Front. Optoelectron. 2017, 10(1): 9–13
DOI 10.1007/s12200-016-0606-3

LETTER

Transformation of Laguerre-Gaussian beam by a ring-lens

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Abstract The propagation property of Laguerre-Gaussian (LG) beams passing through a diffractive ring-lens (RL) was studied, where the RL was generated by a liquid crystal spatial light modulator (LC-SLM). It was found that the LG beam was transformed into a sharp ring at the focal plane first, and then a Bessel-similar beam was formed behind the focal plane but the beam size was enlarged with the increase of propagation distance. With the help of a group of lenses, the beam was further collimated into a Bessel beam. Finally, the "non-diffractive" and self-reconstruction properties of the generated Bessel beams were experimentally verified.

Keywords ring-lens (RL), Bessel beam, spatial light modulator (SLM)

1 Introduction

Due to the properties of "diffraction-free" and self-reconstruction, Bessel beams have recently attracted significant interest in a variety of applications, including atom guiding [1], optical tweezers [2] and laser machining [3]. Owing to their unique features in comparison with usual homogeneously polarized lights [4,5], various optical elements and set-ups have been used to generate Bessel beams, such as an annular aperture located in the focal plane of a lens [6], refractive axicons [7], reflective axicon mirrors [8], and diffractive optical elements [9]. To the best of our knowledge, the ring-lens (RL) has not been reported to generate a Bessel beam. In 1969, J. B. Goodell first described a refractive RL (Goodell termed it an eccentric lens) [10]. He proposed that RL can transform a point light source to a ring light for laser punching. Another important application of RL is focus-error sensing in optical data storage [11]. In this letter, we generated a diffractive RL instead of a refractive RL by introducing a phase hologram onto a liquid crystal spatial light modulator (LC-SLM). The propagation property of Laguerre-Gaussian (LG) beams passing through a RL was studied, and it was found that a sharp ring was formed at the focal plane first and then a Bessel-similar beam was formed behind the focal plane but the beam size was enlarged with the increase of propagation distance. A group of lenses are used to collimate the Bessel-similar beam into a Bessel beam. The "non-diffractive" and self-reconstruction properties of the generated Bessel beams were experimentally demonstrated.

Received January 19, 2016; accepted April 23, 2016

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2 Generation of a diffractive RL by a LC-SLM

The schematic diagram of a RL is shown in Fig. 1, where f indicates the distance between the RL and its focal plane, and r_0 denotes the radius of the focal ring. When a RL is illuminated by a collimated beam, a sharp ring with the radius of r_0 appears on the focal plane.

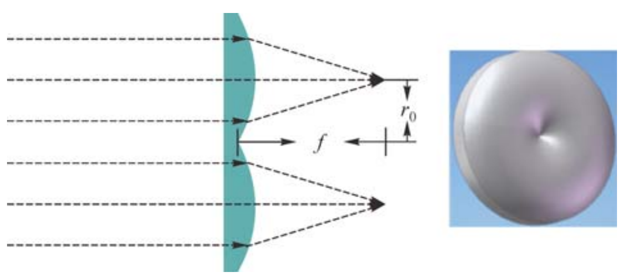

Fig. 1 Schematic diagram of RL

According to the geometric structure of the RL depicted in Fig. 1, the transmittance function of a RL can be written as follows:

$$T(r) = \exp\left[i\frac{2\pi}{\lambda}\left(f - \sqrt{f^2 + (r - r_0)^2}\right)\right], \qquad (1)$$

where λ is the wavelength. It is difficulty to fabricate a RL by silica or other reflective material directly. In this paper, a diffractive RL was proposed. To obtain the diffractive pattern of the RL, numerical modeling of dispersion of Eq. (1) was carried out. A grayscale pattern (1024×768) was depicted by Matlab codes, which can be seen in Fig. 2. Then this pattern was loaded on a LC-SLM so that diffractive RL was obtained.

