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The subwavelength optical elements with a nonlinear dependence of the refractive index change for the formation of specified diffraction patterns using high-performance computer systems

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Abstract. The diffraction of optical vortices with circular polarization by subwavelength optical microelements with a nonlinear dependence of the change in the refractive index of the substrate was investigated in this paper. The relief height of the elements was varied, as well as the direction of change in the refractive index of the substrate. It was shown that it was possible to obtain a focal spot 37.8% smaller than the focal spot formed by a standard diffractive axicon. It is also shown that it was possible to obtain a light segment 29.7% longer than the light segment formed by the diffractive axicon. It was also demonstrated that it was possible to form a series of optical traps for all considered types of substrates using the ring gratings with a relief height $h = 4.24\lambda$ without central zones._

Keywords: subwavelength focusing, optical vortices, FDTD, high performance computer systems, subwavelength ring gratings

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Материалы конференции
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Субволновые оптические элементы с нелинейной зависимостью изменения показателя преломления для формирования заданных дифракционных картин с использованием высокопроизводительных компьютерных систем

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Аннотация. В данной работе исследована дифракция оптических вихрей с круговой поляризацией на субволновых оптических микроэлементах с нелинейной зависимостью изменения показателя преломления подложки. Варьировалась высота рельефа элементов, а также направление изменения показателя преломления подложки. Показана возможность оптимизации высоты рельефа субволновых элементов таким образом, что наблюдалось формирование как узкой световой иглы, так и оптической ловушки.

Ключевые слова: субволновая фокусировка, оптические вихри, FDTD, высокопроизводительные компьютерные системы, субволновые кольцевые решетки_

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Introduction

Materials with a gradient refractive index (GRdient Index, GRIN) are used for communication [1–3], light collimation [1], in biology and medicine [2], and in other applications [3]. It is known that gradient photonic crystals can be used to control acoustic waves [4]. It is also known that metamaterials with a gradient refractive index are used to control the propagation of light in integrated photonic chips [5].

Optical vortices arouse considerable interest in the field of optics due to their special optical properties [6, 7], which can be used for advanced applications such as nonlinear optics [7], information transmission [8], high-order quantum entanglement [7], optical tweezers [9]. Optical vortices are known to solve problems of sharp focusing [11]. It should also be noted that optical vortices are used to form a reverse energy flow [10] using subwavelength axicons with different twist angles and metalens. The formation of a reverse flow using metalens has been demonstrated experimentally [11]. Also, the implementation of an optical trap using Hermite-Gauss beams and Laguerre-Gauss modes is known [6, 10].

Optical vortices are often generated using multi-order diffractive optical elements [12], spiral phase micro-plates, and axicons [13], including helical and twisted axicons. Metasurfaces are also known to generate optical vortices [11].

Respectively, the diffraction of optical vortices (3D) with circular polarization by subwavelength optical microelements with a nonlinear dependence of the change in the refractive index of the substrate is studied in this paper using high-performance computer systems. Two variants of these substrates were considered: an increase in the refractive index from the center to the edges and the reverse case. In addition, the change in the relief height of the ring gratings was considered at the same time. The solution was simulated numerically with the finite difference time domain method (FDTD).

Materials and Methods

The Laguerre–Gauss mode (1,0) with circular polarization was considered as the input laser radiation (the sign of the circular polarization is opposite to the sign of the introduced vortex phase singularity). The wavelength λ is equal to 0.532 μm (σ = 1.5).

The main modeling parameters: the size of the 3D computational region is 6 μm, the thickness of the PML absorbing layer is 0.6 μm. The absorbing layer surrounds the computing region from all sides. Spatial sampling step – $\lambda/20$, time step – $\lambda/(40c)$, where c is the speed of the light.

The lattice period of subwavelength ring gratings is equal to 1.05λ. The profiles of the considered subwavelength elements with the height of the relief $h = 1.06\lambda$ are shown in Fig. 1. The standard substrate (constant refractive index $n = 1.47$) and substrate with a nonlinear dependence of the change in the refractive index were considered. Such a variant of the substrate was called a quantized substrate (Q-substrate).

The refractive index of the Q-substrate varied from 1.47 to 2.7 (the thickness of the rings is the same and equal 0.7λ). The following values n were taken: 1.47, 1.74, 1.77, 1.98, 2.03, 2.17, 2.37, 2.7 (Fig. 1). The direct Q-substrate will be called the case of a change in the refractive index from the maximum in the center (n = 2.7) to the minimum at the edges (n = 1.47) of the element. The reverse case (the refractive index varies from a minimum in the center to a maximum at the edges) will be called the reverse Q-substrate. The results were compared with the action of a diffractive axicon of the same period (i.e. with a numerical aperture NA = 0.95) with a standard substrate at n = 1.47.

