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Operation of a Two-Crystal X-ray Interferometer at the Photon Factory

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A two-crystal X-ray interferometer for phase-contrast X-ray imaging is reported. Mechanical stability of less than 0.1 nm is required to operate the two-crystal interferometer. The feasibility of using such an interferometer at the Photon Factory using synchrotron radiation has been investigated. Interference fringes of 70% visibility were observed with 0.092 nm X-rays. This result indicates that the two-crystal X-ray interferometer can be applied to phase-contrast X-ray imaging.

Keywords: X-ray interferometers; phase contrast; imaging.

1. Introduction

X-ray interferometry is a unique technique which is currently available for phase-contrast X-ray imaging to reveal the structures inside biological soft tissues without staining and without causing serious radiation damage (Bonse & Hart, 1965; Ando & Hosoya, 1972; Momose & Fukuda, 1995). One of the present authors has studied phase-contrast X-ray imaging using an X-ray interferometer and carried out three-dimensional observations with phase-contrast X-ray computed tomography (Momose, 1995; Momose, Takeda & Itai, 1995; Momose, Takeda, Itai & Hirano, 1996*a*,*b*). As a next step we have attempted *in vivo* observation using X-ray phase contrast. However, the size of the field of view in the previous studies was about 5 mm. For *in-vivo* observation a field of view of a few tens of millimetres is desired.

The X-ray interferometer used in our previous experiments was a typical triple Laue type (Bonse & Hart, 1965), which was monolithically cut out from a perfect silicon crystal ingot. The maximum size of the monolithic X-ray interferometer is limited by the diameter of the silicon ingot from which the interferometer is cut. Alternatively, two-crystal X-ray interferometers (Bonse & te Kaat, 1968; Becker & Bonse, 1974) have been successfully operated. Becker & Bonse's, in particular, is available for imaging applications, because the spacing between the crystal blocks can be selected depending on the size of the samples (Fig. 1).

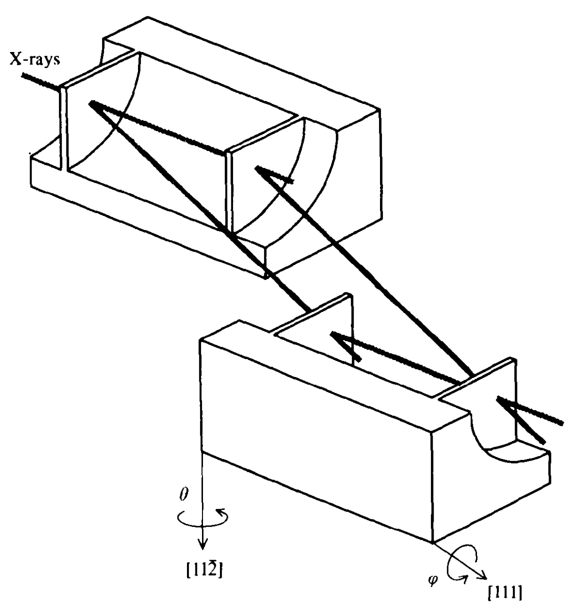

Figure 1
Two-crystal X-ray interferometer. The thickness of the wafers was 1 mm, and the spacing between them was 34.5 mm. Side facets of the crystal blocks were polished and used for pre-alignment.

Because we aim at phase-contrast imaging with a practical exposure time, using a synchrotron radiation source is desirable. Bonse & te Kaat's (1968) type has been operated using synchrotron X-rays for spectroscopic purposes (Begum, Hart, Lea & Siddons, 1986). However, no two-crystal X-ray interferometer has been operated for imaging at any synchrotron facilities, as far as we know.

Therefore, the purpose of this paper is to demonstrate that the two-crystal X-ray interferometer shown in Fig. 1 functions for imaging using synchrotron X-rays. We will present the first interference pattern obtained using synchrotron X-rays at the Photon Factory.

