Diagnostic stand for quality control of diffractive optical element manufacturing

A.V. Mezhenin[1], Yu.G. Kurenkova[1], A.R. Rymzhina[1]

[1]Samara National Research University, Moskovskoe Shosse 34A, Samara, Russia, 443086

Abstract. A diagnostic stand has been created to study the parameters of laser radiation transformed by diffractive optical elements (DOE) designed for operation in the infrared range. The optical systems included in the stand allow recording the intensity distribution formed by the elements of micro-optics in different planes that is necessary to control the focusing quality and to estimate the focus depth. They also provide an opportunity to measure the DOE power efficiency. Experimental approbation of optical systems on the example of a reflecting binary cylindrical lens and a Fresnel lens has been carried out.

Keywords: diffractive optical element, binary cylindrical lens, Fresnel lens, intensity distribution, focusing quality, focus depth, power efficiency.

1. Introduction

The laser technics development [1] and its applications in heat treatment tasks [2]–[4], measurements [5] and scientific research [6], [7] highlighted the need to develop various means of radiation control. One of ways to manage radiation is the use of diffractive optical elements (DOE) [8]–[10], which are artificial two-dimensional structures that make it possible to form beams with given properties.

Progress in the field of laser technology and microelectronics in the late 80's led to the creation of diffractive optical elements with a complex profile of the zones. DOEs with unique characteristics unattainable within the framework of traditional optics appeared. In 1981, a scientific group led by academician A.M. Prokhorov solved the problem of focusing laser radiation in an arbitrary curve with the required intensity distribution and created corresponding diffractive optical element – a focusator [11], [12]. A wide range of focusator applications is now closely related to the ability to realize the required beam intensity distribution on the processed object surface. In addition, radiation control with DOE of this class makes it possible to increase the power efficiency of the processes being implemented.

The main parameters characterizing DOE from the viewpoint of radiation control are the intensity distribution in the focal plane and the power efficiency. In the focusator calculation, the intensity distributions in the incident beam and required one in the focal plane are specified. It is assumed that an object with which the laser beam will interact is in the DOE focus. To verify the optical element quality, it is necessary to compare the focusing area dimensions and the energy distribution within it with the calculated values. Registration of intensity distributions in the focal plane and in planes coplanar to it, located at different distances from it, allows additionally estimate the focus depth.

Energy distribution data are also auxiliary in measuring the power efficiency e, which is the ratio of the energy caught in a given region L of the focal plane to the illuminating beam energy:

$$e = \int_L I(x) d^2x / \int_D I_0(u) d^2u, \tag{1}$$

where $I(x)$ is the focal intensity distribution, $I_0(u)$ is the intensity distribution of the illuminating beam. Currently, software to calculate these values has been created [13]. The quality of the beam formed by DOE can be judged from the results of power efficiency measurements by an indirect method. The higher the experimentally measured value of this parameter, the lower power the incident beam must have to create the necessary energy concentration in the given shape action zone. Consequently, power efficiency directly affects the resistance of an optical element to radiation and its reliability.

The registration of the spatial power distribution in the beam cross-section (in particular, measurement of the laser beam diameters and energy divergence) is a serious problem for CO_2-laser radiation. When imaging in the far infrared range, recording media that are traditional for the visible and near infrared regions cannot be used. Registration of the spatial intensity distribution in the cross section of CO_2-lasers beams is a special case in the problem of infrared long-wave images visualization. For this reason, the so-called 'imprint method' is often used in practice where the intensity distribution is determined from the burning form on the organic glass, for example [10]. This method is also used in the certification of lasers [14]. However, it is not always effective because it does not permit to obtain quantitative information. Film visualizers have low sensitivity, whereas multichannel recorders have low resolution. A significantly higher resolution was obtained on infrared imaging devices based on reading information from multi-element two-coordinate receiving targets using an electronic or optical beam [15]. At present, a number of instruments have been developed, in particular, based on the bolometric [16] or pyrometric [17] effect, allowing real-time registration of far infrared radiation with the possibility of subsequent measurement result digitization.

The purpose of this work is to create a diagnostic stand for studying the parameters of radiation formed by diffractive optical elements and measuring the efficiency of energy conversion by them.

