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Experimental Creation of Chainlike Beams and Investigation of Their Structure

N. D. Kundikova[a], A. V. Ryzhkova[a], T. Alieva[b], M. L. Calvo[b], and J. A. Rodrigo[b]

[a] *Joint Nonlinear Optics Laboratory, Institute of Electrophysics, Ural Division, Russian Academy of Sciences and South-Ural State University, Chelyabinsk, 454080 Russia*

[b] *Department of Optics, Faculty of Physics, Complutense University of Madrid, Madrid, 28040 Spain*

e-mail: knd@susu.ac.ru

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Abstract—The effect of the Gaussian beam width on the focusing properties of the chainlike Gaussian beam formed upon diffraction of laser radiation on a binary amplitude mask is studied. It is found that a decrease in the Gaussian beam width increases the sizes of focal spots and the focus depth, decreases the intensity in the focuses, and does not affect the focus position.

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INTRODUCTION

Recently, increasing attention has been attracted to optical beams with a specific intensity distribution, such as spiral beams [1–3], beams with fractional topological charges [4, 5], and hollow beams [6]. The spiral beams and beams with fractional topological charges have found wide application in technology and biomedicine as sterile instruments for manipulations with microobjects [4, 7]. The specific properties of hollow beams are used to control cooling of atoms [8, 9] and mode transformation [10], as well as in binary spatial light modulators [11], computer holography [12], and hollow fibers [13].

The beams formed due to the diffraction of laser radiation on fractal zone plates have been actively studied in recent years [14–17]. A new class of beams formed due to the diffraction of a plane wave on the Cantor fractal zone plates based on the Fresnel zone plate, which allows one to use the iteration method for eliminating open Fresnel zones on the mask, is described in [18]. As a result of numerical simulation and experimental study, the authors determined the light intensity distribution along the beam propagation axis and found a series of focal spots, each of them having a complex structure consisting of several toroid focuses. The study of focusing properties of Cantor fractal plates showed that the number of focuses and their characteristics (the depth and size) depend on the number of iterations upon the mask formation. A beam with a structure similar to the structure of the beam diffracted by the Cantor fractal zone plates, which was obtained upon light diffraction on a binary amplitude diffraction mask (a mask with two open Fresnel zones), was studied in [19]. The Fresnel zones determine the focal distances of the beam diffracted by the mask. A combination of two open Fresnel zones forms focuses at distances l_1 and l_2; the beam diverges after the first focus, but rapidly converges after the second focus, thus forming a light capsule. The structure of the beam intensity distribution along the propagation axis z resembles a chain and consists of a group of cylindrical capsules lying along the propagation axis at specific distances from each other. These beams received the name chainlike beams or capsule beams.

To manipulate microparticles, it is necessary to know the focusing properties of the beam, namely, the focal distance, the light intensity in the focus, and the depth and radius of the focal spot, which are determined, on the one hand, by the main characteristics of the amplitude mask and, on the other hand, by the properties of the laser beam diffracting on the mask. Experimentally used laser beams are restricted and have a Gaussian intensity distribution; the diffraction of a plane wave on a mask is considered in [19]. Expanding the beam and, thus, losing its energy, one can achieve coincidence of the experimental and model conditions. If the beam diameter is smaller than the diameter of the first Fresnel zone, diffraction will not occur. There is an optimal width of the Gaussian beam at which both the energy loss is small and it is possible to form a beam with desired properties as a result of diffraction.

The aim of this work is to study the effect of the Gaussian beam width on the focusing parameters of the beam formed as a result of diffraction on the binary amplitude mask with two open Fresnel zones, namely, on the focal distance, on the intensity in the focus, and on the depth and radius of the focal spot.

