Generation of doughnut laser beams by use of a liquid-crystal cell with a conversion efficiency near 100%

Djenan Ganic, Xiaosong Gan, and Min Gu

Centre for Micro-Photonics, School of Biophysical Sciences and Electrical Engineering, Swinburne University of Technology, P.O. Box 218 Hawthorn, Victoria 3122, Australia

Mathias Hain, Somakanthan Somalingam, Svetomir Stankovic, and Theo Tschudi

Institut für Angewandte Physik, Technische Universität Darmstadt, AG Licht- und Teilchenoptik, Hochschulstrasse 6, D-64289 Darmstadt, Germany

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We present a novel technique for producing a doughnut laser beam by use of a liquid-crystal cell. It is demonstrated that the liquid-crystal cell exhibits an efficiency in energy conversion near 100%. One of the main advantages of this method is its capability of dynamic switching between a Gaussian mode and a doughnut mode of different topological charges. The liquid-crystal cell is also dynamically tunable over the visible and near-infrared wavelength range. These advantages make the device appealing for laser trapping methods used in single-molecule biomechanics and for optical guiding of cold atoms. © 2002 Optical Society of America

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A $TEM_{01}{}^{*}$ mode laser beam possesses a helical phase distribution. Because its intensity is zero on the axis of the beam, it is usually called a doughnut beam. Such a beam recently attracted significant research interest because of its increasing applications, such as generation of vortex solitons,[1] optical guiding of cold atoms,[2] high-efficiency laser trapping,[3–5] and microstructure rotation in laser tweezers.[6,7] There are direct and indirect methods for generating a doughnut beam. In the direct method the wave front of a laser beam is directly changed by use of a phase mask,[8] by generation of laser beams with helical wave fronts within laser cavity,[9] or by using a hollow optical fiber.[10] To generate doughnut laser beams indirectly one uses computer-generated holograms with an interference pattern recorded on a film[11] or programmable liquid-crystal (LC) displays.[12] However, the applications of doughnut laser beams often are hampered because of the low efficiency or the inflexibility of the methods that are currently used to produce doughnut laser beams and by the fact that all these methods cannot dynamically control the phase distribution.

In this Letter we demonstrate a novel and convenient method of producing a doughnut laser beam by use of a LC cell that is capable of dynamically controlling the phase distribution. LC-based photonic devices are increasingly used in many applications, including light focusing,[13,14] phase modulation,[15] beam steering,[16] and filtering.[17] A LC-based element works by applying an electric field between two walls of a cell containing appropriately oriented LCs. The applied electric field causes LC molecules to tilt, which results in a change in refractive index. By controlling this refractive-index change, we can provide an appropriate phase shift to the incoming wave front to produce a doughnut laser beam.

The electric field, E, of a doughnut beam having a helical wave front with the phase singularity (screw dislocation) along its propagation axis can be expressed as[6]

$$E = E_0 \exp(im\phi), \tag{1}$$

where ϕ is the polar coordinate in the plane perpendicular to the beam axis. Such a beam possesses a topological charge equal to the integer m of a 2π phase change on any closed circle around the beam center. If one could make a phase mask by controlling LC molecules to produce, for example, a gradual phase change from 0π to $2\pi m$ in a circular fashion across the incoming beam wave front [Fig. 1(a)], then a helical wave front of topological charge m would result.

To achieve this conversion of a Gaussian beam ($m = 0$) into a doughnut beam ($m \neq 0$) we created an indium tin oxide (ITO) structure consisting of 16 pie slices on

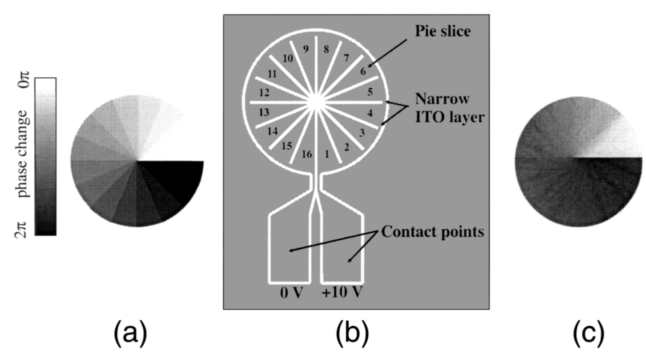

Fig. 1. Phase distribution of a doughnut beam. (a) Theoretical phase distribution of a doughnut beam of charge 1 according to 16 phase steps. (b) Electrode structure of the LC cell with 16 pie slices. The voltage variation as a function of the slice position is shown in Fig. 2(a). (c) Phase wave front of the doughnut beam of charge 1, measured with phase-shifting interferometry.

