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Study of optical properties of X-ray system based on two zone plates

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Abstract

Study of focusing and imaging properties of two Fresnel zone plates (ZP) system for hard X-rays is presented. A phenomenon is demonstrated for the first time of focusing by two ZP located at significant distance from each other. Peculiarities of intensity distribution at the focal plane during a scan by second ZP normally to the optical axis of the system as well as along the optical axis both theoretically and experimentally is investigated. A registration is realized experimentally on the beam line BM-5 ESRF (Grenoble, France) at $E = 9.4$ keV of the focused image of the object. Computer program is elaborated for optical properties simulation using convolution of transmission function and Kirchhoff propagator in paraxial approximation by Fast Fourier Transform (FFT).

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Keywords: X-ray optics; Fresnel zone plate; Focusing

1. Introduction

Further development of X-ray optics significantly depends on creating high efficiency and simultaneously high-resolution lens. Up to now there is a problem to make such lens for hard X-rays. High resolution can be reached by means of Fresnel zone plate (ZP) but as a rule efficiency of such lens is small [1,2]. With the usage of synchrotron radiation even the efficiency of few percents is sufficient for successful experiment, particularly, for obtaining the focused image of the object. In the report [1] authors used ZP from tantalum with zone thickness of 200 nm and the last zone width of 50 nm. The resolution of such ZP is equal to 200 nm, but the efficiency is only 1.5%. Nevertheless, it was sufficient for obtaining the focused image. In the report [2] ZP from gold was performed by means of deep X-ray lithography with zone thickness of 3.5 μm and the last zone width of 50 nm. As was noted by authors, the structure of zones with the width smaller than 200 nm is deviated randomly from the correct form. Moreover, an absorption of X-rays on the gold slab of 3.5 μm width is not small for the X-ray energy 8 keV (the transmission is only ~30%). We note the low efficiency ZP can be used only with synchrotron radiation. For laboratory source we need to have the efficiency about few tens percents. In works [3,4] ZP from silicon monocrystal for axis geometry having 39% efficiency was prepared for the first time by means of electron lithography and ion plasma etching. In experiment on the beam line BL29XU of the synchrotron source SPring-8 (Japan) the resolution of this lens was measured by means of knife scan, which corresponds well to the theoretical estimation $\delta = 1.22\Delta r$. In work [5] crystal ZP was used to obtain the focus image of the phase micro-object. This object consists of letters of small height making on the even surface of silicon crystal.

For creating X-ray optics devices with new properties it is significantly important to develop multiple lens systems. In this work, we present the results of both experimental

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and theoretical study of focusing and imaging properties of double-lens system for hard X-ray radiation based on the ZP made from silicon crystal.

2. The experimental setup and results of measurements

The experimental study with two zone plates was made on the synchrotron source ESRF (Grenoble, France), on the beam line BM-5 (beam from bending magnet). Let us denote the first zone plate by ZP#1, and the second zone plate by ZP#2. The setup used for investigation of focusing properties of two ZP made from silicon at the X-ray energy 9.4 keV are shown in Fig. 1.

The synchrotron radiation beam having a vertical size of 80 μm was made monochromatic by means of two-crystal monochromator Si(1 1 1). The total distance from the source to the entrance slit was equal to 40 m. The size of the slit is equal to $350 \times 350\,\mu m^2$. The beam after the slit falls normally on the first zone plate ZP#1. The distance from the slit to ZP#1 is equal to 30 cm. The second zone plate ZP#2 was located at the distance 39 cm after ZP#1. The zone plate can be adjusted relative to the optical axis with the accuracy of 100 nm. We used two similar ZPs made from silicon mono-crystal with the following parameters: the radius of the first zone 14.38 μm, the number of zones 324, the last zone width 0.4 μm, the aperture 518 μm, the focal length 157 cm, the relief height 6 μm, the thickness of the membrane 2 μm. Raster electron microscopy (REM) image of ZP is shown in Fig. 2. The transmission of the membrane for the X-ray energy 9.4 keV is equal to 93%. The mean transmission of the surface relief is 91%. The intensity distribution is registered by means of FReLoN camera, consisting of specialized CCD detector. The space resolution of the FReLoN camera is about 1 μm. During the measurements the distance to detector has been changed by small steps.