The height of the substrates was fixed and amounted to one wavelength. The relief refractive index for all elements was equal to 1.47. The height of the relief h (corresponding to the phase jump π radians) is equal to 1.06λ in this case.

It should be noted that the effect of the Q-substrate compared to the standard substrate should appear as the action of a collecting (at n = 2.7 at the center) and scattering (at n = 1.47 at the center) lenses. The size of the focal spot was estimated from the full width at half maximum (FWHM), the size of the longitudinal light segment was measured similarly, and will call such as depth of focus (DOF). The relief height h of optical microelements (Fig. 1) ranged from 1.06λ to 4.24λ in this paper.

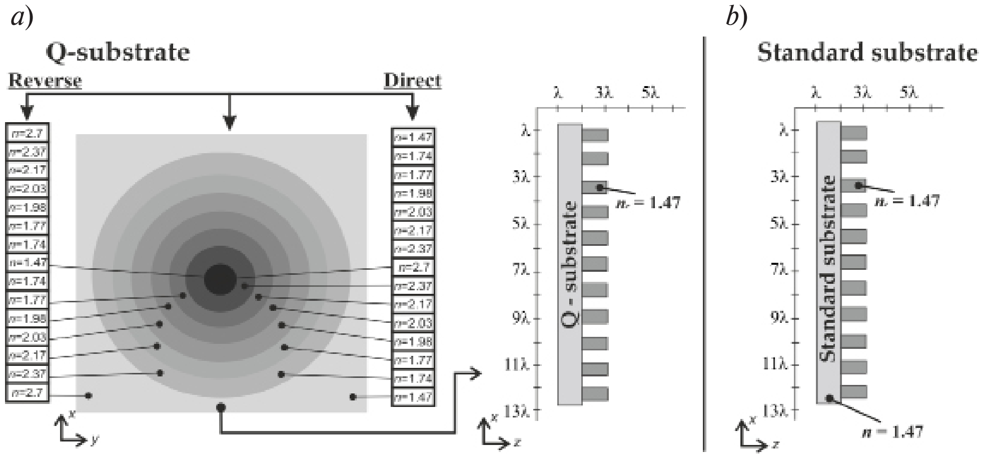

Fig. 1. Profiles of subwavelength optical microelements
with Q-substrate (a) and standard substrate, h = 1.06λ (b)

Results and Discussion

The diffraction of optical vortices on the subwavelength optical microelements with a standard and Q-substrate at different relief heights (from 1.06λ to 4.24λ) was researched in this section. The results of studies for the standard substrate, direct Q-substrate, and reverse Q-substrate are shown in Fig. 2. The FWHM values (in the main) are given for intensity peaks (maximums) outside of the elements.

The minimum focal spot for standard substrate was obtained for the case h = 4.24λ: FWHM = 0.48λ (intensity I = 100%), which is less than the focal spot formed by a standard diffractive axicon with a height h = 1.06λ by 35.1%.

An extended light needle on the optical axis for standard substrate is formed for the cases of relief heights h corresponding to odd phase jumps π and 3π radians: h = 1.06λ and h = 3.18λ, respectively. The longest light needle was obtained at a height of relief h = 3.18λ (DOF = 2.22λ), which was longer than the light needle obtained by a diffractive axicon with a height h = 1.06λ by 4.7%.

The influence of the direct Q-substrate appears in the formation of more distinct maxima on the optical axis. The maximum intensity peak on the optical axis is formed outside the element for the cases h = 1.06λ and h = 2.12λ. The main maxima for other cases (h = 3.18λ and h = 4.24λ) are formed inside the element and the values of FDTD and DOF are given for local maxima outside the element. It should be noted that with an increase in the height of the relief (Fig. 2), an increase in the number of local maxima on the optical axis is observed.

The minimum focal spot size for direct Q-substrate was obtained for the cases h = 4.24λ: FWHM = 0.46λ (I = 77.9%), which was less than the focal spot formed by a diffractive axicon with a standard substrate and with a height h = 1.06λ by 37.8%.

