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Development of a one-dimensional two-stage focusing system with two deformable mirrors

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ABSTRACT

A one-dimensional two-stage focusing system using two deformable mirrors was constructed. To realize the precise elliptical shapes, the mirror deformations were finely adjusted using the pencil-beam scan, which is a method of wavefront measurement. X-rays of 10 keV energy were one-dimensionally focused to a full width at half maximum of 90 nm, which agrees well with the diffraction limit.

Keywords: piezoelectric bimorph mirror, X-ray mirror, Kirkpatrick-Baez mirror optics, adaptive mirror

1. INTRODUCTION

Focused X-ray nanobeams are necessary for achieving a high spatial resolution in various X-ray analysis methods. Techniques have been developed to achieve a small nanobeam focus size. There are various X-ray focusing devices, including the zone plate[1], Laue lens[2], refractive lens[3], total reflection mirror[4,5], and multilayer mirror[6]. Currently, they can focus X-rays down to 50 nm.

Recently, the variability in beam size and the smallness of nanobeams have attracted considerable attention[7–10]. The shape of an X-ray deformable mirror can vary. By the deformation of the mirror shape, the beam size can be varied and can compensate for the wavefront aberration due to other optical devices and the mirror itself.

We developed a novel adaptive focusing system with multiple deformable mirrors that can vary the beam size[11–13]. Figure 1(a) shows a schematic of our proposed two-stage focusing system using two elliptical mirrors. The two ellipses are designed to share a common focal point. For two-dimensional focusing, two pairs of systems are used, aligned according to the Kirkpatrick-Baez (KB) arrangement[14]. In this system, the focus size can be varied while keeping the focal plane fixed and without altering the configuration of the focusing system. In addition, the system allows ideal focusing by compensating for the wavefront errors caused by the misalignment and imperfections in the optical components. To vary the beam size, the mirrors are deformed to a different elliptical shape while keeping the common focal point matched. In addition, the ellipse parameters (the positions of the X-ray source and the final focus and their incident angles at the center of the mirror) are also kept fixed. Consequently, the position of the common focal point is shifted along the arrow shown in Fig. 1(b). Eventually, the numerical aperture (NA) and diffraction-limited beam size can be controlled by varying the illumination area on the second mirror (Fig. 1(b)) according to the shift of the common focal point.

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In this paper, to demonstrate feasibility of the two-stage adaptive focusing system, a one-dimensional focusing system based on our developed ultraprecise deformable mirrors was constructed at SPring-8. The two mirrors were finely adjusted using the pencil beam method[15,16], which is a method of wavefront measurement. The focused beam, having an X-ray energy of 10 keV, was characterized using the wire scan method, yielding a full width at half maximum (FWHM) of 90 nm.

