump power, 8.9 W LG_{01} and 4.3 W LG_{02} modes were generated, all with high mode purity and pure handedness. The LG_{01} mode handedness was controlled with a new technique.

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An optical field can possess a spiralling phase that surrounds a phase singularity and a point of zero intensity. This is called an optical vortex [1]. The laser resonator LG_{pl} modes, of radial index p and azimuthal index l, have optical vorticity when the azimuthal index is non-zero, l ≠ 0, which gives them orbital angular momentum (OAM) [2]. Both their annular intensity profile and OAM have generated significant interest and applications in many areas of science [3–6].

The generation of the LG_{0l} modes can be categorised as either extra-cavity conversion, where a laser output is converted into the desired LG mode external to the laser cavity, or intra-cavity generation, where a laser directly outputs the required LG mode.

Extra-cavity methods are widely used due to their flexibility and firm control of vortex handedness (clockwise or anti-clockwise spiral phase) [7–10]. However, the conversion optics typically have limited power handling capabilities, are designed for a single wavelength, are sensitive to misalignment and input beam dimension, and the generated LG modes may not have a high purity.

The challenge of intra-cavity generation is making a laser operate on a pure annular shaped LG_{0l} mode, which is not normally the natural operation state. Techniques of intra-cavity generation in solid-state lasers include spot-defect mirrors [11], spherical aberration selection [12, 13], q-plate [14], and annular pumping [15]. Each of these techniques are typically restricted in their applicability, for example having power or wavelength sensitive optics, or requiring a very bespoke pump source that needs to be appropriately shaped.

A widely used device for vortex generation is the computer controlled spatial light modulator (SLM). These are used in both extra-cavity [4] and intra-cavity [16] techniques and are flexible due to the computer controlled phase or amplitude modulation patterns. However, the SLM has limitations in operating at high peak or average power levels from dielectric breakdown or thermal degradation, resulting in damage thresholds below those of non-absorbing dielectric coated interfaces [17]. Additionally, individual spatial patterns are wavelength specific and the SLM is a high cost device (>$10 000).

In this letter we present an intra-cavity vortex generation geometry that could be applied to any gain medium both isotropic and anisotropic, which has the advantages of not requiring reshaping.
of the pump beam, having high efficiency, using standard high power capable optical components, and being wavelength insensitive - a full range of attributes not present in previous methods. It has the potential to be widely applied for pure and high power vortex generation, continuous wave or pulsed, across the electromagnetic spectrum.

The structure of an anti-resonant ring (ARR) [18], also called a Sagnac interferometer, is shown in Fig. 1(a). The input beam ($P_{in}$) is split by a 50/50 beamsplitter into two equal parts that propagate in opposite directions around the ring. For a symmetric ring, the returning clockwise ($P_{CW}$) and counter-clockwise ($P_{CCW}$) beams follow common paths and constructively interfere towards the input direction due to phase changes at the BS, creating the return $P_{R}$. In a lossless system the transmitted power to the other port $P_{T} = 0$ due to destructive interference in that direction so $P_{R} = P_{in}$. The ARR is wavelength independent due to the common beam paths and it can support simultaneous independent inputs in both the indicated directions provided that they are incoherent [18].

The coupled laser geometry proposed and implemented is shown in Fig. 1(b). There are two cavities, the ‘primary’ and ‘secondary’, which have separate linear sections between their output couplers and the beamsplitter. The primary cavity is designated to produce the required vortex mode and the secondary cavity acts as a control for this generation. The cavities operate at different wavelengths and use opposite inputs into the ARR, which contains the shared end-pumped gain medium. In this work the linear sections contained only lenses and an aperture for mode size control, but can be designed like any other linear laser cavity.

A laser will oscillate on the lowest threshold mode available. If all transverse modes have the same loss then the mode with the highest overlap integral with the gain region will have the lowest threshold [19]. In the ARR coupled laser, the secondary cavity controls the spatial distribution of the gain so that it matches the desired LG$_{0l}$ vortex mode in the primary cavity.

The transverse population inversion profile of the gain region will match that of the pump below laser threshold, Fig. 2(a), which is typically Gaussian or super-Gaussian shaped in optical end-pumping. As the pump power increases the secondary cavity reaches threshold first by
configuring it to have a higher reflectance output coupler ($R_2 > R_1$), but by its intracavity aperture is restricted to modes that only overlap the centre of the gain region, see Fig. 2(b).

With increasing pump power the gain region better spatially matches the desired $LG_{01}$ mode due to gain clamping of the secondary cavity [20], see Fig. 2(c). The primary cavity then reaches threshold for that mode, with its gain clamping preventing other higher order spatial modes from also reaching threshold. Tailoring the pump beam and mode diameters in both the primary and secondary cavities allows different $LG_{00}$ vortex modes to be selectively excited, see Fig. 2(d). A detailed mathematical description of this technique is planned for future work.

