# Demonstrations of the diffraction and dispersion phenomena of part Fresnel phase zone plates

Binzhi Zhang, Daomu Zhao, and Shaomin Wang

Citation: Applied Physics Letters **91**, 021108 (2007); doi: 10.1063/1.2757126
View online: http://dx.doi.org/10.1063/1.2757126
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/91/2?ver=pdfcov
Published by the AIP Publishing

# Demonstrations of the diffraction and dispersion phenomena of part Fresnel phase zone plates

Binzhi Zhang, Daomu Zhao,[a)] and Shaomin Wang
*Department of Physics, Zhejiang University, Hangzhou 310027, China*

(Received 7 May 2007; accepted 19 June 2007; published online 11 July 2007)

The authors report on experimental demonstrations of the diffraction and dispersion phenomena of part Fresnel phase zone plates (FPZPs) by employing a He–Ne laser beam and a white point source. The experimental results have shown that a part square FPZP can behave like a complete circular FPZP, and a part circular FPZP has a focus at $1/3\ f$ and $f$ with a shift. Some numerical simulations are performed. The simulations and the experiments have shown that the diffraction and dispersion properties of part FPZPs can be well explained by the different diffraction orders. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2757126]

The Fresnel zone plate (FZP) is a kind of beam-forming and focusing device, which has attracted great attentions in the last two decades for its achieved and potential applications in the fields of extreme ultraviolet imaging,[1] x-ray imaging,[2] and imaging and focusing of atoms.[3,4] As the refractive index is very close to unity for all materials at x-ray wavelengths, FZP plays a role of the most promising optical element in x-ray imaging. Lots of efforts have been made to develop the techniques of fabricating[5] and designing[6,7] FZP with the purpose of improving its spatial resolution down to nanometer.[8–11] Many properties of the FZP have been studied, such as aberration,[12] diffraction,[13,14] and stigmatism.[15,16] Among the researches mentioned above, the calculations and experiments are based on complete FZP with symmetric patterns such as a series of concentric circular zones. There are little papers concerning part FZPs because it is too complex to calculate the intensity distribution of radiation in receiving plane. Some kinds of part zone plate (ZP) called off-axis ZP have been made[17] and employed[18–20] as monochromator successfully in several x-ray measurement experiments. Therefore, in order to study some properties of part ZPs more in detail, we demonstrate the diffraction and dispersion phenomena of part FPZP including the square Fresnel phase zone plate (FPZP) and circular FPZP by employing a He–Ne laser beam and a white point source. Some simulations have also been performed to aid the explanation for the experimental results.

Two kinds of experiments have been performed to investigate the optical properties of part square and part circular FPZPs. The reason why we choose FPZP is that for FZP only 10% incident flux goes into the principal images, which can be improved to 40% by using PFZP.[21] The experimental setup is shown in Fig. 1: two light sources, one is 1 mW He–Ne laser beam ($\lambda = 633$ nm) diffracted by a pinhole with diameter $\Phi = 35\ \mu$m (Airy disk, $\Phi_A \approx 10$ mm), while the other is a white point source;[22] a collimating lens with a distance of its foci $f$ off the light source; two FPZPs with $\pi$ phase change for 633 nm including a square FPZP (total zones $N = 100$, first ring $r_1 = 0.53$ mm, width of the finest $\Delta r_N = 27\ \mu$m, principal focal length $f_s \approx 440$ mm) and a circular FPZP (total zones $N = 100$, first ring $r_1 = 0.67$ mm, width of the finest $\Delta r_N = 34\ \mu$m, principal focal length $f_c \approx 710$ mm), each of them couples with a diaphragm; and a camera with Kodak film for recording, where $L$ denotes the distance between the FPZP and the film. The most important advantage of using the point source made by ourselves is that the size of the point source less than 100 $\mu$m can be focused to a very small point, and with the good color rendering and extreme high brightness make it much easier to observe the diffraction and dispersion phenomena.[22,23]

