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Diffractive Lenses for High-Power Terahertz Radiation Beams

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Abstract—Techniques for manufacturing silicon binary (two-level) diffractive lenses and polypropylene kinoform diffractive lenses for the terahertz spectrum range are described. The elements are 1 and 0.8 mm thick, respectively. The silicon lens is manufactured in two versions: with no coating and with a parylene C (polyparaxylylene) antireflection coating. Characteristics of the diffractive optical elements are studied in the beam of a pulse–periodic free electron laser at a radiation wavelength of 141 μm and a repetition rate of 5.6 MHz. The radiation resistance of the parylene coating, tested on the Novosibirsk free electron laser, was not impaired when the coating was exposed to an average power density of 4 kW cm^{-2}, the peak power in a 100-picosecond pulse being almost 8 MW cm^{-2}.

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INTRODUCTION

Diffractive computer optics have been under development for more than 25 years, since the seminal works by A.M. Prokhorov, I.N. Sisakyan, and V.A. Soyfer [1]. Diffractive optical elements (DOEs) are widely used in laser technological installations, optical instruments, and devices for storing and searching for information. DOEs can perform, e.g., various functional transformations of light fields, the functions of a complex multilens objective, and the correction of spherical or chromatic aberrations. The use of flat elements in optical schemes, especially those that employ monochromatic laser light sources, opens up prospects for inexpensive, compact, and functionally complex tools. DOEs are promising elements for controlling radiation in terahertz frequencies, especially in the case of a high-power monochromatic beam of a free electron laser (FEL) [2]. Applications such as obtaining terahertz images, soft ablation, optical discharge generation, and many others, require radiation focusing. In this work, we present two DOE technologies: a kinoform diffractive lens (KDL) and a binary diffractive lens (BDL). Their characteristics were studied on the Novosibirsk FEL workstation.

A BINARY (TWO-LEVEL) DIFFRACTIVE LENS

This work describes our calculations for, and the production and study of, a binary diffractive lens with a focal length of 120 mm, an aperture of 30 mm, and an estimated wavelength of 130 μm. The calculated binary microrelief was formed on polished substrates of high-resistivity float zone silicon (HRFZ Si) [3] with diameters of 100 mm and thicknesses of 1 mm. BDL production consisted of the following stages: (a) silicon wafer scrubbing and control over its parameters, (b) the creation of a protective mask through optical lithography, (c) reactive ion etching (RIE) of silicon [4], and (d) removal of the remains of the metallic mask. Deep microrelief (~30 μm) was obtained by via RIE. The low plasma resistance of the photoresistive mask made it impossible to use without an additional masking layer; otherwise, the relief depth and verticality of the walls would not meet our requirements. We therefore used plasma resistant metal (copper and aluminum) masks in this work. A thin metal film with windows, obtained by photolithography and chemical etching, was applied to the silicon substrate to produce the mask, with the windows then serving for the reactive ion etching of the silicon substrate. Such RIE techniques with multilevel treatment were used in [5]. The metal film was applied and the silicon was etched on the ETNA-100-PT installation (NT-MDT, Russia). To obtain the specified DOE performance characteristics, it was necessary to ensure a wall deflection angle of no more than 10°; we therefore used the Bosch process in an inductively coupled configuration plasma source (ICP–RIE) [6] in C_4F_8/Ar

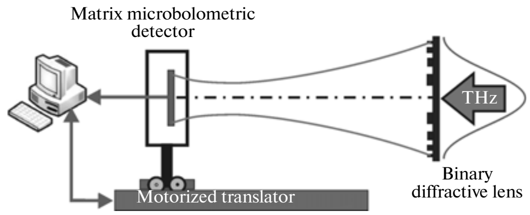

Fig. 1. Optical scheme of the FEL experiment.

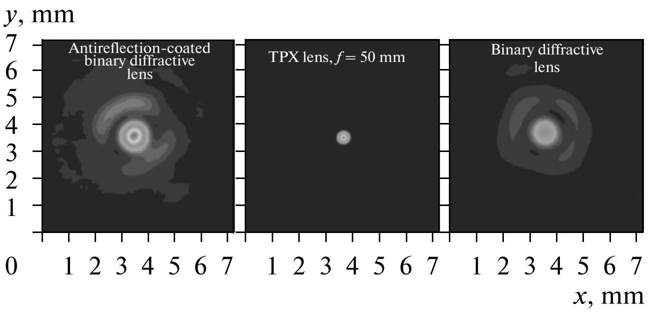

Fig. 2. Intensity distribution in the BDL focal plane, compared to a TPX lens with a focal length $f = 50$ mm.

