Bessel beams formation by hybrid axicons

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Abstract. We present a new type of diffractive optical elements (DOE) – hybrid axicons. The process of formation of identical intensity distributions in focus by different hybrid axicons on the example of Bessel beams is shown. The beams order is determined by the sum of the topological charges of the phase plate (structure charge) and the spiral axicon (zone charge). The results of mathematical modeling of light diffraction on hybrid axicons are presented.

1. Introduction

Bessel beams were discovered in 1987 [1,2]. Bessel beams can be generated by a diffraction vortex axicon [3], an amplitude digital hologram [4-7], a phase DOE [8, 9], a spatial light modulator [10].

As shown in [11], the vortex axicon forms Bessel beams with maximum efficiency. However, in all the works devoted to the experimental formation of Bessel beams, a space-limited approximation of the Bessel beam is formed during propagation in a short length. Before the formation of the Bessel beam form the light distribution in the near region can be quite irregular [12].

In this paper, we consider the structure of a new type of diffractive optical elements — hybrid axicons, in which the axicon structure of the axicon is combined with the dependence of the phase on the polar angle of the phase plate. The topological charge of the phase plate is added to the topological charge of the axicon. Thus, it became possible to form identical Bessel beams with different hybrid axicons.

The paper presents the process of propagation of a light beam formed by a hybrid axicon in the Fresnel diffraction zone until the Bessel beam is formed. It is shown that the shape of the beams before the formation of the Bessel beam is substantially different.

2. Hybrid axicons

The diffraction spiral axicon is described by the complex transmission function of the following form:

\[ \tau(r, \phi) = \exp(i2\pi rv)\exp(in\phi), \]

where \( r, \phi \) are polar coordinates in the axicon plane, \( v \) is a spatial frequency of the axicon's lines, and \( n \) is the number of the vortex component. When illuminated by laser light, the vortex axicon forms an \( n \)-th order Bessel beam \( J_n(\alpha r) \), where \( \alpha = k \cos(\nu \lambda) \) (\( k \) is the wavenumber).

Based on a multilevel spiral axicon, it is possible to form a hybrid axicon, the phase function of which is described by the formula (2):
where \( m \) is the number of the additional vortex component; \( r, \varphi \) are polar coordinates; \( \varphi_0 \) is the phase shift in the zone; \( \nu \) is the spatial carrier frequency; \( n \) is the topological charge of the binary diffractive axicon that forms the basis of the DOE structure and determines the shape of the zones; \( \delta \) is the Kronecker symbol; \( M \) is the number of quantization levels; \( C_m \) is the topological charge in the \( m \)-th zone; \( \lfloor \cdot \rfloor \) is the integer part of a real number. Hybrid axicons based on a binary axicon with the same topological charge of the zones and the zones shift at the polar angle \( \varphi_0 \) are considered in this paper.

### 3. The process of forming bessel beams by hybrid axicons

As shown in [13] Bessel beams can be formed by elements of different structure. Figure 1 shows the phases of hybrid axicons (Figure 1a, b), which form a Bessel beam of the 1st order (Figure 1b, d).

![Figure 1. Hybrid axicons phases (a, b) forming the 1st order Bessel beam (c, d) with topological charges: a) \( n = 2, m_1 = m_2 = m = -1, \varphi_0 = 180 \), b) \( n = 3, m_1 = m_2 = m = -2, \varphi_0 = 90 \).](image)

Hybrid axicons form the same beam only in a small range of distances. The process of beam propagation closer to the element looks substantially different.

We carried out diffraction simulation using Fresnel transform. Figure 2 shows the formation of Bessel beams by a hybrid axicon with topological charges \( n = 2, m_1 = m_2 = m = -1, \varphi_0 = 180 \) at a distance from 0.2 m to 1 m.

For comparison, Figure 3 shows the Bessel beams formation by the hybrid axicon with topological charges \( n = 3, m_1 = m_2 = m = -2, \varphi_0 = 90 \) on the same length.

