

Wavefront Control System for Phase Compensation in Hard X-ray Optics

Takashi Kimura^{1*}, Soichiro Handa¹, Hidekazu Mimura¹, Hirokatsu Yumoto², Daisuke Yamakawa¹, Satoshi Matsuyama¹, Kouji Inagaki¹, Yasuhisa Sano¹, Kenji Tamasaku³, Yoshinori Nishino³, Makina Yabashi², Tetsuya Ishikawa^{2,3}, and Kazuto Yamauchi^{1,4}

¹Department of Precision Science and Technology, Graduate School of Engineering, Osaka University, 2-1 Yamada-oka, Suita, Osaka 565-0871, Japan

²SPRING-8/Japan Synchrotron Radiation Research Institute (JASRI), 1-1-1 Koto, Sayo, Hyogo 679-5198, Japan

³SPRING-8/RIKEN, 1-1-1 Koto, Sayo, Hyogo 679-5198, Japan

⁴Center for Ultra Precision Science and Technology, Graduate School of Engineering, Osaka University, 2-1 Yamada-oka, Suita, Osaka 565-0871, Japan

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A highly precise adaptive optical system that can be used in the hard X-ray region was developed. To achieve highly precise control of the wavefront shape, we discussed an optical system with a bendable mirror of deformation accuracy better than 0.4 nm RMS. Using the system, we demonstrated the controllability of the wavefront of a 15 nm hard X-ray nanobeam. The intensity profile of the wavefront-modified beam was in good agreement with the wave-optically calculated profile. © 2009 The Japan Society of Applied Physics

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1. Introduction

Hard X-ray microscopy based on synchrotron radiation sources has great potential for analyzing the nanoscale structures of both inorganic and organic materials. A resolution of a few tens of nanometers is now possible.^{1–4} Such progress depends not only on the high brilliance of current synchrotron radiation sources but also on the development of high-quality X-ray optical devices. Employing hard X-ray focusing devices, a sub-50 nm beam has already been realized using a Fresnel zone plate,⁵ a multilayer Laue lens,^{6,7} refractive lenses⁸ and X-ray Kirkpatrick–Baez (KB) mirrors.⁹ Mirror optics have many advantages such as a long focal distance and/or high focusing efficiency, but extremely high accuracy is required on the mirror surface to realize focusing up to the theoretical limit. To achieve sub-10-nm focusing, which is widely recognized as one of the next research targets in X-ray microscopy, the required peak-to-valley (PV) accuracy of the condenser mirror has been estimated to be several angstroms.¹⁰ Such unprecedented accuracy may be considered as a major barrier to progress. To overcome this difficulty, we proposed a “condenser and correction (C&C)” system, which combines a condenser and a wavefront-error compensation mirror. Wavefront control optics are widely utilized in astronomy to improve the quality of images obtained from telescopes.^{11–13} In X-ray optics using synchrotron radiation sources, an adaptive focusing mirror to be tuned to the beamline parameters has already been developed using a Si–zirconate lead titanate (PZT)–PZT–Si or glass–PZT–PZT–glass bimorph structure.^{14–16}

In this study, we developed a deformable mirror, which is an essential part of the C&C system. We discussed the method used to design corrector mirrors to achieve highly precise control of a wavefront shape that satisfies Rayleigh’s quarter wavelength criterion,¹⁷ and we configured and tested a C&C system using a 15 nm nanobeam of hard X-rays based on a synchrotron radiation source.

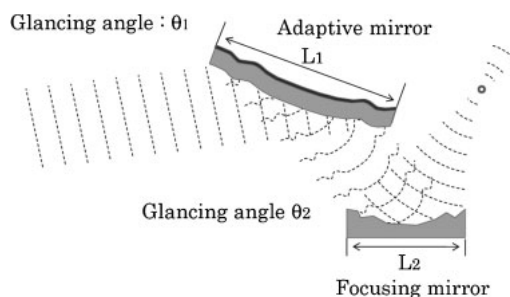


Fig. 1. Schematic of condenser and corrector system.

