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Optical Elements for Focusing of Terahertz Laser Radiation in a Given Two-Dimensional Domain

A. N. Agafonov[a], B. O. Volodkin[a], S. G. Volotovsky[a, b], A. K. Kaveev[c], B. A. Knyazev[d, e], G. I. Kropotov[c], K. N. Tykmakov[a], V. S. Pavelyev[a, b], E. V. Tsygankova[c], D. I. Tsypishka[c], and Yu. Yu. Choporova[d, e]

[a] *Samara State Aerospace University named after S.P. Korolyov (National Research University), Russia*

[b] *Image Processing Systems Institute of the RAS, Samara, Russia*

[c] *Tydex LLC, Saint-Petersburg, Russia*

[d] *Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia*

[e] *Novosibirsk State University, Russia*

e-mail: pavelyev10@mail.ru

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Abstract—Binary silicon-based diffractive optical element (DOE)—Gaussian-to-Square focuser (diameter of aperture is 30 mm) for the terahertz spectral range has been designed and characterized using terahertz radiation of the Novosibirsk Free Electron Laser (NovoFEL) at the wavelength of 141 μm. The preliminary experiments have demonstrated feasibility of application of binary silicon DOE for focusing of terahertz radiation into pre-given focal domain.

Keywords: diffractive optical element, free electron laser, terahertz radiation

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INTRODUCTION

Diffractive optical elements (DOE) have found wide use in technological laser systems and optical devices operating in the ultraviolet, visible and infrared ranges [1]. Application of DOE makes it possible to design versatile optical systems of small weight and size. Though transparent, materials have greater absorption in the THz spectral range than in the visible. For this reason the use of DOE looks preferable in the THz range than refractive elements. DOEs have almost no alternative when the monochromatic beam of a high-power THz free-electron laser (FEL) [2] needs controlling. Such applications as THz holography [3], interferometry and polarimetry require the division of an original beam into a few separate beams of predefined energy.

Other applications (THz-range imaging, soft-tissue ablation, generation of optical discharges, etc.) require THz-range radiation to be focused. The results of research on silicon binary diffractive lenses [4, 5] and beam splitters [4] used for controlling THz laser beams are available.

The paper gives the experimental results of using a silicon binary diffractive element for focusing a Gaussian THz-laser beam in an evenly square spot of flat-top intensity distribution. There are papers [1, 6, 7] on designing DOEs for focusing Gaussian beams in a rectangular spot. With IR-range lasers, this kind of focusing elements is needed to form an even intensity distribution of light on a target surface, e.g. for laser surface treatment in technology or in biological experiments. Zinc selenide or polycrystalline diamond films [6] are used as substrate materials for transmission mid-IR elements. Formation of even intensity distribution in the THz range will allow us to use THz ablation more effectively, give up point-by-point scanning and develop a new generation of laser beam scanners.

In our research work we used reactive-ion etching of high-ohmic silicon plate followed by deposition of an anti-reflective coating on the etched surface to produce a DOE. A FEL at Novosibirsk [2] was used to test the work of the DOE and get first results.

1. GENERATING A DOE THAT FOCUSES LASER LIGHT INTO A SQUARE SPOT

Undoped high-ohmic silicon is used as original material to produce DOEs operating with high-power laser beams in the THz range (e.g. free-electron lasers). In our research we used HRFZ-Si [8] substrates

Fig. 1. The phase function of the focusing element (the white corresponds to phase π, the black—phase 0).

1 mm thick and 38 mm in diameter with two highly polished sides. Reactive-ion etching (RIE) was applied to make a binary relief 29.1 μm deep on the substrate surface. Parylene C anti-reflective coating was deposited on both sides of the substrate to decrease Fresnel reflection losses. Earlier parylene C was used as an anti-reflective coating in research works [9, 10]. The thickness of the parylene C film was about 21 μm on either side.

A stochastic procedure using a genetic algorithm was utilized to compute the micro-relief. The application of the genetic algorithm in computations of a DOE with a small number of quantization levels for transforming a Gaussian beam into a flat-top intensity beam was considered, for instance, in [1].

