Today's Outline - April 28, 2015

Today's Outline - April 28, 2015

- Phase Contrast Imaging

Today's Outline - April 28, 2015

- Phase Contrast Imaging
- Grating Interferometry

Today's Outline - April 28, 2015

- Phase Contrast Imaging
- Grating Interferometry
- Coherent Diffraction Imaging

Today's Outline - April 28, 2015

- Phase Contrast Imaging
- Grating Interferometry
- Coherent Diffraction Imaging
- Holography

Today's Outline - April 28, 2015

- Phase Contrast Imaging
- Grating Interferometry
- Coherent Diffraction Imaging
- Holography

Final Exam information

Tuesday, May 5, 2015, room 240 Life Sciences

Wavefield propagation

In order to understand many of these imaging techniques, it is important to have a good model for wave propagation in an optical system

Wavefield propagation

In order to understand many of these imaging techniques, it is important to have a good model for wave propagation in an optical system

start with a monochromatic plane wave propagating in the z direction, described by the function e^{ikz} with wavelength $\lambda = 2\pi/k$

Wavefield propagation

In order to understand many of these imaging techniques, it is important to have a good model for wave propagation in an optical system

start with a monochromatic plane wave propagating in the z direction, described by the function e^{ikz} with wavelength $\lambda = 2\pi/k$

when the wavefront passes through an optical element or a sample, it is distorted such that the wavefield at $z = 0$ is now a function of the transverse dimensions, x and y: $\psi_0(x, y)$

Wavefield propagation

In order to understand many of these imaging techniques, it is important to have a good model for wave propagation in an optical system

start with a monochromatic plane wave propagating in the z direction, described by the function e^{ikz} with wavelength $\lambda = 2\pi/k$

when the wavefront passes through an optical element or a sample, it is distorted such that the wavefield at $z = 0$ is now a function of the transverse dimensions, x and y: $\psi_0(x, y)$

our goal is to determine the wavefield at a distance z downstream and this is done by constructing a propagation operator $\hat{D}_z$ such that

Wavefield propagation

In order to understand many of these imaging techniques, it is important to have a good model for wave propagation in an optical system

start with a monochromatic plane wave propagating in the z direction, described by the function e^{ikz} with wavelength $\lambda = 2\pi/k$

when the wavefront passes through an optical element or a sample, it is distorted such that the wavefield at $z = 0$ is now a function of the transverse dimensions, x and y: $\psi_0(x, y)$

our goal is to determine the wavefield at a distance z downstream and this is done by constructing a propagation operator $\hat{D}_z$ such that

$$\psi_z = \hat{D}_z \psi_0(x, y)$$

Wavefield propagation

In order to understand many of these imaging techniques, it is important to have a good model for wave propagation in an optical system

start with a monochromatic plane wave propagating in the z direction, described by the function e^{ikz} with wavelength $\lambda = 2\pi/k$

when the wavefront passes through an optical element or a sample, it is distorted such that the wavefield at $z = 0$ is now a function of the transverse dimensions, x and y: $\psi_0(x, y)$

our goal is to determine the wavefield at a distance z downstream and this is done by constructing a propagation operator $\hat{D}_z$ such that

$$\psi_z = \hat{D}_z \psi_0(x, y)$$

The Fourier transform is used to generate this propagation operator in the following way (showing only the x dependence for simplicity)

Wavefield propagation

In order to understand many of these imaging techniques, it is important to have a good model for wave propagation in an optical system

start with a monochromatic plane wave propagating in the z direction, described by the function e^{ikz} with wavelength $\lambda = 2\pi/k$

when the wavefront passes through an optical element or a sample, it is distorted such that the wavefield at $z = 0$ is now a function of the transverse dimensions, x and y: $\psi_0(x, y)$

our goal is to determine the wavefield at a distance z downstream and this is done by constructing a propagation operator $\hat{D}_z$ such that

$$\psi_z = \hat{D}_z \psi_0(x, y)$$

The Fourier transform is used to generate this propagation operator in the following way (showing only the x dependence for simplicity)

$$\psi_0(x) = \frac{1}{2\pi} \int \tilde{\psi}_0(k_x) e^{-ik_x x} dk_x$$

Wavefield propagation

$$\psi_0(x) = \frac{1}{2\pi} \int \tilde{\psi}_0(k_x) e^{-ik_x x} dk_x$$

Wavefield propagation

$$\psi_0(x) = \frac{1}{2\pi} \int \tilde{\psi}_0(k_x) e^{-ik_x x} dk_x$$

in words, this says that at $z = 0$ the wavefield is a superposition of plane waves each of which is a function of the total wavevector $\vec{k} = k_x\hat{x} + k_z\hat{z}$

Wavefield propagation

$$\psi_0(x) = \frac{1}{2\pi} \int \tilde{\psi}_0(k_x) e^{-ik_x x} dk_x$$

in words, this says that at $z = 0$ the wavefield is a superposition of plane waves each of which is a function of the total wavevector $\vec{k} = k_x \hat{x} + k_z \hat{z}$

