High Spatial Resolution Phase Measurement by Micro-interferometry using a Hard X-ray Imaging Microscope

Owing to the highly brilliant undulator radiation in third generation synchrotron radiation facilities, a much higher coherence than ever is available even in the hard X-ray region, and thus, many kinds of X-ray optics requiring coherence can be developed. They are scanning microscopy, diffraction microscopy, holography, interferometry and so on. Among them, the X-ray interferometry is one of the most powerful methods for directly retrieving the phase information of samples. The high coherence available in the facilities has made X-ray interferometry possible, not only of the amplitude-division type [1,2] but also of the wavefront-division type [3]. We proposed and demonstrated a novel hard X-ray micro-interferometer of the wavefront-division type using an optical system of an imaging microscope for high spatial resolution phase measurement [4]. In this report, we present some results indicating the feasibility of this micro-interferometer.

The optical system is shown in Fig. 1. Both object and reference waves are necessary to form a wavefront-division type interferometer. Two zone plates (ZP-A and ZP-B) are arranged closely in the same plane perpendicular to the beam axis. One zone plate (ZP-A) forms a reference wave, while the other zone plate (ZP-B) functions as a magnifying lens. If the two zone plates are illuminated coherently, the corresponding two secondary point sources (S_A and S_B) are produced at their back focal positions. Two spherical waves diverging from these two point sources overlap each other and interference fringes can be formed in an image plane. To prevent the –1st-order diffractive waves from being mixed in the interference region, ZP-A was designed to have a half-moon shape. We call this optical element consisting of two zone plates the "twin zone plate." Its detailed parameters are shown in Fig. 2. It was fabricated by NTT Advanced Technology Corporation [5]. It should be mentioned that the proposed interferometer is analogous to Young's interferometer, and therefore, a high fringe visibility can be expected.

We constructed the hard X-ray micro-interferometer at the Hyogo beamline **BL24XU** (Fig. 1). The photon energy of the fundamental harmonic peak of an undulator was tuned to be 9 keV (λ = 0.138 nm). The spatial coherence region in the vertical direction, which is determined by the vertical source size and the distance from the source, is about 200 µm in the plane of the twin zone plate. From Figs. 1 and 2, the illuminated region is 175 µm, therefore, this region is included in the spatial coherence region. The temporal coherence length, $\lambda^2/2\Delta\lambda$, is about 0.5 µm. Since the maximum optical path difference between the two waves is 34 nm, it is much shorter than the temporal coherence length. Therefore, the coherence condition is completely satisfied. An X-ray zooming tube was employed to observe interference patterns. To convert the interference pattern into the phase-shift distribution, the fringe scanning method was applied. A 125-µm-thick Kapton film was used as a phase plate and arranged in the path of reference waves, as shown in Fig. 1. The phase of the reference wave was varied by rotating the phase plate appropriately.

For a pure phase sample, we first used a 75-µm-thick Kapton film with a transmission of 96.3%. The obtained fringe interval was evaluated to be 10 µm, which was equal to the expected value. Furthermore, a visibility of as high as 60% was also achieved. The sample images obtained are shown in Fig. 3: (a) the absorption-contrast image, (b) the interference pattern, and (c) the phase-shift-distribution image retrieved using the fringe scanning method.

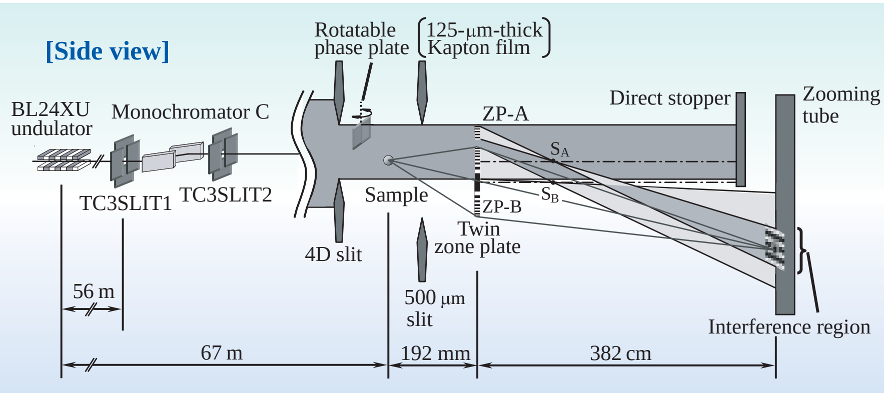

Fig. 1. Schematic illustration of the hard X-ray micro-interferometer. The photon energy used was 9 keV. The optical magnification was ×20. The rotatable phase plate arranged in the path of reference waves was used for the fringe scanning method.