Firstly, the experiments are carried out with the He–Ne laser beam as light source. A part square FPZP is derived from combining a complete square FPZP with a diaphragm, as shown in Fig. 2(a), and light is only allowed to pass through a circular area. Then the laser beam illuminates the part square FPZP after the process of diffraction and collimation. Photos are taken at $L = 400, 440$, and 480 mm, respectively, and the diffraction pattern is just like a rabbit as shown in Figs. 2(c)–2(e). It is found that the position and the size of the rabbit's head on the receiving plane are nearly unchanged. Noticing the appearance of a focus in the center of the diffraction pattern, as shown in Fig. 2(d) which is different from a complete square FPZP,[14] it implies that a part square FPZP can be used as a focusing device like a complete circular FPZP. We have also investigated the circular FPZP with two kinds of diaphragm, as shown in Fig. 1. The diffraction patterns are similar to the patterns in Fig. 3 but in color of red. So a part circular FPZP can also act as a complete one. Therefore, we could suggest the potential ap-

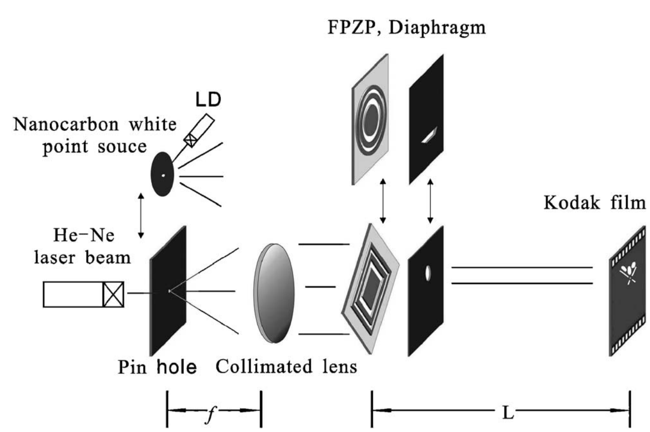


FIG. 1. Scheme of experimental arrangements.

[a)]Electronic mail: zhaodaomu@yahoo.com

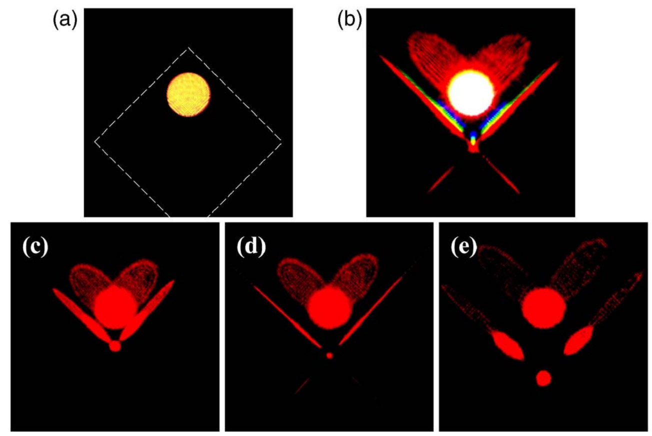


FIG. 2. (Color online) Diffraction pattern like a rabbit. The element used in (a) is a square FPZP rotated axially at an angle of 45° with a diaphragm. (b) The diffraction pattern derived from illuminating FPZP in (a) by a white point source at $L=440$ mm. [(c)–(e)] The part FPZP in (a) is illuminated by He–Ne laser beam, and photos are taken at $L=400,440$, and 480 mm, respectively.

plication that when a FPZP has damaged partly, it can still work if we select an undamaged part.

