

Design and Fabrication of Diffractive Optical Elements

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Diffraction by opaque screens

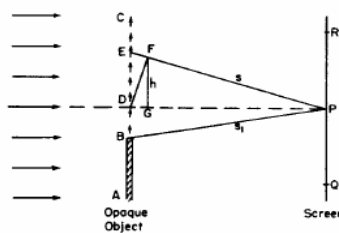
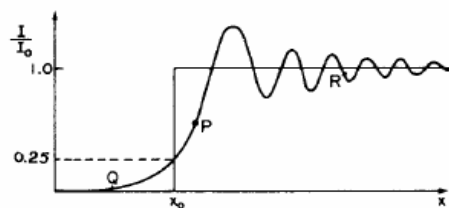


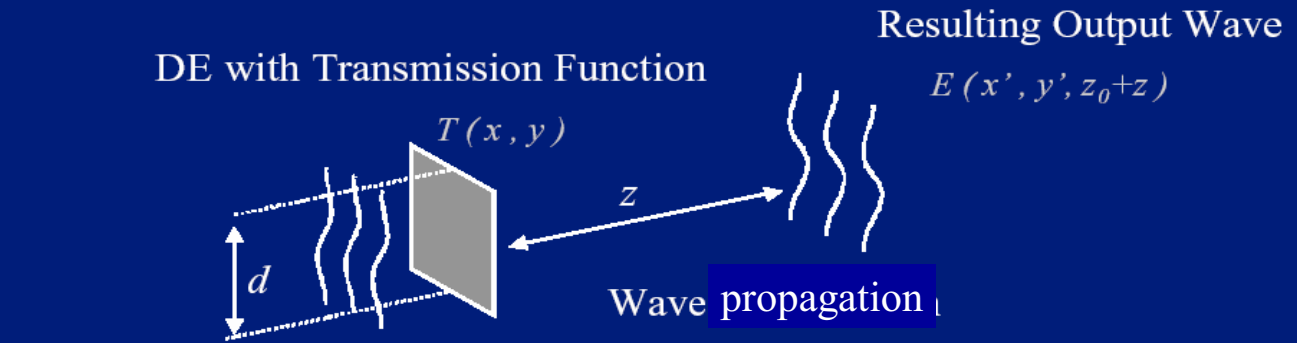
Fig. 30-7. A distant light source casts a shadow of an opaque object on a screen.

Fig. 30-9. The intensity near the edge of a shadow. The geometrical shadow edge is at x_0 .



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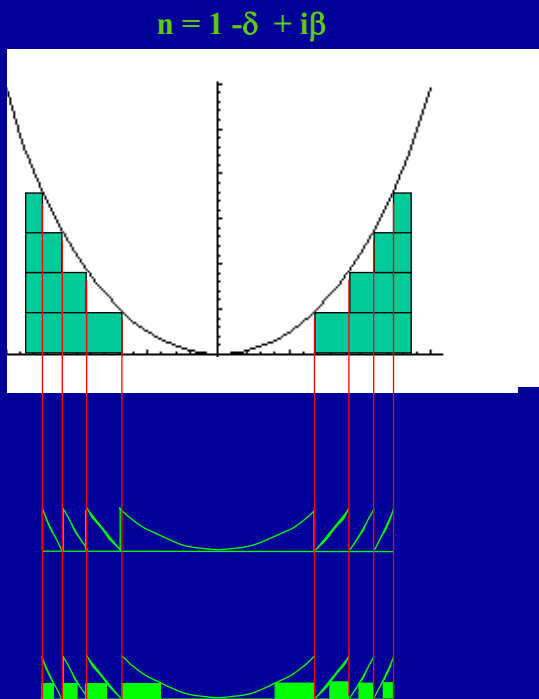
Function principle of DEs



The illumination wave is modulated by the diffractive Element.

The modulated wave propagates through space and results in a certain desired signal wave.

From Refractive to diffractive Optics



β : Imaginary part of complex refractive index;

λ : Incoming wavelength;

μ : Abs. Coefficient;

$\Delta\phi$: Phase shift;

t : Material Thickness;

Refractive Profile



Kinoform Profile:

minimize absorption and simplify fabrication.

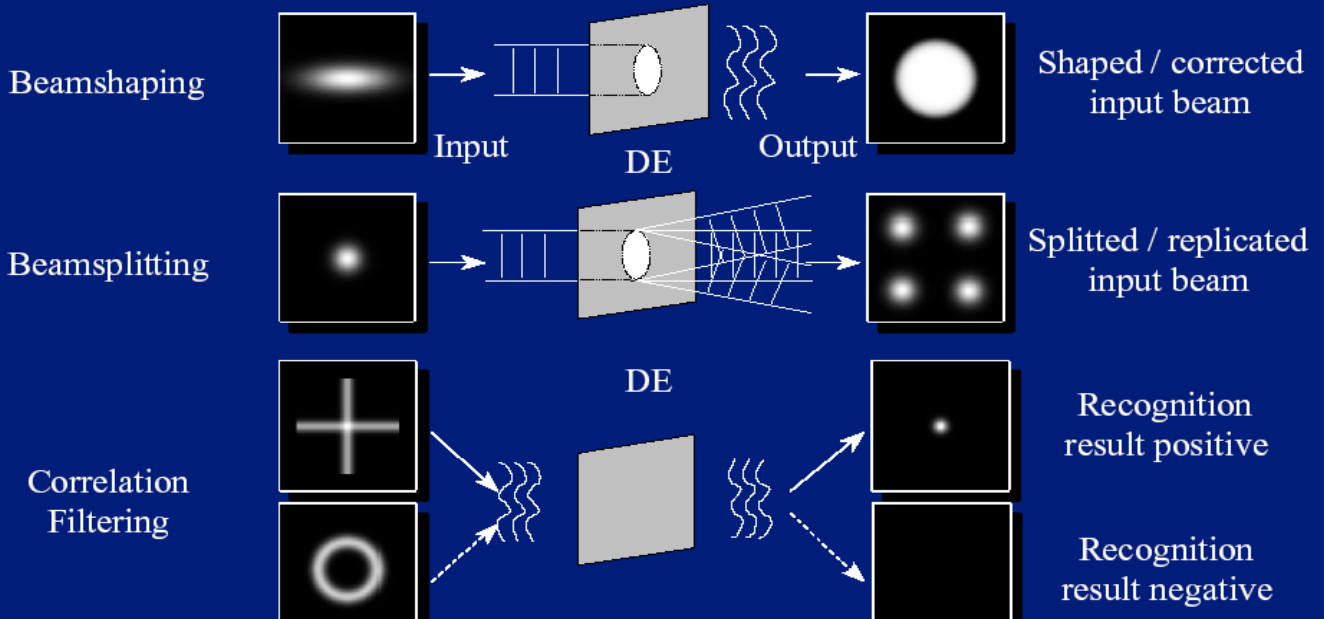
$$\mu = \frac{4\pi}{\lambda} \beta$$

$$\Delta\phi = \delta(2\pi/\lambda)t = 2\pi$$

$$r_1 \ll (2z = \phi \nabla)^2$$

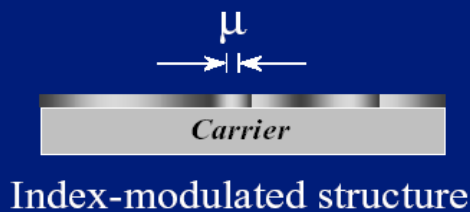
$$r \approx (f\lambda)^{1/2}$$

Some Functions of Diffractive Elements

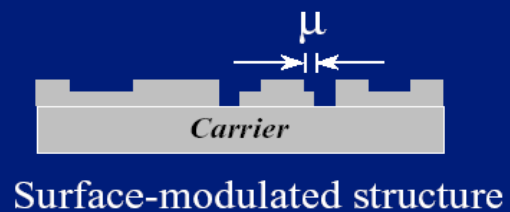


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Realisation of Microstructures



