Optofluidic generation of Laguerre-Gaussian beams

Gavin D. M. Jeffries¹, Graham Milne¹, Yiqiong Zhao², Carlos Lopez-Mariscal³, and Daniel T. Chiu¹,∗

¹Department of Chemistry, University of Washington, Seattle, WA 98195, USA
²Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
³Atomic Physics Division, National Institute of Standards and Technology, Gaithersburg, MD 20899

Abstract

Laguerre-Gaussian (LG) beams have been extensively studied due to their unique structure, characterized by a phase singularity at the center of the beam. Common methods for generating such beams include the use of diffractive optical elements and spatial light modulators, which although offering excellent versatility, suffer from several drawbacks, including in many cases a low power damage threshold as well as complexity and expense. This paper presents a simple, low cost method for the generation of high-fidelity LG beams using rapid prototyping techniques. Our approach is based on a fluidic-hologram concept, whereby the properties of the LG beam can be finely controlled by varying the refractive-index of the fluid that flows through the hologram. This simple approach, while optimized here for LG beam generation, is also expected to find applications in the production of tunable fluidic optical trains.

1. Introduction

The Laguerre-Gaussian (LG) family of optical beams has been studied extensively over the past 15 years in both theoretical and experimental contexts. This interest has largely been due to the special optical properties that LG beams possess, which have led to a number of promising scientific applications. LG beams are generally characterized by a helical phase structure containing a phase singularity, commonly referred to as an optical vortex, which propagates along the centre of the beam. In 1992, Allen et al. [1] first suggested that the electromagnetic field of such a beam would carry orbital angular momentum. This has since been demonstrated experimentally, and optical vortices have been harnessed to drive microviscometers [2], micropumps [3,4], and micromechanical elements [5,6]. Generally, the cross-sectional intensity profiles of the LG beams that have been studied possess a well-defined central null, due to the phase-singularity, surrounded by an integer number of concentric rings. This particular spatial distribution has led to a number of applications, including the trapping of low-refractive-index particles and emulsions [7-10], the observation of improved efficiency in the optical trapping of high index particles [11], applications in atom optics [12,13], in situ vortex beam generation [14], and single-cell nanosurgery [15].

The electric field associated with an LG beam can be described mathematically in cylindrical coordinates by the relationship in Eq. (1) [16]:

©2009 Optical Society of America

∗chiu@chem.washington.edu

OCIS codes: (220.0220) Optical design and fabrication; (050.4865) Optical vortices; (140.3300) Laser beam shaping; (050.1970) Diffractive optics
where $C$ is a normalization constant, $k = 2\pi / \lambda$ is the wavenumber of the beam, $z_R$ is the Raleigh range and $w(z) = \sqrt{2(z_0 + z) / k z_0}$ is the radius of the beam at $z$. $L_p^l \left( \frac{2r^2}{w^2(z)} \right)$ is a generalized Laguerre polynomial. The term $\exp(i\phi)$ describes the helical phase structure that characterizes the LG family of beams. For this work, we assume the radial index $p = 0$, with a goal $l$ index of 1 ($LG_0^l$). Traditionally, the $l$ index has been treated as an integer [17,18], with the interpretation that the orbital angular momentum associated with the resultant electromagnetic field is quantized in discrete units of $l\hbar$ per photon. Recently, however, this view has been reconsidered [17,19-21] and LG beams with fractional helical phases have been experimentally demonstrated. We note that recent work by Gotte et al. [22] reports that LG beams produced using a fractional phase step are unstable, and require a combination of multiple fractional LG modes to propagate.

Spatial Light Modulators (SLMs) are extremely versatile dynamic devices that allow the user to shape with high precision the phase front of a monochromatic optical beam. As such, they are well suited to the generation of vortex beams with selectable phase structure [22-25]. Because SLMs are dynamic and computer-controlled, the parameters of the vortex beams can be tuned in real time over a continuous range. Despite these successes, SLMs do introduce disadvantages. Firstly, commercial SLMs are generally very complex and expensive devices that require specialist control software. Secondly, the liquid crystal layers present in the most commonly used devices are susceptible to damage caused by heating from the incident laser beam. This fact places limitations on the laser power that can be used to generate LG beams with an SLM. With these two issues in mind, we were motivated to investigate solutions for an inexpensive, disposable, easily scalable device that could generate high-fidelity LG modes, with no strict limitations on the applied laser power.

