Intra-cavity vortex beam generation

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ABSTRACT

In this paper we explore vortex beams and in particular the generation of single LG_{0l} modes and superpositions thereof. Vortex beams carry orbital angular momentum (OAM) and this intrinsic property makes them prevalent in transferring this OAM to matter and to be used in quantum information processing. We explore an extra-cavity and intra-cavity approach in LG_{0l} mode generation respectively. The outputs of a Porro-prism resonator are represented by "petals" and we show that through a full modal decomposition, the "petal" fields are a superposition of two LG_{0l} modes.

Keywords: Vortex beams, SLM, Laguerre-Gaussian beams, Porro-prism resonator, Petals.

1. INTRODUCTION

It is well known that light may carry an extrinsic component of angular momentum, orbital angular momentum (OAM), when the electric field or mode has an azimuthal angular dependence of $\exp(il\varphi)$, where l is the azimuthal mode index[1,2]. Such fields carry OAM of $l\hbar$ per photon, and may be found as beams expressed in several basis functions, including Laguerre-Gaussian (LG_{pl}) beams[1], Bessel-Gaussian beams[3] and Airy beams[4] to name but a few. LG_{0l} are otherwise known as vortex beams and LG_{0l} beams are routinely generated external to a resonator cavity[5] and has advanced from cylindrical lens mode converters[1] to spiral phase plates (SPP)[6] and the most frequently used "fork" holograms[7]. Recently these "fork" holograms have been realized with the use of spatial light modulators (SLM)[8]. These modes may also be generated intra-cavity with the aid of special mode selecting elements[9]. Since the discovery of light beams carrying OAM many new research areas have emerged, from transferring OAM to matter in optical tweezers[10] to investigating the conservation and entanglement of OAM in parametric down conversion for quantum information processing[11 - 15]. LG_{0l} beams have found applications in such diverse topics as the guiding of ultra-cold atomic beams[16,17], trapping of small particles[18,19], improvement of confocal microscope performance[20] and LIDAR applications[21]. Such fields are consequently highly topical, and of much interest to the community at large.

An optical vortex is a singularity point where the amplitude vanishes and the phase is undetermined. The phase circulation around the singularity point is an integer multiple of 2π. It results that such a beam possesses an orbital angular momentum. The phase of a vortex beam varies in a corkscrew-like manner along the beam's direction of propagation therefore, it possesses a helical wavefront. LG_{0l} (for p=0 and $l > 0$) modes have an intensity profile that is radially symmetric, with zero intensity at the centre. The particularity of LG_{0l} modes lies in their phase structure which winds as a function of angle φ . In a transverse plane, the phase smoothly advances with angle φ , counter-clockwise for $l > 0$ and clockwise for $l < 0$ where the modes LG_{0-l} and LG_{0+l} constitute an optical vortex. This paper is aimed at exploring the methods of generating optical vortex beams. We will discuss a typical extra-cavity approach that harnesses digital holography through the use of a SLM. We consider vortex beam generation as the fundamental mode of a monolithic microchip laser. These lasers by definition are unable to facilitate intra-cavity beam shaping and we thus explore pump-shaping in the generation of a LG_{01} mode. The final section is based on an investigation of "petal" modes which are outputs of a stable Porro-prism resonator. We show that these modes are indeed a coherent superposition of LG_{0l} modes through a full modal decomposition.

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2. EXPERIMENTAL GENERATION OF VORTEX BEAMS

2.1 A digital holographic approach

The experimental generation of LG_{0l} modes may be achieved though beam shaping either external to a resonator cavity or with the aid of intra-cavity phase diffractive elements. One of the most frequently used techniques in generating LG_{0l} beams external to a resonator cavity is through "fork" holograms and in particular this technique is implemented with the use of a SLM. We are able to modulate the phase of an incident beam with a SLM by digitally addressing its liquid crystal screen with a mathematically generated hologram. The holograms utilised to generate vortex beams are grey-level patterns of spiral surfaces and each shade of grey on this contour plot indicates a phase shift in the range of 0 to 2π where a single variation from 0 to 2π represents one phase dislocation.

The pixelated SLM screen addressed with the hologram operates as a vortex lens where the phase of the input light is altered in accordance with the shade of grey present at each pixel. For a collimated Gaussian beam incident on the SLM screen, the planar wavefront of the Gaussian beam is modified into a beam of a helical wavefront. LG_{0l} beams are generated where the azimuthal index of the mode corresponds to the number of phase dislocations on the hologram and the OAM carried by the vortex increases with an increase in the number of dislocations. Experimentally we generated a multitude of LG_{0l} beams where we directed a HeNe laser ($\lambda = 632.8$ nm) onto a phase-only SLM (HoloEye PLUTO VIS SLM with 1920 × 1080 pixels of pitch 8 μm and calibrated for a 2π phase shift at $\lambda = 632.8$ nm).
The Gaussian output from the laser source was transformed into a vortex beam and a schematic of the experimental setup is illustrated in Fig. 1. A set of the vortex beams attained from this system with its associated holograms are illustrated in Fig. 2[22].