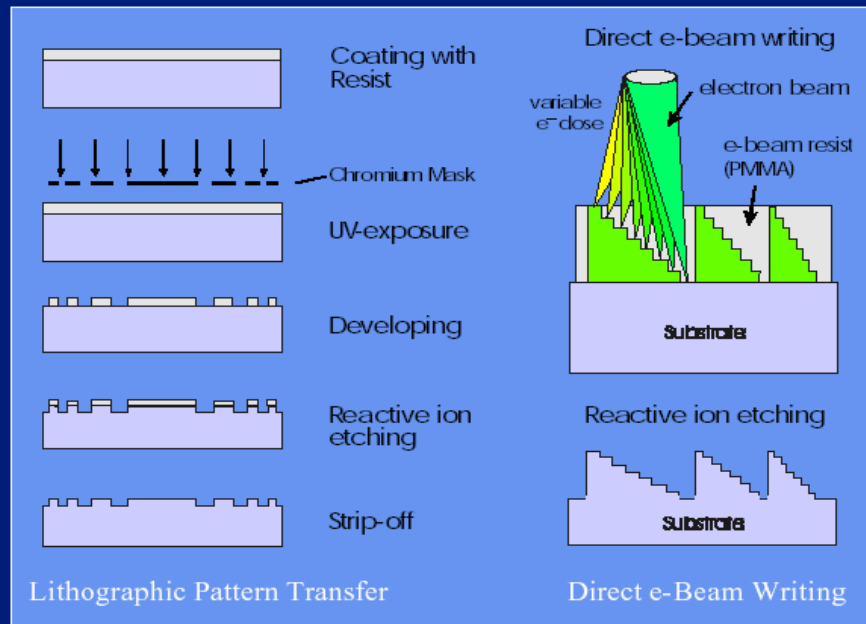
Example: liquid crystal displays



Example: fabrication by laser or e-beam lithography and etching

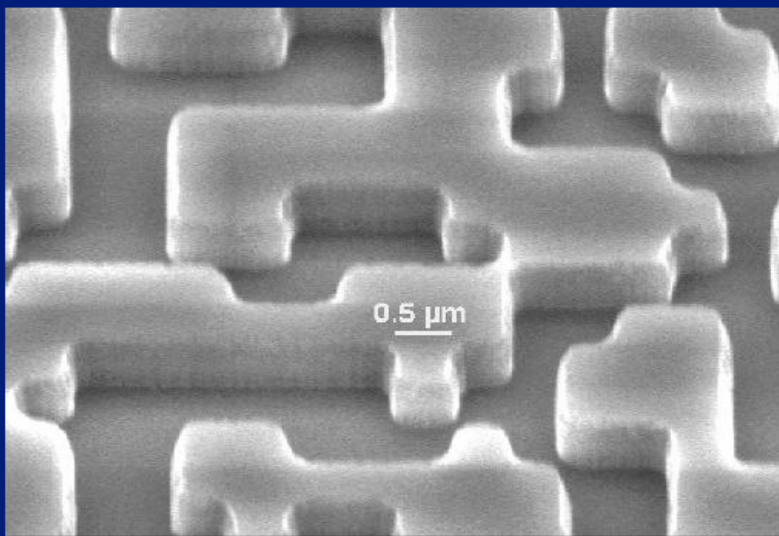
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Fabrication Methods in Detail



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Binary DE

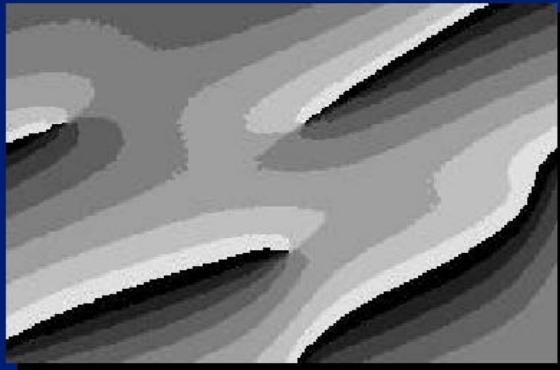


Binary structure of a beamsplitter

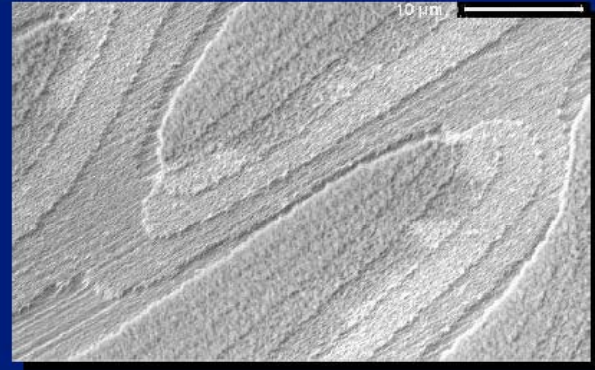
Smallest structures: 0.5 μm !

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Continuous DE

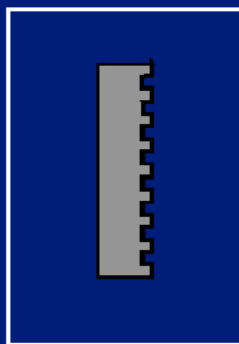


Section of the designed 8-level structure of a beamsplitter

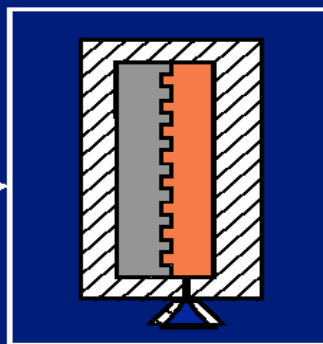


Section of the fabricated 8-level structure of a beamsplitter

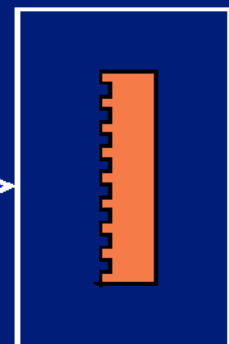
Replication of DEs Example: Injection Molding



Microstructured Shim

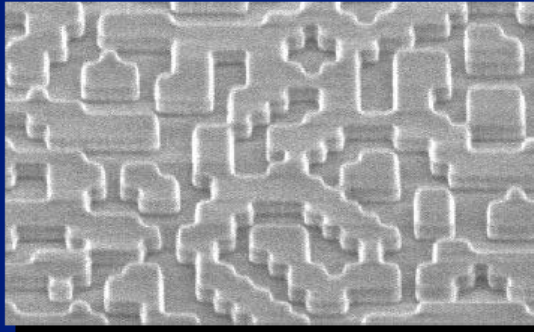


Injection Molding Process

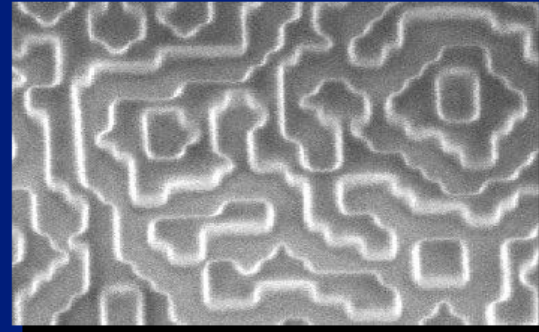


Microstructure in PMMA or Polycarbonate

Replication Methods



Section of a binary quartz-glass master



Section of replicated DE

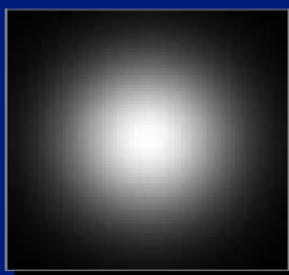
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Implementation Example: Beamshaping (technical analysis)

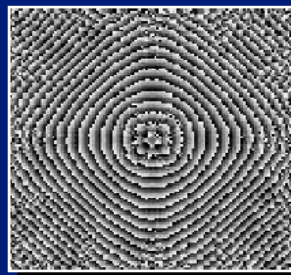
Square-line beamshaper:

Output beam shape as specified

Optical efficiency 86 % (theoretical)

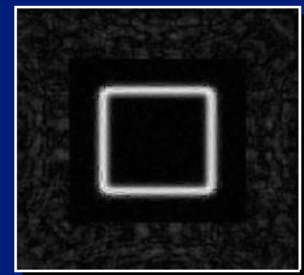


Illumination wave



16-level DE

far field



Output wave

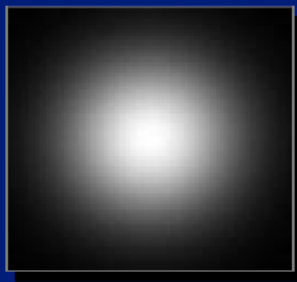
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Implementation Example: Ringfocus (technical analysis)

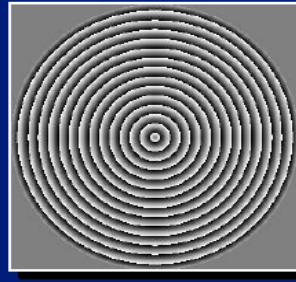
Circle-line beamshaper:

Output beam shape as specified

Optical efficiency greater than 85 % (theoretical)



Illumination wave



16-level DE

far field



Output wave

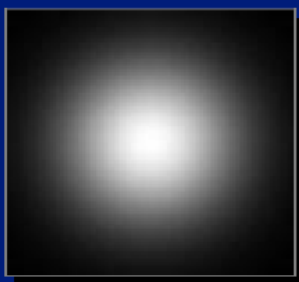
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Implementation Example: Beamsplitter (fabricated)

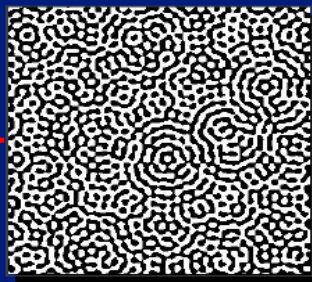
1 to 40 ring beamsplitter:

Deflection angle of each beam 15°

Optical efficiency 60 % ; uniformity of output beams

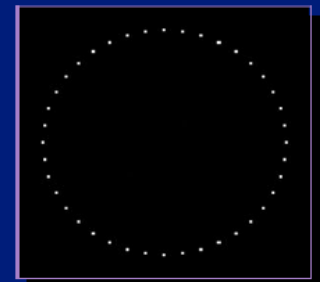


Illumination wave



2-level DE

far field



Output wave

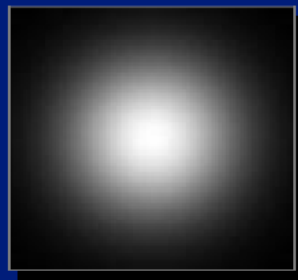
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Implementation Example: Beamsplitter (technical analysis)

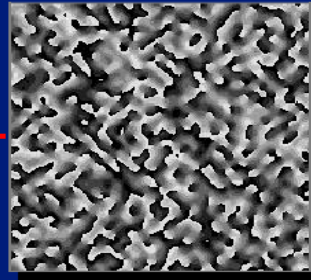
1 to 100 x 100 square beamsplitter:

Optical efficiency 75% (theoretical)

Uniformity of output beams

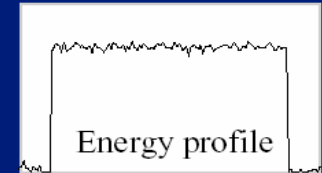


Illumination wave

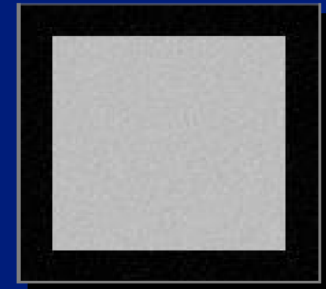


8-level DE

far field



Energy profile



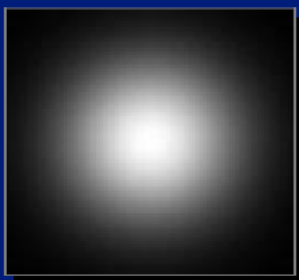
Output wave:
100 x 100 light dots

Example: digital Hologram of Tutenchamun (fabricated)

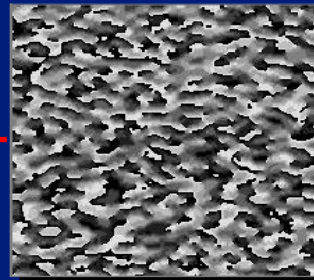
Digital hologram:

Output wave: image of Tutenchamun

Minimum stray light

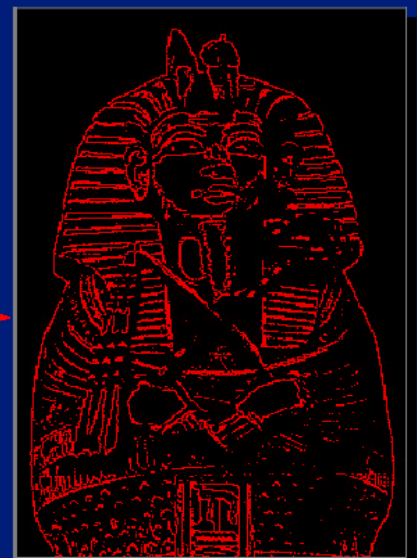


Illumination wave



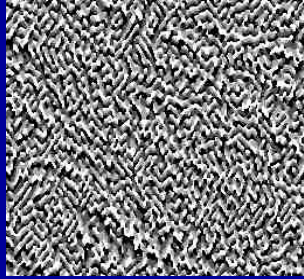
8-level DE

far field



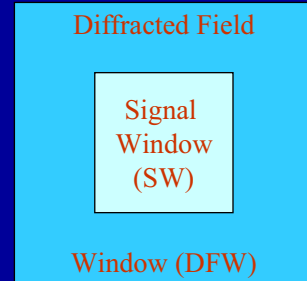
DOE's design problem :

find the phase function, $\Phi_{DOE}(x)$, so that intensity distribution of the diffracted field, $I_g = |E_g|^2 \sim I_o$ (the desired intensity distribution) inside SW



$\Phi_{DOE}(x)$

$$E_g(x; z) = P_z \{ A_G(x) \exp[i\Phi(x)] \}$$

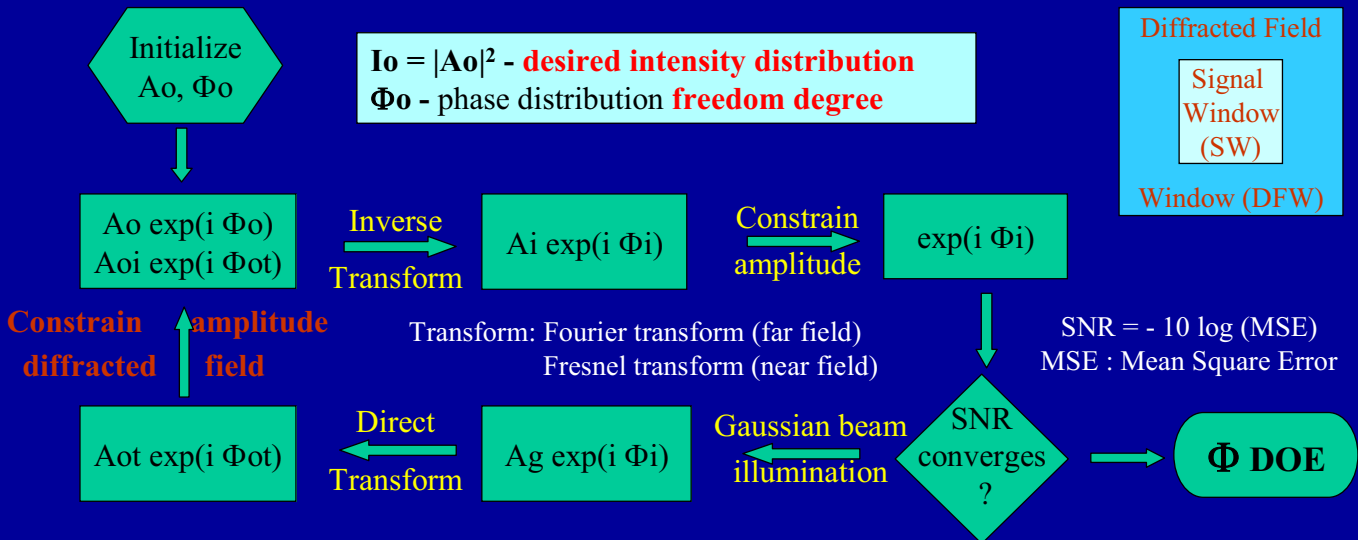


$I_o = |A_o|^2$ - desired intensity distribution
 Φ_o - phase distribution **freedom degree**

Design approaches:

- ▶ ray tracing
- ▶ iterative optimization techniques
- ▶ phase retrieval iterative algorithms

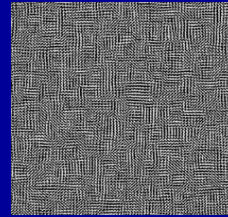
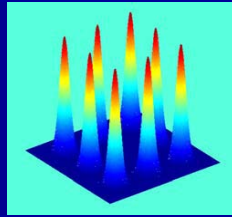
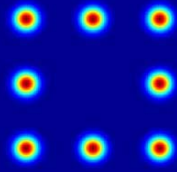
- **ERA: Error Reduction Algorithm**, $A_{oi} = A_o$; DFW = SW
- **AAA : Adaptive Additive Algorithm**, $A_{oi} = \lambda A_o + (1 - \lambda) A_{ot}$ inside SW; DFW > SW
- **CEA : Combined Error Adaptive algorithm**