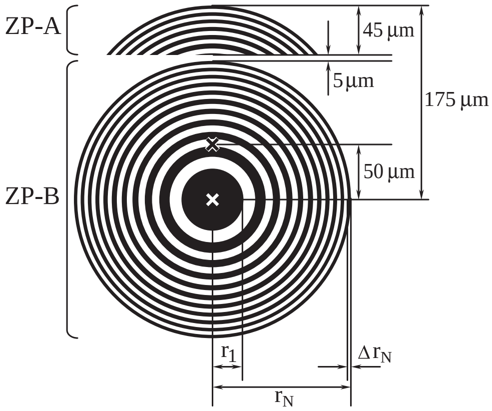

Fig. 2. Design of a twin zone plate made of tantalum. The parameters are as follows: the radius of the innermost zone r_1 of 5 µm, outer diameter $2r_N$ of 250 µm, outermost zone width Δr_N of 100 nm, tantalum thickness of 1 µm, focal length at 9 keV of 181.5 mm and ideal diffraction efficiency at 9 keV of 15.7%.

In Fig. 3(b), the fringe dislocations corresponding to the sample edge were clearly observed. The 75-µm-thick Kapton yields a phase shift of 12.9 rad by calculation. This value agreed well with the resultant distribution in Fig. 3(c).

Next, for another pure phase sample, polystyrene microparticles with a diameter of 7 µm and a transmission of 99.8% were used. The sample images obtained are shown in Fig. 4. Even though the fringe dislocations could hardly be recognized in Fig. 4(b), the sample images were clearly observed using the fringe scanning method, as shown in Fig. 4(c). The spatial resolution of this system was about 160 nm, which was estimated by analyzing the edge response of the phase-retrieved image of a copper #2000 mesh.

From these results, it can be concluded that our new optical system has successfully realized the micro-interferometry in the hard X-ray region. We are now improving the sensitivity of the system to the phase shift. Increasing the signal-to-noise ratio and expanding the interval of the fringe pattern will realize it. Furthermore, by combining our micro-interferometer with a tomographic technique, the three-dimensional refractive index distribution in biological specimens, micropolymers, and optoelectronic devices can be measured without any destruction.

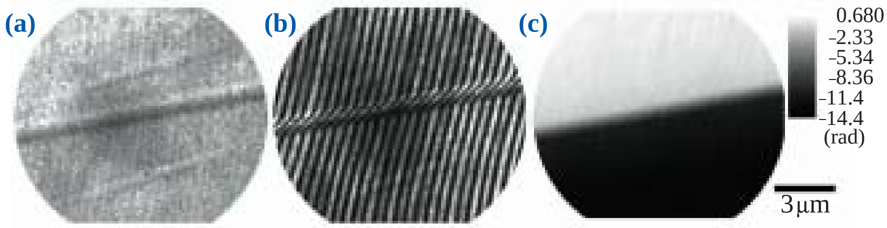

Fig. 3. X-ray micrographs of 75-µm-thick Kapton film: **(a)** Absorption-contrast image. Only the sample edge is slightly observed. **(b)** Interference pattern. The fringe dislocations at the sample edge are clearly observed. **(c)** Retrieved phase-shift image. The sample is observed clearly and the absolute phase shift is evaluated to be 12.0 rad.

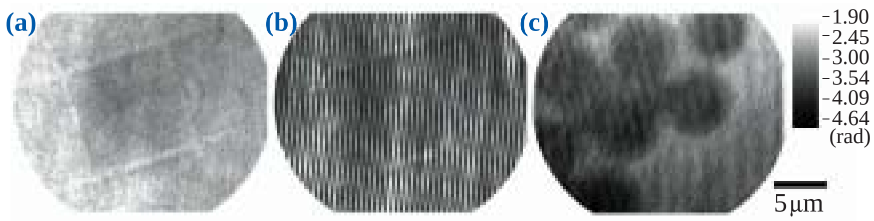

Fig. 4. X-ray micrographs of polystyrene microparticles: **(a)** Absorption-contrast image. The sample is hardly observed. **(b)** Interference pattern. **(c)** Retrieved phase-shift image. The sample is observed clearly and the absolute phase shift is evaluated to be 1.1 rad.

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