Asymptotic research in computer optics

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Abstract. I give an overview of the methods and possibilities of the asymptotic studies for solving the computer optics. I analyze the relevance of the use of the results in the design of diffractive optical elements for laser material processing. I discuss the prospects of the developed approaches for the study of the components of diffractive nanophotonics.

Keywords: Asymptotic method, diffraction theory, scalar approximation, electromagnetic theory, computer optics, laser technology, diffractive nanophotonics

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Introduction

Asymptotic methods have always been in the focus of scientists-opticians [1-3]. These methods have evident interest in recent years [4-11]. Scientists working in the field of diffractive computer optics, also actively used the opportunities provided by asymptotic methods [12-17]. Asymptotic methods are especially good in the study of such class of diffractive optical elements (DOEs), as focusators of laser radiation [14-17]. In the paper I give an overview of the methods and possibilities of the asymptotic studies for solving the computer optics. In particular, I analyze the relevance of the use of the results in the design of diffractive optical elements for laser material processing.

1. Focusators research

For creating a new focusator we have several important steps: obtaining a phase function; study of the phase function; choice of sampling parameters and method for manufacturing diffractive microrelief; calculation and production of focusator; experimental study of the microrelief and output parameters of focusator. To study the phase function of focusator scientists use analytical calculation of the diffraction patterns of the focused radiation. This calculation must take into account the finite size and specific physical parameters of created focusator [12-17]. Typically, the geometric optics approximation is used to calculate the phase function of focusator. Diffractive analysis allows us to explore the limits of this approach. It allowed us to identify the initial values of the physical parameters under which the distortion of the focus area began. This analysis allows us to identify possible errors in the analytical solution of the inverse problem of the diffraction theory.

However, we can carry out diffractive analyzes only for simple phase functions, axially symmetric illuminating beams and focus areas - such as the ring [12], a set of points [18-20], longitudinal [21-24] or cross [15-17, 25-26] segments. In some cases, the analytical study can provide diffractive corrections to the phase function of focusator [14]. Unfortunately, in the framework of the analytical study, we cannot take into account the effect of sampling and quantization of the phase function focusator arising during the manufacture of the DOE. However asymptotic analysis is an important stage of research and complements the capabilities of the computational experiment [21-28].

Unfortunately, asymptotic methods do not allow us to analyze different methods for manufacturing micro-relief of diffractive optical elements [29-36]. Such a study is necessary to select the most appropriate technology for manufacturing DOEs intended for solving a particular problem.

As an example, I cite the results of the asymptotic study of the geometric-optical focusator, concentrated laser beam into the ring [12, 21]. Fig. 1 shows the results of the asymptotic calculation of the intensity distribution in the focal plane of the geometric-optical focusator into the ring with the following parameters: focal length f = 750 mm; focusator diameter $2R$ = 25.6 mm; the wavelength of focused beam λ = 0.6328 µm; focal ring diameter r_0 = 0.1 mm.

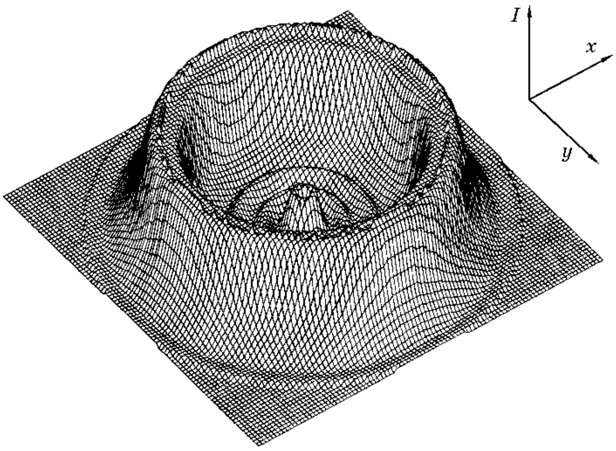

Fig. 1. – The intensity distribution I(x,y) in the focal plane of the focusator into the ring

Asymptotic calculation shows that the diffraction width of the focus ring is comparable to the radius of the ring for focusator with these parameters. As a result, the ring begins to merge with the central spot. The asymptotic calculation shows that such a draining does not occur when the radius of the focal ring in several (and furthermore many) times larger than 0.1 mm. So we clearly see the limitations of the methods of geometrical optics in calculating the phase function of focusator. The results can also be used in the study of other types of DOEs [37-45] and to focus the surface electromagnetic waves [46-48].