the front side of the cell [Fig. 1(b)]. The structure was made by a laser lithography process using a chrome mask. The two contact points were connected to the first and the last pie slices, and all the slices were connected by a narrow (~10-μm) strip of ITO. When a voltage was supplied to the contact points, this narrow strip of ITO had high resistance and gave a linear voltage drop from the first to the last pie slices, as shown in Fig. 2(a). However, the pie slices themselves were much wider and offered very low resistance. The back side of the cell was made from a uniformly coated layer of ITO on a glass substrate. This uniform ITO layer was connected to the ground. The cell was then filled with LC molecules and sealed.

When an appropriate voltage is applied to the connection points on the front side of the cell, it is then redistributed across each of the pie slices. LC molecules inside the cell tilt in the meridian plane according to the electric field strength between the pie slices and the grounded back wall of the cell. The amount of the tilt depends on the voltage on each pie slice, giving rise to a corresponding change in refractive index for the light polarized along the long axis of the LCs. For a given voltage, such as 10 V, one can select a proper thickness of the LC cell to produce a phase change from 0π at the first slice to 2π at the last slice so that the outgoing wave front has a helical shape with a topological charge of 1.

To characterize the dependence of the phase change on the voltage, we placed a LC cell of thickness 9.5 μm between two crossed polarizers, and the intensity variation after the analyzer as a function of the applied voltage was measured. Because the thickness of the LC cell was small, the LC cell could be switched quickly and the retardation was negligible. In addition, the experiment was conducted at room temperature. After the phase unwrapping, this dependence gave a direct relation between the applied voltage and the phase shift of the beam ($\lambda = 632.8$ nm), which is shown in Fig. 2(b). It is clear that the LC cell can produce a maximum of a 4π phase shift, although there exists a saturated response that is caused by the nonlinear response of the LCs. To extend the linear response region one can increase the thickness of the cell or the concentration of the LCs.

To demonstrate the dynamically switching nature of the LC cell we placed the LC cell in the optical setup shown in Fig. 2. A He–Ne laser beam (632.8 nm) of output power 5 mW was used for illumination and was linearly polarized by a polarizer in the direction of the LCs. The beam passed through the first beam splitter, creating a reflection arm and a transmission arm. The transmitted part of the beam passed through the LC cell that modified the wave front, creating a doughnut beam on a screen. For the interference pattern measurement, the reflected beam at BS1 was recombined with the transmitted part at BS2, creating an interference pattern.

The patterns recorded when the reflection arm was blocked are displayed in Figs. 3(a)–3(c). If there is no voltage applied to the LC cell, the incoming laser beam wave front is not changed [Fig. 3(a)]. Applying an appropriate voltage to the cell according to Fig. 2(b) results in a phase shift of 2π or 4π, so that the wave front after the cell can be dynamically converted into doughnut beams with charges 1 and 2 [Figs. 3(b) and 3(c), respectively]. A slight distortion of the circular symmetry in Fig. 3(c) is caused by the saturated response in Fig. 2(b). It was observed that the power of the generated doughnut beams was almost the same as that of the Gaussian beam, which led to a conversion efficiency near 100%.

To confirm the helical nature of the generated wave front we introduced the interference arm shown in Fig. 2. The measured interference patterns corresponding to Figs. 3(a), 3(b), and 3(c) are shown in Figs. 3(d), 3(e), and 3(f), respectively. When the LC is switched off, the interference pattern shows the interference fringes of equal spacing, resulting from two Gaussian beams [Fig. 3(d)]. The fringe splitting in Figs. 3(e) and 3(f) indicates that the