We have previously demonstrated the ability to fabricate binary holograms in a photopolymer material for the generation of LG beams [15], however this being a directly fabricated diffractive optical element (DOE), it is somewhat limited in its scalability. Simply, direct fabrication is limited to the accuracy of the spun-coat photopolymer thickness. Assuming a typical thickness of 50μm, a variance of 0.5% run-to-run is generally acceptable. However this leads to a thickness variance of ~250nm. Using visible wavelengths this variance is almost $\lambda / 2$, resulting in poor control of $l$.

The method we are presenting here relies on the use of a microfluidic-based optical approach [26]. To form LG beams, typically a computer-generated phase hologram, or kinoform, is formed using the superposition of a blazed grating with the desired $LG_0^l$ radial phase distribution, to displace the modes away from the zeroth order (Fig. 1(a)). Conveniently, the structure of the resultant binary kinoform consists of a series of quasi-parallel lines or channels. Binarizing the kinoform allows for ease of fabrication, but has the result of removing the blaze function from the fabricated hologram. As such, the structure can be easily incorporated into a functional microfluidic system when coupled with the appropriate fluidic inlets and outlets. As is the case with most microfluidic devices, this fluidic hologram (FH) platform can be readily reproduced from a single master allowing for ease of scalability and integration. Due to the versatility of optofluidic components, commercial hardware is beginning to be developed, employing them as dynamic alternatives to static optics [27,28]. Figure 1(b-c), shows the beam profile and line scans of a standard beam propagation model and an
experimental image for an \(L_{12}^0\) beam respectively. The beam profile in (c) was taken using the setup displayed in Fig. 5(a), where the slight asymmetry between the x and y directions is due to the linear polarization axis being aligned to the y axis.

2. Fabrication and operation of fluidic holograms

Figure 2 shows our fluidic hologram, which was fabricated in polydimethylsiloxane (PDMS) using a well-established soft-lithography technique [29], outlined in Fig. 3. In our experiments, the fluidic hologram was filled with sucrose solutions of varying concentration and illuminated by a 633nm HeNe laser (Coherent, Santa Clara, CA). The +1 diffraction order was selected using an iris and the propagating mode was imaged onto a beam profiler (BeamPro, Photon Inc, San Jose, CA) and a high resolution CCD camera (GC1380, Prosilica, BC, Canada). Measurements of transmitted power were made using a laser power meter (Nova:PD300-UV, Ophir, Logan, UT). For each sucrose concentration, a profile of the first diffraction order was imaged and the power of that mode measured. The beam fidelity was investigated first through imaging of the isolated mode (Fig. 4) and then by interfering this mode in the far field (~2.5m from generation) with an expanded Gaussian beam as a quasi-plane wave (Fig. 5).

The hologram fabrication consisted of three independent processes: (1) generation of the silicon master, (2) replication of the master in PDMS, and (3) preparation and sealing of the replicated PDMS piece to a flat glass coverslip to form the final microfluidic chip. Figure 3 details our fabrication procedure. The device was fabricated having a PDMS thickness of 4mm, with a channel height of 39\(\mu\)m and width of 52\(\mu\)m; the spacing between the channels was approximately matched to the width of the channels at 48\(\mu\)m. The PDMS was cured on a leveled surface to aid in minimizing distortions of the wavefront due to path-length changes.

Although we fabricated our fluidic hologram in PDMS, we note that a variety of other substrates (e.g. glass and plastic) and microfabrication techniques (e.g. reactive-ion etching, embossing, and injection molding) could also be easily employed [30,31].

3. Tuning the fluidic hologram using refractive-index

To tune the fidelity of the mode generated from the fluidic hologram, we used sucrose solutions of known concentration and, correspondingly, refractive-index. We chose to use sucrose solutions because they are cheap, readily available, and easy to prepare across a wide range of refractive indices. We also note that a wide array of aqueous and oil solutions, such as solutions of sodium chloride [32], can generate the same effect, but without as great a refractive-index range.