2. The objects of the study

In this work, a phase reflecting binary cylindrical lens (Figure 1) and a Fresnel lens with a halftone relief have been chosen as the elements forming laser radiation. The choice of the objects under investigation is due, on the one hand, to the fact that the quantized stepped reliefs have become most widespread [18], [19]. On the other hand, the gradient DOE surface profile provides a higher energy concentration in a given region, despite of the manufacturing complexity. It is of interest to analyze the structure of radiation formed by them within the framework of real experiment.

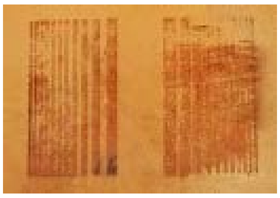

Figure 1. Binary cylindrical lens.

Both optical elements have been calculated to operate at an angle of 45° to the axis of the incident beam. The first element represents two regular structures etched on one substrate. The relief of one of them is inverted with respect to the other. The aperture size of each binary lens is 20×20 mm. The Fresnel lens circular aperture diameter is 40 mm. The binary lens focal distance is 0.6 m, the Fresnel lens focal length is 0.7 m. The stepped profile is made close to the calculated one (overetching does not exceed 100 nm), and the gradient one is characterized by a significant (more than 1 μm) underetching in the central region and even more on the periphery.

3. Diagnostic stand

The intensity distribution registration of DOE-formed radiation is supposed to be carried out in real time using the bolometric IR-camera XPORT-317 operating in the wavelength range 8–14 μm. The presence of this type device in optical system entails the imposition of restrictions on the laser beam power. For this reason, the CO_2-laser LCD-1A with a nominal output power of 1 W has been used as a radiation source. Its maximum power of radiation in a single-mode operation is 3.2 W.

To record the intensity distribution of the radiation formed by DOE, it is necessary that the illuminating beam completely covers its surface, that is, creates conditions for the operation of not only the central but also the peripheral zones of the optical element. Since the LCD-1A output laser beam diameter (1.8 mm) is much smaller than the aperture size of the studying DOEs (see section 2), a two-lens collimator is provided in the optical system. The stand scheme is shown in Figure 2.

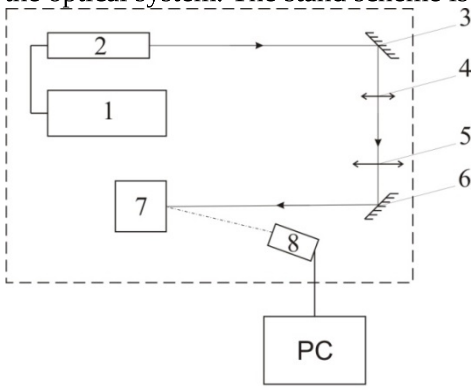

Figure 2. The stand composition: 1 – power supply; 2 – laser; 3 – rotary mirror; 4, 5 – collimator lenses; 6 – DOE; 7 – power meter or screen; 8 – IR-camera; PC – personal computer.

Two collimators have been used in the experiments. The first was formed by two collecting lenses. It was used to study the parameters of the beam formed by the binary DOEs. The second has consisted of the input diffusing and the output collecting lenses and has been used to explore the beam formed by the Fresnel lens. The optical systems used in the stand are described in more detail in [20]. The photos of the stand in two variants are shown in Figure 3.

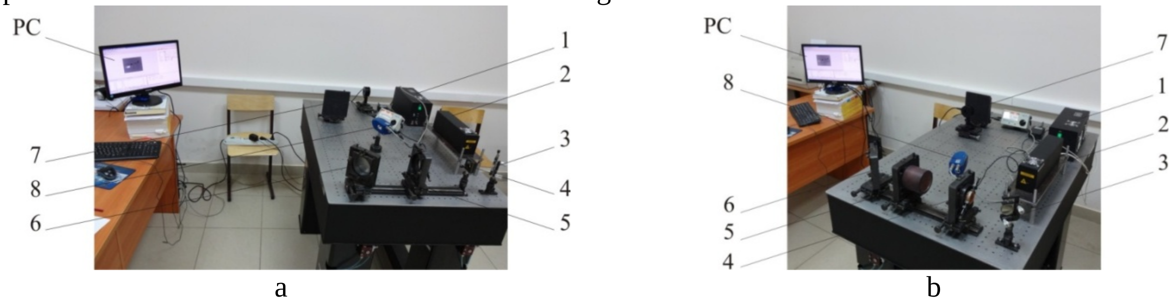

Figure 3. Photos of the stand for studying the characteristics of radiation formed by DOE: (a) binary lenses, (b) Fresnel lens. Numbering corresponds to Figure 2.

