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Development of mirror manipulator for hard-x-ray nanofocusing at sub-50-nm level

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X-ray focusing using Kirkpatrick-Baez (KB) mirrors is promising owing to their capability of highly efficient and energy-tunable focusing. We report the development of a mirror manipulator which enables KB mirror alignment with a high degree of accuracy. Mirror alignment tolerances were estimated using two types of simulators. On the basis of the simulation results, the mirror manipulator was developed to achieve an optimum KB mirror setup. As a result of focusing tests at BL29XUL of SPring-8, the beam size of 48×36 nm^2 ($V\times H$) was achieved in the full width at half maximum at an x-ray energy of 15 keV. Spatial resolution tests showed that a scanning x-ray microscope equipped with the KB focusing system could resolve line-and-space patterns of 80 nm linewidth in a high visibility of 60%. *© 2006 American Institute of Physics.*
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I. INTRODUCTION

The use of x-ray microscopy using a synchrotron radiation source has expanded in the fields of medical, biological, and material sciences owing to its capability of nondestructive, high-resolution, and highly sensitivity analysis. Fresnel zone plates[1] and Kirkpatrick-Baez (KB) mirrors[2–7] are generally employed as x-ray focusing optical devices in x-ray microscopy. KB mirrors, utilizing the total reflection phenomenon, are known to be promising devices for an achromatic and highly efficient focusing system. This optical system consists of two total reflection elliptical mirrors having two focal points of a light source and a collecting point. One mirror is used for vertical focusing and the other for horizontal focusing. To realize an ideal focusing state, both nanometer-level figure accuracy on mirror surfaces and mirror alignments with a high degree of accuracy are required.[8,9]

In this study, we developed a hard-x-ray nanofocusing system using KB mirror optics for a scanning hard-x-ray microscope with a spatial resolution better than 50 nm. A paper regarding the fabrication of ultraprecise mirrors for hard-x-ray nanofocusing has already been published.[10] This article focuses on the development of a mirror manipulator to align KB mirrors accurately. Since a pair of mirrors has multiple degrees of freedom, it is difficult to adjust the alignment of the two mirrors precisely in a short time[11] without knowledge of the relationship between mirror-positioning errors and focal sizes. The required alignment accuracy for ideal focusing was investigated using both a conventional ray-tracing simulator and a wave-optical simulator.[12] The latter can simulate accurate intensity profiles under the nearly diffraction-limited condition. The mirror manipulator was compactly designed and developed on the basis of the simulation results. Using the manipulator, hard-x-ray diffraction-limited focusing with a size less than 50 nm was realized at an x-ray energy of 15 keV.

TABLE I. Parameters of the designed elliptical mirrors.

	First Mirror	Second Mirror
Glancing angle (mrad)	3.65	4.15
Focal length (mm)	253	150
Mirror length (mm)	100	100
Length of ellipse (m)	1000.150	1000.253
Breadth of ellipse (mm)	89.406	132.019
Substrate material	Cz-(111)Si single crystal	Cz-(111)Si single crystal
Surface material	Pt	Pt
Coating thickness (nm)	50	50

II. DESIGN OF ELLIPTICAL MIRRORS

Parameters of the elliptical mirrors shown in Table I are designed to realize a focal size of less than 50 nm under the diffraction-limited condition (shown in Fig. 1). A major feature of our system is that relatively long work distances of 100 mm are selected in consideration of the practical use of an x-ray microscope system. To realize sub-50-nm focusing, these mirrors are designed to have glancing angles of approximately 4 mrad. The mirror surfaces are coated with platinum to give high reflectivity at an x-ray energy of 15 keV. In this case, the focal size was estimated using the wave-optical simulator to be 36 nm$(V)\times$48 nm(H) for the full width at half maximum (FWHM).

III. ANGLE ERROR TOLERANCES REQUIRED FOR DIFFRACTION-LIMITED FOCUSING

We estimated the tolerance limits of mirror-positioning errors required to obtain ideal focal sizes. As is well known, glancing angle rotations, in-plane rotations, and perpendicularity between mirrors have to be finely adjusted in KB mirror alignment (shown in Fig. 2). First, the tolerance limits of these rotations were investigated using a ray-tracing simulator. The tolerances were estimated on the basis of comparison between the calculated focus size and diffraction-limited

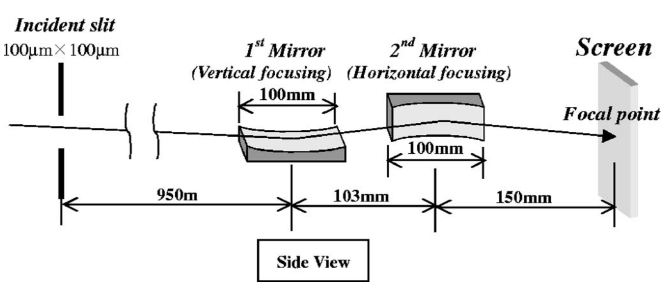

FIG. 1. Optical system using KB mirrors.

