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Generation of Bessel beams from a diffractive ring lens

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ABSTRACT

A method to generate a diffractive ring lens by a spatial light modulator is proposed. The diffractive ring lens is used to focus a Gaussian beam into single ring or multi-rings firstly. It was found that the transformed beam exhibits a Bessel transverse profile over the focal length, but the spot size is enlarged with the increase of propagation distance, allowing for generation Bessel beams with a ring lens.

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1. Introduction

Bessel beams have received much attention in recent years, owing to the properties of “diffraction-free” and self-healing. They have been used in atom guiding [1,2], optical tweezers [3] and laser machining [4]. Various optical elements and setups have been used to generate Bessel beams, such as an annular aperture located in the focal plane of a lens [5], a refractive axicon [6], reflective axicon mirrors [7], computer generated holograms [8] and *spatial light modulator* [9]. In this letter we report the generation of Bessel beams by using a diffractive ring lens (RL). In 1969 Goodell introduced a refractive RL and manufactured by Lucite [10]. RL has been proposed for application in focus-error sensing in optical data storage recently [11]. In this paper, we firstly generate a ring lens by introducing a phase hologram onto a spatial light modulator (SLM). To improve the structure of phase hologram, a multi-rings lens (MRL) is designed which is used to transform a Gaussian beam into concentric rings at the focal plane. Helical phase is also added to the phase hologram of the RL to generate sharp rings with orbital angular momentum (OAM). To distinguish the MRL, RL which transforms a Gaussian beam into a single ring at focal plane is called a single ring lens (SRL). From the propagation property of a Gaussian beam passing through a SRL, the transformed beam exhibits a Bessel transverse profile over the focal length, but the spot size is enlarged with the increase of propagation distance. In view of this propagation property, a lens group is used to collimate the Bessel-similar beam into Bessel beam.

2. Generation of ring beams with ring lens

The schematic diagram of the SRL is shown in Fig. 1(a), in which f indicates the distance between RL and its focal plane, and r_1 denotes the radius of the focal ring. When RL is illuminated by a collimated beam, a sharp ring with the radius of r_1 appears on the focal plane. The scheme of the SRL can be developed to design MRLs which can be seen in Fig. 1(b). For the inner ring, the light illuminated to the region $r < R_1$ is focused into a ring with radius of r_1 ; for the outer ring, the light illuminated to the region $r > R_1$ is focused into a ring with radius of r_2 . MRLs for generating more concentric rings can be constructed from the same method mentioned above. According to the geometric structure of the MRL, the transmittance function can be written as

$$T(r, \phi) = \exp\left(i\frac{2\pi}{\lambda}\left(f - \sqrt{f^2 + (r - r_n)^2}\right)\right) \quad (R_{n-1} \leq r \leq R_n) \quad (1)$$

where n is the number of rings for MRL that can be transformed from a Gaussian beam, λ is the wavelength, r_n denotes the radius of the n -th ring (marked from inner to outer).

Due to the flexibility of the SLM, helical phase can be added to the diffractive MRL which enables to generate ring sharp beams with different OAMs. The transmittance function of MRL with helical phase can be written as follows:

$$T(r, \phi) = \exp\left(i\frac{2\pi}{\lambda}\left(f - \sqrt{f^2 + (r - r_n)^2}\right)\right) \times \exp(im_n\phi) \quad (R_{n-1} \leq r \leq R_n) \quad (2)$$

where ϕ is an azimuthal angle, m_n is the topological charge of the n -th ring. The transmittance function of a SRL can be obtained from Eq. (2) by setting $n = 1$.

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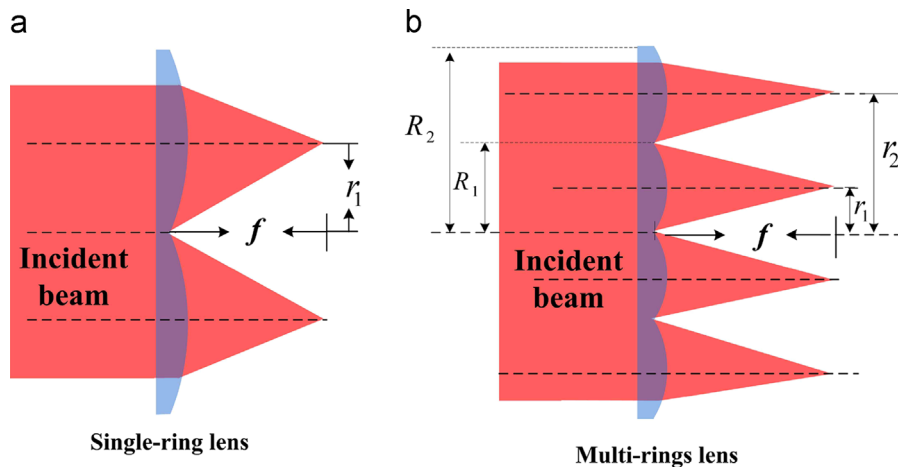


Fig. 1. The schematic diagram of ring lens.