The power efficiency has been determined using a Spectra Physics 407A power meter with an error of ±3 % in the wavelength range of 250 nm–11 μm. The detector measuring head diameter of the device was 1.8 cm.

4. Results and discussion

Figure 4 shows the intensity distributions (images are inverted) obtained for a binary lens located on the left side of the substrate in the focal plane (Figure 4, e) and several planes coplanar to it. The analysis of the snapshots allows us to conclude that a beam is forming and has no sharp boundaries at a short distance from the DOE. The focus area acquires clear boundaries starting at intervals of 40 cm from the lens. The best quality of focusing is achieved at a distance corresponding to the calculated position of the focal plane. Clear contours of vertical segments remain at considerable length. The image begins to blur at a spacing of about 40 cm behind the focal planes. The snapshots involve details those indicate the presence of defects in the reflective coating and technological DOE manufacturing errors.

Figure 5 indicates the intensity distributions in the central sections of the focal segment for the left lens. Digitization of images is carried out using the program OriginPro 8. It can be seen that the intensity along the segment after the DOE transformation retains the Gaussian distribution over the cross section. The transverse distribution, also Gaussian, is characterized by the presence of a maximum with the width of about 2 mm.

Similar reasoning is valid for the right element that is confirmed by the data in Figure 6. A square area corresponding to the DOE geometry is clearly discernible in all the snapshots. The intensity distribution formed in the focal plane (Figure 7) is similar to the focal distribution for the left lens in its parameters.