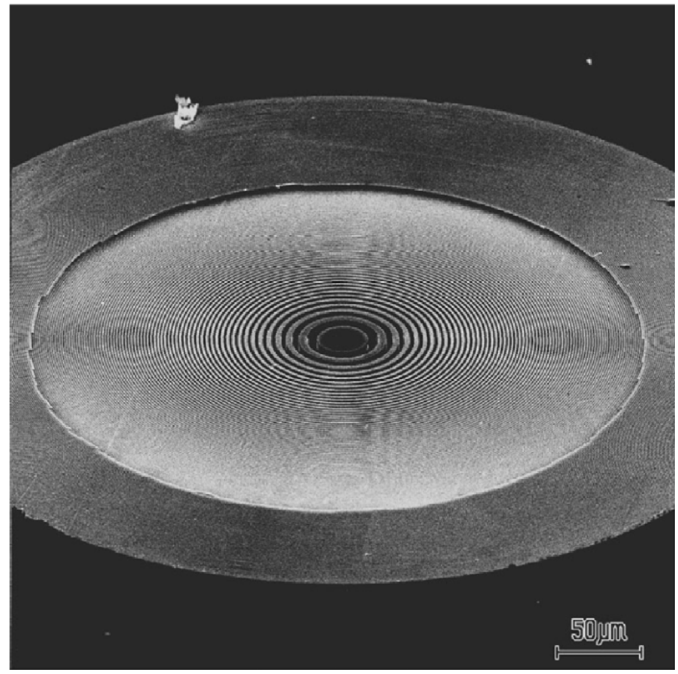

Fig. 2. SEM image of Fresnel zone plate made from silicon.

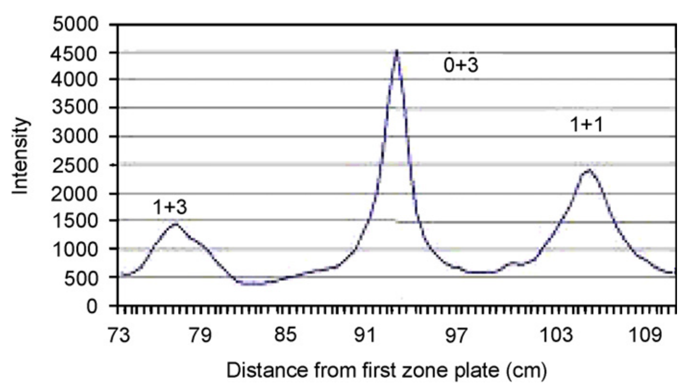

Fig. 3. The measured intensity distribution along optical axis in various cases.

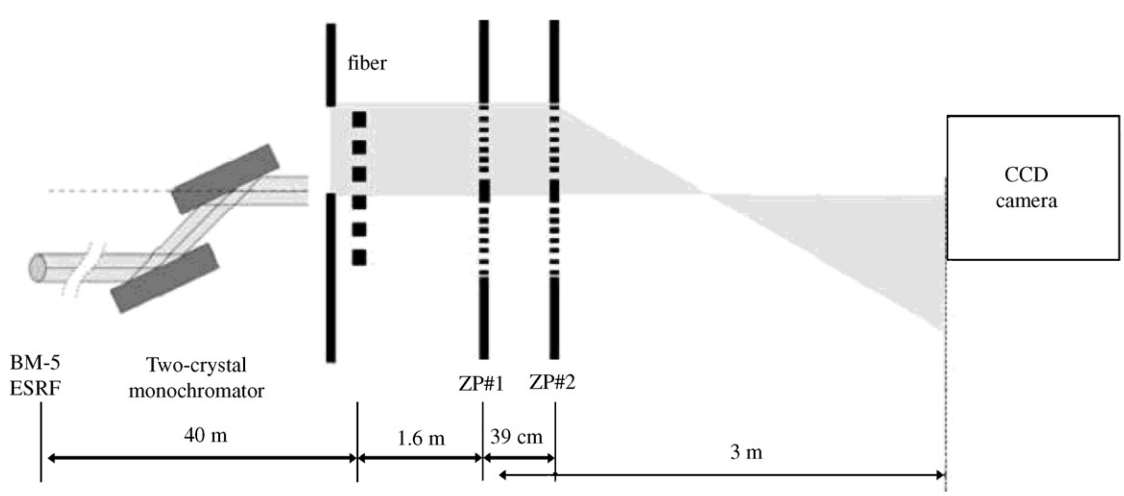

Fig. 1. The experimental setup for study of source focusing.

