PROBLEM OF X-RAY SYNCHROTRON BEAM COLLIMATION BY ZONE PLATE

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ABSTRACT

We present the first results of collimating the synchrotron radiation beam by zone plate located at the long distance from the source. Zone plate (ZP) has been fabricated from silicon crystal. We observe the interference fringes due to existence of various orders of focusing. We record experimentally an amplification of synchrotron beam intensity up to four times by means of ZP. The experimental measurements have been performed at the beam line BM-5 of the European Synchrotron Radiation Facility (ESRF) for the energy interval from 8 to 17.5 keV. The fringes were discussed on the base of analytical theory as well as were studied by means of computer simulation. The radial distribution of intensity is determined as a convolution of the zone plate transmission function and the Kirchhoff propagator in paraxial approximation.

Keywords: Coherent radiation, collimator, Fresnel zone plate.

1. INTRODUCTION

High resolution x-ray microscopy is of growing importance for research and industry in such diverse fields as alternative energy, advanced semiconductor development, bio technology, life sciences, material sciences and nanotechnology. After the discovery of X-rays by Rontgen, in 1895 the optical elements with high efficiency and submicrometer resolution have become available. However, such optical elements are difficult for fabrication. Normally a collimation of synchrotron radiation beams is performed with a use of asymmetric Bragg reflections [1, 2]. This way leads to a commensurate and unavoidable increase in the size of the X-ray beam. The lenses as the elements of an optical system can be used either to focus the beam or to collimate the beam if a point source is placed in its focus,. Aluminum and beryllium refractive collimators were proposed and tested [3, 4]. As we show [5, 6], ZP made from a silicon monocrystal for axial geometry has 39% efficiency. Thus, the recent development of ZP focusing hard X-rays has a corollary that such a lens can be used for the collimation. In this paper we present results of the first test of using the ZP to collimate X-ray from a point source placed in its focus.

The circular zone plate has been fabricated on the surface of silicon crystal by electron beam lithography and deep ion plasma etching as a device for collimating synchrotron X-ray beam. The zone plate has an extremely large aperture 1313 μm; the focal length is 52 m for the photon energy of 15 keV. The experimental investigation has been performed on the beam line BM-5 of the European Synchrotron Radiation Facility (ESRF) for the energy interval from 8 to 17.5 keV.

We investigate by both theoretically and experimentally the peculiarities of intensity distribution after ZP normally to the optical axis. The theoretical calculation is performed by means of semi-analytical calculation of a convolution of the ZP transmission function and the Kirchhoff propagator in the paraxial approximation.

2. EXPERIMENTAL SETUP AND MEASUREMENTS

The experimental study of collimating the synchrotron radiation beam was performed at the ESRF (Grenoble, France), on the beam line BM-5 (beam from bending magnet) by the zone plate located at the long distance from the source. Let us denote the distance from a synchrotron source to the zone plate by L_1, and the distance from zone plate to CCD by L_2. We consider two different experimental setups. The first setup was used for investigation of diffraction properties of silicon ZP which located at the long distance from the source: $L_1 = 54$ m, $L_2 = 2$ m for X-ray energy from 12.4 keV to 17.5 keV. The second setup was used for study collimating the synchrotron radiation at the same x-ray

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energy and $L_1 = 34$ m, $L_2 = 22$ m. In both cases the synchrotron radiation beam having a vertical size of 80 μm was made monochromatic by means of two-crystal monochromator Si (111). The total distance from the source to the CCD is equal to 56 m. The size of the slit is equal to 1313×1313 μm^2. In the both cases the beam after the slit falls normally on the ZP. The distance from the slit to ZP is equal to 30 cm.

