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The comparison of the optical vortices focusing by silicon diffraction axicons and ring gratings with variable relief heights using high-performance computer systems

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Abstract. A study was made of the spatial distribution of the intensity of the Laguerre-super-Gaussian (1,0) modes with circular, radial and azimuthal polarization depending on the change in the height of silicon subwavelength optical elements, the height of which varied from 0.2 to 3 wavelengths. Simulation by the finite difference method in the time domain showed that a change in the height of the considered optical elements significantly affects the diffraction pattern in the near zone. The smallest focal spot size was obtained for "-" circular polarization at an element height equal to two wavelengths.

Keywords: optical vortices, sub-wavelength structures, FDTD, high performance computer systems, ring gratings

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Материалы конференции
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Сравнение фокусировки оптических вихрей кремниевыми дифракционными аксиконами и кольцевыми решетками с переменной высотой рельефа с использованием высокопроизводительных компьютерных систем

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Аннотация. В данной работе исследуется пространственное распределение интенсивности мод Лагерра-суперГаусса (1,0) с круговой, радиальной и азимутальной поляризацией в зависимости от изменения высоты кремниевых субволновых оптических элементов, высота которых менялась от 0.2 до 3 длин волн. Моделирование методом конечных разностей во временной области показало, что изменение высоты рассматриваемых оптических элементов существенным образом влияет на дифракционную картину в ближней зоне. Наименьший размер фокального пятна был получен для «-» круговой поляризации при высоте элемента равной двум длинам волн.

Ключевые слова: оптические вихри, субволновые структуры, FDTD, высокопроизводительные компьютерные системы, кольцевые решетки

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Introduction

The structured laser beams [1], including those in the field of metamaterials and metasurfaces [2], are being actively studied in various fields of optics and photonics at present. In particular, it is known to use metasurfaces to generate an optical vortex in order to increase the throughput of optical communication systems [3]. Among structured beams, a special place is occupied by singular light beams [4], among which we should note beams with screw dislocations (optical vortices), which are currently being actively studied [5]. Optical vortices are known to be used for a number of applications, including the transmission of information over an optical fiber [6], in quantum informatics [7], and in wireless communication systems [8].

The introduction of a vortex phase singularity into the incident beam makes it possible to amplify the longitudinal component of uniformly polarized laser beams on the optical axis in the focal region [9], which makes it possible to change the diffraction pattern due to energy redistribution between the components of the electromagnetic field [10].

The presence of a strong longitudinal component in the focus region makes it possible to improve the optical resolution and is used for a number of applications, among which one can note optical manipulation and material processing [11].

Currently, the silicon and its compounds have a variety of applications [12, 13]. In particular, they are used for the manufacture of semiconductor devices [14], solar batteries [15], in medicine [16], as well as for solving photonics problems [17]. Due to the high refractive index of silicon, it is possible to obtain a high integration density [13], as well as to reduce the size of the focal spot during sharp focusing with optical microelements, including diffractive axicons [18].

The diffraction of optical vortices on silicon subwavelength mycoelements is studied in this paper: diffractive axicons and ring gratings of variable height. The influence of a change in the height of such elements on the subwavelength focusing of the considered laser beams is considered. Numerical calculations (3D) of laser radiation propagation were performed using the finite difference time domain method (FDTD) using high-performance computer systems.

Materials and Methods

This section presents the simulation parameters, types of elements, input beam: wavelength $\lambda = 1.55$ μm, the size of the computational domain for the selected radiation wave x, y, z was in the range [–5.8λ; 5.8λ]. The spatial sampling step is λ/30, the time sampling step is λ/(60c), where c is the speed of light. The thickness of the absorbing PML layer surrounding the computational domain on all sides is 1.16λ. The source is located inside the substrate, which occupies the entire space below the relief and is immersed in the absorbing PML layer. The refractive index of the element is $n = 3.47$.