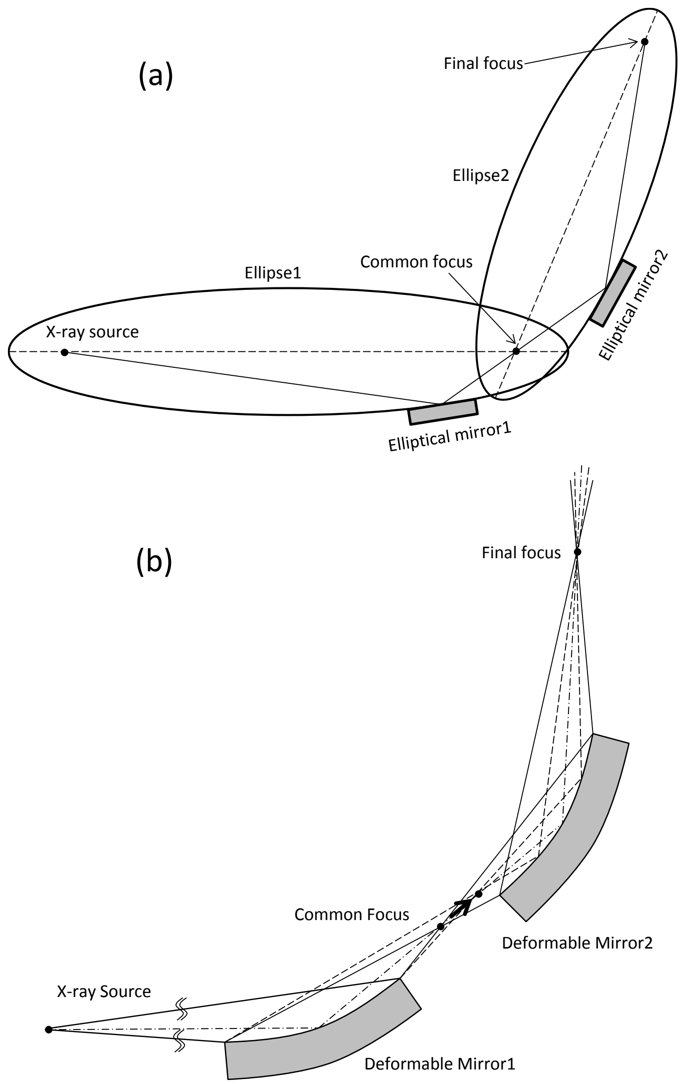

Figure 1. (a) Schematic representation of the proposed two-stage focusing system and (b) concept for control of the numerical aperture.

2. EXPERIMENT

2.1 Deformable mirror

Figure 2 shows the deformable mirror with a piezoelectric bimorph structure used in this study. It comprises a quartz glass substrate, four piezoelectric actuators, and 18 chrome electrodes. The dimensions of the substrate are 50 mm × 100 mm × 5 mm. Commercially available lead zirconate titanate (piezoelectric constant: 135×10^{-12} m/V; Young modulus: 82 GPa) was used as the piezoelectric material. The four actuators, each having dimensions of 17.5 mm × 100 mm × 1 mm, were attached to both the face and back sides. The 18 chrome electrodes, each having dimensions of 17.5 mm × 4.8 mm,

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were formed on the piezoelectric actuators on the face side by magnetron sputtering. The other piezoelectric actuators on the back side have only one monolithic electrode to adjust the whole curvature. To enable precise deformation, the intrinsic figure error of the substrate from the elliptical shape in the spatial frequency region of about 0.5-50 mm was removed by elastic emission machining[18] with figure accuracy better than 2 nm. This is because a shape with a shorter spatial wavelength than that of the electrode array (5.6-mm pitch) cannot be produced by the deformation, and correcting large curvatures in the local area requires power supplies of high voltage. After the process, the effective area was covered with a 100-nm-thick platinum layer.

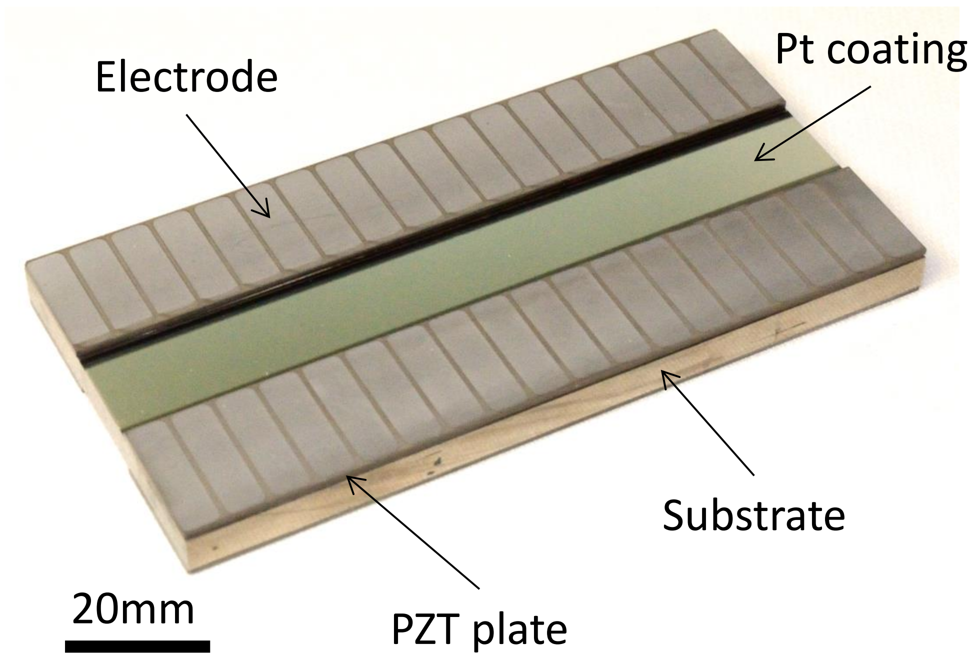

Figure 2. Photograph of the developed deformable mirror (face side).

Table 1. Parameters of the target ellipses.