In our experimental implementation the gain medium was a 0.5% doped Nd:YVO$_4$ crystal, 5 mm long by 2 mm square, using the 1064 nm laser transition. The primary and secondary cavities had $R_1 = 60\%$ and $R_2 = 80\%$ reflectance output couplers, respectively, and equal focal length intracavity lenses $f_1 = f_2 = 75$ mm. The ARR perimeter was 55 mm, with the linear cavity section lengths ranging from 55 mm to 130 mm depending on the laser mode sizes required.

The Nd:YVO$_4$ crystal was end-pumped through a dichroic turning mirror with an unpolarized 808 nm fibre coupled pump module, which had a 440 $\mu$m diameter focus at the crystal. The $LG_{00}$ mode diameters at the gain region were 230 $\mu$m for the secondary cavity, and 330 $\mu$m and 310 $\mu$m in the primary cavity for $LG_{01}$ and $LG_{02}$ generation, respectively.

$LG_{01}$ generation was possible at a range of pump powers, see Fig. 4(a), with optimum performance at maximum pump power due to the crystal thermal lens giving access to a smaller secondary cavity mode size. The $P_1:P_2$ ratio of 24:1 at maximum pump power shows the exceptionally high efficiency of vortex generation in this design.

The overlap of the two cavity modes at the gain region is shown in Fig. 5, which shows the experimentally measured intensity at the gain region and the corresponding primary (red) and secondary (blue) mode positions. The initial alignment was for both cavities to be collinear, as in Fig. 5(b), which made the secondary cavity symmetrically saturate the gain. In this case the primary cavity oscillated on multiple $LG_{01}$ longitudinal modes but with a mixture of handedness directions [15]. It was found that to selectively excite different handedness modes, the secondary cavity mode could be diagonally offset from the central position by adjusting the horizontal and vertical tilt of the secondary cavity output coupler, as in Figs. 5(a) and 5(c). In doing so, the
Fig. 3. The primary (red) and secondary (blue) cavity powers at 23 W pump power versus, (a) secondary cavity LG\textsubscript{00} mode diameter, the primary cavity LG\textsubscript{01} mode diameter was 470 µm; (b) primary cavity LG\textsubscript{01} mode diameter at the gain region, the secondary cavity LG\textsubscript{00} diameter was 230 µm but had higher-order spatial modes when the primary cavity LG\textsubscript{01} diameter was above 540 µm.

Fig. 4. (a) The output powers of the primary vortex cavity (P\textsubscript{1}) and the secondary control cavity (P\textsubscript{2}) against input pump power for LG\textsubscript{01} generation. (b) A typical frequency spectrum of the primary (red) and secondary (blue) cavity modes.

LG\textsubscript{00} mode in the primary cavity remained suppressed without significantly effecting the output powers of the cavities; additionally, it caused the primary cavity LG\textsubscript{01} modes to oscillate with a common handedness. By adjusting the position of the secondary cavity mode either handedness direction could be selectively generated.

The position of the secondary cavity mode in Fig. 5(a) compared to 5(c) was a 90° rotation about the primary cavity central axis. The handedness control was also effective for further 90° rotations, with opposite diagonal positions giving the same handedness modes. The strength of the handedness selection was proportional to the radial distance of the secondary cavity mode, with the optimum position being a balance between maximising this distance whilst maintaining the LG\textsubscript{01} mode of the primary cavity.

The precise mechanism for this method to control the vortex handedness requires further investigation; however, it is likely that the asymmetries introduced in the thermal lens by the off-centre secondary cavity mode caused conditions more favourable to one handedness than the other. Alternatively, transversely asymmetric spatial hole burning from the secondary cavity could have caused preferential oscillation of one handedness, similar to other handedness selection elements [21]. This is due to the standing wave pattern of LG\textsubscript{01} modes having rotating lobes, with
Fig. 5. The handedness control method using the position of the secondary cavity mode for (b) no selection, (a) and (c) opposite handednesses. The top row shows the measured combined mode intensities at the gain region from both cavities, the bottom row contains corresponding illustrations of the cavity mode positions of the primary cavity LG\(_{01}\) mode (red) and the secondary cavity LG\(_{00}\) mode (blue).

The rotation direction dependent on handedness. Despite the precise mechanism being unknown, this method of handedness selection was robust and repeatable. An advantage of this technique is that it does not require additional optical components in the primary vortex cavity that could disrupt the spatial symmetry, alignment, or introduce losses.

