Hard X-ray phase-difference microscopy using self-imaging phenomenon of a transmission phase grating

Nondestructive and quantitative nanometer-scale visualization of internal structures of materials consisting of light elements will bring about significant progress in biological and material sciences. For an imaging technique, not only its spatial resolution but also its sensitivity is a key factor that determines its performance. In conventional hard X-ray imaging, the difference in absorption among materials has been used for contrast formation; however, the sensitivity of this method is low especially for materials consisting of light elements. In the early 1990s, several imaging techniques measuring the phase shift of X-rays were proposed. The so-called 'X-ray phase imaging' has attracted considerable attention owing to its sensitivity to light elements, being three orders of magnitude higher than that of absorption contrast imaging (e.g., [1,2]). Zernike phase-contrast microscopy has been applied to hard X-rays and is now widely used; however it remains nonquantitative for strong-phase objects.

We have proposed a novel X-ray phase imaging microscope consisting of an objective lens and a single transmission grating [3,4]. The microscope can provide a phase image with no high spatial coherence and is quantitative even for strong-phase objects, which is difficult to be covered by Zernike phase-contrast imaging technique. The method uses self-imaging as in X-ray Talbot interferometry [5]; the self-image is largely magnified by placing a grating just behind the back focal plane and resolved using an image detector. This allows us to obtain twin phase images with opposite signs separated by a specific distance. Furthermore, the twin images can be processed to generate a phase image through simple algorithms. The spatial resolution of our microscope was not degraded by the presence of the grating, and the sensitivity to light elements was about two orders of magnitude higher than that of the absorption contrast microscope that was obtained by simply removing the grating. Our proposed method is attractive for easily appending a quantitative phase-sensitive mode to normal X-ray imaging microscopes, and has potentially broad applications in biology and material sciences.

The experimental setup is shown in Fig. 1. The experiments were performed at beamline **BL20XU**. The X-ray beam from an undulator was monochromatized using a Si 111 double-crystal monochromator. The experimental station was located 245 m downstream from the source, the width of which in the horizontal direction (the x-direction in Fig. 1) was 0.4 mm. A commercially available 0.7-μm-thick tantalum Fresnel zone plate (NTT-AT, outermost zone width: 86.6 nm, diameter: 416 μm) fabricated on a 2-μm-thick SiC membrane was used as an objective lens. The X-ray energy was fixed at 9 keV, and the focal length *f* of the Fresnel zone plate (FZP) was 261 mm. To maximize the magnification, we put the detector as far away as possible within the experimental space (6461 mm downstream of the FZP), and put the sample on the object plane (272 mm upstream of the FZP), resulting in a magnification of 23.7. An X-ray camera consisting of a phosphor screen (10-μm P43, Gd_2O_2S:Tb + fine powders), a relay lens, and a cooled charge-coupled device (CCD) camera (Hamamatsu Photonics C4742-98-24A, 1344 × 1024 pixels) was used as the detector. The effective pixel size of the detector was 4.34 μm, which corresponds to 183 nm on the object plane.

A 4.3-μm-pitch gold Ronchi grating (Howa Sangyo Co., Ltd.) was used. Its thickness was set at 0.92 μm as it works as a $\pi/2$ phase grating at 9 keV. It was placed 67.8 mm downstream of the back focal plane of the objective lens, which corresponds to a Talbot order *p* of 1/2.

Figure 2(a) shows a phase-difference image of polystyrene (PS) spheres. We used a 43-step fringe scan with an exposure time of 2 sec each. In this case, the twin images, each of which is a phase image, are separated. The standard deviation of the noise in the background area (the area with no sample) was $2\pi \times 0.003$ rad. Figure 2(b) shows an absorption image of the same area but obtained without the grating. The exposure time was the same as that used to obtain the image in Fig. 2(a). The gray scale of Fig. 2(b) is adjusted such that its background

