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X-ray imaging microscopy at 25 keV with Fresnel zone plate optics

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Abstract

X-ray imaging microscopy with a sputtered-sliced Fresnel zone plate (SS-FZP) has been developed at an X-ray energy of 25 keV. Objects were imaged in transmission with the SS-FZP as an objective with a magnification of 10.2 times, and detected with a X-ray image sensor. The performance of the imaging microscope has been tested with a gold mesh and a resolution test pattern at an undulator beamline 47XU of SPring-8. The resolution test patterns up to 0.5 μm line-and-space structures have been resolved. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Many types of optical elements have been proposed and developed for hard X-ray microscopy. Fresnel zone plates (FZPs), total reflection mirrors, multilayer mirrors, Bragg Fresnel lenses, and refractive lenses have been used as objectives of hard X-ray imaging microscopes. On the contrary, in the soft X-ray region, the highest spatial resolution has been achieved by the FZPs fabricated using electron-beam lithographic techniques. However, those FZPs cannot be applied to hard X-ray microscopy above 20 keV, because the required thickness and aspect ratio of the FZPs are beyond the fabrication capabilities.

Sputtered-sliced FZP (SS-FZP) proposed by Rudolph and Schmahl [1] is one of promising candidates for high-energy X-ray optics, because thick FZP with narrow zone width can be fabricated by the sputter-slice technique. Therefore, the SS-FZP is considered to be suitable for high-energy X-ray imaging element. In this paper, we introduce an imaging X-ray microscope with the SS-FZP as an objective at 25 keV. Results of performance test are also described.

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2. Experimental setup and results

The schematic diagram of the 25 keV X-ray imaging microscope is shown in Fig. 1. The SS-FZP fabricated at Osaka National Research Institute [2] is employed as the objective. It consists of 50 layers of Cu and Al deposited on a gold core. Thickness of the FZP is about 36 μm and the outermost zone width is 0.25 μm. The characteristics of the FZP have been evaluated. The measured focal length is 508 mm, and the measured diffraction efficiency of the first-order is about 15% for 25 keV X-rays.

The experiment has been carried out at an undulator beamline 47XU of SPring-8. The X-rays emitted by an in-vacuum type permanent magnet planar undulator [3] are monochromatized with a Si1 1 1 double crystal monochromator, and illuminated the sample. The photon flux density on the sample plane was 4.2×10^{12} photons/mm^2/s at 25 keV. The transmission images of samples were magnified 10.2 times with the FZP optics. A pinhole with a diameter of about 20 μm was placed at the back focal plane to select the first-order diffracted beam alone. A beam stop with a diameter of about 400 μm was also set in front of the image detector (a cooled charge coupled device (CCD) camera coupled with relay lens and phosphor screen) in order to avoid saturation due to the zeroth-order beam. A gold mesh with 1500 lines/in, a wire diameter of 5.6 μm, a nominal aperture of 11 μm and a thickness of about 3.8 μm (28% absorption contrast), was used as a test sample to check the image formation characteristics of the microscope. The result is shown in Fig. 2. The black and narrow lines indicate the schematic position of the gold mesh. Although the mesh structure can be recognized, strong noises also appear in the measured image. The noises seem to be so-called "speckle" that is usually observed in the visible light microscopy under coherent illumination like a laser light. The coherence of the illumination used in this experiment is fairly high because of the low emittance synchrotron light source. The sample to the source distance is 43 m and estimated source size is about 50 μm in vertical and about 900 μm in horizontal directions. Therefore, angular spread of the illumination beam, defined as D/L, where D is the source size, L is the sample to the source distance, is estimated to be 1.2 μrad in vertical and 21 μrad in horizontal directions. Therefore, the spatial coherent area at the object plane is estimated to be about 43 μm in vertical and 2.4 μm in horizontal directions, and the coherence in vertical direction is 18 times as high as that in horizontal direction. In the observed image, the noise structures can be mostly seen in vertical

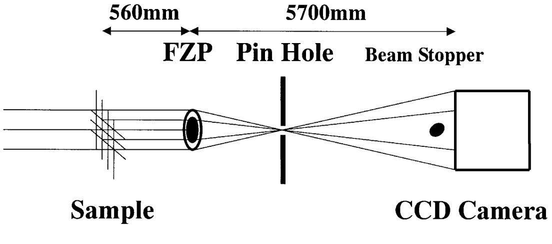

Fig. 1. Schematic diagram of the X-ray imaging microscope under coherent illumination.