Then we take a white point source as light source to demonstrate the dispersion properties of part FPZPs. Figure 2(b) shows the phenomenon of a part square FPZP in Fig. 2(a) illuminated by the point source. The dispersion patterns are similar when the receiving plane moves along the principal axis, so we just select one photo taken at 440 mm away from the part square FPZP. The diffraction patterns of a circular FPZP with two kinds of diaphragms shown in Fig. 1 are also presented in Figs. 3(b)–3(f), which are recorded at $L=240$ mm $(1/3f_c)$, 350 mm $(1/2f_c)$, 470 mm $(2/3f_c)$, 710 mm $(f_c)$, and 710 mm, respectively. In Figs. 3(b)–3(e), variations among the diffraction patterns show that the blue "ships" between dashed lines are nearly unchanged, while other color ships are moving and changing. The same phenomena can also be observed with a part circular FPZP in the shape of a disk. We just choose one photo of Fig. 3(f) to present.

With the purpose of having a general idea about the properties of part FZP, some simulations have been performed. A hundred of strips shown in Fig. 4(a) as a part of a square FPZP whose first zone radius is 0.67 mm are chosen instead of arcs of part circular FPZP to make the integral possible in simulations. The strips with width of 3.8 mm and height of 2.7 mm start from 101st zone of the square FPZP. For the beam at 633 nm the simulation results are presented in Figs. 4(b)–4(e), where the $z$ direction denotes the diffraction intensity. In Fig. 4(b), there are three peaks, which can be explained by the different diffraction orders of the FPZP:[24] the highest peak at center is the third diffraction order also the focus at $1/3\ f_c$; the middle peak is the first

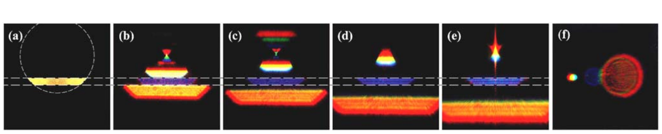


FIG. 3. (Color online) Diffraction pattern like a blue ship. The element used in (a) is a circular FPZP with a diaphragm. [(b)–(e)] The part FPZP in (a) is illuminated by a white point source, photos are taken at about $L=240,350,470$, and 710 mm, respectively. (f) The part circular FPZP in the shape of a disk, the diffraction pattern is taken at about $L=710$ mm.