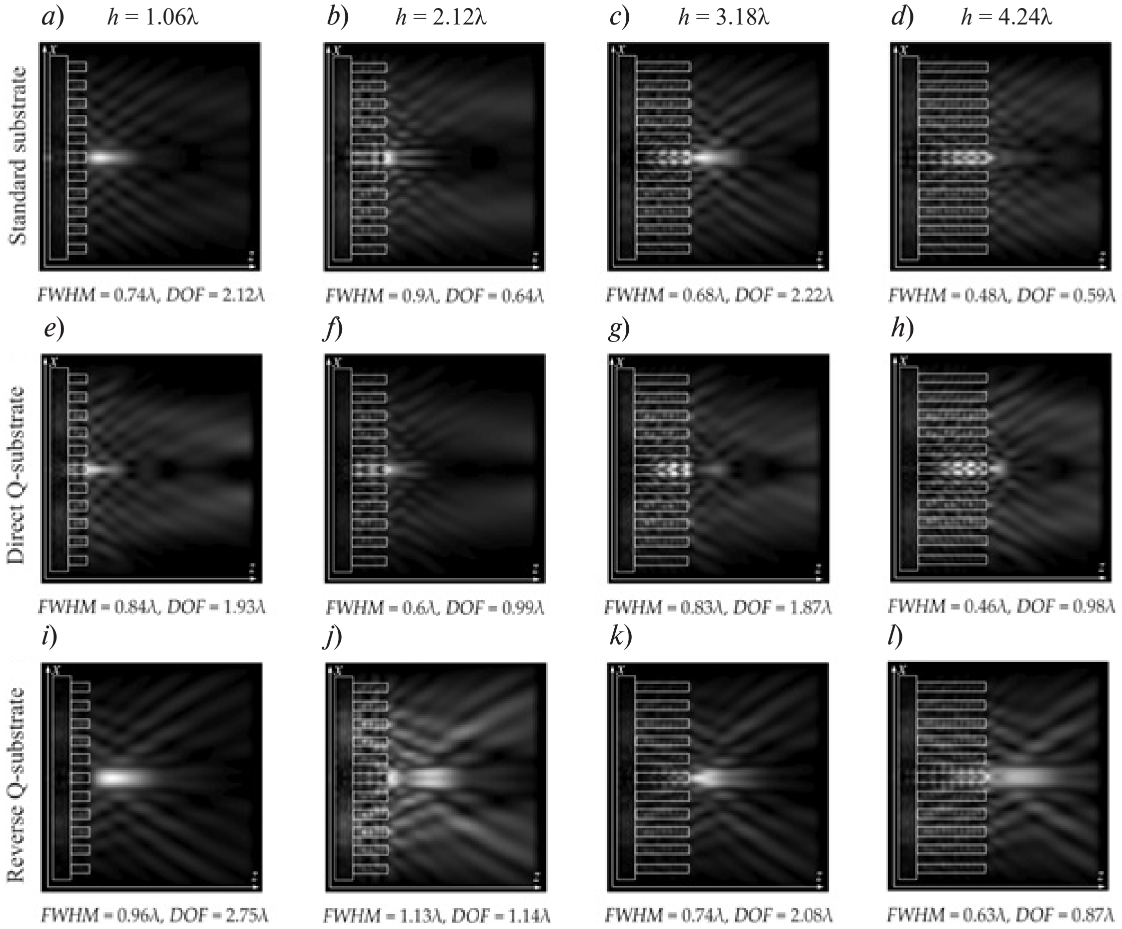

Fig. 2. Laguerre–Gaussian (1,0) modes diffraction on ring gratings (total intensity) with a standard substrate (*a*, *d*, *g*, *j*), direct Q-substrate (*b*, *e*, *h*, *k*), reverse Q-substrate (*c*, *f*, *i*, *l*)

The minimum value of the focal spot for a direct Q-substrate inside the element was obtained at a height h = 4.24λ FWHM = 0.3λ. It was obtained in the last local maximum (at a distance of 0.66λ from the edge of the relief).

All maxima for reverse Q-substrate were formed outside the relief of the elements. Also, the intensity oscillations were observed on the optical axis with the height increases (the maximum was always formed outside the relief in this case). The minimum of the focal spot was obtained for the case h = 4.24λ FWHM = 0.63λ, which was less than the focal spot formed by a diffractive axicon with a height h = 1.06λ and a standard substrate by 14.8%.

The best value of the light needle for reverse Q-substrate is 2.75λ, which was longer than the light needle formed by a diffractive axicon with a standard substrate and height h = 1.06λ by 29.7%.

It should be noted that narrower focal spot was formed inside the element than outside. The minimum focal spot values for the all substrate were obtained at a height h = 4.24λ. Let us fix this height and consider elements without central zones of the relief. The heights of individual relief zones were denoted as hi, $i \in [0, 5]$, where 0 is the center, 5 is the edge. Then the following cases will be considered (h = 4.24λ for the remaining zones): $h_0 = 0$; $h_0 = h_1 = 0$. The main maxima were formed outside the optical elements for all considered cases. The results are shown in Fig. 3.