Let us consider the action of the simplest implementation of an axicon in the form of a binary diffractive axicon with a numerical aperture NA = 0.95 (lattice period 1.05λ), whose phase takes values of 0 and π radians. The height of the relief of a binary element, corresponding to the phase π radians, with a refractive index of the material of the element $n = 3.47$ is equal to:

$$h = \frac{\pi}{k(n-1)} \approx 0.2\lambda, \tag{1}$$

where λ is the wavelength of the considered laser radiation, n is the refractive index, $k = 2\pi/\lambda$ is the wave number.

An optical vortex as an input beam significantly changes the focal pattern compared to a conventional one, for example, a Gaussian beam [9], and the direction of rotation of circular polarization becomes important. Let us call "–" circular polarization the polarization in which the sign of the circular polarization is opposite to the sign of the introduced vortex phase singularity. The case when the sign of the circular polarization is co-directed with the introduced vortex phase singularity will be called "+" circular polarization.

Previously, it was shown that at the second order of the optical vortex and higher for "–" circular polarization, a shadow round light spot was formed [9, 19]. In this paper, the first order of an optical vortex in an incident beam for this type of polarization is considered.

The beams with an amplitude distribution approximated by a super-Gaussian function are often used [20, 21] for the cases where a uniform intensity distribution over the beam cross section is required.

The Laguerre-superGauss (1,0) modes, mainly with "–" circular polarization, were considered as input laser radiation (cases for "+" circular, radial and azimuthal polarizations are also given) in this paper. The amplitude of the Laguerre-superGaussian mode (1,0) is given by:

$$A(r,\varphi) = r \cdot \exp\left[-\frac{r^p}{2\sigma^p}\right], \tag{2}$$

where σ is the beam size in μm, $p = 6$.

Results and Discussion

This section presents the study's results of the changing in the height relief effect of silicon microelements on the diffraction pattern in the near zone.

Figure 1 shows the results of propagation of the considered laser radiation through a diffractive axicon with a relief height h from 0.2λ to 3λ. The total intensity and intensity of the longitudinal

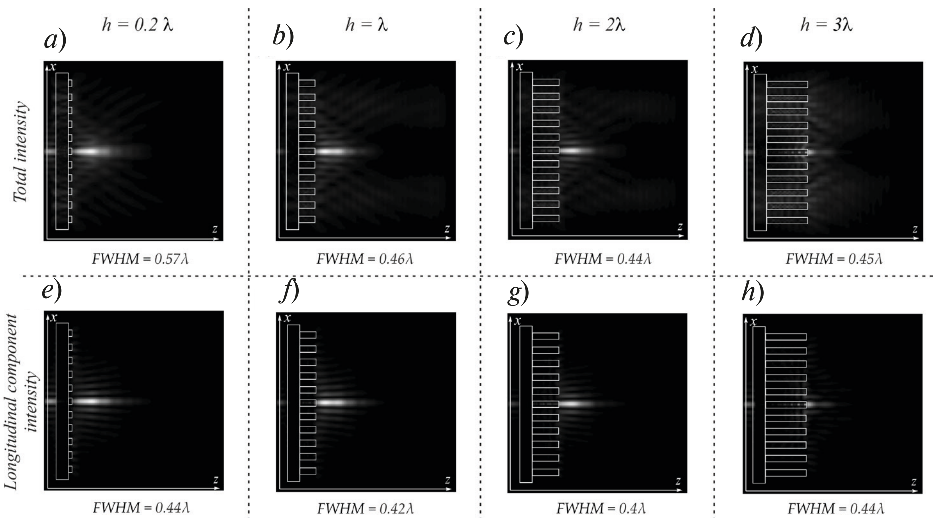

Fig. 1. The longitudinal cross section (*xz*) of the Laguerre-superGauss mode (1,0) propagation («–»circular polarization, intensity): total intensity (*a*, *b*, *c*, *d*), longitudinal component intensity (*e*, *f*, *g*, *h*)

component of the electric field are shown. The size of the focal spot on the optical axis was estimated from the full width at half maximum (FWHM) of the all intensity.

