High-Speed X-Ray Phase Imaging and Phase Tomography by Talbot Interferometry with White SR

High-speed X-ray phase imaging/tomography has been achieved using an X-ray Talbot interferometer with white SR. A differential phase image could be obtained with a 1 ms exposure. The scan time for obtaining a phase tomogram was 0.25 s, and time-resolved (i.e., four-dimensional) phase tomography was also achieved. This achievement advances X-ray phase imaging/tomography from a technique for static imaging to one for dynamic imaging of weakly-absorbing objects.

Various phase imaging methods have been proposed and demonstrated so far in the X-ray region. Most of these activities have been, however, performed by static observation. In particular when using crystal optics, such as a crystal interferometer and an angular analyzer, monochromatic plane-wave X-rays are required, and long exposures are needed. The edge-enhanced contrast generated through the propagation-based method can be observed in real time at synchrotron facilities. However, quantitative measurements of the phase shift cannot be performed with the real-time observation. We aim at pioneering this field for various expected applications in materials science (deformation, phase separation, phase transitions, and so forth) especially in soft matter and also to *in vivo* biological imaging.

An X-ray Talbot interferometer [1], which consists of two transmission gratings, is an attractive candidate device for high-speed X-ray phase imaging because it functions with polychromatic X-rays. It has been theoretically shown that an image generated with X-rays with a bandwidth ($\Delta E/E$) of 1/8 is almost comparable to an image obtained with monochromatic X-rays [2]. Even when white synchrotron radiation is used, X-ray phase imaging is still possible, although the image quality decreases to some extent.

We performed imaging experiments at BL-14C1 where a white SR beam is available from the vertical wiggler. The experimental setup is shown in Fig. 1, where gold gratings of 5.3 µm pitch on Si wafers 200 µm in thickness were aligned along the optical axis. The phase grating was tuned so that a $\pi/2$ phase shift was generated for 36 keV X-rays. A CMOS camera was coupled with a phosphor screen (P46) 20 µm in thickness through a reflecting mirror and coupling lenses. The CMOS camera had a 1280 × 1024 pixel array, with an effective pixel size of 12.7 µm. The camera was operated at a frame rate of 1000 f/s, and the exposure time per image was set to 1 ms.

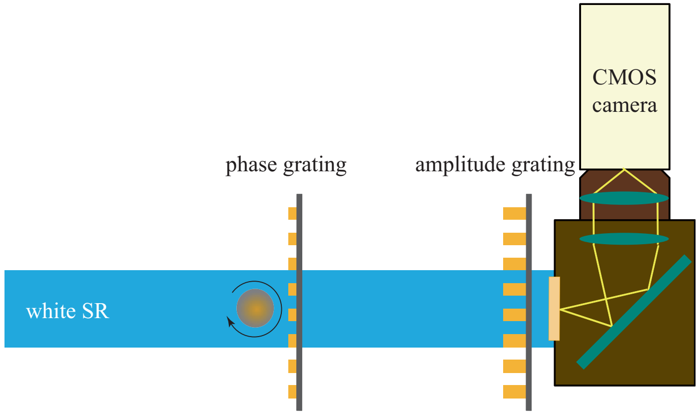

Figure 1
Experimental setup for high-speed X-ray phase imaging/tomography.

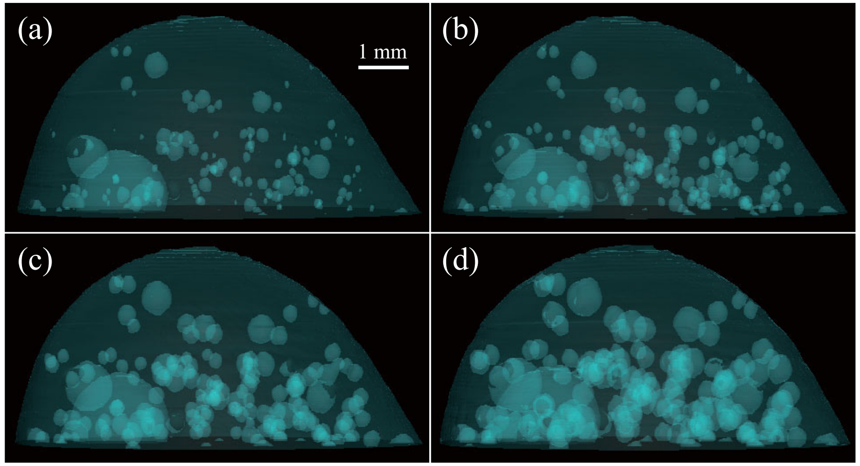

Figure 2
Time-resolved phase tomograms of the glue sample with growing bubbles stimulated by white SR irradiation. The tomograms (surface rendering views) shown are those at (a) 0 s, (b) 2.31 s, (c) 4.66 s, and (d) 7.01 s after beginning the irradiation.

An image of the differential phase shift is normally calculated from several moiré patterns obtained by displacing one of the gratings in the direction of its diffraction vector (the fringe scanning method) [1]. Phase tomography is attained by repeating the fringe scan at every angular position of sample rotation. It is clear that this approach is not suitable for high-speed imaging. We adopted the Fourier-transform method, in which the differential phase image is generated from a single moiré pattern. Then, the frame rate of the differential phase video can be the same as the camera frame rate. In order to apply the Fourier-transform method, carrier fringes must be introduced by inclining the gratings to each other about the optical axis [3]. The spatial resolution in the direction of the carrier fringe frequency is determined by the carrier fringe spacing, which was about 76 µm in the experiment of Fig. 2.

For the phase tomography measurements, a sample was rotated continuously and a video of the moiré pattern was recorded for several rotations, limited by the data storage capacity. A series of phase tomograms were reconstructed from the moiré patterns at angular positions of the sample rotation from $28.18^\circ \times n$ to $28.18^\circ \times n + 180^\circ$, where $n = 0, 1, 2, \cdots$. Thus, a video of phase tomograms (i.e., a four-dimensional phase tomogram) could be generated. In Fig. 2, four phase tomograms at 0, 2.31, 4.66, 7.01 s after the start of white SR irradiation are shown. The sample was some glue on the tip of a rod rotating with a speed of 2 rps on its axis. The tomograms revealed bubbles in the glue expanding by the white SR irradiation.

Use of a Talbot interferometer has thus enabled high-speed X-ray phase imaging and tomography with white SR. Image quality and time resolution can be improved by using a better X-ray image sensor and a suitable band-pass filter, such as a multilayer.

REFERENCES

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