Development of achromatic full-field hard X-ray microscopy using four total-reflection mirrors

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Abstract. We developed achromatic full-field hard X-ray microscopy on the basis of advanced Kirkpatrick-Baez mirrors consisting of four total-reflection mirrors. The microscope system consists of advanced Kirkpatrick-Baez mirrors as an objective, Kirkpatrick-Baez mirrors as a condenser and an X-ray CCD camera. The performance of the system was investigated using a Siemens star chart with a minimum resolution of 50 nm at BL29XUL of SPring-8 at 10 keV. As a result, a spatial resolution of ~150 nm was achieved. Also, no chromatic aberration was confirmed by taking images at an X-ray energy from 8 to 11.5 keV.

1. Introduction
To realize achromatic full-field hard X-ray microscopy, it is essential to employ imaging optics with total-reflection mirrors. Kirkpatrick–Baez (KB) mirrors, which consist of two elliptical mirrors aligned perpendicular to each other, are often used to focus X-rays. However, they are not suitable for full-field X-ray microscopy because they suffer from comatic aberration. To overcome this aberration, advanced Kirkpatrick–Baez mirrors have been proposed [1]. They consist of two elliptical mirrors and two hyperbolic mirrors oriented perpendicular to each other, as in KB mirrors (Fig. 1).
To develop advanced KB mirrors for microscopy with sub-50 nm resolution, ultraprecise aspherical mirrors with a figure accuracy on the order of 1 nm and precise four-mirror alignment are needed [2]. We have successfully fabricated four mirrors with figure errors of 2 nm by EEM [3]. We also have developed an alignment procedure for aligning the mirrors with the required accuracies [2, 4].
In this paper, we report the results of our first experiment, in which a magnified X-ray image is formed using advanced KB mirrors. The performance test was carried out at BL29XUL of SPring-8 at an X-ray energy of 10 keV. Also, the X-ray energy dependence of image formation was investigated by varying the X-ray energy.

2. Experiment
We constructed an imaging system for magnifying transmission X-rays through a sample between the first and second experimental hutches of BL29XUL (Fig. 2). A monochromatized X-ray is focused at the object plane using KB mirrors as a condenser. The transmission X-ray through the sample is collected by advanced KB mirrors. The sample can also be observed using a light microscope to find

the target sample. Finally, a magnified image is formed at the X-ray CCD system placed ~45 m downstream of the objective, which consists of a scintillator (P43), lenses (×2) and a CCD (12.4 μm/pixel, Hamamatsu Photonics). The sample used is a Siemens star chart with a minimum resolution of 50 nm (XRESO-50, NTT AT). The specifications of the advanced KB mirrors are shown in Table 1 (For more details, see references [2, 5]). Also, the parameters of the KB mirrors used as a condenser are shown in Table 2.

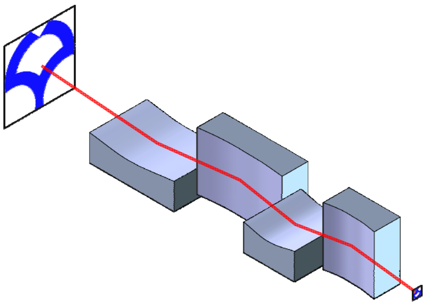

Figure 1. Advanced Kirkpatrick-Baez mirrors

Table 1. Specifications of the advanced KB mirrors used as objective

Numerical aperture (Both directions)	1.2×10^{-3}
Working distance (mm)	50
Magnification factor (H × V)	385 × 210
Acceptable X-ray energy (keV)	< 11.5

Table 2. Parameters of the KB mirrors used as condenser

	Vertical focusing	Horizontal focusing
Mirror length (mm)	200	200
Glazing incidence angle[a] (mrad)	7.8	7.4
Focal length[a] (mm)	555	350
Working distance (mm)	150	
Coating	Pt	

