Conference materials
UDC 535.42
DOI: https://doi.org/10.18721/JPM.183.144

The investigation of Laguerre–Gaussian (0,1) mode focusing in the near-field diffraction by subwavelength variable-height ring gratings

D.A. Savelyev [1] ✉

[1] Samara National Research University, Samara, Russia

✉ savelev.da.2@ssau.ru

Abstract. The parameters of the height of individual zones of subwave ring gratings were established in this paper for which the formation of a long light needle (7.85 wavelengths) is observed in the near diffraction zone with azimuthal polarization of laser radiation. The possibility of reducing the focal spot size to 0.31 wavelengths with circular polarization of the Laguerre–Gauss mode (0,1) was also shown.

Keywords: Laguerre–Gaussian mode, optical needle, FDTD, subwavelength ring gratings, polarization

Funding: This research was funded by the Russian Science Foundation (project No. 24-22-00044), https://rscf.ru/en/project/24-22-00044/).

Citation: Savelyev D.A., The investigation of Laguerre–Gaussian (0,1) mode focusing in the near-field diffraction by subwavelength variable-height ring gratings, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 18 (3.1) (2025) 222–225. DOI: https://doi.org/10.18721/JPM.183.144

Материалы конференции
УДК 535.42
DOI: https://doi.org/10.18721/JPM.183.144

Исследование фокусировки мод Лагерра–Гаусса (0,1) в ближней зоне дифракции субволновыми кольцевыми решетками переменной высоты

Д.А. Савельев [1] ✉

[1] Самарский национальный исследовательский университет имени академика С.П. Королёва, г. Самара, Россия

✉ savelev.da.2@ssau.ru

Аннотация. В работе установлены параметры высоты отдельных зон субволновых кольцевых решеток, для которых в ближней зоне дифракции наблюдается формирование длинной световой иглы (7,85 длин волн) при азимутальной поляризации лазерного излучения. Также показана возможность уменьшения размера фокального пятна до 0,31 длин волн при круговой поляризации моды Лагерра–Гаусса (0,1).

Ключевые слова: мода Лагерра–Гаусса (0,1), оптическая игла, FDTD, субволновая кольцевая решетка, поляризация

Финансирование: Работа выполнена при финансовой поддержке Российского научного фонда (проект № 24-22-00044, https://rscf.ru/project/24-22-00044/).

Ссылка при цитировании: Савельев Д.А. Исследование фокусировки мод Лагерра–Гаусса (0,1) в ближней зоне дифракции субволновыми кольцевыми решетками переменной высоты // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.1. С. 222–225. DOI: https://doi.org/10.18721/JPM.183.144

Introduction

It should be noted that with the development of optical technologies, it has become necessary to form structured optical fields with certain characteristics of phase, amplitude, and polarization [1–3]. Such structured laser beams find application in such areas as data processing [4], creation of three-dimensional images [5], optical manipulation [6], tight focusing [7], formation of optical needles [8] and others. It should be noted that laser beams with phase and polarization singularities [9] have become widely used to solve problems of modern photonics. Their formation is possible using various optical structures, among which are metasurfaces [5, 10], diffractive optical elements [11] and ring gratings [12].

In this paper, the finite difference time domain (*FDTD*) method is used to study the optimization of the height of individual zones of subwavelength ring gratings to form a long light needle. The numerical calculations of the Laguerre–Gaussian (0,1) modes propagation in the near diffraction zone (3*D*) are carried out using high-performance computer systems.

Materials and Methods

The numerical simulation by the *FDTD* method was carried out with the following parameters: the size of the 3*D* region surrounded on all sides by the absorbing *PML* layer was 18λ, the *PML* thickness was 1.1λ, λ = 0.532 μm. The following simulation steps were considered: the time step was λ/(100c), where c is the speed of light, and the spatial step was λ/50.

The ring gratings with a period of 1.05λ were used, in this elements the relief height varied in accordance with the phase of π radians. The refractive index of the relief n was chosen to be 2.46, and the refractive index of the substrate was 1.46. Then, the relief height is:

$$h = \frac{\pi}{k(n-1)} = 0{,}34\lambda, \tag{1}$$

where $k = 2\pi/\lambda$ is the wave number. The height of individual zones of the grating relief changed in multiples of this value.

