Focusing of high-order vortex laser beams by binary axicon with different numerical aperture

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Abstract. The spatial distribution of the focused high-order vortex Gauss-Laguerre beams is investigated subject to the change of the numerical aperture of the diffraction axicon 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.

1. Introduction

It is known that the phase singularity can be used to amplify the longitudinal component of the electric vector of laser radiation [1-8] in the case of homogeneous polarization, which is produced by most modern lasers. In particular, vortex phase functions were considered in [1, 2, 5, 7, 8], and in [3, 4, 6] - superposition of vortex phase functions, both co-axial [3, 4] and spatially separated [6]. The presence of a powerful longitudinal component in the focus region makes it possible to improve the optical resolution and is used for optical manipulation, electron acceleration, material processing, microscopy and other applications [9-13].

Note that the energy of the longitudinal component becomes significant only at high numerical aperture [4, 14]. This requirement can be reduced by using high-order laser beams [15-18]. Also, it was shown that the use of the axicon makes it possible to strengthen the focusing of laser beams in comparison with the lens theoretically [19, 20] and experimentally [21, 22]. Applications of a diffractive axicon with high numerical aperture provide generation of longitudinally polarized laser needles [23-26]. In [27, 28], a comparison was made of the effect of a diffraction axicon and a conical taper for laser beams focusing. Special attention was paid to near-field diffraction by micro-axicons [29-33].

In this paper, we investigate the focusing of vortex beams using diffractive axicons with numerical aperture from 0.5 to 0.95. For the numerical simulation of diffraction we use the FDTD-method with high-performance computing [34]. Calculations were made on the computational cluster with power of 850 GFlops.

2. Investigation of vortex laser beam focusing

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 $\sim 1.3\lambda$, the sampling step of space $\lambda/21$. 


the sampling step of time – λ/(42c), where c is the velocity of light. The Gauss-Laguerre beams were considered as the input laser radiation with circular polarization and order of the vortex phase m from 1 to 3. The vortex direction 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. The results of numerical simulation in the xz plane are shown in figure 1.

**Figure 1.** The propagation of a high-order vortex Gauss-Laguerre beams through the axicons with a different NA, total intensity: input beam (plane xy) – (a), (b), (c); the longitudinal cross section (xz), NA = 0.95 – (d), (e), (f); the longitudinal cross section (xz), NA = 0.5 – (g), (h), (i).

The results of numerical simulation in the xz plane showed that for a numerical aperture NA = 0.95, two cones are formed for the case m = 1 at a small angle and angle corresponding to the numerical aperture of the axicon (a "conical" vortex). For the same numerical aperture at m = 2, an extended light segment is formed on the optical axis: its formation begins upon the completion of the propagation of the outer cone. For the case when m = 3, only one light cone is formed. For the case of a numerical aperture equal to 0.5, an increase in the order of m leads to defocusing.

Consider the cross-section for the axicons considered earlier. In figure 2 shows the simulation results at a distance of λ from the axicon. It should be noted that an increase in m for the case NA =
0.5 leads to a steady increase in the diameter of the central dip. Comparable values of the central dip for both axicons were obtained for the case $m = 3$.

![Figure 2](image)

Figure 2. The propagation of a high-order vortex Gauss-Laguerre beams through the axicons with a different NA, total intensity, cross section at a distance of $\lambda$ from axicon, plane xy: input beam - (a), (b), (c); NA = 0.95 – (d), (e), (f); NA = 0.5 – (g), (h), (i).

Thus, numerically, using the FDTD method, a comparative study of the diffraction of a vortex Gauss-Laguerre beams with circular polarization on diffraction axioms with $\text{NA} = 0.95$ and $\text{NA} = 0.5$ was performed.

3. Conclusion
In this paper we show the effect of the diffraction of vortex laser beams when changing the order of the vortex phase from 1 to 3 and numerical aperture of the focusing binary axicon in the 3D model. To numerically simulate the diffraction of the laser radiation under consideration the finite difference method in the time domain using high-performance computing are used.

It is shown that for a numerical aperture $\text{NA} = 0.95$, two cones are formed for the case $m = 1$ at a small angle and angle corresponding to the numerical aperture of the axicon (a "conical" vortex). For
the same numerical aperture at m = 2, an extended light segment is formed on the optical axis: its formation begins upon the completion of the propagation of the outer cone.

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