Research methods of IR-range DOE

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Abstract. A set of methods for studying diffractive optical elements (DOE) operating in the far infrared region and the parameters of the radiation formed by them has been proposed. The results of optical surface defects local control for DOEs with binary and semitone relief obtained by non-contact methods have been presented. Approbation of the panoramic diagnostics method for determining parameters of laser beam transformed by DOE has been carried out.

1. Introduction

The development of laser technology [1] and its application fields: heat treatment [2]–[4], measurements [5] and scientific research [6], [7], highlighted the need to create various means of radiation control. Control is understood as changing the laser beam direction and its focusing. One of the ways to control radiation is the use of diffractive optical elements (DOE) – artificial two-dimensional structures that change the phase and amplitude of the electromagnetic wave incident on them in each point of their surface and allow them to form beams with given properties. Outwardly, the DOE is a transmissive or reflective plate with a phase microrelief calculated within the framework of diffraction theory [8], [9].

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 zone profile. The DOE with unique characteristics, unattainable for 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 the corresponding diffractive optical element – a focusator – was created. Now a wide range of focusator applications is closely related to the ability of realizing the required beam intensity distribution on the processed object surface [10], [11]. In addition, radiation control via a DOE of this class makes it possible to increase the implemented processes energy efficiency. The latter, however, is valid only with a high manufacturing quality of the optical element.

The DOE microrelief is calculated through the solution of the diffraction theory inverse problems and is realized with the aid of different technological recording devices. In addition to the embedded design parameters, the sharpness and depth of focusing, as well as the diffraction efficiency in different diffraction orders, depend on the closeness degree of the optical element calculated parameters to the actual ones. In this regard, the need to develop a set of actions permitting to make an unambiguous conclusion about the DOE manufacturing quality based on the diagnosis of its microrelief appears.

The microrelief height and the width of individual zones on the surface determine a set of methods for the DOE diagnostics. Traditionally, such non-contact methods as optical microscopy and white light interferometry can be included here. These methods allow local diagnostics of microrelief parameters.
The main parameters characterizing DOE from the viewpoint of radiation control are the intensity distribution in the focal plane and the power efficiency. To check the optical element quality, it is necessary to compare the size of the focusing area and the energy distribution within it with the calculated values. Panoramic recording of the intensity distributions in the focal plane and in planes coplanar to it, located at different distances from it, permits to judge additionally the focusing quality with a focus depth estimate. Data on the energy distribution are also auxiliary when measuring the energy efficiency, which is the ratio of the energy that has caught in a given focal plane region to the illuminating beam energy [12]. 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 impact zone of the given shape. Consequently, power efficiency directly affects the optical element resistance to radiation and its reliability.

The spatial power distribution registration in the beams cross sections (their diameter measurement, mode radius estimate, etc.) for the CO\textsubscript{2}-lasers emission is a serious problem [13]. To visualize the far infrared radiation intensity distribution, in practice, the “imprint method” is often used, when the intensity distribution is determined by the form of burning on an organic glass plate [14] or by the degree of wooden plate blackening. However, this method does not allow obtaining quantitative information. The main characteristics of multichannel recorders and visualizers of IR images are sensitivity and resolution [15]. At the present time, a number of instruments have been developed, in particular, bolometers [16] and pyrometers [17], which permit real-time registration of far infrared radiation with the possibility of measurement results subsequent digitization.

The purpose of this work is to create a set of actions that allow surface diagnostics of diffractive optical elements operating in the infrared range and to study the characteristics of radiation they form.

2. Local diagnostics of DOE microrelief

In this work, phase elements operating in reflection at an angle of 45° to the incident beam axis are chosen as the investigated DOEs forming laser radiation, namely, a binary cylindrical lens and a Fresnel lens with a semitone relief. Their photo masks are shown in figures 1 and 2. The first element represents two regular structures etched on one substrate. The relief of one of them is executed inverted in relation to the other. The aperture size of each binary lens is 20×20 mm. The circular aperture diameter of the Fresnel lens is 40 mm. The choice of objects is conditioned, on the one hand, by the fact that the quantized stepped reliefs have become most widespread [18], [19]. On the other hand, the surface gradient profile, in spite of the manufacturing complexity, makes it possible to achieve higher power efficiency.

Performing measurements of the DOE surface structural elements using the “Levenhuk 2L” optical microscope with a fourfold resolution made it possible to establish a clear compliance with the Fresnel zones geometry for all three lenses (figure 3). The detected deviations of the individual zones boundaries from straightness (up to 30 \( \mu \)m at a length of less than 70 \( \mu \)m) for a right binary lens are of a local nature. The photos were taken with a digital camera DCM310 for the microscope with the Touptek photonics FMA050 adapter.

At a higher resolution (10\(^2\)), images of surface defects in the form of scratches and coating chips were also obtained. The characteristic sizes of these defects for binary lenses are from 5 to 100 \( \mu \)m. However, scratches and chips are rare, and the surface area occupied by them is small. As a result of studies at high resolutions, it was not possible to detect any defects with dimensions of the order of
1 μm for these elements. The Fresnel lens surface is almost completely covered with a network of extended scratches with a width of 10–50 μm. Some defects overlap two or more Fresnel zones.

