Construction of a Talbot Interferometer for phase-contrast imaging

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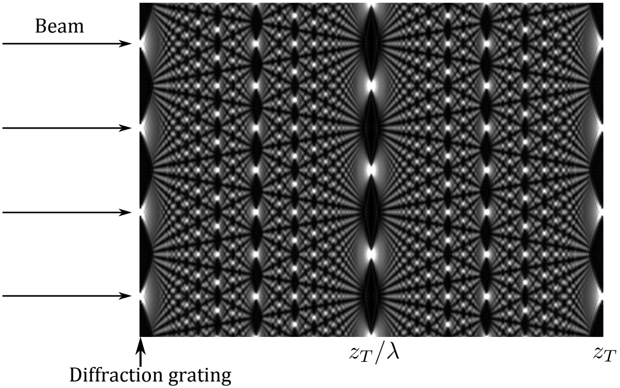
What is the Talbot interferometer?

The Talbot interferometer is a X-ray imaging system that is sensitive to slight variations in the density of matter.

- More sensitive than common absorption imaging
- Gives info on phase shift, absorption and scattering. All from one scan!

How does it work?

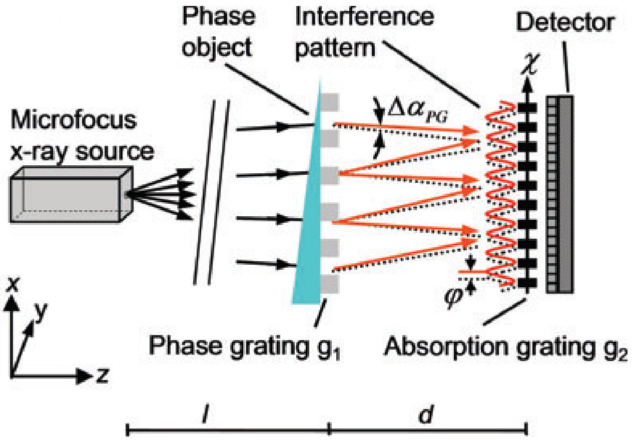
- Monochromatic light passed through a silicon phase grating forms periodic self-image downstream at distances z_T



(B. Goodman, CC Attribution Share-Alike)

How does it work?

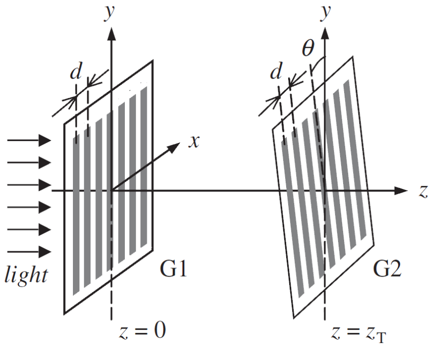
- Placing an object in the beam path changes the phase and thus pattern



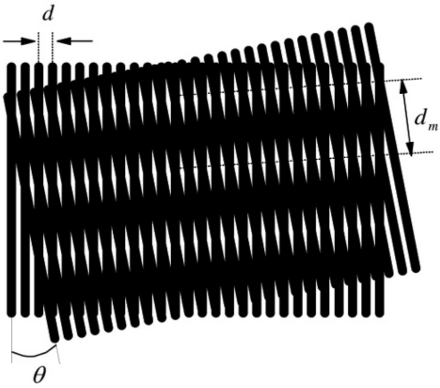
(Engelhardt *et al.*, 2008)

How does it work?

- Gold coated analyzer grating period matched to fringes magnifies pattern through the Moiré effect



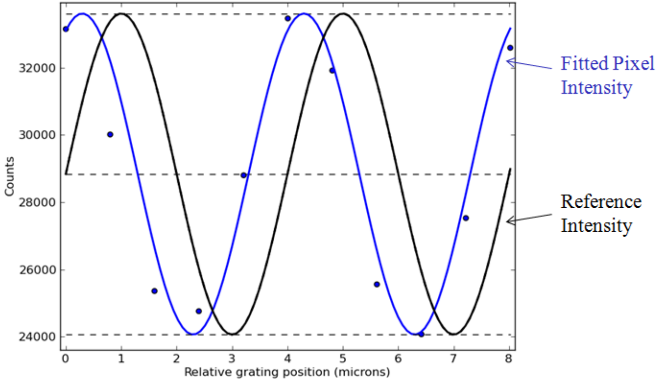
(Momose *et al.*, 2003)



(S. Rasouli, 2007)

How does it work?