We can rewrite the relationships as follows

Wavefield propagation

$$\psi_0(x) = \frac{1}{2\pi} \int \tilde{\psi}_0(k_x) e^{-ik_x x} dk_x$$

in words, this says that at $z = 0$ the wavefield is a superposition of plane waves each of which is a function of the total wavevector $\vec{k} = k_x \hat{x} + k_z \hat{z}$

We can rewrite the relationships as follows

$$k_z = \sqrt{k^2 - k_x^2}$$

Wavefield propagation

$$\psi_0(x) = \frac{1}{2\pi} \int \tilde{\psi}_0(k_x) e^{-ik_x x} dk_x$$

in words, this says that at $z = 0$ the wavefield is a superposition of plane waves each of which is a function of the total wavevector $\vec{k} = k_x \hat{x} + k_z \hat{z}$

We can rewrite the relationships as follows but if $k_x \ll k$ we have

$$k_z = \sqrt{k^2 - k_x^2}$$

Wavefield propagation

$$\psi_0(x) = \frac{1}{2\pi} \int \tilde{\psi}_0(k_x) e^{-ik_x x} dk_x$$

in words, this says that at $z = 0$ the wavefield is a superposition of plane waves each of which is a function of the total wavevector $\vec{k} = k_x \hat{x} + k_z \hat{z}$

We can rewrite the relationships as follows but if $k_x \ll k$ we have

$$k_z = \sqrt{k^2 - k_x^2} \approx k - \frac{k_x^2}{2k}$$

Wavefield propagation

$$\psi_0(x) = \frac{1}{2\pi}\int \tilde{\psi}_0(k_x)e^{-ik_x x}dk_x$$

in words, this says that at $z = 0$ the wavefield is a superposition of plane waves each of which is a function of the total wavevector $\vec{k} = k_x\hat{x} + k_z\hat{z}$

We can rewrite the relationships as follows but if $k_x \ll k$ we have

$$k_z = \sqrt{k^2 - k_x^2} \approx k - \frac{k_x^2}{2k}$$

each of the plane waves $\tilde{\psi}_0 e^{-ik_x x}$ propagates to z by multiplication with a phase factor

Wavefield propagation

$$\psi_0(x) = \frac{1}{2\pi} \int \tilde{\psi}_0(k_x) e^{-ik_x x} dk_x$$

in words, this says that at $z = 0$ the wavefield is a superposition of plane waves each of which is a function of the total wavevector $\vec{k} = k_x \hat{x} + k_z \hat{z}$

We can rewrite the relationships as follows but if $k_x \ll k$ we have

$$k_z = \sqrt{k^2 - k_x^2} \approx k - \frac{k_x^2}{2k}$$

each of the plane waves $\tilde{\psi}_0 e^{-ik_x x}$ propagates to z by multiplication with a phase factor

$$\tilde{\psi}_0 e^{-ik_x x} \rightarrow \tilde{\psi}_0 e^{-ik_x x} e^{ik_z z}$$

Wavefield propagation

$$\psi_0(x) = \frac{1}{2\pi} \int \tilde{\psi}_0(k_x) e^{-ik_x x} dk_x$$

in words, this says that at $z = 0$ the wavefield is a superposition of plane waves each of which is a function of the total wavevector $\vec{k} = k_x \hat{x} + k_z \hat{z}$

We can rewrite the relationships as follows but if $k_x \ll k$ we have

$$k_z = \sqrt{k^2 - k_x^2} \approx k - \frac{k_x^2}{2k}$$

each of the plane waves $\tilde{\psi}_0 e^{-ik_x x}$ propagates to z by multiplication with a phase factor

$$\tilde{\psi}_0 e^{-ik_x x} \rightarrow \tilde{\psi}_0 e^{-ik_x x} e^{ik_z z} = \tilde{\psi}_0 e^{-ik_x x} e^{ikz} e^{-ik_x^2 z/2k} = \tilde{\psi}_z(k_x)$$

Wavefield propagation

$$\psi_0(x) = \frac{1}{2\pi}\int \tilde{\psi}_0(k_x)e^{-ik_x x}dk_x$$

in words, this says that at $z = 0$ the wavefield is a superposition of plane waves each of which is a function of the total wavevector $\vec{k} = k_x\hat{x} + k_z\hat{z}$

We can rewrite the relationships as follows but if $k_x \ll k$ we have

$$k_z = \sqrt{k^2 - k_x^2} \approx k - \frac{k_x^2}{2k}$$

each of the plane waves $\tilde{\psi}_0 e^{-ik_x x}$ propagates to z by multiplication with a phase factor

$$\tilde{\psi}_0 e^{-ik_x x} \rightarrow \tilde{\psi}_0 e^{-ik_x x} e^{ik_z z} = \tilde{\psi}_0 e^{-ik_x x} e^{ikz} e^{-ik_x^2 z/2k} = \tilde{\psi}_z(k_x)$$

$$\psi_z(x) = \mathcal{FT}^{-1}[\tilde{\psi}_z(k_x)]$$

Wavefield propagation

$$\psi_0(x) = \frac{1}{2\pi} \int \tilde{\psi}_0(k_x) e^{-ik_x x} dk_x$$

in words, this says that at $z = 0$ the wavefield is a superposition of plane waves each of which is a function of the total wavevector $\vec{k} = k_x \hat{x} + k_z \hat{z}$