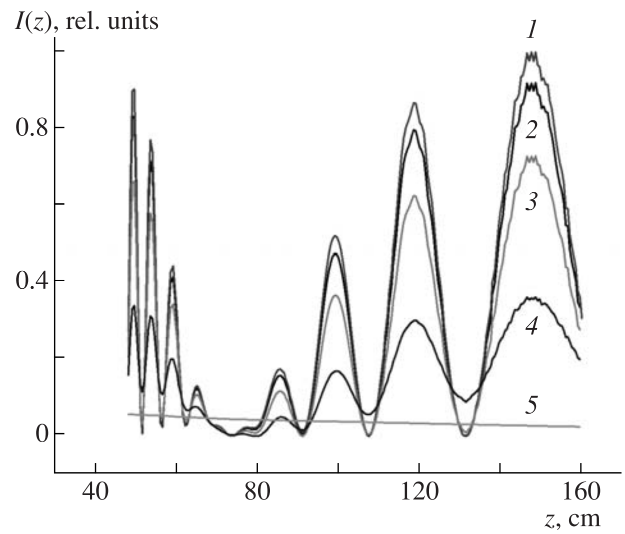

Fig. 1. Dependence of the intensity in the center of the diffracted beam on the distance z for the (*1*) plane wave and Gaussian beam with a diameter of (*2*) 2, (*3*) 1, (*4*) 0.5, and (*5*) 0.1 cm.

ANALYSIS OF THE STRUCTURE OF CHAINLIKE BEAMS

To analyze the effect of the beam width on the main focusing properties of the Gaussian beam appearing as a result of diffraction on a binary amplitude mask with two open Fresnel zones, we performed numerical simulation. The parabolic equation was solved by a spectral method based on the two-dimensional Fourier transform. For investigations, we used one of the two masks studied in [19], namely, the mask with the first and ninth open Fresnel zones. This mask differs from the second mask with the 1st and 19th open Fresnel zones by a smaller number of focuses in the diffracted beam. The structure of these beams is the same. The diffraction was calculated for a mask 1×1 cm in size with the first Fresnel zone radius $a = 0.96$ mm, the main focus at the distance $z_1 = a^2/\lambda = f = 145$ cm, and additional focal spots at the distances $z_2 = f/3 = 48$ cm and $z_3 = f/5 = 29$ cm. The wavelength of radiation diffracting on the mask was $\lambda = 632.8$ nm.

The Gaussian beam amplitude was determined by the expression $A = \exp(-r^2/w^2)$, where $w = w_0\sqrt{1 + (\lambda z/\pi w_0^2)}$ is the beam cross-section radius at the level e^{-1} at the distance z and w_0 is the radius of the cross section of the beam illuminating the transparency. The dependence of the intensity in the diffracted beam center on the distance $I(r = 0, z)$ is calculated for Gaussian beams with different diameters and for a plane wave.

Figure 1 shows the dependence $I(r = 0, z)$ for the plane wave and for the Gaussian beams with diameters $2w_0 = 2$, 1, 0.5 and 0.1 cm. The intensity profiles $I(r, z = \text{const})$ of the diffracted beam at the distances $z = 131.0$ and 148.5 cm for the plane wave and the Gaussian beams with diameters $2w_0 = 1$ and 0.5 cm are shown in Fig. 2.

As expected, no diffraction occurs if the Gaussian beam width is smaller than the width of the first Fresnel zone (Fig. 1, curve *5*). The positions of focuses (of intensity maxima) do not change with decreasing radius of the Gaussian beam. At a radius w_0 comparable with a ($w_0 \sim a$), the focus depth (the intensity peak widths at half maximum) increases, the intensity of the focuses considerably decreases (Fig. 1, curve *4*), and the focal spot radius increases (Fig. 2).

Analysis of Figs. 1 and 2 reveals that the diffraction of Gaussian beams qualitatively does not depend on their diameters: the structure of the chainlike beam remains unchanged and only the energy distribution changes. The calculation shows that, by varying the Gaussian beam diameter, it is possible to control the

