PHASE IMAGING WITH AN X-RAY TALBOT INTERFEROMETER

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ABSTRACT

X-ray Talbot interferometry (XTI) is described as a novel phase-sensitive X-ray imaging method. XTI uses two transmission gratings, and therefore in principle it functions with cone-beam X-rays of a broad energy bandwidth, allowing its instrumentation with a compact X-ray source. Because an amplitude transmission grating is needed, X-ray lithography and electrochemical gold plating were employed to fabricate a high-aspect-ratio pattern. The performance of the phase imaging with XTI was tested using synchrotron radiation, and its high sensitivity was demonstrated by the observation of biological tissues.

INTRODUCTION

Since the middle of the 90’s, X-ray phase-sensitive imaging, including phase tomography, has attracted attention, because the sensitivity in X-ray transmission imaging is much improved, compared with that of the conventional method that relies on absorption for contrast generation.1) In order to generate a contrast depending on the shift of X-ray phase caused by an object, several techniques have been developed so far.2-4) A crystal X-ray interferometer5) was first used in this field,2) and another method using crystals was also proposed to select refracted X-rays.3) Because the methods use crystal optics under the Bragg diffraction condition, monochromatic X-ray plane wave is needed. Bright X-ray source is therefore necessary and, as a matter of fact, synchrotron radiation is used to record an image with a practical exposure time. Another method4) uses no optics provided that X-ray spatial coherence is sufficiently high. In this case, contrast is generated by Fresnel diffraction, and the contrast outlines the surface of an object and structural boundaries in it. Normally, the width of the outlines is several microns, and therefore a high resolution image detector is preferred to resolve them. This implies that sufficient flux is needed into a small pixel. Bright X-ray source such as synchrotron radiation is therefore mainly used. Although an exception, which has been commercialized in Japan, used an image detector with a pixel larger than ten microns,6) the contribution of the X-ray phase contrast...
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The high sensitivity of X-ray phase-sensitive methods, which is potentially a thousand times larger than that of absorption-contrast methods, has been well demonstrated so far using synchrotron radiation. However, their practical applications are not progressing. This is because the instrumentation of X-ray phase-sensitive technique with a compact X-ray source is not as easy as with synchrotron radiation sources.

In order to avoid the drawback of the crystal X-ray optics, grating optics is attractive. We have proposed X-ray Talbot interferometry (XTI), which uses two transmission gratings and generates a contrast based on the Talbot effect, as a novel phase-sensitive imaging. Phase tomography is also attained with XTI. XTI functions with a cone beam of a broad energy band, and therefore is compatible with a compact X-ray source. In addition, an X-ray image detector with a spatial resolution as high as that required in the outline-contrast detection is not necessary. A problem to be resolved to construct an X-ray Talbot interferometer is the fabrication of an X-ray grating with a high aspect ratio. For this purpose, we used X-ray lithography and electrochemical gold plating.

First, the principle of XTI is described, and then imaging results with XTI, which was preliminarily carried out using synchrotron radiation, are presented. Finally, we discuss the prospects of XTI for practical applications.

**PRINCIPLE**

**X-ray Talbot Interferometry**

XTI is based on the Talbot effect in the X-ray region, which is known as a self-imaging effect observed away from an object with a periodic structure, such as a grating, under coherent illumination. For an amplitude grating, self-images are generated at $z = 0, \frac{d^2}{2\lambda}, \frac{d^2}{\lambda}, \frac{3d^2}{2\lambda}, \frac{2d^2}{\lambda}, \frac{5d^2}{2\lambda}$, and so on, where $d$ and $\lambda$ are the period of the grating and wavelength, respectively. For a phase grating, similar patterns are observed at intermediate positions.

![Illustration showing the Talbot effect in the case of plane-wave illumination. For an amplitude grating, self-images are generated at $z = 0, \frac{d^2}{2\lambda}, \frac{d^2}{\lambda}, \frac{3d^2}{2\lambda}, \frac{2d^2}{\lambda}, \frac{5d^2}{2\lambda}$, and so on, where $d$ and $\lambda$ are the period of the grating and wavelength, respectively. For a phase grating, similar patterns are observed at intermediate positions.](image)
illumination. The distances $z_T$ between the object and self-imaging planes are determined by the light wavelength $\lambda$ and the period $d$ of the structure as shown in Fig. 1. When an amplitude grating is coherently illuminated, $z_T = pd^2/\lambda$, where $p$ is an integer. On the other hand, for a phase grating, no intensity contrast is generated at the positions given above. However, at the intermediate positions, $z_T = (p + \frac{1}{2})d^2/\lambda$, periodic patterns are observed, which we consider as self-images of the phase grating. This self-image phenomenon is understood as a result of Fresnel diffraction or multi-beam interference between diffraction orders caused by a grating. Giving the complex transmission function $T(x, y)$ of a grating with a Fourier series expansion as