We can rewrite the relationships as follows but if $k_x \ll k$ we have

$$k_z = \sqrt{k^2 - k_x^2} \approx k - \frac{k_x^2}{2k}$$

each of the plane waves $\tilde{\psi}_0 e^{-ik_x x}$ propagates to z by multiplication with a phase factor

$$\tilde{\psi}_0 e^{-ik_x x} \rightarrow \tilde{\psi}_0 e^{-ik_x x} e^{ik_z z} = \tilde{\psi}_0 e^{-ik_x x} e^{ikz} e^{-ik_x^2 z/2k} = \tilde{\psi}_z(k_x)$$

$$\psi_z(x) = \mathcal{FT}^{-1}[\tilde{\psi}_z(k_x)] = \frac{1}{2\pi} \int \tilde{\psi}_z(k_x) e^{-ik_x x} dk_x$$

Wavefield propagation

$$\psi_0(x) = \frac{1}{2\pi}\int \tilde{\psi}_0(k_x)e^{-ik_x x}dk_x$$

in words, this says that at $z = 0$ the wavefield is a superposition of plane waves each of which is a function of the total wavevector $\vec{k} = k_x\hat{x} + k_z\hat{z}$

We can rewrite the relationships as follows but if $k_x \ll k$ we have

$$k_z = \sqrt{k^2 - k_x^2} \approx k - \frac{k_x^2}{2k}$$

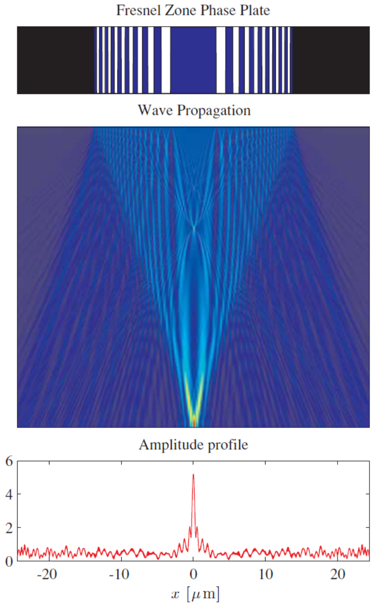
each of the plane waves $\tilde{\psi}_0 e^{-ik_x x}$ propagates to z by multiplication with a phase factor

$$\tilde{\psi}_0 e^{-ik_x x} \rightarrow \tilde{\psi}_0 e^{-ik_x x}e^{ik_z z} = \tilde{\psi}_0 e^{-ik_x x}e^{ikz}e^{-ik_x^2 z/2k} = \tilde{\psi}_z(k_x)$$

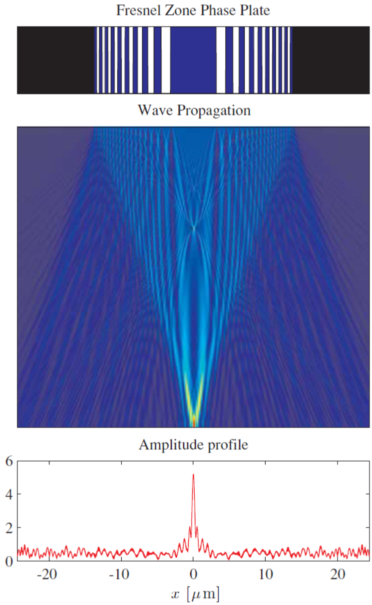
$$\psi_z(x) = \mathcal{FT}^{-1}[\tilde{\psi}_z(k_x)] = \frac{1}{2\pi}\int \tilde{\psi}_z(k_x)e^{-ik_x x}dk_x$$

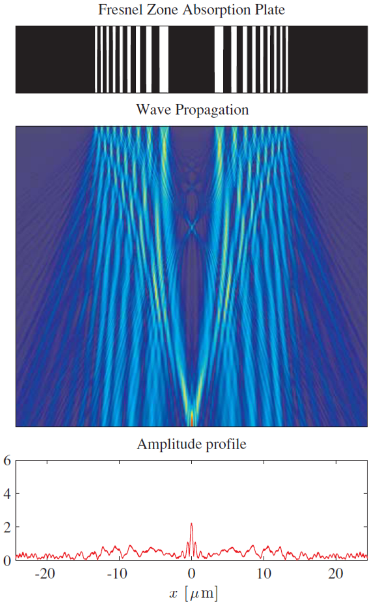
$$\psi_z(x,y) = \hat{D}_z\psi_0(x,y) = e^{ikz}\,\mathcal{FT}^{-1}\left[e^{-iz(k_x^2+k_y^2)/2k}\,\mathcal{FT}[\psi_0(x,y)]\right]$$