Fig. 3 shows a distribution of the integral intensity along the optical axis after the second lens ZP#2 within the region of distances from 73 to 115 cm counted between the first lens and the detector. One can see, the system has three most effective focuses which are formed by the way described below.

The first focus is registered at the distance 77 cm and it is formed by the first order of ZP#1 and third order of ZP#2 (we note it as 1 + 3). The second focus is registered at the distance 93 cm and it is formed by zero order of ZP#1 and third order of ZP#2 (0 + 3). The third focus is registered at the distance 107.5 cm and it is formed by the first order of ZP#1 and first order ZP#2 (1 + 1).

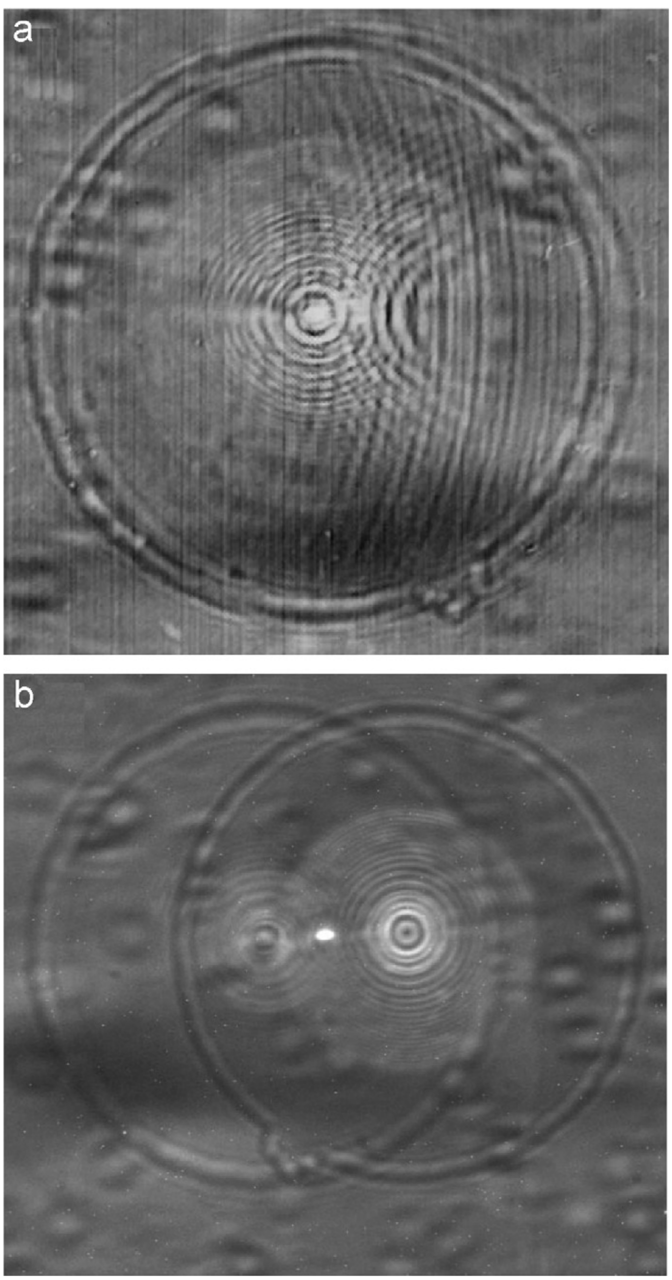

Fig. 4. Moiré pattern at the focus plane when the second lens is shifted on (a)10 μm, (b) 100 μm.

