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Observation of diffraction multifocal radiation focusing

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Abstract. **It is shown experimentally that by placing a flat screen with an axial hole in a diffraction field formed by the first open Fresnel zone upon diffraction of a plane electromagnetic wave from a parallel screen with a hole of a larger diameter, one can observe diffraction multifocal focusing of radiation in the near-field zone of the first screen. The diffraction pattern in the near-field zone of the first screen in focal planes represents circular nonlocalised Fresnel bands with a bright narrow peak at the centre, whose intensity is 6 – 10 greater than that of the incident wave.**

Keywords: *wave diffraction, diffraction radiation focusing, two-component diffraction system.*

1. Introduction

Diffraction of an electromagnetic wave from a circular hole in a flat screen is well described by the classical Fresnel–Kirchhoff diffraction theory [1], which gives exact solutions for two limiting cases – the Fraunhofer diffraction and Fresnel diffraction. In the first case, the dependence of the wave phase on the radius vector determining the position of an elementary secondary light source is linear, which determines the diffraction pattern in the far-field zone. In the case of Fresnel diffraction, the phase is usually expanded up to the second-power term describing the diffraction field in the near-field zone. In the experimental optics, a simple case of Fraunhofer diffraction is used more often, when at a large distance from an aperture a small part of the first Fresnel zone fits in the hole. In this case, all oscillations occur in the plane of the hole and come to the observation point virtually with the same phases.

However, of interest is the case when the entire first Fresnel zone or its greater part fit in the hole. Then, as is known, the diffraction focusing of radiation is observed in the near-field zone with the maximum peak intensity, which is four times greater than the intensity I_0 of the incident wave in the case of the open first Fresnel zone. In Refs [2, 3], it was suggested to place into the diffraction field formed by the first open zone of Fresnel diffraction from a screen with a hole a flat screen with an axial hole of a smaller diameter (Fig. 1). In this case, a further focusing of radiation was theoretically possible resulting in a manifold enhancement of the peak intensity.

The diffraction pattern from the second screen in focal planes represented circular nonlocalised Fresnel bands with a bright narrow peak at the centre, whose intensity was 6 – 10 times greater than that of the incident wave. This optical phenomenon was called the diffraction multifocal radiation focusing (DMRF), and the optical scheme consisting of two flat screens with axial holes of different diameters separated by a strictly specified distance was called the two-component diffraction system.

The calculations performed in Refs [2, 3] showed that DMRF can be observed in a broad wavelength range from 0.4 to 10^3 μm for diameters of the entrance apertures $d_1 = 2d_2 = (25 - 1000)\lambda$ and is stable upon the replacement of the medium of the wave propagation. For large diameters of the entrance holes $d_1 = 2d_2 > 100\lambda$ and wavelengths in the radio-frequency range, such a two-component diffraction system acts like a long-focus lens, which focuses radiation at relatively large distances $z = 1 - 50$ cm from the exit aperture.

The aim of this paper is to verify experimentally the theoretical prediction of the possibility of DMRF in a two-component diffraction system. The DMRF, which allows diffraction focusing of a beam without using conventional refraction elements such as lenses, prisms, etc., can find applications in optics, for example, for correction and transformation of the spatial characteristics of radiation of wide-stripe (~ 100 μm) injection semiconductor lasers and in atomic physics, for example, for focusing of atomic and molecular beams, which are known to exhibit wave properties.

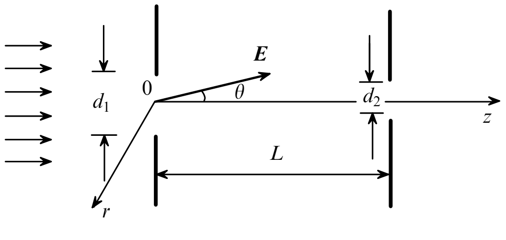

Figure 1. Geometry of the problem on diffraction of a plane wave from a two-component diffraction system (L is the distance on the optical axis between screens with circular holes of specified diameters d_1 and d_2).

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2. Experimental

Fig. 2 shows the schematic of the experiment for observation of DMRF for a plane electromagnetic wave in the two-aperture diffraction system. The radiation from a He – Ne laser *1* passed through a beam expander *2* with a spatial filter *3* and was incident on a system of apertures *4* under study. A microobjective *5* imaged a diffraction pattern on a linear CCD array *6* coupled with a PC *7*. The laser output power was controlled with a photodiode power meter *8*.