Fresnel zone plates



Fresnel zone plates





Grating interferometry

Full field phase imaging can be achieved using an interferometric technique

Grating interferometry

Full field phase imaging can be achieved using an interferometric technique
Talbot effect: vertical grating illuminated by a plane wave

Grating interferometry

Full field phase imaging can be achieved using an interferometric technique
Talbot effect: vertical grating illuminated by a plane wave

for a vertical grating of period p_1 illuminated by a wavelength λ

$$k_x = 2\pi/p_1,\ \ 4\pi/p_1,\ \ 6\pi/p_1,\ \ \cdots$$

Grating interferometry

Full field phase imaging can be achieved using an interferometric technique
Talbot effect: vertical grating illuminated by a plane wave

for a vertical grating of period p_1 illuminated by a wavelength λ

$$k_x = 2\pi/p_1, \;\; 4\pi/p_1, \;\; 6\pi/p_1, \;\; \cdots$$

$\tilde{\psi}_x \sim \mathrm{e}^{\mathrm{i k_x^2 z/(2k)}}$

Grating interferometry

Full field phase imaging can be achieved using an interferometric technique
Talbot effect: vertical grating illuminated by a plane wave

for a vertical grating of period p_1 illuminated by a wavelength λ

$$k_x = 2\pi/p_1,\;\; 4\pi/p_1,\;\; 6\pi/p_1,\;\; \cdots$$

$$\begin{aligned}\tilde{\psi}_x &\sim \mathrm{e}^{\mathrm{i}\mathrm{k}_\mathrm{x}^2\mathrm{z}/(2\mathrm{k})} \\ &\sim e^{i(2\pi/p_1)^2 z/(2k)}\end{aligned}$$

Grating interferometry

Full field phase imaging can be achieved using an interferometric technique
Talbot effect: vertical grating illuminated by a plane wave

for a vertical grating of period p_1 illuminated by a wavelength λ

$$k_x = 2\pi/p_1, \;\; 4\pi/p_1, \;\; 6\pi/p_1, \;\; \cdots$$

$$\begin{aligned} \tilde{\psi}_x &\sim \mathrm{e}^{\mathrm{i}\mathrm{k}_\mathrm{x}^2\mathrm{z}/(2\mathrm{k})} \\ &\sim e^{i(2\pi/p_1)^2 z/(2k)} \\ &\sim e^{i2\pi\lambda z/(2p_1^2)} \end{aligned}$$

Grating interferometry

Full field phase imaging can be achieved using an interferometric technique
Talbot effect: vertical grating illuminated by a plane wave

for a vertical grating of period p_1 illuminated by a wavelength λ

$$k_x = 2\pi/p_1, \;\; 4\pi/p_1, \;\; 6\pi/p_1, \;\; \cdots$$

$$\begin{aligned}
\tilde{\psi}_x &\sim \mathrm{e}^{\mathrm{i}\mathrm{k}_\mathrm{x}^2\mathrm{z}/(2\mathrm{k})} \\
&\sim e^{i(2\pi/p_1)^2 z/(2k)} \\
&\sim e^{i2\pi\lambda z/(2p_1^2)}
\end{aligned}$$

$$d_T = 2p_1^2/\lambda$$

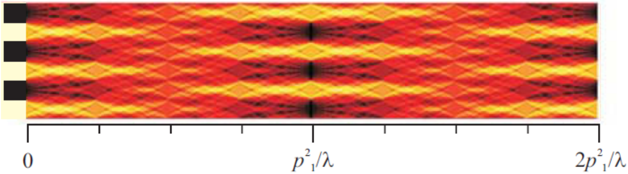
Grating interferometry

Full field phase imaging can be achieved using an interferometric technique
Talbot effect: vertical grating illuminated by a plane wave

for a vertical grating of period p_1 illuminated by a wavelength λ

$$k_x = 2\pi/p_1,\ \ 4\pi/p_1,\ \ 6\pi/p_1,\ \ \cdots$$

$$\tilde{\psi}_x \sim e^{\mathrm{i}k_x^2 z/(2k)}$$
$$\sim e^{i(2\pi/p_1)^2 z/(2k)}$$
$$\sim e^{i2\pi\lambda z/(2p_1^2)}$$
$$d_T = 2p_1^2/\lambda$$



for $p_1 = 1\mu$m and $\lambda = 1$Å we have a repeat distance, $d_T = 20$mm

Grating interferometry

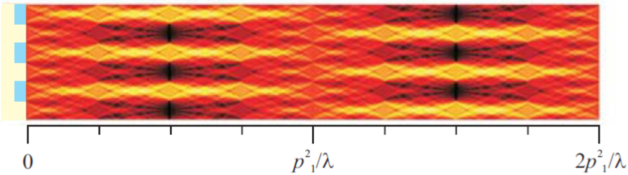
Full field phase imaging can be achieved using an interferometric technique
Talbot effect: vertical grating illuminated by a plane wave

for a vertical grating of period p_1 illuminated by a wavelength λ

$$k_x = 2\pi/p_1,\ \ 4\pi/p_1,\ \ 6\pi/p_1,\ \ \cdots$$

$$\begin{aligned}\tilde{\psi}_x &\sim e^{\mathrm{i}k_x^2 z/(2k)} \\ &\sim e^{i(2\pi/p_1)^2 z/(2k)} \\ &\sim e^{i2\pi\lambda z/(2p_1^2)}\end{aligned}$$