The concentration of sucrose in our experiments ranged from 13.2 wt% to 75.6 wt%, which corresponded to an approximate refractive-index range of 1.353 to 1.479 (Brix values measured at 20°C at 598nm) [33]. The true index of refraction of the sucrose solutions in our experiments could therefore differ by up to 0.004, because we used a wavelength of 633nm rather than 598nm. This does not adversely affect our observations as we are concerned with phase changes as a result of refractive-index, and not absolute values. Besides changing the refractive-index, sucrose solutions can also rotate the polarization of the light passing through them. The specific rotation of D-Sucrose at 633nm and 20°C is +66.57, which corresponds to a maximum retardation of 0.015° for the range of sucrose concentrations used. In our experiments, the optical activity of sucrose has negligible effect due to the very short path-length (~40\(\mu\)m) through the fluidic hologram.

In each run of our experiment, we manually replaced the sucrose solutions in one hologram using a syringe, thereby increasing the sucrose concentrations through the device to tune the relative optical path-length and obtaining the desired phase shift. In principle, however,
solutions of varying refractive-index could be generated on-chip using two inlet reservoirs and controlled microfluidic mixing.

Rapid switching of fluid within a microfluidic DOE was first demonstrated by O. J. A. Schueller et al., and shown to be as fast as 50ms, thus allowing for near real-time DOE adjustments [32]. Although our demonstrated application uses a 2×10^3 μm^2 cross section, more complex channel geometries and smaller channel cross sections could be incorporated, but fluidic resistance may increase as a result, decreasing the switching times. Attention needs to be paid to the flow path also, to ensure that the channel contains no dead volumes as this would affect the fluid-replacement efficiency.

4. Generation of high fidelity LG beams

The nature of the beam produced by our device is determined by the relative path-length difference between passage through the fluidic and the transparent PDMS areas of the hologram. If the relative path-length difference is equal to λ/2, then we observe the generation of integer-\(l\) LG modes, with the value of \(l\) dictated by the choice of azimuthal phase term used for the generation of the photomask, in the initial fabrication of the device. When the relative path-length difference is a non-integer of λ/2, we find that the resulting fluidic hologram generates a perturbed LG beam, with an appearance similar to beams generated using a non-integer value of \(l\) [25].

By varying the refractive-index of the fluid, we are able to modulate the magnitude of the phase step associated with the azimuthal phase term. Our effective azimuthal term \(l\) can be tuned, by varying the refractive-index difference between the substrate and the containing fluid, to allow for selection of the path-length difference to match the λ/2 condition. Figure 4 shows a series of experimental images, taken close to the mode isolation point, illustrating the tuning of the relative path-length difference within the FH.

Determination of the generated mode and beam fidelity was accomplished by interfering the generated LG beam in the far field with a reference beam - an expanded Gaussian. Figure 5(a) shows the setup of the beam paths along with two sets of images. Figure 5(b-d) show the generation of a desired mode through optimum choice of refractive-index solution while Fig. 5(e-g) show a shift in the diffraction pattern as a result of using a refractive-index which generates a path-length not equal to an integer value of λ/2.

The mode images in Fig. 5(b) and (e) were scaled in size to match the beam profile size in Fig. 4, as the longer propagation distance increase of 1.6m in the interference design, results in a larger beam diameter. Imaging the beam directly after mode isolation close to the hologram, may produce results that suffer from overlapping modes and other artifacts generated by the DOE. Imaging the mode at a significant distance away should avoid such problems, allowing us to and analyze in isolation the propagating mode. Interfering this mode with a plane wave should return an interference pattern that strongly resembles the kinoform of the photomask used to generate the FH. Our interference results for two conditions are shown in Fig. 5, where an optimized phase shift (Fig. 5(b-d)) and a non-optimized phase shift (Fig. 5(e-g)) were interrogated. In our experiments we were able to tune the hologram to obtain a desired mode efficiency of 40%, which matches other diffraction optic generation efficiencies [34].

Due to the binary kinoform component, our FH also acts like a tunable diffraction grating [32], where varying the refractive-index of the solution varies the power distribution associated with the diffracted orders. We experimentally verified that a grating with the same period as our kinoform function has the same power variation as the fluidic hologram (Fig. 6(b)). Because we are only varying the relative path difference, and not the spatial periodicity of the structure, we attenuate only the efficiency, not the positions of the diffracted orders. Figure 6(a) shows
the observed power distribution as a function of refractive-index. As the refractive-index of the solution is varied, the efficiency of the hologram varies in a sinusoidal manner (Fig. 6(a)). Maximum efficiency is achieved when the difference in optical path-length between the fluid and substrate is equal to $\lambda/2$. As the path difference between adjacent sections tends to zero, the fluidic hologram has a negligible effect on the beam and the vast majority of the incident light passes through un-diffracted into the zeroth-order spot. This condition corresponds to the intensity minima on the sinusoidal curve in Fig. 6(a).