- Step analyzer grating through one period to change pattern
- Intensity in each pixel oscillates sinusoidally
- Using a reference scan we can detect the changes due to a sample
- Use DFT or fit to function
  $I(x_g) = a_0 + a_1 \sin(2\pi x_g/p_2 + \varphi_1) + a_2 \sin(\pi x_g/p_2 + \varphi_2)$



What I've Done

- Characterizing the Nova600 microfocus X-ray source
  - Resolution - what's the smallest thing we can see?
  - Sensitivity - how different or thick do the materials have be?

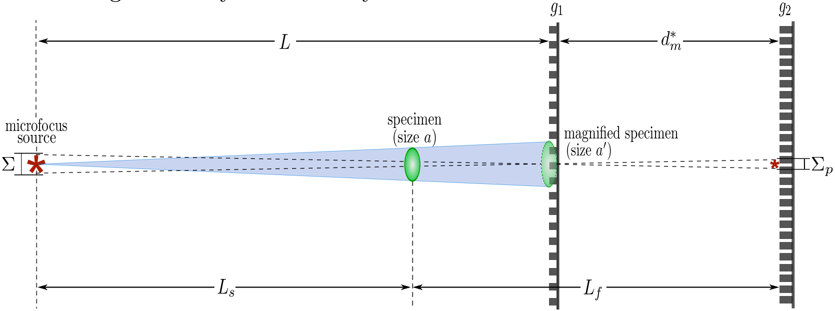
(Oxford Instruments Nova600 microfocus X-ray source)

- Image analysis
  - Run data through DFT or curve fitter to produce images

Resolution

Limiting factors:

- Fresnel diffraction: Fresnel number $\gtrsim 1$
  - $F = \dfrac{a^2}{\lambda L_f}$
- Phase grating period: $\sim 4\mu\text{m}$
  - Effective feature size: $a' = \dfrac{L}{L_s} a$
- Source size: $20\mu\text{m}$
  - Fringe visibility is limited by source size: $V = e^{-(1.887\Sigma d_m^*/Lp_2)^2}$



Resolution Results

- Calculated F and magnification for range of phase grating and specimen distances $\Rightarrow$ max V for range of feature sizes
- For a required visibility of 3%, minimum detectable feature is $\sim 2.3\mu$m
- For a required visibility of 20%, minimum detectable feature is $\sim 2.8\mu$m

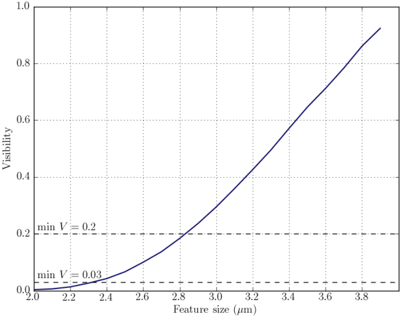


Figure: The maximum visibilities for a range of feature sizes.

Phase Sensitivity

We want to know how sensitive the interferometer will be to phase differences. This is determined by the amount of noise in our data.
Sources of uncertainty:

- Counting statistics
  - $\sigma_p = \sqrt{N_p}$
  - More incident photons $\Rightarrow$ smaller uncertainty, so if you wait long enough you can decrease σ_p as much as you like
- Dark current
  - Counts recorded even without incident photons
  - $N_d \sim 0.3\ e^-/\text{sec} \Rightarrow$ negligible

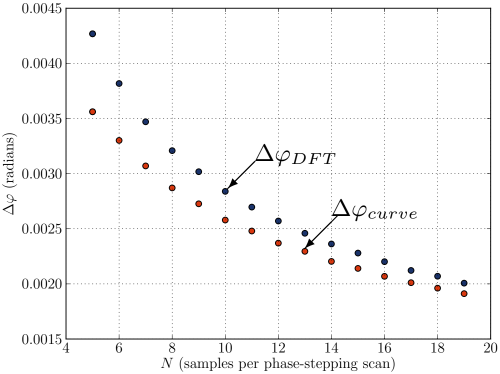
Monte Carlo Method

- Create a perfect sinusoid $a_0 + a_1 \sin(2\pi x + \varphi)$ and sample N equally spaced points (the number of images in a phase-stepping scan)
- Add Gaussian noise with standard deviation $\sqrt{N_p}$ to each point
- Apply the DFT to the noisy points
- Recover estimated a_0, a_1 and φ
- Repeat many times.
- Repeat for curve fitter

The standard deviations of all the extracted φ_{DFT} and φ_{curve} give a reasonable estimate of the sensitivity.