$$d_T = 2p_1^2/\lambda$$



for $p_1 = 1\mu$m and $\lambda = 1$Å we have a repeat distance, $d_T = 20$mm

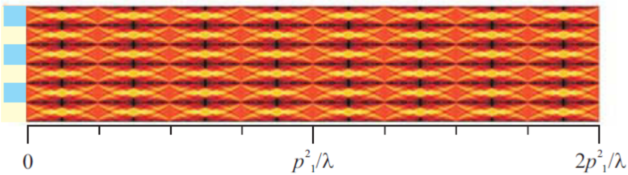
Grating interferometry

Full field phase imaging can be achieved using an interferometric technique
Talbot effect: vertical grating illuminated by a plane wave

for a vertical grating of period p_1 illuminated by a wavelength λ

$$k_x = 2\pi/p_1, \;\; 4\pi/p_1, \;\; 6\pi/p_1, \;\; \cdots$$

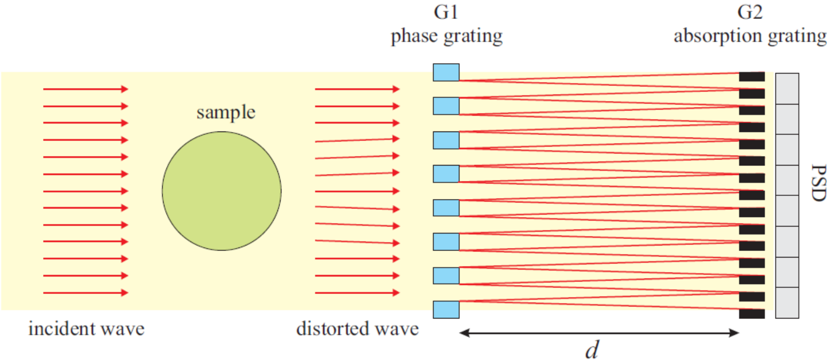
$$\tilde{\psi}_x \sim e^{ik_x^2 z/(2k)}$$
$$\sim e^{i(2\pi/p_1)^2 z/(2k)}$$
$$\sim e^{i2\pi\lambda z/(2p_1^2)}$$
$$d_T = 2p_1^2/\lambda$$



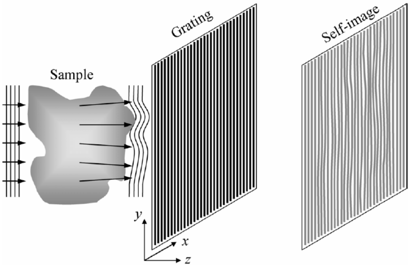
for $p_1 = 1\mu$m and $\lambda = 1$Å we have a repeat distance, $d_T = 20$mm

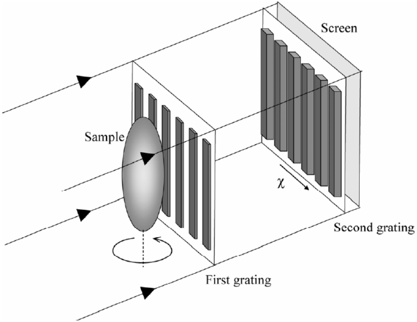
Talbot Interferometer

Use a second grating to measure distortion of phase field due to the sample



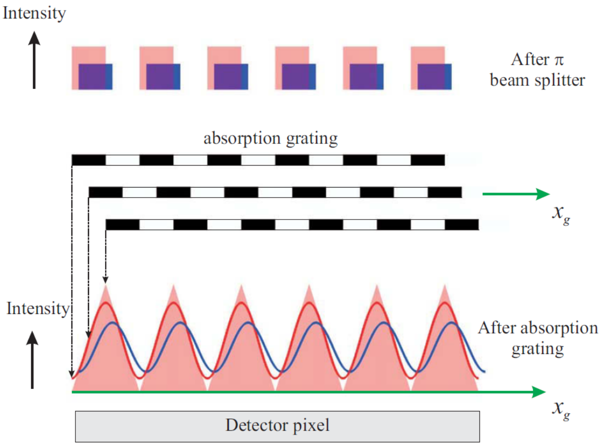
Talbot interferometer setup





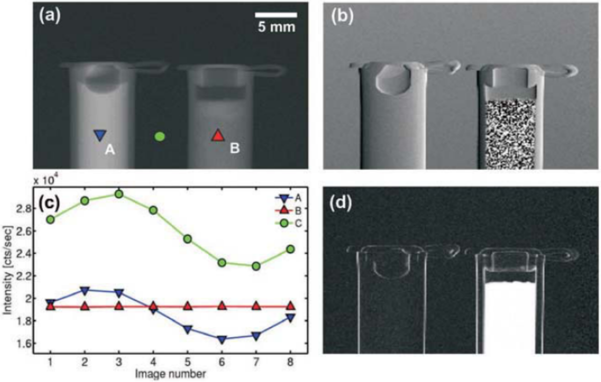
Talbot interferometer

shift second grating to three positions to obtain all the information to produce absorption, dark field and phase contract



