The investigation of the features optical vortices focusing by ring gratings with the variable height using high-performance computer systems

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Abstract. The diffraction of vortex laser beams with circular polarization by ring gratings with the variable height was investigated in this paper. Modelling of near zone diffraction is numerically investigated by the finite difference time domain (FDTD) method. The changes in the length size of the light needle and focal spot size are shown depending on the type of the ring grating.

1. Introduction

The interesting properties of singular beams make it possible to use them for optical manipulations with micro- and nanoparticles [1], material processing [2] and in microscopy [3]. In addition, the optical vortices are used in wireless communication systems [4], for transmitting information over fiber [5] and in quantum informatics [6], for polarization state recognition [7]. Such beams can be obtained using spiral and twisted axicons [8], spiral phase plates [9], multi-order diffractive optical elements [10].

The introduction of a vortex phase singularity into the input beam makes it possible to enhance the longitudinal component of uniformly polarized laser beams on the optical axis in the focal region [7, 11]. So, it is makes it possible to change the diffraction pattern due to the redistribution of energy between the components of the electromagnetic field [12].

The diffractive axicon (ring grating) as the conical axicon forms an extended light needle along the optical axis [13, 14]. It is also possible to obtain dynamic focus by complementing the optical system with an adjustable lens or axicon [15]. The change in the substrate thickness has a significant effect on the diffraction pattern of a limited plane wave by diffraction axicons with different numerical apertures (NA). This action was shown earlier to change the substrate thickness from 0.2$\lambda$ to 0.3$\lambda$ [11].

The features of focusing optical vortices on ring gratings with the variable relief height $h$ are studied in this paper. Numerical calculations (3D) of laser radiation propagation were performed using the finite difference time domain (FDTD) method using high-performance computer systems [16, 17].
2. The investigation of focusing by ring gratings with variable height

Modeling parameters: wavelength $\lambda = 0.532 \, \mu m$, computational cell size $x, y, z \in [-5.6 \lambda; 5.6 \lambda]$. The thickness of the absorbing layer PML $\sim 1.1 \lambda$, the sampling step in space is $\lambda/16$, the time step is $\lambda/(32c)$, where $c$ is the light speed. The refractive index of the considered optical elements and the substrate $n$ was equal to 1.5.

The height $h$ was varied as follows: at the center $h = 3\lambda$, then the height decreased with each subsequent grating ring with a step of $0.25\lambda$ up to $h = 1.75\lambda$ to the edge of the element (the direct ring grating). The opposite case is also considered: in the center there is a minimum, $h = 1.75\lambda$ and the height increases to $3\lambda$ from the center to the grating edge (the inverse ring grating). The diffractive axicon ($h = 3\lambda$) with NA = 0.95 was also considered for comparison. The period of all considered ring gratings was $1.05\lambda$.

The Laguerre-SuperGauss modes (1,0) of degree 6 with circular polarization (polarization is opposite in sign of the introduced vortex phase singularity) and the super-Gaussian beams with the same degree are considered as the input laser radiation (Figure 1).

![Figure 1](image)

Figure 1. The input beams: (a) the super-Gaussian beam, (b) and the Laguerre-super-Gauss mode (1,0).

The research results are shown in Figure 2.

The size of the focal spot on the optical axis was estimated from the full width at half maximum (FWHM) of the intensity, and the length of the light needle was also estimated from the depth of focus (DOF), also at half maximum.

It should be noted that for the case Laguerre-super-Gauss mode (0,1), the most compact focal spot was obtained for the case of the direct ring grating (FWHM = 0.54$\lambda$), and the longest light needle was obtained for the case of the inverse ring grating (DOF = 4.81$\lambda$).

When considering the case of a super-Gaussian beam, it should be noted that focusing inside the element is observed for a direct ring grating. For the case of inverse ring grating, one can note a decrease in the size of the focal spot (FWHM = 0.48$\lambda$) and an increase in the length needle (DOF = 2.12$\lambda$) in comparison with a standard diffractive axicon with the same period (FWHM = 0.92$\lambda$ and DOF = 1.06$\lambda$, respectively).

The graphs with cross-sections for compare direct and inverse ring grating are shown in Figure 3. It should be noted the drop in intensity for the case of direct ring grating (the Laguerre-super-Gauss mode (1,0)).
Figure 2. The longitudinal cross section (xz) of propagation laser radiation: the super-Gaussian beam – (a), (c), (e), and the Laguerre-super-Gauss mode (1,0) – (b), (d), (f).

Figure 3. The cross sections for the cases of Figure 2 (c), (d), (e), (f), the direct ring grating (black line) and inverse ring grating (green line): (a) the super-Gaussian beam, (b) the Laguerre-super-Gauss mode (1,0).
3. The propagation of the pulsed Laguerre-super-Gauss mode (0,1)

One of the factors affecting the distribution of the electric field in the focal region is the duration of the laser pulse [18-24]. Let’s expand on the research from the previous section for Laguerre-super-Gauss mode (0,1). The results of modeling the propagation of these pulsed beams at different times $t$ are shown in Figure 4.

![Figure 4. The propagation Laguerre-super-Gauss mode (1,0) pulses through the: (a), (c), (e), (g) the direct ring grating, (b), (d), (f), (h) inverse ring grating.](image)
The graphs with cross-sections for compare direct and inverse ring grating at the output of the pulse from the element are shown in Figure 5. It should be noted the narrower focal spot for the case of direct ring grating than for inverse ring grating (FWHM = 0.5λ and FWHM = 1.06λ, respectively).

**Figure 5.** The cross sections for the cases of Figure 4, the direct ring grating (black line) and inverse ring grating (green line): (a) t = 15, (b) t = 16.

4. Conclusion
The formation of the Laguerre-super-Gauss modes (1,0) with circular polarization and a super-Gaussian beam by ring gratings with the variable height were investigated. The FDTD method is used for numerical simulation of diffraction.

It should be noted that a significant increase in the length of the light needle is observed with an increase in the height of the grating rings from the center to the edges in comparison with the standard diffractive axicon.

It is shown that or the case Laguerre-super-Gauss mode (0,1), the most compact focal spot was obtained for the case of the direct ring grating (FWHM = 0.54λ), and the longest light needle was obtained for the case of the inverse ring grating (DOF = 4.81λ). And for the case of a super-Gaussian beam should be noted inverse ring grating: one can note a decrease in the size of the focal spot (FWHM = 0.48λ) and an increase in the length needle (DOF = 2.12λ) in comparison with a standard diffractive axicon with the same period (FWHM = 0.92λ and DOF = 1.06λ, respectively).

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