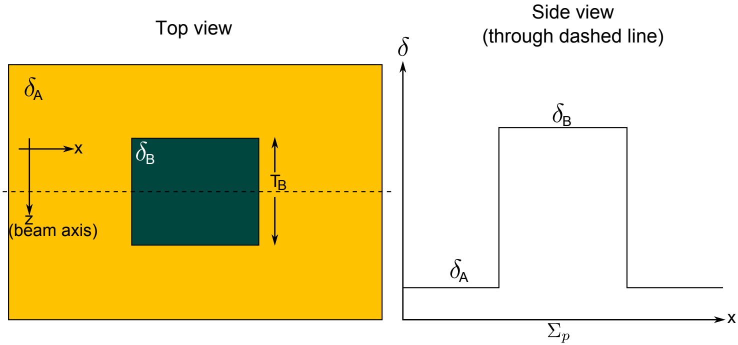
Results

- Since increasing N constrains the sinusoid further, uncertainty improves as N increases
- Curve fitter has less uncertainty than the DFT



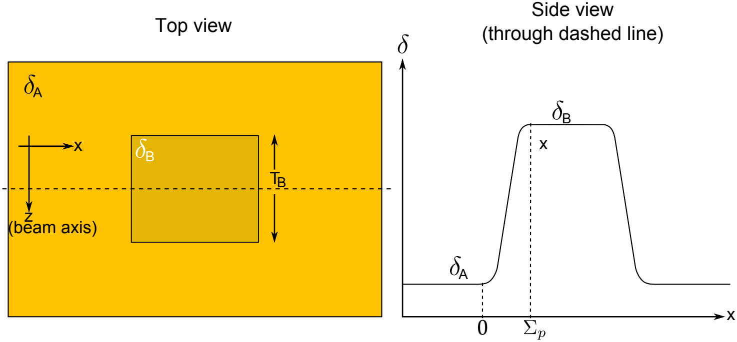
Analysis

Phase shift caused by real part of index of refraction $n = 1 - \delta + i\beta$
Suppose we are imaging a bug (δ_B) in polished amber (δ_A)



Analysis

Then, through convolution of Gaussian source and decrement profile, the decrement difference is $\delta \sim \delta_A + \frac{\delta_B - \delta_A}{\Sigma_p}$



Analysis

Then recorded phase shift is $\varphi = 2\pi \frac{mp_2}{2\lambda\Sigma_p}(\delta_B - \delta_A) \cdot T_B$

- Rearrange this to get: $(\delta_B - \delta_A) \cdot T_B = \frac{\varphi_{min}}{2\pi} \frac{2\lambda\Sigma_p}{mp_2}$
- We can use this to find a minimum decrement difference, given a thickness, *or* a minimum thickness, given a decrement difference

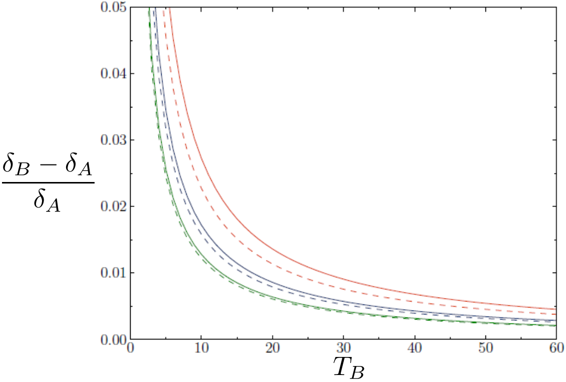
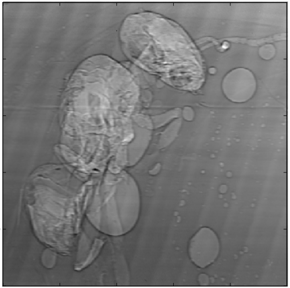
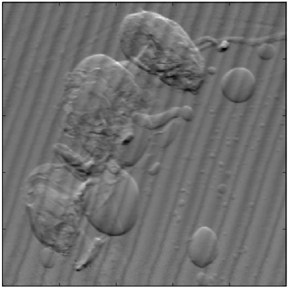


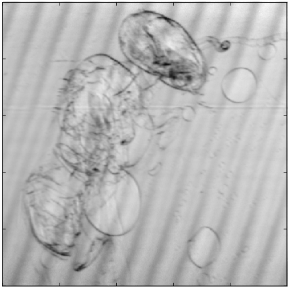
Image Analysis - Hymenoptera



Above: Absorption image

Below: Phase-contrast image





Above: Dark field image

Acknowledgments

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Robin Baur

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