In addition to the sinusoidal intensity variation, we also note the presence of an overall linear attenuation of the beam power with increasing refractive-index, indicated by the dashed line in Fig. 6(a). We attribute this behavior to the possible increase in absorption and scatter of the incident light that occurs as a consequence of increasing the sucrose concentration. The intensity loss associated with absorption implies slight laser heating of the fluid. As a result, the applicability of the technique at high laser powers requires some consideration of the absorption properties of the medium being used to fill the hologram as well as the material from which the hologram is constructed.

Unlike traditional holograms, where dissipation of heat as a result of absorption of light can be a problem, microfluidic-based holograms could conceptually function as diffractive optical elements with an active cooling system, as heat can easily be dissipated from the optical substrate through the fluid. A number of procedural alterations could also be employed to reduce heating, ranging from the use of fluids (e.g. oil or $D_2O$ [35]) and substrates (e.g. glass and silicon) that have lower optical absorption at the operational wavelength and higher thermal conductivity.

This fluidic approach allows for the construction of high-fidelity fixed holograms for forming integer LG modes. As can be seen in Fig. 6(b), the power distribution can be tuned, allowing for maximum efficiency of the integer mode to be obtained. This fact is particularly important in microfabricated holograms, because the channel depth must be accurate to within ~100nm to obtain a power level within 10% of the potential maximum, which is difficult to achieve using standard lithographic techniques. The ability to fine-tune the refractive-index of the medium contained within the fluidic hologram provides a solution to this problem.

5. Conclusion

We have described a cost-effective and simple approach for the generation of high fidelity Laguerre-Gaussian beams, and verified its effectiveness through the successful generation and interrogation of LG modes using an interference technique. Our fluidic hologram can be rapidly fabricated and integrated with other fluidic components and is, in principle, completely scalable. The ease and the high degree of control with which the refractive-index of the hologram can be tuned should facilitate further explorations into the use of fluidic optics for the fields of beam shaping and diffractive optical elements.

Acknowledgments

We gratefully acknowledge NIH GM085485 for support of this work.

References and links

1. Allen L, Beijersbergen MW, Spreeuw RJC, Woerdman JP. Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes. Phys. Rev. A 1992;45(11):8185–8189. [PubMed: 9906912]
2. Parkin SJ, Knöner G, Nieminen TA, Heckenberg NR, Rubinsztein-Dunlop H. Picoliter viscometry using optically rotated particles. Phys. Rev. E Stat. Nonlin. Soft Matter Phys 2007;76(4):041507. [PubMed: 17994994]

3. Leach J, Mushfique H, di Leonardo R, Padgett M, Cooper J. An optically driven pump for microfluidics. Lab Chip 2006;6(6):735–739. [PubMed: 16738723]

4. Ladavac K, Grier DG. Microoptomechanical pumps assembled and driven by holographic optical vortex arrays. Opt. Express 2004;12(6):1144–1149. [PubMed: 19474392]

5. Neale SL, MacDonald MP, Dholakia K, Krauss TF. All-optical control of microfluidic components using form birefringence. Appl. Phys. Lett 2001;78(4):547–549.

6. Friese MEJ, Rubinsztein-Dunlop H, Gold J, Hagberg P, Hanstorp D. Optically driven micromachine elements. Opt. Express 2004;12(4):593–600. [PubMed: 19474861]

8. Gahagan KT, Swartzlander GA Jr. Optical trapping of particles. Opt. Lett 1996;21(11):827–829. [PubMed: 19876172]

9. Lorenz RM, Edgar JS, Jeffries GDM, Zhao YQ, McGloin D, Chiu DT. Vortex-Trap-Induced Fusion of Femtoliter-Volume Aqueous Droplets. Anal. Chem 2007;79(1):224–228. [PubMed: 17194143]

10. Jeffries GDM, Kuo JS, Chiu DT. Dynamic modulation of chemical concentration in an aqueous droplet. Angew. Chem. Int. Ed 2007;46(8):1326–1328.