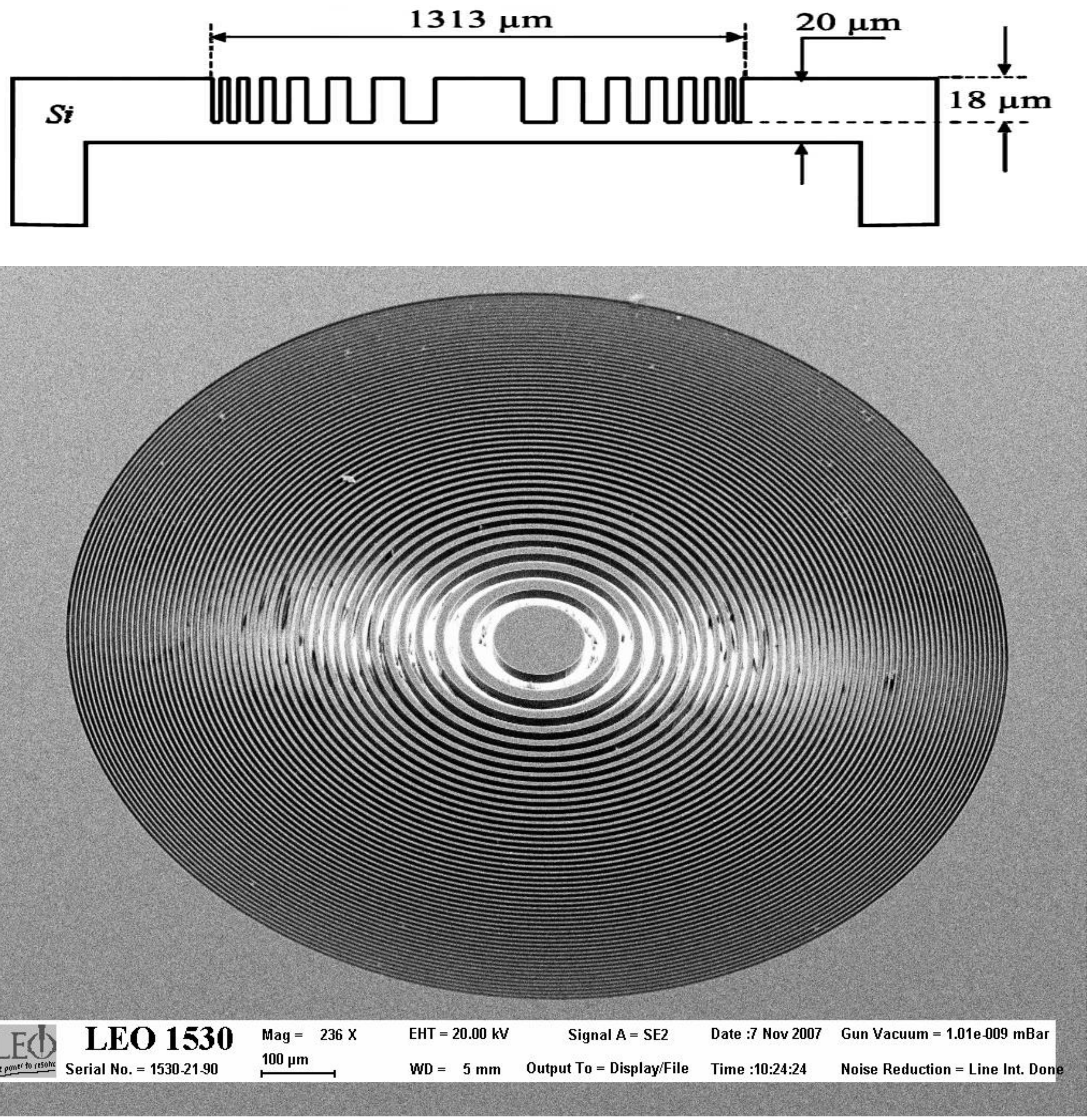
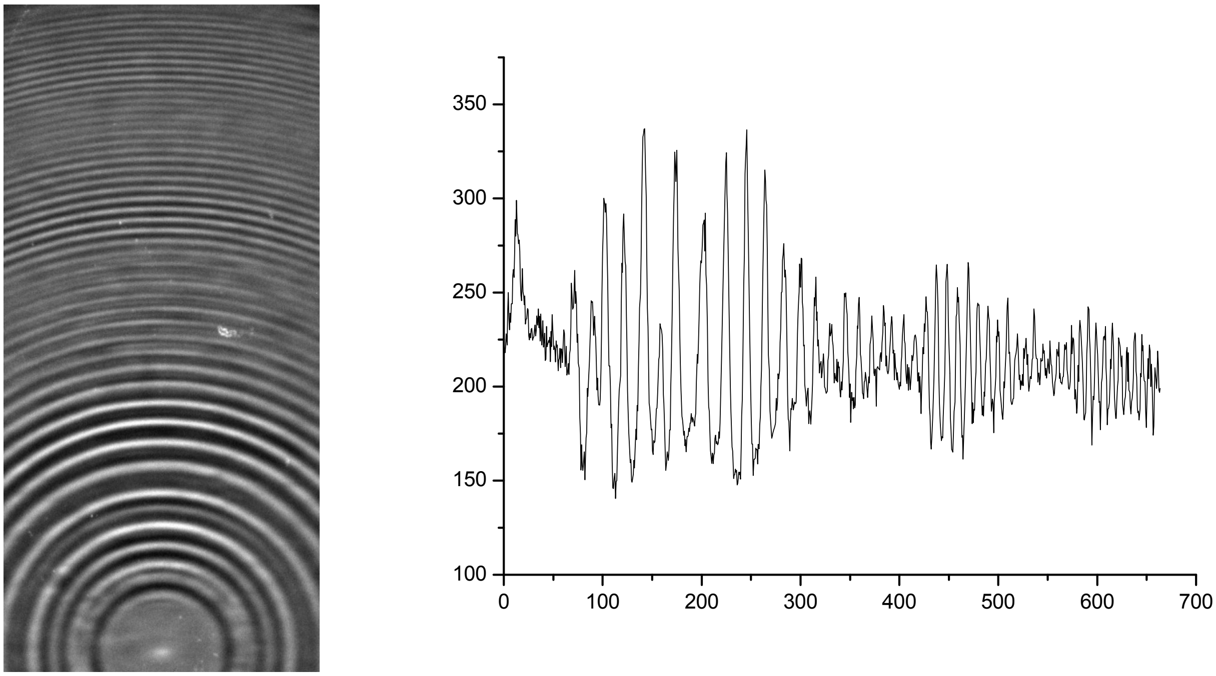
