nm science enabled by waveguides

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Outline

Theoretical background

- propagation of x-rays in waveguides
- waveguide-based lensless imaging / holography

Imaging experiments

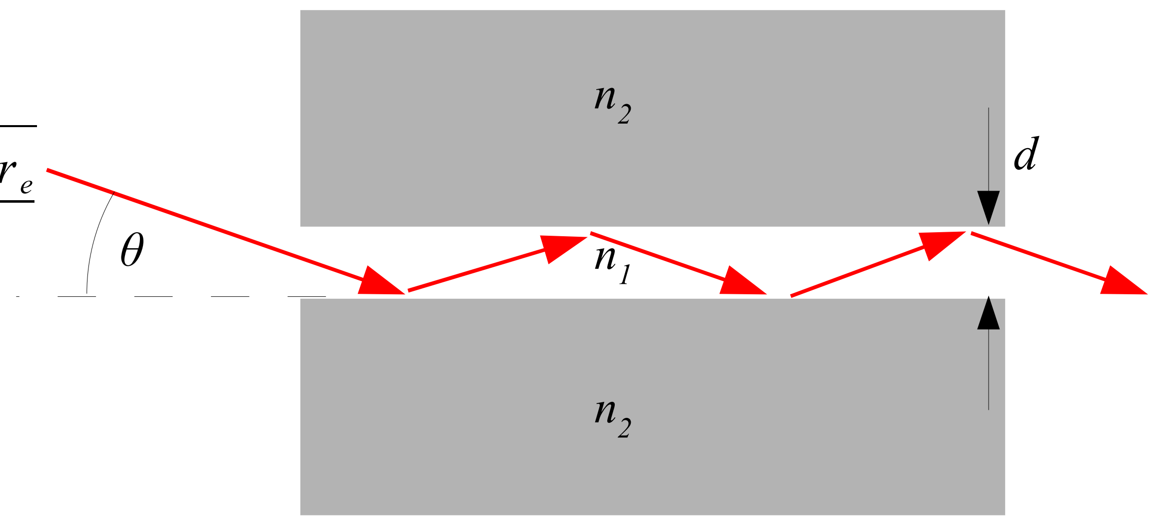
- in-line phase-contrast imaging and in-line holography
- off-axis holography

Outlook

- Can we achieve 1 nm resolution by means of x-ray waveguides?

X-ray waveguides

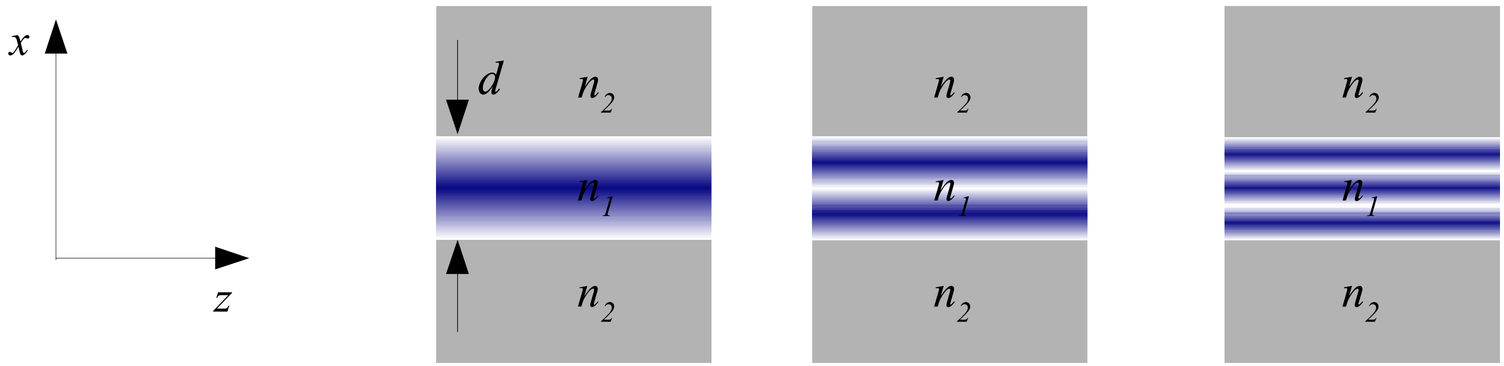
$$\theta < \theta_c \approx \sqrt{2\delta} = \sqrt{\frac{\lambda^2 \Delta\rho_e r_e}{2\pi}}$$



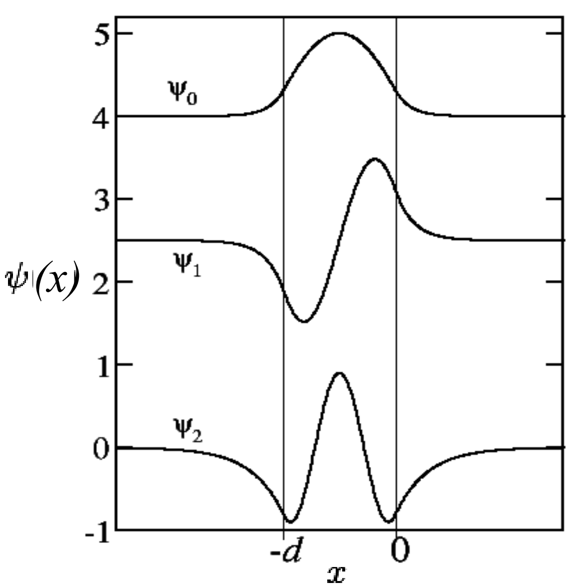
$\mathrm{Re}(n_2) < \mathrm{Re}\,(n_1)$

[Spiller & Segmüller, Appl. Phys.Lett. **24** (1974) 60]

Guided modes of a planar waveguide



standing waves → guided modes

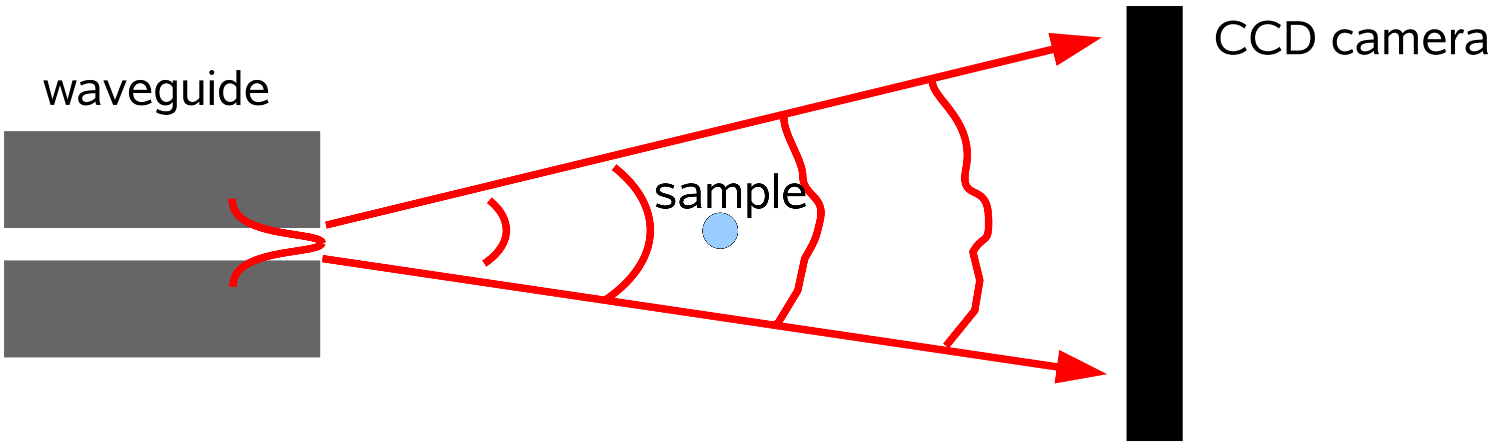


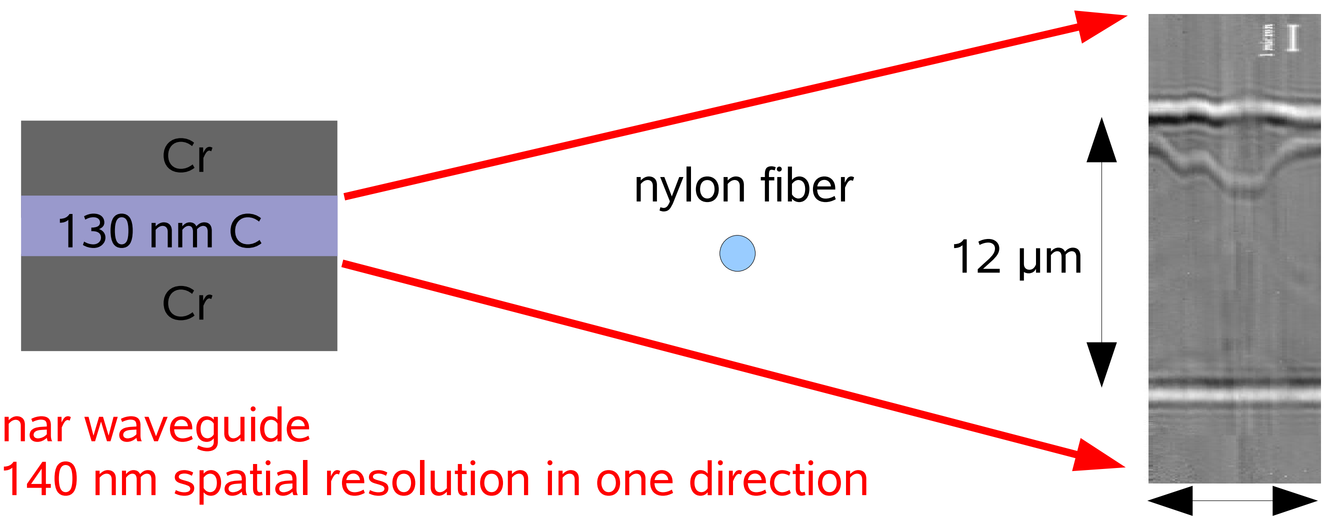
$$\psi(x) = \begin{cases} B\exp(-\gamma x), & \text{if} \quad x \geq 0, \\ B\cos\kappa x + C\sin\kappa x, & \text{if} \quad 0 > x > -d, \\ (B\cos\kappa d + C\sin\kappa d) \times \exp[\gamma(x+d)], & \text{if} \quad x \leq -d, \end{cases}$$

$$\psi(x,z) = \sum_{m=0}^{N-1} c_m \psi_m(x)\exp(-i\beta_m z)$$

$$c_m = \int \psi_{\text{in}}(x)\psi_m(x)\,\mathrm{d}x$$

Phase-contrast imaging

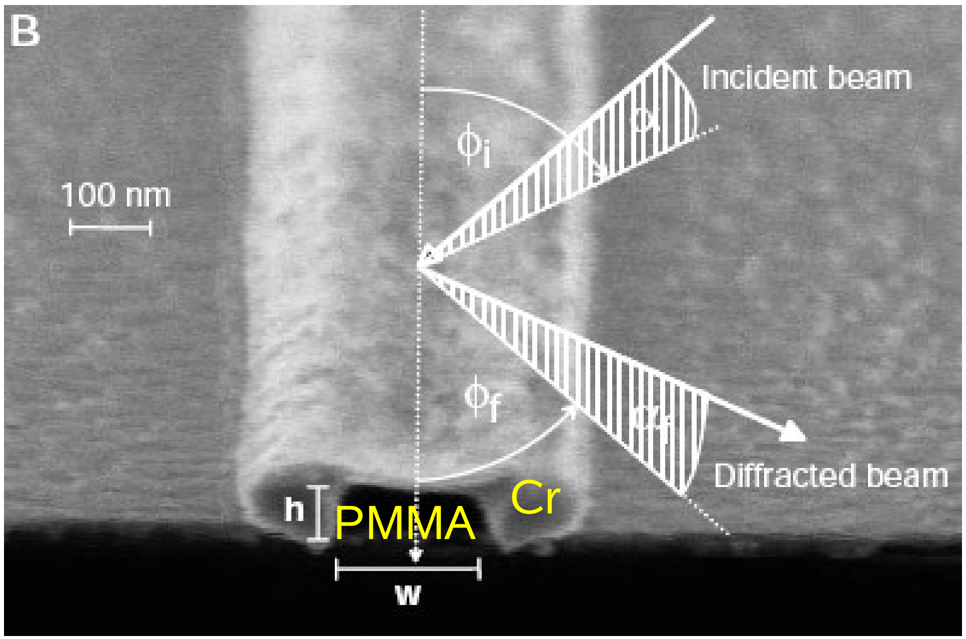


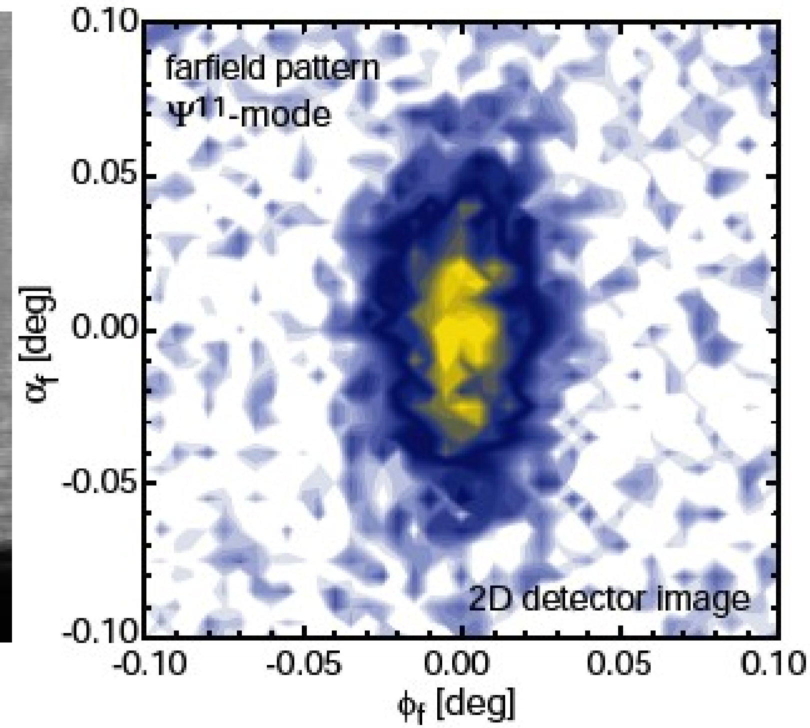


planar waveguide
→ 140 nm spatial resolution in one direction

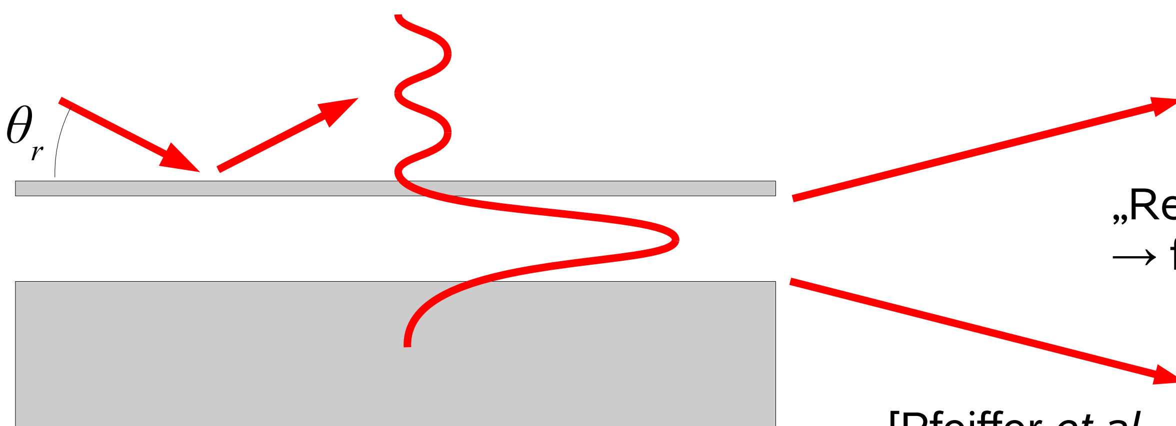
[Lagomarsino *et al.*, Appl. Phys. Lett. **71** (1997) 2557]

