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ABSTRACT

A full-field X-ray microscope utilizing advanced Kirkpatrick–Baez optics, which comprises four concave mirrors, provides high-resolution X-ray images without chromatic aberration. However, a large distance is required between the mirrors and the detector to obtain sufficiently high magnification factor. To achieve reduce this distance, this paper proposes a novel X-ray imaging mirror system consisting of two pairs of concave and convex mirrors, which enables the effective focal length to be decreased by shifting the principal surface. For developing the proposed optics, the mirrors were fabricated with an ion beam figuring system and stitching interferometer, developed by our group, with a peak-to-valley accuracy of ~2 nm. Analysis results indicate that the fabricated mirrors can achieve nearly diffraction-limited imaging performance. We report the mirror fabrication results and the characteristics of the fabricated mirrors.

Keywords: X-ray mirrors, X-ray microscopy, mirror fabrication, advanced Kirkpatrick–Baez mirror optics

1. INTRODUCTION

X-ray mirrors are regarded as one of the best tools for X-ray focusing owing to their large acceptable aperture, high reflectivity, and achromaticity. At present, Kirkpatrick–Baez (KB) mirrors,[1] which utilize two concave mirrors at glancing-incidence arrangements in both the vertical and horizontal axes, are well known and established for collecting and focusing X-rays. An X-ray nanofocused beam has been successfully generated using KB mirrors.[2] In contrast to the case of X-ray focusing, KB mirrors are unsuitable for image forming because it suffers from coma aberration, which stems from grazing-incidence-angle error; therefore, the KB mirror requires precise alignment for the incidence angle and possesses a significantly narrow field of view (FoV).[3,4] To overcome the coma problem, an advanced KB mirror, which consists of two pairs of elliptical and hyperbolic concave mirrors aligned perpendicularly to each other, were proposed.[5,6] The one-dimensional mirror pair allows the double reflection of rays, and hence it almost satisfies Abbe's sine condition. Consequently, the advanced KB mirror can attain a wide FoV owing to the reduction of coma aberration. We have developed an achromatic full-field X-ray microscope with a spatial resolution less than 50 nm by utilizing advanced KB mirrors.[7-9] Spectroscopic full-field X-ray imaging, including XANES imaging and X-ray fluorescence imaging[10], has been successfully preformed using our microscope.

Recently, we have been planning to improve the microscope for achieving practical feasibility. Our conventional setup requires a large distance between the mirrors and camera, e. g., 10-50 m, to obtain a sufficient magnification factor. A more compact apparatus is desirable for application in synchrotron radiation facilities and laboratory-size X-ray sources. However, the advanced KB mirrors designed for a compact setup, the total length of which is less than 3 m, has an inherently low magnification factor. From the viewpoint of the effective pixel size of an image detector, the magnification factor of the objective is important for high-resolution imaging, in addition to the numerical aperture. To achieve a large magnification factor even with a compact setup, we proposed an X-ray imaging optical system based on a combination of concave and convex mirrors.[11]

In this paper, we report fabrication results of the proposed imaging mirror system, which is the most important component for a compact and achromatic full-field X-ray microscope. To realize diffraction-limited imaging performance, ultraprecise surface figuring and a measurement technique are required for the fabrication of the mirrors.

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For this purpose, an ion beam figuring (IBF) system[12] and stitching interferometer,[13,14] which have been developed by our group, were employed.