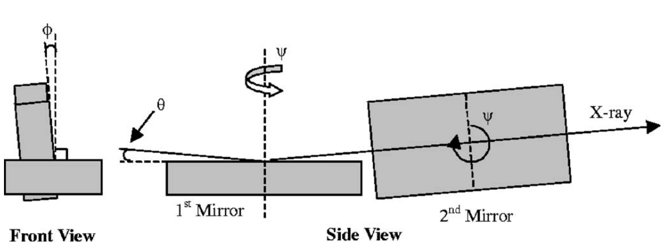

FIG. 2. Angle parameters for KB arrangement. Glancing angle rotation θ, in-plane rotation ψ, and perpendicularity φ.

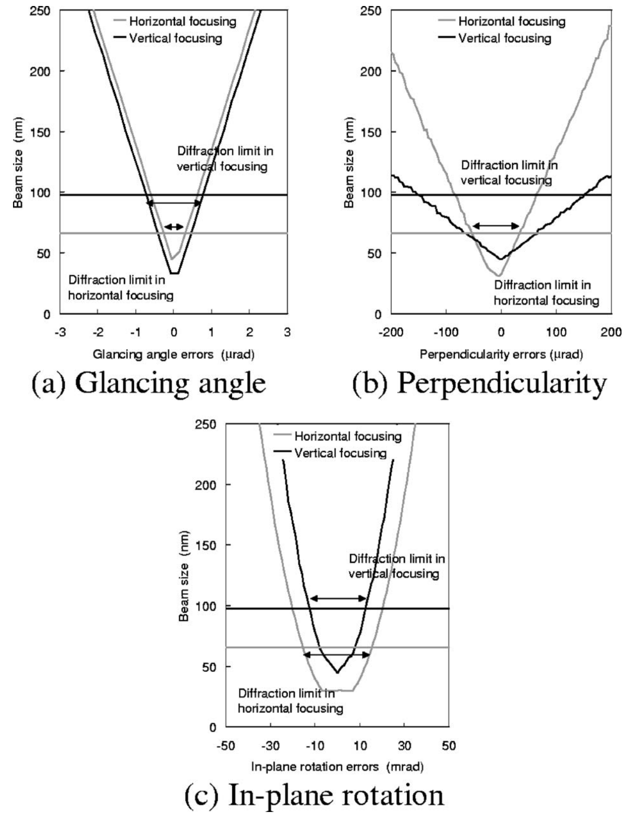

FIG. 3. Mutual relationships between angle errors and beam size calculated with ray-tracing simulator. (a) Glancing angle rotation. (b) Perpendicularity. (c) In-plane rotation. The horizontal lines indicate the diffraction limits defined as the distance between the first minima.

size. The obtained results are shown in Figs. 3(a)–3(c). Horizontal lines in the graphs indicate the diffraction limits predicted by the wave-optical simulator. Here, they are defined as the distance between the first minima instead of the FWHM to compare the obtained results with the diffraction limits accurately. The tolerance is defined as the range indicated by the arrows. Error tolerances required for diffraction-limited focusing are summarized in Table II.

Since the tolerance limits of glancing angle rotations were found to be severe, they were investigated in detail using the wave-optical simulator (shown in Fig. 4). Figure 4(b) shows the relationship between glancing angle errors and FWHM. In the wave-optical simulation, the tolerance limit is defined as the angle at which the focus size increases to 120% of the smallest FWHM.

On the basis of these results, a special control system for the adjustment of glancing angles and perpendicularity between the two mirrors was designed and developed.

TABLE II. Angle error tolerances required for diffraction-limited focusing.

Alignment axis	Vertical focusing mirror	Horizontal focusing mirror
Glancing angle[a] (μrad)	±1.5	±0.9
Glancing angle[b] (μrad)	±0.6	±0.4
Perpendicularity (μrad)	±40	±40
In-plane rotation (mrad)	±13	±16

[a]Wave-optical simulator.
[b]Ray-tracing simulator.

