Investigation of the vortex laser beam shift relative to the optical element using high performance computer systems

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Abstract. The spatial distribution of the Gauss-Laguerre beams with circular polarization is investigated subject to the beam position relative to the element, the axicon numerical aperture and order of the vortex phase in the 3D model. Modeling of diffraction is numerically investigated by the finite difference time domain (FDTD) method using high-performance computing. It is shown that using the diffraction axicon, polarization transformations can be carried out in the near zone, which, in particular, is expressed that the number of dark bands corresponds to the m (vortex laser beam number).

1. Introduction

Optical devices that allow you to adjust the polarization-phase state of a laser beam are studied for practical use [1-5]. Of interest is the conversion of vortex laser beams. The transformation of a laser beam under the influence of astigmatism was considered and the integral transformation of Gauss-Hermite beams into Gauss-Laguerre beams was found in [6]. The astigmatic lens was used in [7], and the method for determining the topological charge of polychromatic optical vortices based on the astigmatic transformation of singular optical beams, where the intensity pattern of the vortex beam took the form of dark bands in the focal plane of a cylindrical lens, was considered in [8]. The astigmatic transformations of Bessel beams with propagation in a uniaxial crystal were studied theoretically and experimentally in [9]. Of interest is the shown analogy between this transformation and the astigmatic distortion of a plane wave by an oblique axicon. In [10], cylindrical and oblique spherical lenses were considered as astigmatic converters, and a comparative experimental study of various astigmatic transformations was carried out. The polarization-dependent effect of astigmatic transformation of vortex rays oriented perpendicular to the axis of a uniaxial crystal was theoretically and experimentally studied in [11].

Measuring the state of the orbital angular momentum of vortex beams is of great importance in various applications. An effective scheme for measuring the states of the orbital angular momentum (topological charge values) of vortex beams with ring lattices is given in [12]. The magnitude of the topological charge value is determined by the number of dark bands, and the sign of the topological charge value can be determined depending on the orientation of the diffraction pattern.
Currently, a large number of papers are devoted to the use of optical vortices [13], as well as the study of their passage through various elements of micro optics [14-17]. The vortex beams are quite sensitive to various deviations in focusing optical system - inclination, displacement from the optical axis, the presence of other aberrations. However, aberrations can be used in a positive way: the inclination of the incident beam or focusing element [18-20], the presence of astigmatism or ellipticity [21, 22], as well as the use of cylindrical lenses [23], introduces distortions into the vortex beam that make possible to visualize its topological charge. The presence of some other aberrations in the focusing system makes possible to reduce the size of the focal spot when the vortex beams are sharply focused [24-26].

Axicon [27, 28] is an optical element that forms a zero-order Bessel beam [29] and the central spot diameter by the half-wave intensity (FWHM), is 0.36 wavelength divided by the numerical aperture (NA) [30]. This is smaller on 37% than the size of the Airy disk formed by a lens with the same NA. The features of the sharp focusing of Gauss-Laguerre beams were studied in [31] and it was shown that the polarization state exerts the greatest influence on the longitudinal component of the light field. The presence of evanescent waves in the near zone is possible to form a focal spot much smaller than the wavelength, which is of interest when using diffractive axicon for sharp focusing [32-36].

The numerical investigation of the propagation of Gauss-Laguerre modes up to the third order inclusively in the near zone was carried out in this work. The axicon numerical aperture is changed and the laser beam is shifted relative to the optical element. The numerical modeling of diffraction is performed using the finite difference time domain method (FDTD) using high-performance computer systems [37, 38]. The calculations were performed on a computing cluster with a power of 850 GFlop.

2. Vortex beam transformation by diffractive axicon with different numerical aperture

This section discusses vortex beam transformation by diffractive axicon with different numerical aperture. The input beams, beams propagation in the plane yz and the optical element view are shown in figure 1 and figure 2.

