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X-ray nanofocusing using a piezoelectric deformable mirror and at-wavelength metrology methods

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ABSTRACT

An adaptive X-ray mirror with shape controllability in a spatial wavelength range longer than 20 mm was developed, and we demonstrated its shape generation and focusing performance characteristics. The shape accuracy in a spatial wavelength range shorter than 20 mm, which cannot be adaptively figured, was controlled in advance offline. A pencil beam method for measuring the slope error and a phase retrieval method for precisely estimating the wavefront error were employed for online shape correction. A focal spot size of 120 nm, which is diffraction-limited, was realized, and the shape accuracy obtained nearly satisfied Rayleigh's quarter-wavelength criterion.

1. Introduction

Adaptive X-ray mirrors, which can deform their own shape, are widely used in synchrotron radiation facilities with the expectation of controllability of the focal length, spot size, and numerical aperture in focusing optics of versatile beamlines [1–10]. In addition, because of its error compensation characteristics, an adaptive mirror does not require a high shape accuracy during manufacturing; thus, multipurpose optical systems can be setup cost-effectively using an adaptive mirror as long as ultimate focusing is not demanded. On the other hand, in the case of ultimate focusing, we use a figured mirror because the achievable shape accuracy of the figured mirror is much higher than that of the adaptive mirror at present [11].

Over the last 10 years, highly brilliant third-generation X-ray sources pushed the development of nanofocusing optics because such sources theoretically enable the effective condensation of X-rays into the focal spot owing to their small size and divergence. Accordingly, the fabrication technology for the figured mirror progressed markedly with the development of the third-generation X-ray sources, and mirrors having diffraction-limited performance are now commercially available, in which figure accuracy is certified to be within PV 2 nm [11].

To realize diffraction-limited performance in mirror optics, Rayleigh's quarter-wavelength criterion must be satisfied [12]. In this criterion, the shape accuracy in peak-to-valley is required to be smaller than $\lambda/8\theta$, where λ and θ are wavelength and grazing incidence angle, respectively. In a relatively short spatial wavelength range, such as shorter than 30–50 mm, 1 nm PV accuracy becomes cost-effective owing to progress of fabrication technology over the last 10 years. At BL29-XUL of SPring-8, in an ultimate case, single nanometer focusing was carried out by using 80 mm- and 20 mm-long Kirkpatrick–Baez mirrors to focus a beam in the horizontal and vertical directions, respectively [13,14]. In horizontal focusing, a compensation technique was employed [14]. In contrast, in vertical focusing, the shape accuracy of the 20 mm-long mirror was sufficient because of its small length.

Now, we are going to upgrade the third-generation X-ray sources [15–17]. After upgrading, brilliance will become more than 100 times higher in the case of SPring-8, and the throughputs of experiments will be drastically increased. Nanometer resolution microscopy especially benefits from such a high flux, and consequently, a multiple-analysis capability is required to understand experimental results in detail and deeper, which is not expected before upgrading. High-resolution scanning X-ray fluorescence microscopy [18,19] and coherent diffraction microscopy [20,21] are the most powerful X-ray microscopy methods developed using third-generation X-ray sources. The former method enables us to perform elemental distribution analysis and bonding state estimation. The latter method enables us to obtain the electron density distribution information, which is

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similar to transmission electron microscopy images. These methods complementarily give us information from both analyzing and imaging viewpoints. High-throughput microscopy using upgraded third-generation X-ray sources makes such multiple analyses possible within the limited experimental term. In multifunctional instruments for such multiple analyses, the X-ray probe size should adaptively change for each method while maintaining diffraction-limited performance. Adaptive optics is the only candidate tool that can be used to appropriately control the optical parameters according to this requirement. Here, diffraction-limited performance is also highly demanded in adaptive mirror optics, differently from the state before upgrading.

As mentioned above, a next-generation adaptive mirror must satisfy Rayleigh's quarter-wavelength criterion over the entire spatial wavelength range. In this research, we developed an adaptive mirror of bimorph structure with shape controllability in a spatial wavelength range longer than 20 mm. A spatial wavelength range shorter than 20 mm is smoothened and figured offline. By these means, the adaptive mirror developed here has the capability to satisfy Rayleigh's quarter-wavelength criterion in all special wavelength ranges in various target shapes. The shape generation and focusing performance characteristics of the adaptive mirror were tested and demonstrated at the BL29-XUL of SPring-8.