The following parameters were used to compute the focusing element: the aperture 30 × 30 mm; the wavelength 141 μm; the focal length 368 mm (the element is designed to operate without an additional lens); the radius of the incident Gaussian beam 9 mm; the number of samples of the phase function 120 × 120; the square focal spot 8.6 × 8.6 mm.

The design depth of the binary relief was found according to formula [1]:

$$h = \lambda/2(n-1), \quad (1)$$

where n is the refraction index of silicon. Given $n = 3.42$, depth $h = 29.1$ μm. The design energy efficiency of the element was $e = 55.6\%$.

2. THE RELIEF-FORMING TECHNIQUE

An ultrasonic bath with washing solution at temperature 80°C was used to clean silicon plates for 30 minutes. Plates were rinsed with bidistilled water before each change of solution. Then the plates were put in $H_2SO_4 : H_2O_2$ (2 : 1) solution for ten minutes and then in HF: H_2O (1 : 20) solution for ten seconds to remove the natural oxide layer from the plate surface. The plates were dried in a centrifuge at 3600 rpm for 60 seconds.

A 200-nm copper layer was coated on Si plates to form a mask to be further processed by optical lithography. The use of none other than metallic masks is determined by their high plasma resistivity and selectivity over silicon, which permits relatively deep reactive ion etching of silicon with good accuracy. Ion-assisted magnetron sputtering with apparatus ETNA-100-MT (Russia) was used to metalize the Si plates at room temperature in the 1.2-Torr argon atmosphere.

In reactive ion etching the copper mask provided etch selectivity that exceeded 1 : 300. However, the copper film has low adhesion to silicon. To overcome this drawback, a 5-nm adhesive chromium layer was deposited on silicon before coating the copper film. Wet chemical etching in 0.1% $FeCl_3$ solution trough a photoresist mask was used to produce the topological pattern in the copper layer. After the etching the remnants of the photoresist were removed with concentrated base solution. $K_3[Fe(CN)_6]$: NaOH : H_2O solution (1 : 3 : 16) was used to etch the chromium sub-layer trough the copper mask.

Immediately after the metallization of the plate a layer of FP-4-04mA photoresist was deposited by 3600-rpm centrifuging at room temperature for 60 second. The resultant photoresist layer was then dried, the thickness of the layer being controlled. An ultraviolet lamp (the intensity maximum at 253 nm, the total radiant power 2.4 W) was used to expose the photo layer through a photo mask for 6 minutes. The development of the pattern was done in 0.5% NaOH solution for 2 minutes.

Reactive-ion etching plant ETNA-100-PT (Russia) was utilized to etch the silicon plate with the copper mask (Fig. 2). It was necessary to secure that the relief walls have the slant of no greater than 10° to get required characteristics of DOEs. For this reason the Bosch process of inductively coupled plasma (ICP) RIE [11] was applied in C_4F_8 atmosphere (passivation) and SF_6/Ar atmosphere (etching). The point of this process is the intentional suppression of the etching phase because of disagreement between the rates of passivation and etching: a small area of unprotected silicon results in a considerable increase of the etching rate (including its lateral component), whereas the growth rate and fixed thickness of the passivation layer remain constant. The suppression of the etching phase was done by adding argon in etching rather than by decreasing the etching time (which is more effective from the economical point of view). The addition of argon resulted in the relief walls and especially relief bottom becoming much less rough. The pressure in the chamber was about 0.1 mBarr and varied depending on the etch phase. A turbomolec-

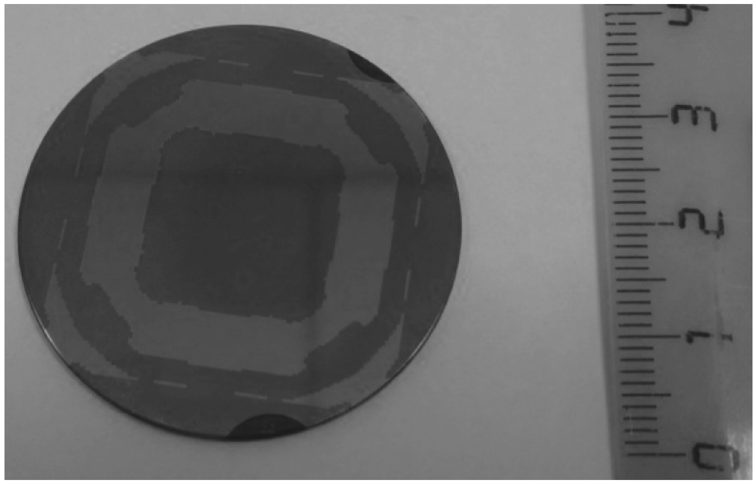

Fig. 2. Photo of the silicon substrate with the protective mask.