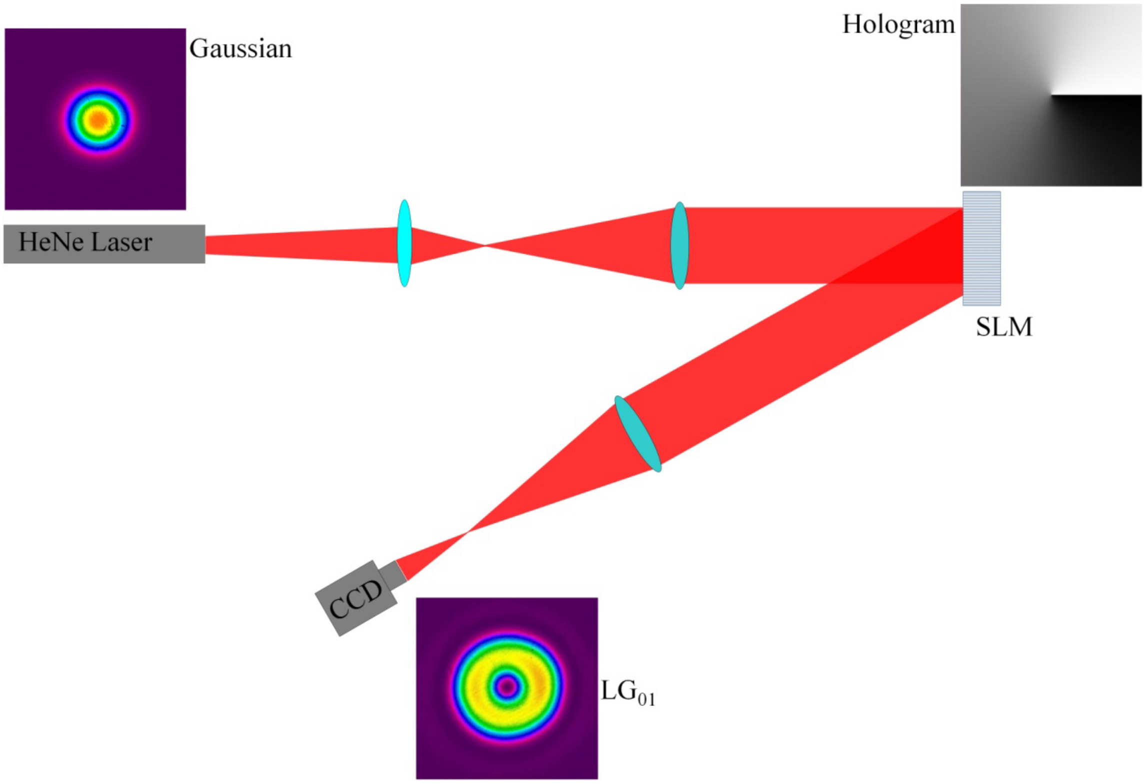

Figure 1: A typical experimental setup where the planar wavefront of a collimated Gaussian beam is transformed into a vortex beam of order 1 with the use of a digital holographic device termed a spatial light modulator (SLM).

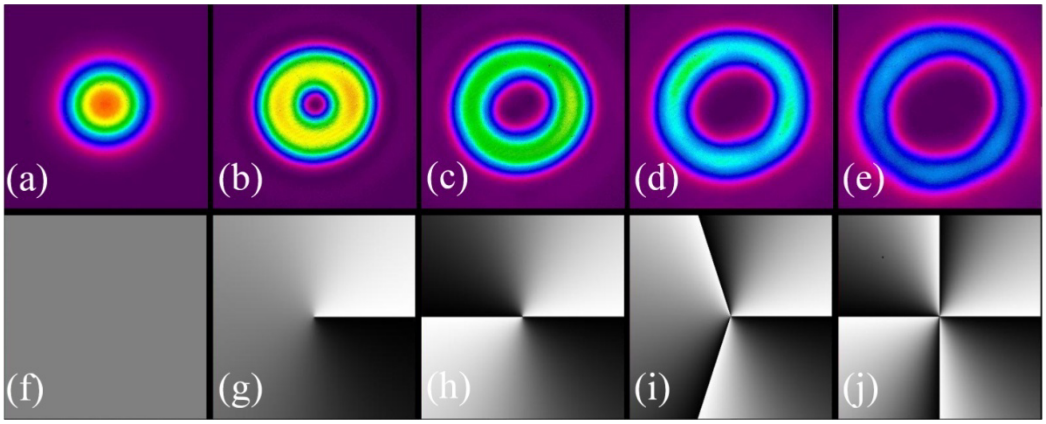

Figure 2: The experimental generation of LG_{0l} beams through digital holography. (a) – (e) Beam profiles that correspond to a unit increase in the azimuthal index starting at 0 for (a) and the associated holograms (f) – (j) indicating an increase in the number of dislocations.

