Hard X-ray Nanoprobe with Spherical-aberration-corrected Quad-spherical-mirror Optics

Yoshio Suzuki, Akihisa Takeuchi
JASRI/Spring-8, Koto 1-1-1 Sayo, Hyogo 679-5198, Japan
yoshio@spring8.or.jp

Abstract. A quad-mirror system is developed for nanofocusing of hard x-ray beam. The optical system consists of four spherical-concave total-reflection mirrors. Each two mirrors are combined in a tandem-mirror configuration to compensate spherical aberrations in grazing-incidence mirror optics, and a pair of the tandem-spherical mirrors is configured in a crossed mirror system (Kirkpatrick-Baez optics) to eliminate astigmatism in grazing incidence optics. Focusing properties are tested at the beam line 20XU of SPring-8. The focused beam size measured by knife-edge scan method is 170 nm x 190 nm at 10 keV. Preliminary experiments on scanning x-ray microscopy are also carried out, and a fine structure of 100 nm-line/100 nm-space is resolved in the measured image.

1. Introduction
The x-ray microprobe is now widely used in many application fields at synchrotron radiation facilities. Several types of optical systems are developed for microfocusing of x-ray beam: Fresnel zone plates, multilayer Laue lens, grazing-incidence total-reflection mirrors, multilayer mirrors, and refractive lens systems. The most important advantage of total-reflection mirror system is its achromatic feature. Wide spectral range is available at a fixed focal length. The most serious problem of total-reflection mirrors in the hard x-ray region is spherical aberration and astigmatism in grazing incident optics. It is well known that the astigmatism in grazing incidence mirror system is perfectly eliminated by the crossed-mirror optics [1]. The simple way of spherical aberration-correction is use of aspherical mirrors [2]. Then, the most widely used total-reflection mirror system for x-ray microfocusing is the crossed-mirror system with aspherical total-reflection mirrors (Kirkpatrick-Baez configuration with elliptic or parabolic mirrors) [3-5]. The focused beam size less than 50 nm is already achieved in the hard x-ray region. However, the fabrication of high-precision aspherical surface is not easy at present. On the contrary, the fabrication of spherical surface is much easier than that of aspherical figure. Therefore, it is still useful to find a way of microfocusing using spherical mirrors. The method of spherical-aberration-correction by a combination of spherical mirrors was firstly suggested by Sakayanagi in tandem-toroidal mirror system for soft x-ray imaging microscopy [6]. We have recently demonstrated spherical-aberration-correction in tandem-spherical-mirror system [7], and applied it to microfocusing of hard x-ray beam. However, in our previous experiment, the achieved beam size was about a half micrometer [8], probably owing to the surface figure errors and limitation on optical configuration, while a focused beam width of 170 nm has been achieved in the one-dimensional focusing experiment.
In this report, newly developed quad-spherical-mirror system that consists of a pair of tandem-spherical-mirror systems is described, and results on x-ray nanofocusing and its application to scanning microscopy are also described.

2. Optical System and Experimental Setup
The concept of spherical aberration correction is shown in Fig. 1. Two spherical (or cylindrical) concave mirrors are aligned in a tandem mirror configuration. The x-ray beam firstly incident on the M2 mirror is reflected again by the next mirror M1 placed just after the M2 mirror. The spherical aberration of the second mirror has opposite sign of that of the first mirror. Therefore, by choosing appropriate parameters, radii of concave surface, angles of incidence, and a distance between two mirrors, it is possible to compensate the spherical aberration of the total optical system. The idea of the spherical-aberration-correction (Cs-correction) was suggested by Sakayanagi in the tandem-toroidal-mirror system for soft x-ray imaging microscopy [6]. The sequential reflection by grazing-incidence mirrors was also important for image forming optics, because the Abbe’s sine condition is approximately satisfied by the sequential reflection. The quad-mirror system with similar configuration was already developed and is called “advanced Kirkpatrick-Baez system” [9]. However, in the previous advanced-KB system, the compensation of spherical aberration was not considered. Only the coma and field distortion (field obliquity) were discussed in the previous advanced-KB optics.

