Ultraprecision ellipsoidal mirror with two-dimensional 100 nm focusing capability

High-precision X-ray optics are indispensable tools for supporting X-ray analytical technologies provided in synchrotron radiation and X-ray free electron laser facilities. X-ray focusing mirrors utilizing the total-reflection phenomenon play an extremely important role in X-ray microscopic analyses by taking advantage of a chromatic aberration-free characteristic. Advancement of fabrication technologies for high-precision X-ray mirrors is important to improve X-ray analytical technologies. Here, we report the development of an ellipsoidal mirror optics for two-dimensional focusing of hard X-rays to 100 nm size [1].

A pair of mirrors with an elliptical-cylinder surface in the Kirkpatrick-Baez (K-B) geometry is typically used as micro-/nano-focusing optics for hard X-rays. In the K-B geometry, two line-focusing mirrors are arranged in tandem to two-dimensionally focus X-rays. Using commercially available elliptical-cylinder mirrors with a sub-nanometer precision, focused beams with a beam size of 50 nm can be used for X-ray analysis. However, the 100 nm focusing of hard X-rays with ellipsoidal focusing mirrors, as shown in Fig. 1(a), which can produce a two-dimensional focused beam with a single reflection, is not accessible by conventional fabrication technologies. Our group addressed the challenge developing nanofocusing ellipsoidal mirrors by improving fabrication technologies including a high-precision machining method [2] and a surface measurement system [3].

Ellipsoidal focusing mirror optics have many advantages, such as highly efficient focusing properties and a simple mirror alignment mechanism, for application to X-ray microscopy compared with elliptical-cylinder mirrors in the K-B geometry. In particular, ellipsoidal mirrors have a major advantage over elliptical-cylinder mirrors that the spatial aperture of sagittal focusing, that is, the focusing in the short-axis direction, can be designed to be larger than that of meridional focusing, that is, the focusing in the long-axis direction. More specifically, an ellipsoidal focusing mirror can produce a smaller diffraction-limited focused beam size than elliptical-cylinder mirrors in the K-B geometry.

The optical parameters of the developed ellipsoidal focusing mirror were designed as follows. The distance between the light source and the mirror center is 50 m. The distance between the mirror center and the focal point is 200 mm. The incident angle at the mirror center is 9 mrad. The mirror surface has a radius of curvature of 44 m and 3.6 mm in the long- and short-axis directions at the mirror center, respectively. Difficulties in the fabrication process of ellipsoidal focusing mirrors are caused by this small radius of curvature in the short-axis direction. The ideal reflectivity is 75% with a platinum surface coating under the total-reflection conditions at an X-ray energy of 7 keV. The diffraction-limited focused beam size of 37 nm × 67 nm (full width at half maximum (FWHM)) is expected at an X-ray energy of 7 keV when the mirror surface has a reflection area of 93 mm × 0.45 mm in the long- and short-axis directions. It is estimated by a wave-optical simulator [4] that a surface figure accuracy of 1 nm (root-mean-square (RMS)) is required for nano-focusing with the ellipsoidal mirror.

The ellipsoidal shape was fabricated on a substrate surface of synthetic fused silica glass with a size of 100 mm × 50 mm × 30 mm as shown in Fig. 1(b). The ellipsoidal focusing mirror was fabricated by the following process. First, the ellipsoidal shape was roughly and efficiently formed by a precision multi-axis grinding machine using a diamond grinding wheel with an accuracy of about 1 μm (peak-to-valley). Then, the increase in the surface roughness on the mirror caused by the grinding was reduced

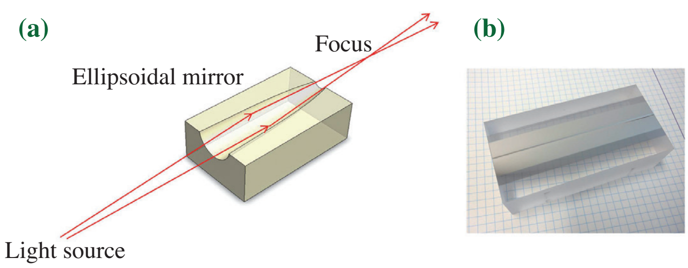

Fig. 1. Ellipsoidal focusing mirror. **(a)** Schematic view. **(b)** Photograph of the developed mirror.