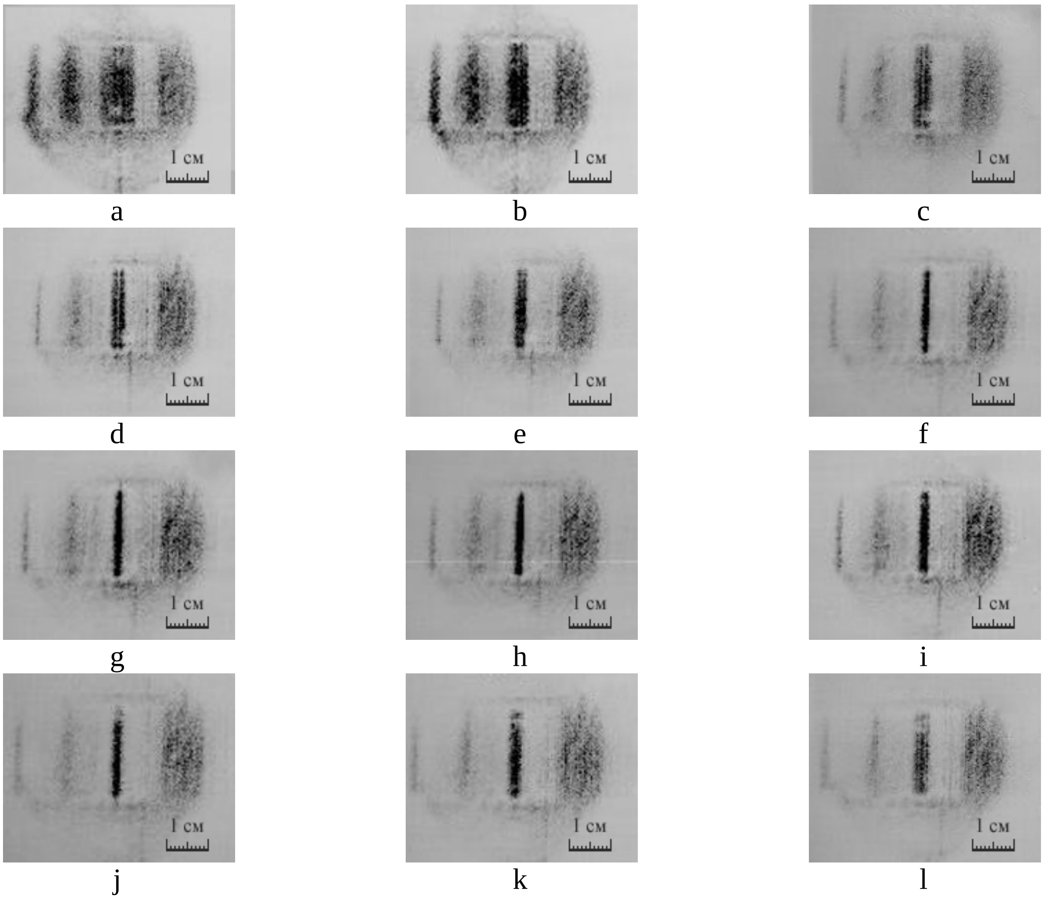

Figure 4. The intensity distributions of the radiation transformed by the left binary lens in the planes located at distances from DOE: a – 30 cm, b – 40 cm, c – 45 cm, d – 50 cm, e – 55 cm, f – 60 cm, g – 65 cm, h – 70 cm, i – 75 cm, j – 80 cm, k – 90 cm, l – 100 cm.

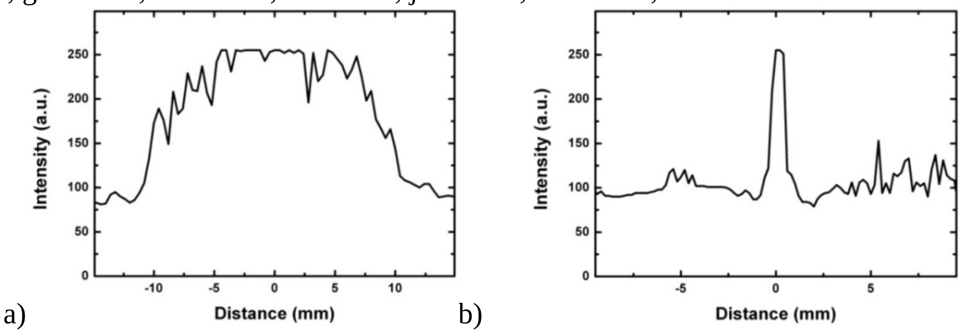

Figure 5. The intensity distributions of the radiation transformed by the left binary lens in the focal segment central sections: (a) longitudinal direction, (b) transverse direction.

