Silicon Diffractive Optical Elements for Transformation of Terahertz Novosibirsk Free Electron Laser Radiation

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Abstract: Binary silicon diffractive optical elements (diffractive lenses, beam-splitters and gauss-to-rectangle focuser) for the terahertz spectral range have been designed and characterized using terahertz radiation of the Novosibirsk Free Electron Laser. Effect of an antireflection coating on the silicon elements was studied.

1. Introduction and background

Diffractive optical elements (DOEs) are most beneficial for beam manipulation at THz frequencies. Such applications like holography, interferometry and polarimetry require dividing a beam into two beams (or more) of equal intensity. Other applications, like imaging, material ablation, generation of continuous optical discharge, and even more exotic for the terahertz range application, namely the field ionization of individual atoms, require focusing of THz radiation, often with a low *f* number. In this paper we report characteristics of three types of silicon binary diffractive optical elements: diffractive lenses (BDLs), beamsplitters (BSs) and gauss-to-rectangle focuser.

2. Radiation source and imaging device

The experiments have been carried out using radiation of the terahertz Novosibirsk free electron laser (NovoFEL) [1]. The laser generated monochromatic radiation as a continuous stream of 100-ps pulses with a repetition rate of 5.6 MHz. The laser beam entered at the workstation as a Gaussian beam with a divergence of 3×10^{-3} rad. The laser beam at the station had the Gaussian shape with a beam radius slightly changing in the range of 9-11 mm (depending on adjustment conditions), which means that practically 100% of beam energy passed through a circle of 30-mm in diameter.

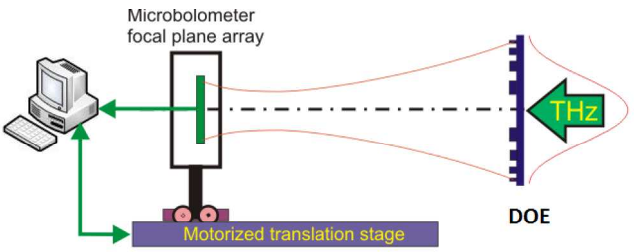

Fig. 1. Experimental setup for DOE characterization

Average power of radiation in the experiments was varied from 5 to 100 W. All experiments have been carried out at λ=141 μm. One of the experimental configurations is shown in Fig. 1. The radiation having passed through the element under study was recorded in real time with a 320×240 microbolometer focal plane 2D array (MFPA) with physical size of 16.32×12.24 mm moving with a motorized translation stage along the optical axis.

3. Silicon binary diffractive lenses and beamsplitters

Binary (two-level) diffractive lenses and beamsplitters have been formed on polished substrates of high-resistivity silicon HRFZ-Si [2] with a diameter of 100 mm and a thickness of 1 mm. A standard photolithographic process followed by plasma etching was used for DOE manufacturing. To create a microrelief profile with a relatively high altitude (about 30 microns) and the walls with small deflection from the vertical, the reactive ion etching (RIE) described in [3] was applied. Fresnel zones have been etched on a high-resistivity one-mm thick silicon plate. Similar techniques with deep reactive ion etching and multilevel resist processing was used in [4]. A microfabrication technique using a gray-scale mask was applied in [5].

Binary diffractive lenses with a diameter of 30 mm were designed and fabricated for following parameters: focal distance of f = 120 mm and illuminating wavelength of λ =130 μm. For wavelength of 141 μm we observed two focuses at a distance of 121 and 42 mm with excellent agreement with theory. The diffraction efficiencies were (21±3)% for the main focus and 3% for the secondary focus. To increase diffraction efficiency the lens was covered with a λ /4 Parilene *C* layer [6, 7]. For the BDL with antireflecting coating they were (36±5)% and 3.6%, respectively.

A beamsplitter of 30-mm in diameter with a rectangular grating etched on a silicon plate was placed across the laser beam. Image in the focal plane was recorded with the MFPA. Distance between zero order and first order focal points enabled to measure diffraction angle of the grating which appeared to be 15^0. The radiation resistance of Parilene *C* layer was investigated by focusing radiation on the layer. Absolute power density was measured using a thermal sensitive Fizeau interferometer [8]. The layer was not damaged being exposed to radiation with the average power up to 4 kW/cm^2.