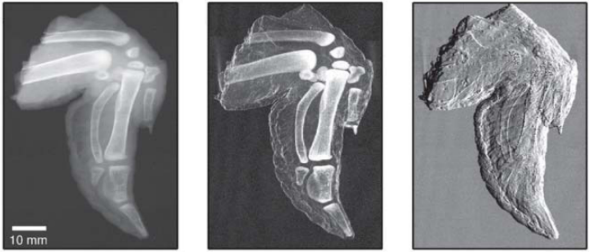
Grating interferometry

Plastic containers filled with water (left) and powdered sugar (right).



(a) absorption image, (b) phase contrast image, (d) dark field image.

Grating interferometry



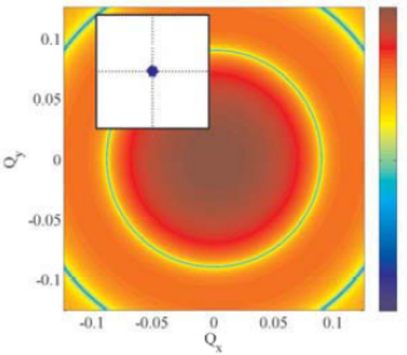
absorption image (left)
dark field image (center)
phase contrast image (right)

SAXS from a sphere

For incoherent beam, illuminating a small particle (a sphere), we have the typical small angle pattern which shows broad features described in a previous chapter

SAXS from a sphere

For incoherent beam, illuminating a small particle (a sphere), we have the typical small angle pattern which shows broad features described in a previous chapter

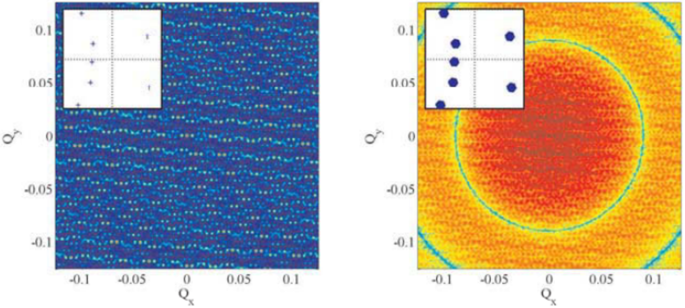


Coherent Scattering from Multiple Spheres

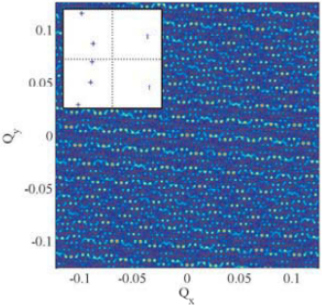
If the beam has coherence at least on the order of the size of the arrangement of the seven spheres shown, one obtains

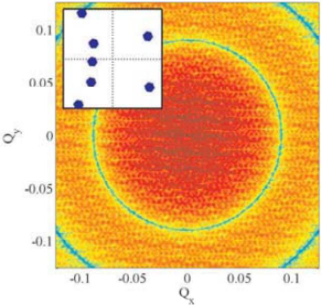
Coherent Scattering from Multiple Spheres

If the beam has coherence at least on the order of the size of the arrangement of the seven spheres shown, one obtains



If the beam has coherence at least on the order of the size of the arrangement of the seven spheres shown, one obtains

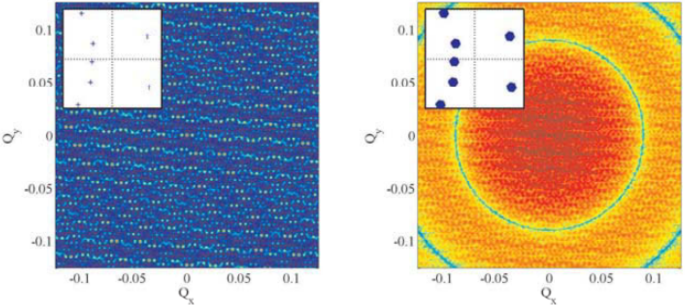




on the left is the "speckle" pattern given by the interference of the coherent beam with the seven spheres

Coherent Scattering from Multiple Spheres

If the beam has coherence at least on the order of the size of the arrangement of the seven spheres shown, one obtains

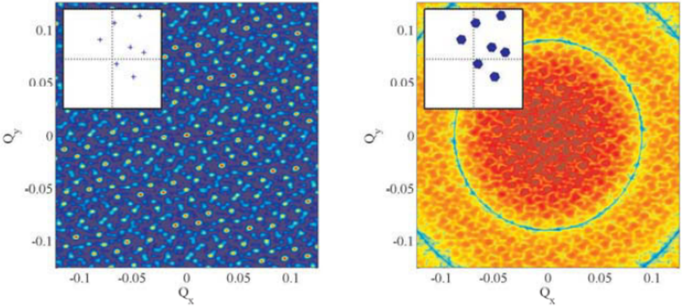


on the left is the "speckle" pattern given by the interference of the coherent beam with the seven spheres

on the right is the full pattern including the SAXS from individual spheres

Coherent Scattering from Multiple Spheres

If the beam has coherence at least on the order of the size of the arrangement of the seven spheres shown, one obtains