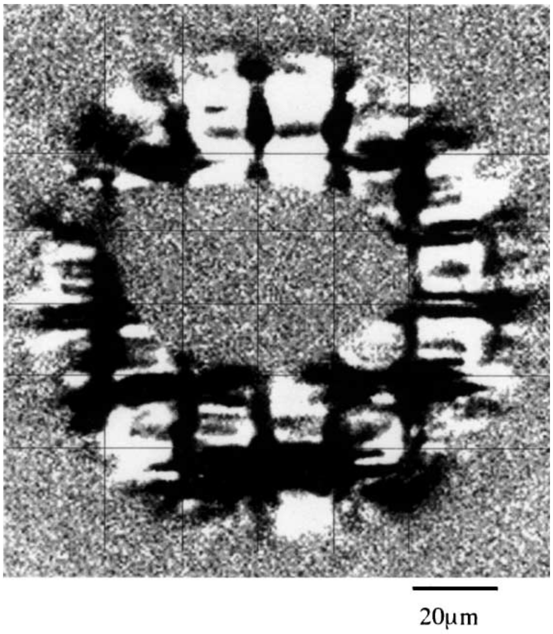

Fig. 2. Image of the gold mesh taken under coherent illumination. Magnification: 10.2; exposure time: 500 ms. Solid lines indicate the schematic position of the gold wires.

direction. If the spatial coherence in vertical and horizontal directions is almost the same, the speckle-like noise pattern will spread uniformly in both vertical and horizontal directions. Recently, White et al. used a kind of diffuser [4] to extinguish the speckle-like noise in imaging optics for EUV light from synchrotron light source. To eliminate the strong speckle-like noise, we tried to use a diffuser for hard X-rays to reduce the spatial coherence. In this experiment, a SiC powder with an average grain size of 13 μm and 0.6 mm thickness, was used as the diffuser. Fig. 3 shows the measured angular spread of the 25 keV X-rays that passed through the diffuser and the broken lines show the instrumental function (the angular spread in vertical and horizontal directions without the diffuser). Both of the values of angular spread of the incoherent illumination beam in vertical and horizontal directions were about 70 μrad. (FWHM), and the transmissivity of the 25 keV X-rays to the diffuser was 15.4%. The experimental setup for the incoherent illumination is shown in Fig. 4. The diffuser was set about 10 mm upstream to the sample, and was rotated to remove the speckle noise from the diffuser itself. The fill factor, the ratio of the angular spread of the illuminating beam at the FZP plane to the diameter of the FZP, was 0.5. The spatial filter (50 μm × 50 μm square aperture) was set at the back focal plane. Fig. 5 shows the observed image of the gold mesh taken under the incoherent illumination. The mesh image is clearly observed without distortion and conspicuous noise. Then the spatial resolution of this microscope was also checked. We prepared a resolution test pattern in order to estimate the spatial resolution. The resolution test pattern has a tantalum microstructure with the thickness of 0.5 μm (3%

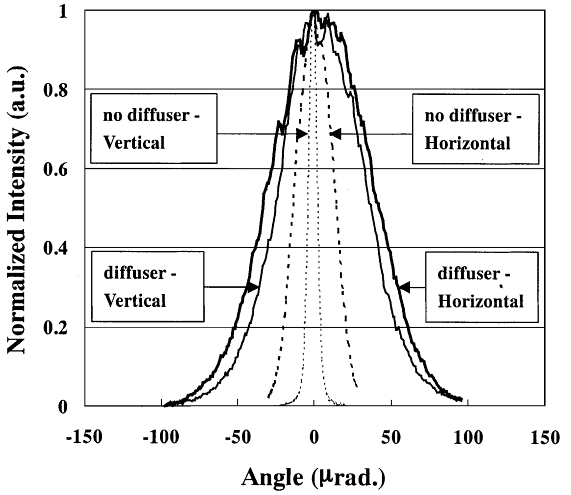

Fig. 3. Measured angular spread of the incoherent beam (solid lines) and of the coherent beam (broken lines).

