X-ray Interferometry Development at the Advanced Photon Source*

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Abstract. In this paper, we report initial test results of a four-bounce Bragg reflection X-ray interferometer at 7.46 keV and, for the first time to our knowledge, at the higher energy of 14.91 keV where the spectral acceptance is much smaller.

INTRODUCTION

The triple Laue (LLL) interferometer is one of the most used X-ray interferometers, be it in ultra-precision metrology¹ or in imaging techniques². The advantage of the LLL interferometer is that it can be used within a wide range of energy and is easy to manufacture when compared to other interferometer types. As a first attempt into x-ray interferometry, we have tested a triple Laue interferometer and measured contrasts better than about 90% when sliding a plastic wedge into one of the two interfering beam paths.

However, the Laue transmission geometry has two drawbacks: (1) absorption losses in each of the blades, and (2) loss of spatial resolution due to the Borrmann broadening in the last blade. These two disadvantages can be overcome by using all Bragg reflection interferometers.

One such design was proposed by Graeff and Bonse³. The main idea was to simultaneously excite two complementary (Si(440) and Si(404)) atomic planes in Bragg geometry to split the beam and gather them again after several Bragg reflections (Fig. 1). The built-in spectral window of such a dispersive device is extremely narrow (compared with the LLL) and it only works at a particular wavelength. This makes it relatively difficult to operate and puts stringent requirements on the crystal.

Graeff and Bonse³ first successfully tested this three-beam interferometer using an X-ray tube (near Ni $K\alpha_2$, 48 hour exposure time). Later, they tested it again at a synchrotron and obtained about 70% contrast with a wedge. The nominal wavelength for this interferometer is $\lambda = 1.66276 \text{ \AA}$, with a corresponding interferometer transmission range $\Delta\lambda/\lambda \sim 4 \cdot 10^{-6}$ for π polarization. The original Graeff-Bonse interferometer incorporated several weak links in the monolith so that one part of the monolith could be translated with respect to the other, thereby introducing micron-range path length differences between the two paths.

As a first attempt with this type of interferometer, we fabricated a simplified version with no movable parts. The crystal, shown in Figure 1, was made of a single block of high-quality float-zone silicon.

We report in this paper the initial test results of this interferometer at 7.46 keV, as well as, for the first time to our knowledge, at the higher energy of 14.91 keV (using the Si(880) and Si(808) reflections) where the spectral acceptance is about an order of magnitude smaller.

FIGURE 1. Four Bragg reflection (BBBB) interferometer geometry (left) and the actual silicon crystal (right).

MEASUREMENTS AT 7.46 keV - Si(440)/Si(404)

The interferometer was tested on the SRI-CAT 1-ID beamline at the Advanced Photon Source (APS). A double-crystal monochromator, which diffracts vertically with Si(111) crystals, was upstream of the interferometer. The interferometer itself diffracts in the horizontal (electron orbit) plane and is housed in a Plexiglas box to minimize air-flow-induced instabilities. For an incoming photon rate from the monochromator of about 10^{13} ph/s, the transmitted rate was about 10^8 - 10^9 ph/s.

Figure 2 shows the setup used to measure the contrast obtained through a 50 μm aperture in front of an ionization chamber detector, while sliding a 4° plastic wedge in one arm of the interferometer. A thin piece of plastic attenuator in the other arm compensates for the absorption loss through the wedge.

FIGURE 2. Wedge contrast setup top view (left) and the fringes obtained with the wedge (right).

The measured contrast was about 93%. The small increase in the contrast (Fig. 2) at larger wedge translation—where the wedge becomes thinner—is an absorption effect. The contrast reaches its peak when the two interfering beams have equal amplitudes.

The crystal contains residual strains, either from the fabrication process or slight imperfections in the silicon material itself. This results in Moiré fringes in the transmitted beam, as shown in Figure 3. The interfringe distance indicates an angular mismatch of 2 arc seconds. The setup to take this picture is also shown in Figure 3.

