The generation of evanescent beams by means of binary diffraction axicons with high numerical aperture

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Abstract. The investigations of the generation of evanescent beams by means of binary diffraction axicon with a numerical aperture (NA) were more than one. It is shown that it is possible to generate evanescent beams using axicons. Numeric simulation of radiation passing through the axicon was investigated by the finite difference time domain method (FDTD).

1. Introduction

Interest in evanescent fields arose long ago [1] due to their applications in such fields as near-field optical microscopy, high-density recording, sub-wave lithography. In particular, one of the approaches to evanescent field’s production is to illuminate the desired target with radiation passing through an aperture with dimensions smaller than the wavelength [2] and requires very close distances between the target and the aperture. Two fundamental effects cause this circumstance: the damped nature of the vanishing field components generated by the aperture, and the rapid expansion of the remaining field [1].

Near-field optics [3-5] is one of the directions effectively used to achieve super-resolution. In this case, there is no restriction on the size of the light spot, since the localization of the laser study can be arbitrarily small. However, as was shown in [6-9], 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 tip of the focusing element [7, 9].

Bessel beams have attracted constant interest since their first mention [10]. Of particular interest at that time were the so-called Bessel-Gaussian beams, which were mathematically interpreted analytically in the paraxial approximation [11]. Later it was also accepted that the definition of Bessel beams could be extended to include additional functions of the same family. It was found that modified Bessel beams do not oscillate in the transverse direction and oblate shape, when it is appropriately apodized by a Gaussian function [12]. These types of beams were subsequently generalized for complex arguments [13]. The generation of evanescent Bessel beams for a radially polarized beam at the interface between dielectric-metal media was considered in [14]. The realization of an evanescent Bessel beam through the surface plasmon interference excited by a radially polarized beam was proposed in [15].
It is also known that the axicon forms a zero-order Bessel beam whose central spot diameter by the half-wave intensity (FWHM) is 0.36 of the wavelength divided by the numerical aperture \([16]\), which is 37% smaller than the size of the Airy disk formed by the lens with the same numerical aperture (NA). Due to the presence of evanescent surface waves in the near zone, it is possible to form a focal spot much smaller than the wavelength, which is of interest in the use of axicon for tight focusing \([17-22]\). In particular, in \([21]\) considered focusing of laser beams with axicons with different NA (maximum NA = 1.02). In \([22]\), diffraction axioms with a numerical aperture up to NA = 1.2 were also investigated.

However, the model of a thin optical element was used in \([21, 22]\). In this paper, we investigate the formation of evanescent beams using a binary diffraction axicon with a period shorter than the wavelength in the 3D model. The numerical aperture of the axicon varied from 0.95 to 2.0. To numerically simulate the diffraction of the laser radiation under consideration, the finite time difference (FDTD) method using high-performance computations is used \([23]\), implemented in the Meep software package \([24]\).

2. Generation of evanescent beams
Simulation parameters: the wavelength \(\lambda = 0.532\) microns, the size of the computational domain \(x, y, z \in [-3.76\lambda; 3.76\lambda]\). The thickness of the absorbing layer PML \(\sim 1.32\lambda\) (0.7 micron). The considered laser beam is the fundamental Gaussian mode with circular polarization (figure 1). The refractive index of the axicon and the substrate is \(n = 1.46\) (corresponding to the material Fused Silica).

![Diffraction axicon](image)

**Figure 1.** Modelling parameters: (a) Gaussian beam; (b) the optical element.

The results of numerical simulation in the xz plane are shown in figure 2. The results of the calculations showed that when the NA of axicon increases, the formation length of the evanescent beam decreases. It should be noted that when NA is more than 1.3, a ring shadow spot is formed on the optical axis, which means an increase in the longitudinal component of the electric field. Its appearance is shown in the bottom line of figure 2.

Consider the cross-section for the axicons considered earlier. In figure 3 shows the simulation results at a distance of 0.1 \(\lambda\) from the axicon, in figure 4 - simulation results at a distance of 1.5 \(\lambda\) from the axicon.

It should be noted that for NA > 1, even at a distance of 0.1 \(\lambda\) from the axicon, the formation of a ring shadow spot begins. For NA = 1.5 at a distance of 1.5\(\lambda\) from the axicon, and further, a ring focal spot is formed.
Figure 2. The longitudinal cross section (xz) of propagation of a Gaussian beam through axicons with a different NA: total intensity – (a) $\text{NA} = 0.95$; (b) $\text{NA} = 1.05$; (c) $\text{NA} = 1.5$; the longitudinal component – (d) $\text{NA} = 0.95$; (e) $\text{NA} = 1.05$; (f) $\text{NA} = 1.5$.

Figure 3. The cross section (xy) of the propagation of a Gaussian beam at a distance of 0.1 $\lambda$ from the axicon: total intensity – (a) $\text{NA} = 0.95$; (b) $\text{NA} = 1.05$; (c) $\text{NA} = 1.5$; the longitudinal component – (d) $\text{NA} = 0.95$; (e) $\text{NA} = 1.05$; (f) $\text{NA} = 1.5$. 
Figure 4. The cross section (xy) of the propagation of a Gaussian beam at a distance of $1.5\lambda$ from the axicon: total intensity – (a) $NA = 0.95$; (b) $NA = 1.05$; (c) $NA = 1.5$; the longitudinal component – (d) $NA = 0.95$; (e) $NA = 1.05$; (f) $NA = 1.5$.

Thus, numerically, using the FDTD method, a comparative study of the diffraction of a Gaussian beam with circular polarization on diffraction axioms with a numerical aperture greater than 1 was performed, and it was shown that it is possible to generate evanescent beams.

3. Conclusion
In this paper, the effects of an increase in the numerical aperture of the optical element (axicon) on the diffraction of a Gaussian beam with circular polarization are considered. Simulation of radiation passing through the axicon was numerically investigated by the finite difference time domain method. It is shown that an increase in the numerical aperture of the element makes it possible to obtain an amplification of the longitudinal component of the electric field, which is expressed in the formation of a ring (shadow) spot.

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