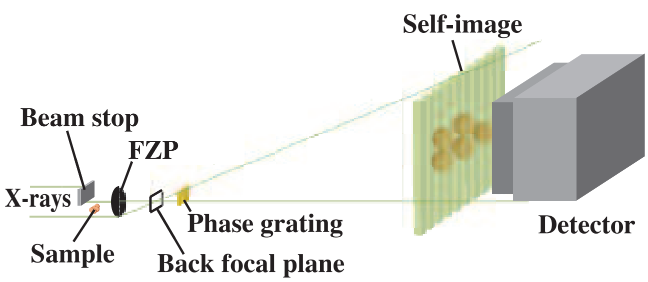

Fig. 1. Setup of phase-difference X-ray microscopy with a transmission phase grating (side view). [3]

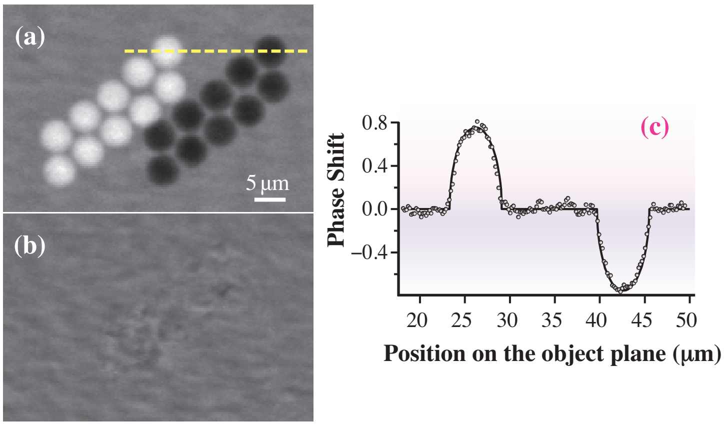

Fig. 2. **(a)** Enlarged phase-difference image of the PS spheres (gray scale, -0.3π - 0.3π). **(b)** Absorption image of the same area as **(a)** obtained by simply removing the grating. **(c)** Section profile along the dashed line in **(a)**. [4]

area is displayed in the same contrast as that of Fig. 2(a). No contrast due to the PS spheres can be seen in the absorption image, indicating that our imaging method has a much higher sensitivity than the conventional imaging microscopy based on the absorption of X-rays. The filled circles in Fig. 2(c) show the section profile along the dashed line in Fig. 2(a), and the solid line in Fig. 2(c) is the phase shift calculated for a PS sphere with a diameter of 5.8 μm. The good agreement of the experimental data with the calculated data shows that the phase shift by the sample is quantitatively retrieved.

The reconstruction of a phase image from a differential phase image was also successfully performed. Figure 3(a) shows the differential phase image of a 1-μm-thick tantalum Siemens star chart and Fig. 3(b) shows its phase image retrieved from Fig. 3(a). The reconstruction was performed in an adaptive deconvolution process based on a Bayesian framework, where the statistical distribution of noise was taken into account. Thus, our method can be used for the phase imaging of a sample larger than the separation distance.

The spatial resolution in the horizontal direction was estimated to be 450 nm from the edge of the Siemens star pattern. The resolution was almost the same as that of the absorption-contrast image obtained simply by removing the grating. The degradation in the spatial resolution due to the grating was thus avoided.

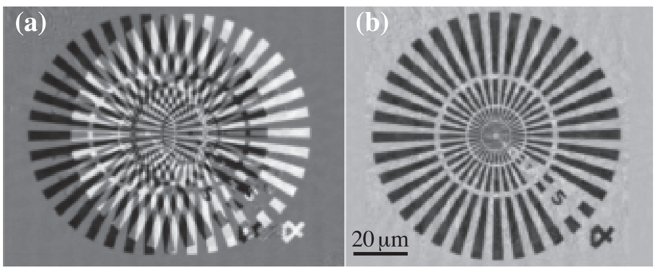

Fig. 3. **(a)** Differential phase image of a 1-μm-thick tantalum Siemens star chart and **(b)** its phase image retrieved from **(a)**. [4]

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