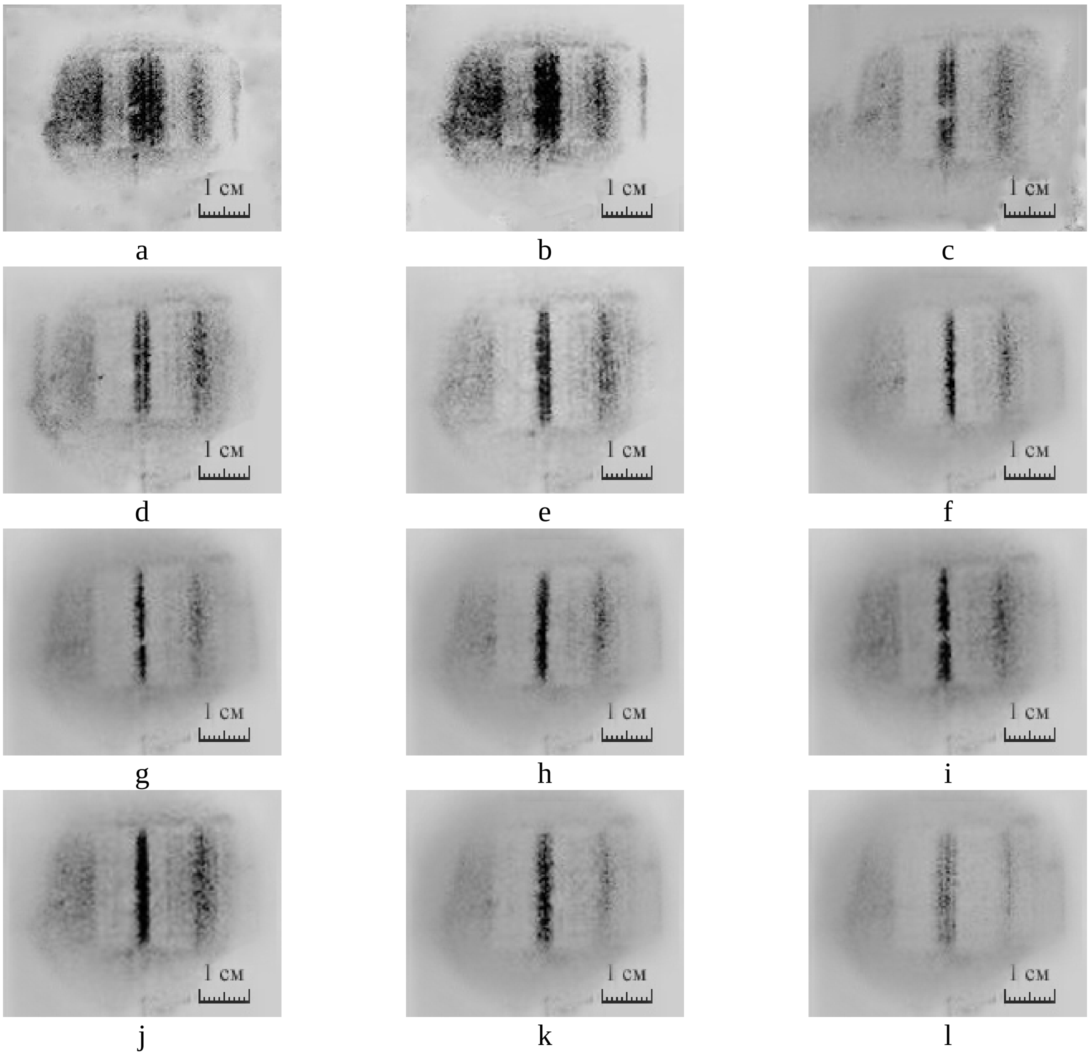

Figure 6. The intensity distributions of the radiation transformed by the right binary lens in the planes located at distances from DOE: a – 30 cm, b – 40 cm, c – 45 cm, d – 50 cm, e – 55 cm, f – 60 cm, g – 65 cm, h – 70 cm, i – 75 cm, j – 80 cm, k – 90 cm, l – 100 cm.

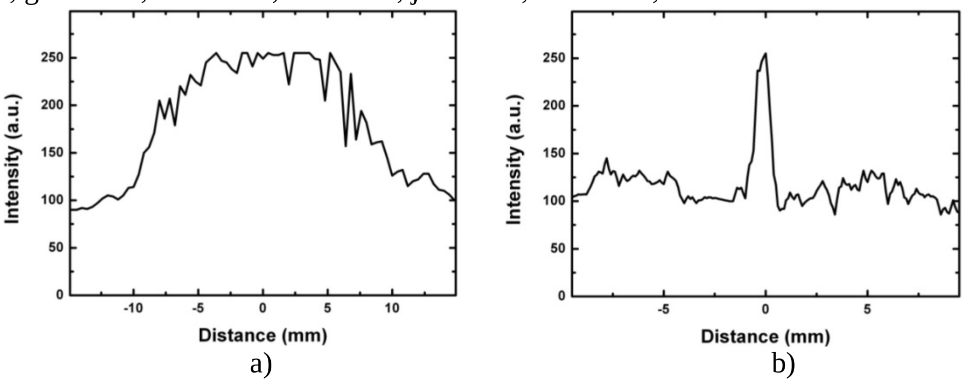

Figure 7. The intensity distributions of the radiation transformed by the right binary lens in the focal segment central sections: (a) longitudinal direction, (b) transverse direction.

In general, the quality of the beam formation by the binary lenses is enough high. The focus depth is approximately ±10 cm from the focal plane position. As expected, the DOE micro-relief profile inversion has no significant effect on the transformed beam characteristics.

Figure 8 illustrates the formation of radiation by the Fresnel lens. In this case, focusing occurs in a circular area. The image begins to delineate from the DOE at a distance of about 40 cm. The intensity distribution remains practically unchanged at distances of ±20 cm from the calculated focal plane position. The regions in the snapshots occupied by radiation do not have sharp boundaries. It indicates the presence of reflective coating defects.