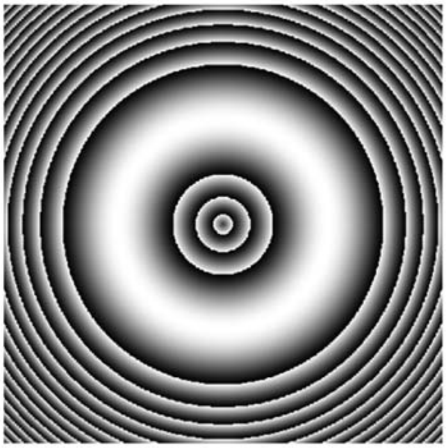

Fig. 2 Diffraction grating pattern of RL

3 Transmission property of LG beams passing through RL

The generation of diffractive RLs by a spatial light modulator (SLM) has been discussed above. And then the propagation properties of a Gaussian beam passing through an RL were studied numerically and experimentally. Angular spectrum theory of plane waves was employed to the numerical simulation. In our experiments, a complex binary amplitude grating was used to generate different modes of LG beams [12]. The schematic diagram is shown in Fig. 3, a He-Ne 632.8 nm collimated laser beam with its linear polarization in the x direction illuminated the binary amplitude grating, and then a 3 × 3 LG beam array was generated. Then different modes of LG beams were illustrated to the LC-SLM (LC-R2500 manufactured by HOLOEYE Co. Ltd). Diffractive pattern of the RL with f = 1 m and r_0 = 2 mm was loaded on a LC-SLM. Then we observed the intensity pattern of the emergent beam at different propagation distances (from 0.5 to 4 m) with a charge coupled device (CCD) camera.

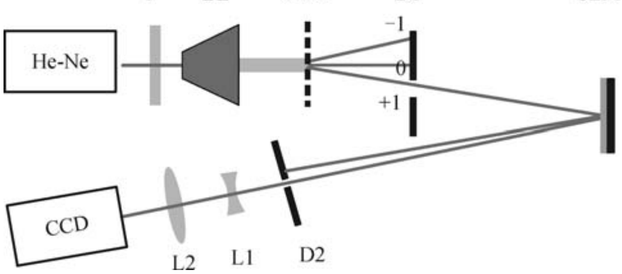

Fig. 3 Experimental schematic diagram. P: polarizer, BE: beam expanders, CGH: computer generated hologram, SLM: spatial light modulator, D: diaphragm, L: lens

Figures 4 and 5 are the simulation results and experimental results of the field distribution of LG_{00} and LG_{02} mode beams passing through a RL, respectively. It can be seen in both simulation results and experimental results that a sharp ring appears at the focal plane, and the intensity distribution in the paraxial region is similar to Bessel beams behind the focal plane, but the beam size is enlarged with the increase of propagation distance.

4 Property of generated Bessel beams

Due to the divergent property of the transformed beams, a scheme to collimate the Bessel-similar beams was proposed. It can be seen in Fig. 3, a lens group was placed at two times of the focal length. The lens group was composed of a concave lens with the focal length of −100 mm and a convex lens with the focal length of 300 mm. The concave lens was fixed, and the convex lens was fixed on a translation stage. Adjusting the distance of the two lenses, the beam size remained unchanged during propagation. Figure 6 shows the intensity distributions of the zero-order and first-order Bessel beam at different propagation distances, and it can be seen that the beam profile remains the same. An theoretical Bessel beam can be described as

$$E(r,\phi,z) = J_m(k_r r)\exp(\mathrm{i}k_z z)\exp(\mathrm{i}m\phi), \qquad (2)$$

where J_m is a m-th order Bessel function, k_z and k_r are the longitudinal and radial wave vectors. Figure 7 shows the transverse profile of the theoretical Bessel and the generated Bessel beam. It was found that transverse profiles are fitted well.

Self-healing property of the generated Bessel beams was also investigated. An obstacle (1.5 mm × 1.5 mm) was placed in the plane perpendicular to the propagation direction. It can be seen in Fig. 8 that both zero-order and first-order Bessel beam can self-reconstruct after a propagation distance (more than 2 m behind the obstacle).

5 Conclusions

In this letter, a method was proposed to generate diffractive RL by LC-SLM, then the propagation properties of different modes of LG beams passing through the RL

