Initial Results on the Feasibility of Hybrid X-Ray Microscopy

P. K. Tseng, W. F. Pong, C. L. Chang, C. P. Hsu, F. Y. Lin, C. S. Hwang, and H. S. Sheu

Physics Department, Tamkang University, Tamsui, Taiwan, ROC
National Synchrotron Research Center, Hsinchu, Taiwan, ROC

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This study presents a hybrid X-ray microscope that magnifies an X-ray image using a group of asymmetrically cut crystals and an X-ray phase contrast imaging system. An asymmetrically cut crystal is inserted between the sample and a CCD-fluorescence assembly. The experimental results demonstrate that the phase contrast image is preserved. This system can be improved using a better diffraction crystal.

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I. INTRODUCTION

When a coherent X-ray passes through a sample, a phase contrast image that consists of fringes at every boundary of the various media is produced. Such a system can be used to observe a thin sample which would otherwise be difficult to observe, because the absorption differences among the various media are small. The image produced by such a system is called an X-ray phase contrast image (XPCI). XPCI experiments have been performed using sophisticated X-ray-optics to ensure coherency [1, 2]. However, if the X-ray source is very small, the X-rays become coherent [3]. The third-generation synchrotron radiation facility is an ideal X-ray source for an XPCI. It can be operated using a simple set up, as shown in Fig. 1 [4].

A synchrotron radiation beam is directly passed through the sample, and a single crystal fluorescence-screen at some distance from the sample transforms the X-rays into a visible light image. The visible pattern on the screen is observed through a microscope or a microscope objective connected to a CCD camera. The basic limitation of this method

FIG. 1: Schematic diagram of a simple set up for an X-ray phase contrast image microscope.
II. PROPOSED HYBRID X-RAY MICROSCOPE

An asymmetrically cut crystal is used to widen the X-ray beam that has passed through the sample, thus overcoming the small photon beam size limitation. Accordingly, the original X-ray phase-contrast pattern is enlarged before it is converted to visible light by the fluorescent screen. Let the lattice constant of the crystal be $d$ and the miss-cut angle with respect to the diffraction lattice plane be $\theta_M$. The Bragg angle is $\theta_B$. The width of the incoming X-ray beam is $W_{in}$, and that of the outgoing beam is $W_{out}$, as shown in Fig. 2. The relationship between $W_{in}$ and $W_{out}$ is

$$W_{out} = W_{in} \frac{\sin(\theta_B + \theta_M)}{\sin(\theta_B - \theta_M)}.$$  

Therefore, the original X-ray phase contrast pattern is enlarged (in one direction) before it is converted into visible light by the fluorescent screen. Another asymmetrically cut diffraction crystal pair is oriented with respect to the original amplification direction and the incoming X-ray beam as shown in Fig. 3, to amplify the X-ray phase contrasted pattern uniformly (in every direction).

In Fig. 3, one asymmetrically cut crystal and one normal crystal (or another asymmetrically cut crystal) are used as a double crystal monochromater (DCM) arrangement to keep the X-ray beam parallel to the incoming synchrotron radiation. Fig. 3 presents a horizontal view and a schematic vertical diagram of this idea. The microscope is called a hybrid X-ray microscope (HXM) because it depends on two magnification principles.

These amplification mechanisms and their limitations must be considered more carefully to demonstrate experimentally the feasibility of the hybrid X-ray microscope. Every set up should meet the following criteria.

FIG. 2: Schematic diagram of the Bragg diffraction by a mis-cut crystal.

is the same as that of an optical microscope.
FIG. 3: Hybrid X-ray microscope using X-ray phase contrast imaging and asymmetric refraction.

1. X-ray intensity. If the magnified factor is $M$, the flux of the incoming X-ray is $L_0$, equivalent to illuminating the magnified pattern with a flux of $(L_0 M)^2$. Therefore the luminosity of the synchrotron radiation source must exceed $L_{\text{Min}}$, where $L_{\text{Min}}$ is the minimum luminosity required when the X-ray illuminates the object. The transmitted pattern can then be directly observed (by the same method).

2. Notably, the visibility of the phase contrast image is limited by the noise of the detector-CCD.

3. The incoming x-ray must be coherent to produce a phase-contrasted image. The synchrotron radiation becomes coherent if the electron beam diameter is small [5]. The light from the third-generation synchrotron radiation facility can become coherent if the source is of limited beam size, as indicated by the emittance of the storage ring.