The general theory of spherical-aberration-correction is not a simple equation. However, the formula can be simplified at a typical condition. When the two concave reflectors have the same curvature, the Cs-correction is simply expressed by the following formula [10].

\[
\frac{1 + \sqrt{5}}{2} \approx \frac{R \theta_1}{(R \theta_2 - 2D)},
\]

where \( R \) is the radius of curvature of reflector surfaces, \( \theta_1 \) and \( \theta_2 \) is a glancing angle to each mirror, and \( D \) is a distance between two mirrors. The tandem-spherical mirror system is not a stigmatic optics as a single spherical mirror system. Therefore, for the purpose of two-dimensional focusing, two tandem-spherical-mirror systems are combined in the crossed mirror geometry (an analogue of Kirkpatrick-Baez configuration) in order to eliminate astigmatism, as shown in Fig. 2. The size of beam incident on the mirror is limited with a cross slit placed in front of the mirror system, and the beam dimension is slightly smaller than the aperture of the mirror (~80% of full aperture), because, usually, the marginal region of mirror surface is not precisely formed.

![Fig. 1. Concept of spherical aberration correction in grazing-incidence total-reflection-mirror optics by tandem-spherical-mirror system. M1 and M2 are spherical-concave mirrors. Fv is a virtual focal point produced by the M2 and Fr is a real focus generated by the tandem mirror system.](image-url)
The experiment has been carried out at the beam line 20XU of SPring-8. The four concave mirrors are general-purpose products supplied from Sigma Koki (Tokyo, Japan). The design radius of curvature of the two concave mirrors (M4 and M3) is 90 m, and the other two concave mirrors (M2 and M1) have radius of 45 m. The length of each mirror is 30 mm. The substrate material of the concave mirrors is borosilicate crown glass (BK7), and the reflection surface is coated by platinum. The concave surface is fabricated by conventional polishing technique. The precise alignment of mirrors was done by monitoring the spherical-aberrations and the astigmatism by means of Foucault’s knife-edge test. The glancing angles of the each mirror experimentally determined to compensate spherical aberration and astigmatism are 4.1 mrad, 3.8 mrad, 5.0 mrad, and 4.6 mrad for M1, M2, M3 and M4, respectively. The focal point is about 23 mm from the edge of M1 mirror.

The beam focusing properties are characterized by conventional edge scan method using a gold wire of 200 µm-diameter as a knife-edge. The focused beam shapes are derived by differentiation of the measured knife-edge scan profiles. Preliminary experiments on scanning microscopy were also carried out using an x-ray resolution test chart as a specimen. The resolution test chart is fabricated at NTT Advanced Technology using electron beam lithography technique and reactive ion etching. The pattern material is tantalum with a thickness of 0.5 µm deposited on a SiN membrane.

![Fig. 2. Schematic diagram of optical system with quad spherical mirrors.](image)

### 3. Results and Discussion

Fig. 3 shows the focused beam profiles measured by knife-edge scan method at an x-ray energy of 10 keV. The full-width at half-maximum (FWHM) of focused beam profile is 170 nm in the horizontal direction and 190 nm in the vertical direction. The measured FWHM of the focus spot is less than 200 nm in the horizontal direction, and less than 230 nm in the vertical direction within the x-ray energy range from 8 keV to 12 keV. The example of scanning microscopy experiments is shown in Fig. 4. The scanning microscopy image of resolution test patterns with a 100 nm-line/100 nm-space and a 50 nm-line/50 nm-space is measured with the focused probe. Here, the x-ray energy of 9.90 keV, just above the Ta L3-absorption edge (9.88 keV), was chosen to achieve the highest absorption contrast for tantalum test pattern. Although the 50 nm-pattern cannot be resolved, the 100 nm line/100 nm space patterns are clearly resolved in the both directions.

The effective numerical aperture of the quad-mirror system is experimentally estimated to be $4.3 \times 10^{-4}$ in the horizontal direction and $7.4 \times 10^{-4}$ in the vertical direction. Therefore, the diffraction-limited beam size for 10 keV x-rays defined by the Rayleigh’s criterion is calculated to be 144 nm in the horizontal direction, and 84 nm in the vertical direction. The measured spot size in the horizontal direction (170 nm in FWHM) is very near to the diffraction-limited resolution. Although the vertical focus (190 nm in FWHM) is about twice of the diffraction-limited spot size, this blurring may come from imperfection of the mirror figure and surface roughness. We consider that the spatial resolution of about 100 nm would be possible using the Cs-corrected tandem-spherical-mirror system.
Fig. 3. Focused beam profiles measured by knife-edge scan method. X-ray energy is 10 keV.

Fig. 4. Scanning XRM image of resolution test chart. X-ray energy: 9.9 keV. Raster scan image of 81 x 81 pixels is acquired with a 50 nm step and 100 ms dwell time.

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