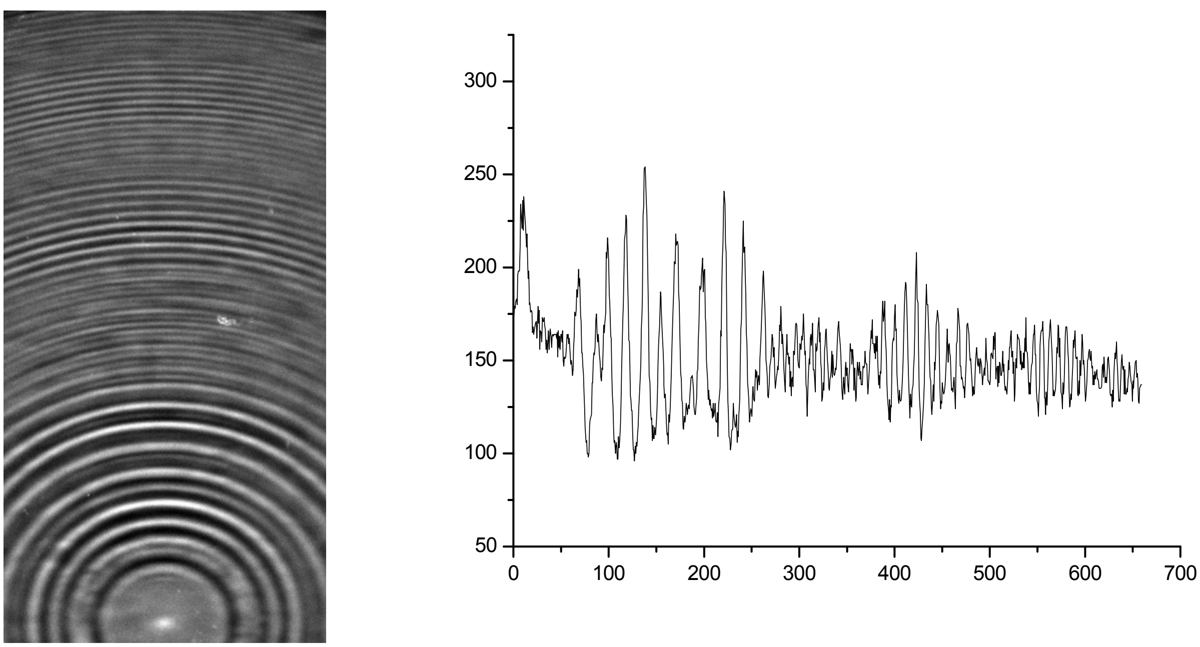


