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The on-axis intensity behavior of the diffracted Laguerre-Gaussian beam, LG_p, by an opaque disk

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Abstract

In this work, we present a detailed study of the on-axis intensity distribution of the Laguerre-Gaussian beam with no azimuthal index, diffracted by an opaque disk, by means of numerical simulation of Fresnel-Kirchhoff diffraction integral. We investigate the effect of the opaque disk size, the beam order, the beam waist, and the focal length. The results show that different focal phenomena may occur including the focal shift, focal split, and focal switch.

Keywords: Laguerre Gaussian beam, diffraction, focal shift, focal split, focal switch

1. Introduction

Higher-order Gaussian transverse modes [1] that are solutions of the paraxial Helmholtz wave equation in free space are eigenfunctions of the Fourier transform known as scaled propagation invariant beams. In cylindrical coordinates, the well-known Laguerre-Gaussian (LG) modes, that are characterized by two indices l and p corresponding to the azimuthal and radial indices respectively, play an important role in many different fields of physics and are widely used for various applications such as optical trapping and micro-manipulation [2,3], free-space

communication [4,5], and quantum information [6,7].
For that reason, the propagation properties of such kinds of structured light beams are extensively studied both experimentally and theoretically by researchers in various mediums and through optical systems [8-14].
When investigating the focusing properties of an optical beam, under certain conditions, the maximum intensity of a focused or diffracted field is not located at the geometric focus, but closer to the lens or the diffraction plane. This phenomenon, which is referred to as focal shift, was first found, in 1960, by Goubau [15] and Van Nie [16]. Then in 1980, Wolf and Li [17-19] discussed and explained focal shift for a fundamental Gaussian beam. Since then, due to its theoretical and practical interests, many studies have explored this phenomenon for different classes of beams such as Laguerre-Gaussian beams [20-23], Hermite-Gaussian beams [24], Bessel-Gaussian beams [25,26], Flat-topped beams [27].
Besides the focal shift, a focal switch or focal split can appear, wherein the maximum intensity jump from its position to another or the focus splits into two peaks [28-31].
The knowledge of the beam propagation behavior through optical systems is one of the keystones to getting the desired results. The present work provides a detailed study of the on-axis intensity distribution of Laguerre Gaussian beam, LG_p^0, diffracted by an opaque disk that not addressed before. The influence of different parameters including opaque disk size, radial beam order, beam waist, and focal length, on the on-axis intensity, is examined. Numerical simulations, using the Fresnal-Kirchhoff diffraction integral, show that such parameters can significantly affect the maximum intensity position, which plays an important role in some applications.

2. Focal phenomena of diffracted Laguerre Gaussian beam by an opaque disk

Consider a cylindrical LG beam with no azimuthal index ($l = 0$) is expressed, at the waist plane$z = 0$, as follows

$$u_{in}(\rho, z = 0) \propto L_p\left(2\frac{\rho^2}{w^2(z)}\right) exp\left(-\frac{\rho^2}{w^2(z)}\right) \tag{1}$$

where $w^2(z) = w_0^2[1 + (z/z_R)^2]$ is the beam width, $z_R = \pi w_0^2/\lambda$ is the Rayleigh length, w_0 is the Gaussian waist radius, and L_p is a Laguerre polynomial of order p. p dark nodal rings.

From the Fresnel-Kirchhoff diffraction theory, the propagated electric field at a distance z is given by [32]

$$u_{out}(r,z) = \int_0^\infty u_{in}(\rho, z=0)\tau(\rho)J_0\left(\frac{2\pi}{\lambda z} r\rho\right) exp\left[\frac{i\pi\rho^2}{\lambda}\left(\frac{1}{z} - \frac{1}{f}\right)\right]\rho d\rho \quad (2)$$

where r is the radial distance to the propagation axis, J_0 is the Bessel function of order zero, and $\tau(\rho)$ is the transmittance functions.

$$\tau(\rho) = \begin{cases} 0 & \rho \leq a \\ 1 & \rho > a \end{cases} \quad (3)$$

with a is the radius of the opaque disk.

