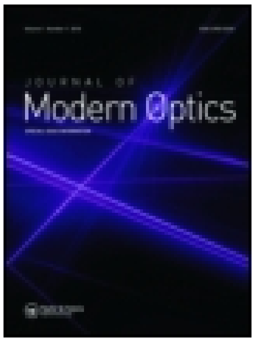

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Journal of Modern Optics

ISSN: 0950-0340 (Print) 1362-3044 (Online) Journal homepage: http://www.tandfonline.com/loi/tmop20

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To cite this article: Andrey N. Agafonov, Boris O. Volodkin, Denis G. Kachalov, Boris A. Knyazev, Grigory I. Kropotov, Konstantin N. Tukmakov, Vladimir S. Pavelyev, Dmitry I. Tsypishka, Yulia Yu. Choporova & Andrey K. Kaveev (2015): Focusing of Novosibirsk Free Electron Laser (NovoFEL) radiation into paraxial segment, Journal of Modern Optics, DOI: 10.1080/09500340.2015.1118163

To link to this article: http://dx.doi.org/10.1080/09500340.2015.1118163

JOURNAL OF MODERN OPTICS, 2015
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Focusing of Novosibirsk Free Electron Laser (NovoFEL) radiation into paraxial segment

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ABSTRACT
We demonstrate results of studies of a silicon binary diffractive optical element (DOE) focusing a terahertz laser Gaussian beam into a paraxial segment. The characteristics of the DOE were examined on a Novosibirsk Free Electron Laser beam of 141-μm wavelength.

ARTICLE HISTORY
Received 20 July 2015
Accepted 2 November 2015

KEYWORDS
Diffractive optical element; free electron laser; terahertz radiation; axial segment

1. Introduction

Diffractive optical elements (DOEs) are widely applied in the production of optical devices for ultraviolet, visible, and infrared ranges [1]. The DOE application enables fabrication of wide-functionality optical devices of reduced mass and overall dimensions [1]. The use of DOEs for control of terahertz radiation was considered in [2–7]. Some results of studies of a silicon binary diffraction lens and a beam splitter [7] used for control of a high-power monochromatic beam of THz-free electron laser (FEL) [8]. Findings on the DOE focusing a Gaussian beam of a THz-FEL into a square focal area are presented in [9].

Practical applications, such as terahertz imaging (including elongated objects), ablation, and optical discharge generation, etc., require focusing of terahertz radiation frequently with a large focal depth. Results of studies of optical elements for visible and infrared ranges intended for focusing a laser beam into a paraxial segment (large focal depth) are given in [1,10,11].

In the present paper, we show the results of studies of a silicon binary diffractive focusator. This element is ionochromatic beam of THz-free electron ntended for focusing of the Gaussian beam of a THz-FEL into a paraxial segment. The element was produced via reactive-ion etching (RIE) of the surface of a high-resistance silicon plate and subsequent application of an antireflection coating. The characteristics of the element were examined at a workstation of the Novosibirsk Free Electron Laser (NovoFEL) [8].

2. Synthesis of DOE for focusing of a laser radiation beam into paraxial segment

For production of THz DOEs working with high-power radiation beams (for example with FEL beams), it is necessary to use undoped high-resistance silicon as the basic material [7]. In the present work, we used optical-quality double-sided polished HRFZ-Si wafers (http://www.tydexoptics.com/pdf/Si.pdf) of 38-mm diameter and 1-mm thickness. A binary microrelief 29.1 μm high was fabricated on a wafer surface via RIE of silicon [12] by a technology that was used previously for the production of THz binary diffractive lenses and a beam splitter [7,9]. A double-sided antireflection coating of Parilene C was applied for decreasing the Fresnel reflection losses in the element. Parilene C was used earlier as an antireflection coating material [7,9,13,14]. The parilene layer thickness was about 21 μm on both sides.

