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Development and application of variable-magnification x-ray Bragg optics

Keiichi HIRANO, Hiroshi SUGIYAMA and Yumiko TAKAHASHI
Institute of Materials Structure Science, Photon Factory, 1-1 Oho, Tsukuba, 305-0801, Japan

1 Introduction

The X-ray Bragg magnifier based on asymmetric diffraction at a nearly-perfect crystal 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 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. 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

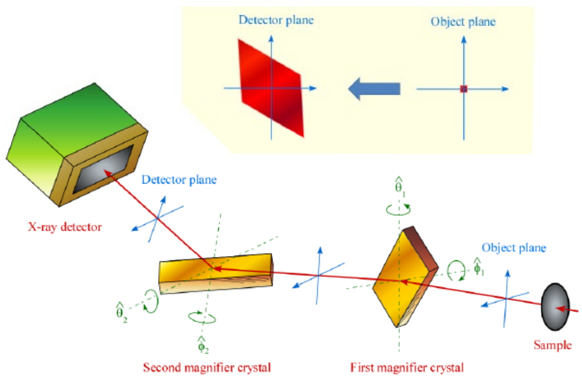

Fig. 1 Variable-magnification X-ray Bragg optics.

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

where α_j is the asymmetric angle and θ_{Bj} is the Bragg angle.

2 Experimental and Results

The experiments were carried out at the vertical-wiggler beamline BL-14B of the Photon Factory. First, the white beam from the light source was monochromated at 0.112 nm by an Si(111) double-crystal monochromator. Then the monochromatic beam transmitted through a sample, and was incident to the variable-magnification x-ray Bragg optics. As magnifiers, we used asymmetrically-cut Si(220) crystals ($\theta_{B1} = \theta_{B2} = 16.96^\circ$, $\alpha_1 = \alpha_2 = 14^\circ$) made of non-doped float-zone silicon crystal. Magnified x-ray images were observed by a module of the PILATUS 100K-S pixel detector (Dectris Ltd.). The pixel size was 172 μm (H) × 172 μm (V) and the number of pixels was 487 (H) × 195 (V).

First we estimated the spatial resolution of the entire optical system at several magnification factors using MTF charts. The results are shown in Fig. 2. It is clearly seen that the spatial resolution is in inverse proportion to the magnification factor. In this experiment, we could control the spatial resolution between 28 μm and 280 μm.

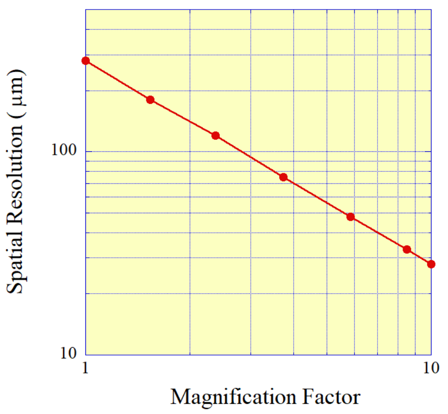

Fig. 2 Spatial resolution of the entire optical system estimated at several magnification factors.

Next, we observed a leaf as a sample at several magnification factors. For example, Fig. 3 shows the obtained images at $M_1 = M_2 = 8.5$. The exposure time was 0.25 sec. Although the shape of the leaf is hardly discernible at a lower magnification, the details of the sample can be clearly seen at the higher magnification.

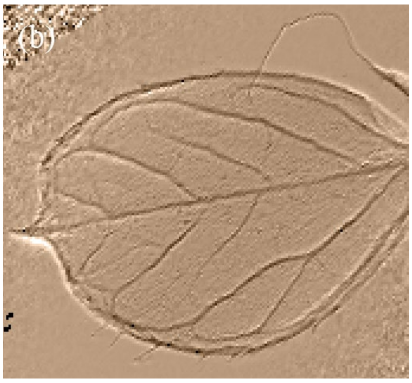

Fig. 3 Obtained image of the leaf at $M_1 = M_2 = 8.5$. The view-field is about 3.5 mm (H) × 3.2 mm (V).

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 0.3 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 using PILATUS and Medipix. 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 (XFELs) and energy recovery linacs (ERLs), which can produce diffraction-limited x-rays in both the horizontal and vertical directions. We hope that our novel x-ray optical system will open up new possibilities for high-sensitivity, wide-dynamic-range, fast and variable-magnification x-ray imaging.

* keiichi.hirano@kek.jp