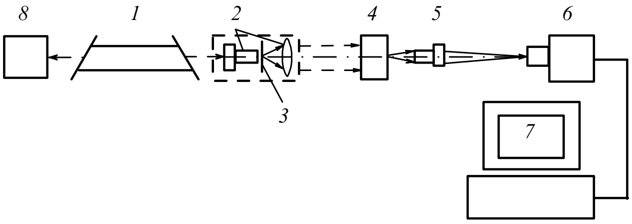

Figure 2. Schematic of the experimental setup for observation of optical DMRF: (*1*) He-Ne laser; (*2*) beam expander; (*3*) spatial filter; (*4*) system of apertures under study; (*5*) microobjective; (*6*) linear CCD array; (*7*) PC; (*8*) photodiode power meter.

The plane of a linear CCD array *6* and the object plane in the diffraction zone of the system under study *4* were aligned by moving the latter along the main optical axis of an expanded collimated light beam.

Let us list the parameters of components of our setup, which are important, in our opinion, for the interpretation of our experimental data. A cw LG-52-1 He – Ne laser emitted a 0.63-μm single-mode Gaussian beam. The beam was expanded up to a diameter of about 3 cm (at the 1/e^2 intensity level) and was incident on the two-component diffraction system.

The diffraction system under study consisted of two circular apertures made of an aluminium foil of thickness 20 ± 4 μm for the first screen and 10 ± 4 μm for the second screen, which greatly exceeds the radiation wavelength. The aluminium foil of the second aperture was placed between two thin glass plane-parallel plates. The diameters of the apertures in the experiment were $d_1 = (365 \pm 10)\lambda$ and $d_2 = (80 \pm 10)\lambda$. The photographs of these apertures shown in Fig. 3 exhibit irregularities of the aperture edges and shapes.

The focal length of a microobjective *5* was 16 mm. We used a K1200TsL1 linear CCD array photodetector 6 [4]. This microcircuit contains 1024 linearly arranged photosensitive 15-μm pixels. According to [4], the sensitivity of the microcircuit was 2.5 mV lux^{-1} and its dynamical range over voltage was 60 dB. According to [4], different photosensitive pixels of the microcircuit differ in their sensitivity by $\sim 8\,\%$ and in the noise level by $\sim 4\,\%$. We performed our measurements in a linear region of the dependence of the output CCD voltage on the illumination intensity.

The output signals from both photodetectors, measured at each point of the scan, were processed with a PC and represented in the form of one-dimensional distributions of the intensity of diffraction waves normalised to the averaged intensity of the incident wave.

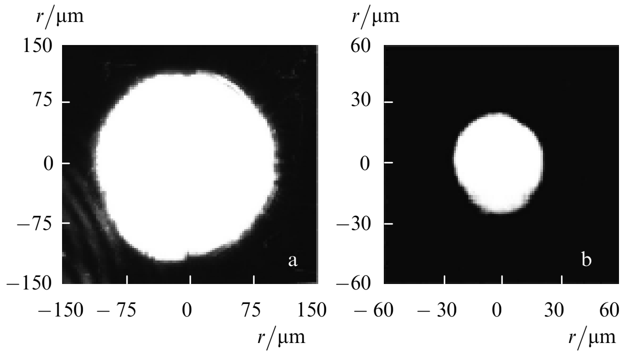

Figure 3. Photographs of apertures under study with diameters $d_1 = (365 \pm 10)\lambda$ (a) and $d_2 = (80 \pm 10)\lambda$ (b).

3. Results and discussion

Experiments were performed in two stages. At the first stage, we fixed the experimental setup and determined the errors of measurement of the well-known diffraction pattern obtained from one circular hole in the Fresnel zone. At the second stage, we placed the second flat screen with a circular hole of a smaller diameter to the diffraction field from the first hole formed by one Fresnel zone. The results of experimental studies and theoretical calculations are presented in Figs. 4 and 5.

