Phase-contrast X-ray imaging system with sub-\(\text{mg/cm}^3\) density resolution

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Phase-contrast X-ray imaging system with sub-mg/cm$^3$ density resolution

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Abstract. We improved the mechanical stability of the optical components of a two-crystal X-ray interferometer used in a phase-contrast X-ray imaging system. A branch beamline was dedicated to the system to suppress the rotation caused by the thermal drift, and the feedback system for stabilizing the interferometer was renewed to speed up the feedback frequency. An interference pattern with 80% visibility was successfully generated using a 17.8-keV synchrotron X-ray. The mechanical stability of the optical components attained was 12 prad over 10 hours, and the rotational accuracy was less than 50 prad by using the new feedback systems. Fine observations of biomedical and organic material samples were successfully performed. We achieved a density resolution of the sectional image of about 0.3 mg/cm$^3$.

1. Introduction

A crystal X-ray interferometer [1] is a powerful optical device used for phase-sensitive X-ray imaging. Since the phase shift caused by the samples is directly detected by the superposition of waves, it can be measured more accurately than when using other optical devices such as an analyzer crystal or a Talbot (grating) interferometer, which detect the spatial gradient of the phase. Due to this advantage, X-ray interferometric imaging [2] has a higher density sensitivity [3] compared with that of other phase-sensitive methods such as diffraction enhanced imaging [4] (DEI) and grating interferometric imaging [5]. Therefore, it provides a way to perform detailed observations of samples mainly composed of light elements, such as biological soft tissues and organic materials without the use of any supplemental agents. A crystal X-ray interferometer requires mechanical stability of the order of an X-ray wavelength (about 0.1 nm) for its optical components. We have been developing an imaging system with highly stable positional tables for the separated two-crystal X-ray interferometer [6]. Our third-generation system attained a stability of 40 nrad for the positional table, and we were able to successfully generate a 60 x 40 mm interference pattern with 50% visibility. We used this system to conduct three-dimensional observations of cancerous tissues [7], which were the visualization of ß-amyloid plaques from the brains of model mice with Alzheimer’s disease [8], and the in vivo observation of cancer implanted in nude mice [9].

A more accurate and stable interferometer is required to make full use of the high-density resolution of the imaging method. We dedicated a branch beamline of the photon factory for the imaging system, renewed the interference-pattern-based feedback positioning system for stabilizing
the interferometer, and took steps to cope with the mechanical vibration from the immediate surroundings to increase the stability and usability of the imaging system. In this article, we will report on the high visibility interference pattern, the mechanical stability and accuracy of the positional table, and examples of detailed three-dimensional images of rat brain.

2. Imaging system fitted with a X-ray interferometer

The interferometer used in the imaging system consists of two crystal blocks containing two crystal wafers, as shown in Fig. 1 (a). The incident X-ray is divided into two beams by the X-ray diffraction of the Laue case at the first crystal wafer of the first block, and these two beams are reflected by the second wafer of the first block and the first wafer of the second block, respectively. The two beams are superimposed at the second wafer of the second crystal, and they generate two interference beams. This configuration has the great advantage that only one rotational movement between the crystal blocks is required to ensure sub-nano-radian accuracy. The relative rotation between the crystal blocks around the z-axis changes the optical path differences in the interferometer and causes the phase difference $d\phi$. The $d\phi$ is given by

$$d\phi = \frac{2\pi}{\lambda} (l+t)d\theta,$$

where $d\theta$ is the relative rotation between the blocks, $d$ is the lattice spacing of the diffraction, $l$ is the distance between the wafers on each block, and $t$ is the thickness of the crystal wafer [10]. In the case of the 17.8-keV X-ray and Si(220) diffraction ($d = 0.192$ nm), $d\theta$ must be stabilized to within 20 prad to attain a phase fluctuation of $\pi/20$ for an interferometer with $l = 200$ mm and $t = 1$ mm.

Fig. 1. (a) Schematic view of separated two-crystal X-ray interferometer and positional tables. (b) Interference pattern generated by upgraded imaging system. The best visibility amounted to 80%.

Our third-generation imaging system consisted of only three tables required to operate the interferometer: S1 for adjusting the interferometer under the Bragg condition against the incident X-rays and S2 and the tilt tables for tuning the $\theta$ and $\rho$ rotation between the crystal blocks, respectively. The S2 table was required to have extremely high rotational precision for interferometer operations. Therefore, a fine adjustment mechanism driven by a laminated piezoelectric actuator (PZT) with 10-picometer positioning precision was used, and a feedback system was integrated [7]. The feedback system (FS) controls the applied voltage to the PZT to cancel the movement of the fringe pattern in the interference image detected by an X-ray imager. The FS precisely suppresses the drift rotation, but the feedback frequency was reduced to 0.5 Hz.