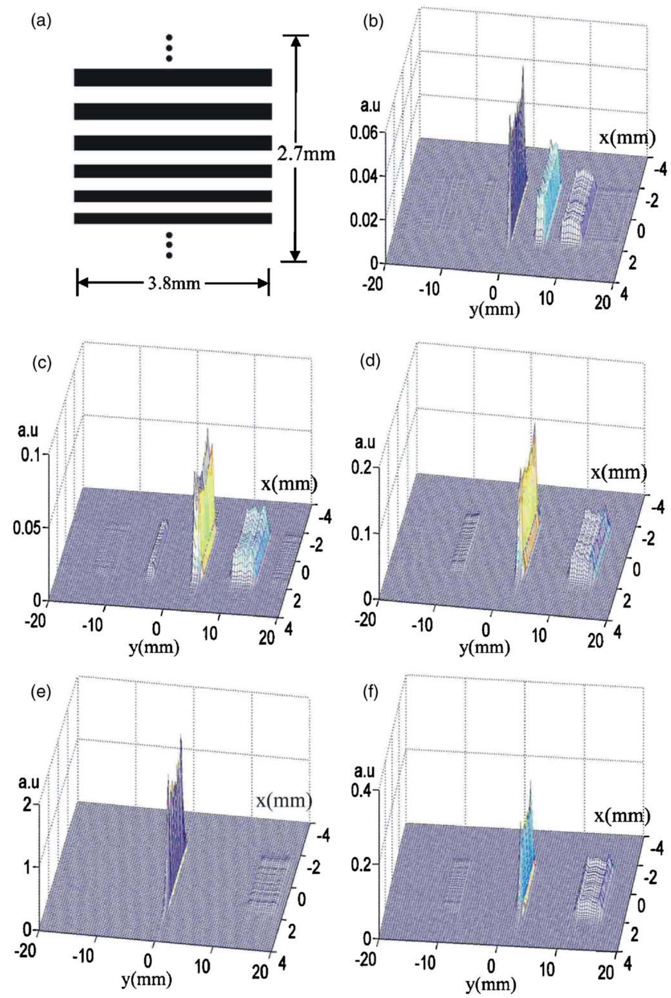


FIG. 4. (Color online) Simulation results of a part zone plate consisting of 100 line strips. (a) The scheme of a part of zone plate consisting of 100 strips. [(b)–(e)] The simulation results of the part zone plate in (a) illuminated by the 633 nm beam, the receiving plane is at about $L=240$ mm $(1/3f_c)$, 350 mm $(1/2f_c)$, 470 mm $(2/3f_c)$, and 710 mm $(f_c)$, respectively. (f) The simulation result of the same part zone plate illuminated by the 450 nm beam, the receiving plane is at about $L=710$ mm $(f_c)$.

diffraction order; and the right peak at about 10 mm in axis $y$ is the zeroth diffraction order. In the left there are several small peaks due to the higher diffraction orders, while in the right of the zeroth diffraction order, a small peak can be considered as the negative first diffraction order. In Figs. 4(c)–4(e), the third diffraction order is moving away from the original position along the -$y$ axis until it disappears. And the first diffraction order moving to center is becoming the principal focus. In Fig. 4(f), when the wavelength of the illuminating beam changes to 450 nm, all diffraction orders have a delay compared to that at 633 nm due to the dispersion phenomenon.

With the results of simulations, Figs. 2 and 3 can be explained more sufficiently. In Fig. 2, the rabbit's head is just the zeroth diffraction order, while the two lines and the focus are the first diffraction order. The "ears" are just the negative first diffraction order. In Figs. 3(b)–3(f), the orange ships below the blue ones and the red disk are zeroth diffraction orders. The orange ship becomes larger and moves to the edge, which is similar to the simulations. The yellow and red ships above the blue ones and the focus in Fig. 3(f) are the first diffraction orders. The yellow ships turn to be the focuses in Figs. 3(b) and 3(e), where the focuses are expected to be in red at 633 nm. So it implies that its focal length is shorter than that of a complete FPZP. This can be explained by the effect of focal shift[25] as the Fresnel number of the part FPZP in direction of axis $y$ is only about 2 here. So a part FPZP almost has the same diffraction and dispersion properties as a complete one except for the focal shift. But the reason for blue ship is uncertain. The positions of the blue ship and the blue disk imply that they are the zeroth diffraction orders spatially separated due to the dispersion properties, which can be learned from Figs. 4(e) and 4(f). But it cannot explain why they are nearly unchanged not like other zeroth diffraction orders. The possible reason is that the approximation in simulation makes the difference between simulations and experiments. Of course effects due to phase shifting properties of the FPZP and reflection between the lens and the FPZP may also play a role. As the part zone plate has been used as monochromator in x-ray measurements,[18–20] we suggest that if a changeable aperture is placed before a complete ZP, then a monochromator can be derived. As the phenomenon of focal shift, there is another way instead of rotating the ZP to adjust the grazing-incidence angle. One can just change the aperture before the ZP to adjust its focal length to fit the beam with different wavelengths. Of course, the ZP can still rotate, but if coupled with a changeable aperture, we think it may be more convenient and powerful.

In conclusion, a series of experiments has been arranged to study the diffraction and dispersion phenomena of two kinds of part FPZPs. The experimental results indicate that a circular part square FPZP can be used as a complete circular FPZP, and a part circular FPZP keeps the main properties of a complete circular FPZP, which can be explained by the different diffraction orders of a ZP. The numerical simulation results mostly meet with the experimental ones. The focal shift of part circular FPZP is also observed. We expect that a part FZP can be a replacement of a FPZ in x-ray imaging when it has problems to work as a complete one, and a part circular zone plate with a changeable aperture can have potential application in some fields of x-ray measurements.

This work was supported by the National Natural Science Foundation of China under Grant No. 60478041. The authors are indebted to the reviewer for valuable advice.