2.2 Pump-shaping in the generation of a LG_{01} mode

The generation of LG_{0l} modes through intra-cavity phase diffractive elements can result in the desired mode as the fundamental mode of the cavity with pure modal quality. This approach, although very attractive is insufficient for the generation of these modes in monolithic microchip lasers. A microchip laser in its simplest form consists of a thin slice of solid-state gain material polished flat and parallel on two sides and where the cavity mirrors, which are flat, are dielectrically deposited onto the surfaces. The eigenmodes for a flat-flat cavity are plane waves for a passive system, however thermally induced refractive index changes due to heat deposition by the incident pump beam results in a waveguide for microchip lasers. This deposited heat assists in thermal expansion of the gain medium that results in end-face curvature and this allows the laser to sustain a stable oscillation in the form of a single-mode waveguide[23]. Monolithic microchip lasers in general have a Gaussian beam as the fundamental eigenmode due to index guiding and gain guiding which are associated with thermal effects and the Gaussian pump profile respectively even several times over the threshold.

Intra-cavity phase elements are thus forbidden in such lasers and the only parameter that can be modified in monolithic microchip lasers for transverse mode selection is in general, the pump beam: its size, shape and power. We thus considered shaping our pump beam such that the transverse profile of the pump beam matches the desired output profile. We reshaped our Gaussian pump beam by the use of a diffractive optical element in the form of a π-plate, which introduced a π phase shift in the central region of an incident collimated Gaussian beam. Experimentally we considered a monolithic microchip that is end-pumped by a single mode Gaussian, fibre coupled diode laser emitting at a wavelength of 808 nm with a maximum power of 160 mW[24]. The microchip consists of a thin slice (5 x 5 x 0.5 mm) of $Nd:YVO_4$ where a schematic of the setup is illustrated in Fig. 3. For a Gaussian pump beam (Fig. 4(a)) we achieved a Gaussian output (Fig. 4(b)) and for a ring shaped pump beam (Fig. 4(c)) we achieved a LG_{01} (Fig. 4(d)) eigenmode of pure modal quality. The idea of pump shaping is employed to a plano-concave cavity (Fig. 5) where intra-cavity phase diffractive elements are permissible. As in the case of the microchip laser we attained a Gaussian output for a Gaussian pump beam and a LG_{01} transverse eigenmode of pure modal quality from a ring shaped pump beam where the experimental beam profiles are illustrated in Fig. 6.

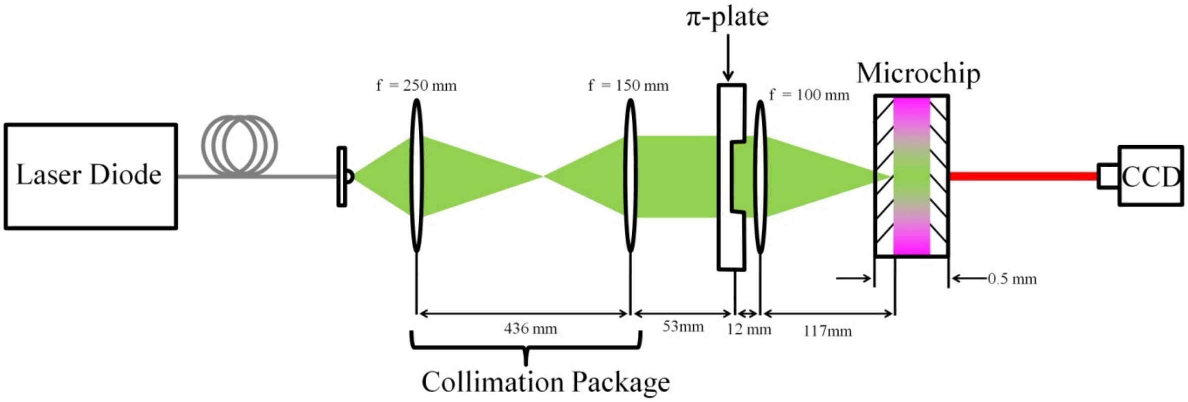

Figure 3: Schematic of the experimental setup for optically pumping a microchip laser with a ring shaped pump intensity profile. The beam shaping element could be removed to revert back to the Gaussian pump scenario[24].

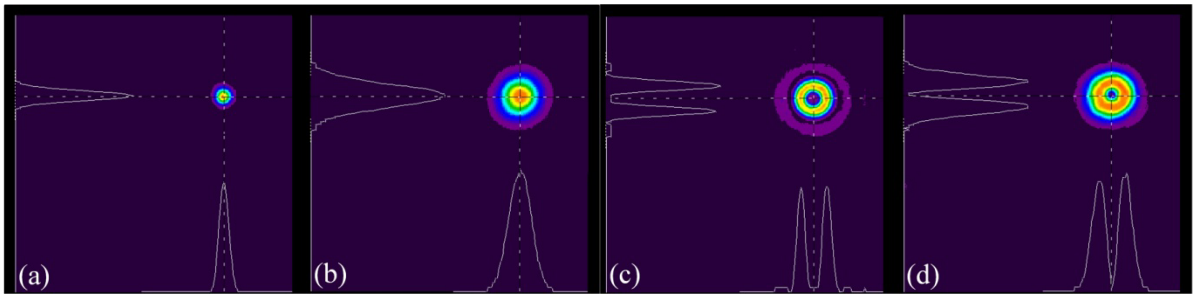

Figure 4: Intensity profiles for (a) Gaussian pump, (b) Gaussian output when pumped with a Gaussian beam, (c) ring shaped pump and (d) output intensity of a microchip laser oscillating in a LG_{01} eigenmode of pure modal quality[24].