Figure 1. top: the sketch of the Fresnel ZP; bottom: REM image of Fresnel ZP made from silicon, the radius of the first zone is 14.38 μm, the aperture is 1313 μm, the number of zones is 100, the relief height is 18 μm, the last zone width is 3.3 μm, the focal length is 52m for the photon energy of 15 keV, a membrane thickness is 2 μm.

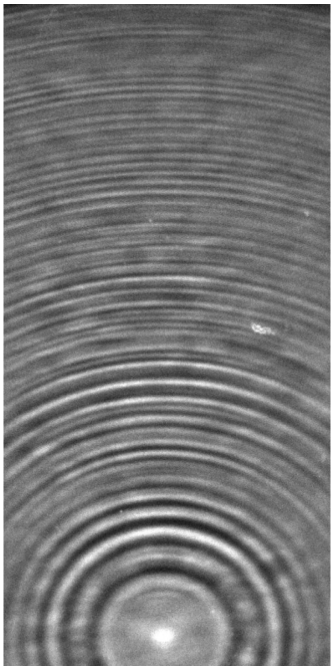
We used ZP made from silicon monocrystal with the following parameters: the number of zones is 100, the radius of the first zone is 14.38 μm, the aperture is 1313 μm, the relief height is 18 μm, a membrane thickness is 2 μm. Correspondingly the last zone width is 3.3 μm, the focal length is 52 m for the photon energy of 15 keV. The sketch and the raster electron microscopy (REM) image of zone plate is shown in Fig.1. The transmission of the membrane for the photon energy of 15 keV is equal to 99.77 %. The mean transmission of the surface relief is 99.93 %. The relative efficiency of the first order zone plate is 39.33 %, the absolute efficiency is 39.15 %.

