Journal of Physics: Conference Series **490** (2014) 012213 doi:10.1088/1742-6596/490/1/012213

The calculation of the diffraction of the laser beams with a phase singularity on the micro-axicons with using high-performance computing

Savelyev D.A., Khonina S.N. *

Samara State Aerospace University named after academician S.P. Korolyov, Samara, Russia
* Image Processing Systems Institute of the RAS, Samara, Russia

E-mail: dmitrey.savelyev@yandex.ru, khonina@smr.ru

Abstract. We analyze the diffraction of the laser beam with a vortex phase singularity on the basis of the finite-difference time-domain method (FDTD). It is shown that, when incident beam has phase singularity, increase of the micro-axicon radius leads to extension of the light needle consisting of longitudinal electric field component. The numerical investigations held of the near-field diffraction for the most common and easily implemented types of polarization of the incident beam - linear and circular.

1. Introduction

An axicon generates a Bessel beam of the zero order, which the focal spot is 30% less (FWHM = 0.36λ/NA) than the size of the Airy disk, formed by a lens with the same numerical aperture [1]. The diffractive axicon is a "flat" analogue of a refractive conical axicon. Advantages of diffractive axicons are in the relative simplicity of manufacture and the ability to achieve high values of numerical aperture, which unachievable for the conical axicon due to the total internal reflection. Thus it is natural to use the diffractive axicon in focusing systems, lithography and nano-structuring, optical manipulation.

Strengthening of the longitudinal component (components z) is important in applications such as microscopy, high-resolution metrology, electron acceleration, material processing and integrated optics [2]. The possibility of focusing a radially-polarized beam in a long light needle, which consists mainly of the z-component of the electric field, is demonstrated in [3]. However, most laser light sources have linear polarization, so the formation of a similar distribution for the corresponding polarization is urgent.

The vortex phase singularity can be used to redistribute energy between the components of the electromagnetic field for linearly polarized radiation [4,5]. The phase jump perpendicular to the polarization axis allows to form the longitudinal component on the optical axis. For sharp focusing we use the binary axicon with high numerical aperture [6,7]. A spiral binary axicon is considered in [7] also. This element provides the same effect but independent on the rotation of the axis of the linear polarization.

In this paper, we consider the simulation of the formation of the longitudinal component on the optical axis by means of the finite-difference time-domain method (FDTD). To strengthen the


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longitudinal component we use phase singularity in the incident beams that is focused by ordinary binary axicon with high numerical aperture. We research the possibility of increasing the distance propagation component z. We will pursue this in two ways: by varying the size of the optical microelement and by increasing the radius of the incident beam.

2. The diffraction of the laser beams on the micro-axicon with different radius

Let's consider a binary micro-axicon with high numerical aperture ($\alpha_0 = 0.95$):

$$\tau_b(r) = \exp\left\{i \arg\left[\cos\left(k\alpha_0 r\right)\cos\left(m\varphi\right)\right]\right\}. \quad (1)$$

To simulate the diffraction of different beams on axicon (1), we used the method of FDTD, implemented in a software package Meep. Calculations were made with using the computational cluster with power of a 775 GFlops. The cluster's characteristics are: 116 cores, compute nodes are 7 dual servers HP ProLiant 2xBL220c, area network is InfiniBand, and controlling network is Gigabit Ethernet. These were used for the calculation of 32 to 48 cores with a standard version of the MPI.

Simulation's parameters are: wavelength λ = 0.532 μm, the maximum radius of the axicon R = 8.6625λ , numerical aperture NA = α_0 = 0.95. The size of the computational domain of *x*, *y*, *z* is [–9λ; 9λ]. The thickness of the absorbing layer PML (on all sides surrounding the computational domain) is 1.5λ, the discretization in space is λ/40, the discretization in time is λ/(80*c*), where *c* is the light speed. The refractive index of the axicon and the substrate is equal to n = 1.5. In this case, the height of the micro-relief is:

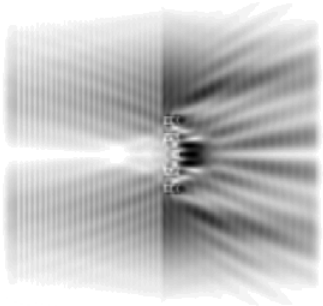
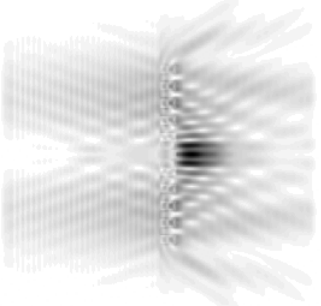
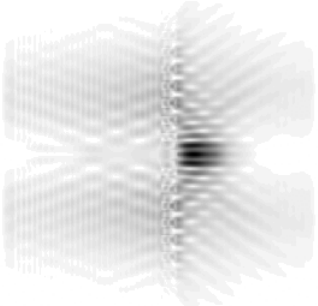
$$h = \frac{\lambda}{2(n-1)} = \quad . \quad (2)$$

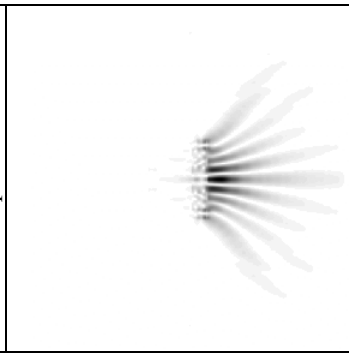
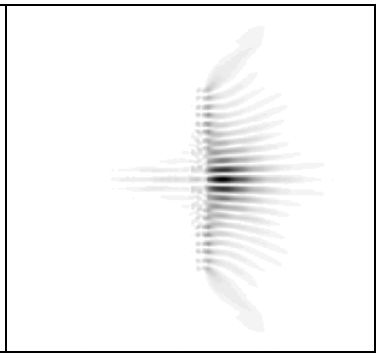
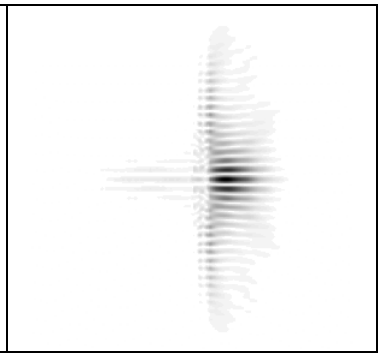
As the incident beams was chosen Laguerre-Gaussian laser mode (0,1) with radius σ = 3.5λ:

$$GL_{01}(r,\varphi,z) = \left(\frac{\sqrt{2}r}{\sigma(z)}\right)\exp\left[ikz - i2\eta(z)\right]\exp\left[\frac{i\pi r^2}{\lambda R(z)}\right]\exp\left[-\frac{r^2}{\sigma^2(z)}\right]\exp\left(i\varphi\right). \quad (3)$$

Fixing the size of the input beam, we vary the size of the relief of axicon. The simulation results for the y-polarization are given in Table 1.

Table 1. Distribution in the YZ plane [21λ × 21λ], y-linear polarization.

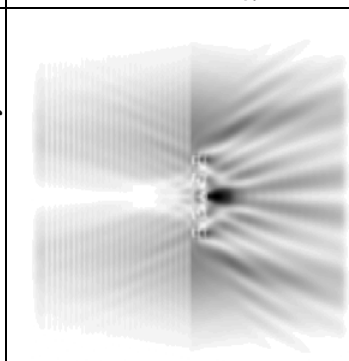
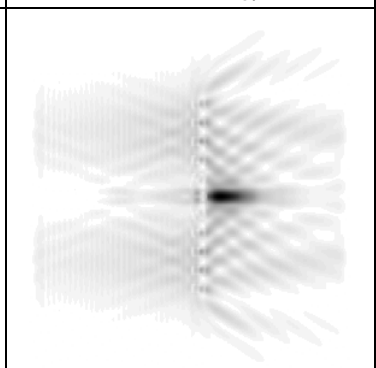
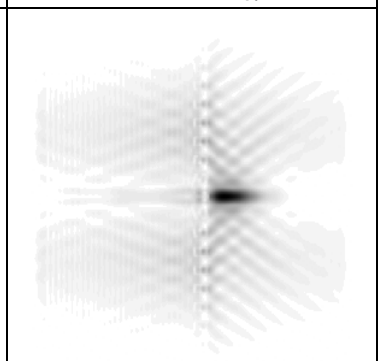
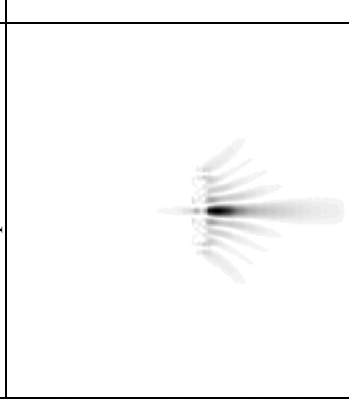
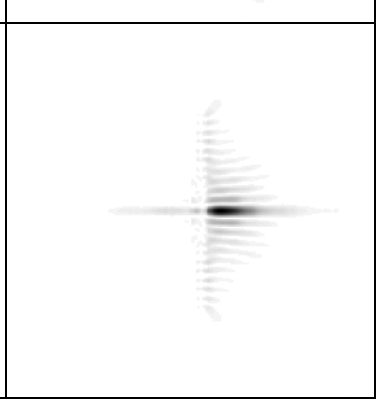
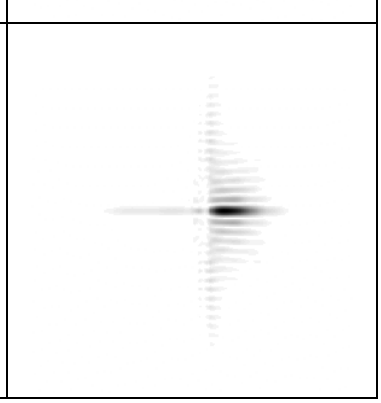
	R = 2.3625λ	R = 5.5125λ	R = 8.6625λ
The longitudinal distribution of the total intensity			