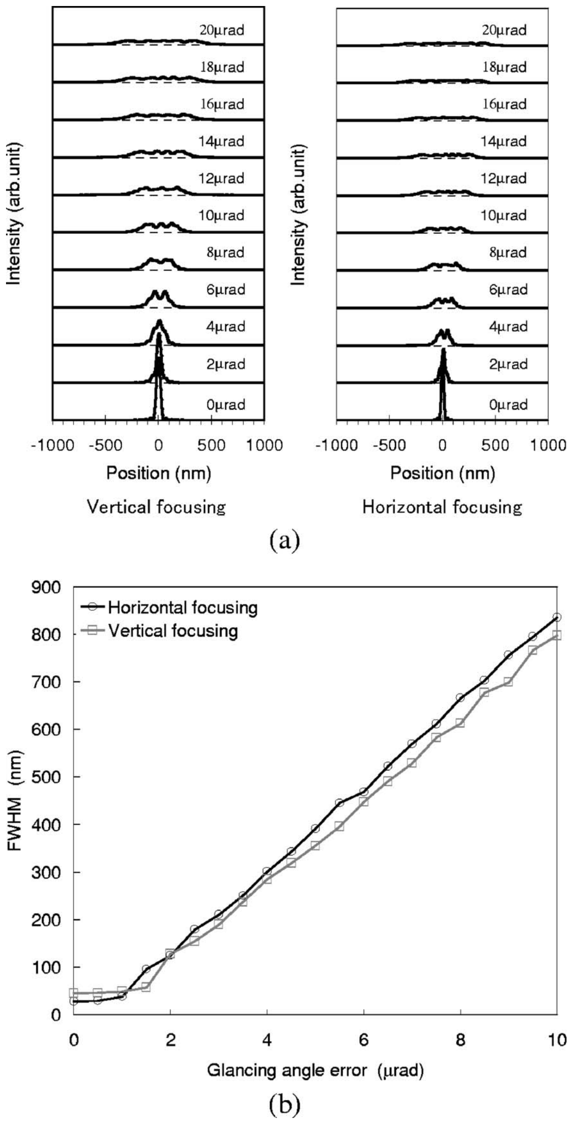

FIG. 4. Simulation results using wave-optical simulator for glancing angle alignments. (a) Series of beam profiles at every 2 μrad error from optimum glancing angle at x-ray energy of 15 keV. (b) Relationship between glancing angle errors and FWHM.

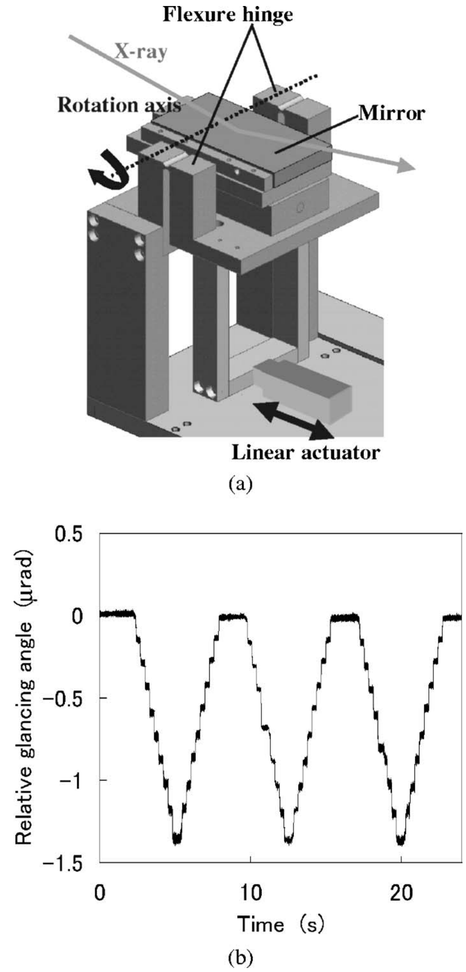

FIG. 5. (a) Adjustment system for glancing angle and (b) a result of performance test.

IV. DEVELOPMENT OF MIRROR MANIPULATOR

A. Adjustment system for glancing angles

A glancing angle adjustment system having a controllability of 0.04 μrad and no backlash was developed using a combined system of flexure hinges and a linear actuator (Fig. 5). In this system, the distance between the rotation center and the supporting point of the linear actuator is 100 mm; a 100 nm step of the linear actuator leads to a 1 μrad step of the glancing angle. The flexure hinges were designed to have a spring constant of 3343 N/rad to provide the linear actuator with a moderate force (approximately 3 kgf) when the glancing angle is equal to 4 mrad. Two flexure hinges were mounted on both sides of the mirrors to avoid abnormal rotation errors such as twist errors. Figure 5(b) shows the result of the performance test, in which displacement angles were measured with a microlaser interferometer (DS-80, Canon Co., Ltd.). The result shows that the system can control the glancing angle without backlash over an angle range of at least 0.2 μrad.