Planar array of optical tweezers

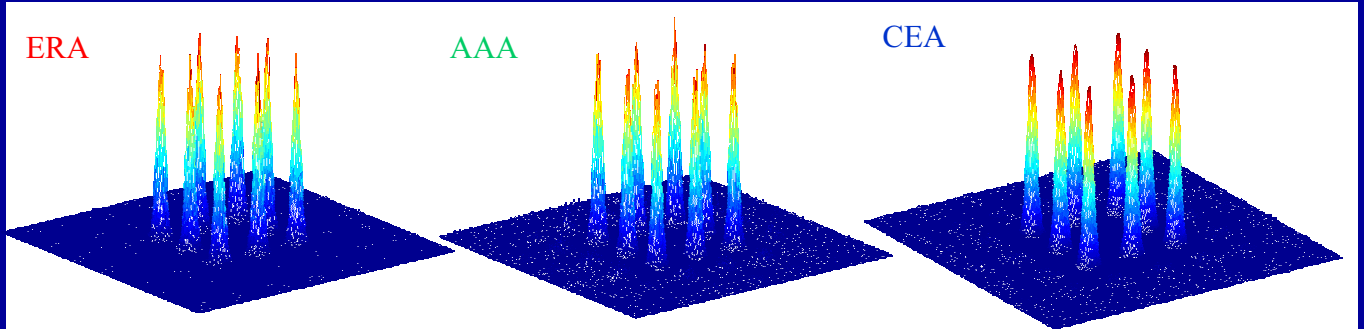
Phase DOE calculated with CEA

Desired amplitude
distribution in the
signal window SW

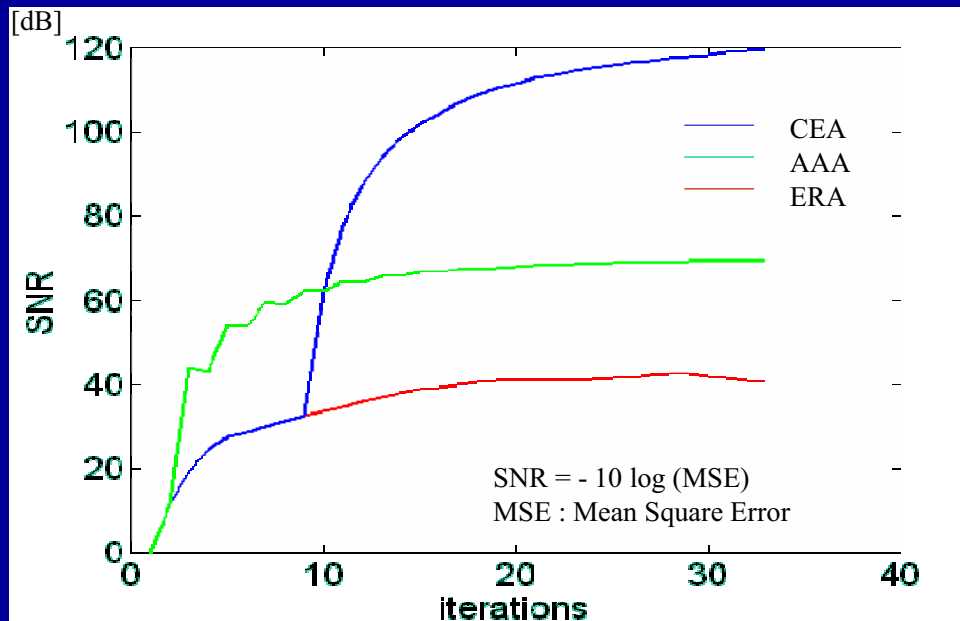


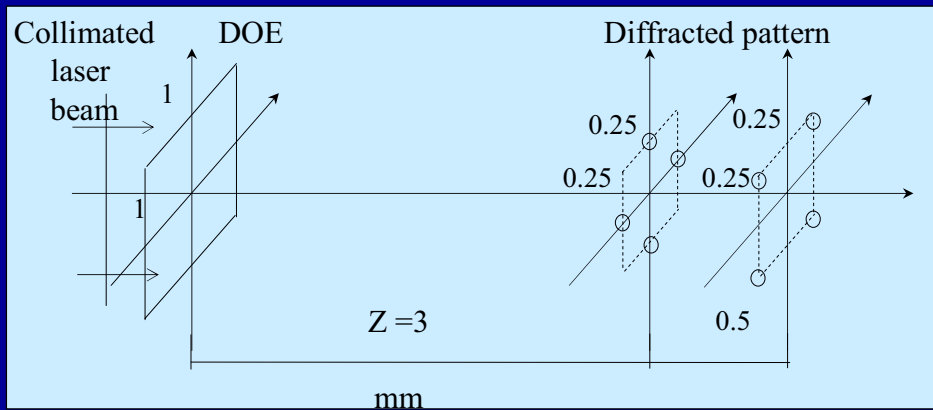
Size 1x1 mm
512x512 pixels
64 phase levels

Intensity distribution of the diffracted pattern obtained from DOE in the far field



Comparison of the iterative algorithms in terms of SNR

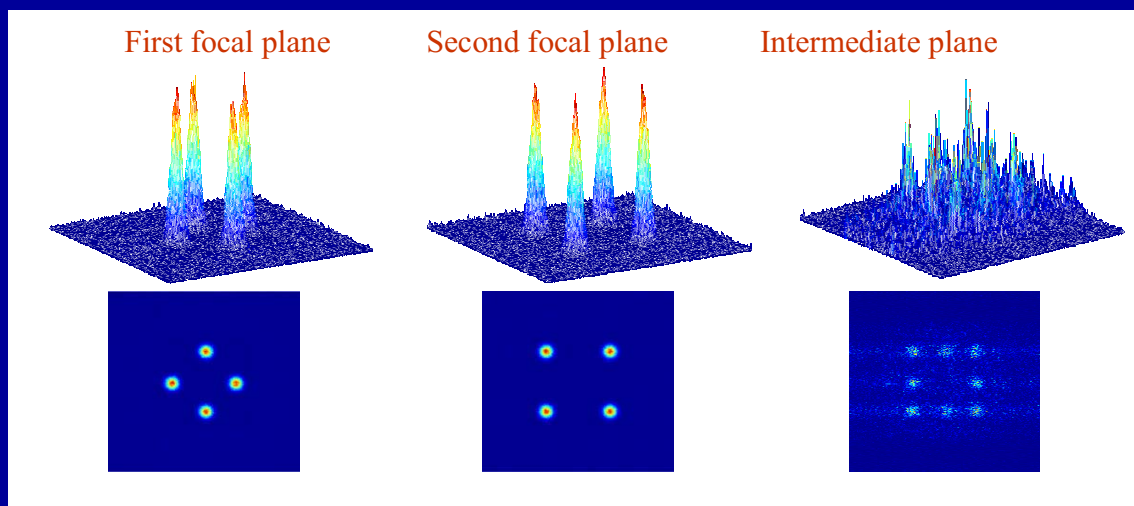


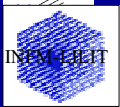


- CEA: calculate the phase functions corresponding to the two planar arrays (40 iterations)
- Micro GA: calculate the optimum phase function that creates the 3D array (40 iterations)

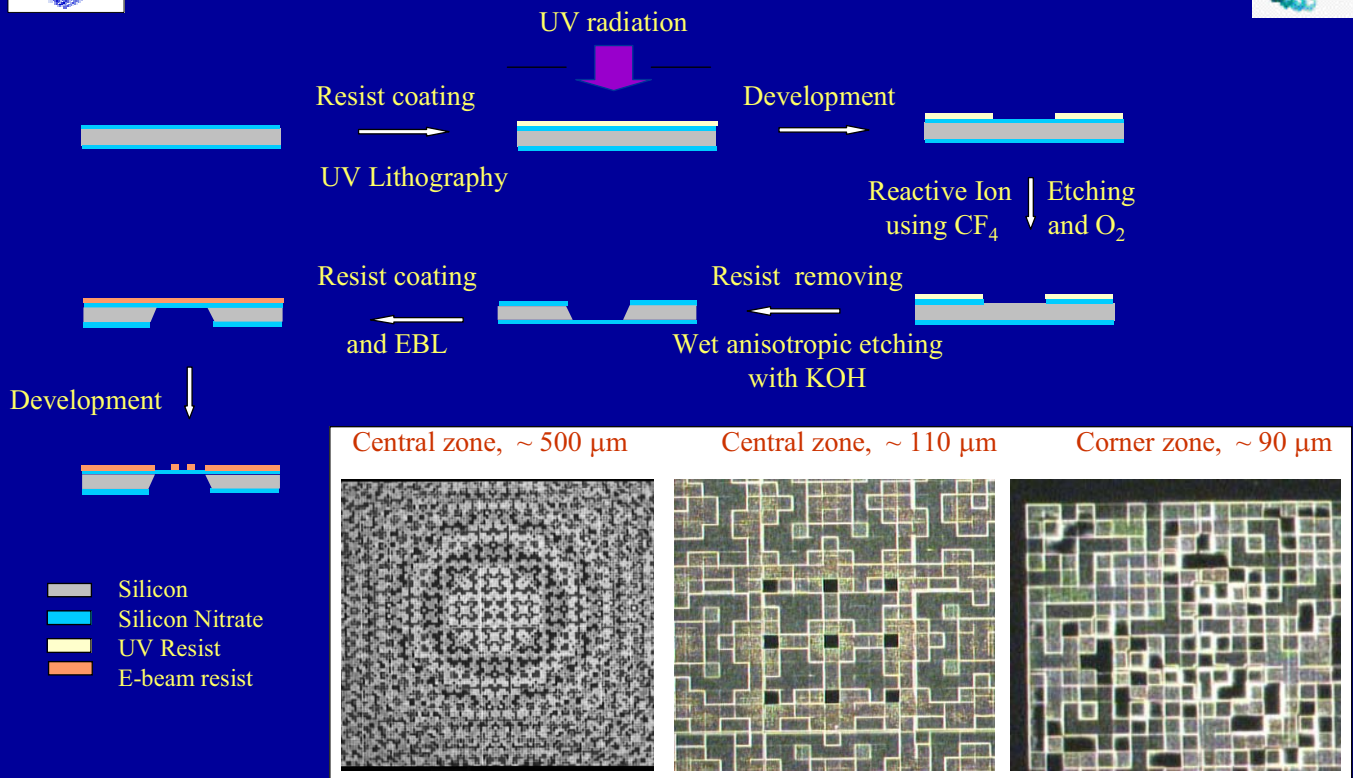


Computed intensity distribution of the diffracted field





DOE's fabrication: flow chart



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Experimental results: CEA + Micro GA

Detected intensity distribution of the diffracted field

First focal plane

Intermediate plane

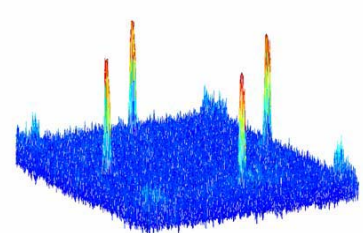
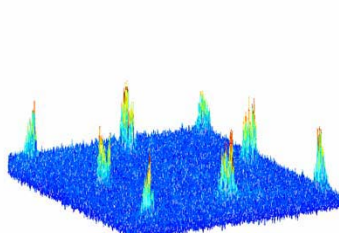
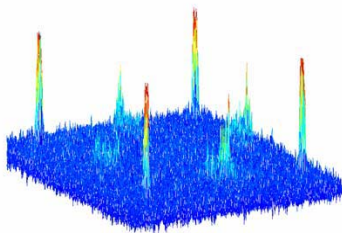
Second focal plane



3 mm



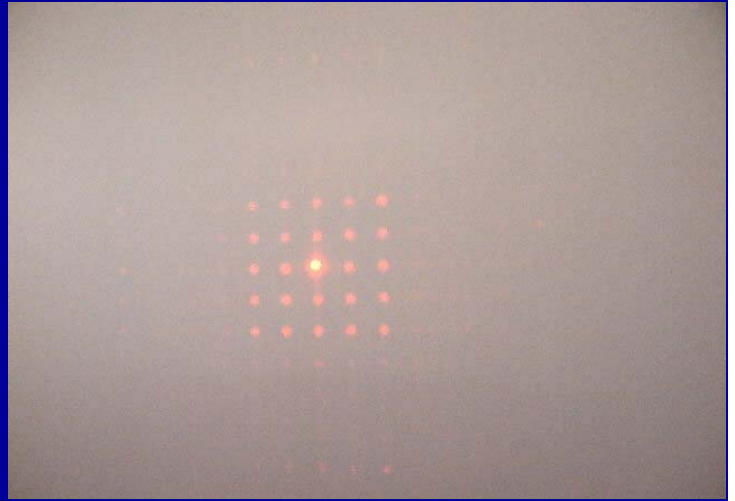
3 mm



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5x5 matrix for simultaneous
Optical trapping



Diffractive nanoptics for DIC x-ray microscopy

1. Contrast in X-ray microscopy

Refractive index in X-ray region: $n = 1 - \delta + i\beta$

$\delta \rightarrow$ phase shift

$\beta \rightarrow$ absorption

example: polyimide

photon energy [eV]	δ	β	δ / β
100	$2.3 \cdot 10^{-2}$	$4.9 \cdot 10^{-3}$	4.7
500	$1.1 \cdot 10^{-3}$	$3.2 \cdot 10^{-4}$	3.4
5000	$1.2 \cdot 10^{-5}$	$7.1 \cdot 10^{-8}$	170

\rightarrow phase sensitive techniques superior to absorption contrast !