	First elliptical mirror	Second elliptical mirror
Mirror length (mm)	100	100
Glazing-incidence angle (mrad)	4	4
Mirror aperture (μm)	400	400
Length between virtual source and mirror center (m)	45	-
Length between mirror center and common focus (mm)	500	500
Length between final focus and mirror center (mm)	-	300
Numerical aperture ($\times 10^{-3}$)	0.4	0.67
Demagnification	150	
Working distance (mm)	250	

Table 1 and Fig. 3 indicate the parameters and shapes, respectively, of the target ellipses. The optical system was designed for the third experimental hutch of BL29XUL at SPring-8, 45 m downstream of the TC slit (a virtual light source). If it is used at an X-ray energy of 10 keV, an FWHM of 85 nm will be obtained at the diffraction-limited condition when 95% of the effective mirror region is used.

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2.2 How to adjust the deformation

To adjust the deformation of the mirror finely and effectively, the following procedure was employed. First, the voltages to be applied to deform the mirror into the target ellipse are determined ex situ using a Fizeau interferometer (VeriFire XPZ, Zygo Corp.). At this time, all the voltages during the adjustment are recorded. The same voltage history should be applied to the mirrors for good repeatability of the mirror deformation, as the mirror deformation is affected by the hysteresis of piezoelectric material. In a beamline, the recorded voltages are applied step-by-step. Then, the deformation is corrected by determining the deformation errors using the pencil beam method until the diffraction-limited focus size is achieved.

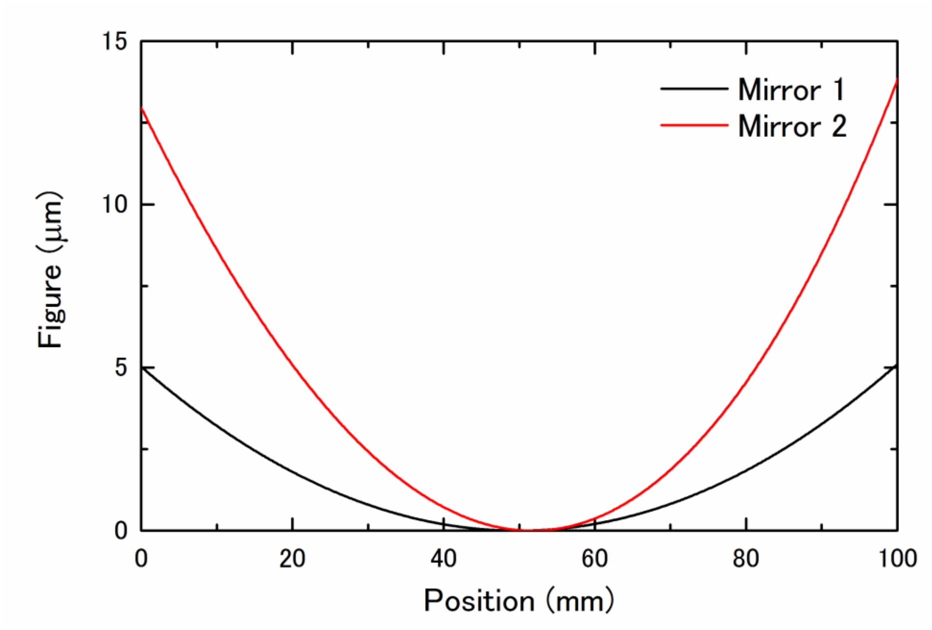

Figure 3. Target elliptical shapes of mirror1 (upstream) and mirror2 (downstream).

2.3 Experimental setup

A focusing optical system was constructed at BL29XUL of SPring-8. Figure 4 shows a photograph and a 3D model of the experimental setup. In the focusing optics, the TC slit image (width of 10 μm) was formed on the common focus and the final focus, demagnifying it with demagnifications of 90 and 150, respectively. The first and second beam monitors were placed on the common focus and final focus, respectively, to apply the pencil beam method. A gold wire with a diameter of 200 μm was placed on the focus instead of the beam monitor only when the wire scan method was applied. A PIN photodiode and an ion chamber were used to detect the X-ray intensity at the upstream and downstream positions, respectively. The entire optical system was placed on a heavy granite table to suppress the vibration. The mirrors were set on a mirror manipulator that can adjust the mirror alignment, i.e., the pitch, yaw, and roll. Also, the electrodes on the mirrors were connected to multiple power supplies with maximum and minimum voltages of +/-250 V by a very weak spring (k = 3 mN/mm) and a cable.