![Image](image1.png)

**Figure 3.** Surface microrelief photographs of investigated elements: (a) left binary lens, (b) right binary lens, (c) Fresnel lens.

The results of investigations with an optical microscope make it possible to conclude that the half-wave zones geometry is kept for all the elements under consideration with high accuracy. The observed defects dimensions are comparable with the illuminating beam wavelength. For this reason, significant distortions of the wave front sections can occur on them. The total area of scratches and coating chips for binary lenses is small compared to their optical surfaces area. We can affirm that the presence of registered defects does not lead to a significant deterioration in the parameters of the beam formed by binary lenses. A network of scratches, which covers the investigated Fresnel lens, is characterized by a large area. Thus, the quality of radiation focusing by this element should be low.

The DOE surface microrelief profile control was performed on a white light interferometer “WLI-DMR”, assembled on the basis of the “Leica DMR” microscope enabling non-contact measurements in the range of 10–30000 nm [20], [21]. The relative displacement of the stripes generated in the Miro interferometer and, consequently, the difference in levels was measured here automatically using the texture analysis system [20].

As a result, the reflecting surfaces profiles of the left (figure 4, a) and right (figure 4, b) binary elements were recorded and the height of the steps forming the relief was measured with high accuracy. The calculated etching depth was 3.75 μm. The measured microrelief height for the left lens was 3.882 μm, and for the right lens – 3.707 μm. The results of measurements allow us to conclude that there is a small overetching (132 nm) for the left element, and an underetching (43 nm) for the right lens. If we turn to the relative values, the deviations of the relief height from the calculated (technological error) in both cases do not exceed 5 %.

![Image](image2.png)

**Figure 4.** Results of measuring the investigated DOEs microrelief profile with a white light interferometer “WLI-DMR”: (a) left binary lens, (b) right binary lens, (c) Fresnel lens.

For the Fresnel lens, the relief height calculated value is 7.5 μm. The measurements in the element central region give a value of 5.729 μm. Consequently, there is a significant underetching (deviation of the relief height from the calculated one – 24 %). Wherein, the gradient profile is characterized by an even greater underetching in the periphery.

Thus, the results of measuring the optical surfaces microrelief parameters by the methods of local control indicate a high manufacturing quality of binary DOEs, and the effect of deviations from the calculated microrelief geometry on the formed beam quality for these elements should be negligible.
The large defects area on the Fresnel lens optical surface, as well as the profile underetching and the absence of vertical walls separating individual half-wave zones, give reason to believe the focusing quality for this element will be low.

3. Diagnostics of the generated radiation parameters by panoramic methods

The results of DOE studies using optical microscopy and interferometry make it possible to judge the correspondence of the optical surface parameters to the calculated ones. However, it is possible to establish the correspondence between the formed beam characteristics and the given or obtained in the simulation only under full-scale experiment conditions. Below, there is a description of the intensity distribution recording techniques for radiation converted by DOE and the power efficiency measuring.

The DOE-converted radiation intensity distribution recording is supposed to be carried out in real time using a bolometric IR camera XPORT-317 operating in the wavelength range 8–14 μm. The presence of such device in the optical system entails the limitations on the laser beam power. For this reason, the “LCD-1A” CO₂-laser with a nominal output power of 1 W is used as a radiation source. Its maximum radiation power is 3.2 W when single-mode operating.

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 all optical element zones located both in the center and at the periphery. Since the output beam diameter of the laser “LCD-1A” (1.8 mm) is much smaller than the apertures dimensions of the DOEs under investigation (see section 2), a two-lens collimator is provided in the optical system. The optical system layout is shown in figure 5. The high laser output power, even with attenuators and taking into account the estimated losses on the collimator lenses (up to 60%), requires the intensity distribution recording from the screen. In this case, the infrared camera should be located at a slight angle to it.

![Figure 5. The optical system general layout: 1 – power supply; 2 – laser; 3, 4 – collimator lenses; 5 – DOE; 6 – power meter or screen; 7 – IR-camera; PC – personal computer.](image)

In the experiments, collimators collected according to the Galilean and Keplerian schemes were used. The collimator, assembled according to the Galilean scheme, consisting of the input diffusing and output collecting lenses, was used to study the beam formed by binary DOEs. A collimator, assembled according to the Keplerian scheme, formed by two collecting lenses, was used to study the parameters of a beam formed by a Fresnel lens. Both collimators made it possible to expand the beam to the aperture size of the elements under investigation. Optical systems used in the stand are described in more detail in [12]. Photographs of assembled optical systems are shown in figure 6.

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 diameter of the device measuring head was 1.8 cm.

Figure 7 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 7, e) and several planes coplanar to it. Both binary lenses has the focal length of 0.6 m. Analysis of the photographs allows us to conclude that beam formation occurs at short distances from the DOE, and the beam itself does not have sharp boundaries. The focal area acquires clear boundaries starting at distances of 40 cm from the element.
The best focusing quality is achieved at a distance corresponding to the calculated position of the focal plane. Clear contours of vertical segments are preserved at considerable distances. The image begins to blur at a distance of about 40 cm behind the focal planes. The snapshots contain details demonstrating defects in reflective coating and technological errors in the DOE manufacturing.