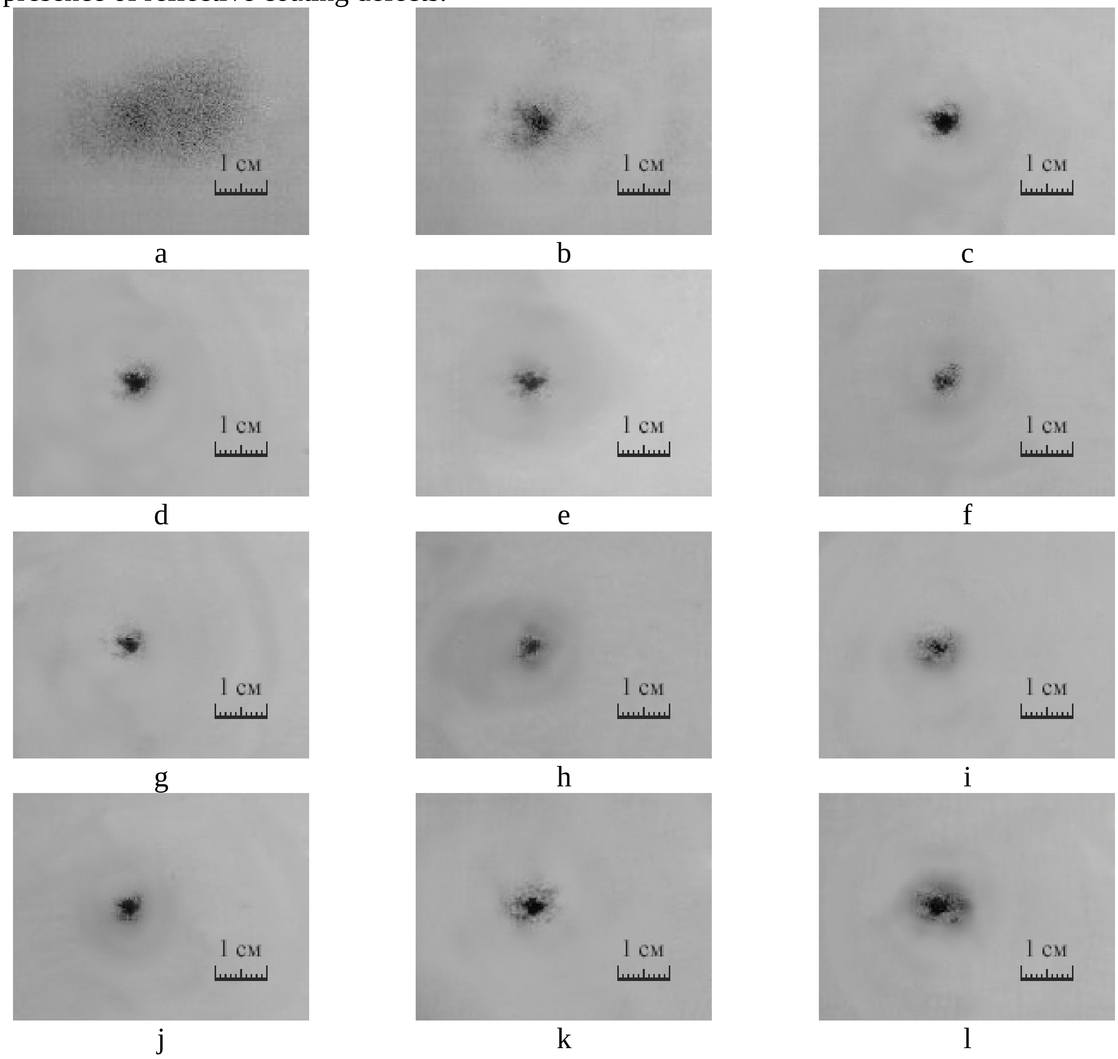

Figure 8. The intensity distributions of the radiation transformed by the Fresnel lens in the planes located at distances from DOE: a – 30 cm, b – 40 cm, c – 50 cm, d – 55 cm, e – 60 cm, f – 65 cm, g – 70 cm, h – 75 cm, i – 80 cm, j – 85 cm, k – 90 cm, l – 100 cm.

