Simulation of the super-Gauss beam abrupt focusing in the near diffraction zone using high-performance computer systems

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Abstract. We investigated the change in the type of focal spot when laser radiation passed through the diffraction axicon and the optical element matched with the circular Airy distribution having abrupt focusing properties. Modelling of near zone diffraction is numerically investigated by the finite difference time domain (FDTD) method. The abrupt formation of a light needle was shown for the optical element matched with the circular Airy distribution and for axicon.

1. Introduction
The formation of light fields with a given structure of amplitude, phase, and polarization (the so-called structured light) is currently necessary to solve many pressing problems in various fields - optical manipulation [1-3], imaging optics [4], optical and quantum communications [5, 6] and other applications [7]. Of particular interest are beams with the auto-focusing property [8], including Pearcey beams [9], circular Airy beams [10-15], hypergeometric [16] and aberration beams [17], as well as others, including generalized beams [18-21]. The sharp auto-focusing property inherent in such beams is in demand in optical manipulation [22, 23], nonlinear effects [24] and for polarization transformations [25-27]. To generate such structured fields, elements of diffraction optics, photonic crystals, and all kinds of metamaterials and metasurfaces are widely used [28-32].

One of the main driving forces of technological change in the XXI century became a miniaturization of technical systems and devices, a tendency to the development of information, sensor components, combined on the basis of nano-and microsystem technology. The development of such a technique has led to the need for the development of elements of nano- and micrometer sizes that could be used to control light at appropriate scales. The possibility of manufacturing microaxicons [33, 34] expanded the range of application of axicons and allowed them to occupy an important place in micro- and nanooptics [35-38]. The applications of cylindrical vector beams for polarization-amplitude modulation of focal distributions and for solving problems of sharp focusing were demonstrated in a number of works [39-42]. The S. N. Khonina et al. [43-45] examined in detail various types of polarizations of laser radiation and their effect on the laser beam focusing. Also it was demonstrated that the state of polarization has the greatest impact on the longitudinal component of the light field in a number of studies [46-49].
We compared the focusing of super Gauss through the diffraction axicon and the optical element matched with the circular Airy distribution. The FDTD method using high-performance computations is applies to numerically simulate the diffraction of the laser radiation [50-53] with using the Meep software package. Calculations were made on the computational cluster with power of 850 GFlops.

2. Investigation of focusing short pulses
In this work, we consider the input field as super-Gauss beam. The optical element consistent with the Airy circular distribution with seven zeros (jumps) was investigated. The normalized jump radiuses of this element are equal to: \( r_1 = 0.487, r_2 = 0.605, r_3 = 0.699, r_4 = 0.783, r_5 = 0.861, r_6 = 0.933, r_7 = 1.0 \). A binary axicon can be considered as a ring diffraction grating [52-54]:

\[
\tau_{ax}(x, y) = \exp \left\{ i \frac{\pi}{\lambda} \left( 1 - \text{sgn} \left( \cos \left( \frac{2\pi}{\lambda} \alpha \sqrt{x^2 + y^2} \right) \right) \right) \right\},
\]

(1)

where \( \lambda \) is the wavelength of illuminating beam, \( \alpha \) corresponds to the numerical aperture of the diffractive axicon, \( \text{sgn}() \) is signum function.

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 super-Gauss with different polarization states was considered as the input laser radiation. The refractive index of the axicon and the optical element matched with the circular Airy distribution is \( n = 1.5 \). The numerical aperture (NA) of the focusing binary axicon was 0.95. The results of numerical simulation in the xz plane are shown in figure 1 (cylindrical polarization) and figure 2 (homogeneous polarization).

![The axicon](image1)

![The optical element matched with the circular Airy distribution](image2)

**Figure 1.** The longitudinal cross section (xz) of propagation laser radiation in case of cylindrical polarization: laser propagation through the axicon (a), (c) and laser propagation through the optical element matched with the circular Airy distribution (b), (d).
Figure 2. The longitudinal cross section (xz) of propagation laser radiation in case of homogeneous polarization: laser propagation through the axicon (a), (c), (e), (g) and laser propagation through the optical element matched with the circular Airy distribution (b), (d), (f), (h).
It should be noted that uniform polarization states (linear and circular) make it possible to obtain a compact light needle for both elements considered. The focusing is observed closer to the optical element for radial polarization. In the case of azimuthal polarization, we observe the annular structure formation. In general, for an optical element matched with the circular Airy distribution, a more pronounced light needle is formed. The focusing of laser radiation by the axicon occurs in the immediate vicinity of the optical element.

We will evaluate the size of the focal spot by the full width at a half maximum intensity (FWHM). The narrower light spot was obtained for the axicon in general case. The smallest focal spot size was 0.33λ for the case of y-linear polarization along x-direction. But on the other hand, for an optical element matched with the circular Airy distribution for linearly polarized beam, the focal spot was greatly flattened (compare 0.83λ and λ, in contrast to the axicon for linear polarizations — 0.33λ and 0.8λ).

Another interesting fact is the following: in the case of radial polarization for the axicon, a compact light needle with a spot size of 0.47λ was obtained. The deterioration in the shape of the light needle and an increase in the size of the focal spot (1.11λ) were observed, however, for the optical element matched with the circular Airy distribution.

It is known that the polarization and laser pulse duration are significant factors affecting the distribution of the electric field in the focal region [51, 52, 57-60]. In particular, polarization has the greatest effect on the longitudinal component of the light field [46-49]. Let us further consider the action of super-Gauss with radial polarization with pulsed radiation passing through the axicon at different times t. The research results are shown in figure 3.

Figure 3. The longitudinal cross section (xz) of propagation super-Gauss pulses at different times for radial polarization: total intensity (a), (b), (c) and longitudinal component intensity (d), (e), (f).
It should be noted that the formation of a stable light needle is observed. The intensity maximum on the optical axis forms outside the element starting from time \( t = 13 \) (at a distance of \( 0.41\lambda \)) and then up to a distance of \( 0.68\lambda \) (\( t = 15 \)).

The size of the focal spot for the time \( t = 13 \) is \( 0.46\lambda \) (the intensity of the longitudinal component of the electric field is equal \( 0.44\lambda \)), for \( t = 15 \) is \( 0.52\lambda \) (the intensity of the longitudinal component is \( 0.45\lambda \)). It should also be noted that the greatest contribution to the total intensity on the optical axis is made by the longitudinal component of the electric field.

### 3. Conclusion

The investigation of the near-field diffraction of a super-Gauss beam with linear, circular, radial, and azimuthal polarizations passing through the diffraction axicon and a sub-wavelength optical element matched with the circular Airy distribution was conducted in this paper. The finite-difference method in the time domain is used with high-performance calculations for the numerical simulation of diffraction of the considered laser radiation.

It should be noted that uniform polarization states (linear and circular) make it possible to obtain a compact light needle for both considered elements. The focusing is observed closer to the optical element for the radial polarization. In the case of the azimuthal polarization, we observe the annular structure formation.

The narrower light spot was obtained for the axicon in general case. The smallest focal spot size was \( 0.33\lambda \), for the case of \( y \)-linear polarization along \( x \)-direction. In the case of radial polarization for the axicon, a compact light needle with a spot size of \( 0.47\lambda \) was obtained. We also examined pulsed laser radiation for radial polarization. The size of the focal spot for the time \( t = 13 \) is \( 0.46\lambda \) (the intensity of the longitudinal component of the electric field is equal \( 0.44\lambda \)).

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