Research Article | Vol. 54, No. 12 / April 20 2015 / Applied Optics 3635

applied optics

Control of transverse mode spectrum of Novosibirsk free electron laser radiation

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Received 19 January 2015; revised 20 March 2015; accepted 20 March 2015; posted 20 March 2015 (Doc. ID 232750); published 14 April 2015

This paper presents experimental results on the formation of given laser modes from an illuminating Gaussian beam of the terahertz Novosibirsk free electron laser at a wavelength of 141 μm. Binary silicon diffractive optical elements were applied. The experimental results obtained are in good agreement with the results of computer simulation.

OCIS codes: (050.1380) Binary optics; (050.1970) Diffractive optics; (140.2600) Free-electron lasers (FELs); (040.2235) Far infrared or terahertz.

http://dx.doi.org/10.1364/AO.54.003635

1. INTRODUCTION

Diffractive optical elements (DOEs) have found wide applications in laser technological equipment and optical devices in the visible and infrared spectral ranges [1]. DOEs matched to visible and infrared range radiation modes (so called modans) are well known [1–3]. It was shown [2,3] that diffractive optics methods allow formation of coherent radiation beams of an almost arbitrary transverse mode spectrum. Designing DOEs to form visible or infrared laser radiation beams of a given mode spectrum provides a solution to a number of fundamental and engineering problems: etalon beam formation [3], micro- and nanoparticle manipulation [1,4], and an increase in fiber-optic sensor sensitivity [5]. It was shown [3,6] that diffractive optics methods make it possible to increase the number of channels in telecommunication fiber systems. Paper [7] presents the results of the investigation of a single-mode beam formed by DOEs for the control of gas discharge. Development of terahertz lasers opens new possibilities in such fields as fundamental research, material science, biomedicine, telecommunications, security, and monitoring [8]. A prospective application of terahertz lasers in lidar systems is considered in [9]. Paper [10] presents the results of gas discharge control using a terahertz laser beam. Most papers on DOEs of the terahertz range are devoted to the investigation of focusing elements (mainly lenses [11,12]) and diffractive gratings (beam splitters [13]). Application of a silicon binary diffraction lens and a beam splitter for control of the NovoFEL radiation was demonstrated in papers [12,13]. Paper [14] presents results on a silicon binary diffractive element designed for focusing a NovoFEL Gaussian beam into a square spot of uniform intensity distribution. Development of DOEs for the formation of terahertz laser beams of certain transverse modes will allow for an improvement in terahertz lidars, an increase in the capacity of prospective terahertz-range free-space telecommunication systems, and control of gas discharge. In paper [15], a spiral polymer plate was applied to form terahertz vortex beams (i.e., beams with topological charge). Such a technique, however, cannot be used for the formation of beams with no topological charge [3]. In this paper, we describe the design and fabrication of silicon binary elements for forming various single-mode beams from a Gaussian beam and present results of their investigation on NovoFEL. The Gaussian–Hermite modes (1, 0) and (1, 1) and Gauss–Laguerre mode (2, 2) were chosen. The characteristics of the Novosibirsk free electron laser (NovoFEL), which was a source of terahertz radiation in our experiments, were described in [8]. We fabricated binary silicon elements to form modes from an illuminating FEL beam by a technology similar to that in [12–14].

2. SYNTHESIS OF DOES FOR FORMATION OF GAUSSIAN MODES

Optical-quality double-sided polished HRFZ-Si wafers [16] of 30 and 38 mm in diameter and 1 mm thick were used for DOE fabrication. The calculated binary microrelief 29.1 μm high was formed on the wafer surface via reactive-ion etching (RIE) of

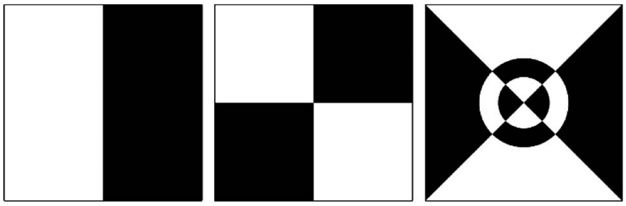

Fig. 1. Phase functions of elements that form beams of (left) Gaussian–Hermite modes (1,0), (middle) (1,1), and (right) Gauss–Laguerre mode (2,2). The white color corresponds to a phase of π and the black color to a phase of 0.