The minimum focal spot was obtained for a direct Q-substrate at $h_0 = 0$, FWHM = 0.47λ. This result is comparable to the result for a direct Q-substrate with the same height of all zones (h_i = 4.24λ).

An extended light needle on the optical axis was formed for the case of the relief height $h_0 = 0$ for reverse Q-substrate (DOF = 3.2λ).

It should be noted that the formation of individual optical traps or their series was observed for all types of considered substrates.

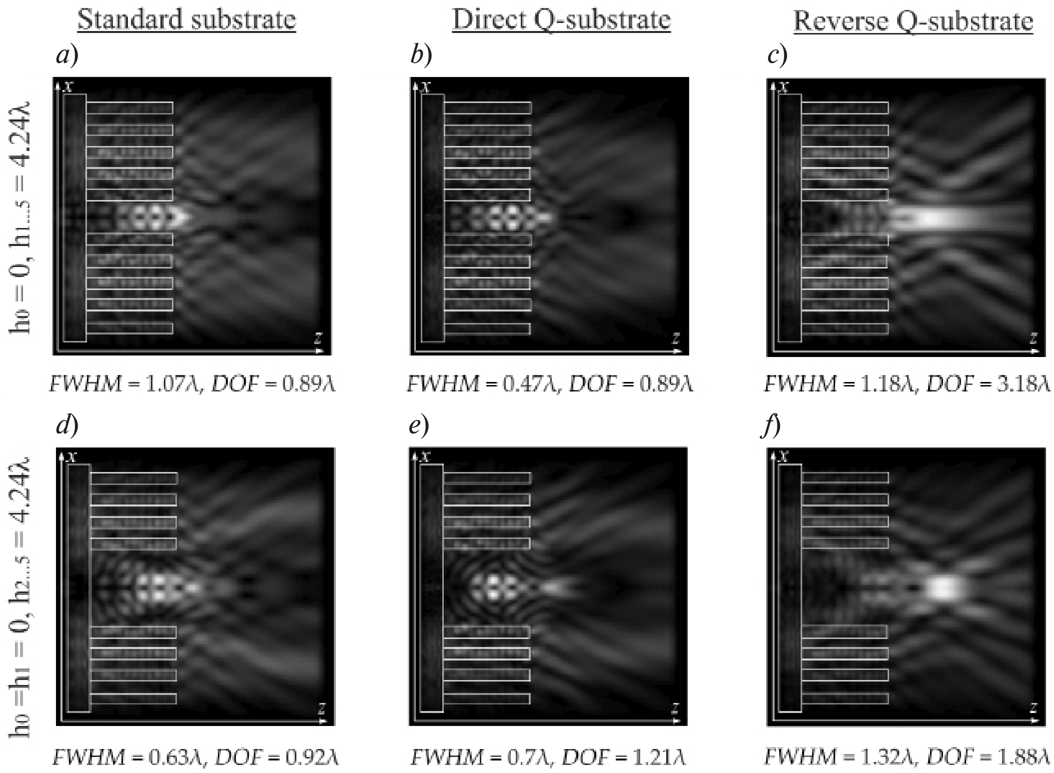

Fig. 3. Laguerre-Gaussian (1,0) modes diffraction on ring gratings without central zones with standard substrate (*a*, *d*), direct Q-substrate (*b*, *e*), reverse Q-substrate (*c*, *f*)

Conclusion

The finite difference time domain method was used in this paper to study the diffraction of the Laguerre-Gauss (1,0) modes on subwavelength ring gratings with variable height for a standard substrate, a direct Q-substrate and a reverse Q-substrate. The relief height of the ring gratings varied from 1.06λ to 4.24λ. A significant decrease in the size of the focal spot, the formation of an extended light segment, and the formation of a series of optical traps were shown for some cases.

An analysis of the electric field intensity pattern showed that the smallest focal spot at the maximum on the optical axis outside the element was obtained for a ring grating with a direct Q-substrate and a relief height h =4.24λ: FWHM = 0.46λ. This result was less than the focal spot formed by a diffractive axicon with standard substrate and with height h = 1.06λ by 37.8%.

The longest light needle (completely formed outside from the element) was obtained for the case of a ring grating with a reverse Q-substrate and a relief height h = 4.24λ, DOF = 2.75λ. This result was longer than the light needle obtained by a diffractive axicon with a standard substrate and with a height h = 1.06λ by 29.7%.

It was also demonstrated that it was possible to form both single optical traps and their series for the considered ring gratings with a relief height h = 4.24λ without central zones.

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