X-ray phase imaging by Bonse-Hart and Talbot interferometer

Atsushi Momose (百生 敦)
Graduate School of Frontier Sciences,
The University of Tokyo,
JAPAN

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Outline

• Advantage of X-ray phase imaging
• Phase imaging by Bonse-Hart interferometer
• Phase imaging by Talbot Interferometer
• Summary
Use X-ray wave nature!

Amplitude attenuation vs. phase shift

- Amplitude decreases by absorption by the object.
- Phase shifts by the difference in velocity of the wave in the object:
  \[ v_{\text{obj}} = \frac{v_o}{n} \]
  \( n \) : refractive index

Amplitude attenuation → absorption contrast
Phase shift → phase contrast
  
  refraction contrast

Phase shift and Refraction

Spatially variant phase shift bends wavefront.

Wave propagates locally in the direction perpendicular to wavefront; that is, wave is refracted.

Phase shift and refraction are essentially the same phenomenon.
Complex refractive index

\[ \delta = \frac{r_e^2 \lambda}{2\pi} \sum_k N_k (Z_k + f'_k) \]

\[ = \frac{\lambda}{2\pi} \sum_k N_k p_k \quad [p_k \equiv r_e \lambda(Z_k + f'_k)] \]

\[ \beta = \frac{\lambda}{4\pi} \sum_k N_k \mu_k^a \]

\[-\log T = \mu t = \frac{4\pi}{\lambda} \beta t = t \sum_k N_k \mu_k^a \]

\[ \Phi = \frac{2\pi}{\lambda} \delta t = t \sum_k N_k p_k \]

Atomic interaction cross sections of absorption \((\mu\epsilon_k^a)\) and phase shift \((p_k)\) are responsible for the difference.

Interaction cross section of atom
Complex refractive indices of materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$\delta$</th>
<th>$\beta$</th>
<th>$\delta/\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>poly-styrene</td>
<td>$5.0 \times 10^{-7}$</td>
<td>$3.2 \times 10^{-10}$</td>
<td>$1.6 \times 10^{3}$</td>
</tr>
<tr>
<td>water</td>
<td>$5.8 \times 10^{-7}$</td>
<td>$6.0 \times 10^{-10}$</td>
<td>$9.7 \times 10^{2}$</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>$1.3 \times 10^{-6}$</td>
<td>$2.9 \times 10^{-9}$</td>
<td>$4.5 \times 10^{2}$</td>
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<tr>
<td>Si</td>
<td>$1.2 \times 10^{-6}$</td>
<td>$4.9 \times 10^{-9}$</td>
<td>$2.4 \times 10^{2}$</td>
</tr>
<tr>
<td>Fe</td>
<td>$3.8 \times 10^{-6}$</td>
<td>$9.7 \times 10^{-8}$</td>
<td>$3.9 \times 10^{1}$</td>
</tr>
</tbody>
</table>

Techniques for X-ray phase imaging

Two-beam interferometry

Analyzer-based method

crystal analyzer

Propagation-based method

grating analyzer
Bonse-Hart interferometer


X-ray interferometer

Rat cerebellum (1mm thick) @ 12.4 keV (PF)

optical image

Fringe-scanning (phase-stepping) method


\[ I = |\Psi_o + \Psi_r|^2 = A + B \cos[\Delta((x,y)) + \Delta(x,y)] \]

\( A \): average intensity \hspace{1cm} \( B \): fringe contrast
Fringe-scanning (phase-stepping) method

\[ I_k = |\Psi_o + \Psi_r|^2 \]
\[ = A + B \cos(\Phi + \Delta + 2\pi k / M) \]
\[ k = 1, 2 \ldots, M \]

when \( M = 4 \)

Cancerous tissues

A. Momose et al., SPIE Proc. 3772, 188 (1999) →


\[ \text{cf. normal mouse liver} \]
Rat kidney

A. Momose et al., J Phys. IV 104 (2003) 599

Phase separation in polymer blend


Aorta of mouse (Atherosclerotic plaque)


A representative atherosclerotic lesion in aortic sinus of the ApoE-KO mouse (36 weeks of age) fed normal diet.

A representative atherosclerotic lesion in aortic sinus of the ApoE-KO mouse (12 weeks of age) fed high-cholesterol diet for 8 weeks.

