Talbot 効果を利用した高感度X線位相差分顕微鏡

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電子デバイスや新エネルギー技術などの開発が盛んに行われている工学分野、あるいは生物・医学分野への応用の観点から、数ナノメートル～数百ナノメートルスケールでの高感度の観察技術の重要性は近年ますます高まっている。硬X線顕微鏡は不透明な厚い物体の内部を観察できる他にはない特長を有しており、最近のX線集光素子の性能向上により既に数十ナノメートルの高空間分解能が実現されている。しかしながら吸収コントラストを利用する場合には、軽元素を中心に構成される弱吸収物体に対する感度が小さいという問題がある。そのため、X線の位相を利用したより高い感度のイメージング（X線位相イメージング）を目指した種々の方法が提案されている。本発表では、我々が最近提案した、X線の Talbot 効果を利用した高感度硬X線顕微鏡について報告する[1,2]。本手法では、高感度・高空間分解の定量的顕微位相イメージングが可能という他の方法にはない特長を有し、Lau タイプの配置にすれば、実験室のノーマルフォーカスX線源も利用できることから[3]、最近注目を集めている。

[1] W. Yashiro *et al.*, *Phys. Rev. Lett.* **103** (2009) 180801.
[2] W. Yashiro *et al.*, *Phys. Rev.* A **82** (2010) 043822.
[3] H. Kuwabara, W. Yashiro, *et al.*, *Appl. Phys. Exp*. **4** (2011) 062502.

（メモ）

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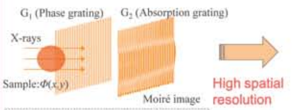
X-ray Talbot Interferometer (XTI) combined with X-ray microscopy

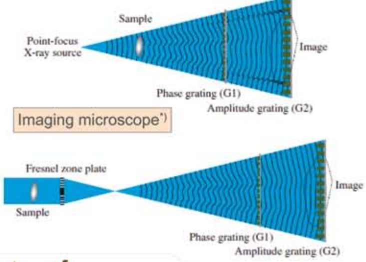
X-ray Talbot interferomter



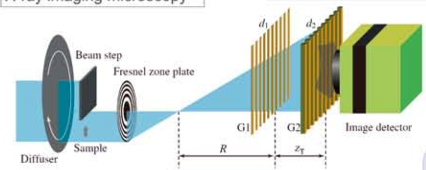
Self-image of G_1 appears at the position of G_2 by the 'Talbot effect', and is deformed by the sample (phase shift $\Phi(x,y)$). The deformation is analyzed by G_2.

Projection microscope

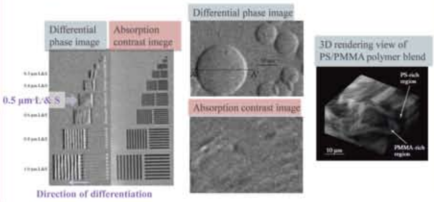
Imaging microscope[*)]



XTI combined with X-ray imaging microscopy[*)]



[*)]Y. Takeda, W. Yashiro, T. Hattori, A. Takeuchi, Y. Suzuki, and A. Momose, APEX 1 (2008) 117002.



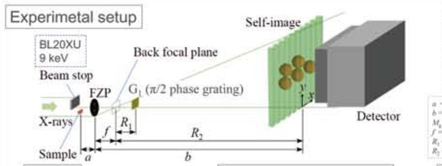
Phase imaging & tomography was successfully performed, but …

・ Spatial resolution is degraded by the grating

・ Sensitivity is not so high because the interferometer measure the 'slop' of the wavefront. Magnification causes a further reduction of sensitivity.

A novel method — X-ray phase difference microscopy

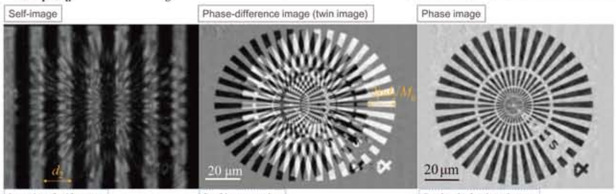
Experimetal setup



G_1 is placed just behind the back focal plane, so that the self-image is magnified largely enough to be resolved by the detector.

a = 272 mm	Outermost zone width of the FZP = 86.6 nm
b = 6461 mm	Pitch of G_1 (d_1) = 4.3 µm
M_g = 23.7	Pitch of the self-image (d_2) = 395 µm
f = 261 mm	Talbot order (p) = 0.5
R_1 = 67.8 mm	Effective pixel size of the detector (Δ) = 4.34 µm
R_2 = 6200 mm	Δ/M_g = 183 nm

Self-image | Phase-difference image (twin image) | Phase image



Intensity of self-mage:

$$I(x,y) \propto \sum_{n,m} \mu_m a'_n a'^*_{n+m} \exp\left[\frac{-2\pi i m x}{d_2}\right] E_{0,n} E^*_{0,n+m}$$

$E_0(-\frac{1}{M}(x+npd_2), -\frac{1}{M}y)$: electric field on the object plane

a'_n: the nth Fourier coefficient of electric field of the self-image on the image plane