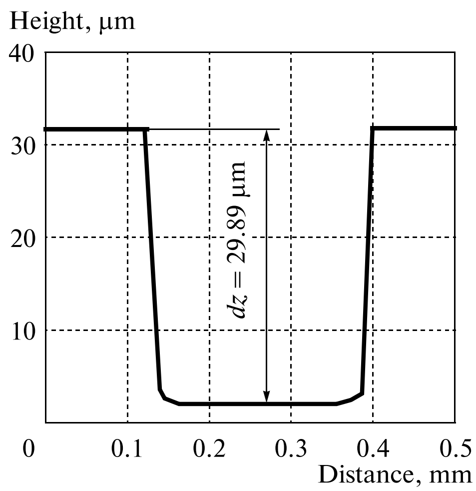

Fig. 3. The profile line of the micro relief (the arrow indicates the height).

ular pump was used for evacuation, which provided rapid renewal of the chamber atmosphere. Consumption of C_4F_8 was about 85 liter/hour, SF_6/Ar about 10/70 liter/hour. The power of ICP source was 300 W. The accelerating source was run only in the etch phase and only in the substrate DC bias self-adjusting mode (200 V), the power of the source being no greater than 15 W. The passivation phase lasted 10 second and the etching phase 7 second; these times were determined to ensure that the relief walls are vertical. The etch depth over one cycle was 100 nm. The total depth of the relief was determined by the number of etching cycles. After each cycle of etching the plate surface was cleaned for a short time in SF_6 by isotropic etching.

3. CONTROLLING THE GEOMETRY OF THE MICRO RELIEF

White-light interferometer WLI-DMR (made at the Jena Fraunhofer Institute, Germany) (Fig. 3) and raster electron microscope FEI Quanta-200 (Fig. 4) were utilized to control the geometric parameters of the DOE relief. The interferometry was used as a fast means for controlling the etch depth and quality of the groove bottom. The raster electron microscopy was applied to control the quality of etching of the groove walls and bottom and to determine the geometric sizes of the relief.

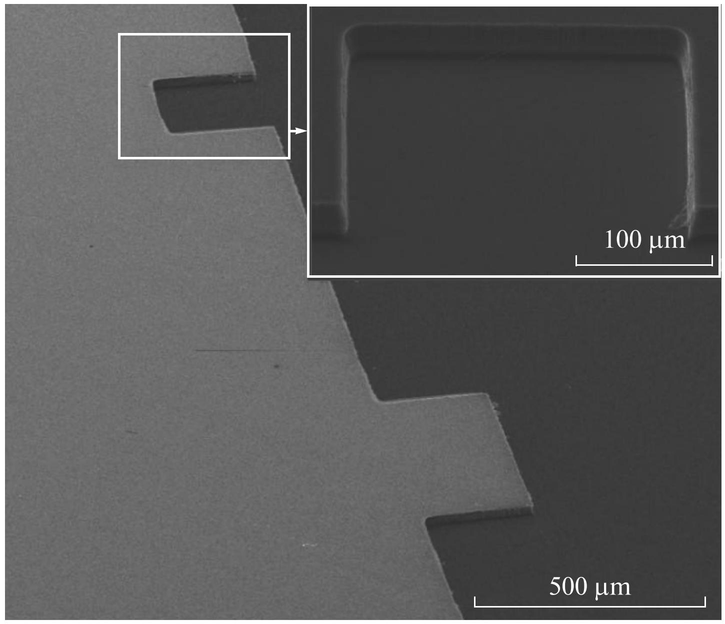

Fig. 4. The electron photograph of the relief.