[a] At the center of the mirror

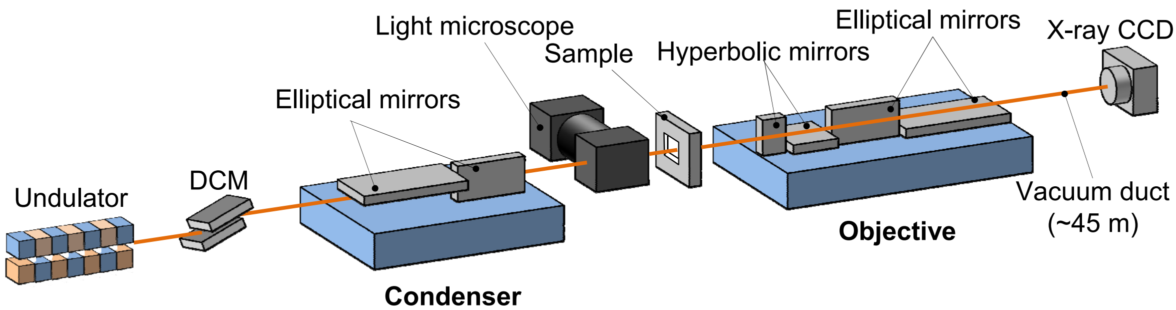

Figure 2. Experimental setup for magnification imaging

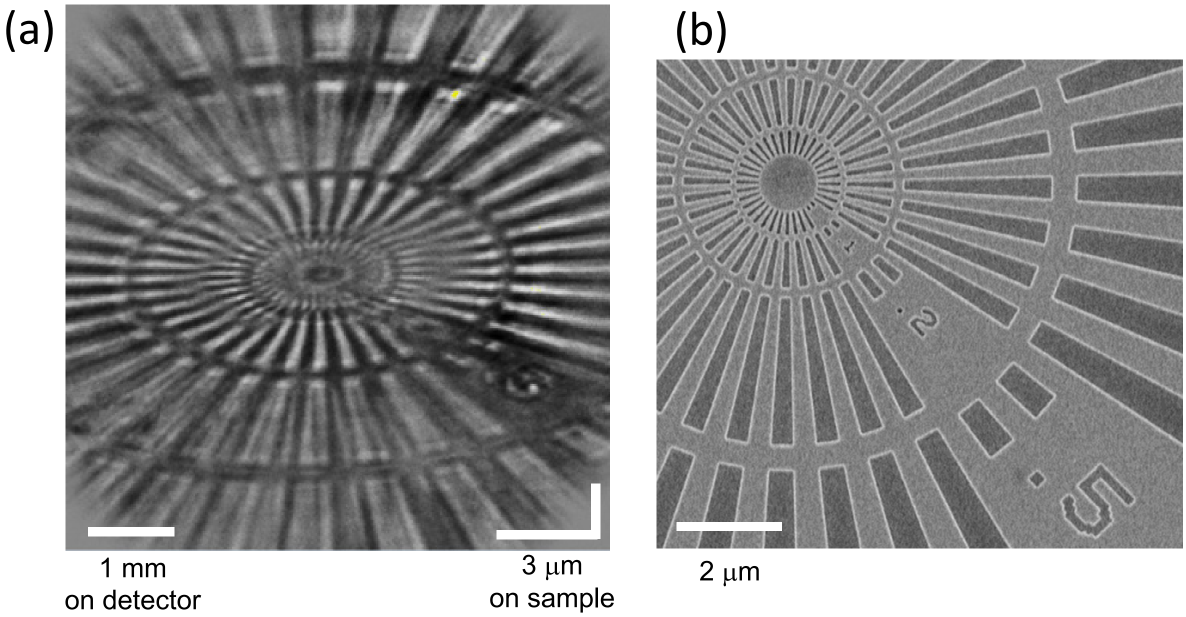

Figure 3. (a) X-ray image and (b) SEM image. Experimental conditions for X-ray imaging: X-ray energy = 10 keV, exposure time = 20 sec. The image was corrected by subtracting the background.