2. Experiment and result

Using a two-crystal X-ray interferometer means that we have to give up the advantage of the monolithic X-ray interferometer in which the X-ray beam paths do not vary mechanically. Therefore, a stage is needed to arrange the two blocks so as to satisfy the condition of interference. Of course, one must be prepared for vibration and temperature drift.

The two-crystal X-ray interferometer shown in Fig. 1 has the advantage that interference is not affected by the relative linear displacement between the blocks. Only the relative rotation around the θ and φ axes shown in Fig. 1 should be tuned. When the φ axis is detuned, a Moiré pattern appears (Becker & Bonse, 1974). However, using a synchrotron source the typical fringe spacing is a few millimeters for $\Delta\varphi = 10''$. Therefore, it is comparatively easy to tune the φ axis.

The θ axis is more important in generating interference, because θ rotation means displacement of the wafer, which functions as an X-ray half mirror, in the direction of the diffraction vector against the other wafer on the same block. One suffers a nominal phase change of 2π when the displacement distance is equivalent to the Bragg plane spacing. Therefore, rotation stability less than the distance of the displacement equivalent to the Bragg plane spacing is required to operate the two-crystal X-ray interferometer. Otherwise, interference fringes sway or smear out.

We have developed a stage for tuning the φ and θ axes, which were driven with piezoelectric translators. The element for θ rotation was fabricated in a monolithic flexure hinge structure. The element for φ rotation was a simple tilt stage and was mounted on the fixed part of the element for θ rotation.

Preliminary alignment of the two-crystal interferometer was important because the angular range in which an interference pattern appeared was narrow. We pre-aligned the two blocks, whose shape was fabricated to be identical, by making the corresponding facets of the blocks parallel to each other using an autocollimator.

To reduce the effect of vibrations the apparatus was mounted on a base with pneumatic suspension. In addition, the X-ray interferometer was covered with a hood to prevent temperature drift due to air flow around the interferometer.

Fig. 2 shows an interference pattern observed with the two-crystal X-ray interferometer at station BL-14B of the Photon Factory, where X-rays from a vertical wiggler were available. We used 0.092 nm X-rays with the 220 reflection. The exposure time was 4 s with an X-ray sensing pick-up tube (Suzuki *et al.*, 1989).

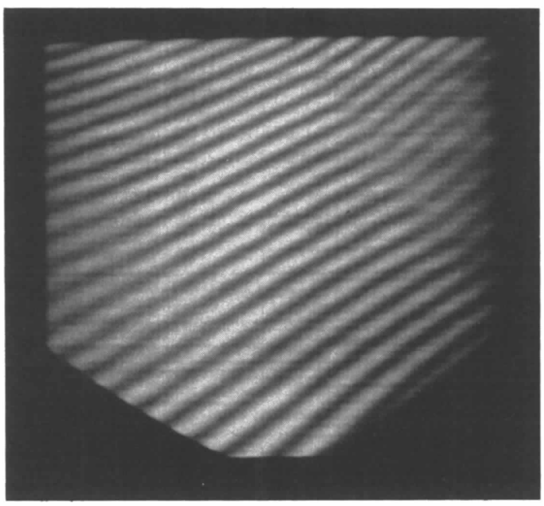

Figure 2
Interference pattern obtained with the two-crystal X-ray interferometer. The fringe spacing was about 0.5 mm. The fringe visibility was 70%.

No object was placed in the beam paths. Therefore, the fringes were caused by deformation of the interferometer and/or lattice strain in silicon crystal. In addition, the misalignment around the φ axis was affected. However, the fringe visibility was 70%, which is enough for fringe analysis in phase-contrast X-ray imaging (*e.g.* Momose *et al.*, 1996*a*).

3. Conclusions

We obtained an X-ray interference pattern using a two-crystal X-ray interferometer for the first time using synchrotron X-rays. With several seconds of exposure, clear fringes of 70% visibility were obtained. This indicates that separate-type X-ray interferometers can be used for phase-contrast X-ray imaging with practical exposure times. Biological and medical imaging, especially *in vivo*, will therefore become available.

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