11. Simpson NB, McGloin D, Dholakia K, Allen L, Padgett MJ. Optical tweezers with increased axial trapping efficiency. J. Mod. Opt 1998;45(8):1943–1949.

12. Clifford MA, Arlt J, Courtial J, Dholakia K. High-order Laguerre-Gaussian laser modes for studies of cold atoms. Opt. Commun 1998;156(4-6):300–306.

13. Arlt J, Padgett MJ. Generation of a beam with a dark focus surrounded by regions of higher intensity: the optical bottle beam. Opt. Lett 2000;25(4):191–193. [PubMed: 18059825]

14. Knöner G, Parkin S, Nieminen TA, Loke VLY, Heckenberg NR, Rubinsztein-Dunlop H. Integrated optomechanical microelements. Opt. Express 2007;15(9):5521–5530. [PubMed: 19532808]

15. Jeffries GDM, Edgar JS, Zhao YQ, Shelby JP, Fong C, Chiu DT. Using polarization-shaped optical vortex traps for single-cell nanosurgery. Nano Lett 2007;7(2):415–420. [PubMed: 17298009]

16. Allen L, Padgett MJ, Babiker M. The orbital angular momentum of light. Progress in Optics 1999;39:291–372.

17. Berry MV. Optical vortices evolving from helicoidal integer and fractional phase steps. J. Opt. A, Pure Appl. Opt 2004;6(2):259–268.

18. Indebetouw G. Optical Vortices and Their Propagation. J. Mod. Opt. 1993;40(1):73–87.

19. Oemrawsingh SSR, Eliel ER, Nienhuis G, Woerdman JP. Intrinsic orbital angular momentum of paraxial beams with off-axis imprinted vortices. J. Opt. Soc. Am. A 2004;21(11):2089–2096.

20. Basistiy IV, Pasko VA, Slyusar VV, Soskin MS, Vasnetsov MV. Synthesis and analysis of optical vortices with fractional topological charges. J. Opt. A, Pure Appl. Opt 2004;6(5):S166–S169.

21. Leach J, Yao E, Padgett MJ. Observation of the vortex structure of a non-integer vortex beam. N. J. Phys 2004;6:71.

22. Götte JB, O’Holleran K, Preece D, Flossmann F, Franke-Arnold S, Barnett SM, Padgett MJ. Light beams with fractional orbital angular momentum and their vortex structure. Opt. Express 2008;16(2):993–1006. [PubMed: 18542173]

23. Curtis JE, Grier DG. Structure of optical vortices. Phys. Rev. Lett 2003;90(13):133901–133904. [PubMed: 12689289]

24. Curtis JE, Koss BA, Grier DG. Dynamic holographic optical tweezers. Opt. Commun 2002;207(1-6):169–175.

25. Lee WM, Yuan XC, Dholakia K. Experimental observation of optical vortex evolution in a Gaussian beam with an embedded fractional phase step. Opt. Comm 2004;239(1-3):129–135.

26. Levy U, Shamai R. Tunable optofluidic devices. Microfluid. Nanofluid 2008;4(1-2):97–105.

27. Kuiper S, Hendriks BHW. Variable-focus liquid lens for miniature cameras. Appl. Phys. Lett 2004;85(7):1128–1130.

Opt Express. Author manuscript; available in PMC 2010 May 27.
28. Philips. Fluid Focus. retrieved
   http://www.research.philips.com/technologies/projects/fluidfocus.html

29. Fiorini GS, Jeffries GDM, Lim DSW, Kuyper CL, Chiu DT. Fabrication of thermoset polyester microfluidic devices and embossing masters using rapid prototyped polydimethylsiloxane molds. Lab Chip 2003;3(3):158–163. [PubMed: 15100767]

30. Fiorini GS, Chiu DT. Disposable microfluidic devices: fabrication, function, and application. Biotechniques 2005;38(3):429–446. [PubMed: 15786809]

31. Kuo JS, Ng LY, Yen GS, Lorenz RM, Schiro PG, Edgar JS, Zhao YX, Lim DSW, Allen PB, Jeffries GDM, Chiu DT. A new USP Class VI-compliant substrate for manufacturing disposable microfluidic devices. Lab Chip 2009;9(7):870–876. [PubMed: 19294296]

32. Schueller OJA, Duffy DC, Rogers JA, Brittain ST, Whitesides GM. Reconfigurable diffraction gratings based on elastomeric microfluidic devices. Sens. Actuators A Phys 1999;78(2-3):149–159.