The transverse intensity of an LG beam of order $\boldsymbol{l = 0}$, $\boldsymbol{p = 5}$ is displayed in figure 1. The p dark nodal rings in the cross-sectional on the right indicate the zeros of the beam's intensity, clearly seen on the left.

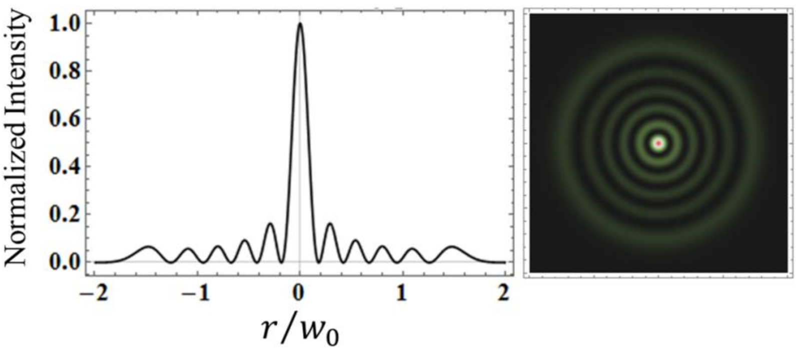

Figure 1. The transverse (on the left) and cross-sectional (on the right) intensity profile of $\boldsymbol{LG}$ beam with $\boldsymbol{p = 5}$ and $\boldsymbol{l = 0}$.

3. Results

In this section, we investigate the on-axis intensity distributions of the diffracted Laguerre-Gaussian beam, LG_p, under conditions of different opaque disk size a/w_0, different radial beam order p, different beam waist w_0, and different focal length f, with $\lambda = 0.0006328\ mm$.

3.1 Different opaque disk sizes:

Figure 2 shows the on-axis intensity behavior of focused LG beam of radial order $p = 5$ (the un-diffracted case) in figure.2(a), and that of the diffracted one by an opaque disk of different sizes in figure.2(b)-(f). It can be seen, from figure.1(a), that there is only one intensity peak located at $z_0 = 240.8\ mm$, a little away from the geometric focal plane. For figure.2(b)-(e), in the presence of opaque disk of different sizes (corresponding to the first, second, third, and fourth zeros intensity), one focal spot changes remarkably into multiple intensity peaks. This phenomenon is accompanied by a permutation of the focal point, in which the maximum intensity jumps from one position to another position. It can be also noticed that the maximum intensity peak shifts from the geometrical focus moving toward the lens and the opaque disk. In figure.2(f), when the whole beam is blocked, it is shown that the axial intensity becomes only one maximum peak, which is also located before the geometrical focus.

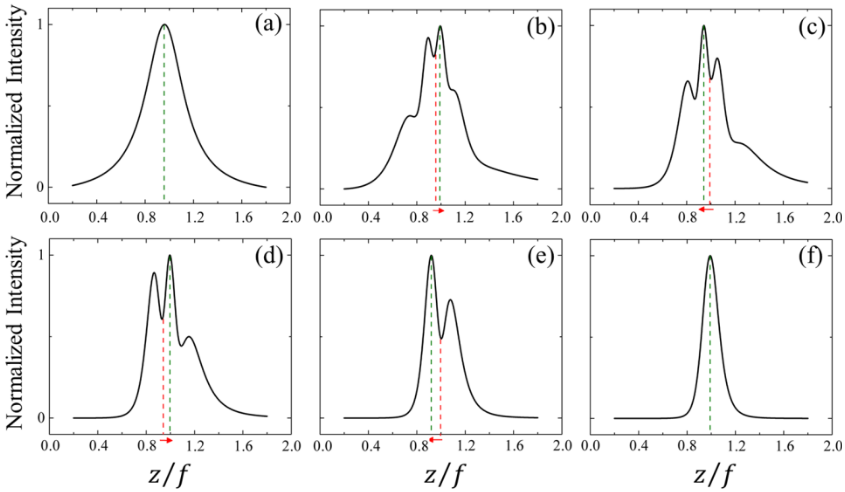

Figure 2. The on-axis intensity distribution of $\boldsymbol{LG}$ beam diffracted by an opaque disk, with $\boldsymbol{p = 5}$, $\boldsymbol{w_0 = 0.5\,mm}$, $\boldsymbol{f = 250\,mm}$, for different opaque disk sizes $\boldsymbol{a/w_0}$ that were chosen to coincide with the zeros of the beam's intensity.