The presence of sharp maxima on the edges of the transverse distribution of the intensity of the wave passed through the first aperture of diameter $d_1 = (365 \pm 10)\lambda$ and

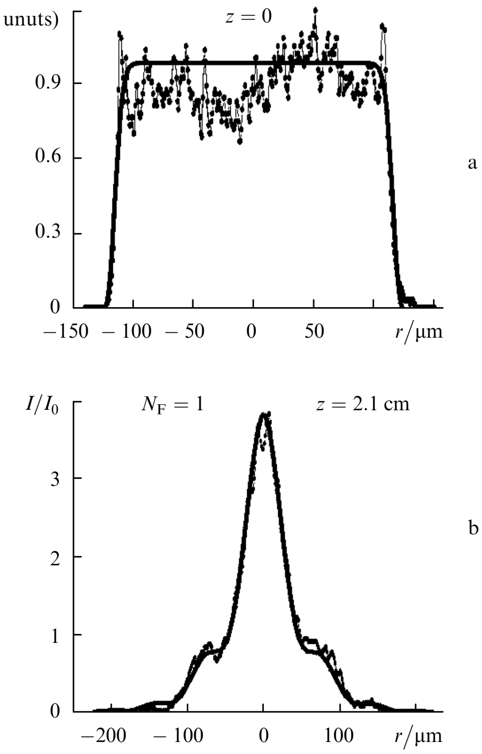

Figure 4. Distributions of the intensity of a plane wave propagated through the first circular aperture of diameter $d_1 = (365 \pm 10)\lambda$ (a) and of the diffraction field formed by the first open Fresnel zone upon diffraction of the wave from this aperture (b). The solid curves are theoretical calculations, dotted curves correspond to the experiment.

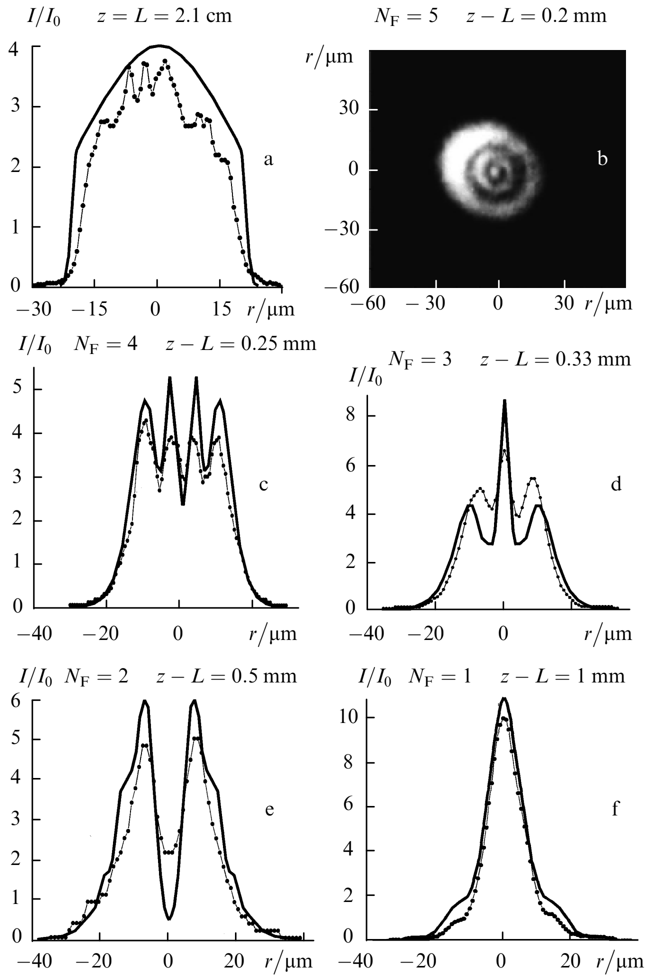

Figure 5. Diffraction focusing of a plane wave in a two-component diffraction system (diameters of holes are $d_1 = (365 \pm 10)\lambda$ and $d_2 = (80 \pm 10)\lambda$) directly from the second hole (a) and at different distances z from it (c–f), and the photograph of the diffraction pattern (b). The solid curves are theoretical calculations, dotted curves correspond to the experiment.

the wall thickness 20 ± 4 μm $\gg \lambda$ (Fig. 4a) is explained by the inevitable diffraction of the wave from the inner walls of the aperture. The irregularity of the intensity profile of a plane-parallel beam can be explained by interference of the incident radiation with the waves reflected from the surface of pixels of the CCD array and its protective glass. The solid curve in Fig. 4a shows the theoretical calculation of the average intensity of the incident wave. All the subsequent distributions of the intensities of diffraction fields obtained both from the first and second screens were compared with this average intensity.

