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Spiral and Subwavelength Binary Axicons of Terahertz Range

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INTRODUCTION

Historically, the first mention of the optical element axicon is associated with McLeod's work [1], so originally it was a refractive optical element (a glass cone) [1]. In classical optics, axicons are used to generate beams with an extended focal length, nondiffractive Bessel beams [2-4]. Refractive conic axicons provide high energy efficiency and low chromatic dependence; however, fabrication of refractive axicons is associated with certain difficulties due to the lack of simple methods of control and certification of conical surfaces [5]. Moreover, refractive axicons have the numerical aperture limited by the angle of total internal reflection [6], therefore, with a decrease in the angle of the axicon at the apex, instead of the formation of the Bessel beam, other effects arise [7]. Diffractive axicons are easier to realize by tools of diffractive optics [8], spatial light modulators [9]. In particular, binary axicons, which are in essence circular gratings [10, 11], can be realized with high precision using circular laser writing systems (CLWS) [12]. Although diffractive optical elements (DOEs) are characterized by significant chromatic dispersion and are used for monochromatic radiation, they have greater functionality than refractive elements. In particular, a wide variety of diffractive axicons with additional properties are known: vortex axicons to generate vortex Bessel beams of nonzero orders [13-15] or helical photonic nanostructures [16], bi-axicons to enhance the longitudinal component of the electric field with sharp focusing of the linearly polarized field [17, 18], composite axicons for the formation nondiffracting hollow optical beams with polygon contour intensity distribution [19, 20] or with spiral intensity [21] for optical manipulation and laser surface structuring.

In this paper, we consider the calculation, modeling, fabrication, and experimental study of silicon axicons for the formation of Bessel beams in the terahertz range. Theoretical analysis and results of numerical simulation of axially symmetric axicons [10, 11], as well as axicons with spiral zones [13-15] which make it possible to form Bessel beams with orbital angular momentum (OAM) from an illuminating Gaussian beam, are presented.

In [15], the results of the fabrication and experimental study of terahertz silicon axicons with spiral zones are presented. A binary micro-relief was fabricated via single reactive-ion etching of silicon substrate via technology previously used in [22].The Novosibirsk free electron laser NOVOFEL [23] was used as a source of coherent terahertz radiation. The results of experiments in [15] are in good agreement with the results of computer simulation. It was experimentally shown [15] that the formed Bessel beams exhibit the properties of "diffraction-free beams" at a certain distance, after which they begin to diverge. In addition, the existence of the self-healing property of terahertz laser beams with orbital angular momentum in free space after passing through an inhomogeneous medium has been shown experimentally [24]. This property is of interest for creating promising lidar and telecommunication systems [25].

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However, the elements described in [15] have a period much larger than the wavelength of the illuminating beam. Therefore, elements [15] are designed to control only the transverse modal content of the generated beams without changing the polarization state of the radiation. At the same time, further development of lidar and telecommunication systems requires the possibility of simultaneous control of the transverse modal content and polarization state of the beams used. In work [26], the results of theoretical analysis and computer modeling of subwavelength axicons are presented - that is, axicons with a period significantly less than the wavelength of the illuminating radiation. In work [26] it was shown, in particular, that the use of a radially symmetric subwavelength axicon makes it possible to form a Bessel beam with a radially symmetric polarization of the second order. The work [27] presents the results of the calculation, fabrication, and experimental study of a subwavelength silicon axicon of the terahertz range. Based on the results of a full-scale experiment, it was shown that the use of a subwavelength silicon axicon makes it possible to form a Bessel beam with a second-order radial polarization from an illuminating Gaussian beam [27, 28]. Thus, the use of silicon diffractive optical elements in the terahertz range with different ratios between the period and wavelength makes it possible to control both the transverse modal content of the formed beam and the transverse modal content and polarization simultaneously.

FABRICATION AND INVESTIGATION OF TERAHERTZ BINARY AXICONS

Binary spiral axicons, the results of which are shown in works [13-15] were calculated using the approach proposed in [29, 13]. In [15, 30], it was shown that the use of spiral axicons allows the formation of Bessel beams with orbital angular momentum from an illuminating Gaussian beam. It was assumed that the period of the spiral axicon is much larger than the wavelength of the illuminating radiation. Therefore, the methods of scalar diffraction theory [8, 29] were used to analyze the operation of such axicons. Figure 1 shows the calculated binary phase functions of axicons designed to form beams with orbital angular momentum with a topological charge of l = 3,4 (black color corresponds to the value of phase 0, the white color corresponds to the value of phase π).

