X-ray phase micro-tomography using an interference microscope with zone plates

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Abstract. Using an x-ray common-path interference microscope with two zone plates at SPring-8 BL20XU, quantitative phase imaging was investigated by the fringe-scanning method. The phase sensitivity was estimated to be $\lambda/62$. Tomographic three dimensional phase image of diamond particles and polystyrene beads of 2.8 $\mu$m in diameter could be clearly reconstructed.

1. Introduction
In x-ray region, phase-contrast is much higher than absorption contrast especially for a specimen which consists of light elements, such as biological specimens. Various phase-contrast microscopes, such as an interference microscope, a Zernike-type phase-contrast microscope, a differential interference microscope, and holography have been developed in the x-ray region. Using an x-ray interference microscope, phase shift of a specimen can be imaged directly and it is suitable for phase tomography.

One possible solution for an x-ray common-path interference microscope is a combination of an x-ray microscope and an off-axis reference beam. A phase shift image was obtained by using fringe-scan technique. Disadvantage of such an off-axis interference microscope is that the spacing of interference fringe is about 10 $\mu$m or less and it is necessary to use fringe-scanning technique to observe a specimen. This problem can be solved by using a co-axial reference beam. This type of microscope was discussed by Wilheim et al. [1]. The authors was developed a common-path interference microscope with two zone plates. A fringe-less phase image of a 300 nm line and 300 nm space patterns could be resolved at 10 keV [2]. A different type of such a microscope was also developed by Koyama et al. [3].

In this paper, we show the performance of phase imaging and phase tomography using the common-path interference microscope.

2. Common-path interference microscope with two zone plates
The optical system is shown in Fig. 1. The two zone plates (ZP1, ZP2) had the same specifics. The diameter and the outermost zone width were 155 $\mu$m and 100 nm, respectively. The zone material was tantalum of 1.0 $\mu$m in thickness. The zone plates were fabricated by NTT Advanced Technology Inc. Two zone plates were placed twice of the focal length apart from each other. Illumination and reference beams were separated by a double pinhole of 50 $\mu$m in diameter. The (+1, 0) order x-rays were transmitted through a specimen and were focused on a CCD camera (Hamamatsu Photonics K.K.,
3.14 µm/pixel at the phosphor screen) with the magnification ratio of 50. The (0, −1) order x-rays of the reference beam were overlapped with the image of a specimen. The two beams interfered with the same phase difference over the image plane. Then, the interference image was observed without any interference fringes. The beam stop 1 prevents the -1st order reference beam of ZP1 from overlapping the image plane. The beam stop 2 prevents the 1st order of ZP2 from overlapping the image plane. The phase of the reference beam could be changed by rotating the phase shifter of 70-µm quartz sheet.

10 keV x-rays of SPring-8 BL20XU were used. This beamline has an in-vacuum undulator and a Si (111) double-crystal monochromator. The monochromator is placed at 46 m from the source. The distance between the source and the experimental hutch was 240 m. In this optical system, illuminating x-rays interfere with x-rays transmitted through the first zone plate at the symmetrical position about the optical axis. Then, spatial coherence area must be larger than the diameter of the zone plate. This relatively long beamline length is suitable to obtain a large coherence area.

Figure 1. Optical system of the interference microscope.

3. 2D phase image
Figure 2 shows a phase image of an aluminum foil obtained by 4-step fringe-scanning method. The standard deviation of the phase shift was 0.13 rad at the area A in the foil (100 × 50 pixels, 62 nm/pixel), and 0.034 rad at the area B. Suppose that the phase sensitivity was three times of this background, it was calculated to be λ/62. Figure 3 shows the phase shift variation with the thickness of the aluminum foil. The result of the 18-µm foil agreed very closely with the calculated value from the Henke table [4]. But the results of the 5 µm and 12.5 µm were slightly larger than the calculations.

Figure 5 shows the phase shift profile of overlapped 2-µm copper foils (total 4 µm). The solid line is the experimental data and the dashed line is calculated one. The obtained phase shift near the copper absorption edge was smaller than the calculated one. But the complicated structure was observed in the obtained profile.

Figure 2. Phase image of the edge of an aluminum foil. The standard deviations of the area A and B are 0.13 rad and 0.034 rad, respectively.

Figure 3. Phase shift variation with the thickness of the aluminum foil. The upper line shows the experimental values and the lower line shows the calculation from the Henke table.
Figure 4. Phase shift profile of overlapped 2-µm copper foils (total 4 µm).

Figure 5. Phase tomography of diamond particles attached to a glass capillary of 7 µm in outer diameter (rendering view).

Figure 6. Phase tomography of polystyrene beads of 2.8-µm diameter in a glass capillary. A: the section image, B: the three dimensional rendering view.

4. Phase tomography

Phase tomography was investigated using test samples, such as diamond particles attached to a glass capillary and polystyrene beads of 2.8 µm in diameter packed in a glass capillary. The phase projections were obtained by 4-step fringe-scanning method. The three-dimensional phase images were reconstructed from the 90 phase projections of different angles of view over the range of 180 degrees. The exposure time of each image was 20 s.

Figure 5 shows the diamond image and Fig. 6 shows the polystyrene image. The almost transparent samples, such as the diamond particles and the polystyrene beads could be clearly observed three dimensionally.

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References
[1] Wilhein T, Kaulich B and Susini J 2001 Opt. Commun. 193, 19.
[2] Watanabe N, Hoshino M, Sato M, Takeda Y, Namiki T, Aoki S, Takeuchi A and Suzuki Y 2006 Proc. 8th Int. Conf. X-ray Microscopy, IPAP Conf. Series 7 pp.372-374.
[3] Koyama T, Tsuji T, Yoshida K, Takano H, Tsusaka Y and Kagoshima Y 2006 Jpn. J. Appl. Phys. 45, L1159
[4] Henke, B L, Gullikson, E M, Davis, J C, Atomic Data Nucl. Data Tables 54, 181-342 (1993). (http://henke.lbl.gov/optical_constants/)