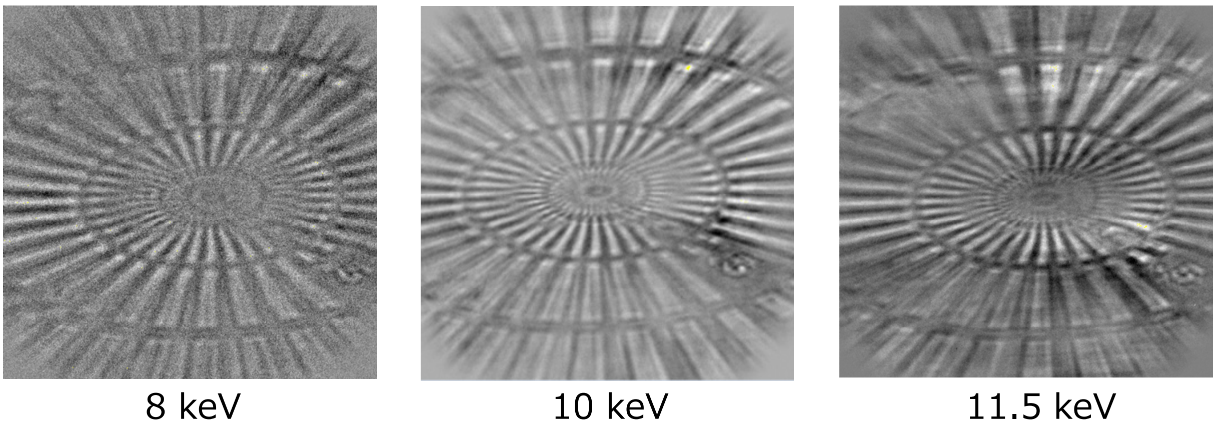

Figure 4. X-ray energy dependence. The exposure time is 20 sec. The image was corrected by subtracting the background.

3. Results and discussion

Figure 3(a) shows the acquired X-ray image. By comparing the X-ray and SEM images, we can conclude that a spatial resolution of ~150 nm was obtained. The observed magnifications are ×393 and ×213 in the horizontal and vertical directions, respectively. The result is in good agreement with that expected from the design. However, speckle noises from a Kapton film used as a vacuum window were observed. Also, the contrast of the line with a certain spatial frequency region was reversed. This is because the MTF (modulation transfer function) has a negative value. That is, the experimental PSF (point spread function) seems to have multiple peaks. This may result from the misalignment of the

focal length. Because the experiment was preliminary and we had insufficient time, we did not make sufficient adjustment of the focal length.
Figure 4 shows the X-ray energy dependence of image formation. We varied the X-ray energy from 8 to 11.5 keV, keeping other conditions fixed. As can be seen, the image quality was not changed. The noise in the image at 8 keV resulted from the absorption of X-rays by air. Because the light path in the atmosphere was ~3 m, the transmissions at 8, 10 and 11.5 keV are 3, 18 and 32%, respectively.

4. Summary and outlook

We have successfully developed a full-field hard X-ray microscope based on advanced KB mirrors. So far, we have achieved ~150 nm resolution at 10 keV. Also, we confirmed that image formation is independent of X-ray energy in the range from 8 to 11.5 keV. In our next experiment, we will take clear images with a spatial resolution of ~ 50 nm by finely adjusting the whole system and eliminating speckle noises. We aim to realize a full-field X-ray fluorescence microscope with sub-50 nm resolution because its achromatic property will be effective for detecting polychromatic X-ray emissions with a wide field of view. Such a fluorescence microscope will become a powerful tool for observing elemental distributions. Also, in the near future, we will apply the system in X-ray free electron lasers. The combination will enable us to image X-ray emissions on an ultrashort time scale.

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