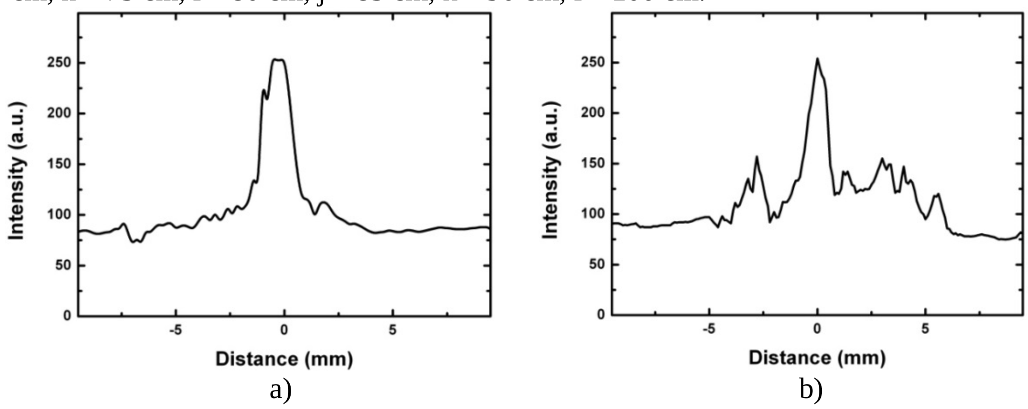

Figure 9. The intensity distributions of the radiation transformed by the Fresnel lens in the focal spot central sections: (a) vertical section, (b) horizontal section.

A significant intensity blurring also takes place within the focal spot. The distributions shown in Figure 9 indicate the lack of focus sharpness too. The spot diameter is about 5 mm in the focal plane. Consequently, the micro-relief structure is characterized by significant deviations from the calculated profile. The focusing quality of radiation by the Fresnel lens can be estimated as not high.

To determine the power efficiency from the formula (1), it is necessary to know the focal region size. Calculations of the focal spot size for the studying DOEs have not been carried out. The vertical segment dimension for binary lenses should correspond to the element dimension, i.e. to be 2 cm, when the incident beam is collimated. In the diffraction limit, the focal segment width for binary DOEs and the focal spot size for the Fresnel lens are about 40 and 25 μm, respectively. However, achieving such a high focusing degree is possible only in the case of elements with a smooth profile of optical surfaces. In this paper, the aim is to show the functional ability of the stand. So, we take the dimensions of the focal regions as they can be realized in practice. Then the focal segment width for binary lenses can be taken equal to the projection length of the central half-wave element zone onto the focal plane (approximately 2 mm). For the Fresnel lens, we assume that the focal spot is circular with a diameter equal to 5 mm according to the experimental data.

For correct measurement of power efficiency with the Spectra Physics device model 407A, the beam size at the collimator output has been regulated. The laser output power decreasing has made it possible to ensure that 100 % of the power entered the meter. The limitation of radiation transmission to the detector receiving area by the focal spot dimensions has been achieved by overlapping the opaque elements on the measuring head in the corresponding regions.

For binary lenses, the power efficiency has been 40 % at the beam power on the collimator output of 1 W (theoretical estimate – 41 %). The Fresnel lens power efficiency has been determined as 63 % at a collimator output beam power of 0.8 W. When the detector's receiving area has been fully open the Fresnel lens efficiency has not exceed 84 %.

5. Conclusion

The diagnostic stand for studying the parameters of laser radiation formed by DOE has been created. Approbation of the optical systems included in the diagnostic equipment has been carried out on the example of the reflecting binary cylindrical lenses and the Fresnel lens with gradient micro-relief.

Intensity distributions characterizing the collimated Gaussian beam transformation by the binary elements and by the Fresnel lens have been obtained. The results indicate a high focusing quality in the first case and unsatisfactory beam parameters in the second.

The power efficiency of the diffraction lenses has been determined. The experimental value of this parameter for cylindrical lenses is close to the theoretical estimate. Low Fresnel lens power efficiency is associated with significant deviations in the element micro-relief profile from the calculated one.

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7. References

[1] Rovinskii, R.Ye. High-power Technological Lasers/ R.Ye. Rovinskii // File *.pdf (1,39 Mb). –– Access mode: http://www.twirpx.com/file/946980/ (04.02.2017), 2005. (in Russian).

[2] Rykalin, N.N. Laser and Electron Beam Materials Processing: Reference Book / N.N. Rykalin, A.A. Uglov, I.V. Zuyev, A.N. Kokora. – Moscow: “Mashinostroyeniye” Publisher, 1985. – 496 p. (in Russian).

[3] Grigor'yants, A.G. Fundamentals of Laser Materials Processing / A.G. Grigor'yants. – Moscow: “Mashinostroyeniye” Publisher, 1989. – 304 p. (in Russian).

