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Fabrication of a multilevel THz Fresnel lens by femtosecond laser ablation

M.S. Komlenok, B.O. Volodkin, B.A. Knyazev, V.V. Kononenko, T.V. Kononenko, V.I. Konov, V.S. Pavelyev, V.A. Soifer, K.N. Tukmakov, Yu.Yu. Choporova

Abstract. **The possibility of fabricating a silicon diffractive four-level THz Fresnel lens by laser ablation is studied. For a microrelief to be formed on the sample surface, use is made of a femtosecond Yb:YAG laser with a high pulse repetition rate (f = 200 kHz). Characteristics of the diffractive optical element are investigated in the beam of a 141-μm free-electron laser. The measured diffraction efficiency of the lens is in good agreement with the theoretical estimate.**

Keywords: *diffraction optics, free-electron lasers, terahertz radiation, laser ablation.*

1. Introduction

The emergence of coherent, high-power sources of THz radiation [1] has created a need for optical elements to control this radiation. It is known that high-power THz beams can be controlled by silicon diffractive lenses and beam splitters [2, 3]. Agafonov et al. [4] present the results of studying a diffractive optical element (DOE) focusing a Gaussian beam of a THz free-electron laser (FEL) into a square focal spot, and in [5] they report the investigation of binary DOEs used to generate Gauss–Hermite and Gauss–Laguerre modes from an illuminating Gaussian beam of a THz laser. Previously, DOEs have been widely used in optical devices of UV, visible and IR range [6]. Application of DOEs allows optical devices to be designed with reduced weight and size characteristics and broad functionality [6]. All diffractive elements of terahertz range, the results of whose studies are given in [2–5], are fabricated by lithographic etching of a silicon substrate. This approach has disadvantages: production of multi-level elements by lithographic etching requires an expensive and complicated procedure of combining photomasks [7], and binary (two-level) elements have limited energy efficiency [6].

This paper presents the results of studying a silicon, four-level, diffractive THz lens (operating wavelength of 141 μm) produced by ablation of a silicon surface by a repetitively pulsed disk Yb:YAG laser. Earlier, Pavelyev et al. [8] have used an approach based on laser ablation of a substrate surface to fabricate power diffractive IR optics on diamond plates. Note that laser ablation allows a multilevel diffraction microrelief to be formed by varying laser radiation parameters and using a translational stage to move a sample rather than through the use of an expensive set of photomasks [8–10]. The main difficulty of the proposed method is to produce a deep, up to 43.6 μm, relief with a smooth bottom because of the roughness development with increasing profile depth in the irradiation region during laser ablation. To minimise roughness, in the present work a femtosecond laser is used in contrast to papers where diamond DOEs are fabricated by using an excimer nanosecond laser [8–10]. To increase the speed of laser machining, we use a regime with a high (up to 200 kHz) pulse repetition rate f and, consequently, with a high average power (30 W), focused radiation intensity in each pulse being sufficiently high for evaporating silicon.

The diffractive element produced by laser ablation was tested on a workstation of the Novosibirsk FEL [1].

2. Fabrication of a diffractive THz lens

To fabricate a THz DOE operating with high-energy beams (e.g., FEL radiation), it is advisable to use high-resistance undoped silicon as an initial material [2, 3]. In the present work we have used a high-resistance silicon substrate with a diameter of 30 mm and a thickness of 1 mm with double-sided polishing of optical quality.

The estimated height of a diffractive lens microrelief is given by the formula [6]

$$h(r) = \frac{\lambda\varphi(r)}{2\pi(n-1)}, \qquad (1)$$

where n is the refractive index of the substrate material, and

$$\varphi(r) = -k\frac{r^2}{2f} \qquad (2)$$

is the phase function of the lens [6], reduced to the [0, 2π] range. The continuous phase function in the present work was replaced by its four-step approximation (quantization over four levels [6]).