To confirm that a laser is oscillating on a pure LG\(_{0l}\) mode and not an incoherent superposition of modes giving a doughnut intensity profile, the phase structure of the mode must be investigated [22]. A Mach-Zehnder interferometer was used to observe the phase profile. The mode was split into two beams. One path in the interferometer was converted to a plane wave reference by expanding and collimating the beam, where a small section of the mode can be assumed to be at constant phase. The other path was diverged with a lens to give spherical curvature to the beam. For a pure handedness LG\(_{0l}\) mode, the interference of these beams gives a spiral pattern from the combination of the azimuthal phase of the mode and radially symmetric phase of the curved wave-front, where the number of spiral arms from the centre is equal to the charge of the vortex |\(l|\). To quantitatively determine handedness purity modal decomposition can be used [22].

The spiral interferograms in Fig. 6 verify the pure and opposite handedness directions obtained (LG\(_{0,-1}\) and LG\(_{01}\)) from the clear spiral pattern fringes. The mode intensity profiles and M\(^2\)_x,y beam quality values are shown in Fig. 6, which matches the expected beam quality of the LG\(_{01}\) mode of M\(^2\)_x,y = 2. The output powers were \(P_1 = 8.9\) W and \(P_2 = 0.9\) W for both handedness directions from 24 W pump power.

The LG\(_{02}\) mode was then targeted in the primary cavity by matching its mode size to the gain region, as in Fig. 2(d), by increasing the primary cavity length. The intensity profile, beam quality, and interferogram of the LG\(_{02}\) mode are shown in Fig. 6, where the expected LG\(_{02}\) beam quality of M\(^2\)_x,y = 3 is matched. The output powers were \(P_1 = 4.3\) W and \(P_2 = 4.4\) W from 24 W pump power. The interferogram had two clearly defined spirals from its centre verifying the doubly charged vortex. The pure handedness was achieved because in this configuration the primary cavity was operating closer to laser threshold. This resulted in fewer longitudinal modes that allowed slight asymmetries in the cavity to allow one handedness state to dominate.

The handedness selection technique used for the LG\(_{01}\) mode could not be used for the LG\(_{02}\) as...
Fig. 6. The primary cavity output $P_1$ in LG$_{0,-1}$, LG$_{01}$ and LG$_{02}$ operation, showing the beam intensity profiles (top row) and spiral interferograms (bottom row).

this was more sensitive to the alignment of the secondary cavity. However, the linear section of the primary cavity could accommodate optical components for handedness selection [20, 21] to provide a simple modification for vortex handedness control.

The ARR was designed to have no transmission; however, due to practical symmetry limitations $P_T \neq 0$ and a ring leakage loss is defined as $L_R = P_T/(P_{CW} + P_{CCW})$. The ARR had a measured $L_R = 0.02\%$ at maximum power, which is 20 times lower than the only previous example of a gain medium internal to an ARR [23]. This was achieved through reducing ARR asymmetries, most significantly by ensuring a 50/50 BS [18] and central thermal lens location in the ring, to minimise the difference in clockwise and counter-clockwise beam imaging [24].

A potential concern of ring transmission leakage is that the two laser cavities in Fig. 1(b) may seed each other and lock together in frequency, which could affect the coupling dynamics required for vortex generation. A typical frequency spectrum of the two laser cavities using a Fabry-Perot etalon is shown in Fig. 4(b). The two cavity frequencies were different, which confirms that they were incoherently sharing the ARR.

In summary, this work has proposed an ARR coupled laser geometry to achieve gain sharing for vortex generation. By tailoring the primary and secondary cavity mode and pump beam sizes pure LG$_{01}$ and LG$_{02}$ vortex modes were selectively and efficiently excited. The principles behind cavity mode size optimisation in the gain competition technique were experimentally demonstrated, a full mathematical model is currently under development. The gain competition methodology can be extended to generate further higher-order modes because there is no theoretical limit to the maximum $l$ that can be obtained. The limiting factor is practical, which is determined by the accuracy of matching the cavity mode to the gain region, with the current record being $l = 3$ [15]. To further extend this practical limit, and augment the gain competition technique in general, pump reshaping methods could be incorporated.

Whilst this work implemented vortex generation it could be adapted to generate other spatial modes [25]. It is a flexible test-bed for laser cavity mode competition studies, which gives unique possibilities for laser control [26]. An interesting capability of this system is the separation of modes in a laser, which could be used to study the formation of higher order modes. Alternatively, it could be used as an adaptive and low loss higher order mode suppression technique.

The ARR coupled laser geometry could be applied to any bulk gain medium as it uses standard optical components and is inherently wavelength independent. This would allow vortex laser sources to be made across the directly accessible electromagnetic spectrum from known gain
media, both isotropic and anisotropic, with the range further enhanced with non-linear wavelength conversion [27]. This method supports broad wavelength tunability, which is challenging in other mostly wavelength specific techniques. The presented technique is also not limited to continuous wave operation; standard methods of generating pulsed laser outputs, for example mode-locking or Q-switching, would enable ultra-short pulse or high energy vortex sources.

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**References**