To make full use of the high-density resolution of the imaging method, we upgraded the imaging system as follows to improve the mechanical stability and controllability of the X-ray interferometer. First, a downstream beamline of the tandem branch beamline (PF BL-14C) of the photon factory in Tsukuba was dedicated to the system, and the experimental hatch was altered to keep the imaging system in operating condition constantly. Second, an active mechanical isolator consisting of air suspension and a feedback system with laser positioning sensors with 100 nm accuracy was stationary.
operated to cut the vibration coming from the floor. Third, the feedback system was renewed to speed up the feedback frequency 0.5 Hz to 10 Hz. Fourth, to suppress the sound from the immediate surroundings, the wall of the hatch was soundproofed and the rigidity of the hatch was increased by adding girders. Based on this dedication, the transportation and setting up of the imaging system for every use became needless, and therefore the thermal fluctuation in the hatch was suppressed to within 0.1 degrees for 1 week by keeping the system in the hatch constantly. In addition, the crystal blocks were maintained in their optimum positions and angles to obtain the largest field of view and highest visibility.

3. Results and discussion

Figure 1(b) shows an interference pattern generated by the upgraded system. The size of the pattern was 43 x 35 mm, which was consistent with the designed size. The energy of the X-ray was set at 17.8 keV, and a CCD-based X-ray imager [11] was used to obtain the pattern at an exposure time of 3 s. The average visibility of the pattern increased to 70% from the previous visibility (60%), and the maximum visibility amounted to 80%, which was the same as that obtained using a monolithic X-ray interferometer. The fringes seen in the pattern were caused by the unevenness of the lattice spacing and/or the deformation of the crystal wafer.

The stability of the X-ray phase was measured under the operation of the FS. Figure 2(a) depicts a time chart of the X-ray phase calculated from the image obtained by the FS (black line) and the applied voltage to the PZT of the S2 table (gray line). The images in the chart show the interference patterns every 10,000 s. This result shows that the phase fluctuation was effectively suppressed by the changes in voltage over the 10 h period. The standard deviation of the phase fluctuation was \( \pi/50 \), which corresponds to a rotation of 12 prad of the S2 table in accordance with Eq. (1).

![Intference pattern](image1)

**Fig. 2.** (a) Chart over time of phase fluctuation and applied voltage to PZT. Images show interference pattern every 10000 s. (b) Chart over time of interference intensity of small area A in center of interference pattern. The target value of the FS changed from 0 to 2\( \pi \) rad in \( \pi/10 \) rad steps every 30 s.

Figure 2(b) shows a time chart of the interference intensity of a small area A in the center of the interference pattern. The target value of the FS changed from 0 to 2\( \pi \) rad in \( \pi/10 \) rad steps every 30 s. The result shows that the intensity was swept exactly at \( \pi/10 \) rad within a few seconds; therefore, the positional accuracy of the S2 table was 60 prad in accordance with Eq. (1).

Figure 3 shows the sectional and three-dimensional images of a mouse brain obtained by using phase-contrast CT. The measurement period was 8 h and the projection number was 500 over 360 degrees. The x-ray intensity in front of the samples was estimated to be about \( 1.4 \times 10^5 \) photons/mm\(^2\)/second. Inner structures such as the cerebral cortex, hippocampus, and striatum were depicted clearly without using any supplemental agents. Since the phase shift is approximately proportional to the mass density, the density resolution was estimated about 0.3 mg/cm\(^3\) from the standard deviation of the phase fluctuations (\( \Delta p \sim 4 \times 10^{-4} \) rad) in the outer area of the sample [12].
4. Summary

A 40 x 30 mm interference pattern with 80% visibility was generated by using the upgrade imaging system. The X-ray phase fluctuation was suppressed within a deviation of $\pi/60$ for 10 hours using the renewed feedback system. The deviation corresponds to 12 prad of the rotation between the separated crystal blocks of the interferometer. The X-ray phase was also swept at $\pi/10$ steps by rotating the positional table carrying the crystal blocks, and the rotational accuracy of the table was proved to be less than 60 prad. Fine two- and three-dimensional images of the mouse brain were obtained with a density resolution of 0.3 mg/cm$^3$.

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