Two-dimensionally confining waveguides





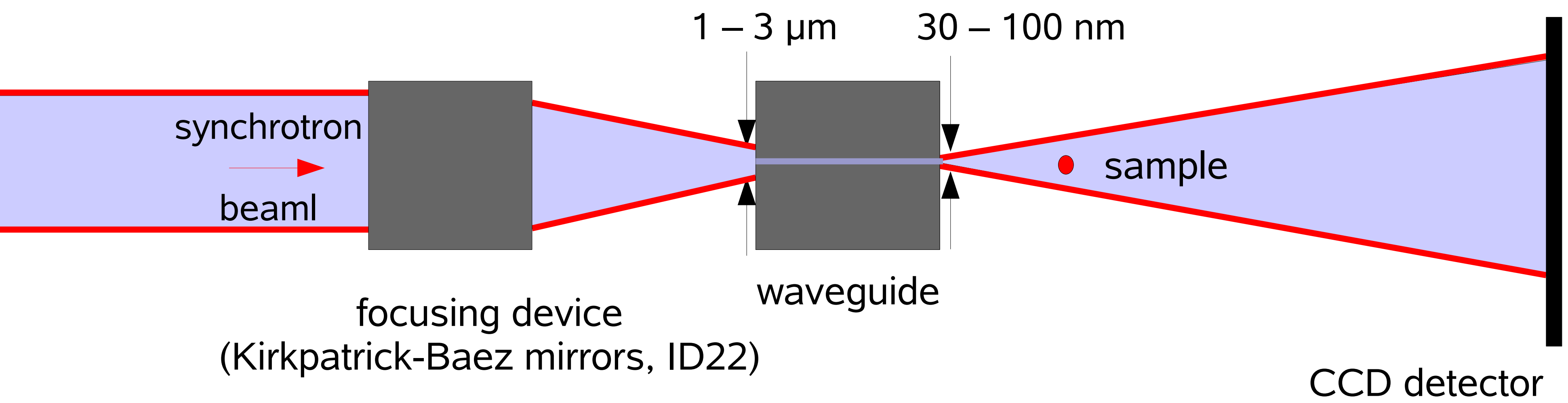
beam dimensions 69 x 33 nm^2



„Resonant beam coupling"
→ flux: 2 x 10^4 ph/s

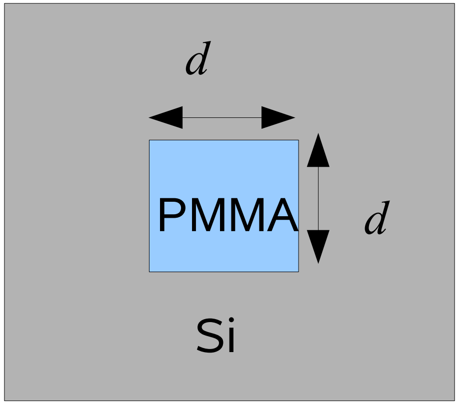
[Pfeiffer *et al.*, Science **297** (2002) 231]

Direct coupling of a focused beam



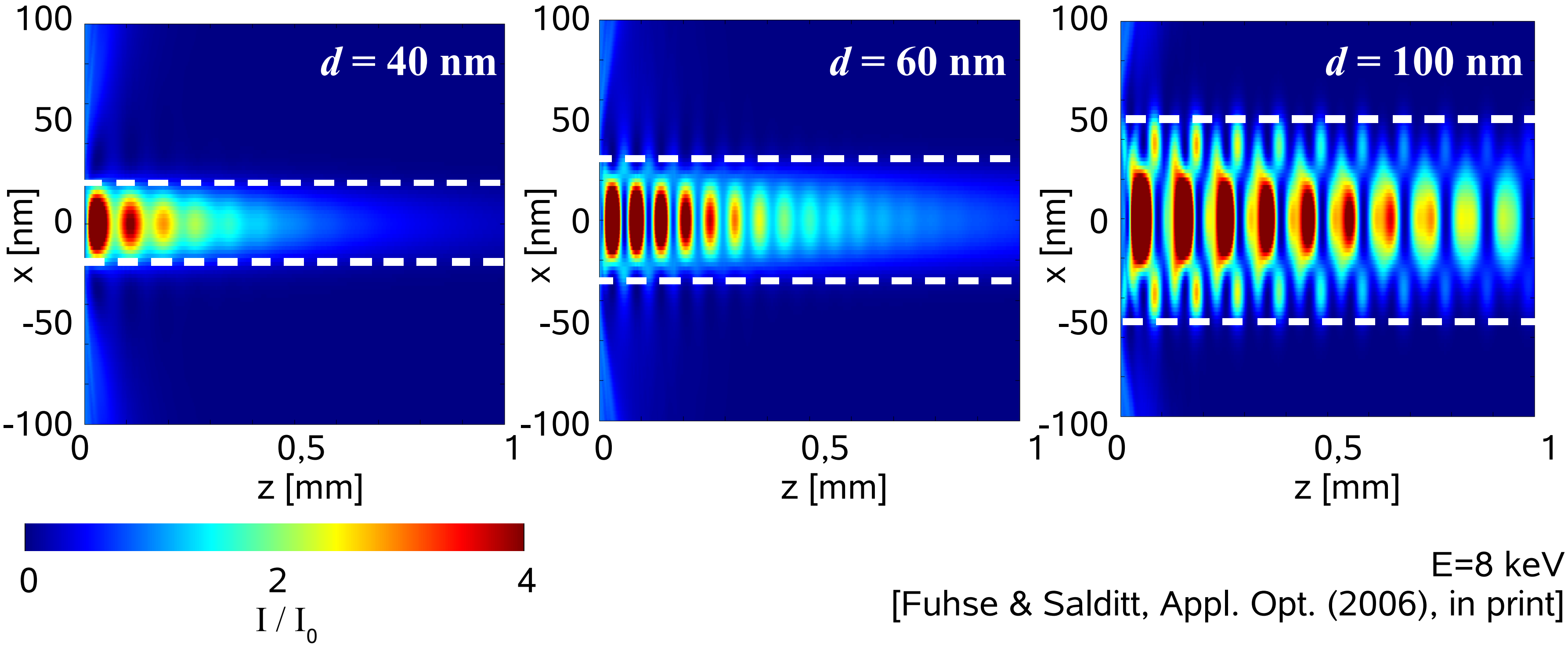
typical flux: 10^6-10^7 ph/s from 2D waveguides
[Jarre, Fuhse, Ollinger, Seeger, Tucoulou, Salditt, Phys. Rev. Lett. **94** (2005), 074891]

Direct coupling into 2D waveguides



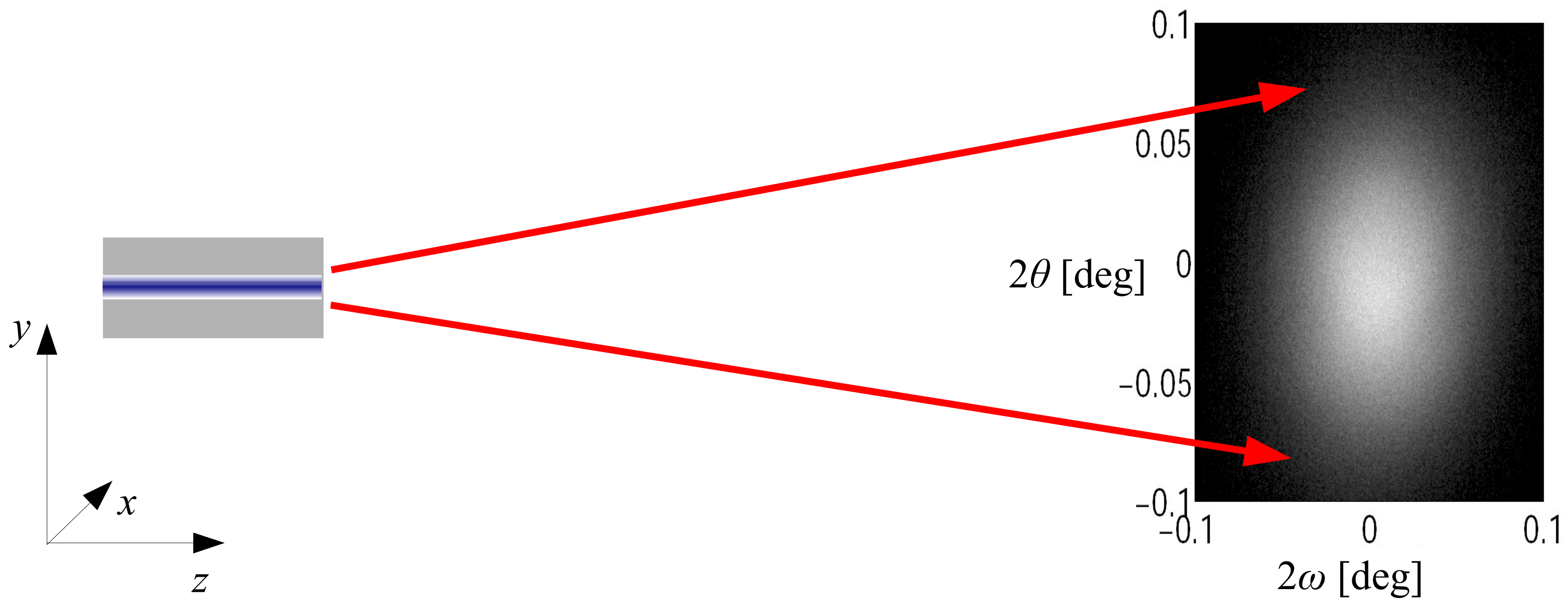
finite-difference field calculations
based on the parabolic wave equation:

- strong absorption in the cladding
- excitement of multiple guided modes
- stronger damping of higher-order modes
  → field is dominated by the fundamental mode



E=8 keV
[Fuhse & Salditt, Appl. Opt. (2006), in print]

Far-field pattern

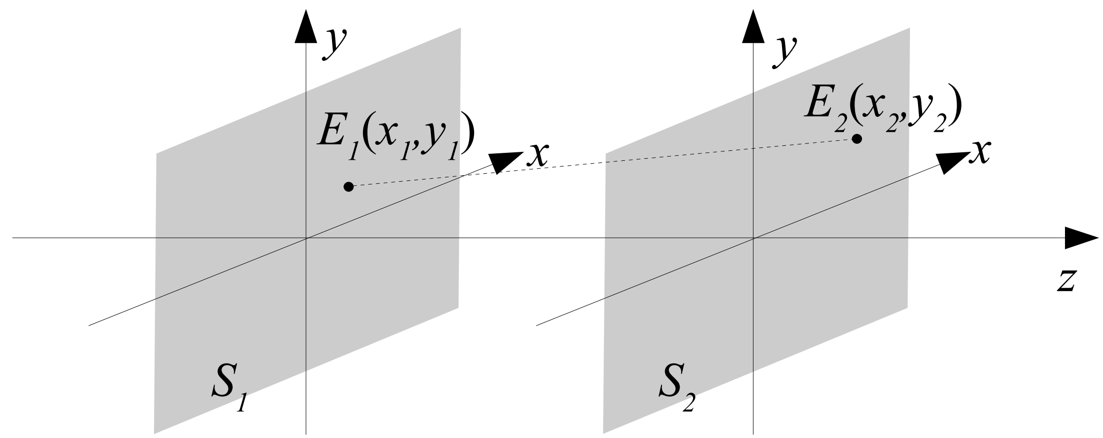


- Far-field intensity (Fraunhofer approximation):

$$I(2\theta, 2\omega) \propto \left| \int E(x,y) \exp(ik\, 2\theta\, y) \exp(-ik\, 2\omega\, x)\, \mathrm{d}x\mathrm{d}y \right|^2$$

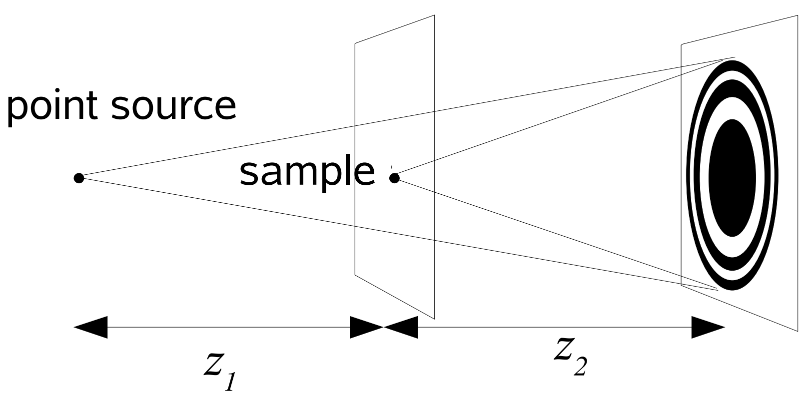
- guiding-core cross-sectional dimensions determine numerical aperture and spatial resolution → **spatial resolution ≈ diameter of the guiding core**