The binary microrelief was calculated by a stochastic procedure [11] modification based on a genetic algorithm. The calculation was performed with the following parameters: a 30-mm aperture diameter, a 141-μm working wavelength, a 110-mm distance between the plane of element placement and the beginning of the paraxial segment point, a 9-mm radius of the Gaussian illuminating beam; the number of phase function counts along the radius was 200; the paraxial segment length was 30 mm.

The calculated microrelief height of a radially symmetric DOE is defined by the formula (see [1]).

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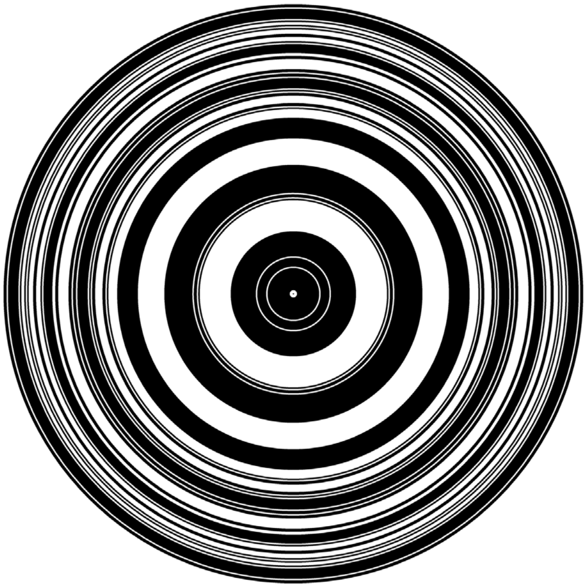

Figure 1. Calculated phase function of focusator (white color: phase value of π; black color: phase value of 0).

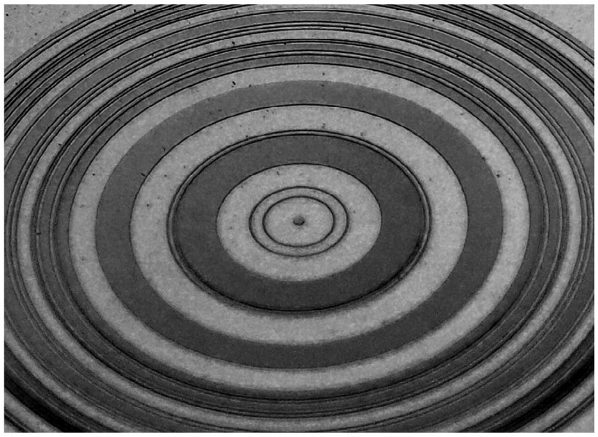

Figure 2. Photo of fabricated element.

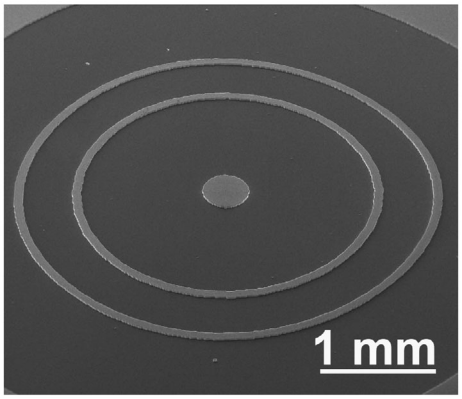

Figure 3. Photo of central fragment of microrelief produced.

$$h(r) = \lambda\varphi(r) / 2\pi(n-1) \qquad (1)$$

where n is the refractive index of the wafer material and $\varphi(r)$ is the phase function of the DOE [1]. Figure 1 shows the phase function $\varphi(r)$ calculated for a binary (double-level) focusator.

The silicon refractive index is $n = 3.42$, and therefore the calculated binary microrelief height is $h = 29.1$ μm for a 141-μm wavelength. The calculated value of the focusator energy efficiency varied in narrow boundaries for different paraxial segment cross-sections, making $e = 19.27\%$ on the average. Figure 2 shows the element fabricated.