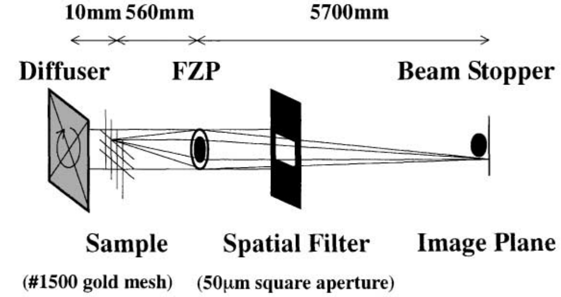

Fig. 4. Schematic diagram of the X-ray imaging microscope under incoherent illumination.

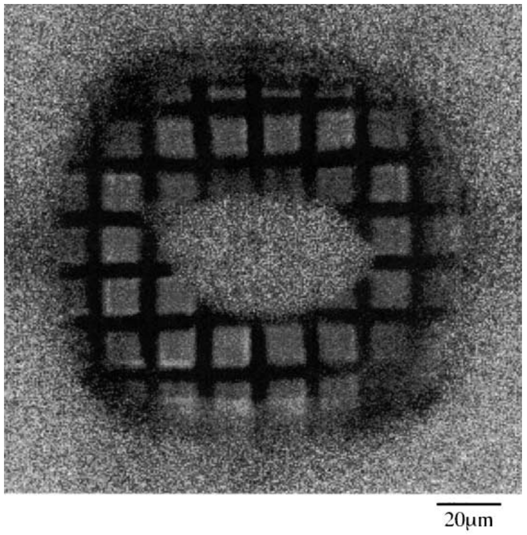

Fig. 5. Image of the gold mesh taken under incoherent illumination. Magnification: 10.2; exposure time: 60 s.

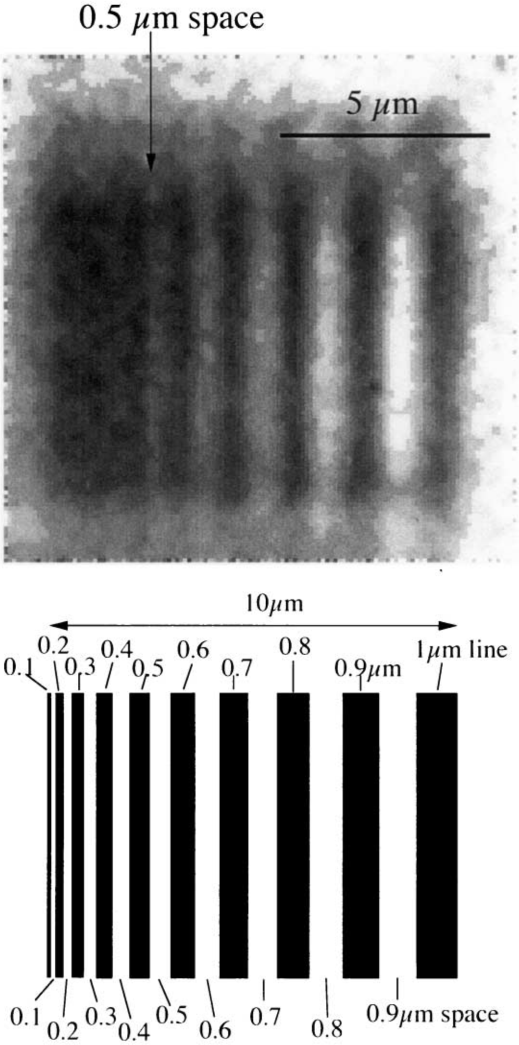

Fig. 6. Measured image and the corresponding drawing of the resolution test pattern. Magnification: 10.2; exposure time: 240 s.

absorption contrast) on Si_3N_4 membrane of 2 μm, and its finest structure is 0.1 μm line-and-space. Fig. 6 shows the measured image of the resolution test pattern and the schematic drawing of the test pattern. A 0.5 μm line-and-space has been resolved in the measured image.

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