**Figure 6.** Optical systems for studying the characteristics of radiation formed by DOE: (a) binary lenses, (b) Fresnel lens. Item numbers correspond to figure 5.

**Figure 7.** 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 8. 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 9. 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 8 indicates the intensity distributions in the central sections of the focal segment for the left lens. Images digitization is carried out using the program OriginPro 8. It can be seen that the intensity retains the Gaussian distribution over the cross section along the focal segment after the DOE transformation. The transverse distribution, also Gaussian, is characterized by the maximum presence with the width of about 2 mm.

Similar reasoning is valid for the right element that is confirmed by the data in figure 9. A square area corresponding to the DOE aperture geometry is clearly discernible in all the snapshots. The
intensity distribution formed in the focal plane (Figure 10) is similar to the focal distribution for the left lens in its parameters.

In general, the beam formation quality for binary lenses is enough high, the focusing depth is approximately \(\pm 10\) cm from the focal plane position. As expected, the DOE micro-relief profile inversion has no significant effect on the transformed beam characteristics.

![Figure 10](image)

**Figure 10.** The intensity distributions of the radiation transformed by the right binary lens in the focal segment central sections: (a) longitudinal direction, (b) transverse direction.

Figure 11 illustrates the formation of radiation by the Fresnel lens. In this case, focusing takes place in a circular area. The image begins to delineate at a distance of about 40 cm from the DOE. The intensity distribution remains practically unchanged at distances of \(\pm 20\) cm from the calculated focal plane position (0.7 m). The areas in the snapshots occupied by radiation do not have sharp boundaries, what indicates the presence of reflective coating defects.

A significant intensity blurring also takes place within the focal spot. The distributions shown in figure 12 also indicate the focusing sharpness lack. The spot diameter in the focal plane is about 5 mm. Consequently, the microrelief is characterized by significant deviations from the calculated profile. The radiation focusing quality for the Fresnel lens can be estimated as not high.

To determine the power efficiency, it is necessary to know the focal region sizes. Calculations of the focal spot dimensions for the studying DOEs have not been carried out. For a collimated incident beam in case of binary lenses, the vertical dimension of the segment must correspond to the element dimension, that is, to be 2 cm. In the diffraction limit, the focal segment width for binary DOEs and the focal spot size for the Fresnel lens are 39 and 23 \(\mu\)m, respectively. Attainment such a high focusing degree is possible only in the case of elements with a smooth optical surfaces profile. In this paper, the aim is to conduct diagnostics of the converted beam parameters. So, we take the dimensions of the focal regions as they can be realized in practice. Then the focal segment width for binary lenses will be 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 was 40 % at the collimator output beam power of 1 W (theoretical estimate was 41 %). The Fresnel lens power efficiency was 63 % at the collimator output beam power of 0.8 W. When the detector receiving area was fully open, the Fresnel lens efficiency did not exceed 84 %.

Thus, the experimental study of the radiation transformed by DOE completely confirmed the conclusions drawn from the results of optical surfaces diagnostics by the local control methods. Registration of the radiation intensity distribution in the focal planes and ones coplanar to them, focusing quality estimation and the DOE power efficiency measurement allow us to conclude that the
binary elements provide the parameters of converted beam close to the calculated. The parameters of radiation formed by the Fresnel lens are far from the required ones.

Figure 11. 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 12. The intensity distributions of the radiation transformed by the Fresnel lens in the focal spot central sections: (a) vertical section, (b) horizontal section.

4. Conclusion
In this paper, we proposed a technique for studying the optical surface microrelief of DOEs operating in the far infrared region. Also, parametric diagnostics of the beam they form was conducted using reflecting phase elements – binary cylindrical lenses and a Fresnel lens with a semitone relief.

The DOE microrelief local control is performed by non-contact optical methods. Measurements with optical microscope make it possible to establish the correspondence of the individual structural elements (half-wave zones) geometry to the calculated parameters, to obtain images of surface defects
(coating defects) and to determine the effect of distortions on the radiation formation, when we know the area occupied by them. Measurements of the DOE microrelief profile permit to record deviations in the profile height from the calculated parameters with high accuracy. The control is carried out with an interferometer with a low-coherence radiation source. The measurement procedure is automated.

Approbation of the panoramic diagnostics method for laser beam parameters formed by DOE was carried out. The intensity distributions characterizing the collimated Gaussian beam transformation by binary elements and by the Fresnel lens, as well as power efficiency measurements in zero diffraction order, indicate a high focusing quality in the first case and unsatisfactory beam parameters in the second. The results of the transformed radiation panoramic diagnostics are in good agreement with the conclusions made on the basis of the microrelief local control.

Thus, a set of measures has been developed that allows us to make an informed conclusion about the DOE manufacturing quality and the transformed beams parameters.

5. References

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