All main maximums are formed outside the optical element. It should be noted that, at first, the size of the focal spot at the maximum decreases up to the height $h = 2\lambda$, and then an increase is observed. At a height $h = 3\lambda$, a significant shift of the maximum peak to the edge of the element relief is observed with a broadening of the focal spot size.

If estimate the value of the focal spot in the immediate vicinity of the element (at a distance of 0.1λ), then an increase in intensity is observed at all heights considered (from 40% at $h = 0.2\lambda$ to 90% at $h = 3\lambda$). The focal spot width was smaller than at the maximum and was FWHM = 0.36λ for heights from 0.2λ to 2λ and FWHM = 0.46λ for $h = 3\lambda$. The width of the focal spot for the longitudinal component of the electric field was less than the total width. It should also be noted that as the height of the relief increases, a reduction in the length of the light needle is observed.

The best value for the focal spot width was obtained for the height $h = 2\lambda$ (total intensity). For this case, we will also consider other polarizations ("+" circular, radial and azimuthal). The results are shown in figure 2.

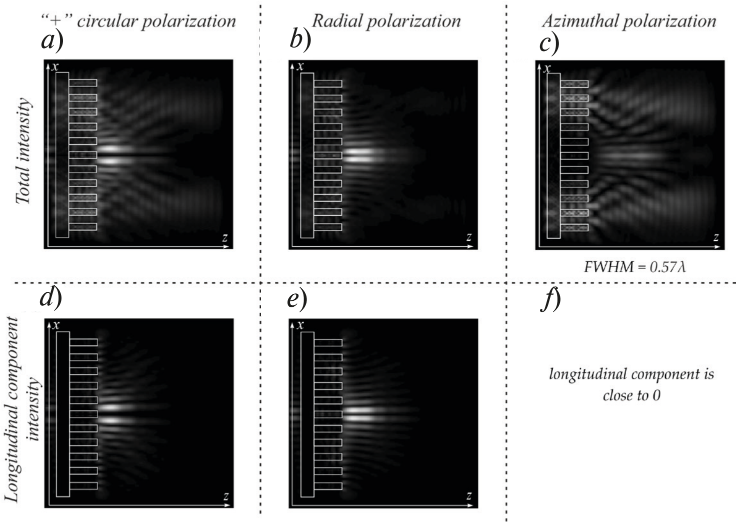

Fig. 2. The longitudinal cross section (*xz*) of the Laguerre-superGauss mode (1,0) propagation, intensity: «+ »circular polarization (*a*, *d*), radial polarization (*b*, *e*), azimuthal polarization (*c*)

As previously shown [18], the following is true for optical vortices of the first order: a zero value of the central focal spot indicates "+" circular polarization, and a nonzero one indicates "–" circular polarization. Similarly, for radial polarization there will be a zero value at the central focal point, and a non-zero value means azimuthal polarization.

Actually, you can see confirmation of this fact (Fig. 2). The rings obtained in the case of "+" circular polarization are smaller in length along the axis and the central shadow spot is larger than in the case of radial polarization (the length along the optical axis is greater). For the case of azimuthal polarization, the formation of a light needle on the optical axis is observed, but the intensity value is only 57% of the maximum. The size of the focal spot at the maximum on the optical axis is 0.57λ and is formed at a distance of 3.66λ from the edge of the relief.

Previous studies have shown that under certain conditions, a conventional round protrusion can be used to recognize polarization and focusing, and the focusing will be better than for a diffractive axicon with a similar grating size [18]. But the relief height also plays a key role [21].

In further studies, the central part of the relief changed, as shown in figure 3 ("–" circular polarization). Let's start from the height of the central cylinder $h_1 = \lambda$, the height of the remaining zones is the same and equal to 0.2λ. Next, the height h_1 has been increased to 2λ, the height of the next zone will be equal to λ, and the rest by 0.2λ (Fig. 3, *b*, *e*). And finally, $h_1 = 3\lambda$, the height of the first ring is 2λ, the height of the second ring from the center is λ, and the rest are 0.2λ each (Fig. 3, *c*, *f*).