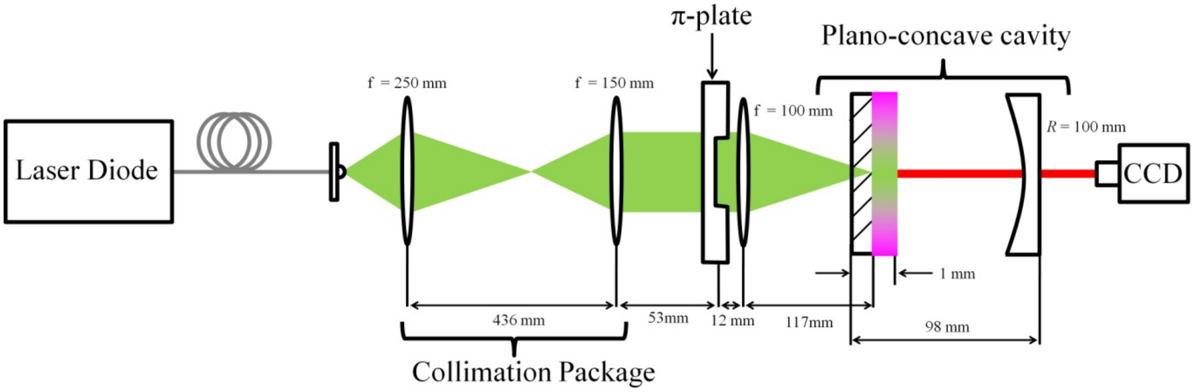

Figure 5: Schematic of the experimental setup for optically pumping a plano-concave laser cavity with a ring shaped pump intensity profile. The beam shaping element could be removed to revert back to the Gaussian pump scenario.

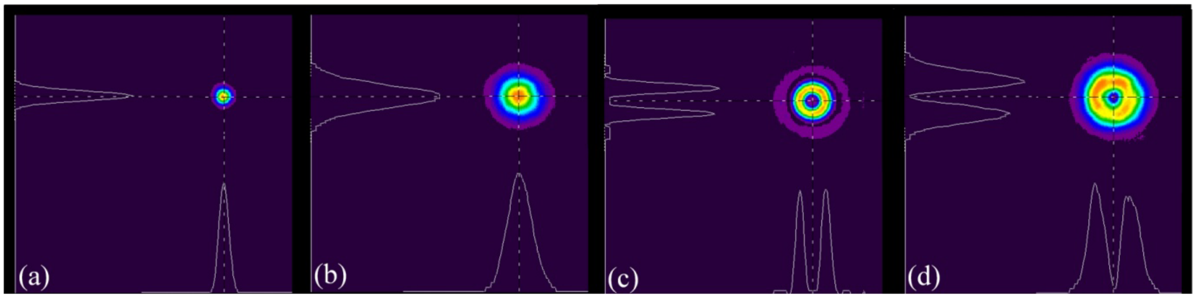

Figure 6: Intensity profiles for (a) Gaussian pump, (b) Gaussian output when pumped with a Gaussian beam, (c) ring shaped pump and (d) output intensity of a plano-concave laser cavity oscillating in a LG_{01} eigenmode of pure modal quality.

2.3 Superpositions of LG_{0l} modes

Vortex beams as indicated have a singularity point where the amplitude vanishes and the phase is undetermined. These beams are circularly symmetric with the vanishing component situated at the centre of the beam. Such fields are observed at the output of Porro-prism resonators where the field is sub-divided into a set of "petals" surrounding a hollow centre. Porro-prism laser resonators are an adaptation of conventional flat-flat laser cavities where the flat mirrors are replaced with right angle prisms (see Fig. 7). These prisms, which are often referred to as porro prisms, have a valuable property that, independent of angle of incidence, all rays incident on the prism are reflected back parallel to the initial propagation direction. This property allows for this laser configuration to be insensitive to misalignment and such resonators have been utilised for their ruggedness in military applications[25]. The key feature of these resonators is the complex field distributions that are experimentally observed and the output spatial modes of this laser are represented by "petals" (see Fig. 8) and Kaleidoscope modes[26,27].