Coherent imaging

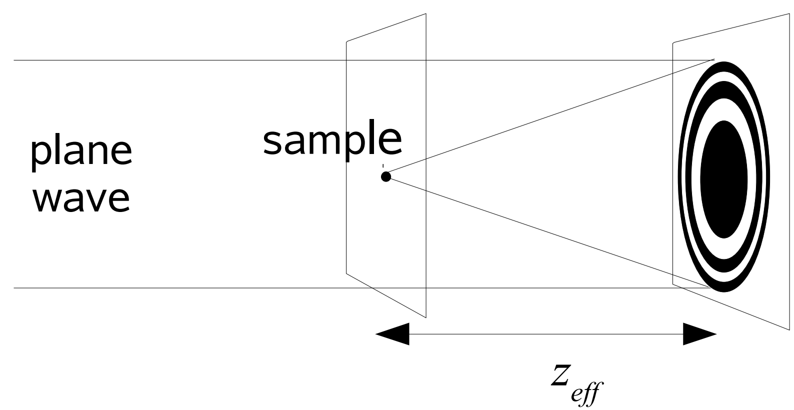


Kirchhoff's diffraction formula
(Fresnel approximation):

$$E_2(x_2, y_2) = \frac{\exp(ikz)}{i\lambda z} \int E_1(x_1, y_1) \exp\left(ik \frac{(x_2 - x_1)^2 + (y_2 - y_1)^2}{2z} \right) \mathrm{d}x_1 \, \mathrm{d}y_1$$