$$T(x, y) = \sum_n a_n \exp\left(2\pi i \frac{nx}{d}\right),$$  \hspace{1cm} (1)

where a periodic structure is made along the $x$-axis. Assuming unit-amplitude monochromatic plane-wave illumination, the field $E(x, y, z)$ behind the grating is given by

$$E(x, y, z) = \sum_n a_n \exp\left(-\pi i \frac{n^2\lambda z}{d^2}\right) \exp\left(2\pi i \frac{nx}{d}\right),$$  \hspace{1cm} (2)

with paraxial approximation. Thus, it can be understood that the wave field becomes similar to $T(x, y)$ at the specific distances ($z = z_T$).

Here, let's consider a case that the wavefront incident to the grating is deformed for instance due to the phase shift, or refraction, at an object placed in front of the grating as shown in Fig. 2. Then, $E(x,y,z)$ is correspondingly deformed as

$$E(x, y, z) = \sum_n a_n \exp\left(-\pi i \frac{n^2\lambda z}{d^2}\right) \exp\left(2\pi i \frac{nx}{d}(x - z\varphi_z(x, y))\right),$$  \hspace{1cm} (3)

where

$$\varphi_z(x, y) = \frac{\lambda}{2\pi} \frac{\partial \Phi(x, y)}{\partial x}$$  \hspace{1cm} (4)

is the angle of beam deflection in the $x$ direction induced by the phase shift $\Phi(x, y)$. Thus, if the deformed self-image is detected and analyzed, one can retrieve the wavefront incident upon the grating. However, the period $d$ is normally too small to resolve with a conventional image detector. Therefore, XTI uses another grating at the position of the self-image as shown in Fig. 3.
Then, moiré fringes are observed by the superposition of the grating, which should be an amplitude one, on the deformed self-image. Assuming that the gratings have symmetric structures, the moiré pattern \( I(x, y, z) \) is given by

\[
I(x, y, z) = b_0(z)c_0 + 2 \sum_{n \neq 1} b_n(z)c_n \cos \left[ \frac{2\pi n}{d} \left( y\theta + z\varphi_s(x, y) + \chi \right) \right],
\]

where \( b_n(z) \) and \( c_n \) are the \( n \)th Fourier coefficients of the self-image of the first grating and the intensity transmission function of the second grating, respectively. \( \theta \) (\( \ll 1 \)) is the inclination angle between the gratings about the \( z \) axis, and \( \chi \) is the displacement of one grating against the other in the \( x \) direction.

**Phase Measurement**

For quantitative understanding, it is preferable to be able to obtain \( \phi_s(x, y) \) by measuring the moiré pattern. We applied the technique of phase-shifting interferometry for that purpose as described below.

After multiple images are acquired by changing the displacement \( \chi \) with a constant step of \( d/M \) (\( M \): integer), we calculate

\[
\arg \left[ \sum_{k=1}^{M} I_k(x, y, z) \exp \left( -\frac{2\pi ik}{M} \right) \right] = \arg \left[ \sum_{n} b_n(z)c_n C_{n,M} \exp \left[ \frac{2\pi i}{d} \left( y\theta + z\varphi_s(x, y) \right) \right] \right], \quad (M \geq 3)
\]

where \( I_k(x, y, z) \) is a moiré pattern measured when \( \chi = kd/M \). \( C_{n,M} \) is defined by

\[
C_{n,M} = \sum_{k=1}^{M} \exp \left[ \frac{2\pi i}{M} (n-1) \right] = \begin{cases} M & \text{when } n-1 = qM \quad (q : \text{integer}) \\ 0 & \text{otherwise} \end{cases}
\]

If higher orders (\( n \geq 2 \)) are negligible, eq. (6) reduces to

\[
\arg \left[ \sum_{k=1}^{M} I_k(x, y, z) \exp \left( -\frac{2\pi ik}{M} \right) \right] = \frac{2\pi}{d} \left\{ y\theta + z\varphi_s(x, y) \right\},
\]

as in the case of two-beam interferometry.
We consequently could use eq. (8) because of the fact supporting its validity, as described below. As indicated by eq. (7), some higher orders do not cause systematic errors depending on \( M \) even when \( b_n(z)c_n \) in eq. (6) have non-zero values.\(^{14} \) The conditions are listed in Table 1. If \( M = 3 \), the lowest order that will cause a systematic error is 2. However, since even orders can be ignored if the gratings have 1:1 line-and-space (L&S) patterns, fifth order is the lowest one. It is notable that \( M = 5 \) is a suitable choice because the lowest order that will cause a systematic error is 9, the magnitude of which is normally very small.