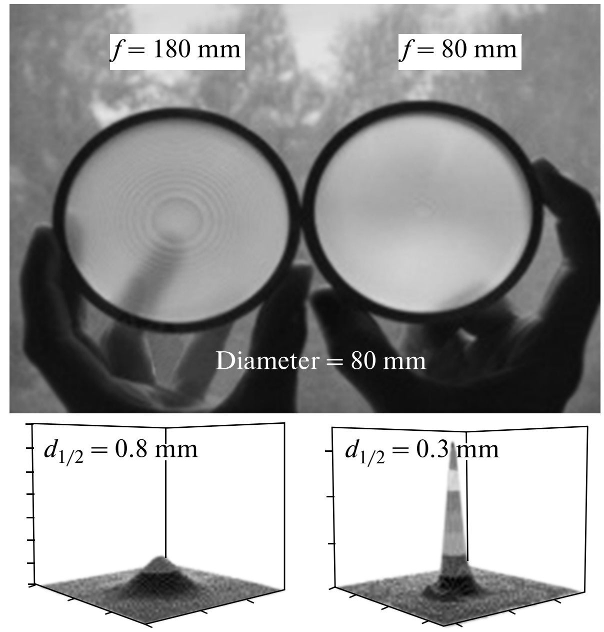

Fig. 3. Kinoform polypropylene diffractive lenses and the respective intensity distributions in their focal planes.

(passivation) and SF_6/Ar (etching) atmospheres. The geometrical parameters of the resulting microrelief were controlled by means of white light interferometry and scanning electron microscopy.

The BDL optical characteristics were studied on one of the FEL workstations. The tests were performed according to the scheme shown in Fig. 1. FEL radiation was targeted at a diffractive element, and the image was recorded with an uncooled matrix microbolometric detector [7] mounted on a motorized translator and moving along the beam's axis.

We observed two focuses at distances of 121 and 42 mm that agreed with the preliminary calculations and theoretical expectations. The diffraction efficiency values were $21 \pm 3\%$ for the principal focus and 3% for the secondary focus. To increase the efficiency of diffraction, the lenses were covered with antireflection parylene C. Parylene C was used as an antireflection coating in [8, 9]. The diffraction efficiencies for the antireflection-coated lenses were 36 ± 5 and 3.6%, respectively. We tested the BDL's radiation resistance by irradiating the periphery of an antireflection-coated silicon plate (outside the diffraction structure) with TPX lens-focused terahertz FEL radiation. The absolute values of the radiation power density distribution were measured with a thermosensitive interferometer [10]. The lenses remained undamaged up to a power density of 4 kW cm^{-2} in the Gaussian distribution maximum, corresponding to a peak power of almost 8 MW cm^{-2} for a 100-picosecond pulse.

KINOFORM DIFFRACTIVE LENSES (KDLs)

The authors of [11] described KDLs with diameters of 25 mm and focal lengths of 50 mm, manufactured on polymer using a silicon imprinting matrix. In this work, we studied the performance characteristics of lenses 80 mm in diameter with a parabolic Fresnel zone profile, manufactured via the hot vacuum imprinting of polypropylene using a metal matrix. For our study, KDLs with focal lengths $f = 200$ and $f = 80$ mm were manufactured for wavelength $\lambda = 130$ mm (Fig. 3).

Polypropylene is one of the least absorbing materials in the terahertz range. Owing to the thinness of the lenses (0.8 mm), they turned out to be virtually transparent to terahertz radiation and were able to operate for a long time in beams with powers of several tens of watts. To make use of the entire KDL working aperture, the terahertz beam was widened by a factor of 2.5 using a telescope with off-axis parabolic mirrors. The principal focus of the lens with focal length $f = 80$ mm was observable at a distance of 77.6 mm (at a radiation wavelength of 141 μm). The width at the beam's half-height in the caustic region was 0.23 mm. We were unable to record the first-order focus that, according to theory, should exist at a distance of 25 mm when an imprinted profile is nonideal, due to the geometrical limitations of the microbolometers' matrix frame. KDLs are widely used on FEL workstations both for focusing and for constructing images with diffraction-limited spatial resolution [12].

CONCLUSIONS

Our experiments demonstrated the possibility of using computer diffractive optic techniques to create terahertz-range lenses. The experimental results agree well with the known theoretical results and allow us to hope for future terahertz-range diffractive optical elements that form prespecified two-dimensional intensity distributions, i.e., terahertz-range focusers.

Improving silicon microrelief technology by increasing the number of microrelief quantization levels in particular will enable us to increase the diffraction efficiency of silicon elements designed to focus high-power terahertz radiation beams.

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