Development and Application of Variable-Magnification X-Ray Bragg Optics

A novel X-ray Bragg optics has been developed for variable-magnification of an X-ray beam at the vertical-wiggler beamline BL-14B. Our X-ray Bragg optics is composed of two magnifiers in a crossed arrangement, and the magnification factor, *M*, is controlled through the azimuth angle of each magnifier. We could successfully control the magnification factor between 0.1 and 10 at the wavelength of 0.112 nm. At various magnification factors, X-ray images of a nylon mesh were observed with an air-cooled X-ray CCD camera. Not only absorption-contrast but also edge-contrast due to Fresnel diffraction was observed in the magnified images.

The X-ray Bragg magnifier based on asymmetric diffraction at a nearly-perfect crystal [1] is a useful optical element for X-ray radiology and microscopy, and has been used at synchrotron facilities, for example, for X-ray microtomography (μ-CT), analyzer-based phase-contrast imaging [2] and inline holography. One of the most striking features of the X-ray Bragg magnifier is that it can cover a wide range of resolution from submicrometer up to submillimeter, thus filling the gap between X-ray microscopy and radiology. Another attractive feature is that it can be combined with X-ray single-photon-counting detectors such as PILATUS and Medipix, opening up a new possibility for high-resolution, wide-dynamic-range, high-sensitivity and fast X-ray imaging.

In the conventional X-ray Bragg magnifiers, however, it was difficult to change the magnification factor. In order to solve this problem, we developed a variable-magnification X-ray Bragg optics [3, 4]. Thanks to the tunability of the magnification factor, we can locate a region-of-interest (ROI) in a sample under low magnification, and then observe the details of the ROI under an optimized magnification. Our X-ray Bragg optics consists of two magnifier crystals in a crossed arrangement as schematically shown in Fig. 1. The first crystal magnifies the incident beam in the horizontal direction while the second crystal does so in the vertical direction. The glancing angle of each crystal, θ_j, is set at the Bragg condition. Here, the subscript *j* is 1 for the first magnifier and 2 for the second magnifier. The $\hat{\phi}_j$ -axis is perpendicular to the diffracting lattice planes of the *j*-th crystal, and we can scan the azimuth angle, ϕ_j, while keeping the Bragg condition. The magnification factor of each magnifier is given by

$$M_j(\phi_j) = \frac{\cos\alpha_j \sin\theta_{Bj} + \sin\alpha_j \cos\theta_{Bj} \sin\phi_j}{\cos\alpha_j \sin\theta_{Bj} - \sin\alpha_j \cos\theta_{Bj} \sin\phi_j},$$

where α_j is the asymmetric angle and θ_{Bj} is the Bragg angle. For example, calculations show that the magnification factor is tunable between 0.01 and 100 through the azimuth angle, ϕ_j, under the conditions of $\theta_{B1} = \theta_{B2} = 16.96°$ and $\alpha_1 = \alpha_2 = 16.7°$. Although the magnified image is usually deformed as shown in the inset of Fig. 1, this image deformation can be corrected by the 2×2 transformation matrix and bilinear interpolation method.

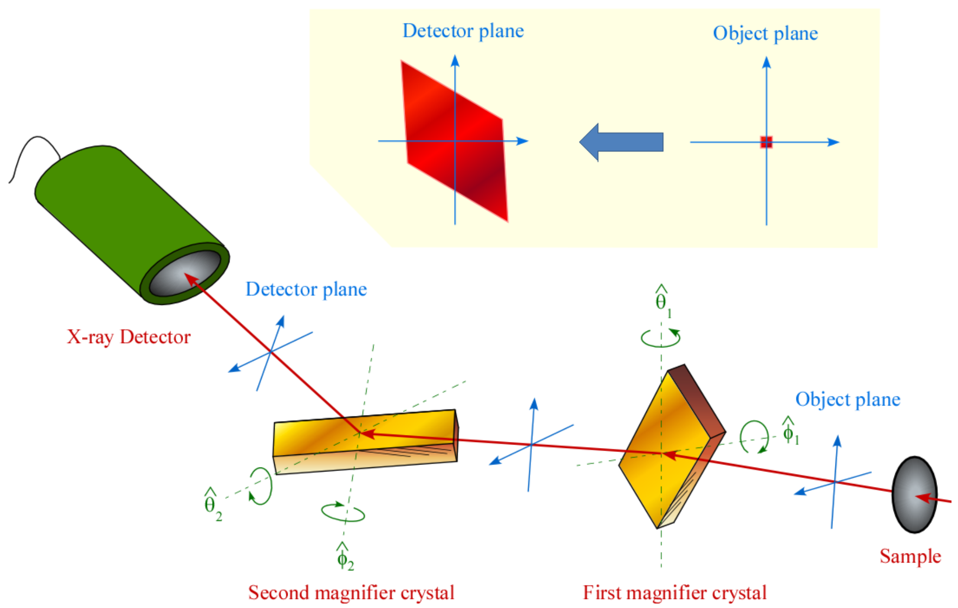

Figure 1: Variable-magnification X-ray Bragg optics.