2. Condenser and Correction System

The C&C system discussed here is made up of an aspherical condenser mirror and an adaptively bendable flat mirror placed upstream. The wavefront of the incident X-ray is modified according to the shape of the bendable mirror. The mirror is intentionally bent to compensate the phase error induced by the imperfection of the condenser. A schematic drawing of the optical system proposed here is depicted in Fig. 1. In this system, the apertures of the focusing mirror and bendable mirror are designed to be equal. Thus, the following relation holds:

$$\theta_1 L_1 = \theta_2 L_2, \quad (1)$$

where θ_1 and θ_2 are the glancing angles of the adaptive and focusing mirrors, and L_1 and L_2 are the lengths of the mirrors, respectively. In the mirror optic, the wavefront phase ϕ is modified by the shape of the mirror through the following relation:

$$\phi = 2kd \sin \theta, \quad (2)$$

where k represents the wave number of the X-ray and d is the deviation of height from the ideal shape. The compensator mirror is designed to be longer than the condenser mirror to reduce the required figure accuracy of the compensator mirror, because the glancing angle of the compensator mirror θ_1 becomes smaller with increasing length L_1 by eq. (1), and a small glancing angle of the compensator mirror reduces the required accuracy by

*E-mail address: kimura@up.prec.eng.osaka-u.ac.jp

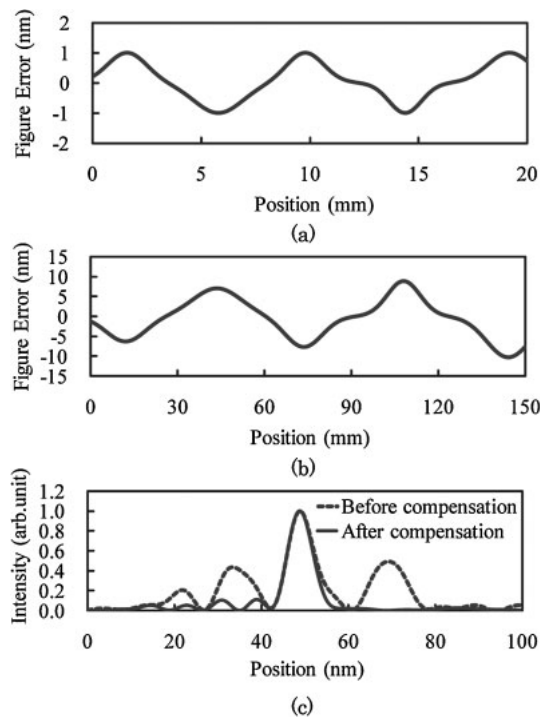


Fig. 2. Results of wave-optical simulation of the system. (a) Figure error of focusing mirror. (b) Figure error of adaptive mirror. (c) Intensity distribution profiles at focal point before and after phase error compensation.

Table I. Optical parameters of wave-optical simulation of the system.

	Adaptive mirror	Focusing mirror
Length (mm)	150	20
Glancing angle (mrad)	0.93	7.0
Focal length (mm)	—	20

eq. (2). This means that a less accurate adaptive mirror can easily compensate for the wavefront distortion induced by the very small shape error of the condenser mirror, the glancing angle of which is relatively large. In addition, upon increasing the ratio of L_1/L_2 , the spatial wavelength of the figure generated on the corrector becomes longer. This guideline for designing the compensator overcomes the limitation of the focused beam size, which is correlated with the figure accuracy of the condenser mirror. We consider that the C&C system is a promising system for realizing the next-generation 10-nm-level focusing of hard X-rays. A simulation result is shown in Fig. 2 to demonstrate the capability of the system at an X-ray energy of 20 keV. As shown in Table I, the length of the compensator is 7 times that of the condenser. This means that the shape accuracy realized on the compensator is reduced to 1/7 of the condenser mirror accuracy. The lines in Fig. 2(c) show the calculated beam profiles before and after phase error compensation. The satellite peaks are seen to be clearly reduced in intensity by the correction of the phase error.

3. Phase Corrector Mirror System

We designed and fabricated a bendable mirror with a Si-PZT monomorph structure. A schematic and a photograph of the

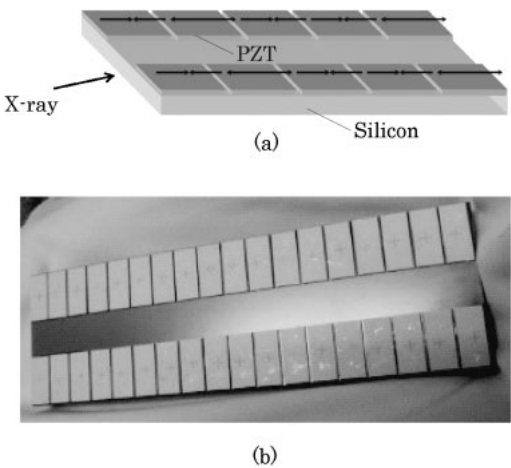


Fig. 3. Developed adaptive mirror. (a) Schematic. Arrows show expansion and contraction directions of PZT. (b) Photograph.

Table II. Parameters of the adaptive mirror.