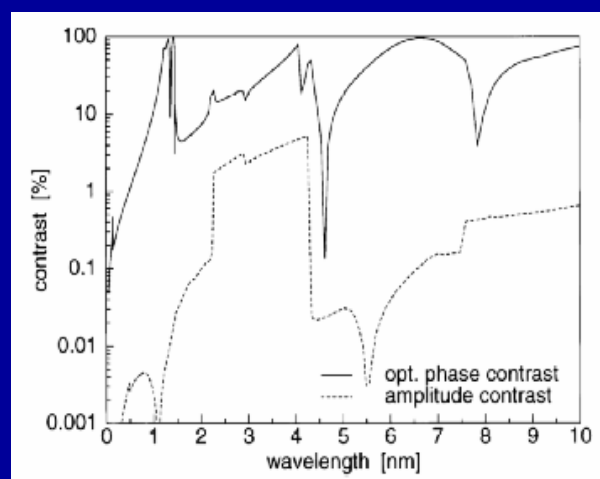
Motivation for microscopy techniques using phase information

Absorption contrast: $\sim E^{-3}$

Phase contrast: $\sim E^{-1}$

Use of phase shifting, real part of refractive index

- orders of magnitude higher contrast
- tremendous reduction of dose applied to object
- additional transmission information on low side of absorption edges (XANES, XRF !)



Amplitude and phase contrast for a model protein $C_{94}H_{139}N_{24}O_{31}$

Phase objects **cannot be seen (difficult) when in focus with ordinary XRM (single ZP)**

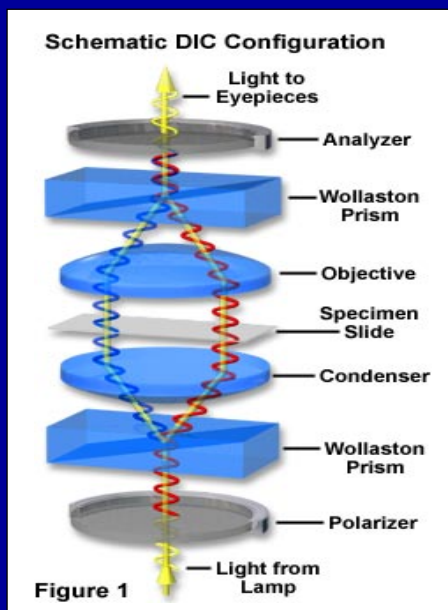
Phase objects **retard or advance light that passes through them due to spatial variation in their refractive index and/or thickness**

Needs for DIC microscopy

The image of DIC microscopes is formed from the interference of two mutually coherent waves with lateral displacements (shear) (of the order of the minimum size of the imaged structure and are phase-shifted relative to each other

Imaging characteristics

The intensity distribution in measured DIC images is given by a non linear function of the spatial gradient of a specimen's optical path length distribution along the direction of shear

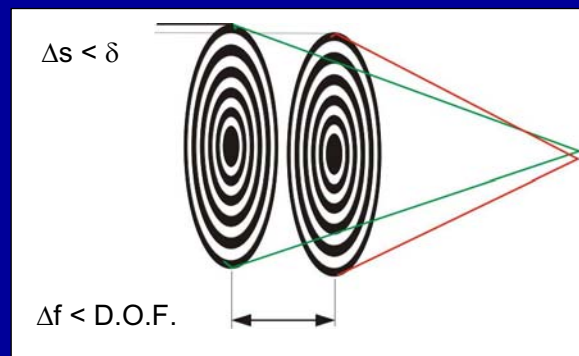


Visible light microscopy (Nomarsky set-up)

Shear of wave front division or distance of Airy disks in focal plane is smaller than optical resolution ("differential")

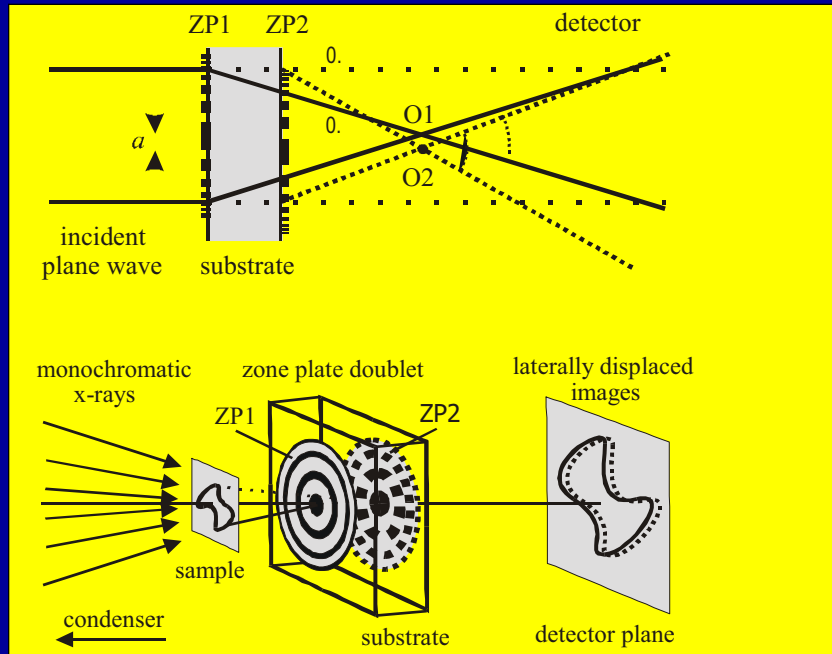
DIC for X-ray microscopy with ZPs:

- Distance Δf of both ZPs smaller than depth of focus
- Displacement Δs smaller than resolution δ



Differential Interference Contrast DIC

Working principle

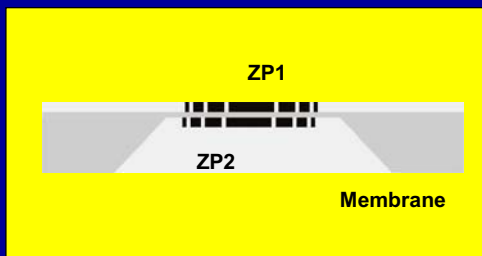


TXM set-up

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ZP doublet for X-ray microscopy in DIC mode