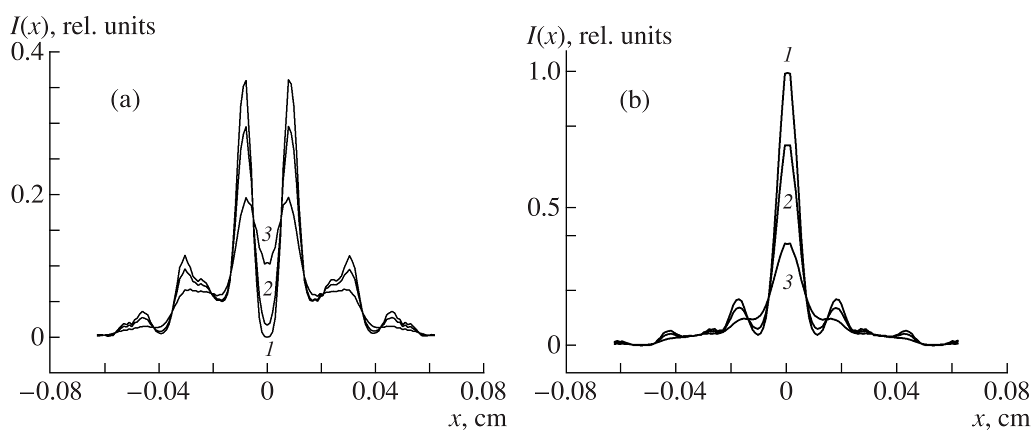

Fig. 2. Intensity profiles of the (*1*) plane wave and Gaussian beam with the diameter $2w_0$ = (*2*) 1 and (*3*) 0.5 cm at the distance (a) 131 and (b) 148.5 cm.