In the calculations we used the following parameters of the lens: aperture diameter, 30 mm; working wavelength,

M.S. Komlenok, V.V. Kononenko, T.V. Kononenko, V.I. Konov A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia; National Research Nuclear University ‘MEPhI’, Kashirskoe sh. 31, 115409 Moscow, Russia; e-mail: komlenok@nsc.gpi.ru;
B.O. Volodkin, K.N. Tukmakov S.P. Korolev Samara State Aerospace University, Moskovskoe sh. 34, 443086 Samara, Russia;
B.A. Knyazev, Yu.Yu. Choporova Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent’eva 11, 630090 Novosibirsk, Russia; Novosibirsk State University, ul. Pirogova 2, 630090 Novosibirsk, Russia;
V.S. Pavelyev, V.A.Soifer S.P. Korolev Samara State Aerospace University, Moskovskoe sh. 34, 443086 Samara, Russia; Image Processing Systems Institute, Russian Academy of Sciences, ul. Molodogvardeiskaya 151, 443001 Samara, Russia

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141 µm; focal length, 120 mm; radial step of phase-function quantization, 250 µm; and number of quantization levels of the microrelief, 4. The four-level microrelief was realised on a silicon wafer surface by laser ablation. High-resistance silicon was structured by a disk Yb:YAG laser (λ = 1030 nm, τ = 400 fs, f = 200 kHz). The energy distribution at the sample surface was Gaussian (diameter at the 1/e level was about 10 µm); the maximum pulse fluence was 15 J cm^{-2} and significantly higher than the ablation threshold (about 0.5 J cm^{-2} [11]). Choosing a high fluence was due to the need to remove a large amount of material. To produce a four-level Fresnel lenses required surface profiling in the form of 250-µm-wide concentric rings of different depth, i.e., 14.5, 29.1 and 43.6 µm, corresponding to the phase function of the lens 3π/2, π and π/2. The sample was mounted on a rotating disk whose axis was moved up and down by means of a translational stage (Fig. 1). The profile depth was varied by changing the number of passes. The photo of the formed lens is shown in Fig. 2.

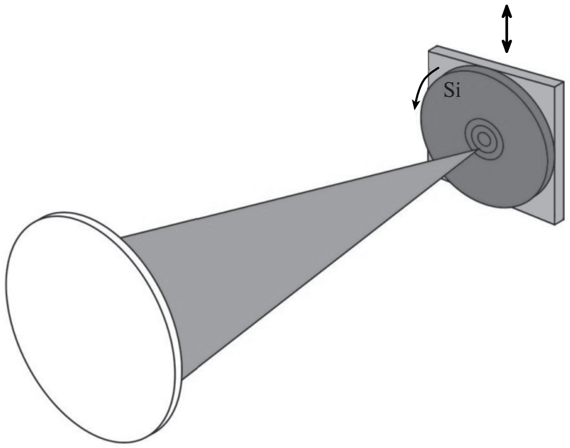

Figure 1. Scheme of laser irradiation (λ = 1030 nm, τ = 400 fs, f = 200 kHz) of a silicon wafer to produce a given profile on a surface.

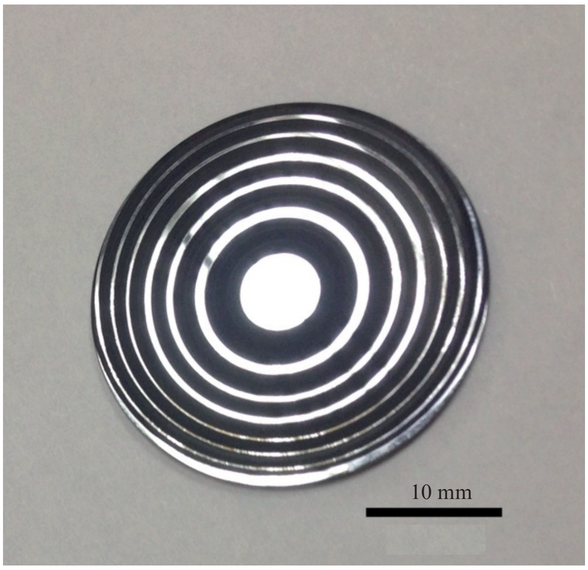

Figure 2. Photo of the fabricated silicon four-level Fresnel lens.

3. Control of geometrical parameters of the microrelief

The formed microrelief has a developed surface topology and relatively large level difference, which precluded the use of white-light interferometry and scanning probe microscopy to measure the relief height. To measure the height of the diffraction microrelief, the chip of the produced lens was examined using a scanning electron microscope (SEM) (FEI Quanta 200) (Fig. 3).