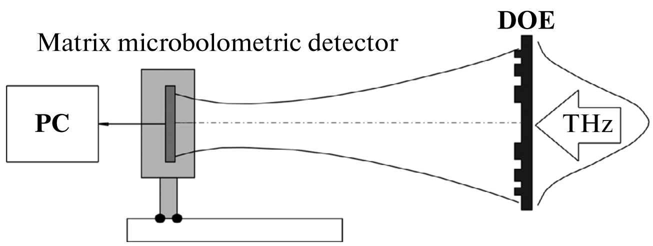

Fig. 5. The optical arrangement used in the experiments.

4. TESTING THE DOE USING THE FREE-ELECTRON LASER

The optical properties of the DOE we manufactured were studied at a work station of Novosibirsk free-electron laser. The experimental setup is shown in Fig. 5. The laser generated monochromatic radiation as a continuous stream of 100 ps pulses with a repetition rate of 5.6 MHz. At the station, the laser beam had the Gaussian shape. The average power of radiation in the experiments could be varied from 5 to 100 W. In the experiments the minimum wavelength was restricted to 141 μm. A 320 × 240 pixel microbolometer focal plane array (the physical size 16.36 × 12.24 mm) [12] was used to detect the radiation passed through the element.

5. EXPERIMENTAL RESULTS

Figure 6 shows the distribution of THz radiation intensity in the square-shaped focal spot produced by the DOE. The depression in the middle of the square is formed because the element was computed for the beam waist which differed from the actual one. In the experiment the laser beam had the beam waist of 11 mm, whereas the radius used in computations was 9 mm. The result of computer simulation of the focal intensity distribution for beam waist a 9-mm laser-mode radius is given in Fig. 7a. The interaction of a DOE computed for a 9-mm beam with a beam of 11-mm laser-mode radius was simulated to give the result presented in Fig. 7b.

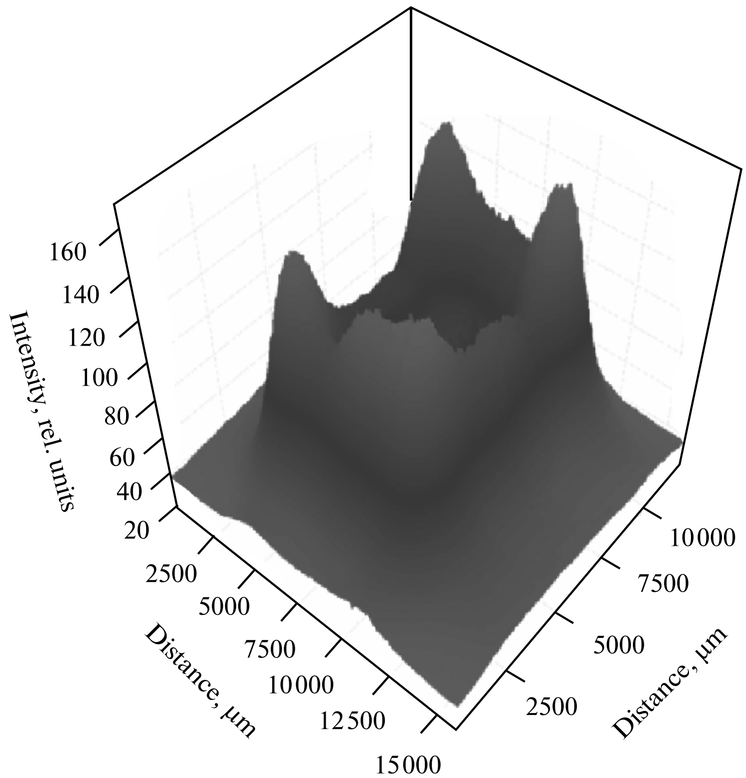

Fig. 6. Intensity distribution of THz radiation in the focal plane of the DOE.

Fig. 7. The focal-plane intensity distribution of the DOE designed for a 9-mm beam when the radius of the incident beam is 9 mm (a) and 11 mm (b). Computer simulation.

CONCLUSIONS

The experiments showed that it is possible to make diffractive optical elements that can operate in the THz range and produce required two-dimensional intensity distributions in the focal plane.

Improvement in this field involves fabrication of micro reliefs with an increased number of quantization levels, which can raise the diffraction efficiency of silicon DOEs used for focusing THz-radiation beams into arbitrary focal shapes.

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