B. Adjustment system for perpendicularity between mirrors

The perpendicularity can be preadjusted within the required accuracy because it can be determined only by the relative rollings between the two mirrors. The schematic diagram of the system is shown in Fig. 6. This system consists of two autocollimators (KT-7000, Katsura Opto Systems Co., Ltd.), a pentaprism, and tilt stages. A pentaprism, having a

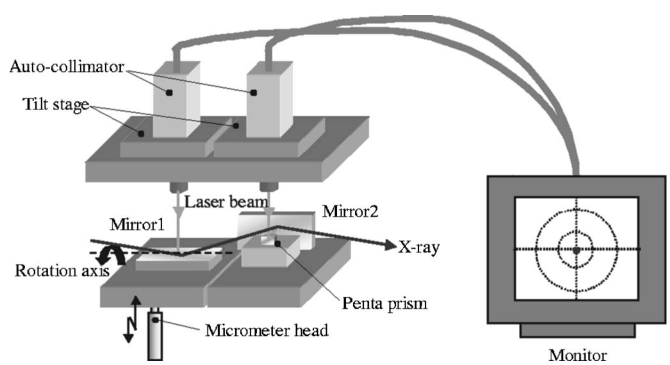

FIG. 6. Adjustment system for perpendicularity between two mirrors.

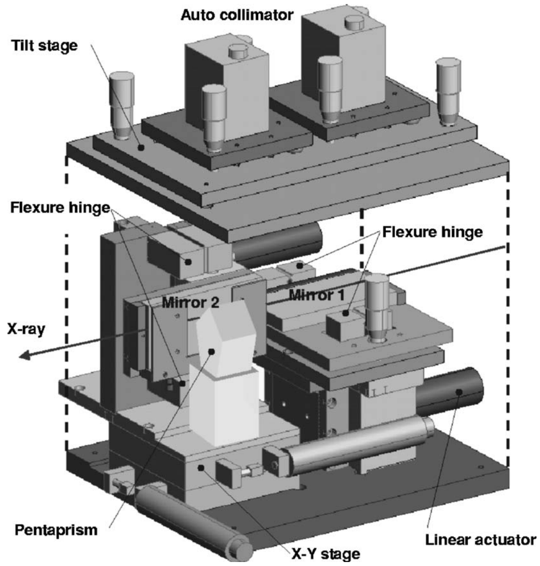

FIG. 7. Schematic diagram of developed mirror manipulator.

90° deviation tolerance of 36.4 μrad, is employed to irradiate the laser beam of the autocollimator onto the surface of the horizontal focusing mirror. The parallelism between the two autocollimators was adjusted with a sufficiently flat mirror. The most important point is that accurate perpendicularity adjustment can be achieved easily and rapidly as long as the optical axes of the two autocollimators are parallel. This system enables perpendicularity adjustment with an angle resolution of 36.4 μrad.

C. Mirror manipulator

Figure 7 shows a schematic diagram of the developed manipulator equipped with the adjustment systems. For in-plane rotation adjustment, only micrometer heads are employed, because the acceptable range is more than ±10 mrad.

V. EXPERIMENTS ON FOCUSING PROPERTIES

A. Experimental setup

Focusing tests at an x-ray energy of 15 keV were performed at the 1-km-long beamline (BL29XUL) of SPring-8.[13] The mirror manipulator was placed at the third experimental hutch, which was 950 m downstream of a double crystal monochromator (shown in Fig. 8). The in-plane rotations and perpendicularity were adjusted with the

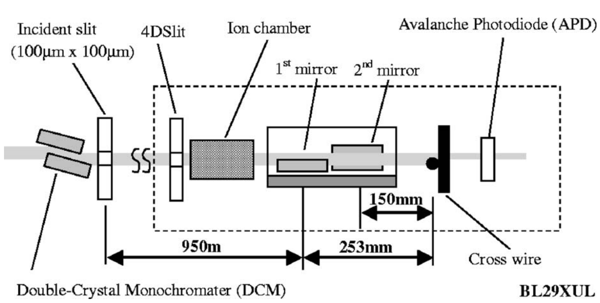

FIG. 8. Experimental setup for focusing tests.

required accuracies in advance. The glancing angle alignments were finely tuned while measuring the intensity profiles.

