Transformation of a Gaussian vector beam by an axicon with a subwavelength period

D A Savelyev

1Samara National Research University, Moskovskoe Shosse 34, Samara, Russia, 443086
2Image Processing Systems Institute - Branch of the Federal Scientific Research Centre “Crystallography and Photonics” of Russian Academy of Sciences, Molodogvardejskaya str. 151, Samara, Russia, 443001

e-mail: dmitrey.savelyev@yandex.ru

Abstract. I considered diffraction of a Gaussian beam with linear polarization on a diffractive axicon with a numerical aperture equal to 1.3 and 1.5. I studied the changes in diffraction pattern numerically using the method of finite differences in the time domain. I shown that diffraction pattern in the near zone essentially depends not only on the value of the period of the annular grating, but also on the height of the diffractive relief. It is possible to form not only a compact light spot, but also a shadow spot (light ring), also a redistribution of energy between various components of the electric field, i.e. polarization transformation, can occurs.

1. Introduction

Near-field optics [1-5] is one of the directions effectively used to achieve superresolution. In this case, there are no restrictions on the size of the light spot, since the localization of the laser study can be arbitrarily small. However the compactness of the localization of light essentially depends on the size of the details of the surface relief [6-8] or the size of the point of the focusing element [9, 10].

The Fresnel zone plates [11] and meta-lenses [12, 13] are often used in solving problems of subwave focusing. In particular, in [12] linear polarization was converted to radial with using meta-lenses and sharp focusing of light was carried out. Nevertheless, the manufacture of such lenses is a difficult task.

It is well known that the axicon [14, 15] forms a zero-order Bessel beam [16] whose central spot diameter by the half-wave intensity (FWHM) is 0.36 wavelength divided by the numerical aperture [17], which is 37% smaller than the size of the Airy disk formed by the lens with the same numerical aperture (NA) [18].

The ability to produce microaxicons [19, 20] has expanded the range of applications in which these optical components can be employed, giving them a prominent position in micro- and nano-optics [21–23].
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 [24-31]. In particular, the value of evanescent waves was shown in [29] when the field was focused into the focal spot much less than the diffraction limit. In [30, 31], using thin optical models, the problem of focusing laser beams with diffractive axicons with a numerical aperture up to NA = 1.2 was considered.

In this paper the transformation of a vector Gaussian beam by means of a binary diffraction axicon with a period shorter than the wavelength in the 3D model was study. The numerical aperture of an diffractive axicon is 1.5. The finite difference time method (FDTD) is used to numerically simulate the diffraction of the laser radiation under consideration using high-performance computations [32] implemented in the Meep software package [33].

2. Transformation of a Gaussian beam by a diffractive axicon
Simulation parameters: the wavelength $\lambda = 0.532$ microns, the size of the computational domain $x, y, z$ is 4 microns. The thickness of the absorbing layer PML $\sim 1.3\lambda$, the sampling step of space $\sim \lambda/21$, the sampling step of time $\sim \lambda/(42c)$, where $c$ is the velocity of light. The Gaussian beams were considered as the input laser radiation with linear polarization. The refractive index of the diffractive axicon and the substrate is $n = 1.7$. The numerical aperture (NA) of the focusing diffractive axicon was 1.3 and 1.5. The appearance of the considered beam and optical element is shown in figure 1. Figure 2 shows longitudinal sections with a change in the height $(h)$ of the relief of the diffractive axicon with NA = 1.3. Similar studies for the diffractive axicon with NA = 1.5 are shown in figure 3.

![Figure 1. The input beam and the optical element.](image)

![Figure 2. Longitudinal sections with a change in the height of the diffractive axicon (NA = 1.3), intensity: in the plane XZ (a) $h = 0.71\lambda$, (b) $h = 1.09\lambda$, (c) $h = 1.43\lambda$; in the YZ plane (d) $h = 0.71\lambda$, (e) $h = 1.09\lambda$, (f) $h = 1.43\lambda$.](image)
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Figure 3. Longitudinal sections with a change in the height of the diffractive axicon (NA = 1.5), intensity: in the plane XZ (a) h = 0.71λ, (b) h = 1.09λ, (c) h = 1.43λ; in the YZ plane (d) h = 0.71λ, (e) h = 1.09λ, (f) h = 1.43λ.