In addition, actual grating patterns are not completely rectangular and the spatial coherency of X-rays that impinge on the gratings is normally incomplete. These factors decrease higher orders and contribute to reducing errors in obtaining \( \phi(x, y) \) with eq. (8).

When a sample is placed and rotated in front of the first grating, phase tomography can be performed using the technique described above. \( \phi(x, y) \) caused by the sample can be obtained by the subtraction procedure between two data measured with and without the sample. Then, the phase shift caused by the sample \( \Phi(x, y) \) can be calculated by integration as indicated by eq. (4).

\[
\Phi(x, y) = \frac{2\pi}{\lambda} \int \delta(x, y, z) dz. \tag{9}
\]

Therefore, one can reconstruct \( \delta(x, y, z) \) from the \( \Phi(x, y) \), which is called X-ray phase tomography.

### EXPERIMENTAL RESULTS

**Gratings**

As mentioned, the second grating should be an amplitude grating. Therefore, the grating pattern should be sufficiently thick so that X-ray amplitude, or intensity, is modulated fully. We selected gold as a material for the grating pattern because its absorption coefficient is comparatively large. Nevertheless, the thickness should be more than a few tens of microns. As for the grating period, it should be smaller than or comparable to

![Fig. 4 Image of scanning electron microscopy (SEM) of the amplitude grating fabricated by X-ray lithography and electrochemical plating of gold.](image-url)
the X-ray spatial coherence length, which is several microns typically, and as a result a pattern of a high aspect ratio must be fabricated.

Conventional lithographic techniques do not meet this demand, and therefore we applied X-ray lithography. The synchrotron radiation beamline 11 of NewSUBARU, Japan, which is dedicated to LIGA (Lithographie Galvaniformung Abformung) process fabrication, was used. A 30-µm X-ray resist film (MAX001, Nagase Chemtex Co., LTD) was spin-coated on a 200-µm Si wafer with a 0.25-µm Ti layer, and then a 4-µm L&S resist pattern \((d = 8 \mu m)\) was fabricated by X-ray exposure. Finally, Au lines were formed by electrochemical plating between the resist lines, which were retained after the plating to support the Au lines (Fig. 4). The height of the Au lines was nearly 30 µm, and the effective area of the grating was 20 mm × 20 mm.

The first grating for XTI also had a gold pattern, but its thickness was much thinner than that of the second. The thickness was experimentally evaluated to be optimal for X-rays around 0.65 Å as a \(\pi/2\) phase grating.

**Performance of XTI**

An X-ray Talbot interferometer was arranged at the beamline 20XU of SPring-8, Japan, where

![Visibility of moiré fringes as a function of X-ray wavelength. The distance between the gratings was set to be \(d^2/2\lambda\).](image)

![Figure 5](image)

**Fig. 5** Moiré patterns and their fringe visibilities observed with 0.65-Å X-rays varying the distance between the gratings.

![Visibility](image)

**Fig. 6** Visibility of moiré fringes as a function of X-ray wavelength. The distance between the gratings was set to be \(d^2/2\lambda\).
undulator X-rays were available at 245 m from the source point. Figure 5 shows moiré patterns observed with 0.65-Å X-rays with their visibilities as a function of the distance between the gratings. The moiré fringes were generated by setting $\theta = 1.3^\circ$. At $z = d^2/2\lambda$, which was the best position for XTI with a $\pi/2$ phase grating, the fringe visibility exceeded 0.8. Increasing the distance, the visibility minimized at $z \approx d^2/\lambda$ and again increased, indicating that this phenomenon occurred by the Talbot effect.

The Fourier-transform of the moiré pattern at the best condition is also shown in Fig. 5. Spots of 0th, 1st, and 3rd orders existed, and higher orders and even orders were not detected. This result assured that our selection of 5 for $M$ was reasonable for the experiments of phase tomography presented below.

Next, keeping the condition $z = d^2/2\lambda$, the visibility was plotted as a function of $\lambda$ (Fig. 6). This result shows that the Talbot interferometer functioned in a wide energy range; the visibility was over 0.3 even at 0.4 Å.

**Phase tomography**

The X-ray Talbot interferometer was used for the tomographic observation of biological soft tissues. A sample was fixed on the tip of a rotation rod and immersed in formalin filled in a cell. The measurement of $\phi_x(x, y)$ was repeated at each angular position of sample rotation with a step of 0.72° over 180°. Images were recorded with a CCD-based X-ray image detector whose effective pixel size was 4.34 µm.