silicon. The elements were fabricated at the Research and Education Center of Nanotechnology at the Samara State Aerospace University (Samara, Russia). The RIE of the silicon wafer surface was carried out with the use of the equipment ETNA-100-PT (produced by NT-MDT, Zelenograd, Russia).

The phase transmission functions of the binary elements were taken as the phase distribution functions in the cross section of the forming Gaussian modes. It was shown earlier in [1] that low-order Gaussian mode formation from a Gaussian illuminating beam using a pure phase element would be better performed with the binary element phase function taken as the phase distribution function of the forming mode. The reason is that in this case, over 70% of the partial power of the forming mode in the beam will be behind the element, although only the illuminating beam phase is influenced. The noise, which appears to be due to the difference between the intensity distribution in the illuminating beam and in the forming mode cross section, falls mainly on the high-order modes.

The elements for the formation of the Gaussian–Hermite modes (1, 0) and (1, 1) and Gauss–Laguerre mode (2, 2) were designed and fabricated. They have the following parameters: an operating wavelength of 141 μm, a 30 mm aperture for the Gaussian–Hermite mode (1, 0), and a 38 mm aperture for the Gauss–Laguerre mode (2, 2) and Gaussian–Hermite mode (1, 1). The mode radius of the forming Gauss–Laguerre beam (2, 2) was 5 mm. Elements with 25 × 25 and 50 × 50 μm discretization steps were fabricated.

The calculated binary phase functions of the elements are presented in Fig. 1. The step height is equal to $h = \lambda/2(n - 1) = 29.1$ μm [1], where the refractive index of silicon is 3.42. An image of the element fabricated for formation of the Gauss–Laguerre mode (2, 2) is shown in Fig. 2.

3. CONTROL OF MICRORELIEF GEOMETRY PARAMETERS

The resulting DOE geometry parameters were checked by the white light interferometry method (see Fig. 3) with the use of a white light interferometer (produced by Fraunhofer Institute, Jena, Germany) and by the raster electronic microscopy technique with the use of a Quanta-200 (FEI) microscope. The interferometry method was applied in express control of the etching depth and the bottom quality. The electronic microscope was employed for estimation of the wall and bottom quality, as well as for the determination of the microrelief element size.

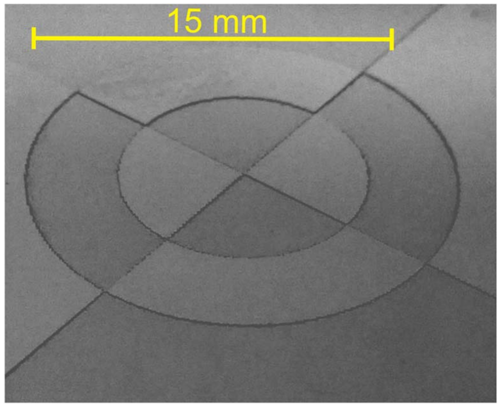

Fig. 2. Photography of an element fabricated for the formation of Gauss–Laguerre mode (2, 2), with an image scale.

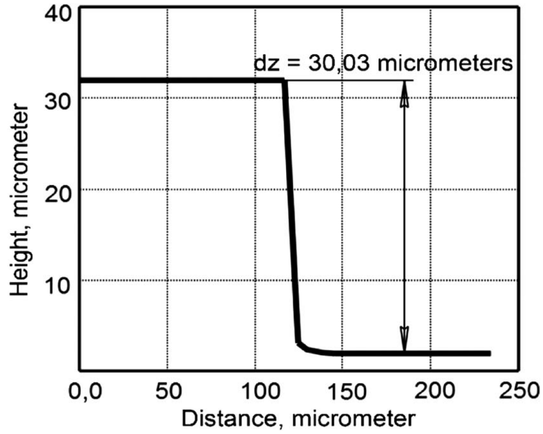

Fig. 3. Profile of the microrelief produced. The arrow marks the relief height.