FIGURE 3. Moiré fringes recorded on a Polaroid film at 7.46 keV (left) and the setup used (right).

PHASE CONTRAST IMAGING

Using a nonabsorbing sample of animal cancer cells deposited on a thin plastic film, phase contrast images were obtained (Fig. 4). With minor changes in the setup, three methods of phase contrast imaging techniques^{2,4,5} were used. The arrows in the images point to the same details in the sample.

The first type of phase contrast image is a Fresnel (or propagation) image⁴, when the sample is *downstream* of the crystal (Fig. 4a) with the CCD camera at 30 cm from the sample. Here, the interferometer is irrelevant, and only the lateral coherence of the beam matters. Fresnel images are sensitive to sharp phase jumps, and the edges are well enhanced. These enhancements come from the interference between the distorted and undistorted wave-fronts (assuming a plane wave) at the edge of a phase object.

The second type of phase contrast image is an angle-resolved or differential phase image⁵. The sample is placed in one arm of the interferometer, while the other arm is blocked (Fig. 4b). A phase gradient across a wave-front is equivalent to a change in the local propagation direction of the wave⁶. Thus, using a crystal reflection as an angular analyzer, one can detect the small angular deviations of the beam and, thus, detect the edges of the phase object (or location of the phase jumps). In the

interferometer, the reflections after the sample act as such angle analyzers. The contrast in the cells is in the horizontal plane, which is the diffraction plane of the setup.

FIGURE 4. Phase contrast images of animal cancer cells deposited a thin plastic film. (a) Fresnel imaging and setup. (b) Angular-resolved imaging and setup (c) Holographic imaging and setup.

The third type of phase contrast image (Fig. 4c) corresponds to a pure phase or a holographic image, where interference occurs between an object and a reference beam. When a point-to-point interference occurs between an object wave going

through the sample and a reference wave, the contrast is due only to the local optical thickness of the sample. The dark horizontal strip in this image is a Moiré fringe. Unlike the previous two techniques, this method of phase contrast is sensitive to *all* phase changes and not just to sharp phase jumps (edge detection). Thus, smooth changes in phase can be detected. Although the quality of the above images is not great, they provide a qualitative comparison of the different methods of phase contrast imaging.

MEASUREMENTS AT 14.91 keV - Si(880)/Si(808)

Although this interferometer was originally designed to work at 7.46 keV using Si(440)/Si(404) reflections, it is sometimes useful to be able to work at a higher energy. The ratio between the sensitivity of phase contrast and absorption is proportional to the X-ray energy, and beam-path absorption (air) losses are smaller for higher energy. Thus, we proceeded to test the interferometer at 14.91 keV, using the Si(880)/Si(808) reflections.

FIGURE 5. (a) Crystal Moiré Fringes at 15 keV. (b) The same Moiré fringes with a plastic wedge halfway into one beam.

At this higher order reflection, the interferometer spectral transmission is about $\Delta\lambda/\lambda \sim 2 \times 10^{-7}$. For an incoming photon count rate (14.91 keV) of about 10^{13} ph/s, the transmitted count rate was about 10^7 ph/s. Figure 7a shows a Moiré pattern at 14.91 keV, from the Si(880)/Si(808) reflections using dental film. In Figure 5b, we inserted an 8° plastic wedge to cover half of one of the arms of the interferometer. The resulting effect of this linear phase gradient is a tilt of the fringes, which confirms that Moiré pattern is indeed a two-beam interference effect. No fringes were seen with one arm of the interferometer blocked.

CONCLUSION

The use of only external Bragg-reflected beams, like in the BBBB interferometer, allows for less absorption loss and higher spatial resolution than the transmission setups (useful for imaging). We have started using asymmetric crystals to enlarge the usable beam size over several millimeters (~ 10 mm) for large samples. High contrast Moiré patterns over the whole expanded beam have been obtained. With new crystals and design, we hope to reduce the residual strain of the interferometer so as to avoid the Moiré pattern and obtain a clean and flat field of view.

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