Figures 1 and 2 show that the beams formation is different. The same Bessel beam is formed only in a limited area, which can be used for optical capture and rotation of micro-objects. The presence of several maxima in the defocused beam greatly simplifies the capture of micro-objects, and precise focusing places the micro-objects into the Bessel beam for subsequent rotation.
Figure 2. Bessel beams formation by the hybrid axicon with topological charges $n = 2$, $m_1 = m_2 = m = 1$, $\phi_0 = 180$ at different distances: a) 0.2 m; b) 0.3 m; c) 0.4 m; d) 0.5 m; e) 0.6 m; f) 0.7 m; g) 0.8 m; h) 0.9; i) 1 m.

Figure 3. Bessel beams formation by the hybrid axicon with topological charges $n = 3$, $m_1 = m_2 = m = -2$, $\phi_0 = 90$ at different distances: a) 0.2 m; b) 0.3 m; c) 0.4 m; d) 0.5 m; e) 0.6 m; f) 0.7 m; g) 0.8 m; h) 0.9; i) 1 m.
4. Conclusions
We considered a simulation of the process of light propagation during diffraction on hybrid axicons. In the near diffraction region, substantially different intensity distributions are formed. Despite this, there is an interval of distances from the hybrid axicon, where almost identical Bessel beams are formed. The topological charge of the formed Bessel beams consists of the topological charges of the structure and separate zones of the hybrid axicon.

5. References
[1] Durnin J 1987 Exact solution for nondiffractive beams I The scalar theory Journal of the Optical Society of America A 4(4) 651-654
[2] Durnin J, Miceli J J and Eberly J H 1987 Diffractive-free beams Physical Review Letters 58(15) 1499-1501
[3] Khonina S N, Kotlyar V V, Skidanov R V, Soifer V A, Jefimovs K, Simonen J and Turunen J 2004 Rotation of microparticles with Bessel beams generated by diffractive elements Journal of Modern Optics 51(14) 2167-2184
[4] Paranin V D, Karpeev S V, Kazanskiy N L and Krasnov A P 2016 Converter of laser beams with circular polarization to cylindrical vector beams based on anisotropic crystals Proceedings of SPIE 9807 98070R DOI: 10.1117/12.2234831
[5] Turunen J, Vasara A and Friberg A T 1988 Holographic generation of diffractive-free beams Applied Optics 27(19) 3959-3962
[6] Vasara A, Turunen J and Friberg A T 1989 Realization of general non-diffracting beams with computer-generated holograms Journal of the Optical Society of America A 6(11) 1748-1754
[7] Lee H S, Stewart B W, Choi K and Fenichel H 1994 Holographic nondiverging hollow beam Physical Review A 49(6) 4922-4927
[8] Paakkonen P, Lautanen J, Honkanen M, Kuitiinen M, Turunen J, Khonina S N, Kotlyar V V, Soifer V A and Friberg A T 1998 Rotating optical fields: experimental demonstration with diffractive optics Journal of Modern Optics 45(11) 2355-2369
[9] Khonina S N, Kotlyar V V, Soifer V A, J Lautanen J, Honkanen M and Turunen J 1999 Generating a couple of rotating nondiffracting beams using a binary-phase DOE Optik 110(3) 137-144
[10] Devis J A, Carcole E and Cottrell D M 1996 Intensity and phase measurements of nondiffracting beams generated with a magneto-optic spatial light modulator Applied Optics 35(4) 593-598
[11] Fedotowsky A, Lehnovec K 1974 Optimal filter design for annular imaging Applied Optics 13(12) 2919-2923
[12] Stafeev S S, O'Faolain L and Kotlyar M V 2018 Rotation of two-petal laser beams in the near field of a spiral microaxicon Computer Optics 42(3) 385-391 DOI: 10.18287/2412-6179-2018-42-3-385-391
[13] Skidanov R V, Ganchevskaya S V 2014 Formation of Bessel beams by vortex axicons Computer Optics 38(3) 463-468

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