The Laguerre–Gaussian mode (0,1) with circular and azimuthal polarizations was considered as the input beam. The sign of the circular polarization was chosen to be opposite to the sign of the vortex phase singularity in order to maximize the intensity value on the optical axis.

The assessment of the formed light segment on the optical axis in the transverse region was determined by the full width at half maximum (*FWHM*) intensity value on the optical axis, and similarly in the longitudinal region (depth of focus – *DOF*).

Results and Discussion

A diffraction axicon with a height of $h = 0.34\lambda$ was used as a standard element for comparison (Fig. 1, *a*, *e*). Also a diffraction patterns in the case of a simultaneous increase in the height of all relief zones are shown in Fig. 1, which led to a reduction in the size of the light needle for azimuthal polarization and its slight increase for circular polarization. Also it should be noted that the focal spot broadened for circular polarization.

Let us move on to changing the size h_i of individual zones of the ring gratings relief. The following cases of changing the height of the relief rings were considered (Fig. 2): with a step of 0.34λ (π), from the minimum height in the center ($h_1 = 0.34\lambda$) to the maximum height at the edge of the element ($h_8 = 2.72\lambda$); a similar change in height, but with the height of even elements $h_2 = h_4 = h_6 = h_8 = 0$ ($h_1 = 0.34\lambda$, $h_3 = 1.02\lambda$, $h_5 = 1.7\lambda$, $h_7 = 2.38\lambda$); the case when the height of

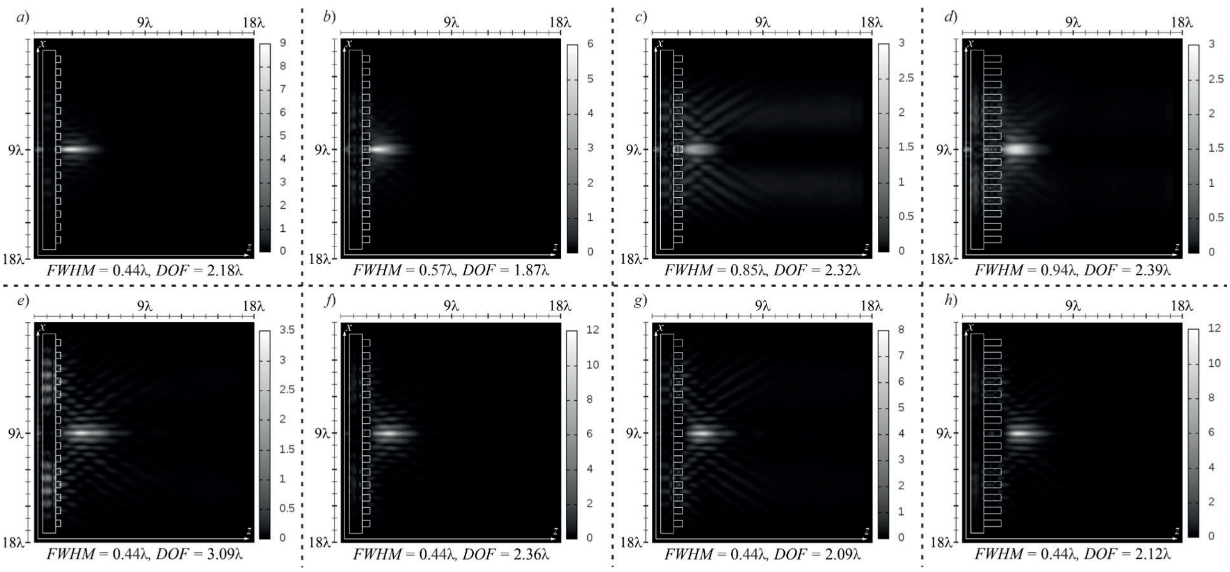

Fig. 1. Laguerre–Gaussian mode (0,1) diffraction, intensity, (*a–d*) circular polarization and (*e–h*) azimuthal polarization: (*a*, *e*) $h = 0.34\lambda$, (*b*, *f*) $h = 0.51\lambda$, (*c*, *g*) $h = 0.68\lambda$, (*d*, *h*) $h = 1.36\lambda$

