The size reducing of the focal spot with focusing short pulses using high-performance computer systems

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Abstract. We investigated the change in the type of focal spot when pulsed radiation passed through the diffraction axicon. The Gauss beam and the Gauss-Laguerre mode (1,0) were considered as the input laser radiation with linear polarization. Modelling of diffraction is numerically investigated by the finite difference time domain (FDTD) method. The formation of a shadow focal spot in the immediate vicinity of an optical element and amplification of the longitudinal component of the electric field were shown.

1. Introduction
The many papers recently have appeared that consider the possibility of reducing the size of the focal spot during sharp focusing. Most often, amplitude or phase apodization of the pupil of the lens [1-4] and special types of polarization of laser radiation [5-7] are proposed, as well as a combination of these characteristics [8-11]. D. Savelyev and S. Khonina [12] shown that polarization has the greatest effect on the longitudinal component of the light field. However, another factor affecting the field distribution in the focal area is the duration of the laser pulse [13-16]. Note that this factor is particularly important in applications such as laser printing, micro- and nano-textures [17, 18].

The analysis of the effect of the pulse duration on the field distribution in the focal area is carried out as a rule on the basis of the field expansion in plane waves and integral expressions [13-16, 19, 20]. This is due to the possibility of using analytical representations and reducing the time of the computational process. However, in some cases it is required to use a more accurate calculation model, in particular, a direct solution of Maxwell’s equations. The FDTD method [21] is one of the most accurate approaches for modeling temporal processes in micro-optics and allows one to obtain correct results of the propagation and diffraction of short pulses.

The spatial structure of the laser beam is important in applications based on the interaction of electromagnetic radiation with matter. The classical elements offer little possibilities in controlling the spatial structure of the laser beam [22]. The widest range of spatial transformations of laser radiation is provided by means of diffractive optics. The most commonly used diffraction gratings and spatial light modulators (SLM) [23-25]. With all the dynamic advantages, spatial modulators lose to diffractive optical elements in efficiency and resolution. It was shown that focusing laser radiation by a diffraction axicon with a high numerical aperture makes it possible to achieve sharper focusing than with an aplanatic objective with the same numerical aperture value of the system [26].

The presence of a phase singularity in the beam, which can change the polarization properties of the radiation even for beams with a uniform polarization, is played an important role [27]. Various
types of polarizations and their influence on the focusing of laser radiation were considered in [28, 29]. It is known that the phase singularity can be used to amplify the longitudinal component of the electric vector of laser radiation [30–33] in the case of uniform polarization, which many of modern lasers produce. The presence of a powerful longitudinal component in the field of focus improves optical resolution and is used for optical manipulation, material processing, microscopy, and other applications [34, 35].

In this paper, we explore the possibility of reducing the size of the focal spot when focusing short pulses by a diffraction axicon. To numerically simulate the diffraction of the laser radiation, the FDTD method using high-performance computations is used [36], implemented in the Meep software package [37]. Calculations were made on the computational cluster with power of 850 GFlops.

2. Investigation of focusing short pulses
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 $\lambda/(42c)$, where $c$ is the velocity of light. The Gauss beam and the Gauss-Laguerre mode $(1,0)$ were considered as the input laser radiation with linear polarization. The refractive index of the axicon and the substrate is $n_{ax} = 1.5$. The numerical aperture (NA) of the focusing binary axicon was 0.95. The input beams and the considered optical scheme is shown in figure 1.

![Figure 1](image)

Figure 1. Modelling parameters: (a) the Gauss-Laguerre mode $(1,0)$, (b) the Gauss beam, (c) the computational domain.

The results of numerical simulation in the xz plane at different times $t$ are shown in figure 2. It should be noted that the focusing of laser radiation occurs in the immediate vicinity of an optical element. The formation of a shadow focal spot near the optical element is observed for the case of a Gaussian beam. The amplification of the electric field $z$-component on the optical axis should be noted for the case of the Gauss-Laguerre mode $(1,0)$.

The intensity distributions of the longitudinal component of the electric field for the cases $t = 8$ and $t = 9$ for the Gaussian beam and Gauss Laguerre modes are shown in figure 3.
Figure 2. The longitudinal cross section (xz) of propagation short pulses at different times: the Gauss beam, (a) $t = 6$, (c) $t = 7$, (e) $t = 8$, (g) $t = 9$; and the Gauss-Laguerre mode $(1,0)$, (b) $t = 6$, (d) $t = 7$, (f) $t = 8$, (h) $t = 9$. 
Figure 3. The longitudinal cross section (xz) of propagation short pulses at different times, z-component: the Gauss beam, (a) $t = 8$, (c) $t = 9$; and the Gauss-Laguerre mode (1,0), (b) $t = 8$, (d) $t = 9$.

It is worth noting that for the Gaussian beam, focusing occurs inside the element. The formation of a light needle can be observed for the Gauss Laguerre mode (1,0). The size of the light needle (full-width at half-maximum - FWHM) intensity for the case $t = 8$ is $0.68\lambda$, for the case $t = 9$ is $0.55\lambda$.

3. Conclusion

The formation of pulsed radiation (the Gauss beam and the Gauss-Laguerre mode (1,0)) with linear polarization passed through the diffraction axicon with numerical aperture 0.95 was investigated. To numerically simulate the diffraction of the laser radiation under consideration, the finite difference in the time domain method using high-performance computing is used. It should be noted the formation of a shadow focal spot in the immediate vicinity of an optical element. Amplification of the longitudinal component of the electric field also occurs, and the formation of a light needle near the optical element is observed (for the Gauss Laguerre mode (1,0)). The size of the light needle intensity for the case $t = 8$ is $\text{FWHM} = 0.68\lambda$, for the case $t = 9$ is $\text{FWHM} = 0.55\lambda$.

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