to 0.2 nm (RMS), which is adequate for the X-ray mirror, using a processing machine with a rotational-type working head made by our group. In the next step, the surface figure error was removed to satisfy the accuracy of the estimated value by using a computer-controlled fabrication process employing a processing machine with a nozzle-type working head made by our group. After that, the mirror surface was uniformly coated with a platinum thin film by a DC magnetron sputtering system. The surface accuracy of the developed mirror was comparable to the reproducibility of our measurement system, which is based on a stitching interferometry developed by our group. The surface figure error of the finished ellipsoidal mirror was 1.0 nm (RMS) at an entire area of 93 mm × 0.45 mm and 0.8 nm (RMS) over the central area of 50 mm × 0.45 mm. The surface roughness of the mirror was 0.3 nm (RMS).

We evaluated the focused beam performances of the developed ellipsoidal mirror at SPring-8 **BL29XUL**. The mirror was set 50 m from a source slit with a size of 5 μm for the evaluation to obtain a sufficiently small focused beam size estimated by geometric demagnification. We made a dedicated alignment device for the ellipsoidal focusing mirror, which can align the incident angle and the in-plane rotation with a precision of 0.1 μrad. After the precision alignment using Foucault's knife-edge test, the focused beam profiles were measured by the knife-edge scanning method using a gold wire with a diameter of 200 μm. Figure 2 shows the measured focused beam profiles at an X-ray energy of 7 keV. We evaluated two focused beams reflected by two areas on the mirror surface: the entire area of 93 mm × 0.45 mm (Figs. 2(a) and 2(b)) and the central area of 50 mm × 0.45 mm (Figs. 2(c) and 2(d)). Figure 2 shows focused beam profiles in the meridional ((a) and (c)) and sagittal ((b) and (d)) directions. We achieved focused beam sizes of 95 nm × 132 nm and 85 nm × 125 nm (FWHM) from each reflection area. The obtained focused beam sizes were larger than the diffraction-limited size. This is due to the lack of the absolute accuracy of the surface measurement system.

The developed fabrication technologies for the ellipsoidal focusing mirror are applicable to other high-precision mirror optics with a two-dimensional aspherical surface, which are expected to be utilized in various advanced optical systems.

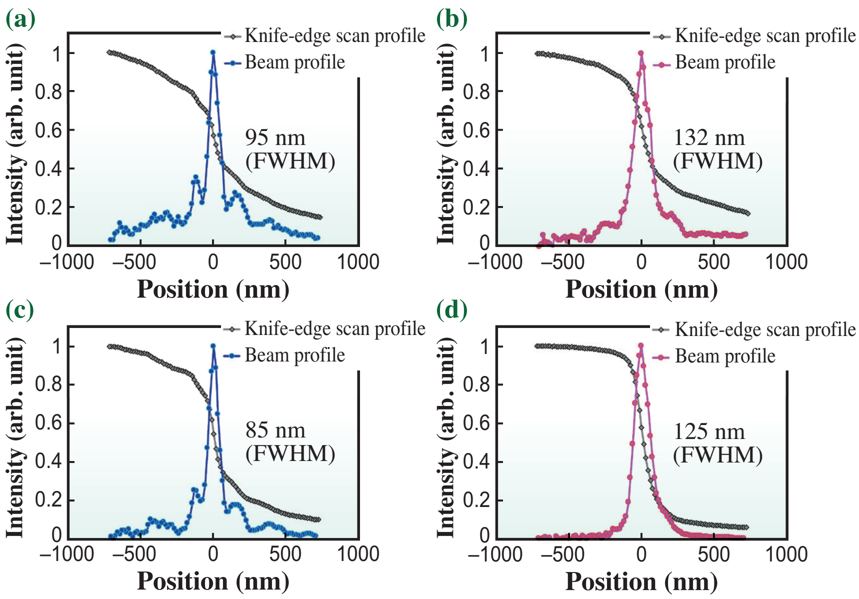

Fig. 2. Measured focused beam profiles. Two reflection areas on the mirror surface were evaluated: the entire area of 93 mm×0.45 mm ((**a**) and (**b**)) and the central area of 50 mm×0.45 mm ((**c**) and (**d**)). Beam profiles were measured in the meridional ((a) and (c)) and sagittal ((b) and (d)) focusing directions. [1]

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