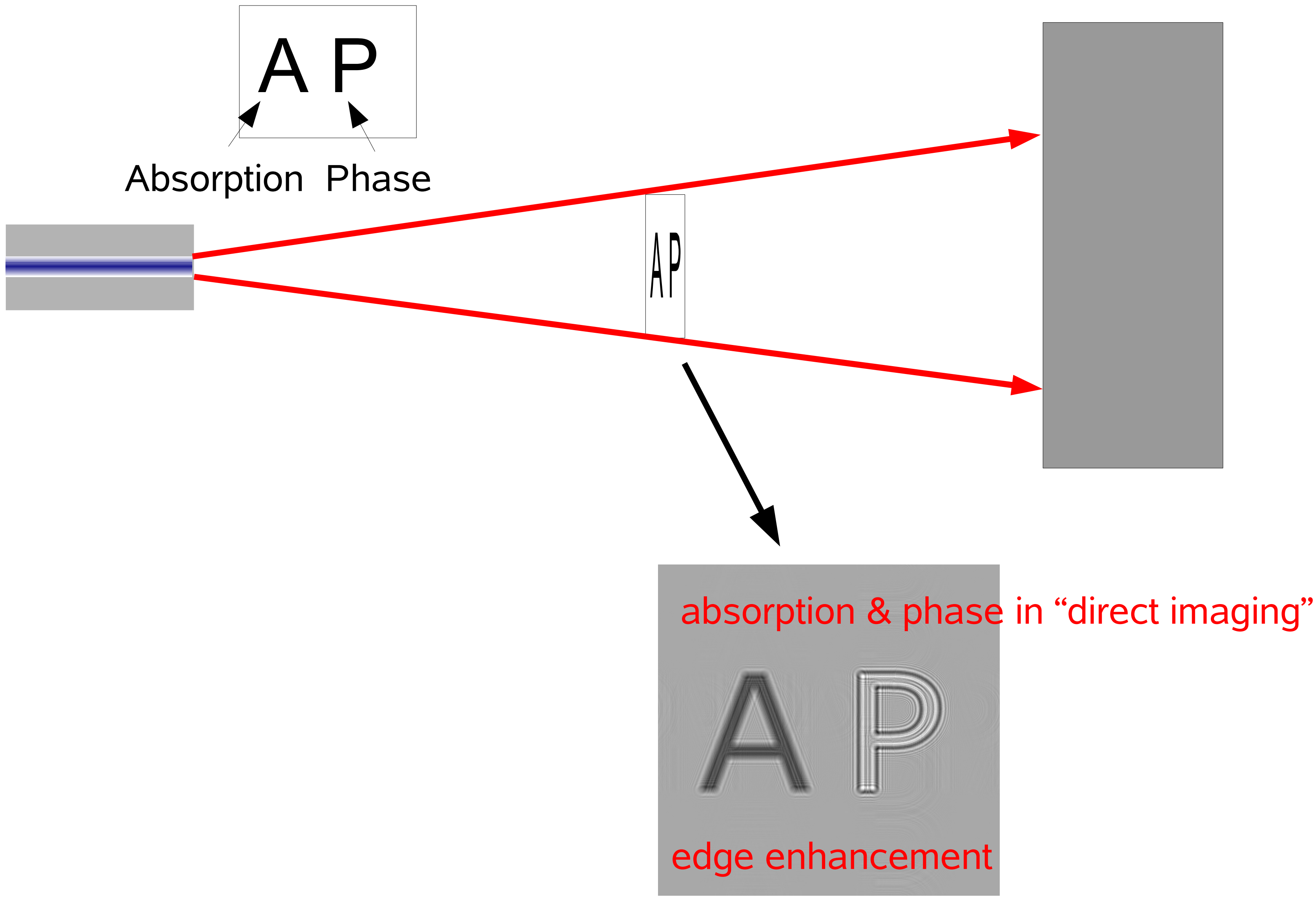


$$M = \frac{z_1 + z_2}{z_1}$$

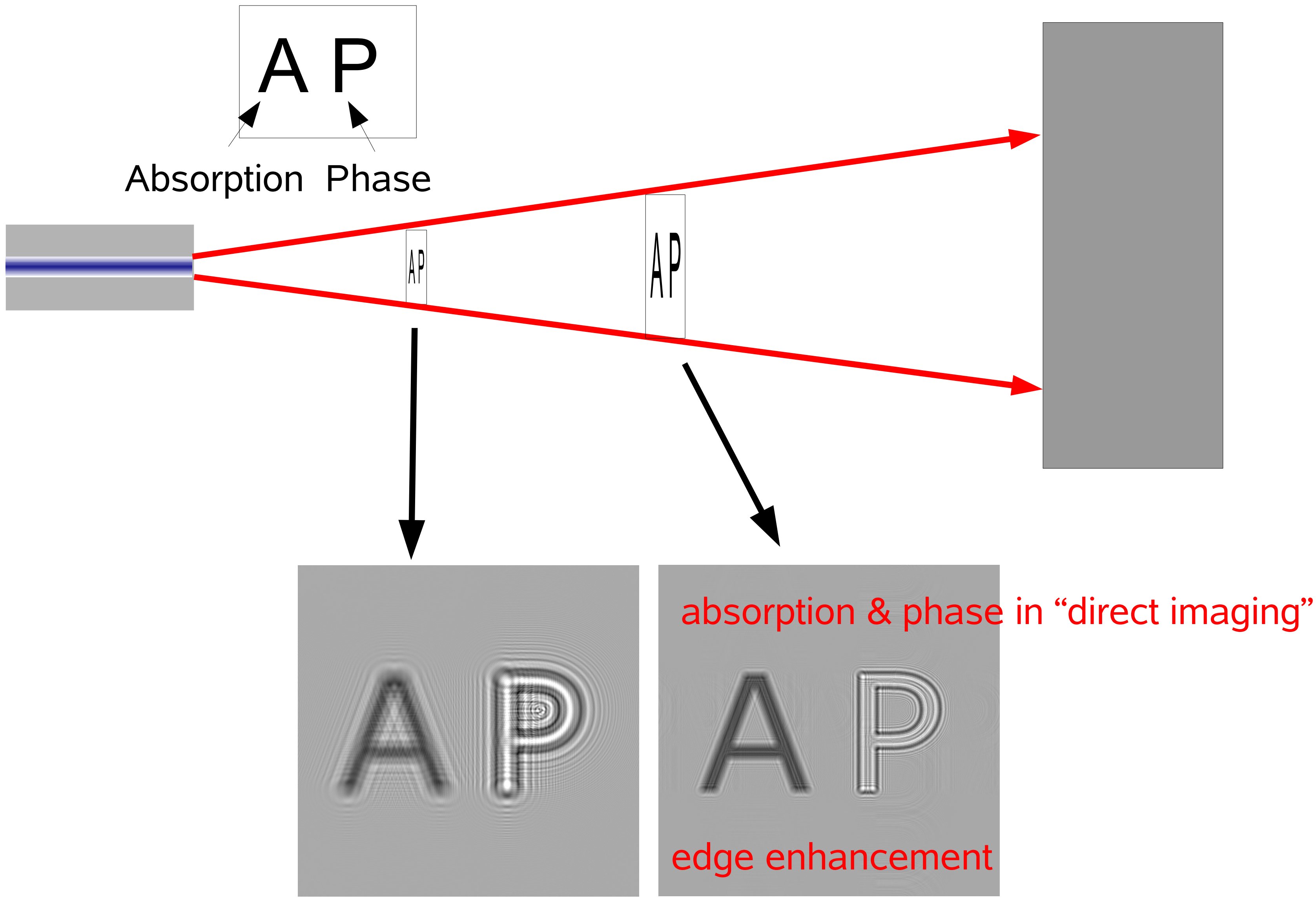


$$z_{eff} = \frac{z_1 z_2}{z_1 + z_2}$$

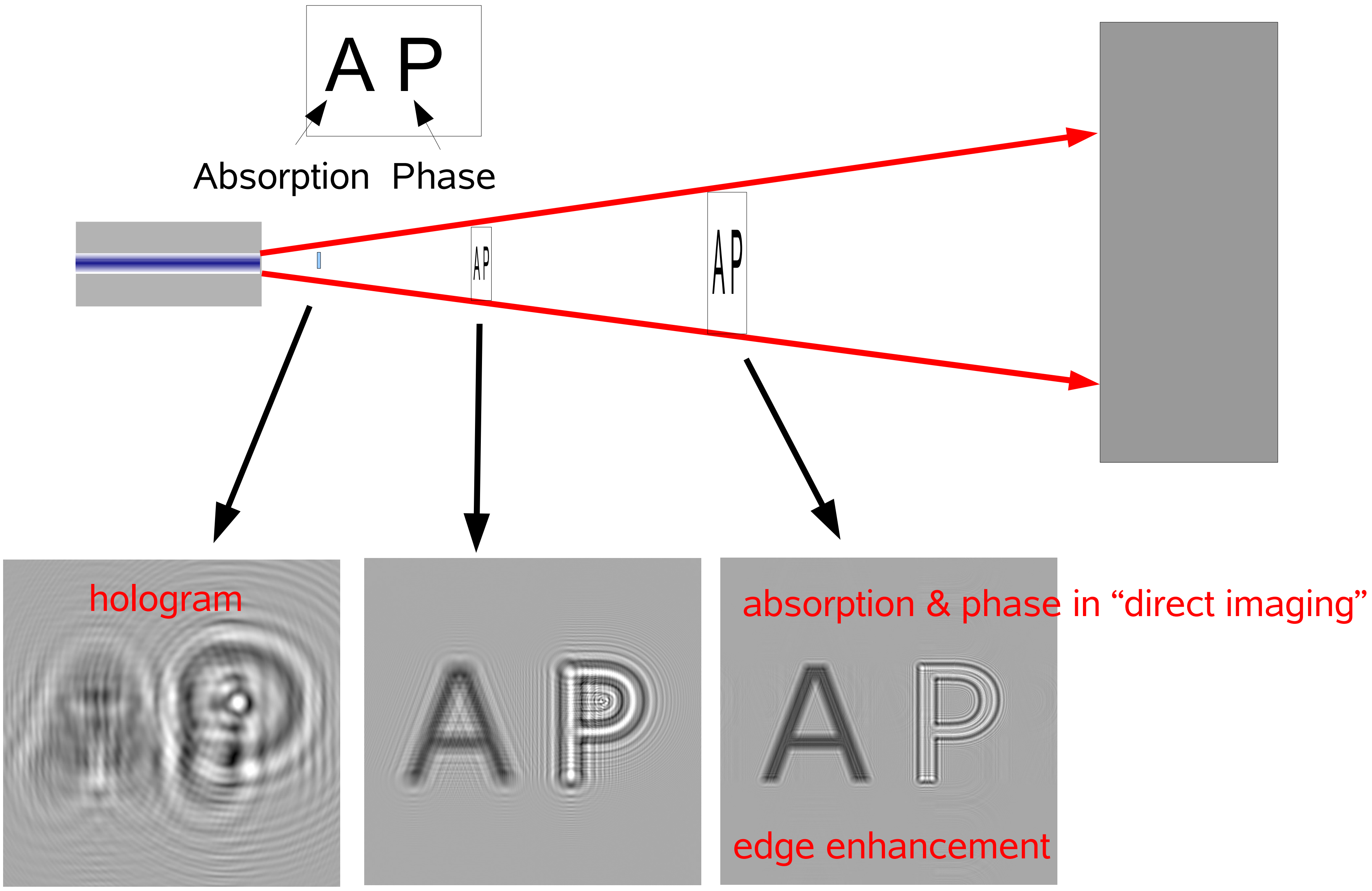
Imaging regimes



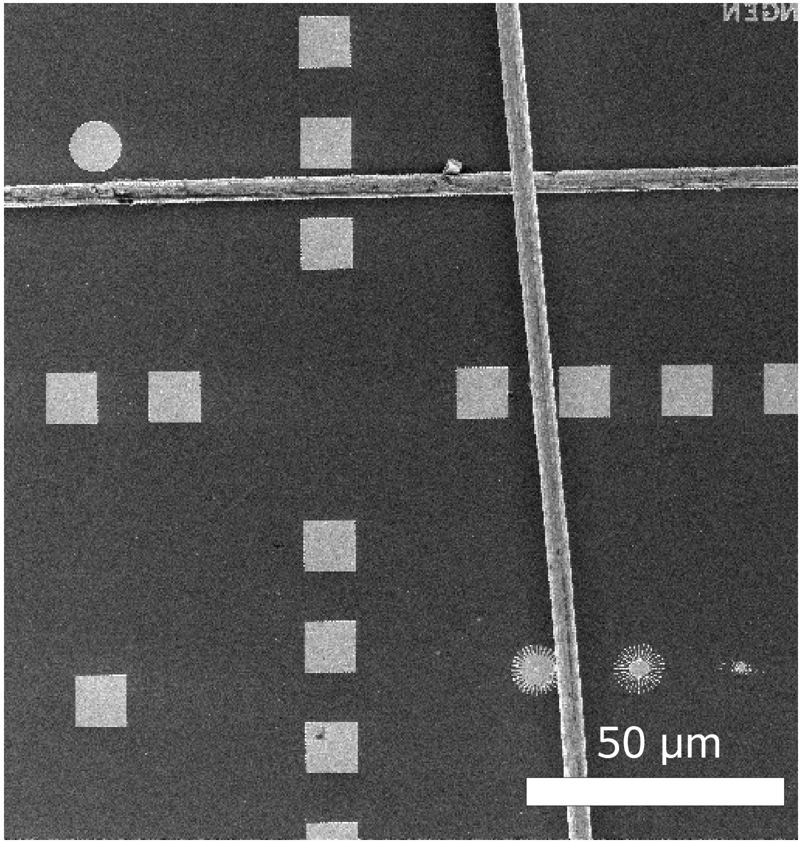
Imaging regimes



Imaging regimes



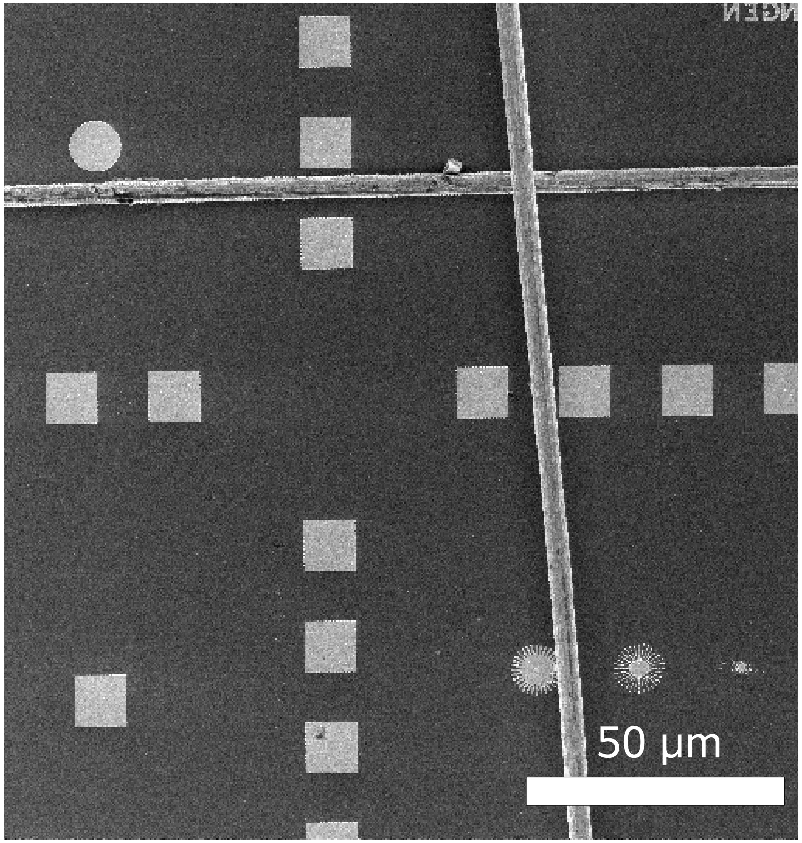
“Direct” imaging of large objects



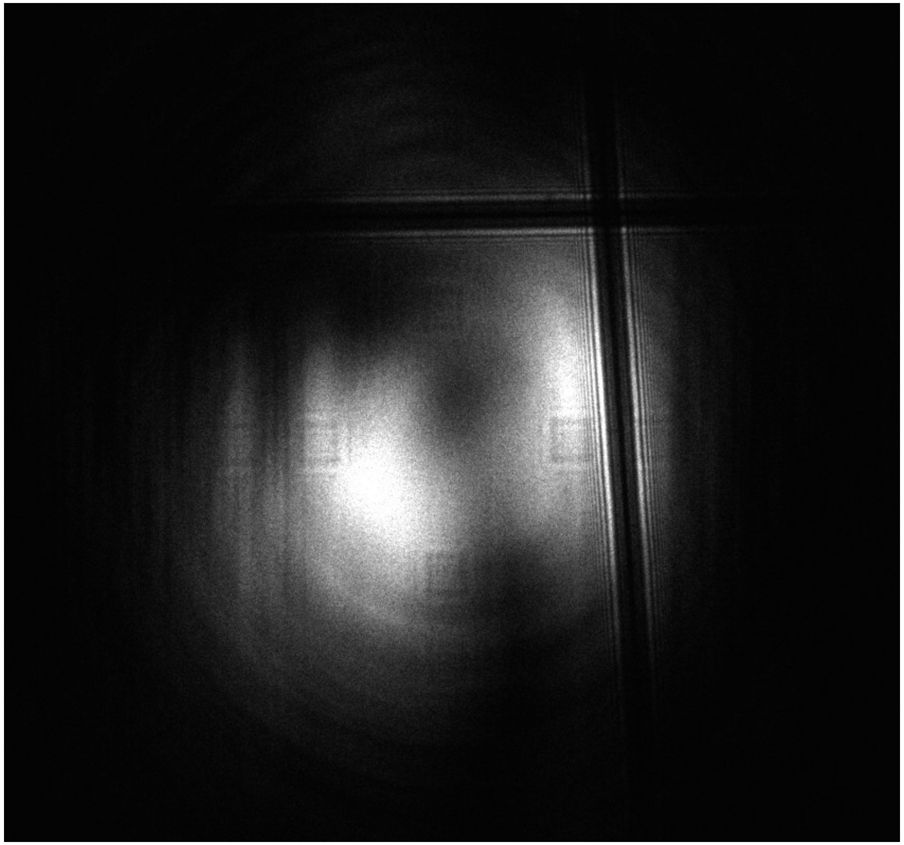
SEM

gold structures (d=150 nm) → phase-shifting sample @E=10.4 keV
tungsten wires (⌀ 4.5 µm) → absorbing sample @E=10.4 keV

“Direct” imaging of large objects



SEM

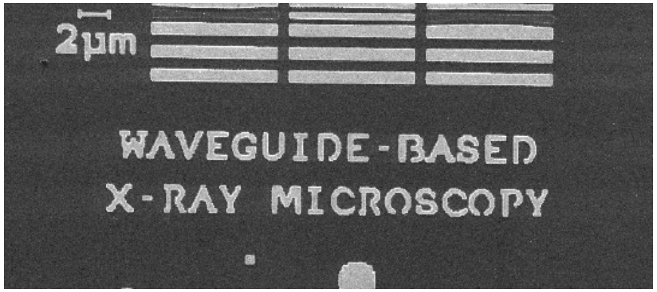


recorded image (E=10.4 keV)

gold structures (d=150 nm) → phase contrast (edge enhancement)
tungsten wires (⌀ 4.5 µm) → absorption contrast

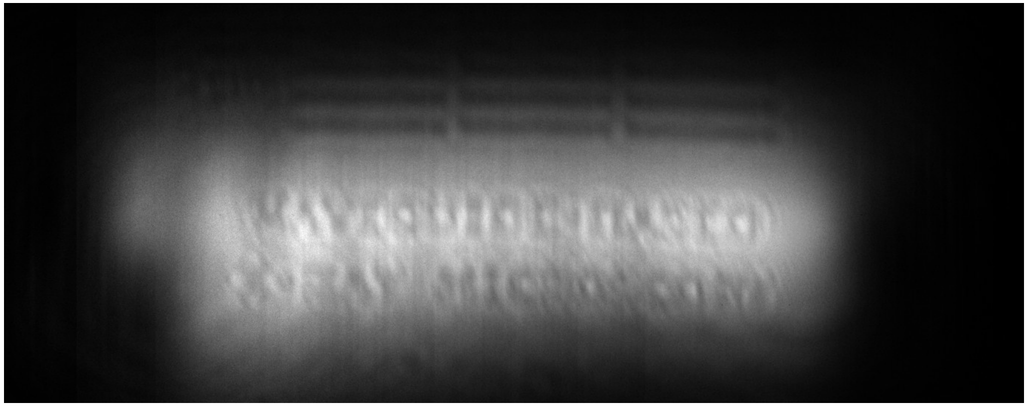
Imaging of smaller features

sample (Au, d=150 nm)



(SEM)

hologram (11 individual exposures)



Imaging of smaller features

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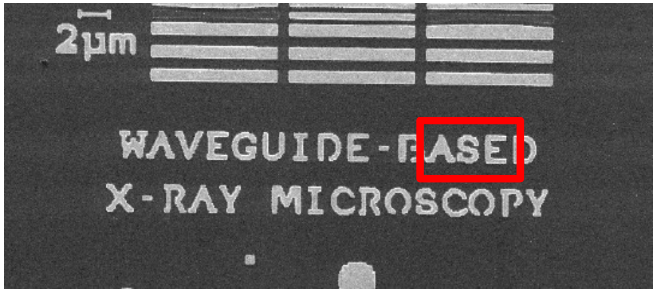

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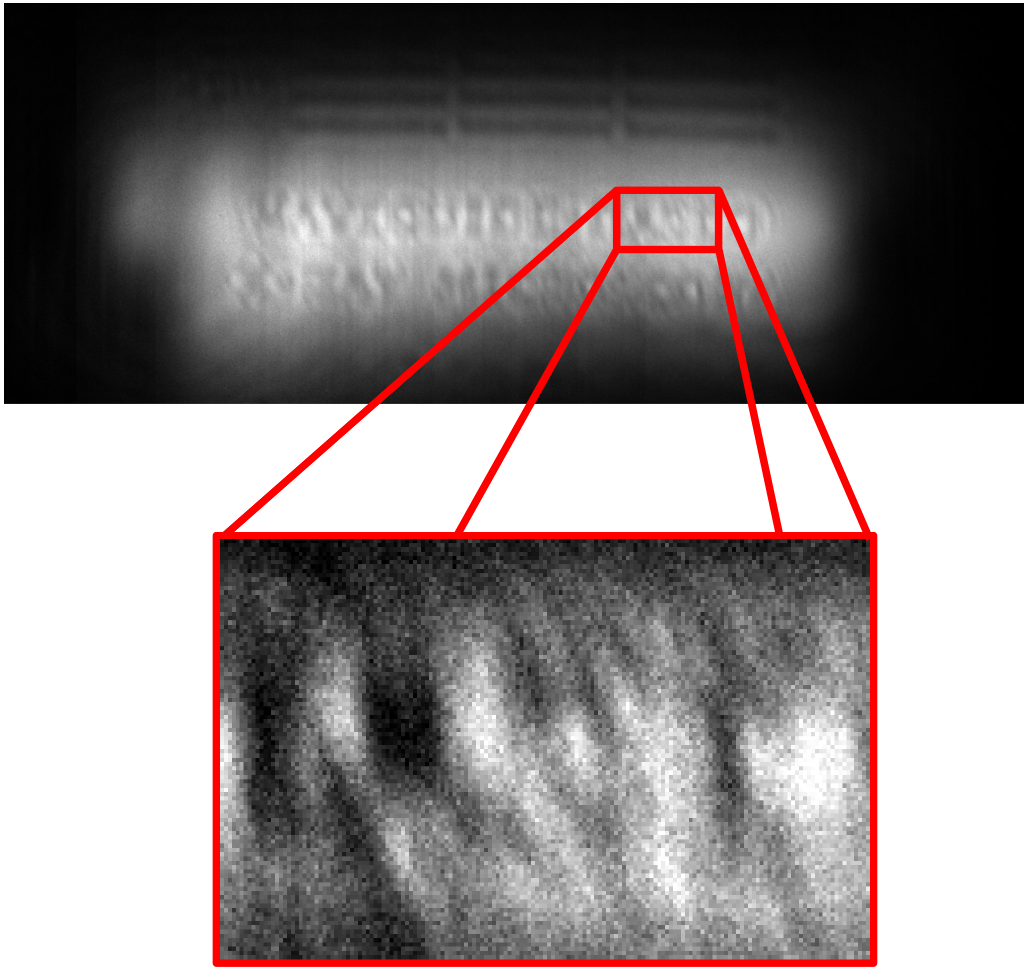
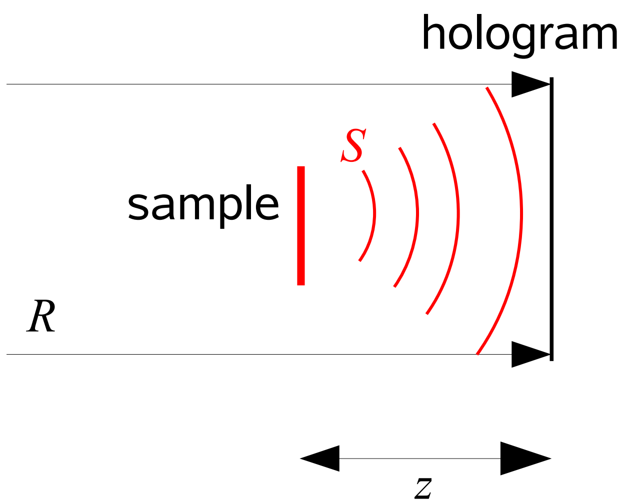