2. Experiment

2.1. Mirror design and fabrication

We designed and fabricated an adaptive mirror with shape controllability in a spatial wavelength range longer than 20 mm. A schematic drawing and a photograph of the mirror are shown in Fig. 1. The mirror is 100 mm long, and is equipped with 18 piezoelectric actuators on its top and back surfaces along its longitudinal edges. The employed piezoelectric material is PZT (lead zirconatetitanate) because of its large piezoelectric constants. We employed an integrated piezoelectric actuator, in which 18 actuators are mounted on one PZT substrate, to reduce speckles in the reflected X-ray beam [22]. The size of the PZT substrate is 100 mm long, 17.5 mm wide, and 1 mm thick. Chromium electrodes are deposited on both sides of the substrate. On the obverse side, 18 electrodes are deposited at 0.8 mm intervals. Each electrode has an area of 4.8 mm × 17.5 mm. The mirror substrate is made of quartz glass and is 100 mm long, 50 mm wide, and 5 mm thick. The center area between two PZT substrates glued along the longitudinal edges is used as a mirror. The surface is coated with platinum. The adaptive mirror is set in a holder, in which the mirror is supported and wired electrically to electric terminals. A photograph of the holder and supporting points of the mirror are shown in Fig. 2(a) and (b), respectively. The supporting points are near the Bessel points on the back surface and side wall of the mirror. The mirror is weakly pushed from the opposite side by springs to maintain the posture so that the mirror can be used for both vertical focusing and horizontal focusing. The holder is bolted on the tilting stage by which the grazing incidence angle can be tuned. The target ellipse for the demonstration of online shape control is shown in Table 1. The grazing incidence angle at the mirror center is designed to be 4 mrad.The employed X-ray energy was 15 keV so that the allowable shape error in this case is about 3 nm to satisfy Rayleigh's quarter-wavelength criterion. Before the demonstration of online shape control, the target shape is generated offline. The mirror shape is measured using an optical interferometer (ZygoVeriFire XPZ) and corrected by modifying the voltage pattern for the piezoelectric actuators. Fig. 3 shows the obtained

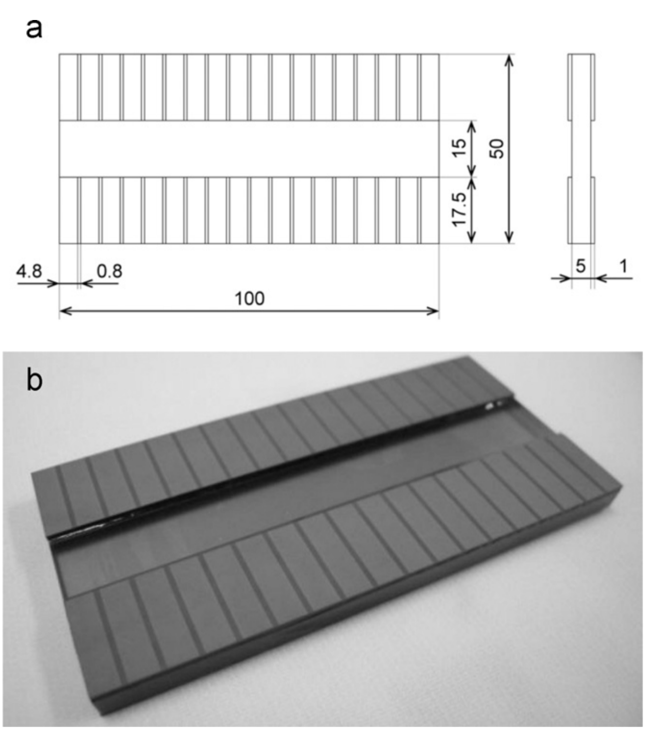

Fig. 1. Schematic drawing (a) and photograph (b) of the adaptive mirror.

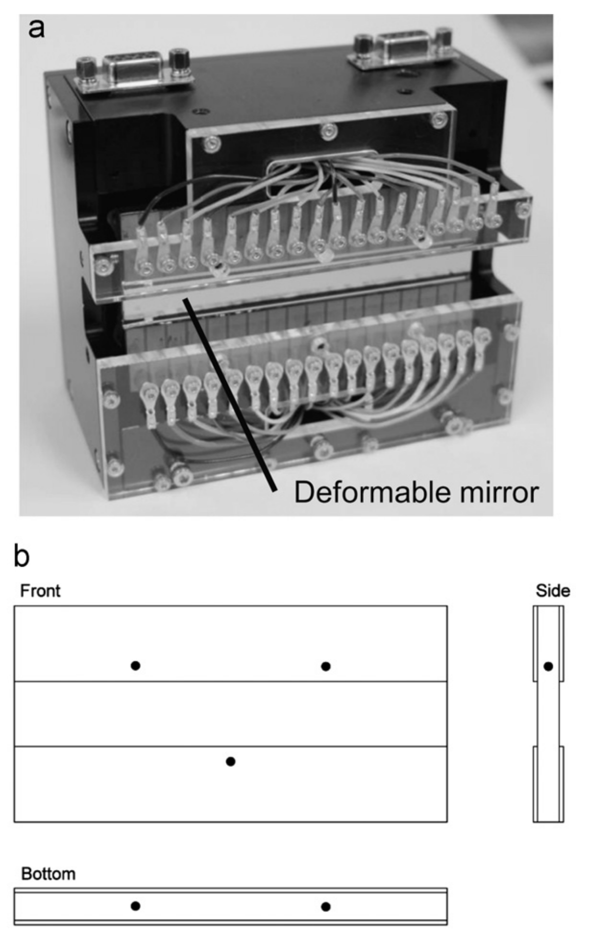

Fig. 2. Schematic drawing of adaptive mirror holder (a) and supporting points of the mirror (b) in the holder.