Silicon substrate parameters	
Height (mm)	150.0
Width (mm)	50.0
Thickness (mm)	10.0
Piezoelectric ceramic parameters	
Height (mm)	7.5
Width (mm)	17.5
Thickness (mm)	1.0
Number of plates	18 × 2

mirror are shown in Fig. 3, and its specifications are summarized in Table II. The mirror has 18 PZT actuators and can adaptively generate the required shape as a convolution of sinusoidal waves. To generate one period of a sinusoidal curve, a pair of adjacent concave and convex regions is needed; thus, the minimum period of the sinusoidal shape that can be generated by the 18 PZT actuators is 1/9 of the mirror length. The intensity profile at the focal point is correlated with the Fourier transformation of the figure error of the mirror. This means that the compensator can improve the beam profile in a region nine times as wide as the main peak width at the focal plane.

To generate and maintain the required shape of the bendable mirror, the voltage supplied to each PZT element is feedback-controlled using a shape monitor system with a Fizeau interferometer (Zygo GPI-XP HR) facing the bendable mirror. The mirror was fabricated by elastic emission machining,^{18–20)} which is a deterministic fabrication method. The PV shape accuracy of the mirror was 2 nm when the voltage applied to each PZT element was set to zero. Figure 4 shows the adaptively generated profile and the required profile of the bendable mirror. The PV and RMS differences between the two profiles are about 3 and 0.4 nm, respectively.

4. Wavefront Control Test

Using the constructed optical system, we demonstrated the controllability of the wavefront phase at the 1-km-long beamline of SPring-8 (BL29-XUL).^{21,22)} A schematic and

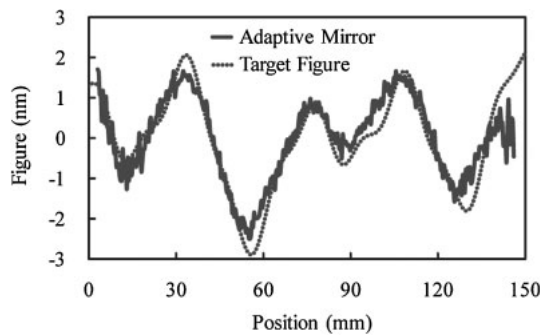


Fig. 4. Results of the deformation test of an arbitrary shape.

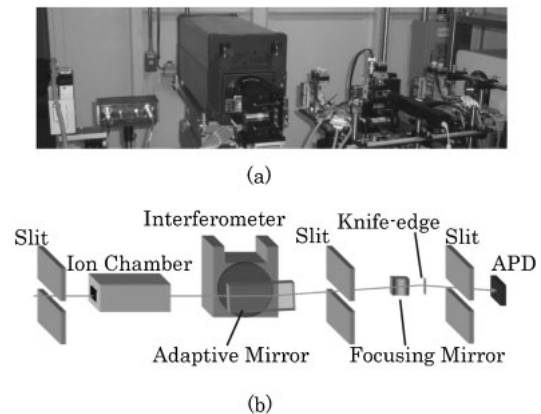


Fig. 5. Schematic and photograph of the installed optical system. (a) Schematic. (b) Photograph.

Table III. Optical parameters of wavefront control experiment.		
	Adaptive mirror	Focusing mirror
Length (mm)	100	15
Glancing angle (mrad)	1.0	7.0
Focal length (mm)	—	22.5

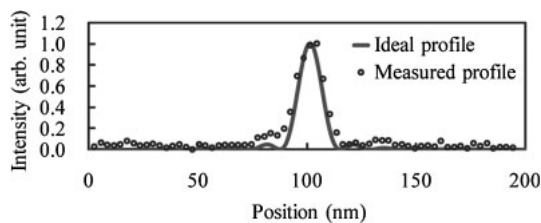


Fig. 6. Intensity distribution profile of focused beam at the focal plane.

photograph of the installed system are shown in Fig. 5. The optical parameters of the condenser mirror are shown in Table III. The compensator can be used as a total-reflection mirror under the conditions in Table III. The condenser mirror is a graded Pt/C multilayer optic²³⁾ with a theoretical full width at half maximum spot size of 15 nm at an X-ray energy of 20 keV. Figure 6 shows the intensity distribution profile of the focused beam obtained only using the multilayer condenser mirror. The condenser mirror was estimated to have sufficient accuracy to realize nearly diffraction-limited focusing down to 15 nm. We set the bendable mirror to be flat or slightly deformed, and

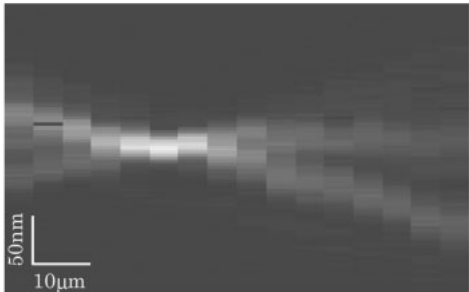
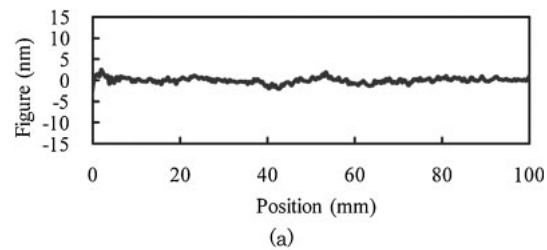


Fig. 7. Shape of flat adaptive mirror and intensity distribution near the beam waist. (a) Shape of adaptive mirror surface. (b) Intensity distribution near the beam waist.