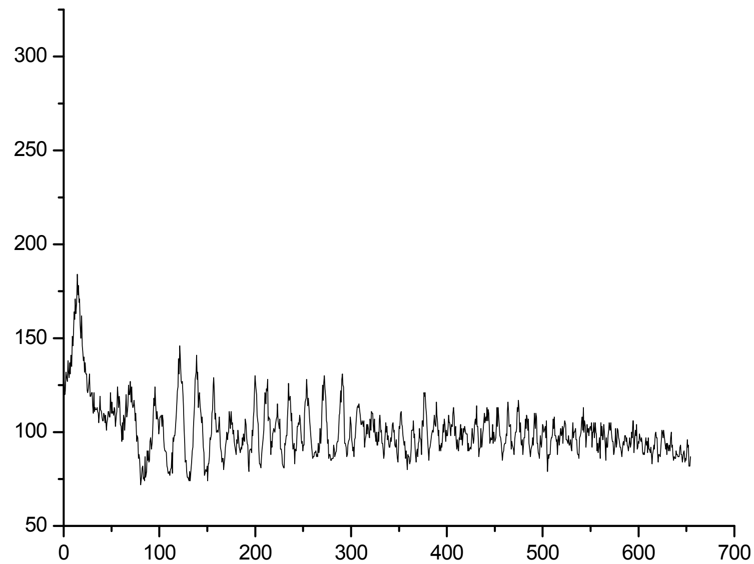


(a) E = 17.5 keV



(b) E = 15.5 keV





(c) 12.4 keV

Figure.2. Intensity spacial distribution for various energy E = 17.5 keV (a), 15.5 keV (b) and 12.4 keV (c). Left panels show images, right panels show a radial intensity profiles.

The intensity spacial distribution is registered by means of FReLoN camera, consisting of specialized CCD detector. The resolution of the FReLoN camera is about 1 µm. Fig. 2 shows a radial distribution of the intensity normally to the optical axis for the distances $L_1 = 54$ m and $L_2 = 2$ m. We have recorded interference fringes due to existence of different orders of ZP focusing. For this geometry we have obtained the maximum contrast for the X-ray energy E = 17.5 keV.

Let K be the amplification of synchrotron radiation beam. Table 1 shows some experimental results for X-ray energy from 10 keV to 17.5 keV. We have recorded the maximum amplification K = 4 of synchrotron radiation for X-ray energy $E = 15$ keV.

E(keV)	*L_1(m)*	*L_2(m)*	*K*
10	*34*	*22*	*2*
12.5	*34*	*22*	*3.5*
15	*34*	*22*	*4*
17.5	*34*	*22*	*2*

Table 1. Experimentally measurement of amplification synchrotron beam radiation.

3. THEORY AND COMPUTER SIMULATIONS

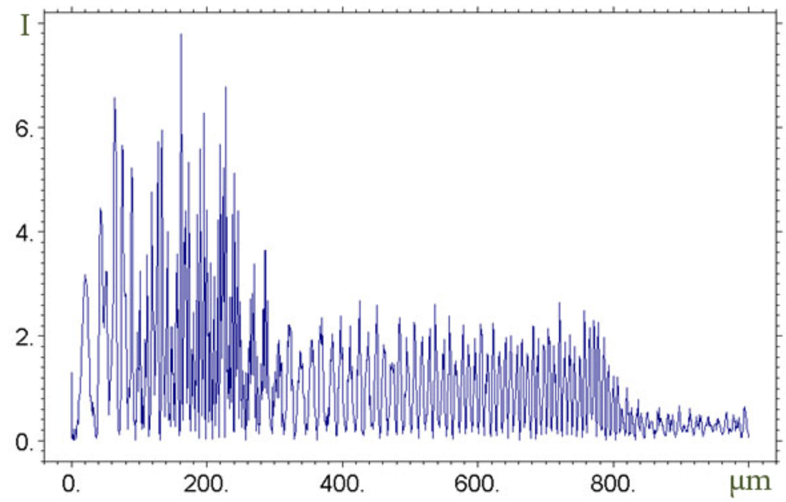
We have performed theoretical calculations of the radial intensity distribution after ZP normally to the optical axis. The calculation was performed by means of analytical transmission function and the Kirchhoff propagator in paraxial approximation. It is assumed that the incident wave is a spherical wave from the point source. Here we give the formulas which were used but without a derivation. The relative intensity $I(r) = |E(r)|^2$.

$$E(r) = T + (1-T)(-2\pi i c)\exp(i\pi c t^2)\sum_{n=1}^{N} \int_{(2n-1)^{1/2}}^{(2n)^{1/2}} dt_1 t_1 \exp(i\pi c t_1^2) J_0(2\pi c t t_1) \quad (1)$$