4. STUDIES OF ELEMENTS WITH THE USE OF NOVOFEL

In the experiments performed at the one of the workstations of NovoFEL facility, the optical characteristics of the DOEs were examined. The optical scheme for the measurement of intensity distribution in different planes is shown in Fig. 4. The laser

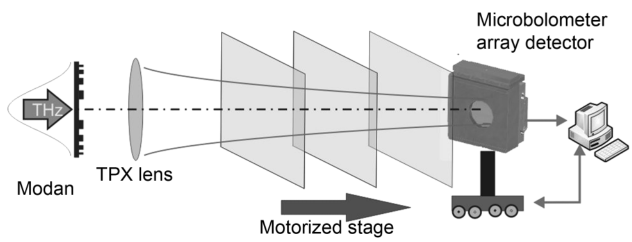

Fig. 4. Optical scheme of the experiment for intensity distribution measurement in resulting beam cross sections.

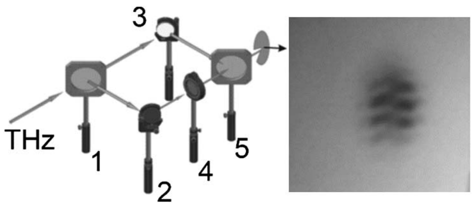

Fig. 5. Optical scheme (left) of the experiment for the study of phase structure of mode beams by the interferometric method (1 and 5, polypropylene-film beam splitters; 2 and 3, mirrors; 4, modan). The interference pattern was obtained using a photo camera and a phosphor plate (right).

beam had a Gaussian intensity distribution. The average radiation power in the experiments was tens of watts. The experiments were carried out at $\lambda = 141$ μm. The radiation transmitted through the element was focused with a TPX lens ($f = 150$ mm) and recorded with a microbolometer array detector [17] with a physical size of 16.36 × 12.24 mm. The detector was placed on a motorized stage that could be moved along the optical axis of the system.

Figure 5 presents the optical scheme to study the phase structure of the resulting mode beams. A modan was placed in one of the Mach–Zender interferometer arms. Since the sensitive area of the microbolometer matrix was too small, the interference pattern was recorded with a thermal sensitive phosphor plate produced by Macken Instruments, Inc. and a visible range CCD camera. When illuminated by a mercury lamp, the phosphor plate lit up in the yellow spectral region [18]. The incident terahertz radiation illuminated the plate, and thus the intensity of luminescence in the exposed area decreased proportionally to the local temperature increase. Although the phosphor plate had a relatively low sensitivity to terahertz radiation, its screen size of 76 × 76 mm allowed for the recording of the whole diffraction pattern (Fig. 5, right).

5. EXPERIMENTAL RESULTS

Figure 6 shows the etalon intensity distributions of the forming modes. The left parts of Figs. 7–9 show the results of the measurements (see the experimental scheme in Fig. 4) of the single-mode beam intensity distribution in planes at different distances behind the TPX lens in comparison with the calculated distributions shown on the right.

The experiments were carried out with a Gaussian beam of a mode radius of about 15 mm. The diffraction beam was generated via illumination of a binary modan with an initial Gaussian laser beam. The calculated intensity distributions in planes at different distances from the TPX lens are presented in the right-hand parts of Figs. 7–9. The results shown in Figs. 7–9 demonstrate that the intensity structure of the formed beams is preserved during their propagation. The experimental results are in general agreement with the numerical simulation results. The misfit in the experimental and calculated results is apparently due to the deviation of the illuminating beam from a pure Gaussian one with a plane wave front. It also comes from the high-order modes in the initial beam. Figure 10 shows the results of the study on the phase structure of the formed Gaussian–Hermite (1, 0) single-mode beams. The band shift in the diffraction pattern (see Fig. 10, right) is consistent with the phase shift between the two "lobes" (see Fig. 6, left) in the Gaussian–Hermite mode (1, 0) cross section, which is close to π.