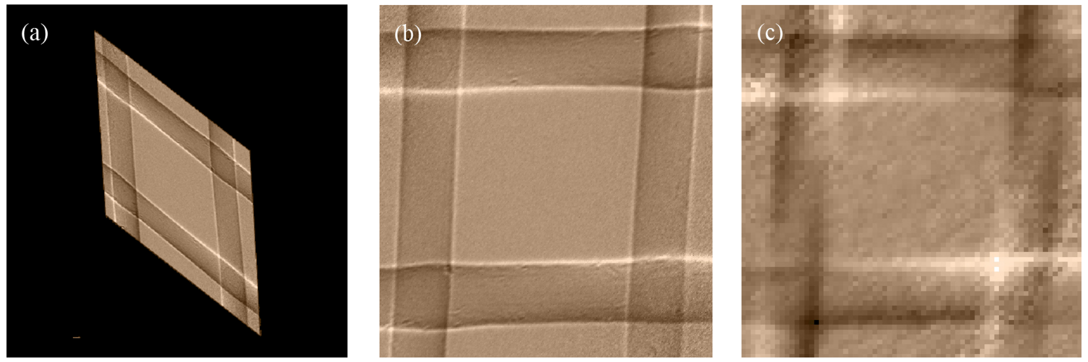

Figure 2: (a) Deformed magnified image and (b) corrected magnified image of the nylon mesh obtained at $\phi_1 = \phi_2 = 60°$ ($M_1 = M_2 = 5.9$). (c) Corrected image obtained at $\phi_1 = \phi_2 = 0°$ ($M_1 = M_2 = 1$). The period of the nylon mesh was about 1.1 mm in both the horizontal and vertical directions.

In order to verify the feasibility of our variable-magnification X-ray Bragg optics, we performed experiments at the vertical-wiggler beamline BL-14B. The white beam from the light source was monochromated at 0.112 nm by a Si(111) double-crystal monochromator. For magnifiers, we used asymmetric Si(220) crystals ($\theta_{B1} = \theta_{B2} = 16.96°$, $\alpha_1 = \alpha_2 = 14°$) made of non-doped float-zone silicon crystal ($\rho \geq 2000\ \Omega \cdot cm$). Magnified X-ray images were observed by a fiber-coupled X-ray CCD camera (Photonic Science Ltd., X-ray Coolview FDI 40mm). The pixel size was 23 μm (H) × 23 μm (V) and the number of pixels was 1384 (H) × 1032 (V).

First, we estimated the spatial resolution of the optics at several magnification factors using MTF (Modulation Transfer Function) charts. For example, the spatial resolution was estimated to be about 15 μm in the vertical direction and 20 μm in the horizontal direction at $\phi_1 = \phi_2 = 60°$ ($M_1 = M_2 = 5.9$). We found that the main determining factors of the spatial resolution were the pixel size of the X-ray CCD camera and the penumbral blurring. Then we observed a nylon mesh as a sample. The period of the mesh was about 1.1 mm in both the horizontal and vertical directions. Figure 2(a) shows a raw image observed at $\phi_1 = \phi_2 = 60°$ ($M_1 = M_2 = 5.9$) with the exposure time of 4 sec. Figure 2(b) shows a corrected image. For comparison, Fig. 2(c) shows an image obtained at $\phi_1 = \phi_2 = 0°$ ($M_1 = M_2 = 1$) . It is worth noting that not only absorption-contrast but also edge-contrast due to Fresnel diffraction is observed in Figs. 2(b) and (c).

In the experiment we could control the magnification factor from 1.0 up to 10 with reasonable throughput even at a second-generation synchrotron radiation facility such as the Photon Factory. In fact, the exposure time was as short as 10 sec at the maximum magnification factor ($M_1 = M_2 = 10$). A much wider range of magnification factor will be realized at third-generation synchrotron radiation facilities where submicrometer resolutions have already been achieved with the conventional fixed-magnification X-ray Bragg optics. We expect that the performance of our variable-magnification X-ray Bragg optics will be maximized at linac-based X-ray sources such as X-ray free-electron lasers (XFEL) and energy recovery linacs (ERL), which can produce diffraction-limited X-rays in both the horizontal and vertical directions.

REFERENCES

[1] K. Kohra, in *Proceedings of the Sixth International Conference on X-Ray Optics and Microscopy*, edited by G. Shinoda, K. Kohra, and T. Ichinokawa (Univ. of Tokyo Press, Tokyo, 1972), pp. 35-45.
[2] K. Hirano, *Jpn. J. Appl. Phys.* **50**, 026402 (2011).
[3] K. Hirano, Y. Takahashi, and H. Sugiyama, *Nucl. Instrum. Methods Phys. Res. A* **741**, 78 (2014).
[4] K. Hirano, Y. Takahashi, and H. Sugiyama, *Jpn. J. Appl. Phys.* **53**, 040302 (2014).

BEAMLINE

BL-14B

K. Hirano[1], Y. Takahashi[1], H. Sugiyama[1], and Y. Yamashita[2]
([1]KEK-IMSS-PF, [2]RIKEN SPring-8 Center)