A piece of rabbit liver with cancer (VX2) was first observed with 1.0-Å X-rays. Cancerous lesion depicted with a lower grayscale value was clearly differentiated from a normal tissue as shown in Fig. 7. Furthermore, the bright area seen in the cancerous lesion was necrosis. This feature is comparable to the observation result by phase tomography using a crystal X-ray interferometer.
Because the X-ray Talbot interferometer functioned with 0.4-Å X-rays as suggested by Fig. 6, a mouse tail containing a bone was observed at this wavelength (Fig. 8). The advantage of using higher-energy X-rays is that not only soft tissues but also cartilage and bone are imaged in the same view, while a bone generates a more marked phase change at its surface in the lower energy region, causing errors in the measurement of \( \Phi(x, y) \). As shown in Fig. 8, soft-tissue structures are depicted with a cartilage (intervertebral disc) and a bone in the same tomogram.

**DISCUSSIONS**

**Performance of XTI**

Phase tomograms map the refractive index difference in samples. The detection limit of the refractive index difference was estimated by the standard deviation in a uniform area of a tomogram; the standard deviation of the surrounding formalin region of the tomogram shown in Fig. 7 was calculated to be \( 1.5 \times 10^{-9} \). Because the refractive index difference is approximately proportional to the mass density, the standard deviation can be converted to the detection limit of density variation, which is calculated to be 1.0 mg/cm\(^3\) because the refractive index of water is 1 - \( 1.5 \times 10^{-6} \) for 1.0-Å X-rays. This is comparable to the value attainable by the phase tomography with a crystal X-ray interferometer. Because roughly 1% of X-rays incident to the crystal X-ray interferometer contribute to interference and impinge on a sample, the X-ray dose on the sample is much lower than that by XTI. However, under the comparison on the assumption of the same X-ray source, XTI rivals the crystal X-ray interferometry for the samples, such as polymer materials,\(^{17}\) to which the radiation damage is not as crucial as to biological samples.

The spatial resolution is limited by the period of the grating in principle. We evaluated the resolution by the full width at half maximum (FWHM) of the differential contrast profile across the sample surface of the tomogram. From Figs. 7 and 8, 14 \( \mu \)m and 16 \( \mu \)m were obtained, respectively. The resolution was slightly worse when higher-energy X-rays were used. This is explained by the fact that the distance between the gratings was larger for higher-energy X-rays.
Prospects

In this paper, the performance of XTI was demonstrated using synchrotron radiation. However, because XTI functions with cone-beam X-rays of a broad energy bandwidth in principle, the compatibility of XTI with a laboratory X-ray source is promising. In this case, the distance between two gratings should be

\[ z_T = \frac{(p + \frac{1}{2})Rd^2}{R\lambda - (p + \frac{1}{2})d^2} \]

for a phase grating, where \( R \) is the distance from a source to the first grating, whose period is \( d \).

The period of the second grating \( d' \) is given by \( d' = d(R + z_T)/R \). Although spherical gratings are ideal for XTI with a cone beam, plane gratings are available provided that \( R \) is sufficiently larger than the size of the field of view. Therefore, the technology developed to fabricate the grating used in the present work is transferred to cone-beam XTI although the aspect ratio and effective area should be further improved particularly for clinical applications. The details of the design concept of cone-beam XTI will be described elsewhere.

What kinds of X-ray sources are available for cone-beam XTI? Since XTI is based on the Talbot effect, the spatial coherence length \( l \), which is defined to be \( l = \lambda R/(2\pi\sigma) \) where \( \sigma \) is the source size, is desirable to be comparable to or larger than \( d \). The smaller \( \sigma \) is, the higher the fringe visibility is. At the same time, a sufficient flux is needed for imaging with a practical exposure time. Thus, a brilliant X-ray source is required, and conventional X-ray generators do not meet these demands. Therefore, a breakthrough is needed in the development of new compact X-ray sources, such as a table-top synchrotron.

As for an image detector, XTI does not require a spatial resolution for resolving the grating pattern. Therefore, a variety of X-ray image detectors would match with XTI. Here, it should be noted that an image detector in combination with the two gratings can be considered as a phase-sensitive image detector. In this sense, XTI is a breakthrough for the development of the first X-ray wavefront sensor.

SUMMARY

The principle of XTI was described with phase imaging results with it. The key for the construction of an X-ray Talbot interferometer is the fabrication of amplitude grating, because a high-aspect-ratio pattern must be formed. We fabricated a gold grating by means of X-ray lithography and electrochemical plating. The X-ray Talbot interferometer with the gold grating functioned with synchrotron X-rays down to 0.4 Å wavelength. Provided that a grating with a higher aspect ratio and a wider effective area is fabricated, XTI is an attractive candidate for practical X-ray phase imaging, such as clinical diagnoses, because XTI has an advantage that cone-beam X-rays of a broad energy band width are available, allowing the compatibility with a
compact X-ray source.

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