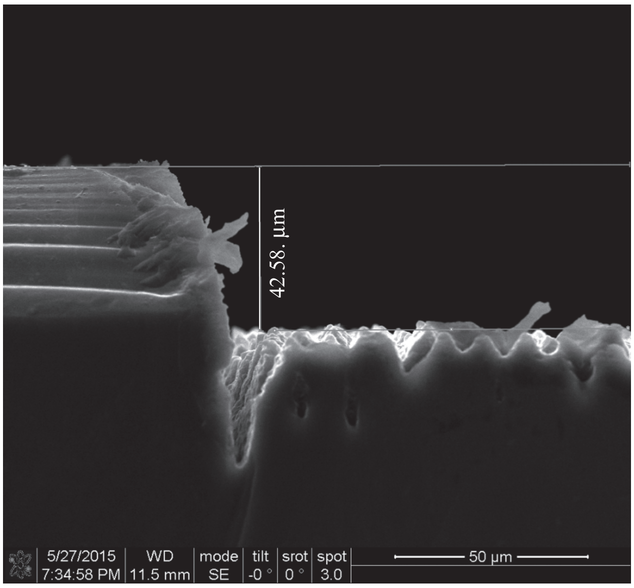

Figure 3. SEM image of a cleaved lens fragment (equivalent to the calculated height difference of 43.6 µm).

The results of electron microscopy show that the use of laser ablation allows one to produce a predetermined height of the diffraction microrelief with high accuracy. However, one should note significant machined surface roughness and presence of a groove near the edge of the step, which is due to the slowing of the translational stage movement during the change in its direction. The size of the roughness increased with increasing profile depth and amounted to about 5 µm at a maximum depth of 43.6 µm.

4. 4. Investigation of the element using a Novosibirsk free electron laser

Figure 4 shows the scheme of the experiment, during which the FEL radiation with a wavelength of 141 µm illuminated the manufactured silicon four-level diffractive lens. To measure the intensity distribution along the optical axis, we used a 320×240 matrix microbolometer detector (MMBD), which allows one to capture both video and still frames [12]. The physical size of the MMBD is 16×12 mm, and the size of one pixel of the matrix is 50 µm. The MMBD was mounted on a motorised stage and moved along the optical axis at a distance of 100–165 mm from the DOE.

The measured axial intensity distribution formed by the lens is shown in Fig. 5. Shifting the focal plane by 5 mm along the optical axis is, apparently, due to the deviation of the wavefront of the illuminating beam from a plane one.

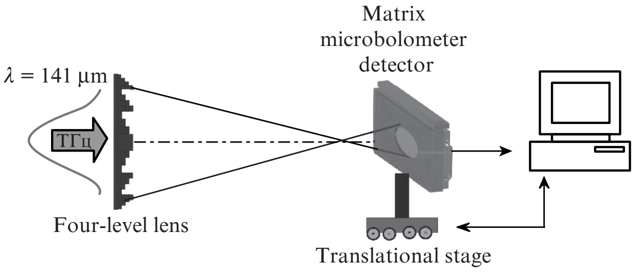

Figure 4. Optical scheme of the setup for testing the diffractive lens.

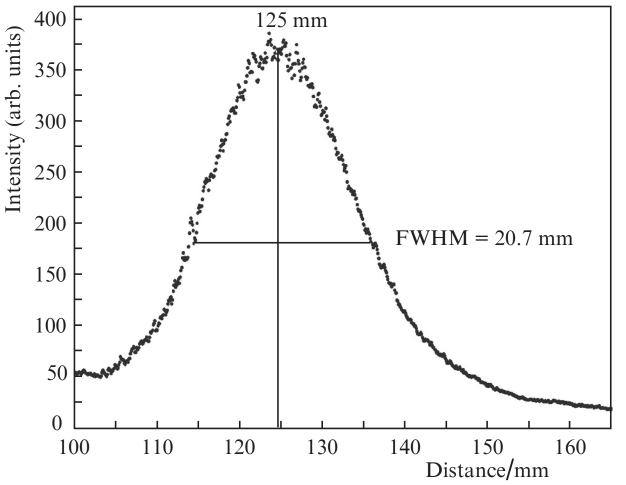

Figure 5. Measured intensity distribution along the optical axis. Points show the experimental data, the vertical line marks the maximum power of the beam at a distance of about 125 mm from the diffractive lens.