3.2 Different radial beam order:

Figure 3 displays how the on-axis intensity distribution of the diffractedLG beam by an opaque disk is affected when varying the beam order p. For all the beam orders, a slightly focal shift occurs with showing a focal split accompanied by a focal switch in some cases such as figure.3(b) and (d).

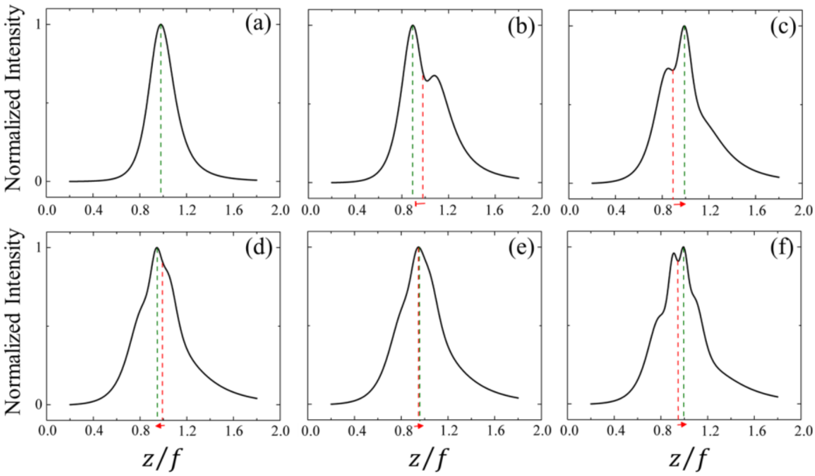

Figure 3. The on-axis intensity distribution of $\boldsymbol{LG}$ beam diffracted by an opaque disk, with $\boldsymbol{a/w_0 = 0.3}$, $\boldsymbol{w_0 = 0.5\,mm}$, $\boldsymbol{f = 250\,mm}$, for different radial beam order $\boldsymbol{p = 1, 2, 3, 4, 5, 6}$, respectively.

3.3 Different beam waist:

Figure 4 illustrates the effect of the beam waist on the on-axis intensity behavior of the diffracted LG beam by an opaque disk. It can be seen that for $w_0 > 0.5$, the maximum intensity peak keeps the same position.

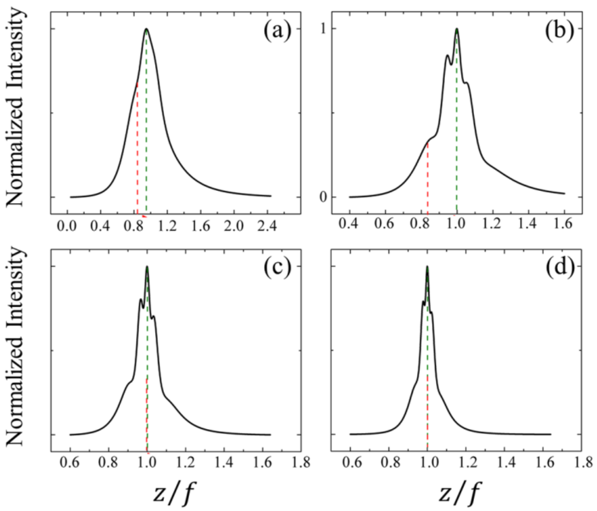

Figure 4. The on-axis intensity distribution of $\boldsymbol{LG}$ beam diffracted by an opaque disk, with $\boldsymbol{a/w_0 = 0.3}$, $\boldsymbol{p = 5}$, $\boldsymbol{f = 250\,mm}$, for different beam waist $\boldsymbol{w_0 = 0.5, 0.7, 0.9, 1.1\,mm}$, respectively.