2. CONCAVE–CONVEX IMAGING MIRROR SYSTEM

Fig. 1 (a) shows a schematic diagram of the proposed imaging mirror system. The system consists of two pairs of elliptical concave and hyperbolic convex mirrors that are aligned perpendicularly to each other. The focal length is defined as the distance from the focal point to the principal plane, which is an intersection plane formed by extensions of the incident rays to the optical system and the outgoing rays. The combination of elliptical concave and hyperbolic convex mirrors enables the principal plane to be near the object plane (Fig. 1 (b)), resulting in a short focal length and high magnification factor. In the one-dimensional imaging mirror pair, the mathematical focal point of the hyperbola coincides with that of the ellipse. Thus, the system satisfies the principle of equal optical path and Abbe's condition, and the spherical and coma aberrations are eliminated. Additionally, the aberration of field curvature tends to be compensated in the concave–convex imaging mirror system because the radius of the image surface is determined by the sum of the radii of curvature of the mirrors.[11] Hence, the proposed optics has a wide FoV. The system comprises nearly planar mirrors that are easily fabricated using established processing and measurement techniques, and therefore, diffraction-limited imaging performance can be attained.

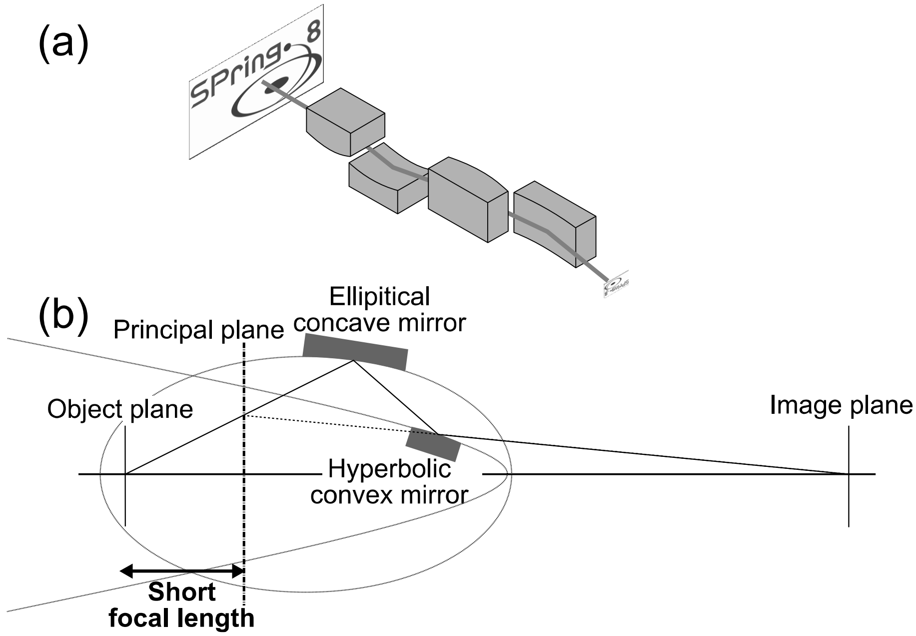

Figure 1. Schematic diagrams of the concave–convex imaging mirror system: (a) arrangement of the mirrors; (b) cross-section of the one-dimensional imaging mirrors shown in (a).

3. OPTICAL DESIGN OF ONE-DIMENSIONAL IMAGING MIRROR

We designed a one-dimensional imaging mirror pair for imaging hard X-rays at sub-50-nm resolution under total-reflection conditions. The length of the entire imaging system was set to be approximately 2 m so that it is compatible for practical application in X-ray analysis and laboratory-size X-ray sources. The glancing incident angles were less than 6 mrad. The lengths of the mirrors were approximately 8 mm, which is remarkably short compared to those of conventional X-ray mirrors. The focal length of the optical system was 6.51 mm, resulting in a magnification factor of 321 even with such a compact setup. The numerical aperture of the system was 1.6×10^{-3}, which would realize a resolution of 40 nm at an X-ray energy of 10 keV. Wave-optical calculations based on Fresnel–Kirchhoff's diffraction integral, which we previously proposed,[14,15] revealed that both mirrors should be fabricated with a peak-to-valley (PV) shape accuracy of 2 nm.[11]

Table 3. Parameters of the designed one-dimensional imaging mirror.