3. EXPERIMENTAL RESULTS

An X-ray energy of 10 keV was used in this experiment. First, the predetermined initial voltages were applied. Then, the deformation was finely corrected while characterizing the deformation error using the pencil beam method. At this time, the upstream mirror was first adjusted using the beam monitor placed on the common focus. Finally, the downstream mirror was finely adjusted using the beam monitor placed on the final focus. In this adjustment, the wavefront aberration

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caused by the deformation errors of both the mirrors was minimized. That is, the downstream mirror compensated for the wavefront aberrations of the whole system. Figure 5 shows the measured figure errors before and after the fine adjustment. After the fine adjustment, the figure errors of the upstream and downstream mirrors were improved from 41 to 3 nm and from 45 to 6 nm peak-to-valley, respectively. The figure error of the downstream mirror includes the figure error of the upstream mirror as described above. The characterized beam intensity distribution at the final focus is indicated in Fig. 6. The achieved FWHM was found to be 90 nm, which agrees well with the diffraction limit. Also, the experimental profile was similar to the calculated one, obtained using the figure error shown in Fig. 5(b, after correction). Thus, the side lobes at the left side were caused by the remaining deformation errors. More careful corrections are needed to achieve a sharp peak without side lobes.

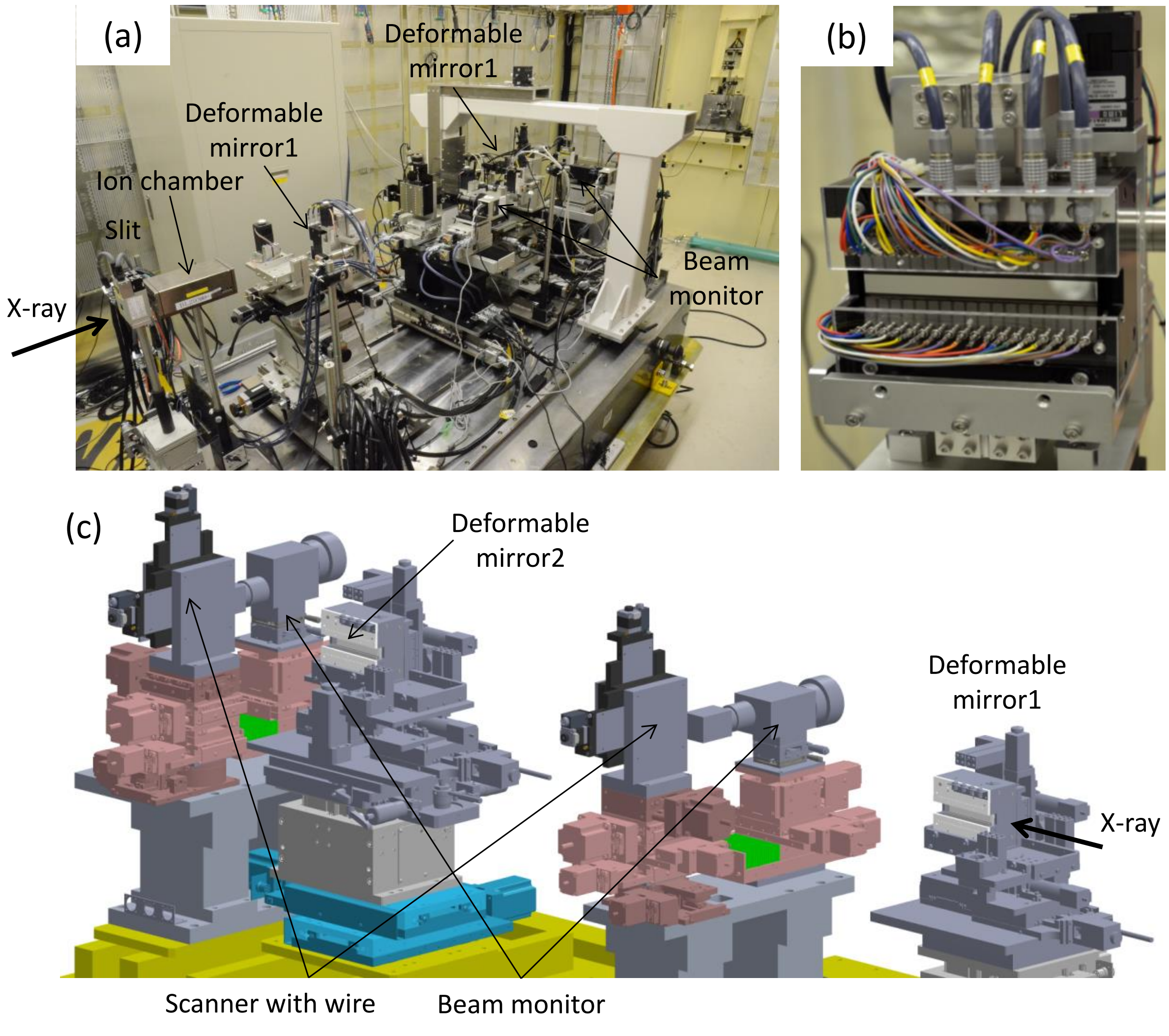