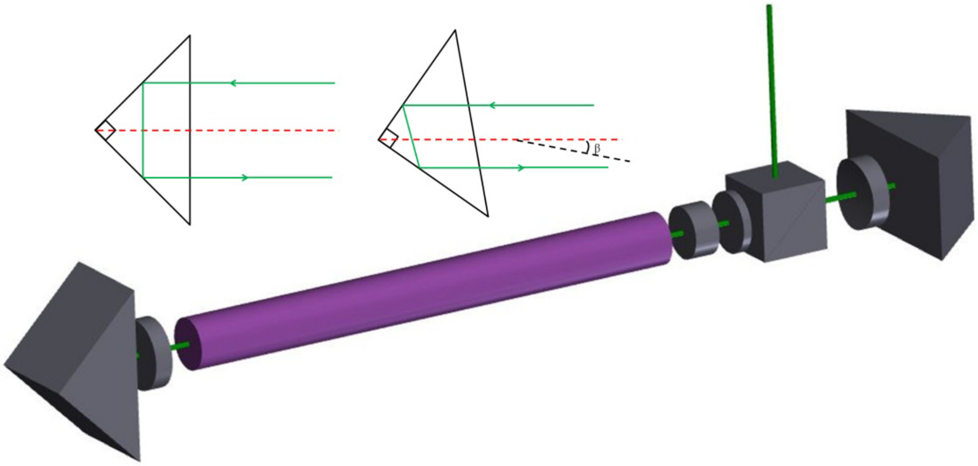

Figure 7: Porro-prism laser resonator where the conventional resonator mirrors are replaced with right angled prisms[27]. The inset indicates that independent of the orientation of the prism, all rays incident on the prism are reflected back parallel to the initial propagation direction.

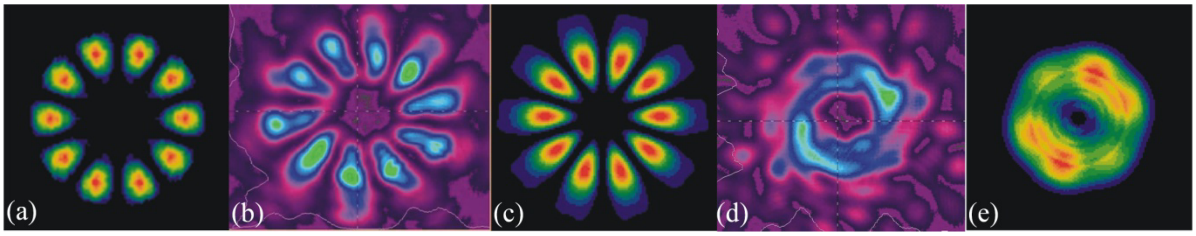

Figure 8: (a) Petal mode, (b) Experimental beam pattern, (c) Average of 5 cycles of higher-order modes at 1000 round trips (d) Experimental beam with Porro prisms tuned away from the petal pattern (e) Average of 1000 round trips of a non-petal configuration[25].

Comprehensive models of this resonator exist[26,27] where we have applied a physical optics approach to the Porro-prism resonator which correctly predicts the salient features of the transverse modal patterns observed experimentally. There is however one pressing issue, what are these petal modes? It is useful to recall that the coherent superposition of two LG_{0l} modes of equal but opposite handedness results in a field represented by $2l$ "petals" in the azimuth[28] as in Fig. 9.

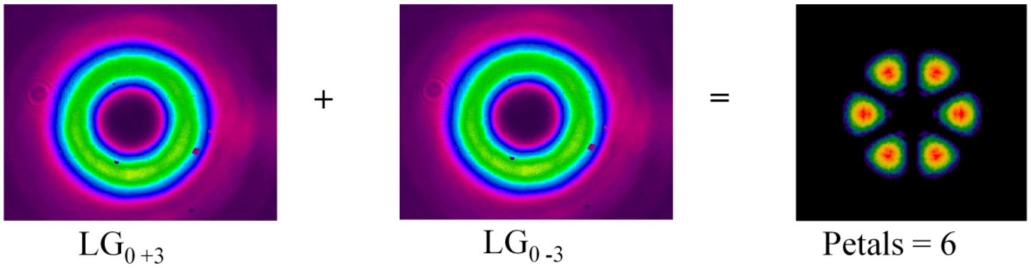

Figure 9: The coherent superposition of two Laguerre-Gaussian modes of opposite handedness results in an output of $2l$ "petals" in the azimuth[28].

To infer whether these "petal" structures are indeed a coherent superposition of two LG_{0l} modes of opposite handedness we have recently decomposed a "petal" field obtained from a spot perturbed solid-state resonator cavity. In this study we considered a spot defected plano-concave cavity in which a thin circular opaque disk was positioned on the plane mirror. The disk was chosen large enough so as to obstruct Gaussian oscillation but one that facilitated higher-order Laguerre-Gaussian operation and the output of the laser was a circular symmetric "petal" transverse eigenmode. The *g*-parameter of the resonator was chosen to be 0.1 for a cavity length of 270 mm as in Fig. 10. The gain medium used was a 4 mm x 30 mm Nd:YAG rod, which was end-pumped with a Jenoptik (JOLD-75-CPXF-2P W) 75 W multi-mode fiber-coupled diode at 808 nm. . The opaque disk was 200 µm in diameter and was fabricated by photolithography on a glass plate for minimal round trip losses (4%) to the unobstructed field. The experimentally observed "petal" fields are illustrated in Fig. 11 (a) – (e) and are compared with theoretical plots (Fig. 11 (f) – (j)) that were generated as a coherent superposition of two LG_{0l} fields[29].