2. Temperature calculation

Asymptotic analysis allows us to optimize the phase function of focusator for use in a specific laser processing technology of a given type of material [49-55]. Focusators have broad prospects for application in a variety of laser materials processing technologies [49-55]: hardening, cutting, welding, drilling, branding, etc. Therefore, the problem of investigating the temperature characteristics of the laser effects produced by focusators is very important. Known focusators form a predetermined intensity distribution in some areas. Laser technology requires forming a desired temperature distribution on the object surface intended for processing. In [26], we conducted an analysis of the temperature distribution formed by focusator into segment (focusator focuses laser light into a line segment located in the focal plane). Asymptotic approach allowed us to obtain a phase function of focusator focusing laser beam into the line segment with a predetermined temperature profile. For example, in [26] we calculated optical element for focusing the circular (and ring) beam into the line segment with a constant temperature distribution. Fig. 2 shows the simulation results for these focusators. Fig. 2a shows a normalized graph of the calculation of temperature distribution along the focal segment for thermal focusator focusing uniform beam of circular cross section of radius R = 5 mm with the following parameters: the wavelength of the focused radiation λ = 1.06 μm; focal length f = 100 mm; length of focal segment $2d$ = 2 mm; $(4at_0)^{½}$ = 20 μm (here a is thermal diffusivity, t_0 is the duration of the laser action).

Fig. 2b shows the calculated normalized graph of the temperature distribution along the focal segment for the heat focusator focusing uniform beam of annular cross section with radii R_1=3 mm and R_2=5 mm with the following parameters: the wavelength of the focused radiation λ=1.06 μm; focal length f=400 mm; length of focal segment 2d=8 mm; $(4at_0)^{½}$ = 0.2 mm (here used value for thermal diffusivity of the steel a=12 mm/s^2). We can interpret the data in Fig. 2 as a result of forming by the heat focusator a constant temperature profile on the steel surface by the end of the laser pulse duration t_0 = 0.001s. For investigated focusators standard deviation from the constant temperature is 8.8% (for the illuminating beam of circular cross-section, Fig. 2a) and 12.2% (for the illuminating beam of the annular cross-section, Fig. 2b). It is about two times better than using geometrical optics focusators.

3. Electromagnetic theory

In recent years, we are actively developing new asymptotic methods within the electromagnetic theory for calculating the field generated by DOE [56-65].

For example, in [57] we presented an asymptotic method for solving problems of diffraction on the diffractive microrelief. This method combines the geometric-optical approach and solution to the problem of diffraction by a periodic structure with a period comparable to the wavelength. We solved the problem of diffraction by a standard quasi-periodic structure that combines the functions of a beam splitter and a diffraction lens. On the basis of the standard solution of the problem we got a simple expression for the field in a plane adjacent to the DOE. The resulting expression allows us to estimate the distribution of the field at the output of the DOE without resorting to complex computational methods.

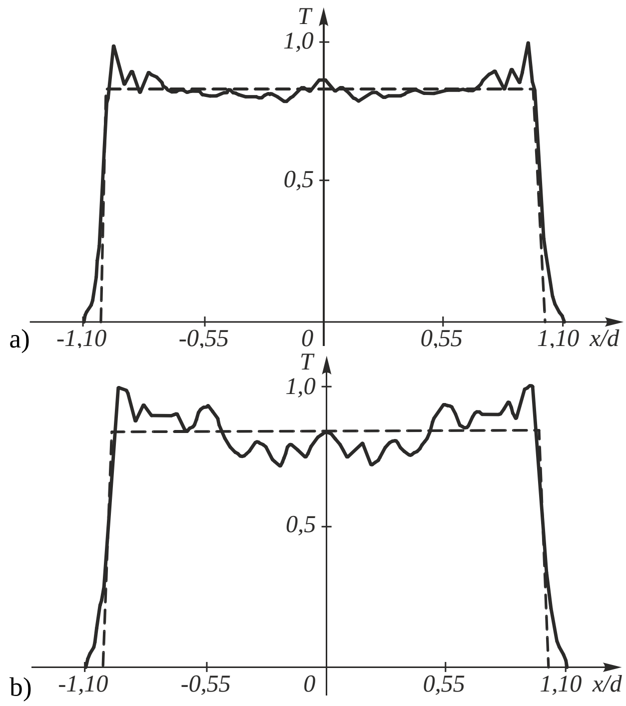

Fig. 2. – The temperature distribution *T* on the focal segment for thermal focusators: a) uniform illuminating beam with a circular cross-section; b) uniform illuminating beam with an annular cross-section