3. Control of geometric parameters of microrelief

The geometric parameters of the DOEs fabricated were controlled by the methods of white light interferometry with the use of WLI-DMR interferometer (production of Fraunhofer Institute, Jena, Germany) and raster electronic microscopy with the use of Quanta-200 (FEI) microscope (see Figure 3). The interferometry method was applied as a tool to expres-control the etching depth and the bottom quality. The formed microrelief height deviated from the calculated value by 10% at most. An electronic microscope was used for estimation of the wall and bottom quality and determination of the microrelief element size.

4. Studies of elements using NovoFEL

The optical characteristics of the fabricated DOEs were examined at one of the workstations of NovoFEL. The optical scheme of the experiment is shown in Figure 4. The laser generated a monochromatic radiation with a 100-ps pulse duration at a 5.6-MHz repetition frequency. The laser beam had a Gaussian-type intensity distribution. During the experiments, the average radiation power was tens of watts. The laser wavelength was tuned to $\lambda = 141$ μm at which all experiments were carried out. The radiation transmitted through the element was registered with the aid of a 320 × 240-microbolometer array detector [15].

5. Experimental results

Figure 5 shows the results of the measurements of the THz radiation intensity distribution in planes at different distances from the focusator. Note that the intensity distribution of the focused beam is still close to the Gaussian type.

It was noted [11] that the elements used for the formation of a paraxial segment from the Gaussian beam and calculated by an iteration procedure had optical power.

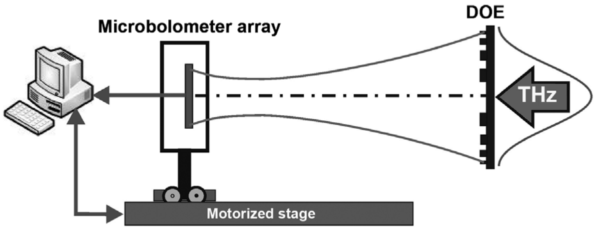

Figure 4. Optical scheme of experiment with FEL.

This fact explains the "self-reproduction" of the Gaussian beam during its propagation along the focusing segment (see Figure 5).

The energy efficiency values measured in different planes during the experiment are in good agreement with the calculated values (see Table 1).

Figure 6 shows the intensity distribution along the optical axis obtained experimentally and in the numerical simulation.

The application of the fabricated optical element enabled the formation of paraxial intensity distribution in the given space boundaries of 110–140 mm (see Figure 6).

It was shown [16] that in the case of the Gaussian beam focused by a spherical lens, the beam width would be $\omega^2 = \omega^2_0 + (z/k\omega_0)^2$, where $\omega = \sigma/\sqrt{2}$; z is the distance from focal plane; ω_0 is the beam width in the focal plane; k is the wavenumber; and σ is the beam mode radius. It can be shown also that for a lens with a focal distance of $f = 125$ mm and the experimental parameters used, the intensity on the optical axis will fall down 7.7-fold at a distance of 15 mm from the focal plane. A comparison of the results shown in Figure 6 with the estimation of the spherical lens focal depth shows that the application of the fabricated element makes it possible to increase the focal depth significantly. It is very important, for example, for the development of THz scanning systems.