[4] Grigor'yants, A.G. Laser Treatment Technological Processes: Textbook for High Schools / A.G. Grigor'yants. – Moscow: Bauman MSTU Publisher, 2006. – 664 p. (in Russian).

[5] Paranin, V.D. Method of measurement of thickness of uniaxial anisotropic crystals and thermal control of bessel beam transformation / V.D. Paranin, S.V. Karpeev // Computer Optics. – 2016. – Vol. 40(1). – P. 36-44. DOI: 10.18287/2412-6179-2016-40-1-36-44.
[6] Paranin, V.D. Generation of radially polarized beams based on the refractive optical elements with interference polarizing coatings / V.D. Paranin, S.N. Khonina, S.V. Karpeev // Computer Optics. – 2015. – Vol. 39(4). – P. 492-499. DOI: 10.18287/0134-2452-2015-39-4-492-499.
[7] Paranin, V.D. A converter of circularly polarized laser beams into cylindrical vector beams based on anisotropic crystals / V.D. Paranin, S.V. Karpeev, A.P. Krasnov // Computer Optics. – 2015. – Vol. 39(5). – P. 644-653. DOI: 10.18287/0134-2452-2015-39-5-644-653.
[8] Kazanskiy, N.L. Application of radiation focusators for nanoporous crystalline materials structure formation /N.L. Kazanskiy, S.P. Murzin, V.I. Tregub, A.V. Mezhenin // Computer Optics. – 2007. – Vol. 31(2). – P. 48-51.
[9] Kazanskiy, N.L. Formation of the laser radiation to create nanoscale porous materials structures / N.L. Kazanskiy, S.P. Murzin, A.V. Mezhenin, E.L. Osetrov // Computer Optics. – 2008. – Vol. 32(3). – P. 246-248.
[10] Murzin, S.P. Laser nanostructurizing of metal materials by application of moveable radiation focusators / S.P. Murzin, V.I. Tregub, A.V. Mezhenin, E.L. Osetrov // Computer Optics. – 2008. – Vol. 32(4). – P. 353-356.
[11] Soifer, V.A. Diffractive Computer Optics / edited by V.A. Soifer. – Moscow: “Fizmatlit” Publisher, 2007. – 736 p. (in Russian).
[12] Soifer, V.A. Methods of Computer Optics: Textbook for High Schools / edited by V.A. Soifer. – Moscow: “Fizmatlit” Publisher, 2003. – 688 p. (in Russian).
[13] Pavelyev, V.S. IR range Power Optics on Diamond Films: Tutorial / V.S. Pavelyev, D.L. Golovashkin, V.A. Soifer. – Samara: SSAU Publisher, 2007. – 64 p. (in Russian).
[14] ROFIN DC Industrial CO_2 Slab Laser: Operating Manual. – Hamburg: ROFIN-SINAR Laser GmbH, 2002. – 199 p.
[15] Abil’siyatov G.A. Technological lasers: Reference book: in 2 vol. Vol. 2. / edited by G.A. Abil’siyatov. – Moscow: “Mashinostroyeniye” Publisher, 1991. – 544 p. (in Russian).
[16] X-Control XPORT Version 0.5: User Manual. – Leuven: XenICs, 2006. – 28 p.
[17] Infrared thermometer KELVIN: User Manual. – Moscow: Euromix, 2005. – 16 p.
[18] Kononenko, V.V. Study of the diamond diffractive cylindrical lens / V.V. Kononenko, V.I. Konov, S.M. Pimenov, A.M. Prokhorov, N.L. Kazanskiy, V.S. Pavelyev, V.A. Soifer // Computer Optics. – 1999. – Vol. 19. – P. 102-106.
[19] Khonina, S.N. Investigation of the axial line formation by optimized binary DOE / S.N. Khonina, R.V. Skidanov, D.G. Kachalov, V.S. Pavelyev, O.Yu. Moiseev // Computer Optics. – 2010. – Vol. 34(3). – P. 350-359.
[20] Kurenkova, Yu.G. Optical systems for research parameters of laser radiation transformed by infrared range diffractive elements / Yu.G. Kurenkova, A.V. Mezhenin // Proceedings of the III International Conference and the Youth School “Information Technologies and Nanotechnologies” (ITNT-2017), Samara, 25–27th April, 2017. – Samara: Novaya tekhnika, 2017. – P. 127-130.