Diffraction of the incident wave (Fig. 4a) from the first hole in the near-field zone is determined by open Fresnel zones. At the distance $z = L = d_1^2/4\lambda$ from the first screen, one first Fresnel zone with the maximum intensity $I = 4I_0$ at the centre of the diffraction pattern fits in the hole (Fig. 4b).

The second aperture of diameter $d_2 = (80 \pm 10)\lambda$ placed at the point $z = L = 2.1$ cm cuts the central part in the diffraction pattern formed by the first hole at one open Fresnel zone (see Fig. 5a). Diffraction of this wave from the second hole shown in Fig. 5b confirms the theoretical prediction that the diffraction of a plane wave from a two-aperture system is qualitatively similar to the Fresnel diffraction – five open Fresnel zones with a bright narrow peak at the centre are observed. Upon further propagation, the peak intensity of the wave decreases to a minimum (the dark centre of the diffraction pattern), which corresponds to the diffraction pattern for an even number of open Fresnel zones $N_F = 4$ (Fig. 5c). At a distance of $z - L = 0.33$ mm from the second screen, the diffraction wave again is focused at the centre (Fig. 5d) with the maximum intensity that is 6.5 times greater in the experiment (and 8.5 times greater in the theory) than the incident-wave intensity I_0. In this case, the diffraction pattern is qualitatively similar to that formed by three open Fresnel zones. Finally, at the point $z - L =$ 1.0 mm, the first Fresnel zone is open with the maximum diffraction focusing of radiation, whose intensity in the focus is 10 times greater in the experiment (and 11 times greater in the theory) than the incident-wave intensity I_0 (Fig. 5f).

Thus, in the near-field zone of the second screen, the qualitative pattern of the Fresnel diffraction is observed, which is accompanied by multifocal focusing and a further increase in the wave intensity at open odd Fresnel zones. This is the DMRF observed in the two-component diffraction system with small Fresnel numbers.

Table 1 presents the calculated absolute values of the systematic and random error components and total errors, as well as the statistic estimates of the error. The errors for each diffraction pattern are integrally averaged over the operating aperture of the CCD array and are reduced to the average intensity over the aperture. The statistic estimate of the error was performed by calculating, before averaging, the root-mean-square deviation at each point of the experimental profiles of the light intensity.

Our calculations showed that the total error is mainly determined by the errors due to the limited spatial resolution of the microobjective, interference from the protective glass

Table 1. Systematic, random, and total errors integrally averaged over the aperture and the statistic estimate of the total error.

Configuration of the optical system	Number of Fresnel zones	Error (%)			
		Systematic	Random	Total	Statistic
One aperture	1	0.5	5	5	5
	2	1	10	10	5
	3	1.5	10	10	8
	4	3.0	8	10	10
Two apertures	1	5	5	7	5
	2	5	10	10	5
	3	5	8	10	8
	4	7	15	15	10

of the CCD array, and the inefficient charge transfer in the CCD array. It follows from Table 1 that for the diffraction pattern with the Fresnel number $N_F \leqslant 2$ the total error was 10 %, while for diffraction patterns with the higher Fresnel numbers this error was 15 %. This is explained by a decrease in the pattern contrast at high spatial frequencies.

4. Conclusions

Thus, the observation of the theoretically predicted DMRF in the two-component diffraction system with small Fresnel numbers showed that the diffraction pattern in the focal planes of this system represents circular non-localised Fresnel bands with a bright narrow peak at the centre, whose intensity is 6.5 – 10 times greater than the incident-wave intensity.

The theoretical calculation performed within the framework of quasi-optical approximation for an ideal thin conducting screen [2, 3] is in qualitative and quantitative agreement with the results of experiments in which the screens had a finite thickness that was far greater than the radiation wavelength. The best agreement between the theory and experiment was observed at the maxima of the diffraction pattern. The experiments showed that Fresnel diffraction from real objects whose linear dimension exceeded the radiation wavelength was stable with respect to the 'rough' external boundary conditions (the screen thickness, irregularities of the edges and shape of the hole), as well to the nonuniformity of the initial distribution of the incident-wave intensity.

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