Formation of sub-10 nm hard X-ray beam

Third-generation synchrotron and recently operated X-ray free electron laser facilities can produce almost fully coherent light even in the hard and soft X-ray ranges. These high-performance X-rays have been stimulating research on X-ray microscopy with nanometer spatial resolution. X-ray microscopic systems must be equipped with a focusing device. In the past decade, various optical devices have been improved by the development or application of advanced manufacturing technologies. There are many types of X-ray focusing devices that utilize reflection, refraction, and diffraction. One of the features of these devices is the experimentally achieved focused beam size, which has been decreasing rapidly and has reached less than 50 nm. Such focusing devices are now commercially available.

For several years, there has been theoretical interest among many researchers in X-ray microscopy fields in the smallest beam size that can be achieved. X-rays can be focused by their interaction with matter. The focused beam size is determined by the numerical aperture of the optical design, wavelength of the employed X-rays, and several aberrations inherent to optical devices. Several theoretical simulation-based studies on each type of focusing device have been carried out. The results indicated that the realization of a focal beam size of less than 10 nm is theoretically possible.

We have been developing an optical system for sub-10 nm hard X-ray focusing using laterally graded multilayer mirrors. The Kirkpatrick-Baez optical system is used for two-dimensional hard X-ray focusing. In this optical system, hard X-rays are individually focused in the vertical and horizontal directions. Two one-dimensional elliptically curved mirrors are used. The focused beam size is determined by the optical system design. To decrease the focused beam size, the optical system should be designed so that its numerical aperture is large. The numerical aperture is strongly related to the maximum X-ray incident angle in reflective optics. Multilayer surfaces are used for reflecting X-rays with a relatively large incident angle.

Last year, we constructed a KB optical system with two multilayer mirrors and performed one-dimensional focusing tests. Figure 1 shows an optical system design. The optical system is designed assuming the use of the 1-km-long beamline **BL29XUL**, in which the experimental hutch is approximately 1 km from the monochromator and almost full coherent hard X-rays are available. The surface profile of the focusing mirror is elliptically curved in accordance with the elliptical functions determined in the optical system design.

Figure 2 shows a photograph of the experimental setup. This experimental system is now installed in the 1-km-long beamline BL29XUL. The grazing incidence deformable mirror is used to control the shape of the wavefront of the incident X-ray entering the focusing mirror. To measure the wavefront of focusing X-rays, which is originated from the imperfection of the focusing mirror, the phase retrieval method using intensity profiles around the focal point is employed. We employed the phase retrieval method, which can use many intensity profiles around the focal point.

The experiment we carried out was as follows. Initially, while maintaining a flat surface profile of the deformable mirror, the incident angle and focal

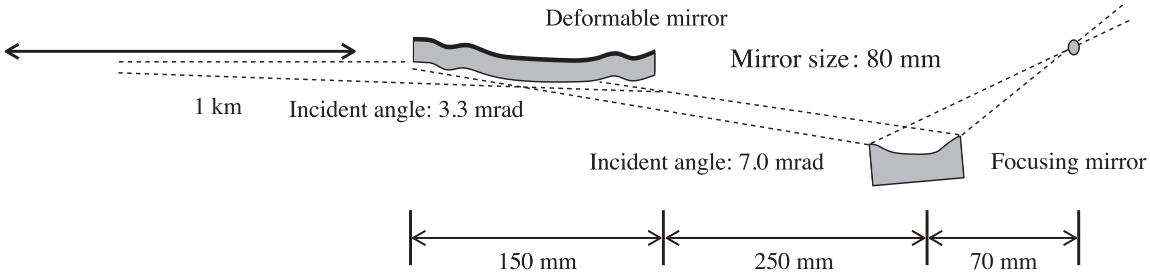

Fig. 1. Schematic of optical system for sub-10 nm hard X-ray focusing.

Fig. 2. Photograph of sub-10 nm focusing system installed in the 1-km-long beamline (BL29XUL).

length of the focusing mirror were adjusted to obtain the minimum focused beam size. Then, 16 intensity profiles around the beam waist were measured. After that, the wavefront error profile was used to estimate the phase retrieval using all the profiles. Then, the shape of the deformable mirror was adjusted in accordance with the estimated profile, to compensate for the wavefront error. Finally, the intensity profiles were remeasured after wavefront correction. The experimental conditions except for the shape of the deformable mirror were the same before and after wavefront correction.

Figure 3 shows a comparison between the ideal and measured profiles when the smallest beam size is obtained. The result indicated that nearly diffraction-limited focusing was realized. The ultimately achieved focused beam size was 7 nm.

The recent rapid advances in ultraprecise machining are the main factors responsible for breaking the 10 nm barrier. Laterally graded multilayer mirrors have the potential to be used in designs with larger NAs that permit relatively large incident angles. Based on the minimum period in multilayer films, a 3 nm beam should be achievable. A focusing system based on adaptive optics is also promising for realizing ultimate X-ray focusing.

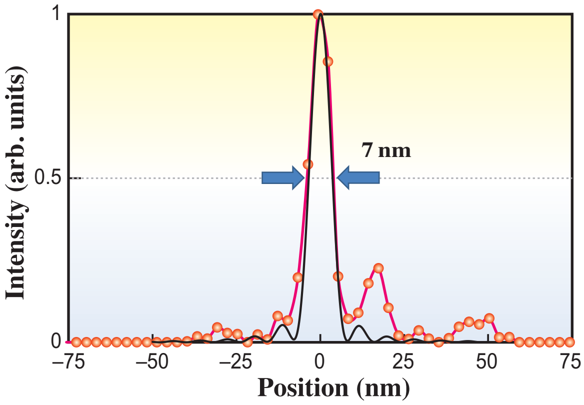

Fig. 3. Measured intensity profile of hard X-ray focused beam. X-ray energy is 20 keV.

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