	Hyperbola	**Ellipse**
a (m)*	1.03	1.72×10^{-2}
b (m)*	3.27×10^{-4}	9.76×10^{-5}
Distance from object (mm)**	25	14
Glancing incident angle (mrad)**	2.34	5.71
Mirror length (mm)	8.6	8.2
Focal length (mm)	6.51	
Magnification factor	321	
Numerical aperture	1.61×10^{-3}	

*Ellipse: $x^2/a^2 + y^2/b^2 = 1$, Hyperbola: $x^2/a^2 - y^2/b^2 = 1$. **At the center of the mirror.

4. FABRICATION OF MIRRORS

We fabricated the elliptical concave and hyperbolic convex mirrors by using an IBF system for surface figuring and a stitching interferometer for measurement. The mirrors were fabricated on Si-Cz (001) ingot substrates with effective areas of 8.2 × 3.0 mm^2 (ellipse) and 8.7 × 3.0 mm^2 (hyperbola), as shown in Fig. 2. We processed the mirrors with the deterministically controlled dwell time of the ion beam. The distribution of the dwell time was calculated from the distribution of removal amounts by the deconvolution method.[12] The total processing time was 45.7 h for two mirrors. Fig. 3 shows the fabrication results of hyperbolic convex and elliptical concave mirrors. The residual shape errors were almost 2 nm PV, which are comparable to the required shape accuracy. After the fabrication, the surfaces of the mirrors were coated with a molybdenum (Mo) layer to realize high reflectivity for X-rays. Surface roughness characterization using a white-light interference microscope (Zygo, NewView 5030), as shown in Fig. 4, revealed that Mo-coated surfaces have root-mean-square (RMS) roughness values of approximately 0.35 nm over areas of 64 × 48 μm^2, which were almost same values as those of unprocessed surfaces. These smooth surfaces would not degrade the reflectivity for X-rays.

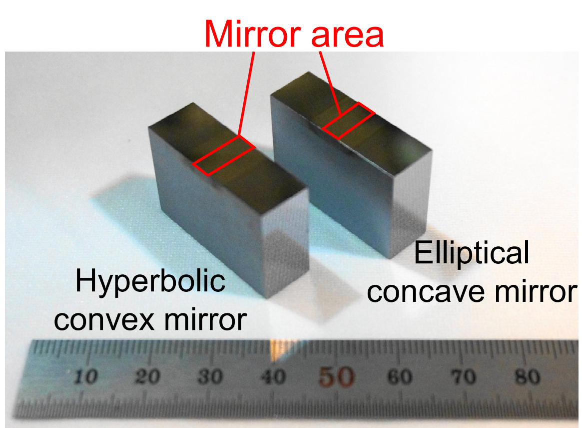

Figure 2. Photograph of the fabricated hyperbolic convex and elliptical concave mirrors.

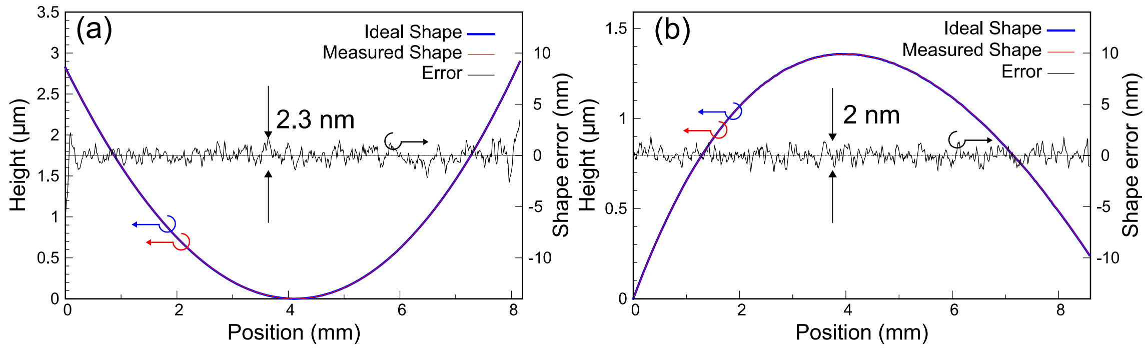

Figure 3. Shapes of ideal and fabricated mirror surfaces, together with the residual shape errors from the ideal shapes. (a) Elliptical concave mirror. (b) Hyperbolic convex mirror.