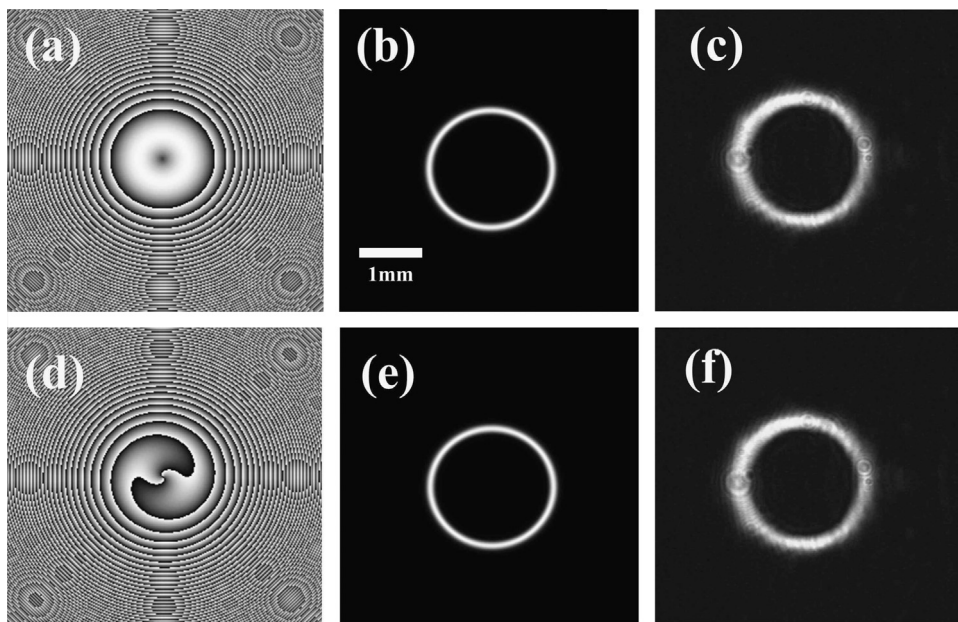


Fig. 2. The phase holograms of SRLs (left column), simulated intensity pattern (mid column), and experimental intensity pattern (right column) at focal plane. The focal lengths of those three RLs are 1 m. (a) $r_1 = 1 \text{ mm}$ and $m_1 = 0$, and (d) $r_1 = 1 \text{ mm}$ and $m_1 = 2$.

Fig. 2 shows the phase holograms of SRLs and their intensity patterns on the focal planes when a Gaussian beam is incident. It is found that both SRL with or without a helical phase can transform a Gaussian beam into a ring on the focal plane. Fig. 3 shows the phase holograms of MRLs and their intensity patterns at the focal plane when a Gaussian beam is transformed. In our scheme, MRL with helical phases at different regions are generated. To identify the topological charges of the concentric rings, a computer generated hologram (CGH) is used. If the diffractive order of the CGH matches the topological charge of the incident helical beam, the beam will be degraded into a simply Gaussian beam with a central bright spot. This central bright spot was used to check the topological charge of helical beams [12]. Fig. 4(a), (b) and (c) shows the far-field distributions when concentric rings (inner, middle and outer) of Fig. 3(f), respectively, are incident to the CGH independently (diaphragms are used to filter different rings). It is found that concentric rings with different OAMs are successfully generated on the focal plane which suggests potential applications in high density information storage.

3. Generation of Bessel beams with single ring lens

The generation of diffractive RLs by a SLM has been discussed above. In this sector, the propagation properties of a Gaussian beam passing through a SRL are studied numerically and experimentally. Angular spectrum theory of plane waves is employed to the numerical simulation. An experimental scheme is also designed which can be seen in Fig. 5. The collimated laser beam ($\lambda = 632.8 \text{ nm}$) with a linear polarization illuminates the SLM (LC-R2500 from HOLOEYE). A CCD is placed at variable distances from the SLM to observe the intensity distribution. The diffractive SRLs are chosen as that in Fig. 2(a) and (d). The simulation results, shown in Fig. 6, agree with the experimental results, shown in Fig. 7 very well. It is found that a sharp ring pattern appears at the focal plane, and the transformed beam exhibits a Bessel transverse profile over the focal length, but the spot size is enlarged with the increase of propagation distance, which is different from ideal Bessel beam that can be described as

$$E(r, \phi, z) = J_m(k_r r) \exp(ik_z z) \exp(im\phi) \quad (3)$$

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