4. Silicon gauss-to-rectangle focuser

The binary silicon gauss-to-rectangle focuser has been designed and fabricated to transform Gaussian beam with beam radius of 9 mm into rectangular uniform intensity distribution (Fig. 2a). Illuminating the focuser by Gaussian beam with beam radius of 11 mm led to deviation of intensity distribution from desired form in the center of focal rectangle (Fig. 2b,c).

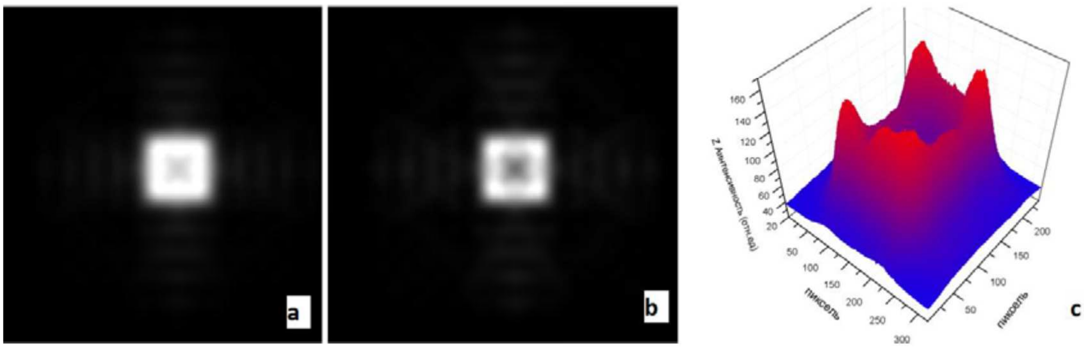

Fig. 2. Focal intensity distribution as result of computer simulation a) for beam radius of 9 mm b) for beam radius of 11 mm; c) measured intensity distribution in the focal plane of gauss-to-rectangle focuser (illuminating beam radius was 11 mm)

The preliminary experimental results (Fig.2c) are in good agreement with results of computer simulation (Fig.2b).

5. Conclusion

The experiments have demonstrated feasibility of application of different kinds of binary silicon DOE for transformation of terahertz radiation.

6.Acknowledgment

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7. References

[1] B. A. Knyazev, G. N. Kulipanov, N. A. Vinokurov, “Novosibirsk terahertz free electron laser: instrumentation development and experimental achievements“, Measur. Sci. Techn. **21**, 054017, 13p. 2010

[2] http://www.tydexoptics.com/pdf/Si.pdf

[3] Franz Laermer и др. Method of anisotropically etching silicon. Patent number: 5501893, 1996.

[4] S. Wang, J. Xu, T. Yuan, R. Blaikie, S. M. Durbin, X.-C. Zhang, D. R. S. Cumming, “Multilevel silicon diffractive optics for terahertz waves,”*Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures* **20**, pp. 2780-2783, 2002

[5] W. Däschner, P. Long, R. Stein, Ch. Wu, and S. H. Lee, "Cost-effective mass fabrication of multilevel diffractive optical elements by use of a single optical exposure with a gray-scale mask on high-energy beam-sensitive glass," *Appl. Opt.* **36**, 4675-4680, 1997

[6] A. J. Gatesman, “An antireflection coating for silicon optics at terahertz frequencies,” *Microwave and Guided Wave Letters, IEEE* **10** , 264-266, 2000

[7] H.-W Hübers, J Schubert, A Krabbe, M Birk, G Wagner, A Semenov, G Gol’tsman, B Voronov, E Gershenzon, “Parylene anti-reflection coating of a quasi-optical hot-electron-bolometric mixer at terahertz frequencies,” *Infrared Physics & Technology* **42**, pp. 41-47, 2001

[8] N.A. Vinokurov, B.A. Knyazev, G.N. Kulipanov, A.N. Matveenko, V.M. Popik, V.S. Cherkassky and M.A. Shcheglov, “Vizualization of radiation from high-power terahertz free electron laser with a thermosensitive interferometer,” *Technical Physics* **52,** pp. 911-919, 2007.