μ_m: the complex degree of coherence at two points separated by mpd_2/M_g

By fringe scanning

$$P(x,y) = a'_{-1}a'^*_0 E_{0,-1}E^*_{0,0} + a'_0 a'^*_1 E_{0,0}E^*_{0,1}$$

Taking argument

$$\arg[P(x,y)] = \frac{\Phi(x_s+pd_2/M, y_s) - \Phi(x_s-pd_2/M, y_s)}{2}$$

Retrieval of a phase image:

$$\Phi(x_s,y_s) = 2\frac{-J_1\sum_{j=-J_2}^{-1}\mathcal{P}_j + J_2\sum_{j=0}^{J_1-1}\mathcal{P}_j}{J_1+J_2}$$

$$\mathcal{P}_j \equiv \arg[P(x-(2j+1)pd_2, y)]$$

$J_1, J_2 \geq 1$ (J_1, J_2: integer)

Advantages

Our microscopy provides a phase image

– quantitatively even in the case of strong-phase objects, which is difficult to be covered by Zernike's phase-contrast imaging technique.

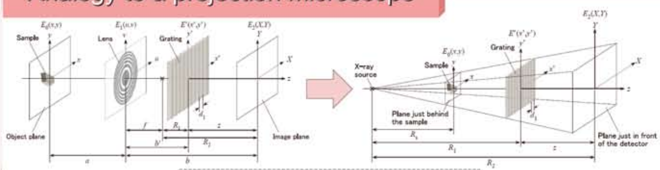
– with a high spatial resolution that is almost same as that of the absorption contrast image without the grating

– with a high sensitivity which is much higher than that of the XTI combined with the X-ray microscope because it does not provide a *differential* phase image but a phase-*difference* image directly

– without high spatial coherence that is not necessary to be mostly coherent on the objective

– without specially designed optics and *not* high mechanical stability

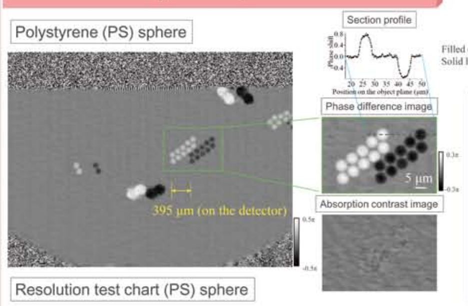
Analogy to a projection microscope



Formulation similar to a projection microscope is possible except that there is no defocusing effect.

Quantitativity and spatial resolution

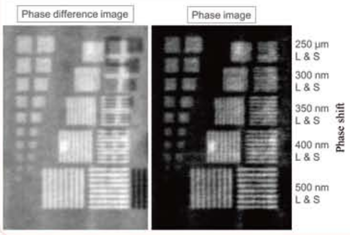
Polystyrene (PS) sphere



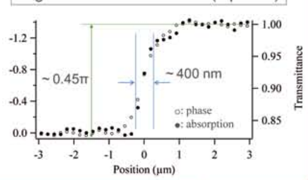
Quantitativity
The phase-difference images were quantitative (5.8 µm-diameter PS sphere and 1 µm-thickness Ta test pattern).

Spatial resolution
0.3 µm line & space (L & S) was resolved. From the section profile of an edge of Siemens star chart in the horizontal direction), the width of point spread function was almost same as that of the absorption contrast image obtained by removing the grating.

Resolution test chart (PS) sphere

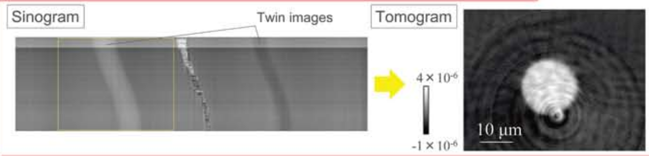


Edge of Siemens star chart (1 µm Ta)

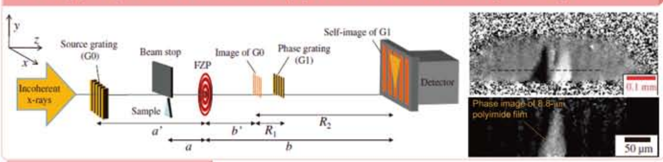


Phase tomography (an example of PS sphere)

Sinogram | Twin images | Tomogram



Lau-type phase microscopy with a laboratory X-ray source



Summary

➢ A novel X-ray phase (phase-difference) imaging microscopy was proposed.
➢ Phase difference images (twin phase images) were obtained in an experiment using synchrotron radiation source.
➢ The sensitivity in the phase difference image was about two orders of magnitude higher than that of the absorption contrast X-ray microscopy that is atteined by removing the grating.
➢ The spatial resolution is as same as that of the absorption contrast microscopy.
➢ Phase tomography was also successfully performed.
➢ Lau-type X-ray phase microscopy with a laboratory X-ray source (a normal-focus X-ray source) was also realized and a phase image was successfully obtained.

References

- W. Yashiro, Y. Takeda, A. Takeuchi, Y. Suzuki, and A. Momose, *Phys. Rev. Lett.* **103** (2009) 180801.
- W. Yashiro, S. Harasse, A. Takeuchi, Y. Suzuki, and A. Momose, *Phys. Rev.* A **82** (2010) 043822.
- H. Kuwabara, W. Yashiro, S. Harasse, H. Mizutani, and A. Momose, *Appl. Phys. Exp.* **4** (2011) 062502.