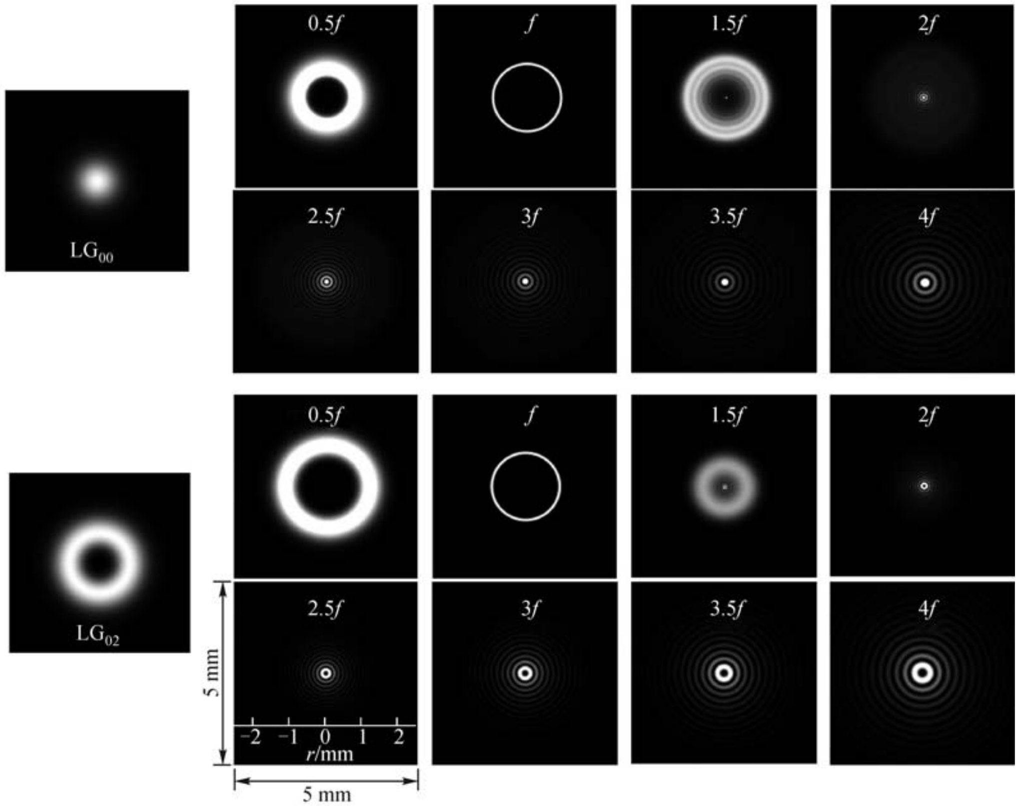

Fig. 4 Simulation results of LG_{00} and LG_{02} mode beams passing through RL

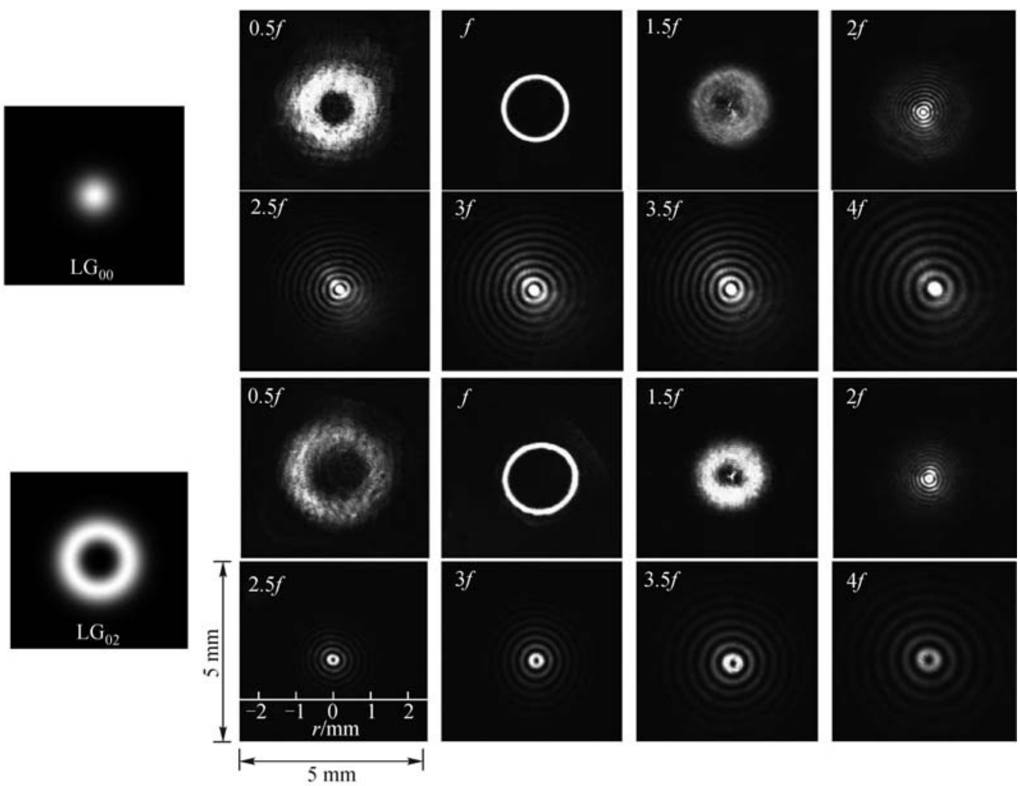

Fig. 5 Experimental results of LG_{00} and LG_{02} mode beams passing through RL

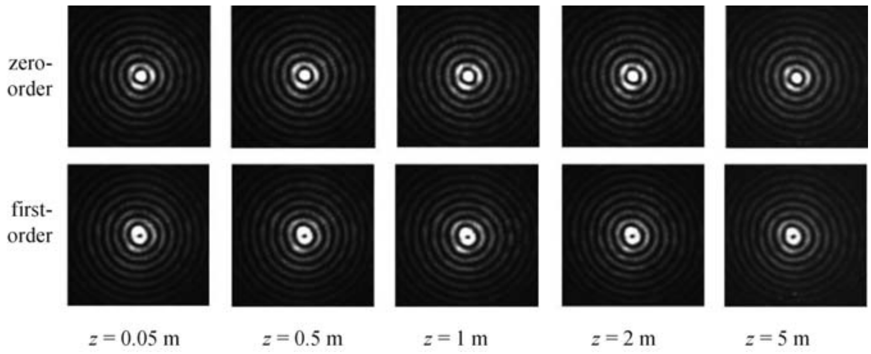

Fig. 6 Field distributions of generated Bessel beam at different propagation distance

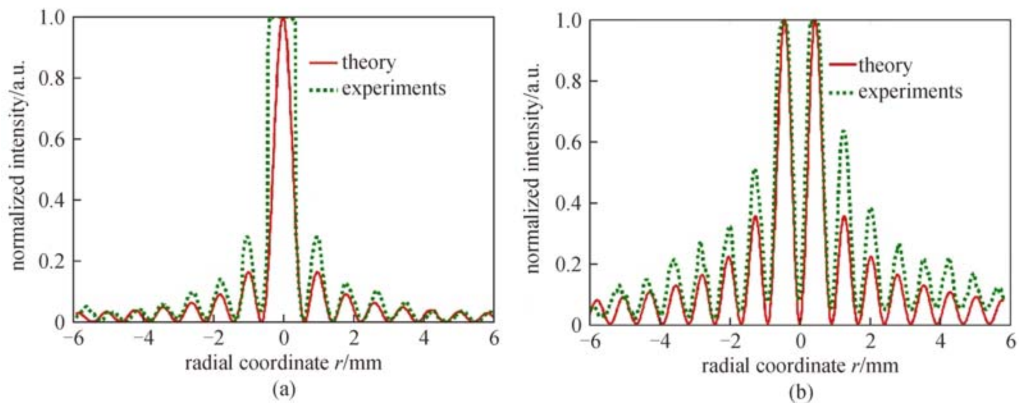

Fig. 7 Transverse profiles of the generated Bessel beams and theoretical Bessel beams. (a) Zero-order; (b) first-order

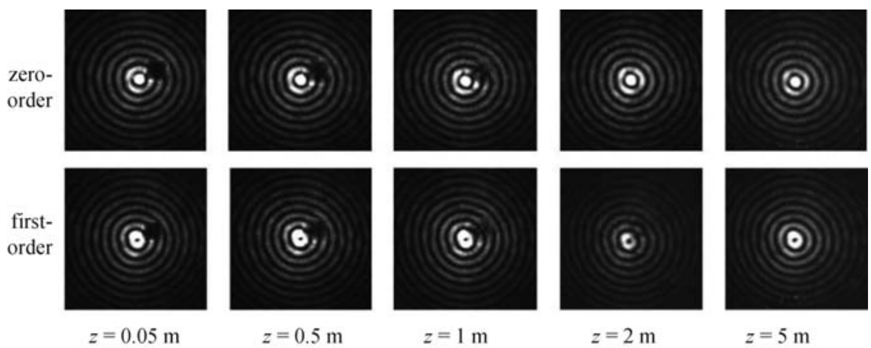

Fig. 8 Field distributions of generated Bessel beam passing through an obstacle at different propagation distance

was studied. It was found that LG beams were focused into a sharp ring at focal plane and the paraxial intensity distribution was similar to Bessel beam behind the focal plane. The Bessel-similar beams were collimated into Bessel beams by a lenses group which opens a new method to generate Bessel beams.

Acknowledgements This work was supported by the Program for ChangJiang Scholars and Innovative Research Team in University, PCSIRT (IRT1212), the National Natural Science Foundation of China (Grant Nos. 61475021 and 61108047).

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