→ **holographic reconstruction required**

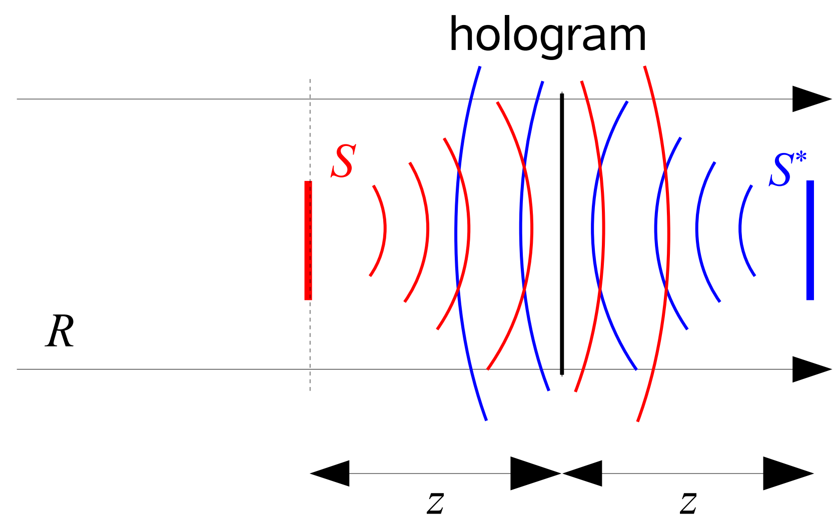
In-line holography

recording:



$$I(x,y) \sim |S(x,y) + R(x,y)|^2$$

reconstruction:



$$E_R(x,y) \sim I(x,y)R(x,y)$$

$$= (RR^* + SS^* + R^*S + S^*R)R$$

$$= |R|^2R + |S|^2R + |R|^2S + R^2S^*$$

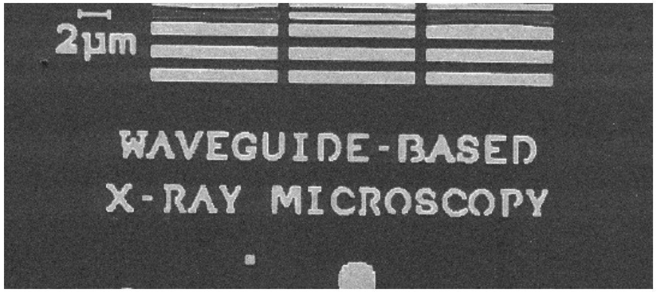
reference beam

signal wave

phase-conjugate wave
"twin image"

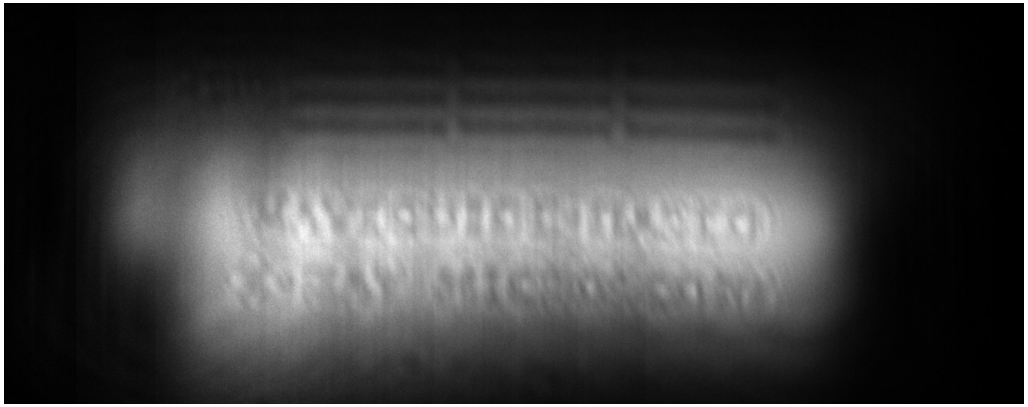
Holographic reconstruction

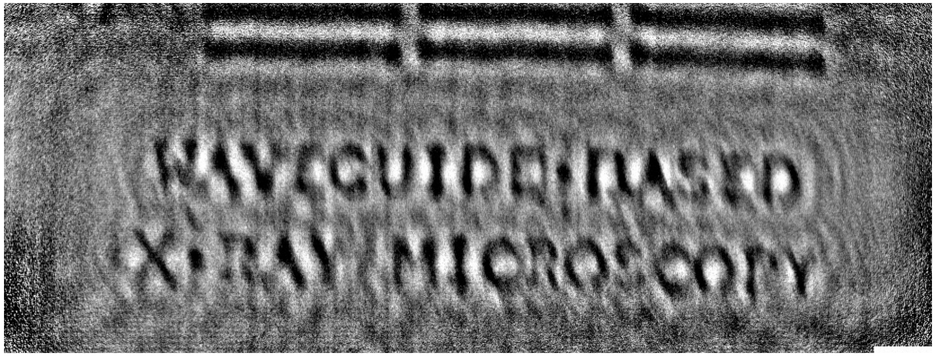
sample (Au, d=150 nm)



(SEM)

hologram (11 individual exposures)

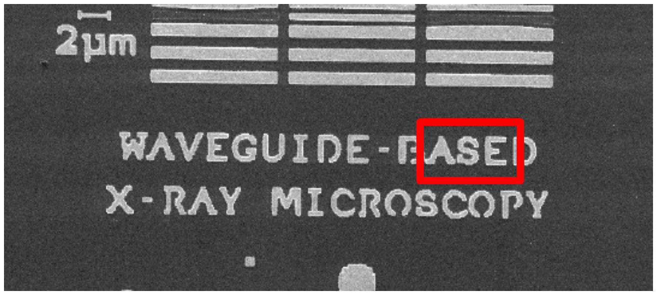




phase of the reconstructed wave

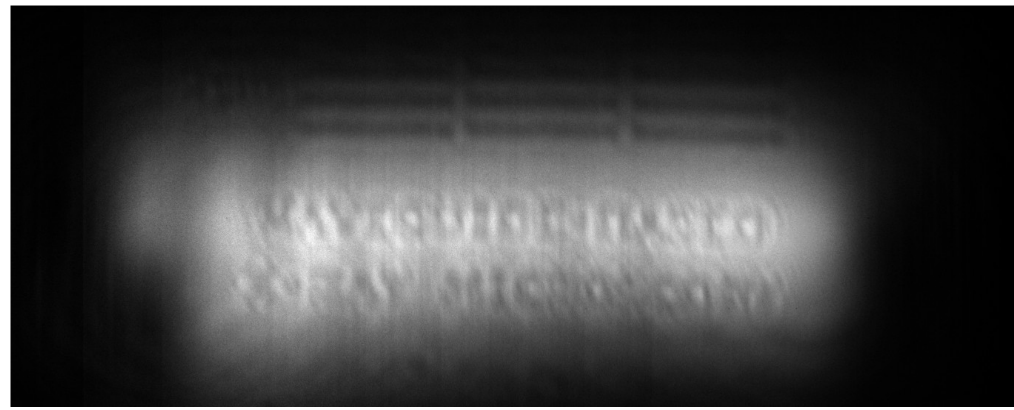
Holographic reconstruction

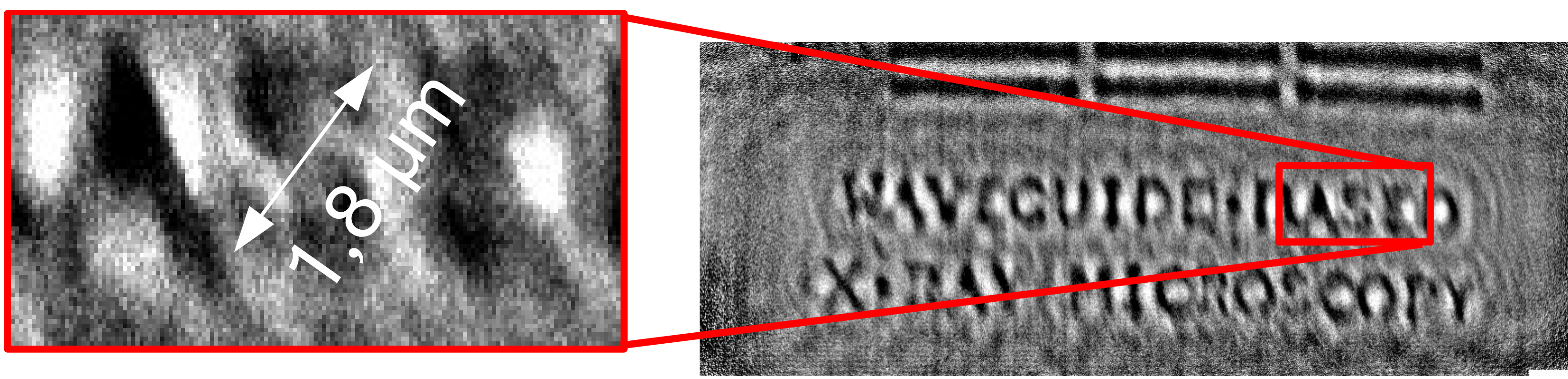
sample (Au, d=150 nm)



(SEM)

hologram (11 individual exposures)



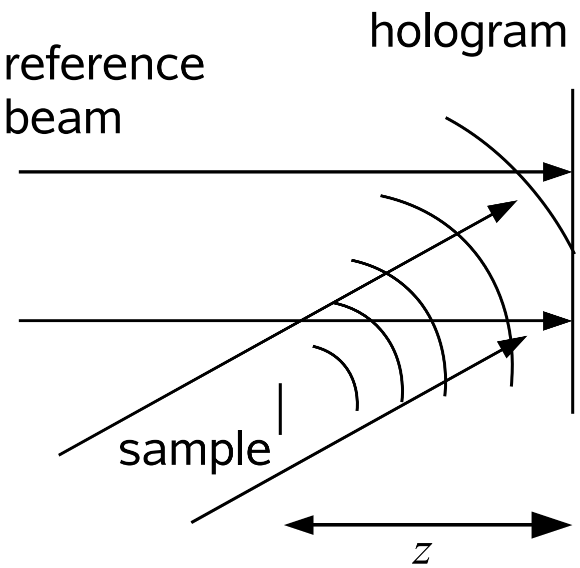


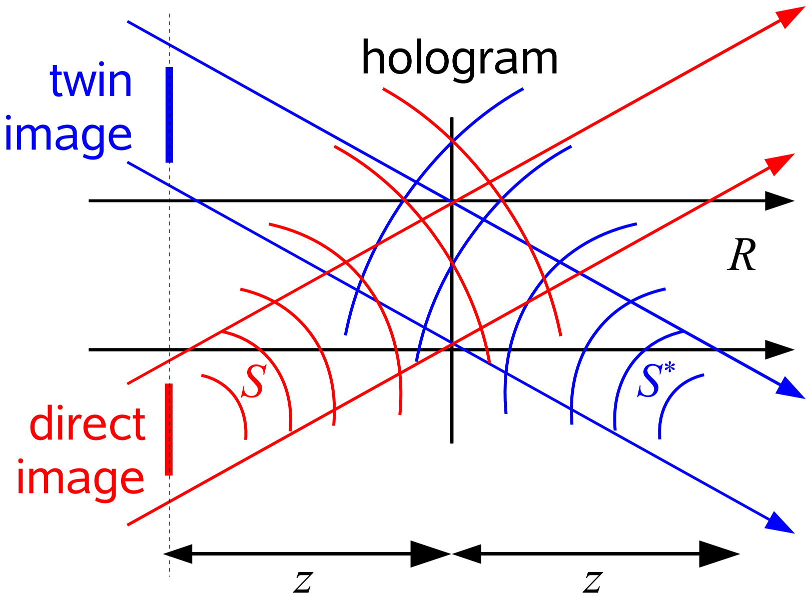
resolution ≈ 360 nm

→ but: d_{WL} < 100 nm

phase of the reconstructed wave

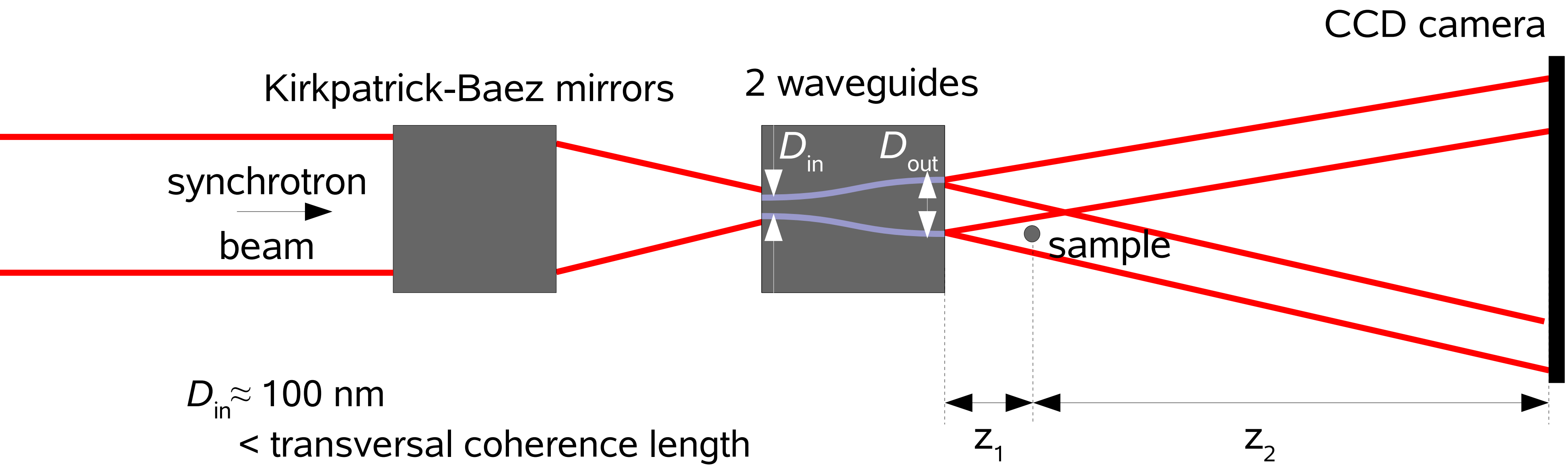
Off-axis holography





→ direct image and twin image are spatially separated!