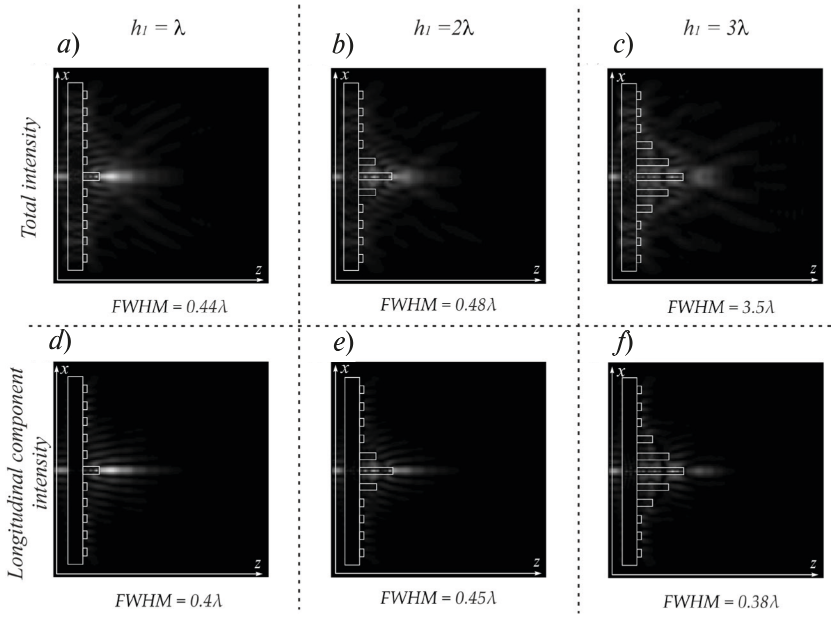

Fig. 3. The longitudinal cross section (*xz*) of the Laguerre-super-Gauss mode (1,0) propagation on ring gratings with variable relief height: $h_1 = \lambda$ (*a*, *d*), $h_1 = 2\lambda$ (*b*, *e*), $h_1 = 3\lambda$ (*c*, *f*)

It should be noted that only for the case $h_1 = \lambda$, the main maximum is formed outside of the element (at a distance of 0.76λ from the edge of the element), so all FWHM values (Fig. 3) are given on the 0.1λ from the edge of the central cylinder. That is, increasing the height in the selected format leads to the formation of an intensity peak inside the element. In the general case, a broadening of the focal spot size is observed outside the element; nevertheless, at $h_1 = 3\lambda$ for the longitudinal component of the electric field, the result improved by 13.6% at a comparable intensity value.

Conclusion

The simulation by the finite difference time domain method showed that a change in the height of subwavelength silicon elements significantly affects the diffraction pattern in the near zone. Diffractive axicons and annular gratings with different heights of individual grating rings were considered as such elements. The relief height of optical elements varied from 0.2λ to 3λ.

The Laguerre-superGaussian (1,0) modes with circular, radial, and azimuthal polarizations were considered as input laser radiation.

An analysis of the electric field intensity pattern showed that the smallest focal spot size was obtained for the diffractive axicon at $h = 2\lambda$: FWHM = 0.44λ (for the maximum) and 0.36λ (in the immediate vicinity of the element, at 65% of the total intensity). All main maxima for axicons were formed outside the optical elements. It should also be noted that as the height of the relief increases, a reduction in the length of the light needle of radiation is observed.

The results of numerical simulation for ring gratings with different heights showed that, in the general case, an increase in height leads to the formation of a maximum inside the element, however, at $h_1 = 3\lambda$ for the longitudinal component of the electric field, the result improved by 13.6% at a comparable intensity value (outside, near the edge of the element).

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