Figure 6 shows three-dimensional intensity distributions in planes spaced by 115, 125 and 135 mm from the plane of mounting the diffractive lens. Note that the focused beam still preserves the Gaussian shape.

The lens diffraction efficiency measured during the experiment was 35.9%. The Fresnel reflection losses [13] in the silicon wafer (refractive index of silicon $n = 3.42$) were estimated to be about 49%. Thus, when depositing an antireflection coating, the diffraction efficiency of the element can in principle be increased to almost 75%, which agrees well with the theoretical estimate of 81% [6]. Some decrease in the diffraction efficiency is, apparently, due to scattering by inhomogeneities resulting from the processing of the silicon surface by laser pulses with a high fluence. It is known that the use of the fluence that is significantly greater than the ablation threshold of silicon leads to the formation of volcano-like structures on the surface [11]. Therefore, one way to improve efficiency is to optimise the conditions of laser processing of the sample.

Another way is to reduce Fresnel reflection losses. To do this, a bilateral parylene antireflection coating can be deposited on silicon THz DOEs [2, 3]. Previously, as an antireflection coating, parylene has been used in [14, 15]. Agafonov et al. [2] have demonstrated experimentally that the application of a bilateral antireflection coating on silicon THz DOEs reduces Fresnel losses to negligible values. Thus, the development of the technology of forming a multilevel diffractive microrelief together with the subsequent deposition of an antireflection coating will solve the problem of creation of high-performance multifunctional optics to control high-power beams of a terahertz laser.

5. Conclusions

A multilevel silicon diffractive THz Fresnel lens has been fabricated for the first time by femtosecond laser ablation. The morphology of the DOE has been analysed by using a scanning electron microscope.

The silicon Fresnel lens has been tested with a 141-μm free-electron laser and its diffraction efficiency, which amounts to 35.9%, has been measured. Results of the full-scale research of the four-level diffractive lens are in good agreement with numerical simulations.

The experiments have shown the feasibility of laser ablation of the silicon surface to fabricate effective multilevel THz DOEs.

Improving the proposed technology of forming a silicon microrelief, in particular increasing the number of its quantization levels, will eventually increase the energy efficiency of silicon DOEs designed to focus beams of THz radiation.

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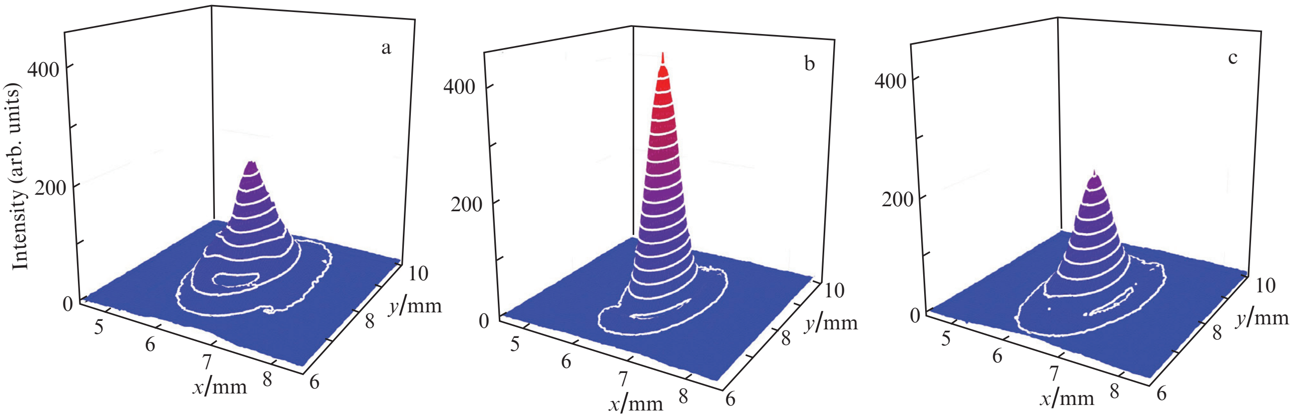

Figure 6. Three-dimensional intensity distributions in planes spaced from the plane of the lens mounting at a distance of (a) 115, (b) 125 and (c) 135 mm.

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