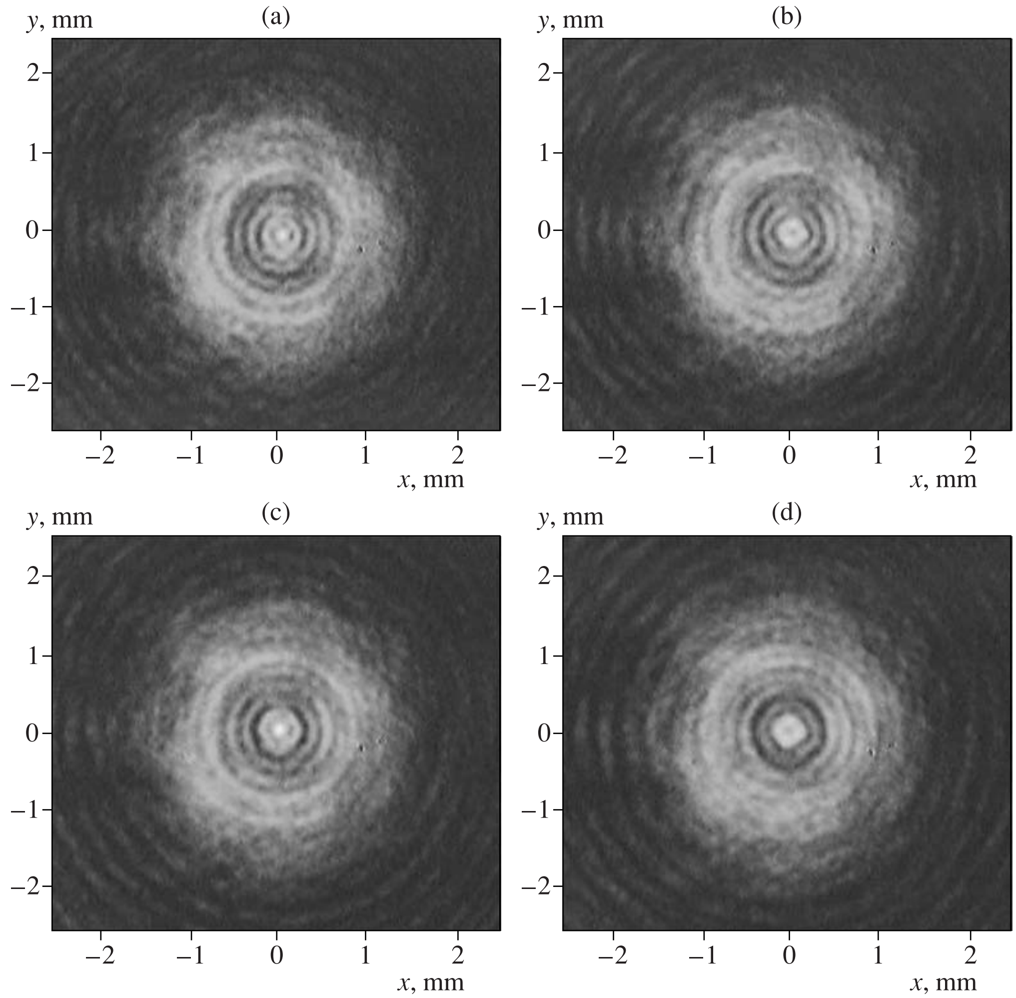

Fig. 3. Intensity distribution of the diffracted beam in the plane perpendicular to the propagation axis at the distance (a) 48, (b) 50.5, (c) 52.5, and (d) 55 cm.

intensity and radius of the focal spot. A Gaussian beam whose width exceeds the size of the Fresnel zone on the mask (in our case, a beam with a diameter exceeding $2w_0 = 0.5$ cm at the level e^{-1}) can be used for formation of capsule beam.

EXPERIMENTAL STUDY OF THE STRUCTURE OF CHAINLIKE BEAMS

The experiments were performed at the wavelength $\lambda = 632.8$ nm. The laser beam was expanded by an optical system to a width of 2 cm. The expanded Gaussian beam with the diameter $2w_0 = 2$ cm was diffracted by a binary amplitude mask 1×1 cm^2 in size with the first and ninth open Fresnel zones and $a = 0.96$ mm. The intensity distribution of the beam diffracted on the binary amplitude mask was recorded at distances ranged from 48 to 104 cm with a step of 0.5 cm using a CCD matrix. The CCD matrix had a registration zone of 640×480 pixels, each pixel of about 10 μm. The chosen region of distances corresponds to the position of the second focal spot at $z_2 = f/3$. The focuses forming this spot are spaced not as closely as near the focal spot at $z_3 = f/5$ and not as largely as near the main focus at $z_1 = f$, which ensures favorable conditions for recording the intensity distribution.

Figure 3 shows the photographs of intensity distribution in the region of z from 48 to 55 cm, each photograph being 4.8×4.2 mm in size. As is seen from Fig. 3, the center of the beam exhibits a light spot—a region of high intensity (Fig. 3a); 2.5 cm further, this spot is replaced by a dark point—a zone with a low intensity (Fig. 3b); after next 2 cm, the dark point is replaced by a light spot (Fig. 3c), which again transforms to a dark point after next 2.5 cm (Fig. 3d).

To qualitatively analyze the diffracted beam structure, we measured the intensity on the beam axis at distances of 48–104 cm. The intensity in the center of the chainlike beam versus the distance along the propagation axis is shown in Fig. 4 (curve *1*). This figure also presents the corresponding dependences calculated by

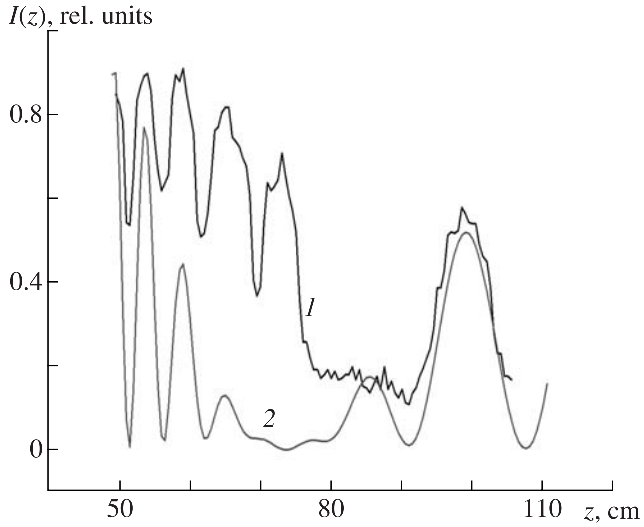

Fig. 4. Variations in the intensity in the beam center along the propagation axis. (*1*) Experimental data and (*2*) results of numerical simulation.

