Silicon subwavelength axicons for terahertz beam polarization transformation

V S Pavelyev¹, S A Degtyarev¹, K N Tukmakov¹, A S Reshetnikov¹, B A Knyazev¹, Yu Yu Choporova¹

¹Samara National Research University, Moskovskoe Shosse 34A, Samara, Russia, 443086

Abstract. The diffractive optical element (DOE) for transforming of linearly polarized THz radiation beam into a cylindrically polarized beam is investigated. Optimal diffractive microrelief height is determined by numerical simulation.

1. Introduction

The development of new sources in the terahertz range, including the powerful ones, such as free-electron lasers (FEL) [1], requires creating the elements to control the beams of such radiation. The works [2–7] are devoted to the development of elements of diffraction optics in the terahertz range. In many applications, diffractive optical elements (DOEs) were used to focus the terahertz laser beam [2–5], in other applications, they were used to control the transverse-mode composition of the beam [6–7]. The results of the study of silicon binary elements intended for the formation of Hermite–Gaussian, Laguerre–Gaussian, and Bessel single-mode beams from the illuminating beam of a high-power free-electron terahertz laser are presented in the works [6–7]. However, in [6, 7] it was only a question of changing the transverse mode composition without changing the polarization state of the illuminating beam. At the same time, some relevant applications of laser radiation require to control the transverse-mode composition and polarization state of the beam simultaneously [8]. Such applications are lidars [9], telecommunication systems [10–13], laser processing of materials [14–16], and material microstructuring [17, 18], problems of super-resolution [19–23] and excitation of plasmon waveguides [24]. The work [25] shows the results of the feasibility study of organizing a multichannel terahertz communication system based on controlling the transverse-mode composition of a coherent beam of terahertz radiation. The approach to the formation of terahertz radiation beams with a given transverse mode composition and a given polarization state described in [26] and based on the use of the Mach-Zander interferometer is quite complicated to implement. There are works on controlling the polarization state of a coherent beam in the optical range using subwavelength diffractive optical elements [27–29]. In the work [30], the authors designed, produced, and examined a diffractive optical element for converting linearly polarized terahertz radiation into a cylindrically polarized beam – a subwavelength axicon.

2. Design, simulation, and fabrication of a subwavelength axicon

The results of studies of optical diffractive axicons are provided in the works [31–39]. It was shown earlier [29] that the subwavelength axicon can be used to convert a linearly polarized beam into a second-order radially polarized beam. In the works [29, 35, 36], it was shown that the beams with this...
type of polarization ensure the efficient formation of reverse energy flow in the focal region in case of linear focusing. In the work [30], the authors performed a numerical simulation of the propagation of a Gaussian beam through a subwavelength silicon axicon with the design parameters of the axicon produced in [30] based on the solution of the Maxwell equations by the finite element method implemented in the Comsol Multiphysics software package. To study the dependence of the quality of the formed beam on the microrelief height, additional numerical experiments were performed in the present work. The calculation results are presented in Table 1. It was assumed that a Gaussian beam with a wavelength of 129 μm illuminates the axicon with a period of 60 μm, while the microrelief height varied from 40 to 60 μm. The radius of the computational domain in the numerical experiment was chosen equal to 580 μm. The selected size of the computational domain was sufficient to analyze the transverse structure of the formed beam. The refractive index of the axicon substrate material (silicon) for a given wavelength is $n = 3.452 + 0.386i$. Thus, the numerical simulation predicts the possibility of efficient formation of a radially polarized beam in the terahertz range. Notably, the optimal relief height is 50 μm (Table 1), which corresponds to the design value of the microrelief height of the produced element [30].

### Table 1. Results of a numerical study of the dependence of the quality of the formed beam on the subwavelength axicon relief height in case of propagation of a Gaussian beam with horizontal linear polarization through the subwavelength axicon: distribution of amplitude, horizontal and vertical components of the formed radially polarized beam

| Relief height | Amplitude | Horizontal component | Vertical component |
|---------------|-----------|----------------------|--------------------|
| 40 microns    | ![Amplitude](image1.png) | ![Horizontal component](image2.png) | ![Vertical component](image3.png) |
| 50 microns    | ![Amplitude](image4.png) | ![Horizontal component](image5.png) | ![Vertical component](image6.png) |
| 60 microns    | ![Amplitude](image7.png) | ![Horizontal component](image8.png) | ![Vertical component](image9.png) |

In the work [30], substrates made of high-resistance silicon with a diameter of 50 mm and a thickness of 1 mm with two-sided polishing of optical quality were used as the base material for the fabrication of the subwavelength axicon. The parameters of the diffractive microrelief of the produced elements in [30] were controlled using white light interferometry (Fig. 1) and microscopy. An analysis
of the results of microinterferometry (Fig. 1) demonstrates the high accuracy of the fabrication of the specified microrelief height in [30].

![Graph showing profilogram of the microrelief](image)

**Figure 1.** Profilogram of the microrelief in the central area of DOE (white light interferometer WLI-DMR) [30].

### 3. Investigation of the subwavelength axicon

The subwavelength axicon produced in [30] (Fig. 2) was investigated using radiation of the Novosibirsk free electron laser at the Budker Institute of Nuclear Physics of Siberian Branch Russian Academy of Sciences. DOE was illuminated with a linearly polarized beam with a Gaussian intensity distribution in the cross-section (mode radius $\sigma = 11$ mm, wavelength $\lambda = 128.7$ $\mu$m). The incident beam was polarized along the $x$-axis using a wire polarizer (Fig. 3). The beam propagated through the axicon; the image of the beam after the propagation was recorded by the Pyrocam IV pyroelectric camera with a matrix of $320 \times 320$ pixels (the size of one element is $80$ $\mu$m). The total image size was $25.6 \times 25.6$ mm$^2$. Three images were recorded at different distances: (1) without an analyzer, (2) with an analyzer that transmits an electromagnetic wave with initial $E_x$ polarization, and (3) with an analyzer that transmits a wave with orthogonal $E_y$ polarization (Fig. 3). Typical results obtained in the optical experiments are provided in Table 2. The experimental results presented in Table 2 and in [30] are in qualitative agreement with the results of the numerical simulations provided in Table 1 and in [30]. The existing discrepancies between the results of numerical simulations and the real experiment are explained by the technological errors in the microrelief formation (jagged edges of the DOE zones [30]).

![Central fragment of axicon’s photomask](image)

**Figure 2.** Central fragment of axicon’s photomask (discretization step was 10 $\mu$m).

| № | 1 | 2 | 3 |
|---|---|---|---|
| **Analyzer** | No | Initial direction | Orthogonal direction |
| **Image** |  |  |  |
4. Conclusions
The results of the investigation of the silicon subwavelength axicon produced in [30] have been presented. The work [30] showed experimentally the capability of the produced element to efficiently form a cylindrically polarized beam from an illuminating Gaussian beam of a terahertz laser. The results of the experimental research are in good agreement with the results of the numerical simulation. The existence discrepancies between the results of numerical simulation and the real experiment are explained by the technological errors in the microrelief formation [30].

The dependence of the quality of the formed beam on the height of the produced diffraction microrelief was investigated numerically. An optimum microrelief height of 50 μm was determined.

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6. References
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