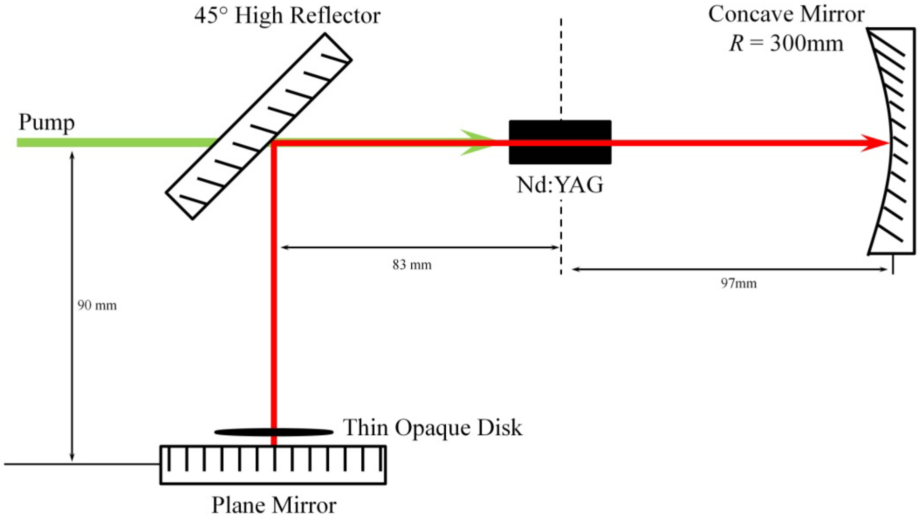

Figure 10: Experimental setup where an Nd:YAG solid-state medium is longitudinally pumped with a 75 W multi-mode fiber coupled diode. A thin opaque disk (stop) is positioned on the plane mirror and chosen to be large enough to completely obstruct Gaussian oscillation and permit higher-order mode selection[29].

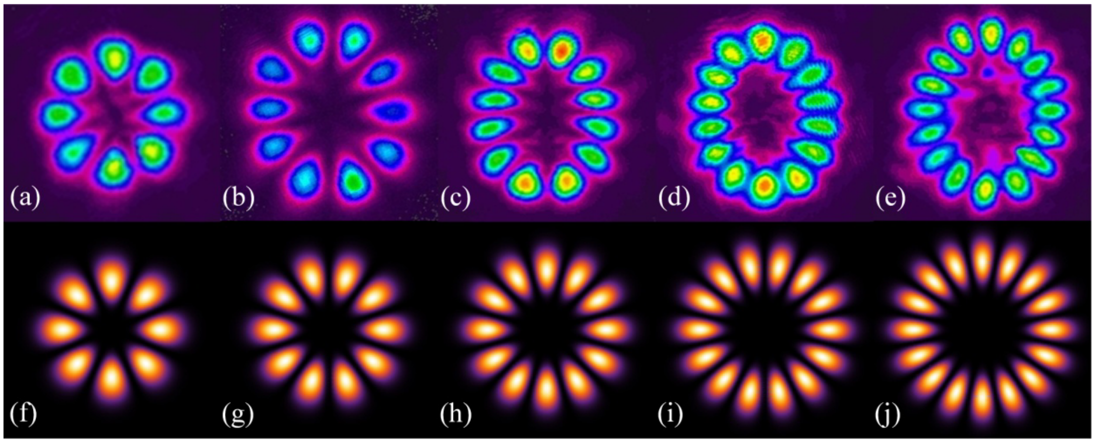

Figure 11: A comparison between experimentally generated superpositions of TEM_{0l} transverse modes, (a) – (e), and theoretically simulated profiles (f) – (j) where the azimuthal order, l, in (a) is 4 and increases in unit value for the subsequent experimental images[30].

A full modal decomposition on the "petal" fields was implemented. This was accomplished by executing an inner product of the incoming field with a phase pattern on an SLM (match filter) set to $\exp(il\varphi)$, where the azimuthal component (l) of the phase pattern on the SLM was varied from –10 to +10, and the weighting of the azimuthal harmonics found by an optically executed inner product. Theoretically in the Fourier plane of the interaction for a 12-petaled field we found that the intensity at the centre of the beam has some value for phase patterns of l equal to -6 or +6 and is null for all other values of l. The intensity of all the interactions are then used to determine the relative weighting of each harmonic of the petal field and Fig. 12 shows the results for the 12-petal field. It is clear that the field is an equally weighted superposition of harmonics with l of –6 and +6, and zero for all other harmonics. Two experimental images of the field in the Fourier plane of the SLM are illustrated as insets in Fig. 12, indicating a good agreement with the expected result. This study has confirmed that the "petal" field is composed of a coherent superposition of two vortex beams of equal but opposite helicity.