numerical simulation. As is seen, the experimental and calculated results qualitatively agree at the distances of 48–66 cm and of 90–104 cm. Quantitatively, the curves do not coincide, in particular, the minimum intensities never reach zero values (Fig. 4, curve *1*). The experimental and calculated dependences are qualitatively different in the range of 66–90 cm. This discrepancy can be caused by several factors: the photographs presented do not correspond to the zone of zero intensity in the beam center, the size of pixels of the CCD matrix is larger than the size of the zero-intensity zone, and the intensity distribution is affected by the multibeam interference. Analysis of the photographs shows that the intensity in the beam center does not reache zero in any of the 112 photographs. According to calculations, the minimum size of the zero zone in the region studied belongs to the focal spot $z_2 = f/3$ and reaches a value of about 20 μm, while the size of the CCD pixel is 10 μm. Thus, neither the choice of photographs nor the size of the CCD pixel can be responsible for the nonzero intensity in the center of the focal spot. Most probably, the intensity distribution of the diffracted beam is influenced by the multibeam interference.

Thus, this study shows that, in its structure and propagation character, the Gaussian beam passed through a diffraction transparency coincide with the chainlike beam calculated in [19]. At the same time, the analysis of the results allows us to suggest that, to use the capsule beams, it is necessary to create experimental conditions that eliminate the effect of multibeam interference.

CONCLUSIONS

As a result, it is experimentally shown that, for transformation of the Gaussian beam into a beam with the capsule-like structure, it is sufficient that the Gaussian beam width covered the open Fresnel zones on the mask. It is shown that a decrease in the Gaussian beam width decreases the intensity and increases the width of the focal spot, increases the focus depth, and does not affect positions of the focal spots.

REFERENCES

1. E. Abramochkin and V. Volostnikov, Opt. Commun. **102**, 336 (1993).
2. E. Abramochkin, V. Volostnikov, and N. Losevsky, Opt. Commun. **141**, 59 (1997).
3. E. Abramochkin and V. Volostnikov, Opt. Commun. **83**, 123 (1990).
4. S. H. Tao, W. M. Lee, and X.-C. Yuan, Opt. Lett. **28** (20), 1867 (2003).
5. S. Tao, X.-C. Yuan, J. Lin, et al., Opt. Express **13** (20), 7726 (2005).
6. Qiansen Xie and Daomu Zhao, Opt. Commun. **275**, 394 (2007).
7. L. Paterson, Science **292**, 912 (2001).
8. T. Kuga, Y. Torii, N. Shiokawa, et al., Phys. Rev. Lett. **78**, 4714 (1997).
9. J. Yin, Y. Zhu, and Y. Wang, Phys. Rev. A: **57**, 1957 (1998).
10. W. L. Power, L. Allen, M. Babiker, and V. E. Lembessis, Phys. Rev. A: **52 P**, 479 (1995).
11. F. K. Fatemi and M. Bashkansky, Opt. Lett. **31**, 864 (2006).
12. N. R. Heckenberg, R. McDuff, C. P. Smith, and A. G. White, Opt. Lett. **17 P**, 221 (1992).
13. J. Yin, H. Noh, K. Lee, et al., Opt. Commun. **138**, 287 (1997).
14. G. Saavedra, W. D. Furlan, and J. A. Monsoriu, Opt. Lett. **28**, 971 (2003).
15. J. A. Monsoriu, G. Saavedra, and W. D. Furlan, Opt. Express **12**, 4227 (2004).
16. J. A. Rodrigo, T. Alieva, M. L. Calvo, and J. A. Davis, Proc. SPIE–Int. Soc. Opt. Eng. **5622**, 1474 (2004).
17. J. A. Davis, L. Ramirez, J. A. Rodrigo, et al., Opt. Lett. **29 P**, 1321 (2004).
18. J. A. Rodrigo, T. Alieva, M. L. Calvo, and J. A. Davis, J. Mod. Opt. **52** (18), 2771 (2005).
19. M. L. Calvo, J. A. Rodrigo, and T. Alieva, Proc. SPIE–Int. Soc. Opt. Eng. **6027**, 1 (2005).

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