A wire-scanning method with a gold wire of 200 μm in diameter was employed to measure the intensity profiles at the focal plane. A linear-encoder-based feedback *X-Y* stage having a positioning resolution of 1 nm (Sigma Tech Co., Ltd.) was utilized to scan the wire two dimensionally.

We also demonstrated the use of a scanning x-ray microscope with a test pattern mounted on the *X-Y* stage close to the wire. The test pattern has periodic lines and spaces of various linewidths to investigate the best spatial resolution. In this experiment, scanning pitches are 16, 18, and 20 nm/pixel for the patterns having linewidths of 80, 90, and 100 nm, respectively. Exposure time is 1 s/pixel for each scan.

B. Experimental results

The beam intensity profiles were obtained by differentiating the curves of the intensity data measured using the wire-scanning method. As a result of focusing tests, a FWHM of 48×36 nm^2 ($V \times H$) was achieved (shown in Fig. 9). The measured profiles agree well with the wave-optically simulated profiles. This result suggests that the mirror alignments were carried out with sufficient accuracy, realizing diffraction-limited focusing.

Figure 10 shows the relationships between x-ray fluorescence intensity (tantalum $L\alpha$ line) and the beam position when the line-and-space patterns were vertically scanned with the focused beam to evaluate the spatial resolution. The peaks and valleys in the graph show tantalum lines and spaces, respectively. The subscripts in the graph correspond to the visibility between the peak and the valley. The tantalum lines of 80 nm in width were resolved with a high visibility of 60% by vertically scanning the patterns. Similarly, by horizontally scanning the patterns of 80 nm linewidth, a visibility of 55% was obtained (data not shown). The resolution evaluation with patterns of less than 80 nm linewidth was impossible, owing to the poor quality of the patterns of less than 80 nm linewidth. However, we expect that our fo-

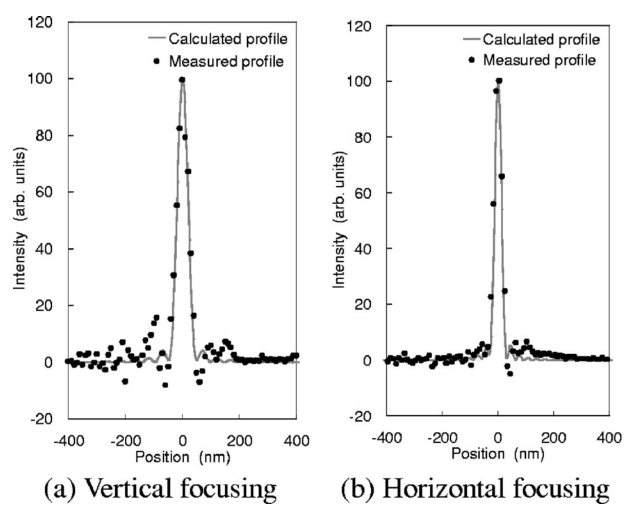

FIG. 9. Two-dimensional intensity profiles experimentally obtained, where scanning pitch is 10 nm. (a) Vertical focusing. (b) Horizontal focusing.

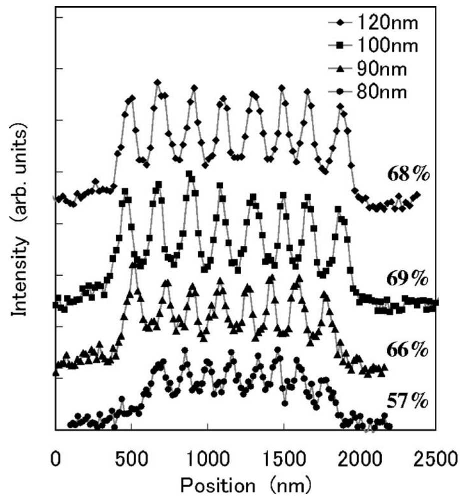

FIG. 10. Evaluation of spatial resolution in vertical direction using test patterns of various linewidths.

cusing system is capable of resolving the pattern of less than 50 nm linewidth, considering the results shown in Fig. 9. Additionally, we could not achieve better resolution in horizontal direction than that in vertical direction. The reason is that the smallest beam could not be kept for a couple of hours. If the incident angles of two mirrors changed from the best angle to have a 1.5 μrad error, the FWHM in the horizontal direction is broadened to more than 50 nm, but the FWHM in vertical direction hardly changes [see Fig. 4(b)].

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