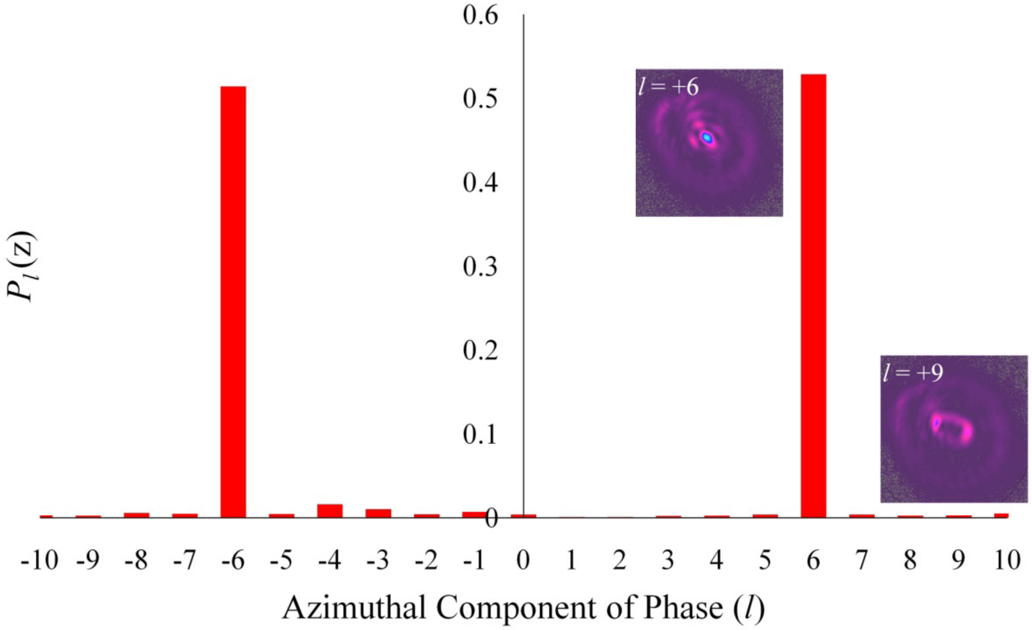

Figure 12: The relative weighting of the azimuthal components is measured from a modal decomposition of the petal field. The azimuthal component (l) of the match filter in the inner product was varied from -10 to +10 and the intensity at the midpoint of the field in Fourier plane of a 12-petal field indicates that this field is superimposed between a $LG_{0\,+6}$ and $LG_{0\,-6}$ mode. The insets are actual experimental images of the decomposed field[29].

3. CONCLUSION

We have outlined two physical approaches in the generation of vortex beams and in particular the generation of Laguerre-Gaussian, LG_{0l} modes. The first of these approaches harness digital holography by use of a spatial light modulator (SLM). The holograms utilised to generate vortex beams are grey-level patterns of spiral surfaces and each shade of grey on the contour plot indicates a phase shift in the range of 0 to 2π. The second approach is achieving a LG_{01} mode as the fundamental mode of a monolithic microchip laser cavity through pump-shaping. We shaped a Gaussian pump beam by the use of a diffractive optical element termed a π-plate. This introduced a π phase shift in the central region of the incident collimated Gaussian beam and we were thus able to achieve a ring-shaped pump profile. Pumping with this profile created an arbitrary good overlap between the pump and the desired mode and we achieved a LG_{01} mode of pure quality. We have also explored the Porro-prism resonator where the outputs are represented by “petals”. Through an apertured plano-concave solid-state resonator cavity we achieved a multitude of these “petal” beams and through a full modal decomposition we infer that the “petal” modes are due to a coherent superposition of LG_{0l} modes of equal but opposite handedness.

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REFERENCES

[1] Beijersbergen M. W., Allen L., Van der Veen H. E. L. O. and Woerdman J. P., “Astigmatic laser mode converters and the transfer of orbital angular momentum,” Opt. Commun. 96, 123-132 (1993).

[2] Allen L., Beijersbergen M. W., Spreeuw R. J. C., and Woerdman J. P., “Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes,” Phys. Rev. A 45, 8185- 8189 (1992).

[3] Arlt J. and Dholakia K., “Generation of high-order Bessel beams by use of an axicon,” Opt. Commun. 177, 297-301 (2000).

[4] Sztul H. I. and Alfano R. R., “The Poynting vector and angular momentum of Airy beams,” Opt. Express 16, 9411-9416 (2008).

[5] Kennedy S. A., Szabo M. J., Teslow H., Porterfield J. Z. and Abraham E. R. I., “Creation of Laguerre-Gaussian modes using diffractive optics,” Phys. Rev. A. 66, 043801-1-043801-5 (2002).