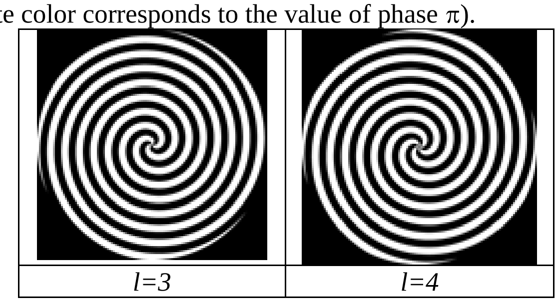

Fig.1. Binary phase of axicons designed to form a beam with orbital angular momentum with a topological charge l (l=3,4)

The results of fabrication and experimental study of silicon spiral binary axicons intended for formation from illuminating powerful Gaussian beam of terahertz free electron laser of Bessel beams with a given value of topological charge are shown in [15]. To produce a binary diffractive microrelief on the surface of the silicon substrate corresponding to the binary phase function of the spiral axicon, [15] used a single reactive-ion etching technique of the silicon substrate using the Bosch process, previously used in [22]. Elements (Fig.2), the results of the study (for $|l|$=1, $|l|$=2) of which are given in [15] had the following parameters: calculated wavelength λ=141 µm, period of radial-symmetrical structure d = 3.1 mm, microrelief height h = 29.1 µm.

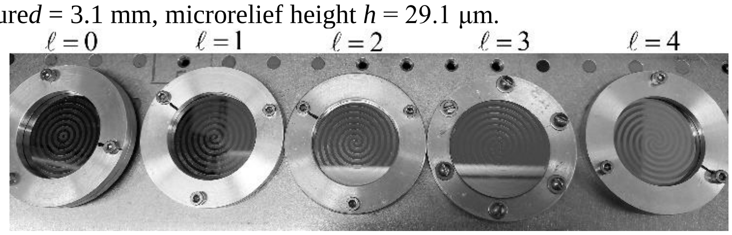

Fig.2. Photo of fabricated axicons designed to form a beam with orbital angular momentum with topological charge l (l=0-4)

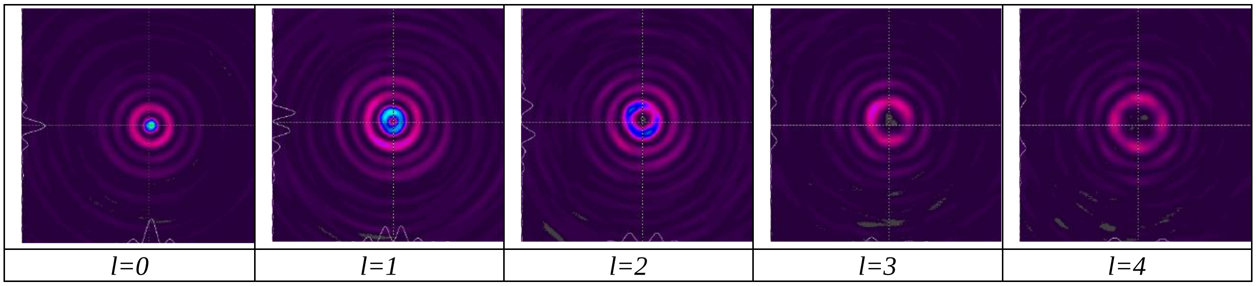

Fig.3. Bessel beams with orbital angular momentum with topological charge *l* (*l* = 0-4), formed by made binary spiral axicons

As a source of powerful terahertz coherent radiation, the Novosibirsk free electron laser NovoFEL [23] was used in work [15]. The results of optical experiments demonstrate good mutual agreement with the results of the computer simulation [15].The ability of spiral binary axicons to form Bessel beams of the terahertz range with orbital angular momentum with a given topological charge was experimentally shown. The control of the transverse modal content of coherent terahertz beams is of great importance for the development of promising lidar and telecommunication systems of the terahertz range.The results of the study of the propagation of terahertz beams with orbital angular momentum, formed with the help of manufactured spiral binary axicons, in inhomogeneous media are shown in [24].The ability of terahertz coherent beams with orbital angular momentum to self-healing in free space after passing through a heterogeneous medium is experimentally shown, which is of great importance for the developing of lidar systems. Previously, transverse mode division multiplexing (MDM) using diffractive optical elements was considered in telecommunication systems of optical range [31-33].The experimental results of the study of the possibility of using terahertz beams with orbital angular momentum with a given topological charge for the design of telecommunication multi-channel systems with transverse mode multiplexing of communication channels are shown [30]. The experimental model [30] of a two-channel terahertz communication system based on the formation and selection of orbital angular momentum beams using binary spiral axicons [15] was demonstrated. However, [15, 24, 30] refers only to the control of the transverse modal content of the beam being formed without changing the polarization state of the beam. The prospects for further improving the capabilities of telecommunication systems by simultaneously controlling the transverse modal content and polarization state of the beams to be formed are shown in [34-36].

The results of design, manufacture, and study of a radial binary axicon of the terahertz range with a subwavelength period (radial symmetric structure period d = 60 μm, microrelief height h = 50 μm, wavelength λ=129 μm) is shown [27, 28]. The binary subwavelength silicon axicon [27,28] was also made by reactive ion etching (RIE).