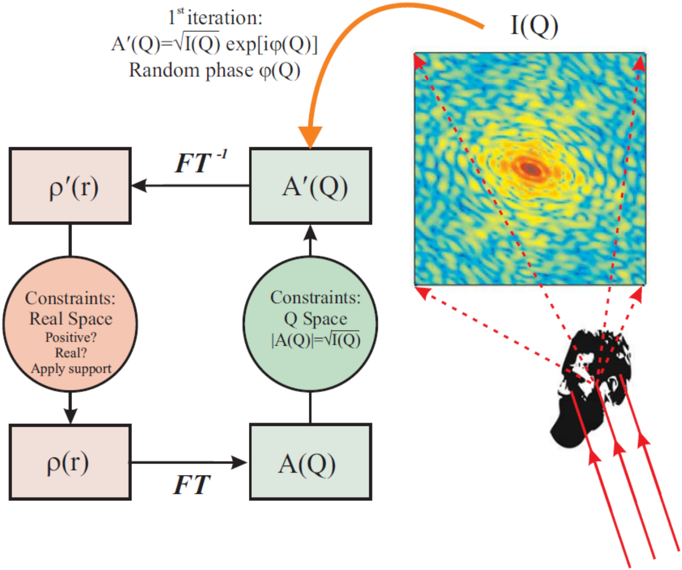


on the left is the "speckle" pattern given by the interference of the coherent beam with the seven spheres

on the right is the full pattern including the SAXS from individual spheres

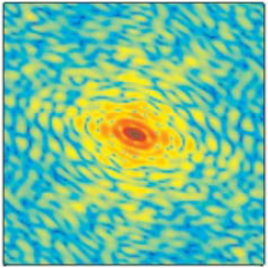
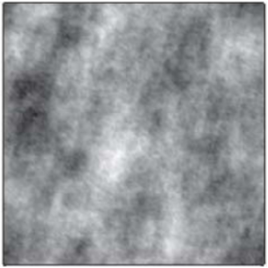
the speckle changes with a different arrangement of spheres

Oversampling and image



Iterative Reconstruction

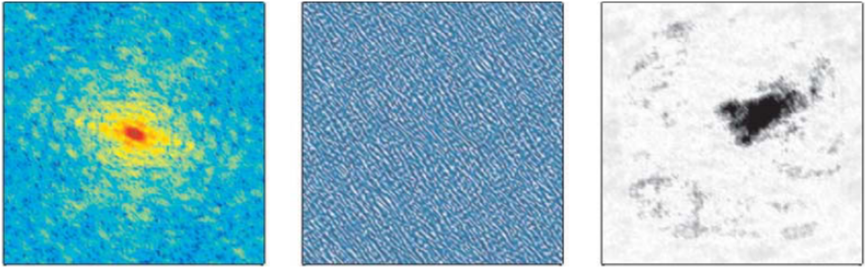
start with experimental data and a randomly generated phase

Iterative Reconstruction

start with experimental data and a randomly generated phase

intermediate step shows partial phase retrieval but distorted scattering pattern

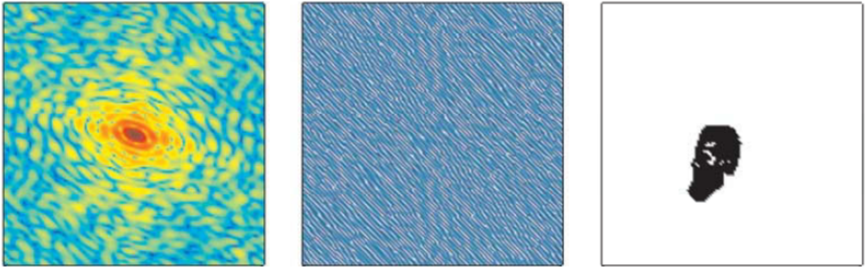


Iterative Reconstruction

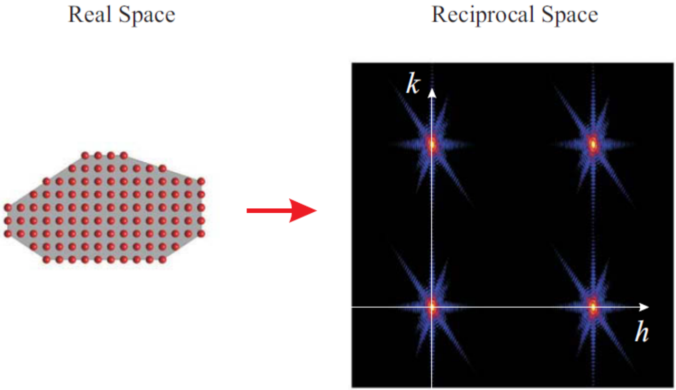
start with experimental data and a randomly generated phase