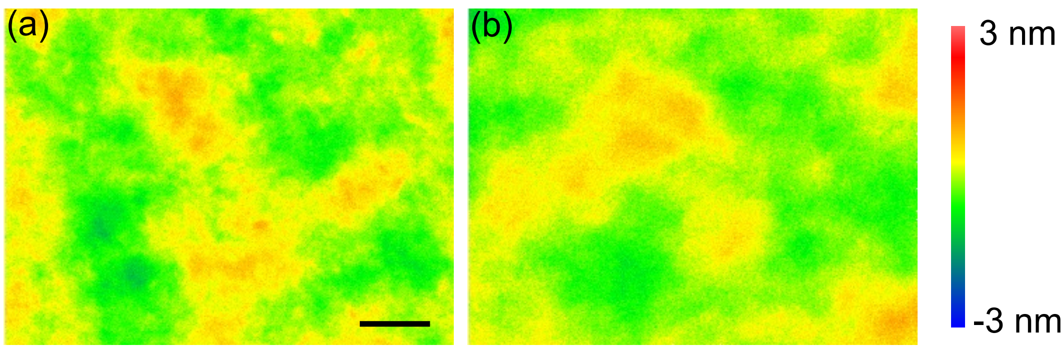

Figure 4. Surface profiles (64 × 48 μm^2) of the (a) elliptical and (b) hyperbolic mirrors, the RMS roughness values of which were 0.357 and 0.348 nm, respectively, measured by a white-light interference microscope after coating of an Mo layer. The scale bar is 10 μm.

5. DISCUSSION

As shown in Fig. 3, the residual shape errors predominantly exist in a range of spatial wavelength of 0.1-0.3 mm. The spatial resolution of the shape correction by the IBF processing was limited by the diameter of the ion beam, which was 0.5 mm. Thus, it is suggested that the high-frequency shape errors originated from the primary surface of the substrate that was finished by conventional polishing. Fig. 5 shows the results of power spectral density (PSD) analysis of the shape errors of elliptical and hyperbolic mirrors before and after processing. PSDs in the low spatial frequency range were effectively decreased thanks to the deterministic processing. On the other hand, shape errors with a spatial frequency ranging from 0.02 mm to 0.3 mm were obviously dependent on the primary shape errors. A highly accurate pre-polishing method for the substrate will be needed to decrease shape errors.

Finally, a demagnified image of the point source, which corresponds to the line spread function of the imaging mirror, was obtained using our wave-optical simulator in order to confirm the characteristics of the fabricated imaging mirrors. Fig. 6 shows the result of the calculation with/without shape errors. The X-ray energy used was 10 keV. Intensity profiles on the focal point calculated with shape errors were in good agreement with the ideal profile, although the peak intensity was slightly decreased because of the high-frequency shape errors on the mirrors. The results indicate that the fabricated mirrors could achieve nearly diffraction-limited imaging performance.