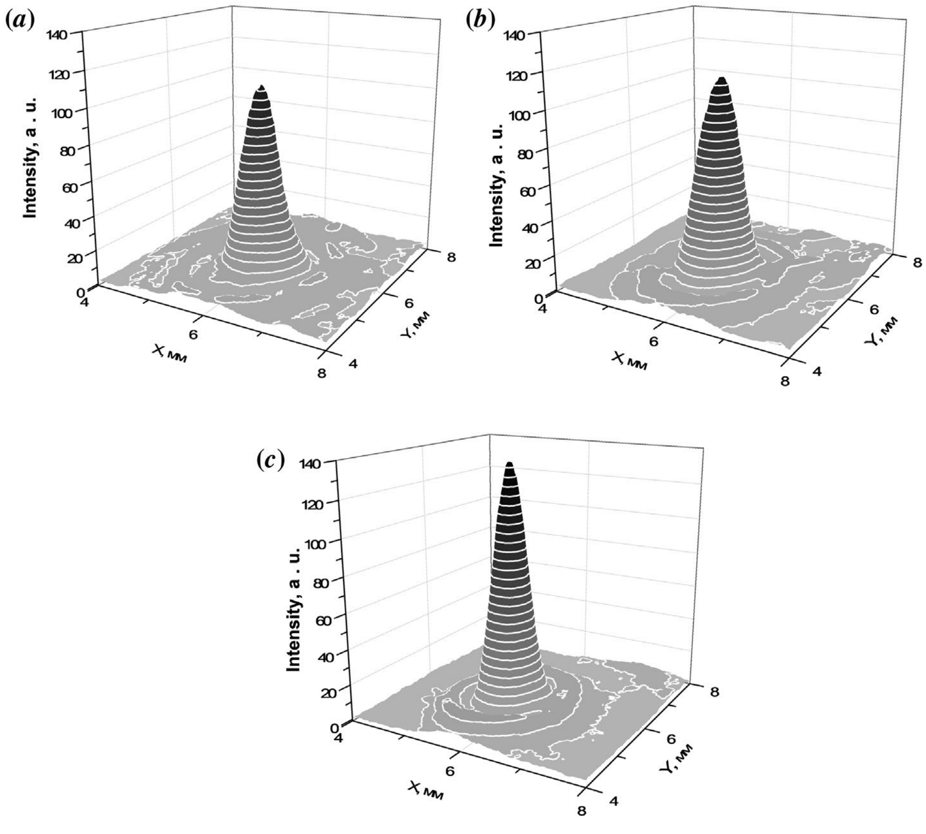

Figure 5. THz beam intensity distribution in planes at different distances *z* from element positioning plane, (*a*) *z* = 110 mm, (*b*) *z* = 125 mm, and (*c*) *z* = 140 mm.

Table 1. Measured energy efficiency of fabricated focusator.

Distance between DOE plane and registration plane, mm	110	125	140
Energy efficiency *e*, %	18.6	18.2	17.4

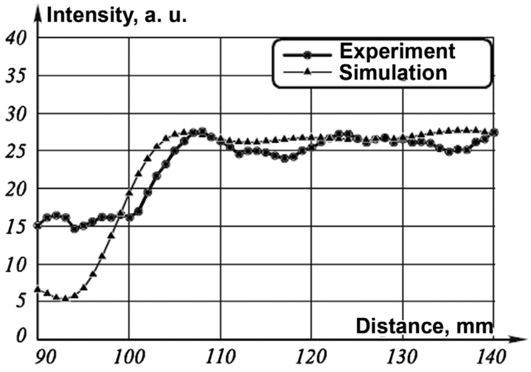

Figure 6. Intensity distribution along the optical axis formed by element fabricated.

6. Conclusion

The experiments have shown the possibility of the application of binary DOEs for the formation of paraxial intensity distribution of THz radiation. Improvement in the technology of silicon microrelief formation, in particular, increase in the number of levels of microrelief quantization, in future will enable increasing the energy efficiency of silicon elements intended for THz beam focusing into paraxial focal areas.

This work was supported by the Ministry of Education and Science of the Russian Federation and RFBR under grants 13-02-97007 and 11-02-12171-ofi-m. The experiments were carried out using equipment belonging to the Siberian Center of Synchrotron and Terahertz Radiation.

Operation of the user station “Terarad”, belonging to the Novosibirsk State University, was supported by the Ministry of Education and Science of the Russian Federation (MES RF). The diffractive optical elements were designed under the support of MES RF (project 1879) and fabricated under the support of RFBR under grant 13-02-97007. The equipment for characterization of the DOEs was developed with the support of Russian Science Foundation (project 14-50-00080). The experiments were carried out using equipment belonging to the Siberian Center of Synchrotron and Terahertz Radiation.