The height of the element h = 0.71λ is the relief height corresponding to the phase jump π of the radians, h = 1.43λ corresponds to the phase jump of 2π radians, h = 1.09λ is the selected intermediate height value. It should be noted that for h < 1.43λ a shadow spot near the optical element is observed.

Let us consider the componentize decomposition of the total intensity in the XY plane (the cross section). The results of numerical simulation for NA = 1.3 with h = 0.71λ are shown in figure 4, for h = 1.09λ are shown in figure 5, for h = 1.43λ are shown in figure 6. Similar results for NA = 1.5 for corresponding heights are shown in figures 7-9.

The redistribution of the electric field from the component x to other components occurs for a height h = 0.71λ, with an increase in the numerical aperture to 1.5. It is worth noting that the appearance of diffraction is significantly influenced by a change in the height h. The height can be considered as a waveguide structure, especially the central part of the diffractive axicon with increasing h. And the central cylinder, as was shown in [7, 34], has a strong effect on the diffraction of the laser beam.

Figure 4. The cross section (NA = 1.3) for the case h = 0.71λ: (a) the total intensity, (b) the intensity of the component z, (c) the intensity of the component x, (d) the intensity of the component y.
The combination of NA and a certain height h leads to the formation of a shadow focus (ring) as shown on figures 4-9. It is also worth noting that increasing the height of the relief can be analogous to the increase in the numerical aperture of the optical element. A compact subwavelength spot is formed along the axis of polarization (see figures 6 and 9).

The polarization transformations of the fundamental Gaussian mode near the optical element observed in figures 7-9. The size of the shadow spot by half-width by half-drop intensity (FWHM) for the case h = 1.09λ is greater. The longitudinal component is more clearly defined.

As a rule, when a linearly polarized field passes through a diffractive axicon with a high numerical aperture, some energy redistribution occurs in the orthogonal components of the vector field. In this case, much more energy enters the longitudinal component of the field than in the transverse component, orthogonal to the original polarization [6, 24-27]. In our case, less energy has gone to the longitudinal component of the field than to the transverse component. It is also worth noting that, the redistribution of energy between the components of the electromagnetic field occurs in the same manner.
Figure 7. The cross section (NA = 1.5) for the case h = 0.71λ: (a) the total intensity, (b) the intensity of the component z, (c) the intensity of the component x, (d) the intensity of the component y.

Figure 8. The cross section (NA = 1.5) for the case h = 1.09λ: (a) the total intensity, (b) the intensity of the component z, (c) the intensity of the component x, (d) the intensity of the component y.

Figure 9. The cross section (NA = 1.5) for the case h = 1.43λ: (a) the total intensity, (b) the intensity of the component z, (c) the intensity of the component x, (d) the intensity of the component y.
3. Conclusion
A comparative study of the diffraction of a Gaussian beam on a diffractive axicon with a subwavelength period is numerically performed in this paper using the FDTD method. The effect on the parameters of the formed light segments on the height variation of the optical element under consideration was studied. It is shown that with the aid of a diffraction axicon it is possible to carry out polarization transformations in the near zone, which is expressed in the formation of a shadow spot next to the element.

The redistribution of the electric field from the component x to other components occurs for a height \( h = 0.71\lambda \), with an increase in the numerical aperture to 1.5. It is worth noting that the appearance of diffraction is significantly influenced by a change in the height \( h \). The central cylinder has a strong effect on the diffraction of the laser beam.

It is also worth noting that increasing the height of the relief can be analogous to the increase in the numerical aperture of the optical element. A compact subwavelength spot is formed along the axe of polarization for case \( \text{NA} = 1.5 \) and \( h = 1.43\lambda \).

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