Figure 1. The input beams, beams propagation in the plane yz and the optical element.
Simulation parameters: the wavelength $\lambda = 0.532$ microns, the size of the computational domain $x, y, z \in [-3.8\lambda; 3.8\lambda]$. The thickness of the absorbing layer PML $\approx 1.3\lambda$, the sampling step of space $\lambda/21$, the sampling step of time $\lambda/(42c)$, where $c$ is the velocity of light. The Gauss-Laguerre beams were considered as the input laser radiation with circular polarization. The order of the vortex phase $m$ was changing from 1 to 3. The direction of the vortex in the laser beam was opposite to the direction of circular polarization. The refractive index of the axicon and the substrate is $n = 1.5$. The numerical aperture (NA) of the focusing binary axicon was 0.95 and 0.5, $\Delta$ - the displacement of the laser beam relative to the center of the optical element.

Figure 2. All types of input beams with increasing $m$, intensity, in the plane XY: $m = 1$ (a), (d), (g), (j); $m = 2$ (b), (e), (h), (k); $m = 3$ (c), (f), (i), (l).
The results of numerical simulation (intensity) in plane YZ are shown in figures 3-5. At the same time, cross-sections at a distance of $2\lambda$ from the element in the XY plane are also shown there.

**Figure 3.** The result of numerical simulation with a change in the orientation of the beam relative to the optical element ($m = 1$).

For a numerical aperture $NA = 0.95$, two cones formed for the case $m = 1$: at a small angle and at an angle corresponding to the numerical aperture of the axicon (a “conical” vortex), for $NA = 0.5$, in this case the second cone is less pronounced. For $NA = 0.5$ “conical” vortex is formed at presence of a 1 μm shift.

For the case when $m = 2$ for $NA = 0.5$ with a shift of 1 micron, the diffraction pattern is similar to pattern for the case $m = 1$ for $NA = 0.5$ with a shift of 1.25 microns, and for the case when $m = 3$ $NA = 0.5$ with a shift of 1.25 micron, the diffraction pattern is similar to pattern for the case $m = 2$ for $NA = 0.5$ with a shift of 1 microns.
Figure 4. The result of numerical simulation with a change in the orientation of the beam relative to the optical element (m = 2).

The following circumstance should be noted when analyzing cross sections: it was previously shown that to obtain the number of dark stripes equal to the order of the optical vortex, it is required to select the certain position of the optical element [39, 40]. A.A. Almazov and al. [40] showed the dependence of the intensity distribution of laser beams with a change in the angle of inclination of laser beams incident on a phase diffractive optical element.

If analyze the pictures of the intensity distributions of figures 3–5, it can see that for the numerical aperture NA = 0.5, there is a dependence of the number of dark bands equal to the order of the optical vortex. In particular, this effect is observed with the value $\Delta = 1\ \mu m$ and $\Delta = 1.25\ \mu m$ for all the considered cases with $m = 1, 2, 3$. 

Figure 5. The result of numerical simulation with a change in the orientation of the beam relative to the optical element (m = 3).

To confirm the above fact, consider the graphs of sections. Figure 6 shows the graphs of the intensity cross sections (2\(\lambda\) from the element) for \(\Delta = 1.25\) with \(m = 1\) (blue color), \(m = 2\) (red color), \(m = 3\) (green color). It should be noted that the number of minimums is equal to the value of the order of the vortex phase \(m\).
3. Conclusion

A comparative study of the Gauss – Laguerre mode diffraction with circular polarization on an axicon with a subwave period with a different numerical aperture was carried out numerically using the FDTD method. The direction of the vortex in the laser beam was opposite to the direction of circular polarization. The effect of increasing the order of the vortex phase on the form of diffraction patterns when the laser beam is shifted relative to the optical element is studied.

It is shown that using the diffraction axicon, polarization transformations can be carried out in the near zone, which, in particular, is expressed in the fact that the number of dark bands corresponds to the number of the vortex laser beam \( m \). It can be seen that for the numerical aperture \( NA = 0.5 \), there is a clearer dependence of the number of dark bands equal to the order of the optical vortex. In particular, this effect is observed with the values \( \Delta = 1 \, \mu m \) and \( \Delta = 1.25 \, \mu m \) for all the considered cases with \( m = 1, 2, 3 \).
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