intermediate step shows partial phase retrieval but distorted scattering pattern

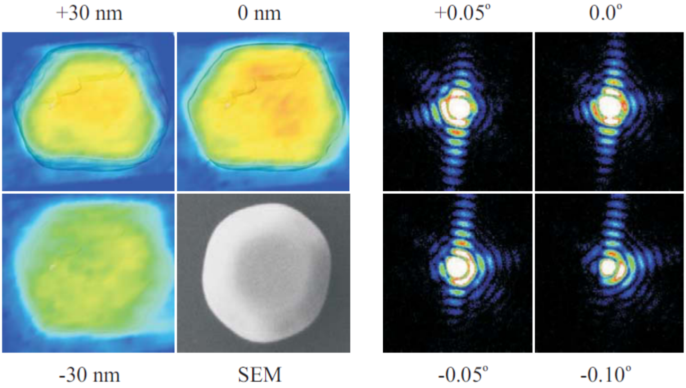
convergence to reonstructed phase, scattering and real space image



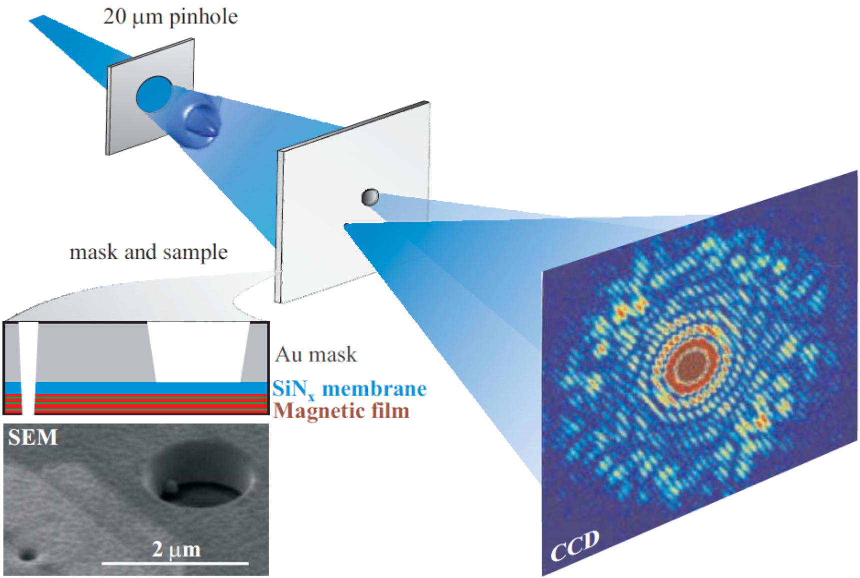
Gold nanoparticle imaging by CXI



Gold nanoparticle imaging by CXI

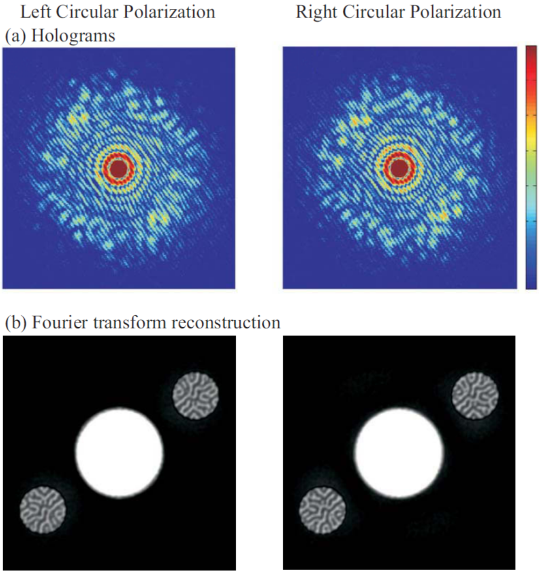


Holography



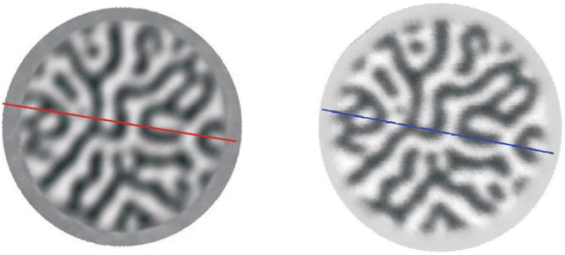
20 μm pinhole
mask and sample
Au mask
SiN$_x$ membrane
Magnetic film
SEM
2 μm
CCD

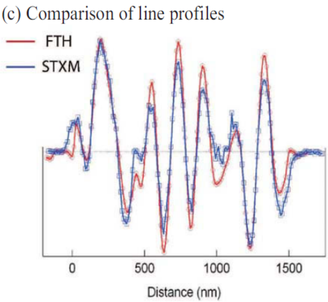
Holography



Left Circular Polarization
Right Circular Polarization
(a) Holograms
(b) Fourier transform reconstruction

Holography




(c) Comparison of line profiles
FTH
STXM
0
500
1000
1500
Distance (nm)