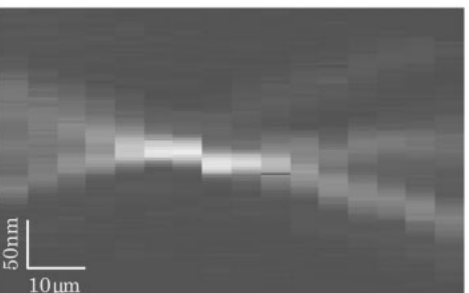
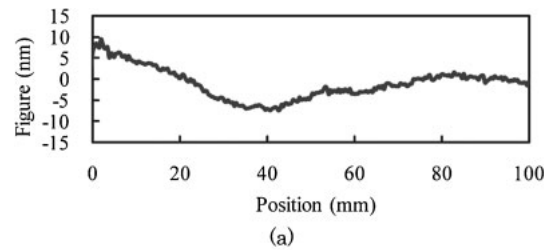


Fig. 8. Shape of bent adaptive mirror and intensity distribution near the beam waist. (a) Shape of adaptive mirror surface. (b) Intensity distribution near the beam waist.

measured the beam profiles under both conditions. In the beam profile measurements, a knife-edge method using a phase object of platinum was employed.²²⁾ Figures 7(a) and (b) respectively show the shape of the compensator mirror and the intensity distribution near the beam waist in the case that the compensator was set to be flat. Figure 8 shows the results of the same experiment in the case that the mirror was bent with an amplitude of 10 nm corresponding to a phase error of $\lambda/3$, as derived from eq. (2). In Figs. 7(b) and 8(b), the beam profile is slightly distorted and asymmetric. Figure 9 shows the wave-optically calculated beam profile using the ideal condenser and the bendable mirror with the

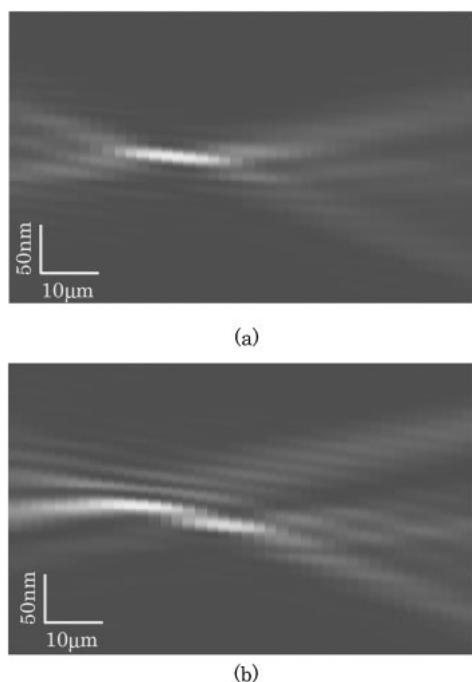


Fig. 9. Calculated intensity distributions near the beam waist with different adaptive mirror figures. (a) Calculated intensity distribution with the flat figure. (b) Calculated intensity distribution with the bent figure.

shapes shown in Figs. 7(a) and 8(a). Although the vibration of the optical table causes the measured beam profile to be slightly unclear, from the degree of agreement between Figs. 7(b), 8(b), and 9, we consider that the fabricated phase compensator works well with accuracy satisfying Rayleigh's criterion and that the proposed C&C system can achieve an extremely small spot size in hard X-ray focusing based on synchrotron radiation sources.

5. Discussion

A wavefront accuracy of $\lambda/4$ is required to realize diffraction-limited focusing according to Rayleigh's criterion. We demonstrated this level of controllability of the wavefront using the C&C system proposed and realized in this work. We derived and demonstrated a wavefront measurement method for hard X-rays reflected by focusing mirrors.^{10,24} In the method, the phase information is recovered from the measured intensity distribution on the focal plane by a phase retrieval procedure. Combining this measurement method and the optical system proposed here, we can expect to realize on-site focus tuning with sufficient controllability for future X-ray microscopy with extremely high performance. Such on-site phase tuning can be used not only to compensate the figure error of the condenser mirror but also to ease the alignment works.

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