References

[1] Soifer, V.A.; *Computer Design of Diffractive Optics*; International Science Publishing Ltd. & Woodhead Pub. Ltd.: Cambridge, 2012.

[2] Agafonov, A.N.; Choporova, Y.; Kaveev, A.K.; Knyazev, B.A.; Kropotov, G.I.; Pavelyev, V.S.; Tukmakov, K.N.; Volodkin, B.O. *Appl. Opt.* 2015, *54* (12), 3635–3639.

[3] Walsby, E.D.; Alton, J.; Worrall, C.; Beere, H.E.; Ritchie, D.A.; Cumming, D.R.S. *Opt. Lett.* 2007, *32* (9), 1141–1143.

[4] Sypek, M.; Makowski, M.; Hérault, E.; Siemion, A.; Siemion, A.; Suszek, J.; Coutaz, J.-L. *Opt. Lett.* 2012, *37* (12), 2214–2216.

[5] Siemion, A.; Siemion, A.; Makowski, M.; Sypek, M.; Hérault, E.; Garet, F.; Coutaz, J.-L. *Opt. Lett.* 2011, *36* (11), 1960–1962.

[6] Siemion, A.; Siemion, A.; Makowski, M.; Suszek, J.; Bomba, J.; Czerwiński, A.; Sypek, M. *Opt. Lett.* 2012, *37* (20), 4320–4322.

[7] Agafonov, A.N.; Volodkin, B.O.; Kaveev, A.K.; Knyazev, B.A.; Kropotov, G.I.; Pavelyev, V.S.; Soifer, V.A.; Tukmakov, K.N.; Tsygankova, E.V.; Choporova, Yu. Yu. Optoelectron. Instrum. Data Process., 2013, 49 (2), 189–195

[8] Knyazev, B.A.; Kulipanov, G.N.; Vinokurov, N.A. *Measur. Sci. Techn.* 2010, *21*, 054017, pp 13.

[9] Agafonov, A.N.; Volodkin, B.O.; Volotovsky, S.G.; Kaveev, A.K.; Knyazev, B.A.; Kropotov, G.I.; Tykmakov, K.N.; Pavelyev, V.S.; Tsygankova, E.V.; Tsypishka, D.I.; Choporova, Yu.Yu.; *Comput. Opt.* 2013, *37*, (4), 464–470. Russian.

[10] Golub, M.A.; Karpeev, S.V.; Prokhorov, A.M.; Sisakyan, I.N.; Soifer, V.A. *Sov. Tech. Phys. Lett.* 1981, *7* (10), 618–623. Russian.

[11] Kachalov, D.G.; Pavelyev, V.S.; Khonina, S.N.; Skidanov, R.V.; Moiseev, O.Y. *J. Mod. Opt.* 2011, *58* (1), 69–76.

[12] Ayón, A.A.; Braff, R.; Lin, C.C.; Sawin, H.H.; Schmidt, M.A. *J. Electrochem. Soc.* 1999, *146* (1), 339–349.

[13] Gatesman, A.J. *IEEE Microw. Wirel. Compon. Lett.* 2000, *10*, 264–266.

[14] Hübers, H.W.; Schubert, J.; Krabbe, A.; Birk, M.; Wagner, G.; Semenov, A.; Gol’tsman, G.; Voronov, B.; Gershenzon, E. *Infrared Phys. Technol.* 2001, *42*, 41–47.

[15] Dem’yanenko, M.A.; Esaev, D.G.; Knyazev, B.A.; Kulipanov, G.N.; Vinokurov, N.A.; *Appl. Phys. Lett.* 2008, *92*, 131116 1–3.

[16] Karlov, N.V. *Lectures on Quantum Electronics*; “Mir” Publishers: Moscow; CRC Press: Boca Raton, FL, 1993.