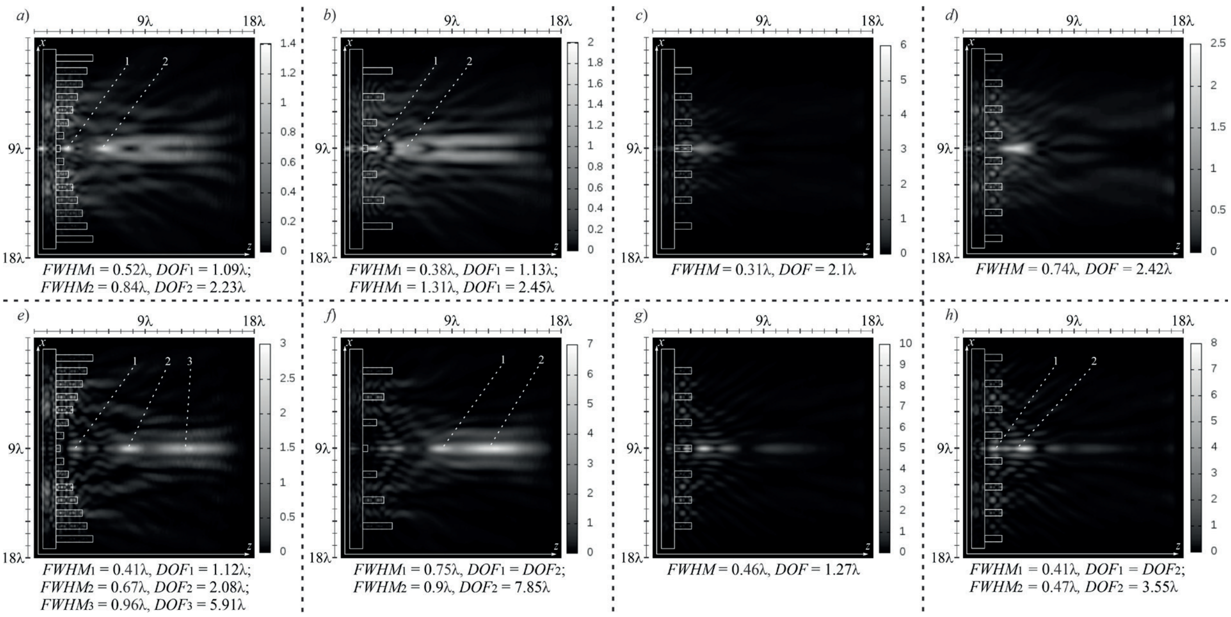

Fig. 2. Laguerre–Gaussian mode (0,1) diffraction, intensity, (*a–d*) circular polarization and (*e–h*) azimuthal polarization: (*a*, *e*) $h_1 = 0.34\lambda$, $h_2 = 0.68\lambda$, $h_3 = 1.02\lambda$, $h_4 = 1.36\lambda$, $h_5 = 1.7\lambda$, $h_6 = 2.04\lambda$, $h_7 = 2.38\lambda$, $h_8 = 2.72\lambda$; (*b*, *f*) $h_1 = 0.34\lambda$, $h_3 = 1.02\lambda$, $h_5 = 1.7\lambda$, $h_7 = 2.38\lambda$, $h_2 = h_4 = h_6 = h_8 = 0$; (*c*, *g*) $h_1 = h_3 = h_5 = h_7 = 1.36\lambda$, $h_2 = h_4 = h_6 = h_8 = 0$; (*d*, *h*) $h_1 = h_3 = h_5 = h_7 = 0$, $h_2 = h_4 = h_6 = h_8 = 1.36\lambda$

the odd zones was the same ($h_1 = h_3 = h_5 = h_7 = 1.36\lambda$), and the height of the even zones was 0, and also the opposite case ($h_2 = h_4 = h_6 = h_8 = 1.36\lambda$, and the height of odd zones is 0).

The required distribution on the optical axis can be formed by selecting the heights of individual relief zones. The formation of a long light needle, a set of optical bottles, and a sharply focused beam are shown in Fig. 2.

It should be noted that the reduction in the number of ring gratings relief zones made it possible to increase the size of the light needle in the case of azimuthal polarization (Fig. 2, *e*, *f*), and a significant reduction in the size of the focal spot is observed for circular polarization: from *FWHM* = 0.52λ to *FWHM* = 0.38λ (Fig. 2, *a*, *b*) in the case of changing all relief zones, as well as from *FWHM* = 0.94λ to *FWHM* = 0.31λ in the case of the same height of the remaining non-zero relief zones (Fig. 1, *d*; Fig. 2, *c*).

