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Development of X-ray Multiple Image Radiography

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1 Introduction

X-ray imaging is a powerful method for visualizing the inner structures of various specimens non-destructively. At the Photon Factory (PF), several cutting-edge x-ray imaging techniques, such as interferometer-based imaging [1] and analyzer-based imaging [2-4], were successfully developed and applied for observing industrial materials and biological specimens. In general, although the sensitivity of the analyzer-based imaging is usually lower than that of the interferometer-based imaging, the analyzer-based imaging can cover a wider variety of samples than the interferometer-based imaging. Further, the analyzer-based imaging can produce both absorption-contrast and phase-contrast images from a set of images recorded at different angles of the analyzer crystal. Recently, it was shown that the analyzer-based imaging can also produce ultra-small angle x-ray scattering (USAXS) images reflecting microstructures in a sample [5]. This new x-ray imaging technique is called multiple image radiography, and is currently under development at the Photon Factory. In this paper, we show recent results obtained by the x-ray multiple image radiography.

2 Principle of x-ray multiple image radiography

The x-ray optics of multiple image radiography is essentially same with that of the x-ray analyzer-based imaging as schematically shown in Fig. 1. This optics is composed of collimator crystal and analyzer crystal in non-dispersive (+, -) arrangement. The monochromatic x-rays are, at first, expanded by the collimator and then

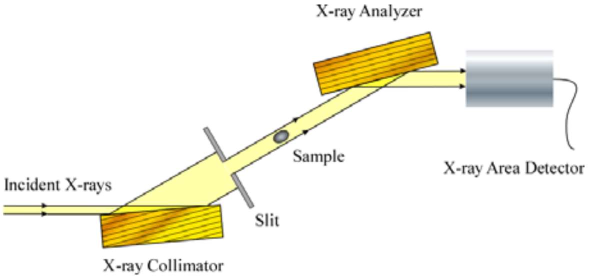

Fig.1: X-ray optics of multiple image radiography

incident upon a sample on a rotation stage. The transmitted x-rays through the sample are analyzed by the analyzer, and then recorded by an x-ray area detector. In the x-ray multiple image radiography, it is necessary to scan the analyzer crystal over the Bragg diffraction region, and to record diffracted image at each analyzer angle. The scanning angle of the analyzer is usually set several times larger than the angular region of the Bragg diffraction. The absorption-contrast, refraction-contrast (differential-phase-contrast) and phase-contrast images are obtained by the following equations:

$$I_{abs}(x,y) \propto \sum_j I(x,y,\Delta\theta_j)$$

$$I_{refract}(x,y) \propto \sum_j \Delta\theta_j \times I(x,y,\Delta\theta_j) \Big/ \sum_j I(x,y,\Delta\theta_j)$$

$$I_{phase}(x,y) \propto \int_0^x I_{refract}(x',y)dx'$$

where $\Delta\theta_j$ is the offset angle of the analyzer from the Bragg angle and I(x, y, $\Delta\theta_j$) is the recorded image at $\Delta\theta_j$. From a set of the recorded images, we can also draw a rocking curve for each pixel at (x, y), and obtain the full width at half maximum (FWHM). Due to the effect of the USAXS in the sample, the FWHM observed at each pixel is slightly larger than that obtained without the sample. By mapping this increase of the FWHM, $\Delta_{fwhm}(x, y)$, we can obtain a USAXS-contrast image reflecting the microstructures in the sample.

3 Experimental and results

Preliminary experiments of the x-ray multiple image radiography were performed at the vertical-wiggler beamline BL-14B. The white beam from the light source was monochromated at 0.112 nm by the Si(111) double-crystal monochromator. The incident monochromatic x-rays were expanded in the horizontal direction by an asymmetrically-cut Si(220) collimator crystal (α = 8°). As a sample, we observed a plastic tube filled with fine fibers. The diameter of the tube was about 3.8 mm. The transmitted x-rays through the sample were analyzed by a Si(220) crystal (α = 0°). The diffracted x-rays by the analyzer were recorded by an x-ray CCD camera (Photonic Science Ltd., XFDI) that consisted of a GdO_2S:Tb scintillator, glass fiber plate, and CCD. The effective pixel size was 23 μm (H) × 23 μm (W) and the number of pixels were 1384 (H) × 1032 (V).

The analyzer was scanned from $\Delta\theta$ = -10 arcsec to $\Delta\theta$ = +10 arcsec in 1.0 arcsec steps. At each angle, the sample was rotated around the vertical axis from 0° to 180° in steps of 0.72°. The exposure time for each image was 150 msec. The total measurement time was about 2.5 hours. Figure 2 shows (a) absorption-contrast and (b) phase-contrast tomograms reconstructed by the filtered back-projection method. The phase-contrast tomogram of the plastic tube is much clearer than the absorption-contrast tomogram. On the other hand, the absorption-contrast tomogram of the fine fibers is almost as clear as the phase-contrast tomogram. This contrast enhancement is considered to be due to Fresnel diffraction and USAXS.

The USAXS-contrast image is currently under analysis and will be reported elsewhere.

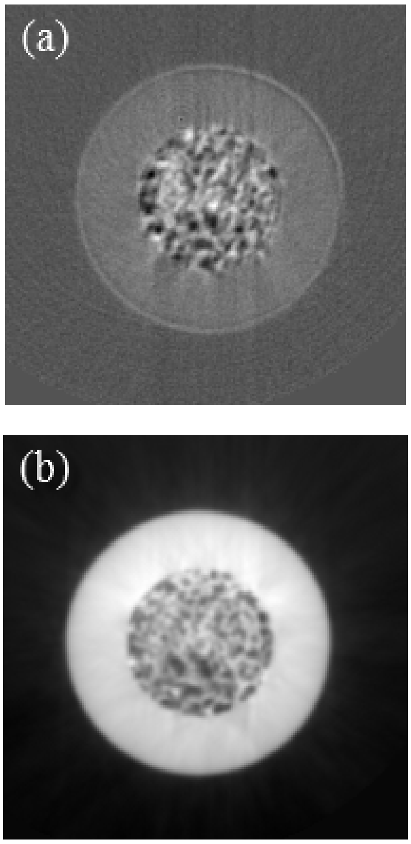

Fig. 2 : (a) Absorption-contrast and (b) phase-contrast tomograms of the plastic tube filled with fine fibers. For the reconstruction, the filtered back-projection method was used. The diameter of the tube was about 3.8 mm.

4 Conclusions

The preliminary experiments of the x-ray multiple image radiography were carried out at the vertical wiggler beamline BL-14B. At the wavelength of 0.112 nm, both absorption-contrast and phase-contrast tomograms of the plastic tube filled with the fine fibers were successfully reconstructed by the filtered back-projection method. The phase-contrast tomogram of the plastic tube was much clearer than the absorption-contrast tomogram, whereas the absorption-contrast tomogram of the fine fibers is almost as clear as the phase-contrast tomogram. This contrast enhancement of the fine fibers is considered to be due to Fresnel diffraction and USAXS. Further analyses are currently under way and the results will be reported elsewhere.

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