First ZP doublet generated by E. Di Fabrizio and S. Cabrini



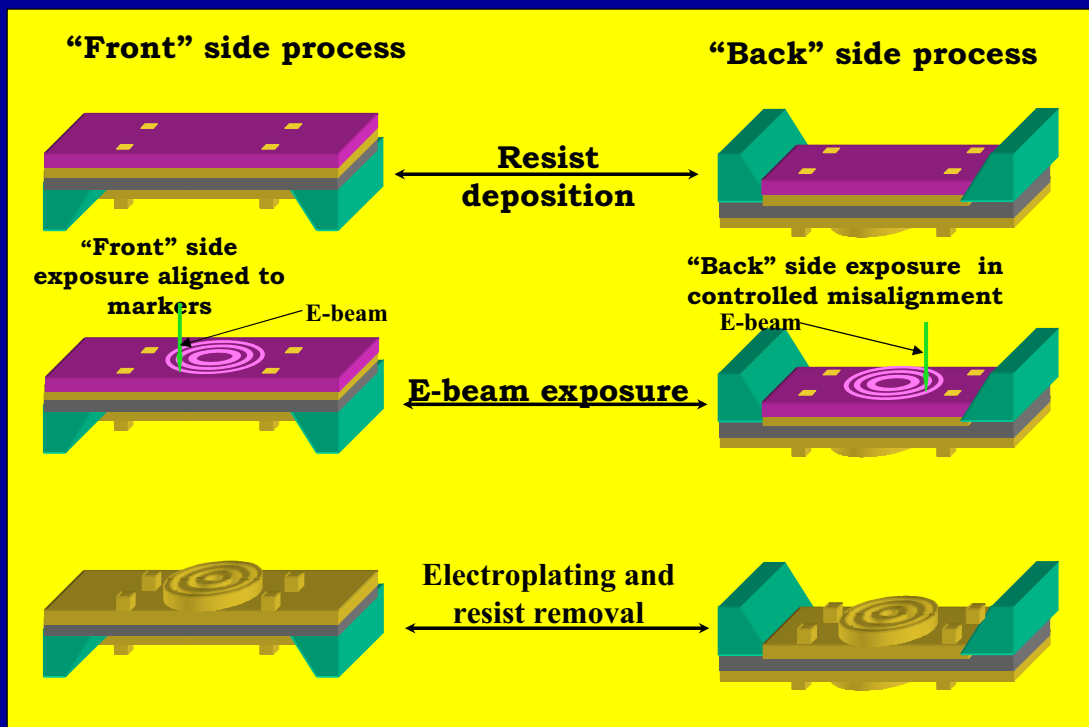
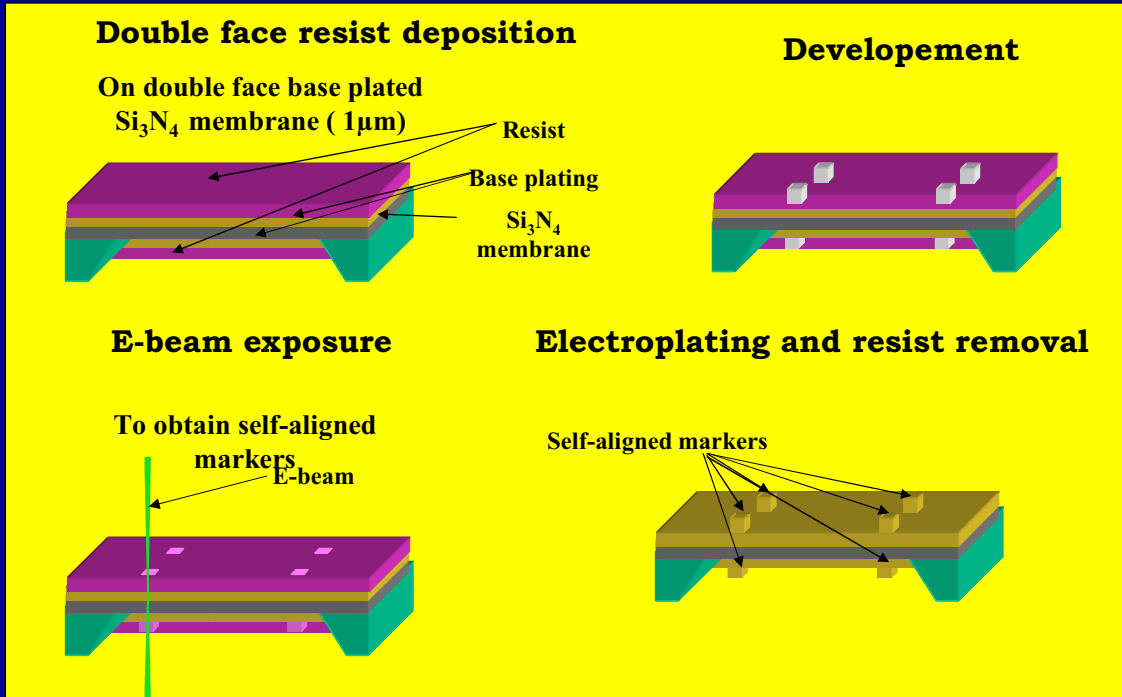
Technique: e-beam lithography and nanostructuring

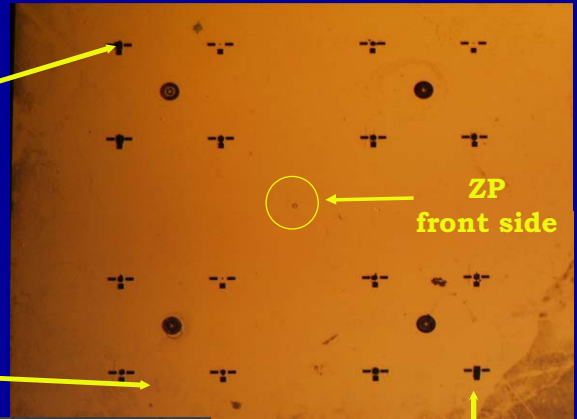
Diameter: 75 μm
Outermost zone width: 200 nm
Focal length @ 4 keV: 50 mm

Efficiency: 10 %

Nominal displacement: 100 nm

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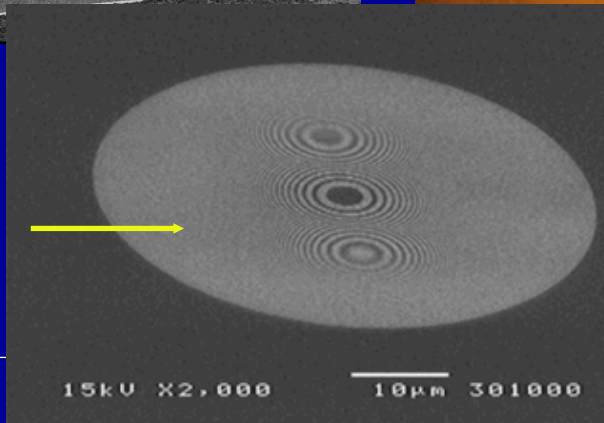




SiN membrane

Alignment markers

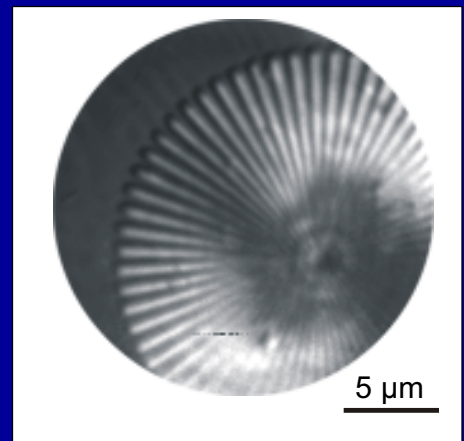
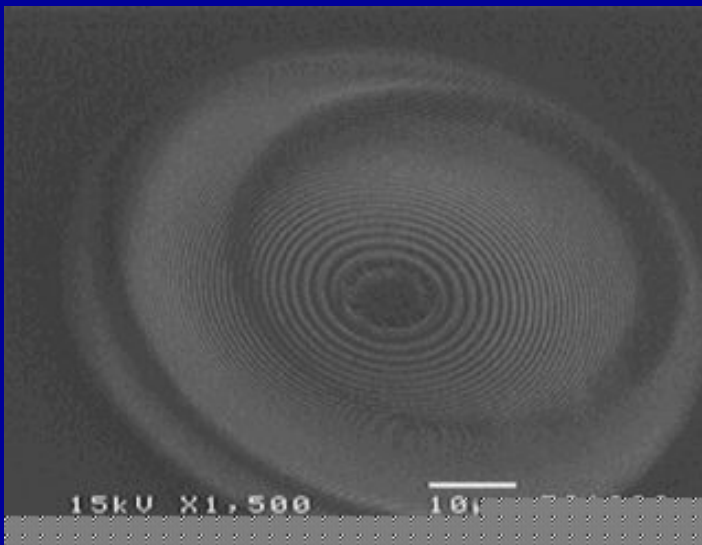
Zone plate Objective



Xray lithographic image of the ZP doublet

Efficiency of each zp=14%(first order)

Efficiency of zero order =35%

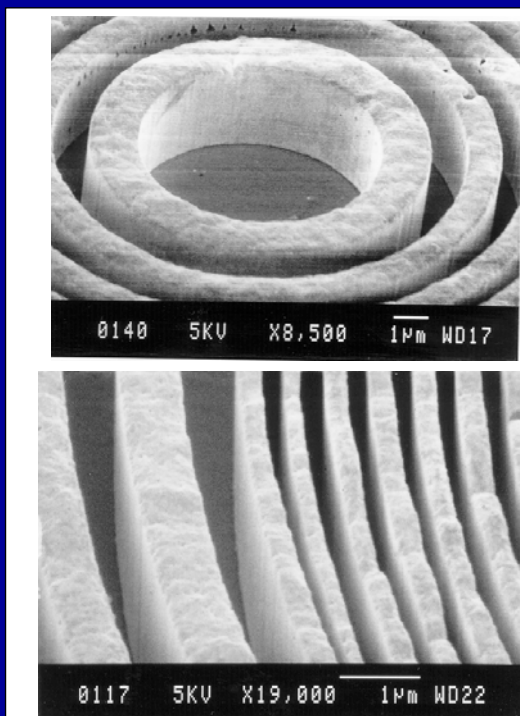


$$\eta_{tot} = t_{ZP1}\eta_{ZP2} + t_{ZP2}\eta_{ZP1} = 9.6\%$$

Resolution test~ 160 nm

Potentiality of X-ray lithography for DIC fabrication for multi-keV energy

Expected fabrication parameters with Xray litho are:
Thickness: no limitation (several tens of microns)
Resolution: below 50 nm
Aspect ratio: > 10 for sub 100 nm ZP resolution and > 15 above 200 nm ZP resolution
Controlled misalignment: < 30 nm
Expected Xray energy: above 10 keV