4. As the emittance increases, the synchrotron becomes partially coherent. The phase contrast curve in the X-ray image gradually disappears. It is important to find the extent of the partial coherency of the small third generation ring, like NSRRC.

5. If the diffraction crystal is perfect, then the phase of the diffracted beam would be preserved. The hybrid microscope would work well in such a case. In the real world, it is very difficult to produce such a perfect crystal especially after asymmetric cutting. In general, the available single crystals have a more or less mosaic structure.
III. EXPERIMENTAL RESULTS

We carefully choose a reasonably good quality area in the asymmetric cut crystal, so as to diffract the X-ray wave without changing its phase. An experiment is performed to determine whether the image is diffracted with its phase contrast fringes. The photon flux in the proposed SR source, which is a 1.5 GeV storage ring (at a maximum electron current of 200 mA), is too weak to generate a magnified image by asymmetric diffraction, so a reverse experiment is designed to test the idea. An asymmetric crystal (Si(111)) (2000 ohm-cm) is oriented in a reverse way as shown in Fig. 4. A white synchrotron radiation beam is incident, and the cross section of the diffracted beam in only one direction becomes small.

In the proposed experimental setup, the miss-cut angle is about 10 degree. The orientation of the crystal is fixed at approximately 13.3 degrees so the angle of the diffracted beam is 26.6 degrees (This angle is used because the intensity of the diffracted monochromatic X-ray from the source is maximal and $\tan(2\theta) = 0.5$).

The diffracted monochromatic beam is extremely weak. Therefore, a cooled CCD detector with an exposure time of at least 10 minutes must be used. The best image is obtained by extending the exposure time from 10 minutes to as much as one hour. The characteristics of the phase-contrasted image are exploited to determine whether the phase of the diffracted beam can be retained. The phase-contrast curves become thicker as the distance from the sample to the fluorescent screen increases.

IV. DISCUSSION

Fig. 5(a) depicts the sample source used in this experiment, which is an insect-entrapped in Baltic amber. After the X-ray microscope is de-magnified (or squeezed) by asymmetric diffraction, it becomes thin in the X-direction, as displayed in Fig. 5(b). Phase-contrast curves appear in every boundary as ordinary phase contrast images. The factor
FIG. 5: (a) Image of an insect in amber obtained by ordinary X-ray phase contrast microscopy. This mosquito-like insect, entrapped in Baltic amber, is used as the sample for asymmetrically cut diffraction imaging. (b) Image of the insect in Fig. 5(a) after the SR light passes through the insect and is diffracted by an asymmetrically cut crystal. (c) Simulated image of a mosquito-like insect after asymmetric refraction. Fig. 5(b) is demagnified only in the X-direction.

The distance from the sample to the fluorescent crystal is changed from the minimum (30 cm) to 65 cm in steps of 5 cm to demonstrate that the dark curves came from the phase contrast image. Fig. 6 displays the results. The curves of the boundaries obtained by phase contrast imaging became broadened as the distance from the sample to the fluorescent crystal increased. This agrees qualitatively well with the figures.

Only a small part of each image (the left half of the head of the insect) is enlarged. Fig. 7 depicts this image for comparison. This picture clarifies the change in the thickness of the boundary curves. However the comparison of the experimental results (Figs. 5 and 6) and the simulated asymmetric diffraction reveals that some fine phase contrast fringes are absent from the experimental results. The authors think that the diffraction surface was not sufficiently flat and the crystal used herein was not sufficiently perfect to yield the expected detailed structure. Perhaps the intensity of the diffracted beam was too weak and buried by noise. The surface of the diffraction crystal has been etched extensively so the original surface could not be observed before etching. We also believe that single crystal grains were exposed on the diffraction surface. We are trying now to improve the crystal and develop new surface processes.
FIG. 6: Series of X-ray phase contrast images obtained by changing the distance between the sample and the fluorescent crystal from 30 (left most picture) to 65 cm (in steps 5 cm). The phase contrast-boundary-curves of each figure become thicker in the right of pictures.

FIG. 7: The left half of the head of the insect shown in Fig. 6 is enlarged and the images are shown together for comparison.

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References

When the dimensions of the light source are small, the emitted light will become (transversal) coherent. This fact was known when Young demonstrated his interference of light experiment. This is also true for synchrotron radiation.