Figure 4. (a) Photograph of experimental setup, (b) photograph of deformable mirror set on the manipulator, and (c) 3D model of experimental setup.

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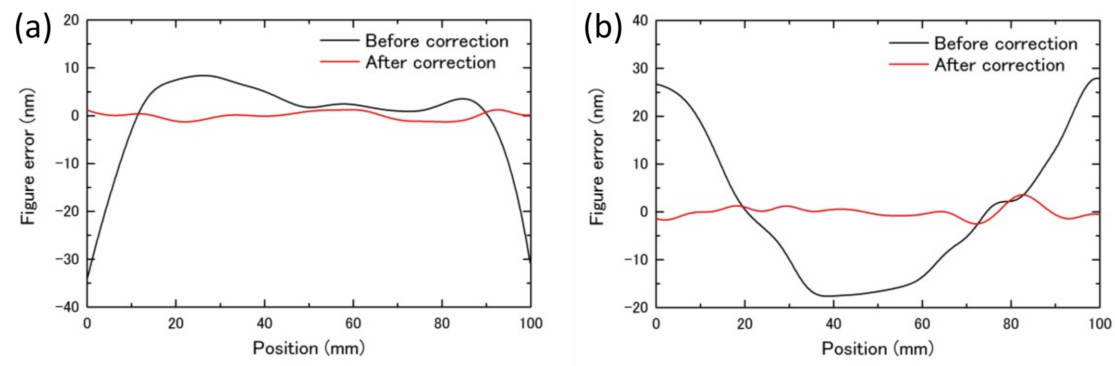

Figure 5. Figure errors determined using the pencil beam method before and after the fine corrections: (a) at the common focus, (b) at the final focus.

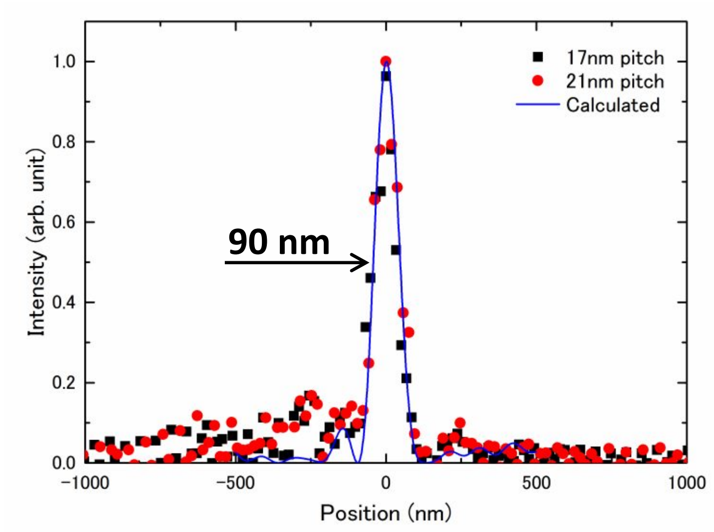

Figure 6. Characterized beam intensity profile together with a profile calculated using the figure error after the fine correction shown in Fig. 5(b). Measurement condition: scanning pitch of the wire scanning method = 17 and 21 nm, X-ray energy = 10 keV.

4. SUMMARY AND OUTLOOK

We constructed a one-dimensional two-stage focusing system using two deformable mirrors. Adjusting the deformation of the two mirrors using the pencil beam method enabled us to achieve the nearly diffraction-limited FWHM of 90 nm. Thus, we established the alignment procedure of a two-stage focusing system. Using this procedure, the two-dimensional two-stage focusing system will be able to be constructed in the very near future. Furthermore, an apodized focused beam[18], which can be obtained by blocking the side lobes at the common focus with a slit, is promising for coherent diffraction imaging[19,20] because it can perform non-scanning coherent diffraction microscopy for extended objects. The novel focusing system in combination with the variable NA function and the apodized focused beam will open new frontiers in X-ray analysis and X-ray microscopy.

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