The smallest focal spot size was $FWHM = 0.31\lambda$, and the longest light needle was $DOF = 7.85\lambda$, which was 2.54 times larger than the light needle formed by a standard diffractive axicon with $h = 0.34\lambda$. Experiments have shown that using electron-beam lithography it is possible to produce similar elements (with different heights of individual relief rings).

Conclusion

The numerical simulation using the *FDTD* method showed that it is possible to optimize the height of individual zones of ring gratings to obtain the required distribution on the optical axis in the near diffraction zone.

The parameters have been established at which the size of the formed light segment is maximum ($DOF = 7.85\lambda$): the height of even zones is zero, and the height of odd zones of the element increases from the center to the edges ($h_1 = 0.34\lambda$, $h_3 = 1.02\lambda$, $h_5 = 1.7\lambda$, $h_7 = 2.38\lambda$) with azimuthal polarization of the Laguerre–Gaussian mode (0,1). The minimum size of the focal spot ($FWHM = 0.31\lambda$) was also obtained at zero height of even zones and $h_1 = h_3 = h_5 = h_7 = 1.36\lambda$ with circular polarization of the laser radiation.

REFERENCES

1. **Shen Y., Nape I., Yang X., Fu X., Gong M., Naidoo D., Forbes A.,** Creation and control of high-dimensional multi-partite classically entangled light, Light: Science & Applications. 10 (1) (2021) 50.
2. **Dorrah A.H., Capasso F.,** Tunable structured light with flat optics, Science. 376 (6591) (2022) 6860.
3. **Rosales-Guzmán C., Ndagano B., Forbes A.,** A review of complex vector light fields and their applications, Journal of Optics. 20 (12) (2018) 123001.
4. **Angelsky O.V., Bekshaev A.Y., Hanson S.G., Zenkova C.Y., Mokhun I.I., Zheng, J.,** Structured light: ideas and concepts, Frontiers in Physics. 8 (2020) 114.
5. **Choi E., Kim G., Yun J., Jeon Y., Rho J., Baek S.H.,** 360 structured light with learned metasurfaces, Nature Photonics. 18 (8) (2024) 848–855.
6. **Yang Y., Ren Y.X., Chen M., Arita Y., Rosales-Guzmán C.,** Optical trapping with structured light: a review, Advanced Photonics. 3 (3) (2021) 034001.
7. **Ke L., Yang Y., Zhu M., Zhou H., Chen Y., Tian Y., Li C., Fang B., Hong Z., Jing X.,** Tight focusing of fractional-order topological charge vector beams by cascading metamaterials and metalens, Microsystems & Nanoengineering. 10 (1) (2024) 146.
8. **Savelyev D.A.,** The optical needles formation by ring gratings of variable height with quantized substrate [in Russian], Opticheskii Zhurnal. 92 (5) (2025) 12–25.
9. **Porfirev A.P., Kuchmizhak A.A., Gurbatov S.O., Juodkazis S., Khonina S.N., Kulchin Y.N.,** Phase singularities and optical vortices in photonics, Phys. Usp. 192 (8) (2022) 841–866.
10. **Ahmed H., Kim H., Zhang Y., Intaravanne Y., Jang J., Rho J., Chen S., Chen X.,** Optical metasurfaces for generating and manipulating optical vortex beams, Nanophotonics. 11 (5) (2022) 941–956.
11. **Khonina S.N., Kazanskiy N.L., Skidanov R.V., Butt M.A.,** Advancements and applications of diffractive optical elements in contemporary optics: A comprehensive overview, Advanced Materials Technologies. 10 (4) (2025) 2401028.
12. **Savelyev D.A.,** Peculiarities of focusing circularly and radially polarized super-Gaussian beams using ring gratings with varying relief height, Computer Optics. 46 (4) (2022) 537–546.

THE AUTHORS

SAVELYEV Dmitry A.
dmitrey.savelyev@yandex.ru
ORCID: 0000-0003-2282-3895

Received 14.08.2025. Approved after reviewing 18.08.2025. Accepted 19.08.2025.