[6] Beijersbergen M. W., Coerwinkel R. P. C., Kristensen M., and Woerdman J. P., “Helical-wave-front laser-beams produced with a spiral phaseplate,” Opt. Commun. 112(5-6), 321–327 (1994).

[7] Bazhenov V. Yu., Vasnetsov M. V., and Soskin M. S., “Laser beams with screw dislocations in their wavefronts,” JETP Lett. 52, 429–431 (1990).

[8] Curtis J. E., Koss B. A., and Grier D. G., “Dynamic holographic optical tweezers,” Opt. Commun. 207(1-6), 169–175 (2002).

[9] Senatsky Y., Bisson J-F., Shelobolin A., Shirakawa A. and Ueda K., “Circular modes selection in Yb:YAG laser using an intracavity lenswith spherical aberration,” Laser Phys. 19, 911-918 (2009).

[10] He H., Friese M. E. J., Heckenberg N. R., and Rubinsztein-Dunlop H., “Direct observation of transfer of angular momentum to absorptive particles from a laser beam with a phase singularity,” Phys. Rev. Lett. 75, 826 (1995).

[11] Mair A., Vasiri A., Weihs G. and Zeilinger A., “Entanglement of the orbital angular momentum states of photons,” Nature 412, 313-316 (2001).

[12] Vaziri A., Weihs G., and Zeilinger A., “Experimental Two-Photon Three-Dimensional Quantum Entanglement,” Phys. Rev. Lett. 89, 240401 (2002).

[13] Barreiro J. T., Wei T. C., and Kwiat P. G., “Beating the channel capacity limit for linear photonic superdense coding,” Nature Phys. 4, 282 (2008).

[14] Leach J., Jack B., Romero J., Jha A. K., Yao A. M., Franke-Arnold S., Ireland D., Boyd R. W., Barnett S. M., and Padgett M. J., “Quantum Correlations in Optical Angle-Orbital Angular Momentum Variables,” Science 329, 662 (2010).

[15] Gibson G., Courtial J., Padgett M. J., Vasnetsov M., Pas’ko V., Barnett S. M. and Franke-Arnold S., “Free-space information transfer using light beams carrying orbital angular momentum,” Opt. Express 12, 5448-5456 (2004).

[16] Wang Z., Dong Y. and Lin Q., “Atomic trapping and guiding by quasi-dark hollow beam,” J. Opt A: Pure Appl. Opt. 7, 147-153 (2005).

[17] Fatemi F. K. and Bashkansky M., “Cold atom guidance using a binary spatial light modulator,” Opt Express 14, 1368-1375 (2006).

[18] Jesacher A., Fürhapter S., Bernet S. and Ritsch-Marte M., “Size selective trapping with optical cogwheel tweezers.” Opt. Express 12, 4129-4135 (2004).

[19] Gu M., Morrish D. and Ke P. C., “Enhancement of transverse trapping efficiency for a metallic particle using an obstructed laser beam,” Appl. Phys. Lett. 77, 34-36 (2000).

[20] Zhao W., Tan J. and Qui L., “Improvement of confocal microscope performance by shaped annular beam and heterodyne confocal techniques,” Optik 116, 111-117 (2005).

[21] Shiina T., Yoshida K., Ito M. and Okamura Y., “Long-range propagation of annular beam for lidar application,” Opt. Comm. 279, 159-167 (2007).

[22] Dudley A., Nock M., Konrad T., Roux F. S. and Forbes A., “Amplitude damping of Laguerre-Gaussian modes,” Opt. Exp., 22(18), 22789 – 22795 (2010).

[23] Zayhowski J. J., “Microchip Lasers,” Optical Materials 11, 255-267 (1999).

[24] Naidoo D., Godin T., Fromager M., Cagniot E., Passilly N., Forbes A. and Aït-Ameur K., “Transverse mode selection in a monolithic microchip laser,” Opt. Commun., Submitted June, (2011).

[25] Burger L. and Forbes A., “Porro prism lasers: a new perspective”, Proc. SPIE 7070, 70700L-1 – 70700L-8 (2008).

[26] Litvin I. A., Burger L. and Forbes A., “Petal-like modes in Porro prism resonators,” Opt. Express 15(21), 14065-14077 (2007).

[27] Burger L. and Forbes A., "Kaleidoscope modes in large aperture Porro prism resonators," Opt. Express 16(17), 12707 – 12714 (2008).

[28] A. Forbes, "New paradigms for old problems: some (small) advances in laser resonator research at the CSIR", Proc. SPIE 7579, 757906-1 – 757906-5 (2010).

[29] D. Naidoo, K. Aït-Ameur, M. Brunel and A. Forbes, "Intra-cavity generation of superpositions of Laguerre-Gaussian beams," J. of Appl. Phys. B: Lasers and Optics, Submitted May, (2011)

[30] D. Naidoo, A. Forbes, K. Ait-Ameur and M. Brunel, "Constructing petal modes from the coherent superposition of Laguerre-Gaussian modes," Proc. SPIE 7913, 791304-1 – 791304-9 (2011).