Images of the central fragment of the manufactured subwavelength binary axicon [27], obtained using scanning electron microscopy, are given in Fig. 4.

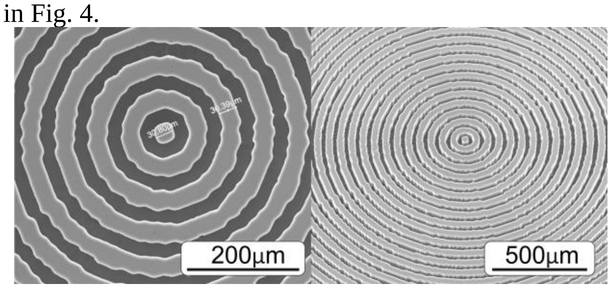

Fig. 4. Images of the central fragment of the manufactured subwavelength axicon obtained using scanning electron microscopy

Figure 5 shows a photo of the manufactured element.

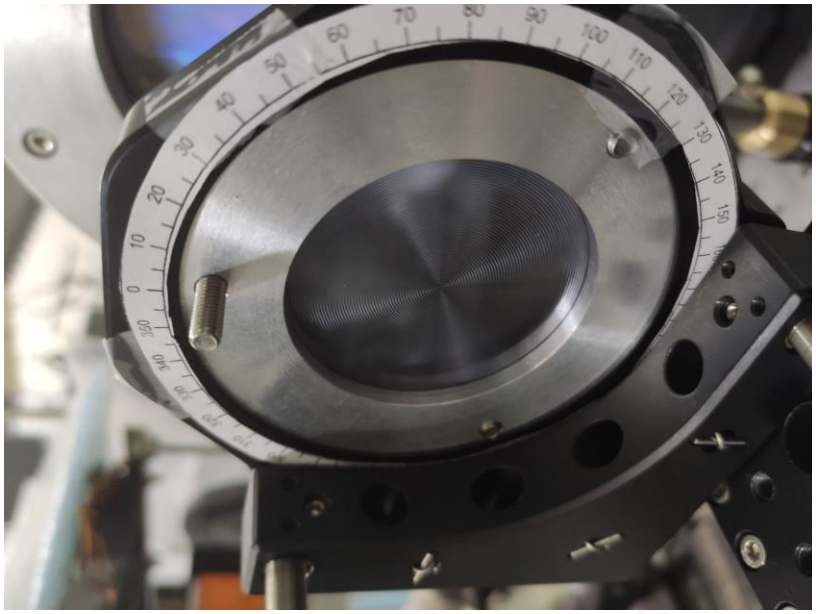

Fig.5. Photo of the manufactured subwavelength axicon

The results of numerical modeling demonstrating the ability of a subwavelength binary radial-symmetric axicon to convert a linearly polarized laser beam into a Bessel beam with a radial polarization of the 2nd order is considered in [37].The results of the experimental study of the manufactured subwavelength binary silicon axicon are considered. As a radiation source, the terahertz Novosibirsk free electron laser NOVOFEL was used [23]. During experiment [27,28] polarization state of the formed beam was investigated. Figure 6 shows results of measurement of the intensity of beam [28] formed by subwavelength axicon for different angles of polarizer rotation installed after axicon illuminated by the linearly polarized beam of terahertz laser.

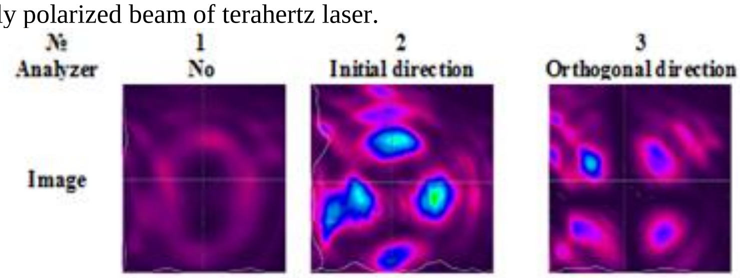

Fig.6. Results of intensity measurement in beam cross-section for different angle of polarizer rotation installed after subwavelength axicon illuminated by linearly polarized radiation of terahertz laser [28]

The results of numerical and natural experiments [27,28] are in good mutual correspondence and demonstrate the ability of a subwavelength binary radial-symmetric axicon to convert a linearly polarized laser beam into a Bessel beam with radial polarization of the 2nd order. Thus, axicons with a subwavelength period allow controlling not only the transverse modal content of the formed beam but also its polarization state.

CONCLUSION

Thus, the use of silicon binary diffractive optical elements allows (depending on the ratio of the structure period and wavelength) both to control the transverse modal content of the terahertz beam being formed (including the possibility of forming a beam with orbital angular momentum with a given topological charge) and the transverse modal content and polarization state simultaneously.

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