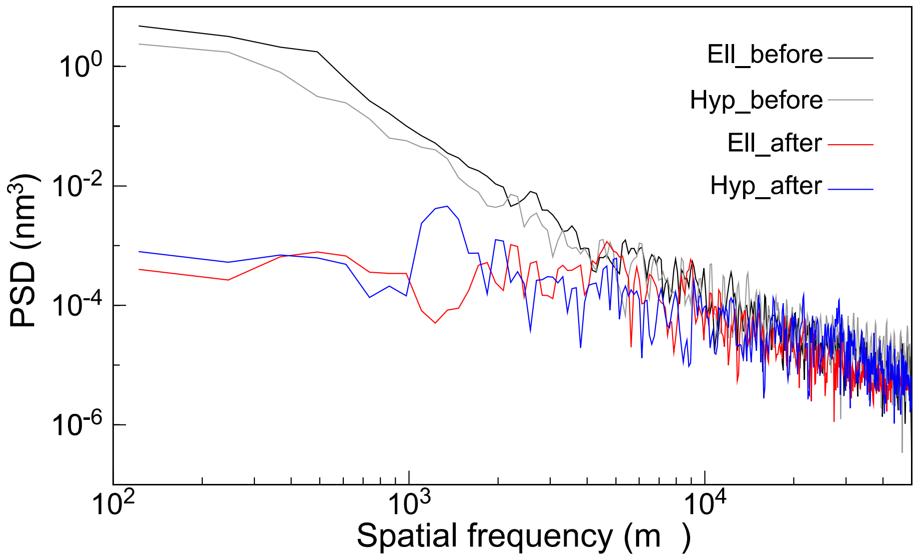

Figure 5. Comparison of power spectral density function of the shape errors of elliptical and hyperbolic mirrors before and after processing, shown in log scale.

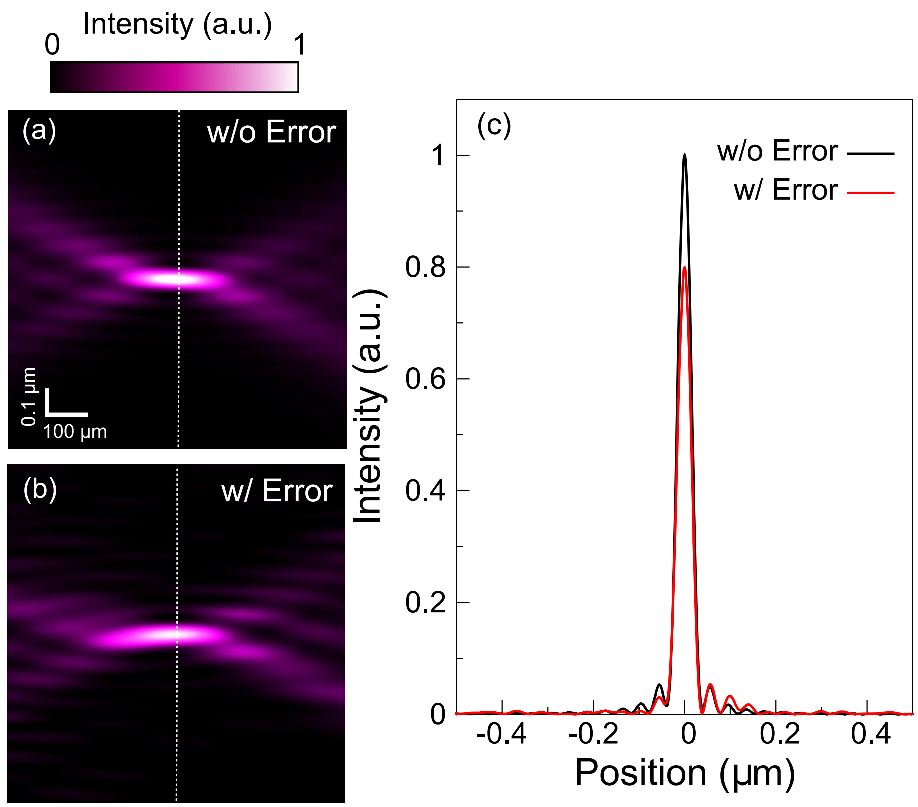

Figure 6. Calculated intensity profiles of demagnified images of the point source at an X-ray energy of 10 keV. (a, b) Expected X-ray beam structure near the focal point calculated (a) with and (b) without shape errors. X-ray beams enter from the left side in each figure. The dashed white lines indicate the best focal plane. (c) Normalized intensity profiles on the focal plane that leads to the line spread function of the imaging mirrors. The full width at half maximum of the profile calculated with shape error (red) was 37.5 nm and that of the ideal profile (black) was 36.1 nm.

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