Waveguide-based off-axis holography



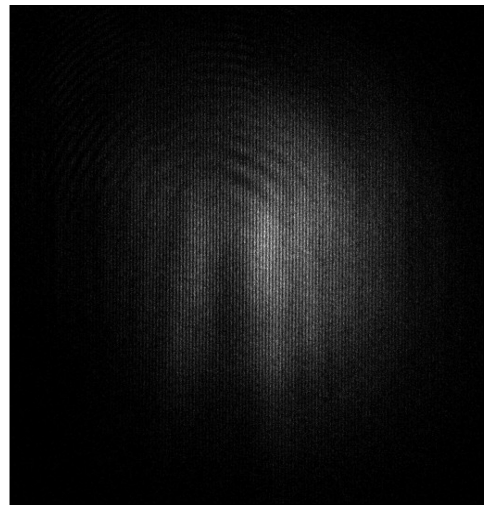
$D_{in} \approx 100$ nm
< transversal coherence length

$D_{out} \approx 5$ µm

magnified off-axis hologram

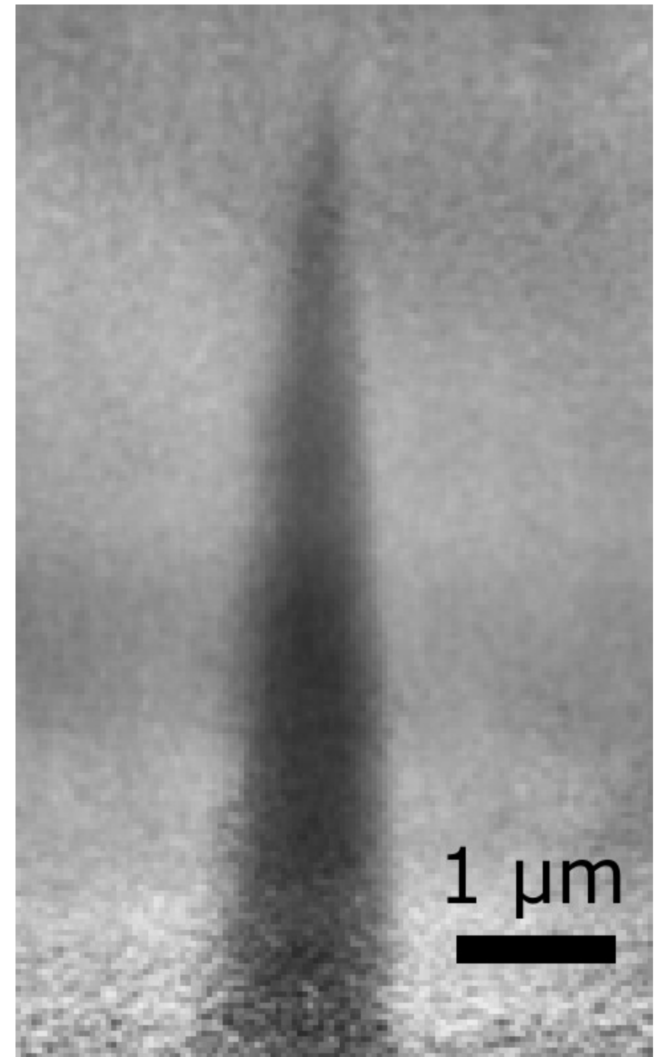
$$M = \frac{z_1 + z_2}{z_1}.$$

Off-axis holography

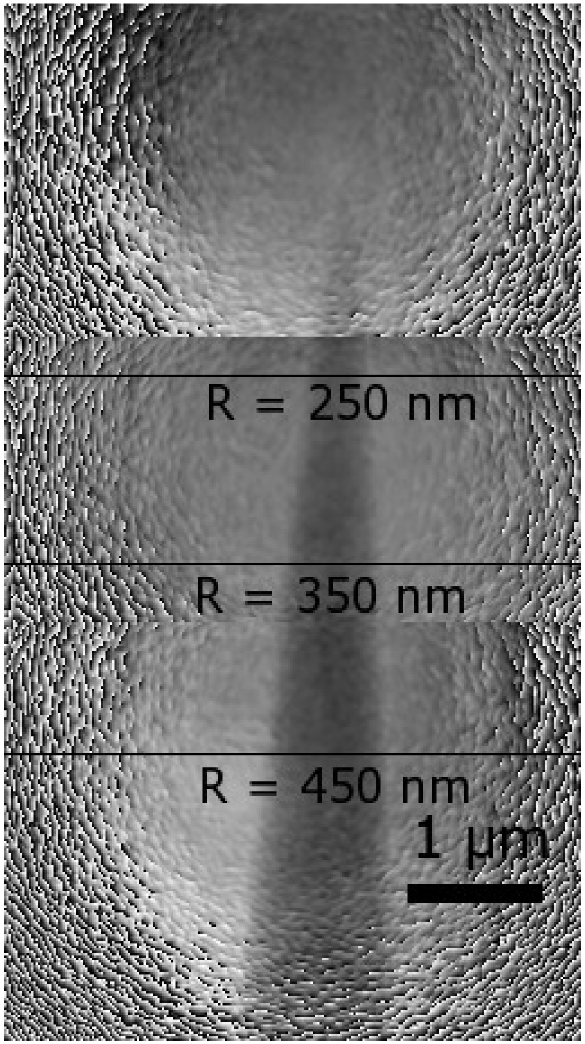


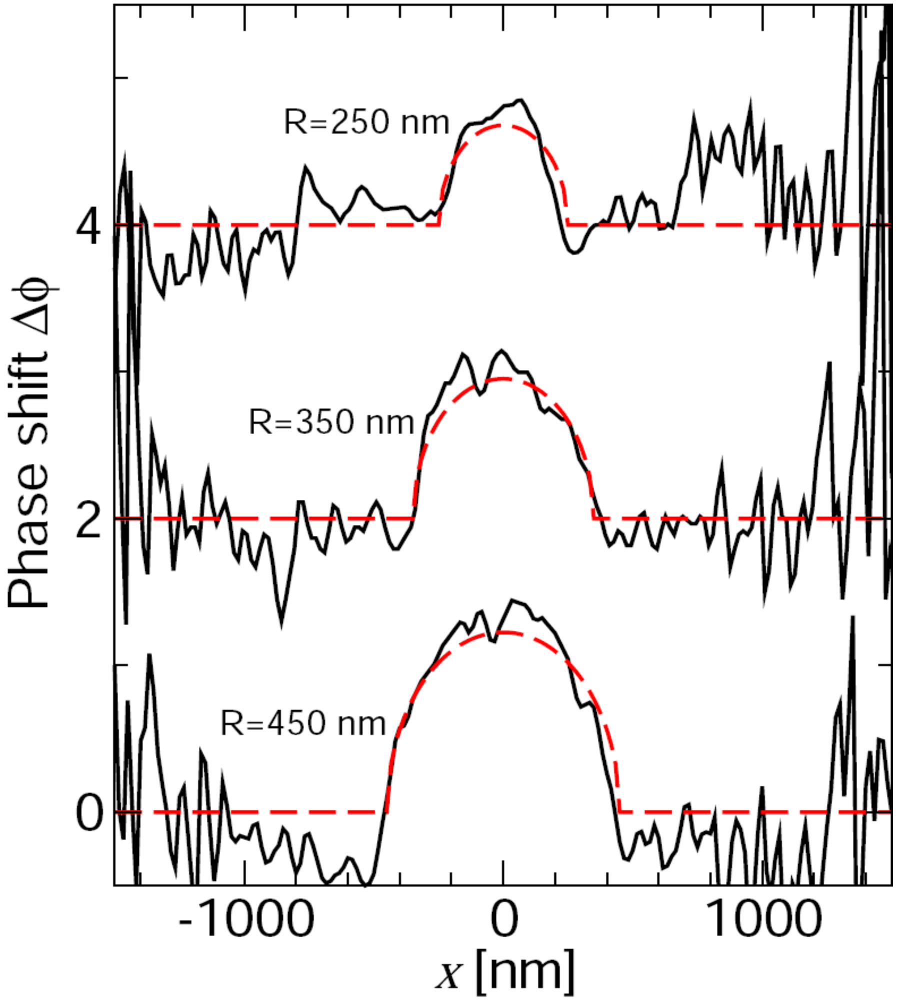
off-axis
hologram
(E=10.4 keV)

phase of the
reconstructed wave
(from 25 holograms)



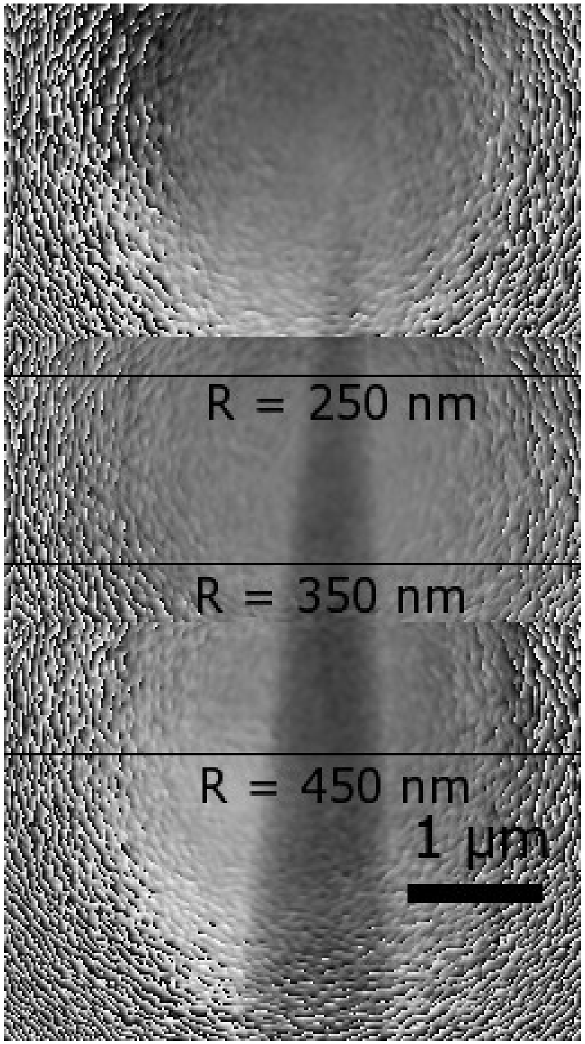
Quantitative analysis

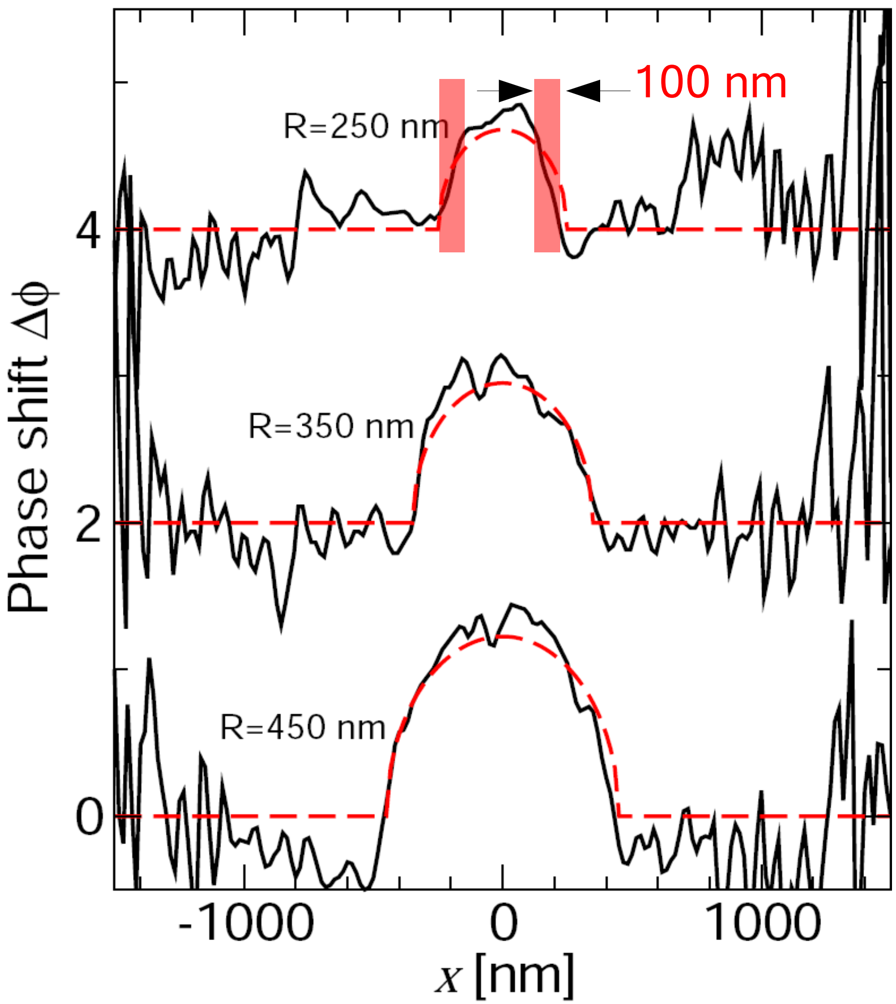




→ Phase of the reconstructed wave in <u>quantitative</u> agreement with the simulation!

Quantitative analysis





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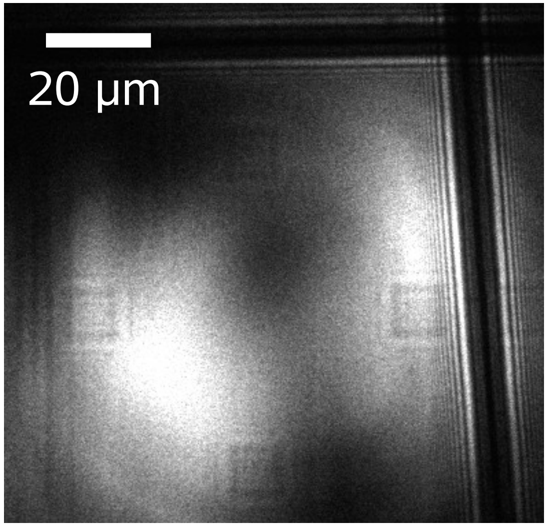
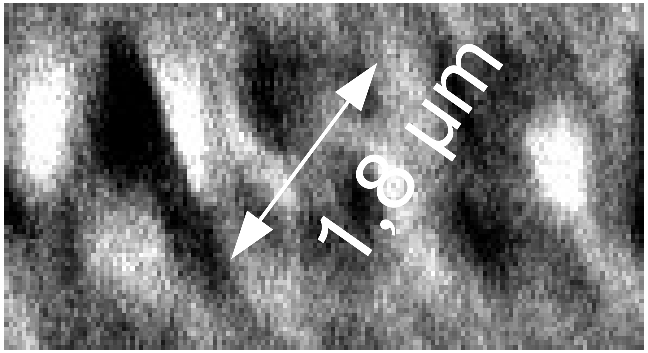
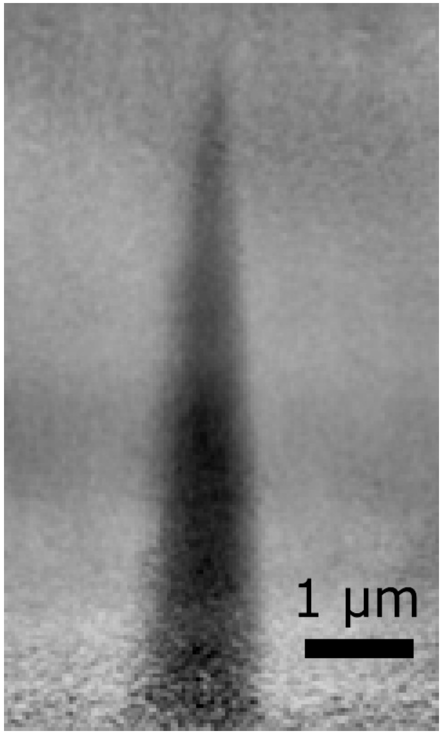
Summary: State of the art



- lensless imaging with a single waveguide:
  - "direct" imaging of large objects (phase & absorption)
  - holographic reconstruction of smaller features resolution ≈ 360 nm but: severe artifacts ("twin image")





- off-axis holography with two waveguides
  - better image quality
  - better spatial resolution (≈ 100 nm)
  - **quantitative** determination of the phase (→ projected electron density)

Perspectives

- **3D imaging: tomography:**
  small numerical aperture → large focal depth
  large penetration depth (in particular in the hard-X-ray regime)

  ERL seems to be a well-suited source!