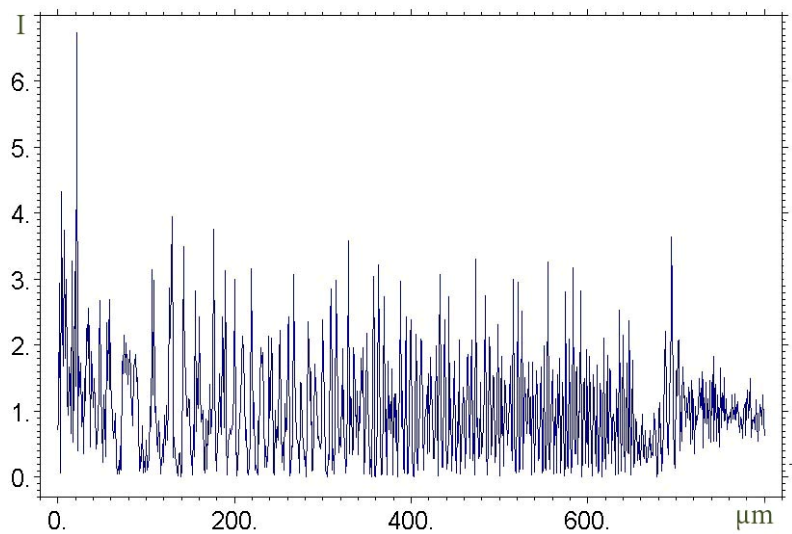
where $J_0(z)$ is a Bessel function of zero order, and the following notations are used

$$T = \exp(-iK\delta p - K\beta p), \quad K = \frac{2\pi}{\lambda}, \quad c = \frac{r_1^2}{\lambda}\frac{(L_1+L_2)}{L_1 L_2}, \quad t = \frac{r L_1}{r_1(L_1+L_2)}. \quad (2)$$

Here δ is a decrement of refraction index, β is an absorption index, λ is a wavelength of the radiation, p is the relief height, r_1 is the radius of the first Fresnel zone, N is a number of etched zones.



(a)



(b)

Figure 3. Calculated radial relative intensity distribution for the following parameters. (a) E = 15 keV, L_1 = 34 m, L_2 = 22 m. (b) E = 15.5 keV, L_1 =54 m, L_2 = 2 m. The parameters of the ZP are the same as in experiment.

The results of theoretical calculation are shown on the Figure 3. Let us consider the Fig. 3(a). The ZP focal length of the first order is equal to F = 52.1 m. The source image is imaginary and is located at the same side with the source at the distance $L_f = F/(F/L_1 - 1) = 97.7$ m. Correspondingly the aperture radius $R = 656.5$ μm will lead to the aperture image $R' = R(1 + L_2/L_f) = 804$ μm. The ZP focal length of the third order is equal to $F = 17.4$ m. This time the source image is real and it is located at the distance $L_f = F/(1 - F/L_1) = 35.5$ m. The aperture radius will lead to image $R' = R(1 - L_2/L_f) = 250$ μm. We can consider the higher order focusing. Thus for the fifth order we have $F = 10.4$ m, $L_f = 15.0$ m, $R' = 304$ μm. One can see the estimated values of R' are revealed as a stepwise change of the mean intensity. The intensity oscillations are determined by considered orders and minus first order of focusing. The zero order is small because the phase shift is close to π. We note the calculated radial distribution does not coincide with the experimental one because the experimental two-dimensional image is averaged over the source size.

In the Fig. 3(b) the distance L_1 is close to the focal length of the first order, however the distance L_2 is rather small. The intensity oscillations are determined by the interference of various orders of focusing. To observe the collimated beam one needs to increase the distance L_2 up to values where all orders of focusing except the first order give the small contribution.

CONCLUSIONS

High efficiency and low absorption Fresnel colimator with the focal length 52m for the photon energy of 15 keV have been fabricated by electron beam litography and deep ion plasma etching of silicon. The experimental testing of the first order diffraction zone plates (Fresnel colimator), when a point source is placed in the focus, has been conducted on the synchrotron radiation source ESRF.

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