It is worth noting that the refractive index of silicon ($n = 3.42$) is larger than that of the materials used for the fabrication of modans for visual and near infrared wavelength ranges [1]. Thus, because of the Fresnel losses, silicon binary modans have smaller energy efficiency than their analogs for visual and NIR ranges. This problem, however, can be solved easily with an antireflection coating on both sides of the modans, as was realized for silicon binary lenses and gratings

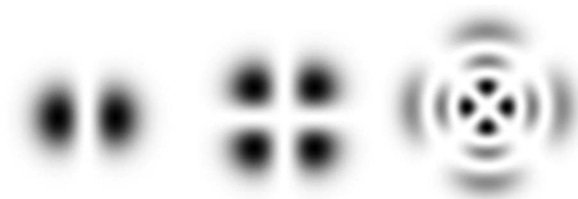

Fig. 6. Etalon intensity distributions of modes: (left) Gaussian–Hermite (0, 1), (middle) Gaussian–Hermite (1, 1), and (right) Gaussian–Laguerre (2, 2).

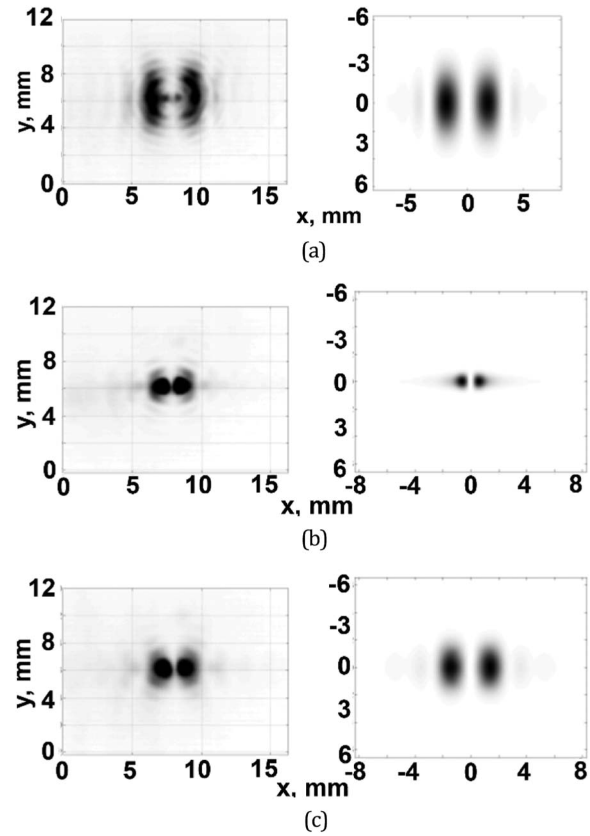

Fig. 7. Intensity distribution of the formed Gaussian–Hermite (1, 0) single-mode beam in planes behind the TPX lens at distances of (a) 125 mm, (b) 150 mm, and (c) 175 mm. Left part: experiment; right part: theory.