- **temporal resolution:**
  single-shot experiments with highly-brilliant pulsed sources
  XFEL seems well-suited

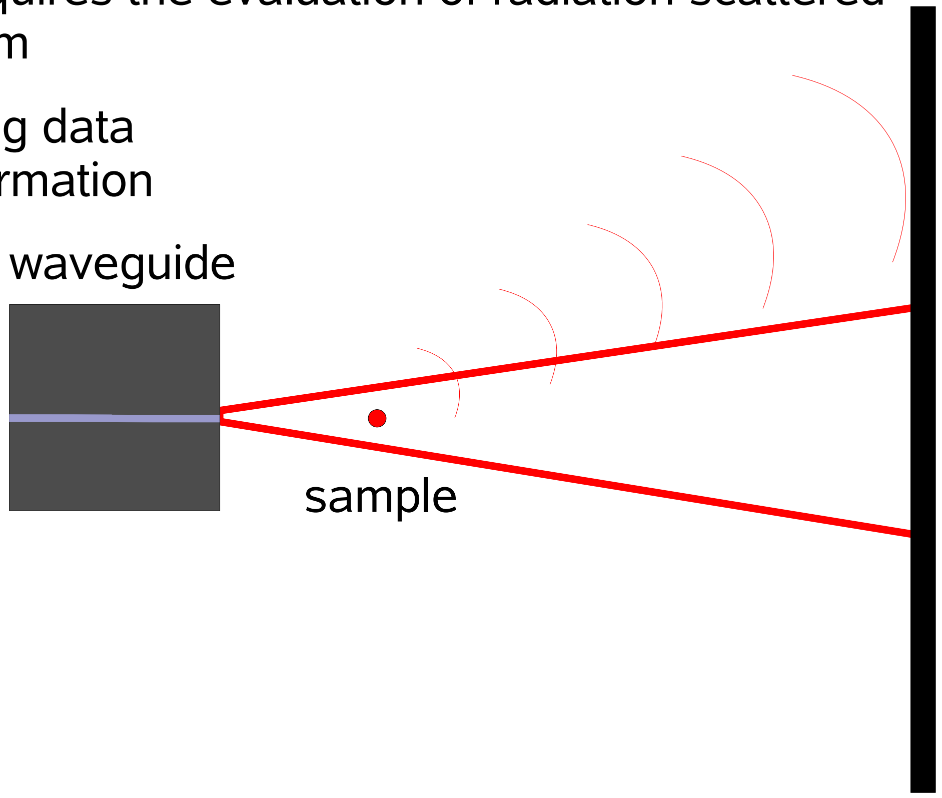
- **increase spatial resolution:**
  cross-sectional dimensions of the guiding core

  fundamental limit: ~ 10 nm

  depending on the electron density of the utilized materials
  [C. Bergemann,H. Keymeulen and J. F. van der Veen, Phys. Rev. Lett. **91**, 204801 (2003)]

Can we achieve 1 nm resolution?

- waveguide core dimensions determine NA of the waveguide beam
  spatial resolution ≈ core dimensions
- higher spatial resolution requires the evaluation of radiation scattered outside the waveguide beam
- measure coherent scattering data
  problem: loss of phase information



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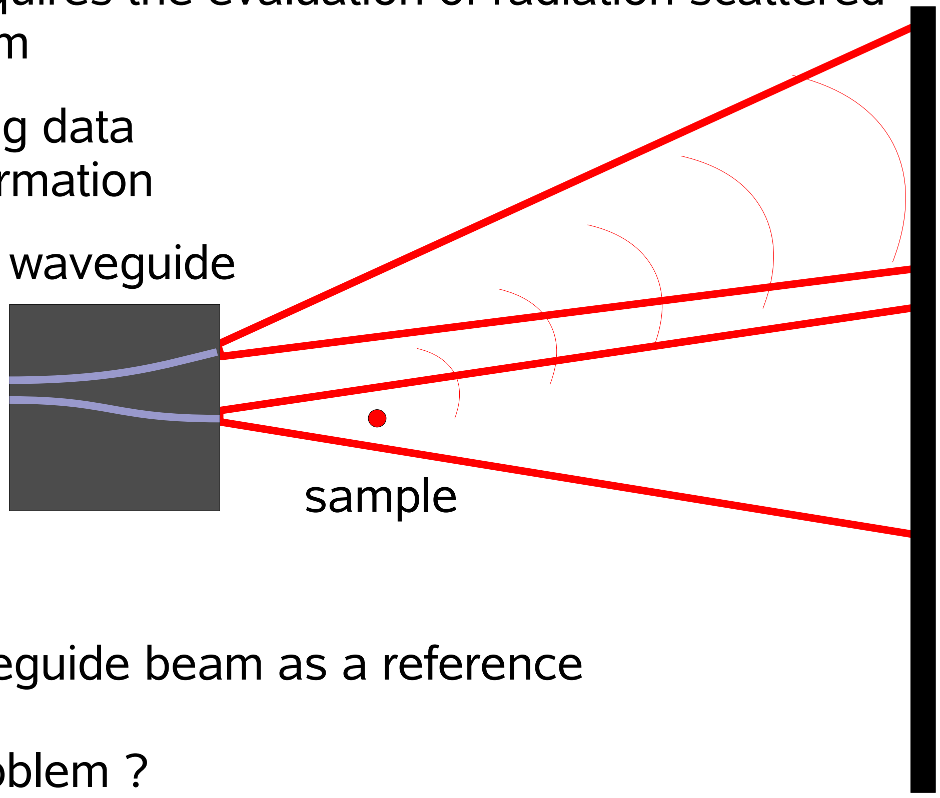
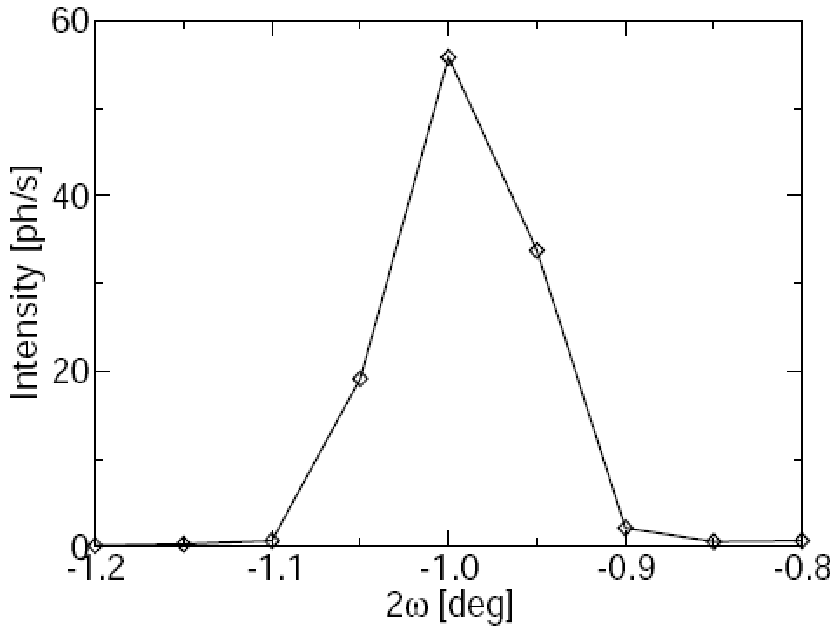


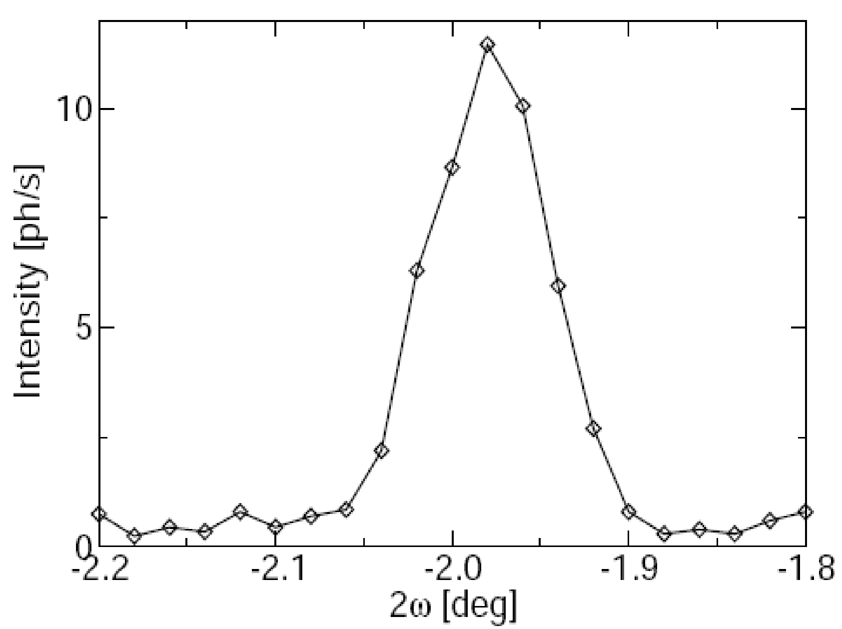
use an additional bent waveguide beam as a reference
to measure the phase!
→ solution of the phase problem ?
→ How far can we bend the waveguides ?

Can we achieve 1 nm resolution?

beams from bent waveguides (Si/calixarene, d ≈ 60 nm, E=12 keV)
(ROBL beamline, ESRF)



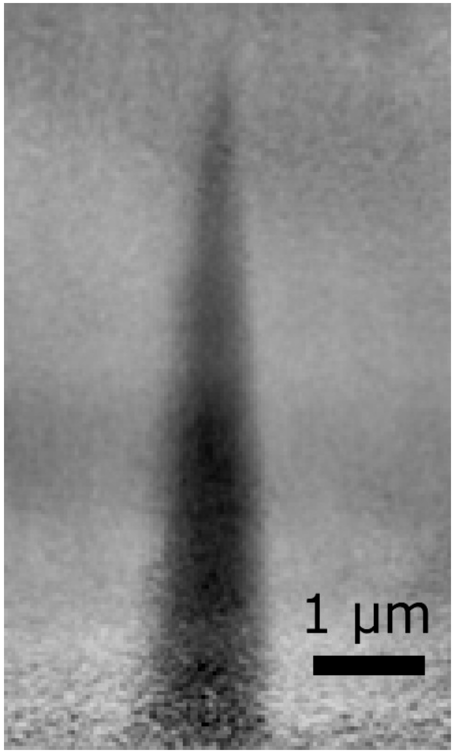
bent to 1°
losses: a factor of about 3



bent to 2°
losses: a factor of about 15

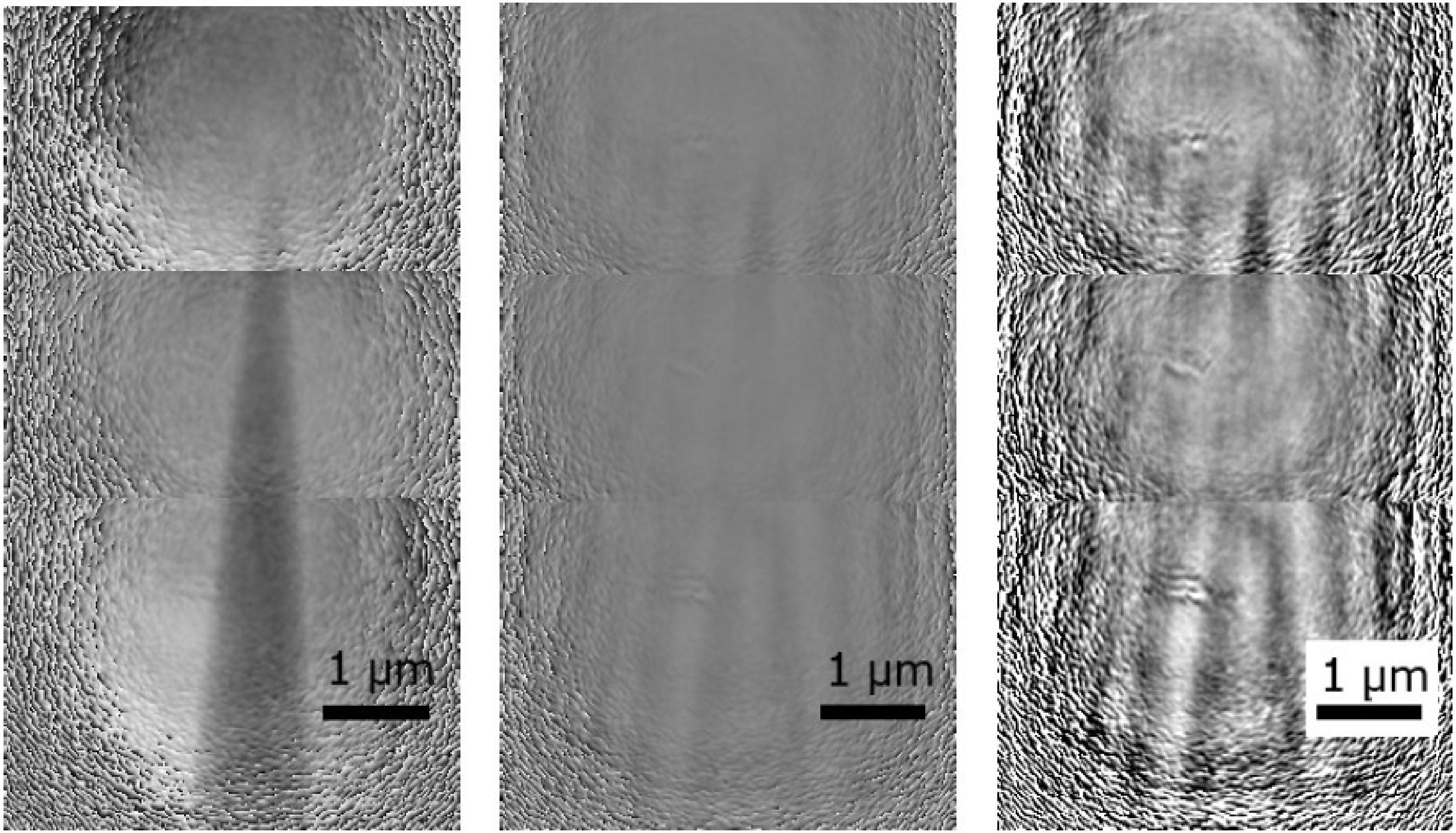
NA = 2° → spatial resolution ≈ λ / 2NA ≈ 1.5 nm