33. Instruments, RA. Sucrose solution Brix values versus refractive index. 2008.

34. Kennedy SA, Szabo MJ, Teslow H, Porterfield JZ, Abraham ERI. Creation of Laguerre-Gaussian laser modes using diffractive optics. Phys. Rev. A, Atomic Molec. Opt. Phys 2002;66(4):043801–043805.

35. Golic M, Walsh K, Lawson P. Short-wavelength near-infrared spectra of sucrose, glucose, and fructose with respect to sugar concentration and temperature. Appl. Spectrosc 2003;57(2):139–145. [PubMed: 14610949]
Fig. 1.
Generation of $LG_0^1$ beams. (a) Illustration showing the generation of the binary hologram pattern, by combining the spiral phase profile with a blaze kinoform then binarizing the result through thresholding. (b) Theoretical output of the first diffracted-order mode. (c) Experimental measurement of the first diffracted-order mode. Insets in (b) and (c) show the line profiles through the center of the beam. The scale bar in (c) represents 1mm.
Fig. 2.
Schematic illustration and image of the constructed fluidic-hologram device. (a) A 3D rendering of the device, showing fluidic input-output ports. (b) A photograph of two fully assembled fluidic holograms bonded to a glass coverslip, with access ports punched for the two holograms. The scale bar in the image represents 2 mm.
Fig. 3.
Outline of the fabrication procedure to form a fluidic hologram, illustrating the key stages. The silicon wafer is coated with a negative photoresist, exposed to UV through the photomask, then developed forming a master. This master is fluorosilane treated and a PDMS cast is made. Port holes are punched into the PDMS cast for tubing and then bonded to a glass coverslip using an oxygen plasma treatment.
Fig. 4. Five examples of experimental measurements of the first diffraction-order beam generated from a single fluidic hologram, with a varied refractive index solution content, taken at a propagation distance of 0.7m. Panels (a) to (e) show the generated modes with path-length differences from less than $\lambda/2$ to greater than $\lambda/2$, created by varying the sucrose concentration. Each panel is noted with the refractive-index of the medium contained within the fluidic hologram. These beam profile were measured using the setup displayed in Fig. 5(a). The scale bar in (a) represents 1mm.
Fig. 5.
Interference images of the generated modes with a plane wave. The left panel (a) shows a schematic of the setup to generate the interference on a camera, with a propagation distance from hologram to camera of 2.5m. M1, M2 are mirrors, L1-L2 and L3-L4 are telescoping lens pairs, Pol is a polarizer, BS is a polarizing beam splitter, WP is a half-wave plate, ND is a neutral density filter, FH is the fluidic hologram, and M/C is a mirror in the interference setup or the beam profile camera in the setup used to image the modes in Fig. 4. Panels (b) & (e) are mode images taken on the CCD camera. (c) & (f) are raw interference images of the LG mode interfered with an expanded Gaussian beam. (d) & (g) are threshold images of (c) & (f) to illustrate the characteristic fork structure. The pattern in (d) matches the binary mask used to generate the fluidic hologram, suggesting the resulting mode has an $l$ index of 1. The scale bar in (b) represents 4mm, (b) and (e) are scaled the same. The scale bar in (c) represents 0.5mm, (c-d) and (f-g) are all scaled the same.
Fig. 6.
Changes in intensity as a function of refractive-index. (a) A plot of the first-order intensity versus the solution refractive-index, exhibiting a sinusoidal variation. The solid trend line illustrates a refractive-index periodicity of 0.043. The dashed trend line indicates an overall power attenuation, suggesting an increase in absorption/scatter of the illuminating light as the sucrose concentration is increased. (b) A comparison plot illustrating the inversely proportional response of the zeroth and first-order diffraction modes, from a linear fluidic grating of the same periodicity as the blazing function used in our fluidic hologram. Intensities were measured from linescans of mode images taken across the polarization axis.