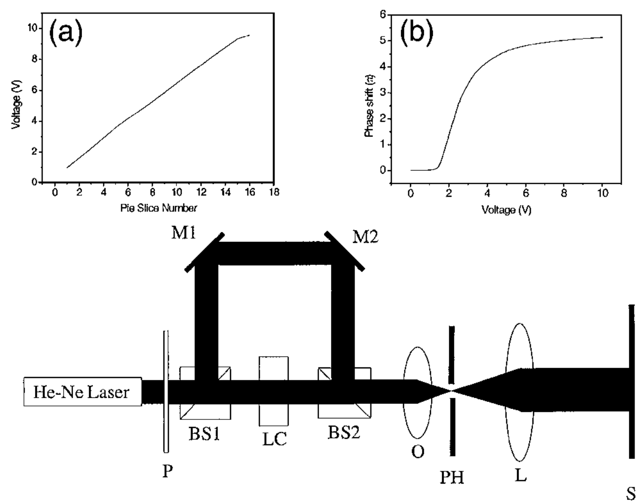

Fig. 2. Experimental setup for generation of a doughnut beam through the LC cell and interference measurement of its phase distribution: P, polarizer; BS1, BS2, beam splitters; O, objective; L, lens; M1, M2, mirrors; PH, pinhole; S, screen. (a) Voltage variation as a function of the slice position of the LC cell. (b) Unwrapped phase shift of the LC cell as a function of applied voltage.

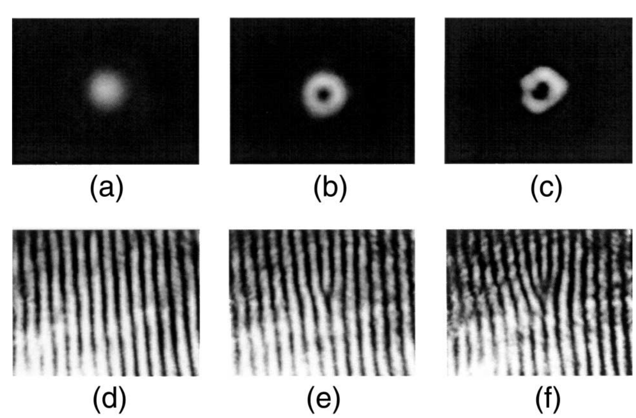

Fig. 3. (a)–(c) Intensity distributions of laser beams transmitted through a LC cell and (d)–(f) the corresponding interference patterns. (a), (d) Gaussian beams; (b), (e) doughnut beam of charge 1; (c), (f) doughnut beam of charge 2.

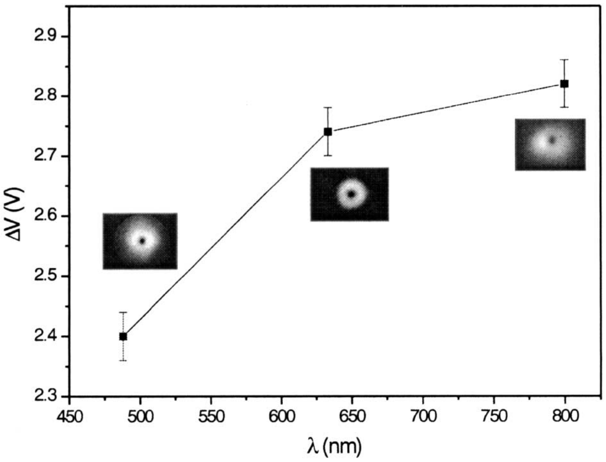

Fig. 4. Variation of the voltage between the two contact points [see Fig. 1(b)] as a function of the wavelength for the generation of a doughnut beam of charge 1.

LC-modulated beam becomes a doughnut beam and the number of splitting fringes gives the number of topological charges.[11] A direct wave-front test was also performed by use of a phase-shifting interferometry method.[18] The reconstructed wave front of the charge-1 doughnut beam [Fig. 1(c)] is similar to the theoretical wave front in Fig. 1(a).

Another feature of the designed LC cell is tunable over a range of wavelengths. Simply changing the applied voltage produced a doughnut beam ($m = 1$) at wavelengths 488 and 800 nm, as depicted in Fig. 4. The dependence of the voltage change on the illumination wavelength shown in Fig. 4 indicates a reduced efficiency at wavelength 800 nm, implying that the LCs used in this experiment exhibit a certain amount of dispersion and a nonlinear response near this wavelength.

In conclusion, the LC cell that we have designed and demonstrated in this Letter exhibits a dynamic conversion of a Gaussian laser beam into a doughnut beam of different topological charges with a conversion efficiency near 100%. The cell is dynamically tunable in the visible and near-infrared ranges of wavelengths. Unlike the computer-generated hologram,[11] such a device preserves the beam path of an optical system.

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