3.4 Different focal length:

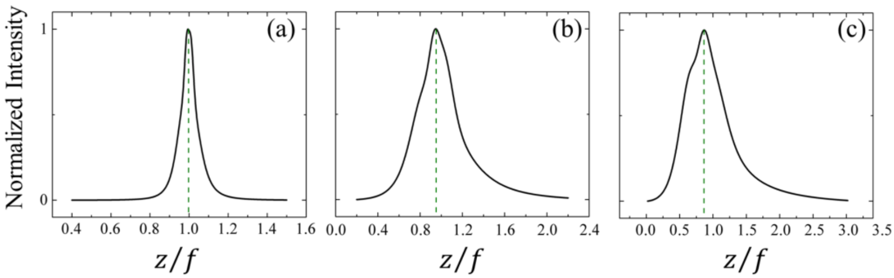

Figure 5. The on-axis intensity distribution of $\boldsymbol{LG}$ beam diffracted by an opaque disk, with $\boldsymbol{a/w_0 = 0.3, p = 5, w_0 = 0.5\ mm}$, for different focal length $\boldsymbol{f = 50, 250, 500\ mm}$, respectively.

Figure 5 exhibits the on-axis intensity behavior of the diffracted LG beam, by an opaque disk, when the lens is changed. It can be seen that the lens of the small focal length (figure.5(a)) gives a closer position to the geometrical focus of maximum intensity peak.

3.5 Focal shift evolution:

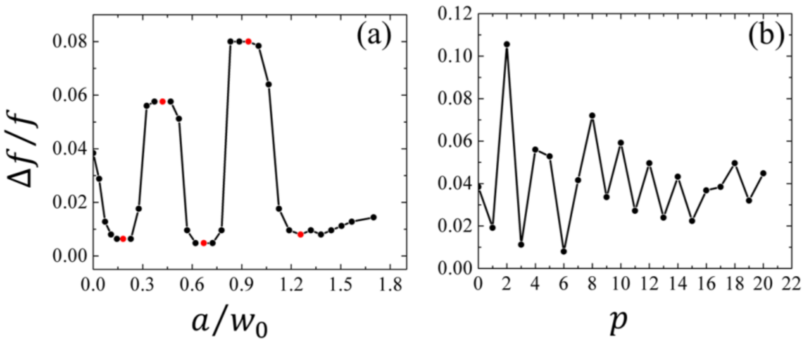

Figure 6. The focal shift variation, of the diffracted $\boldsymbol{LG}$ beam by an opaque disk, as a function of (a) the opaque disk size and (b) the beam order. $\boldsymbol{\Delta f = f - z_0}$, where $\boldsymbol{f}$ is the geometric focal length and $\boldsymbol{z_0}$ is the corresponding plane to the maximum intensity.

Figure 6 shows how the focal shift varies under different opaque disk sizes (figure.6(a)) and different beam orders (figure.6(b)). From figure.6(a), the amount of the focal shift oscillates between a min and max value, which is maybe due to the focal switch. The red points indicate that the focal switch occurs. In figure.6(b), in general, the focal shift of the even orders is larger than that of the odd orders.

4. Discussion

From the results, it is found that the on-axis intensity distribution of an LG beam diffracted by an opaque disk exhibits a focal shift accompanied by a focal split and focal switch. It's well known that the focal shift effect depends strongly on the Fresnel number of the system, and since the opaque disk doesn't limit the beam size thus the Fresnel number keeps the same, in contrast to the truncated case. Although, the focused beam without an obstacle also exhibits a slight focal shift, the same as the case of the opaque disk. Even it is negligible but the precise position of the maximum intensity has a crucial role for some applications. The present work has discussed the influence of different parameters on the on-axis intensity behavior, of the LG beam diffracted by an opaque disk, including the position of the maximum intensity.

5. Conclusion

In summary, using the Fresnel-Kirchhoff diffraction integral, we have studied, numerically, the intensity distribution of diffracted Laguerre-Gaussian beam, LG_p, by an opaque disk, along the longitudinal direction. We have explored how the on-axis intensity is affected when altering the opaque disk size, the beam order, the beam waist, and the focal length. The simulation results show that the maximum intensity peak can shift along the optical axis or split into multi peaks or jump from its position. These results help us to understand and control the intensity distribution along the axis.

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