[1] M. Wieland, R. Frueke, T. Wilhein, C. Spielmann, M. Pohl, and U. Kleineberg, Appl. Phys. Lett. **81**, 2520 (2002).
[2] T. Wilhein, B. Kaulich, E. D. Fabrizio, F. Romanato, S. Cabrini, and J. Susini, Appl. Phys. Lett. **78**, 2082 (2001).
[3] O. Carnal, M. Sigel, T. Sleator, H. Takuma, and J. Mlynek, Phys. Rev. Lett. **67**, 3231 (1991).
[4] R. B. Doak, R. E. Grisenti, S. Rehbein, G. Schmahl, J. P. Toennies, and Ch. Woll, Phys. Rev. Lett. **83**, 4229 (1999).
[5] M. Peuker, Appl. Phys. Lett. **78**, 2208 (2001).
[6] E. Di. Fabrizio, F. Romanato, M. Gentili, S. Cabrini, B. Kaulich, J. Susini, and R. Barrett, Nature (London) **401**, 895 (1999).
[7] L. Kipp, M. Skibowski, R. L. Johnson, R. Berndt, R. Adelung, S. Harm, and R. Seemann, Nature (London) **414**, 184 (2001).
[8] W. Chao, B. D. Harteneck, J. A. Liddle, E. H. Anderson, and D. T. Attwood, Nature (London) **435**, 1210 (2005).
[9] C. G. Schroer, Phys. Rev. B **74**, 033405 (2006).
[10] G. C. Yin, Y. F. Song, M. T. Tang, F. R. Chen, K. S. Liang, F. W. Duewer, M. Feser, W. Yun, and H. P. D. Shieh, Appl. Phys. Lett. **89**, 221122 (2006).
[11] H. Toda, K. Uesugi, A. Takeuchi, K. Minami, M. Kobayashi, and T. Kobayashi, Appl. Phys. Lett. **89**, 143112 (2006).
[12] M. Young, J. Opt. Soc. Am. **62**, 972 (1972).
[13] M. Bottema, J. Opt. Soc. Am. **59**, 1632 (1969).
[14] L. J. Janicijevic, J. Opt. (Paris) **13**, 199 (1982).
[15] S. M. Wang, X. Q. Jiang, Q. Lin, E. Bernabeu, J. Alda, and V. Martin, Optik (Stuttgart) **93**, 190 (1993).
[16] L. N. Hazra, Y. Han, and C. Delishe, J. Opt. Soc. Am. A **11**, 2750 (1994).
[17] B. Niemann, T. Wilhein, T. Schliebe, R. Plontke, O. Fortagne, I. Stolberg, and M. Zierbock, Microelectron. Eng. **30**, 49 (1996).
[18] T. Wilhein, D. Altenbernd, U. Teubner, E. Förster, R. Hässner, W. Theobald, and R. Sauerbrey, J. Opt. Soc. Am. B **15**, 1235 (1998).
[19] B. Niemann, P. Guttmann, D. Hambach, G. Schneider, D. Wei$\beta$, and G. Schmahl, Nucl. Instrum. Methods Phys. Res. A **467-468**, 857 (2001).
[20] U. Vogt, T. Wilhein, H. Legall, and H. Stiel, IPAP Conf. Ser. **7**, 334 (2006).
[21] A. R. Jones, Br. J. Appl. Phys. **2**, 1789 (1969).
[22] S. M. Wang, L. G. Hu, B. Z. Zhang, D. M. Zhao, Z. Y. Wei, and Z. G. Zhang, Opt. Express **13**, 3625 (2005).
[23] S. M. Wang, L. G. Hu, B. Z. Zhang, J. Wang, and D. M. Zhao, Opt. Express **14**, 932 (2006).
[24] T. Wilhein, B. Kaulich, and J. Susini, Opt. Commun. **193**, 19 (2001).
[25] Y. Li and E. Wolf, Opt. Commun. **39**, 211 (1981).