Blood vessels in mouse liver

Blood was replaced with saline. $E = 17.7$ keV

Two-crystal X-ray interferometer

Drug effect on tumor
Paclitaxel (Mitotic inhibitor)

vs. MRI


X-ray Phase CT  
4.74-T micro-MRI  
Optical Image

Talbot Effect

W. H. F. Talbot (1836)

Amplitude grating  
\[ d = \frac{1}{2}\frac{\lambda}{\lambda} \]
\[ 1 = \frac{1}{2}\frac{\lambda}{\lambda} \]
\[ 2 = \frac{1}{2}\frac{\lambda}{\lambda} \]
\[ 3 = \frac{1}{2}\frac{\lambda}{\lambda} \]
\[ 4 = \frac{1}{2}\frac{\lambda}{\lambda} \]
\[ 5 = \frac{1}{2}\frac{\lambda}{\lambda} \]

Phase grating
Talbot Interferometer

Phase object
Phase shift: $\Phi(x, y)$

1st grating

2nd grating

X-rays

Moiré pattern
Deformed self-image

Image flow

Differential phase map (wrapped)

Differential phase map (unwrapped)

Phase map

Phase tomogram
Fabrication of X-ray Gratings

100 mm X-ray Amplitude Grating
X-ray lithography + gold electroplating

SEM image
Au: 29.1 µm height
5.3 µm pitch

Laboratory of Advanced Science and Technology for Industry, University of Hyogo

Phase Tomography

Rabbit liver with cancer (VX2)

Combination of X-ray Talbot Interferometer and X-ray Imaging Microscope

Projection microscope

Imaging microscope

Talbot-type X-ray microscope @ SP8


Phase Tomography of Polymer Blend

Phase difference microscope


Four-dimensional X-ray phase tomography

SPring-8, BL28B2
Photon Factory, BL-14C1

Pitch: 5.3 μm
~\(\pi/2\) grating for 25 keV

Pitch: 5.3 μm
30 μm height
Measurement of differential phase
Fourier-filtering approach

Carrier fringes (rotation moiré) with sample

Extraction of 1st order with translation to origin.

FT

Differential phase

Phase tomogram

Reconstruction of 4D tomogram

Differential phase image

Sample rotation (time)

180°-rotation

A phase tomogram

sinogram
Larva of nokona regalis (Head part)


Larva of nokona regalis (Tail part)
Third Contrast visibility image

Absorption image
Visibility image (Dark-field image)
Differential phase image


Tomography with visibility

Visibility map

\[
I(x, y; z_T) = \sum_{n} a_n(x, y; z_T) \exp(2\pi i n f_0 y)
\]

\[
V(x, y; z_T) = \frac{2a_1(x, y; z_T)}{a_0(x, y; z_T)}
\]

Visibility tomogram of melamine sponge
### Origin of visibility reduction

Phase shift: \( \psi(x,y) = \psi_s(x,y) + \psi_f(x,y) \)

- \( \psi_s(x,y) \): Component varying slowly comparing to the system spatial resolution
- \( \psi_f(x,y) \): Wave front fluctuation with the scale smaller than the system spatial resolution

Differential phase contrast

Visibility reduction

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**X-ray Talbot-Lau Interferometer**

- **Talbot interferometer**
  - Coherence length > grating pitch
  - Microfocus X-ray generator
  - Low power
  - Long exposure

- **Talbot-Lau interferometer**
  - Functions with any X-ray sources

The spacing of a multiple-slit is determined so that fringes generated by X-rays from each slit are overlaid constructively.

Objective

Implementation of X-ray phase imaging outside synchrotron facilities for practical applications by Talbot(-Lau) interferometry.

X-ray Talbot-Lau Interferometer for Pre-clinical Test

- Multi-slit: 22.8μm pitch
- π/2 phase grating: 4.3μm pitch
- Amplitude grating: 5.3μm pitch
- Object

X-ray generator
  - Focus: 300μm
  - Target: W
  - Tube voltage: 40kV
  - Filter: 1.6mm Al

X-ray image detector
  - Direct-conversion FPD
  - Pixel: 85μm
metacarpophalangeal joint of human thumb

Differential phase image  Absorption image  Small-angle scattering image

Human Knee

Conventional X-ray image

Differential phase image

Prof. J. Tanaka, MD
Prof. M. Nagashima, MD
Saitama Medical School, Japan
Summary and Prospect

Bonse-Hart X-ray Interferometry

—provides the most sensitive X-ray phase imaging opportunity. About a thousand times higher sensitivity comparing with monochromatic absorption-contrast method is actually demonstrated for biological soft tissues and polymers.

—is implemented at the Photon Factory, KEK and SPring-8 for users. The machine at the Photon Factory is a type of two crystal configuration, providing a large field of view.

Talbot X-ray Interferometry

—enables X-ray phase imaging/tomography with a simple configuration, although its sensitivity is not as high as that by the Bonse-Hart interferometry.

—enables the combination with an X-ray imaging microscope, appending a phase-contrast mode.

—enables high-speed X-ray phase imaging, which may promote X-ray phase imaging for various dynamical observation.

—is expanding from synchrotron facilities for practical applications; ex. medical diagnoses in hospitals.