Acknowledgments



- Ansgar Jarre, Jens Seeger, Sebastian Kalbfleisch, (Insitute of X-ray Physics, Göttingen)
- ESRF:
  - ID22 (Remi Tucoulou) → imaging experiments
  - ROBL (Norbert Schell) → curved waveguides
- Institute of Material Physics, Göttingen: Talaat Al-Kassab (tungsten tips)
- German Federal Ministry of Education and Research (BMBF, grant no. 05 KS4MGA/9)

Comparison off-axis / in-line

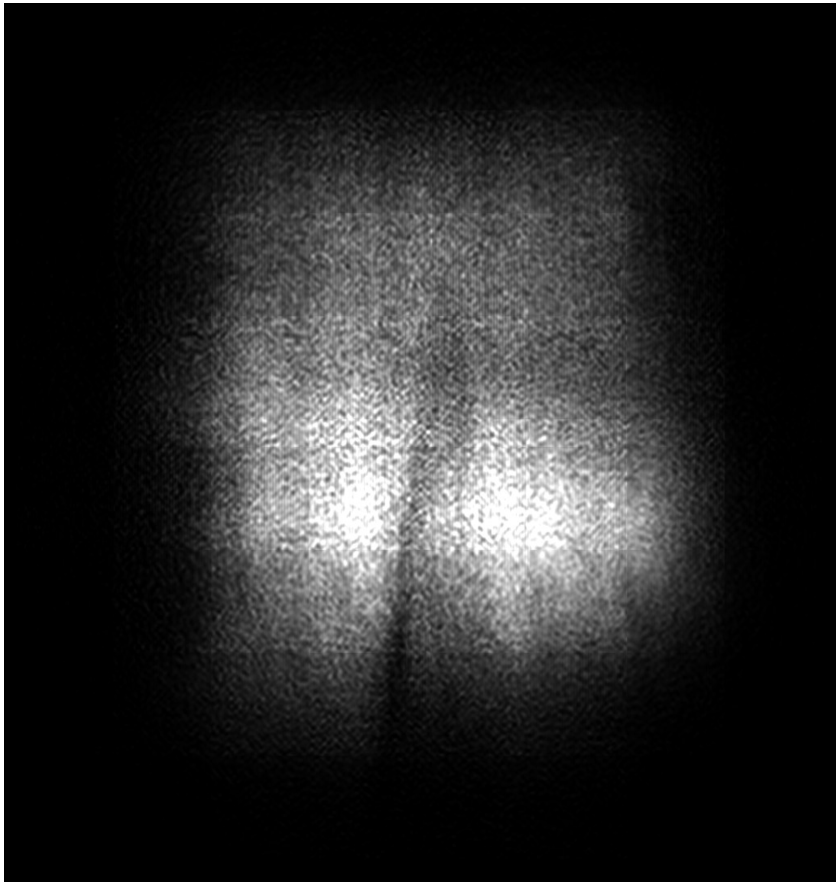


(a) Reconstructed first-order beam (off-axis reconstruction).

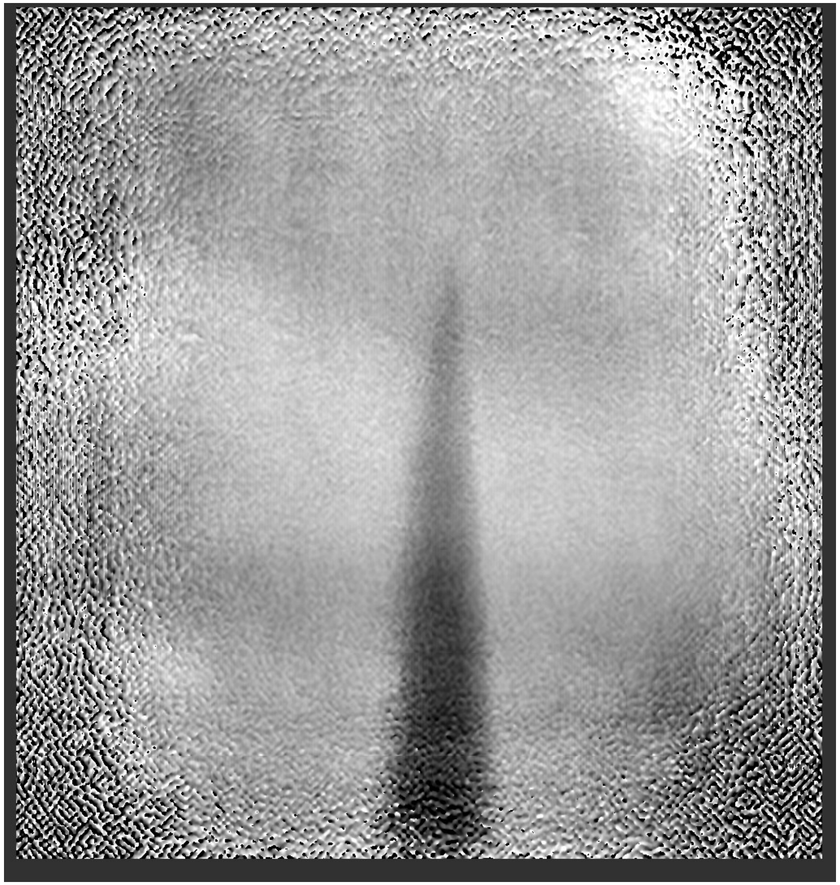
(b) Reconstructed zeroth-order beam (in-line reconstruction).

(c) Contrast-enhanced zeroth-order reconstruction.

Comparison of phase and intensity

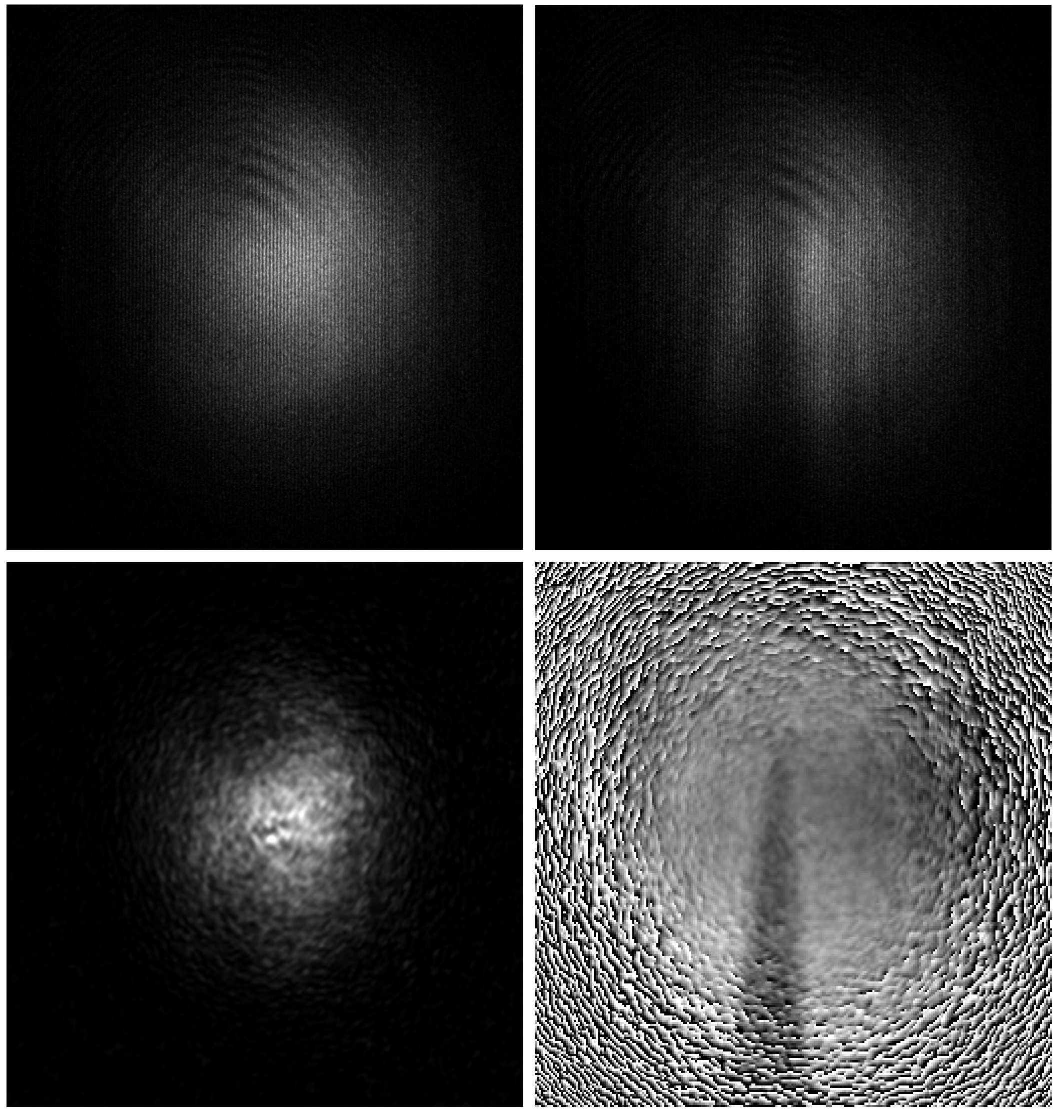


intensity



phase

Off-axis holography



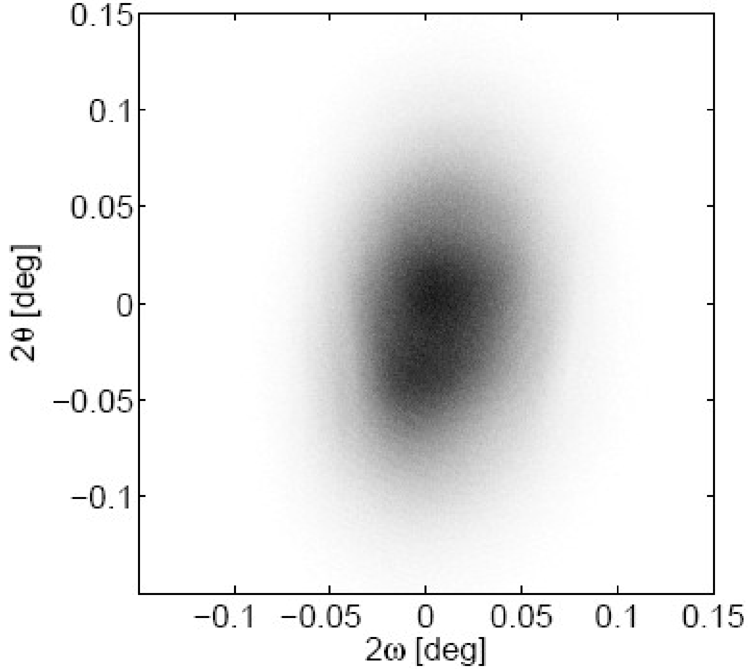
far-field without sample

hologram of the sample

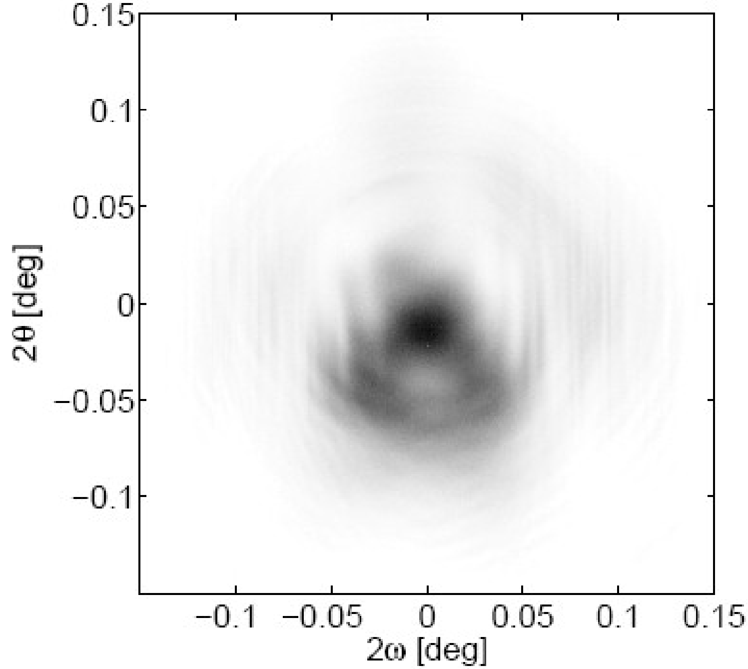
reconstruction (intensity)

reconstruction (phase)

Beam damage



(a) New waveguide.



(b) Used waveguide.

Fabrication of x-ray waveguides