We have obtained the results of calculation for the intensity distributions of electromagnetic radiation in the focal plane of the focusator into ring for various combinations of system parameters. Calculation of the field in the focal region, we carried out on the basis of the distribution of the field at the output of the DOE calculated within the electromagnetic theory [57]. Further, the field in the focal plane, we calculated using the propagator, described in [58], on the base of the field at the output of the DOE.

Fig. 3 shows an example for calculation of fields generated by focusators into the ring for the values shown in Table. 1 (all dimensions are in microns). For small relationship σ/f (σ is parameter of an illuminating Gaussian beam, f is the focal length), the intensity distribution in the focal plane of focusator into the ring is close to the intensity distributions obtained [12, 21] in the framework of scalar approximation. In this case, the energy distribution has good axial symmetry. The symmetry is improved in the case of increasing the focal length. The asymmetry in the energy distribution along the ring appears at the increase in the ratio σ/*f*. The presence of asymmetry is due to the following factors:

- presence of linear polarization of the incident wave destroys radial symmetry, since the electric fields from different points of the focusators come at different angles in different points of the focal plane;
- in the case of linear polarization of the incident wave the diffractive coefficient depends on the direction of the local grating, it appears with increasing ratio σ/*f*.

Table 1. The parameters of focusators

Parameter	Value (option 1), μm	Value (option 2), μm
Wavelength λ	1	0.1
Parameter of Gaussian beam σ	50	50
The distance from the optical element to the observation plane	1000	100
Focal length *f*	1000	100
Dimensions of the optical element	500×500	500×500

Uneven intensity of light in the observation plane of focusator into ring caused unevenness coefficient values in transmission (reflection) of the *E*- and the *H*-polarization depending on the current value of the period of the band structure (diffraction grating).

Conclusion

In recent years, scientists were actively developing asymptotic methods in the frame of the electromagnetic theory for calculation of the field formed by the DOEs [56-64]. We use this methods not only for the study of diffractive optical elements (in particular, of short-focus DOEs), but also for the study of nanophotonics components [66-74], for the design of equipment for hyperspectral remote sensing [75-79] and solving other urgent tasks of diffractive nanophotonics [80].

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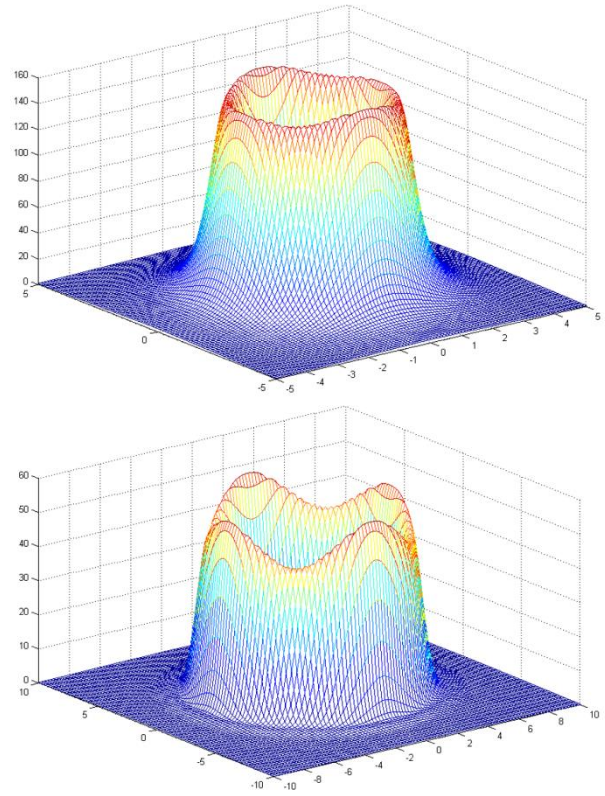

Fig. 3. – The calculated intensity distribution in the focal planes of focusators into the ring with the parameters given in the Table 1 (option 1 - the top; option 2 - the bottom)

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