The longitudinal distribution, component z			

It should be noted that the decrease in the radius of the relief leads to a redistribution energy of longitudinal components on the optical axis with simultaneous decrease in the intensity of the light needle.

As the many tasks require the formation of a symmetrical spot, we also consider the circular polarization of the incident beam for the same case (Table 2). We consider the circular polarization in direction opposite to the direction of the vortex phase singularity. Obtained results are similar to the previous case.

Table 2. Distribution in the YZ plane [21λ × 21λ], circular polarization.

	R = 2.3625λ	R = 5.5125λ	R = 8.6625λ
The longitudinal distribution of the total intensity			
The longitudinal distribution, component z			

3. Diffraction of the laser beams with different radius

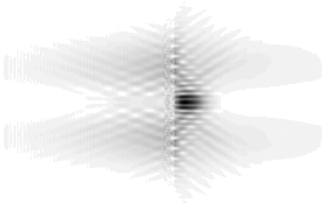
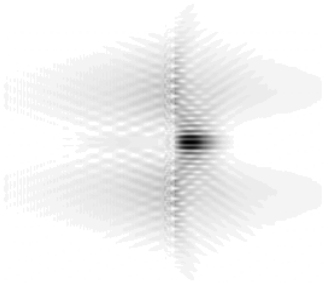
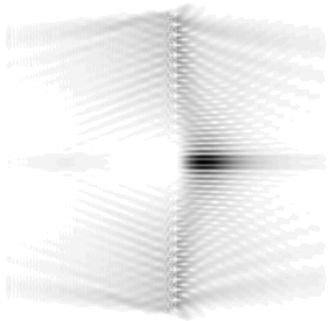
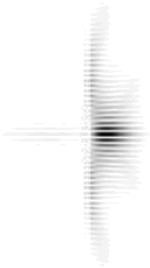
In this section we consider a change of the radius of the light beam. We increase the size of the computational domain, while reducing the number of pixels per micron. The following parameters have been changed: the maximum radius of the axicon R = 14.9625λ, the size of the computational domain x, y, $z \in [-15.5\lambda; 15.5\lambda]$, discretization in space is λ/30, discretization in time is λ/(60c).

Table 3 shows the longitudinal section for the Laguerre-Gaussian mode (0,1) with different radius σ for y-linear polarization.

As seen from Table 3, increasing the radius of the beam leads to the elongation of the light focus formed by the axicon. The central part of the focal domain mainly consists of the longitudinal component (just z-component is present on the optical axis). Thus, using an axicon with high numerical aperture we can form the light needle containing mostly the longitudinal component of the electric field. The length of the needle is proportional to the radius of the axicon fully illuminated with the linearly polarized vortex beam.

Thus, in this paper it is shown the possibility of formation of a long light needle that is mainly z-polarized by means of binary high NA axicon illuminated by a laser beam with linear or circular polarization. This is achieved by entering into the illuminating beam vortex phase singularity. The length of the light needle is proportional to the radius of the axicon and radius laser beam.

Table 3. Distribution in the YZ plane [34λ × 34λ], a different radius of the input beam.

	σ = 3.5λ	σ = 5λ	σ = 14.56λ
The input beam			
The longitudinal distribution of the total intensity			
The longitudinal distribution, component z			

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