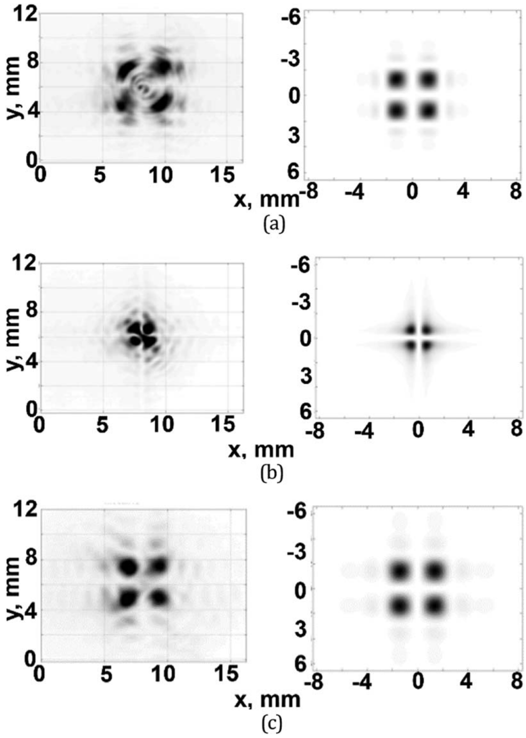

Fig. 8. Intensity distribution of the formed Gaussian–Hermite (1, 1) single-mode beam in planes behind the TPX lens at distances of (a) 125 mm, (b) 150 mm, and (c) 175 mm. Left: experiment; right: theory.

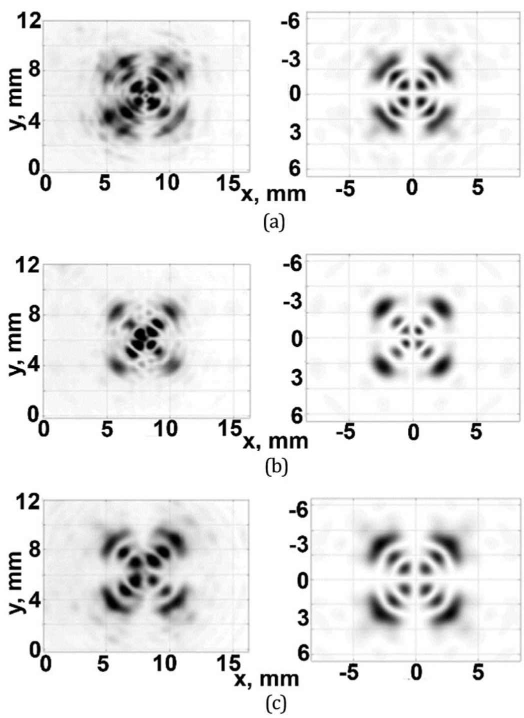

Fig. 9. Intensity distribution of the formed Gauss–Laguerre (2, 2) single-mode beam in the planes behind the TPX lens at distances of (a) 125 mm, (b) 150 mm, and (c) 175 mm. Left: experiment; right: theory.

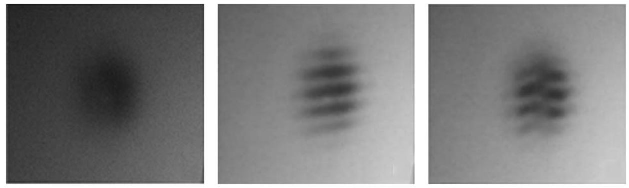

Fig. 10. Results of studies on phase structure of formed single-mode beam. (Left) initial Gaussian beam; (middle) interference of two Gaussian beams; (right) interference of Gaussian beam with Gaussian–Hermite (1, 0) single-mode beam.

[12,13], where deposition of Parylene C layers doubled the DOE transmittance.

6. CONCLUSION

The experiments showed the feasibility of the application of binary DOEs to the transformation of a high-power terahertz Gaussian beam of a free electron laser into Gaussian–Hermite and Laguerre–Gaussian modes. The quality of the beams formed can be further improved with the generalized Kirk–Jones method [3] for the calculation of the DOE phase functions. The possible applications of high-power Gaussian–Hermite and Laguerre–Gaussian beams include the control of continuous optical discharge of a determined plasma column configuration, formation of nondiffracting beams for terahertz radar, and an increase in the capacity of information channels for prospective THz telecommunication systems.

Ministry of Education and Science of the Russian Federation (1879); Russian Foundation of Basic Research (13-02-97007, 15-02-06444); Russian Science Foundation (14-50-00080).

The experiments were carried out with the application of equipment belonging to the Siberian Center of Synchrotron and Terahertz Radiation. The authors are grateful to G. N. Kulipanov and N. A. Vinokurov for interest in this work and stimulating discussions, and to the NovoFEL team for the invaluable support of the experiments.

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