We show two images (Figs. 4 and 5), which corresponds the displacements of the second ZP across optical axis of 10 and 100 μm. It can be seen on Fig. 4 that for small displacement the image shows a Moiré pattern alloying to adjust ZP#1 and ZP#2 relative to the optical axis with accuracy up to 100 nm. We have measured the focus sizes for all three distances of focusing by the system of two ZPs in our experiment using the knife scan method. For (1 + 1) the focus size is equal to 2 μm; for (0 + 3) it is equal to 0.7 μm; for (1 + 3) it is equal to 1.1 μm. It can be noted that these sizes depend significantly on the source size. The source size influences the efficiency as well.

3. The theory and computer simulations

As is known [6], there exists analytical theory for the focal spot structure at the focal plane for one zone plate. Both cases of circular zones (for 2D-focusing) and linear zones (for 1D-focusing) allows analytical description. As for the system of two circular ZPs located at significant distance between them, the analytical calculations are absent and, probably, they are impossible in principle. Nevertheless, it is possible to assume that, at least, focus distances for such system can be the same as for two thin parabolic refractive lenses. To obtain the formula similar to the lens formula for the system of two ZPs, we calculate the ray trajectory from the point source through two lenses up to the point of intersection with the optical axis.

Let us denote the distance from the source to the first lens as r_0, the distance from the first lens to the second lens as L and the distance from the second lens to the image plane as r_i. Let the focal length for the first lens be F_1, and for the second lens—F_2. As a result we obtain the formula which can be written in the following symmetric form:

$$A_1 + A_2 - LA_1A_2 = 0, \quad A_1 = \frac{1}{F_1} - \frac{1}{r_0}, \quad A_2 = \frac{1}{F_2} - \frac{1}{r_i}. \tag{1}$$

It is easy to verify that the formula satisfies to the reciprocity principle because after a replacement source by detector, first lens by second lens and vice versa the formula stays the same. It is useful for our purpose to write this formula as equality for the distance r_i, namely,

$$r_i = F_2 \frac{1 - LA_1}{1 + (F_2 - L)A_1}, \quad A_1 = \frac{1}{F_1} - \frac{1}{r_0}. \tag{2}$$

For the zone plates used in the experiment we obtain $F_1 = F_2 = \rho_1^2/\lambda n = 1.57/n$ m, where $\rho_1 = 14.38$ μm is the radius of the first Fresnel zone, $\lambda = 0.132$ nm is the wavelength of X-rays and n is the order of focusing. Applying formula (2) for $r_0 = 40.3$ m, $L = 0.39$ m and various orders of focusing we obtain r_i as 0.368 m (1 + 3), 0.529 m (0 + 3) and 0.693 m (1 + 1) that is very close to the values 0.38, 0.54 and 0.685 m, which were obtained in experiment. Thus, it is verified that for rather long distance between them the system of two zone plates shows focusing properties which are rather closed to these for refracting lenses with the same parameters. Nevertheless, the small difference takes place. On the other hand, it is evident, that for small distance between the zone plates and in the limit of zero distance they must work as one zone plate with the doubled relief height and be quite different from refractive lenses. Probably there is some lower limit on the distance between the zone plates where formula (2) still works. This interesting question will be investigated in subsequent works.

We have elaborated the computer program for simulating the intensity distribution at the plane perpendicular to the optical axis due to focusing a radiation from the point source by system of two zone plates. The program allows one to calculate a transmission of the transverse intensity distribution through the empty space by means of a convolution of the known complex wave field with the Kirchhoff propagator in the paraxial approximation. A calculation is performed by means of two Fourier transformations with a usage of the algorithm of Fast Fourier Transformation (FFT), because the Fourier image of the Kirchhoff propagator has a simple analytical form. Subsequently, making a calculation for the first lens and then for second lens, we obtain the intensity distribution at any distance after the second lens.

4. Conclusion

It was shown both experimentally and theoretically that the system of two zone plates located at significantly large distance between them is able to focus the synchrotron radiation beam similarly to the set of two refractive lenses. Both the formula for two lens on the focus distance and the formula for the focus displacement turn out to be valid. On the other hand, at small distance, evidently, the set of two zone plates is not similar to the set of two refractive lenses. Our study allows us to make a conclusion, that a usage of two zone plates allows one to decrease the focus distance. This may be useful for many applications. The obtained results show as well, that the study of the set of two zone plates must be continued because this system show new peculiarities absent in the case of two refractive lenses.

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