Depth of focus

High resolution/
aspect ratio

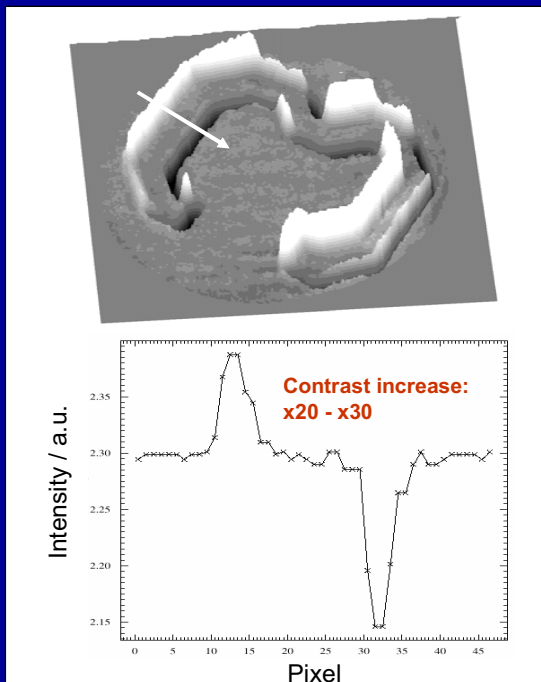
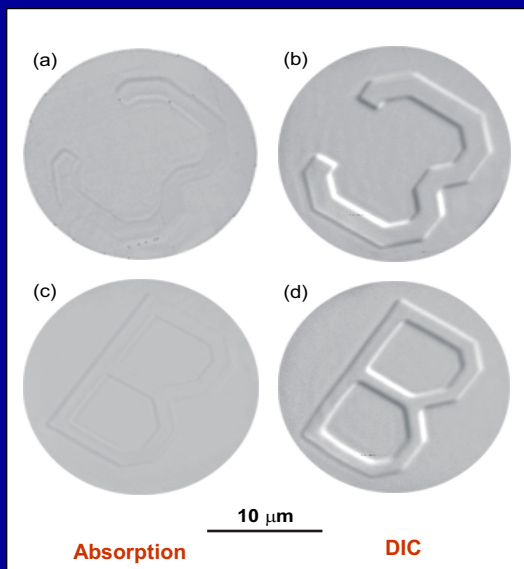


Alignment accuracy

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DIC X-ray microscopy with a full-field imaging microscope @ 4 keV

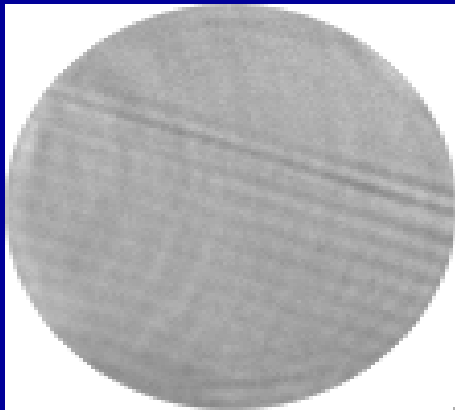
2 μm thick PMMA test structures with a transmission of 98.8 % @ 4 keV



B. Kaulich, T. Wilhein, E. Di Fabrizio, S. Cabrini, F. Romanato, M. Altissimo, J. Susini (Nov 2000)

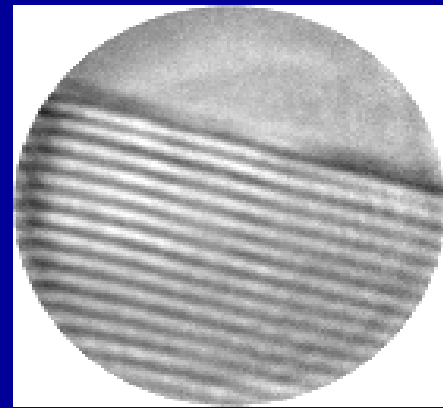
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PMMA zone plate structure (250 nm)
2 micron thick: exposure time 10s



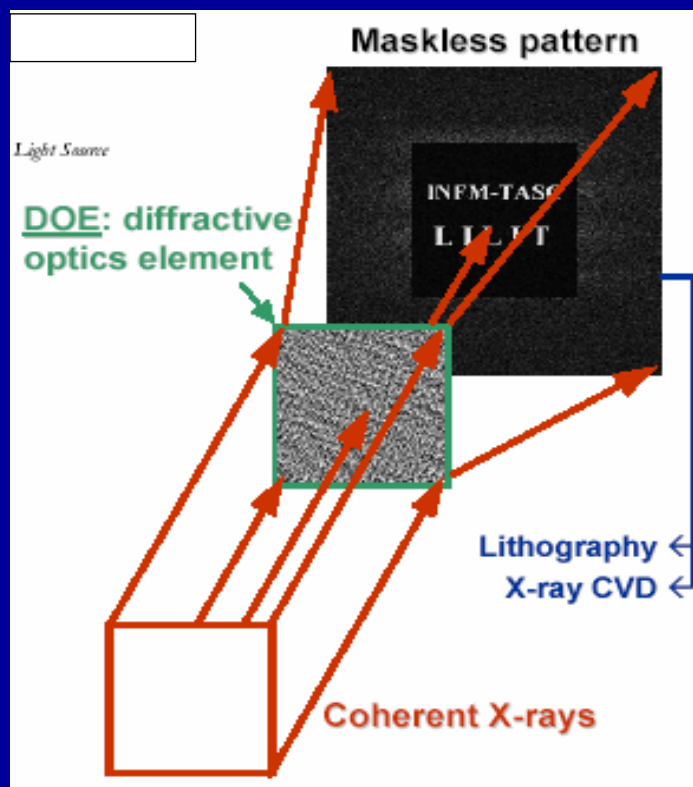
Bright field

5 μm



X-DIC transmission

General scheme of DOE shaping



Numerical computation:

given a set of **input** data find the optimum **output** data which fit the requests

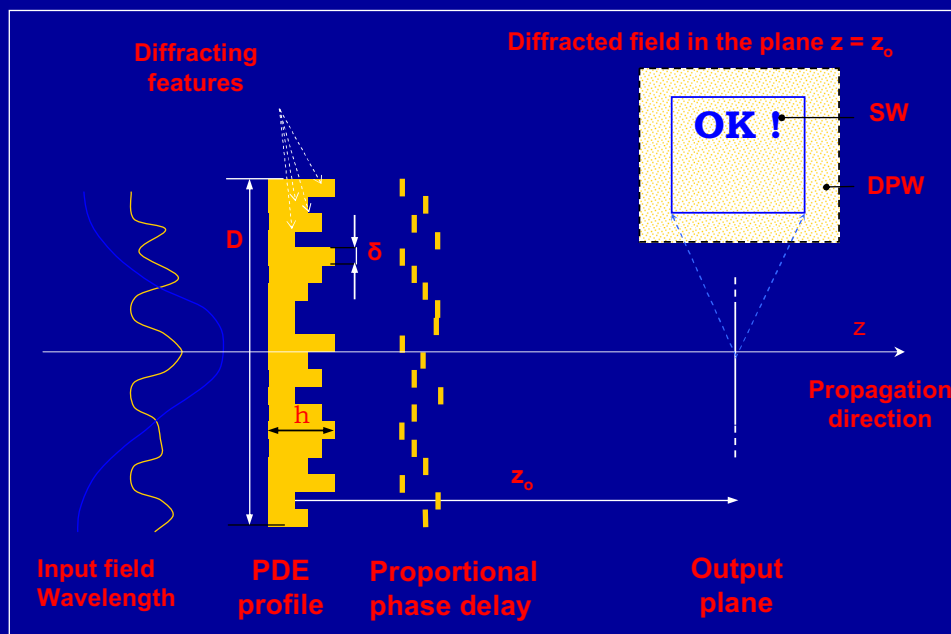
input data :

- Source space: wavelength, size, geometry, intensity distribution
- Image space: intensity or/and phase or/and polarization field distribution
- DOE: size, resolution, material

output data:

- DOE's phase or/and amplitude function

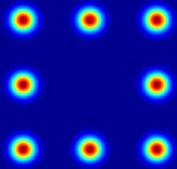
Diffractive optical element scheme



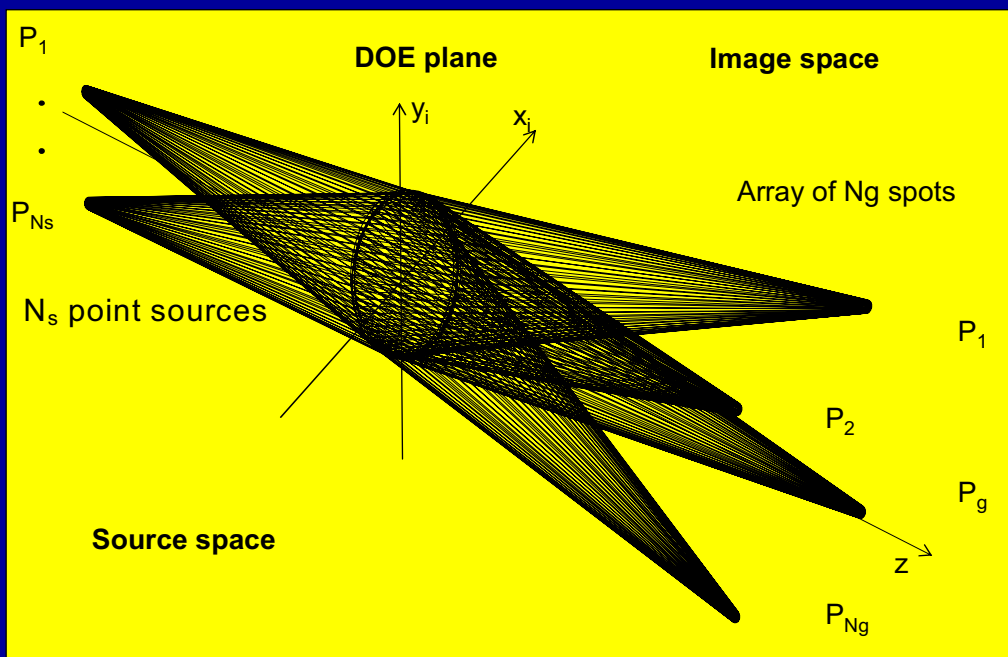
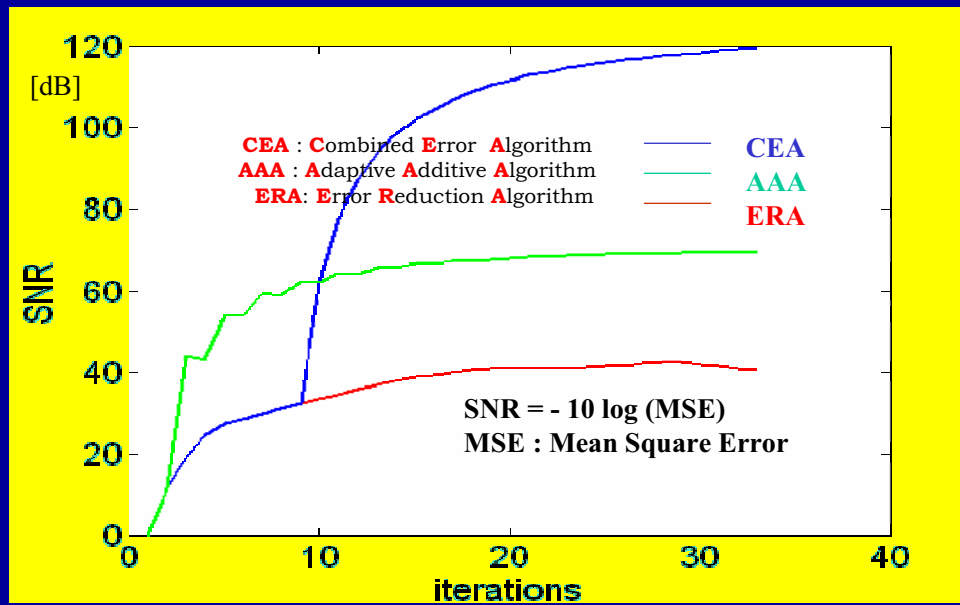
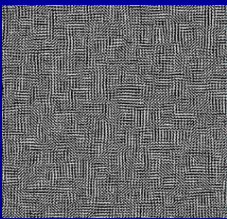
DOE's phase function:

$$\Phi_{\text{DOE}}(\mathbf{x}) = 2\pi (n-1) h(\mathbf{x}) / \lambda$$

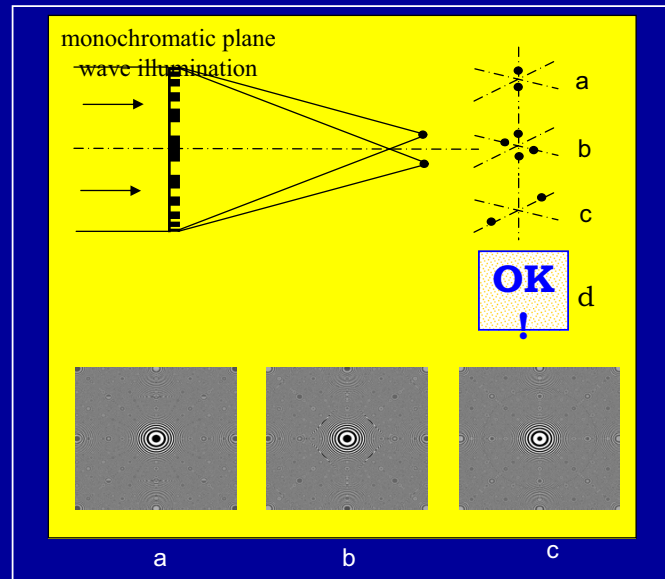
Intensity distribution



Phase DOE

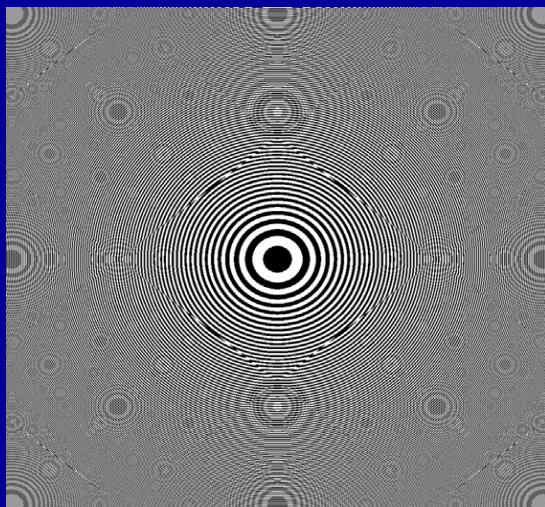


Optical scheme and calculated layout of 3 DOE's that generate 2 and 4 spots (a-b) on the same focal plane, and 2 spots along the same optical axis(c) (d) Full beamshaping

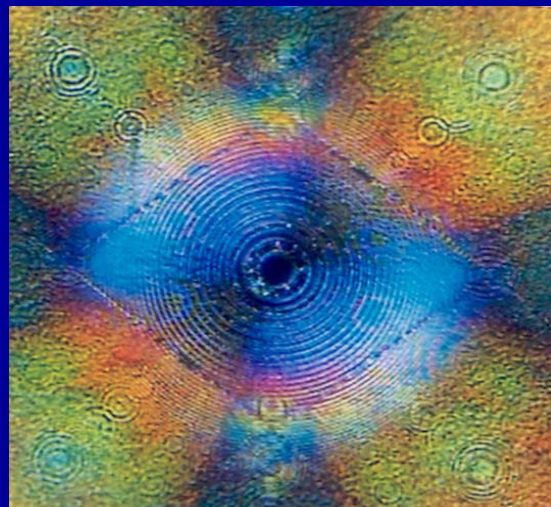


The calculations are referred to a photon energy of 4 KeV and 5 cm focal length

Calculated pattern of a 4 spot ZP



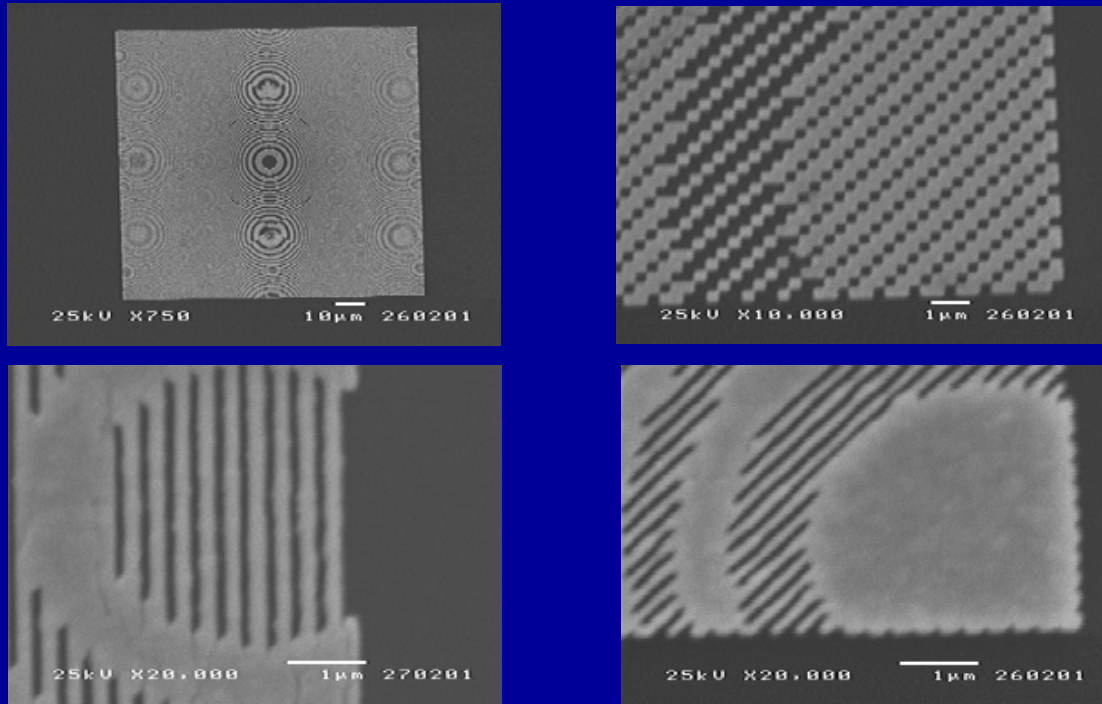
DIC visible light micrograph of 4-spot ZP



DOE size 0.1 x 0.1 mm², pixel size: 100 nm, energy 4 keV designed and generated by the Lilit beamline group (2001)

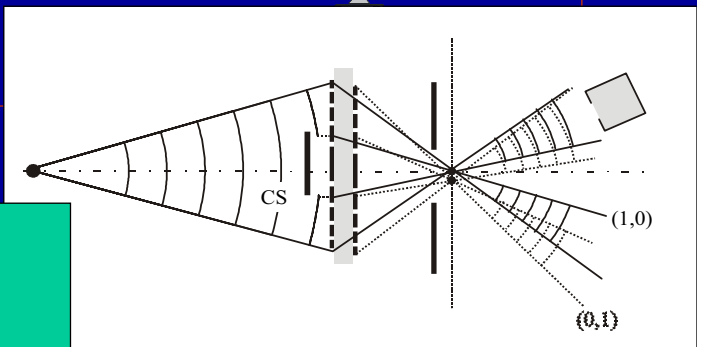
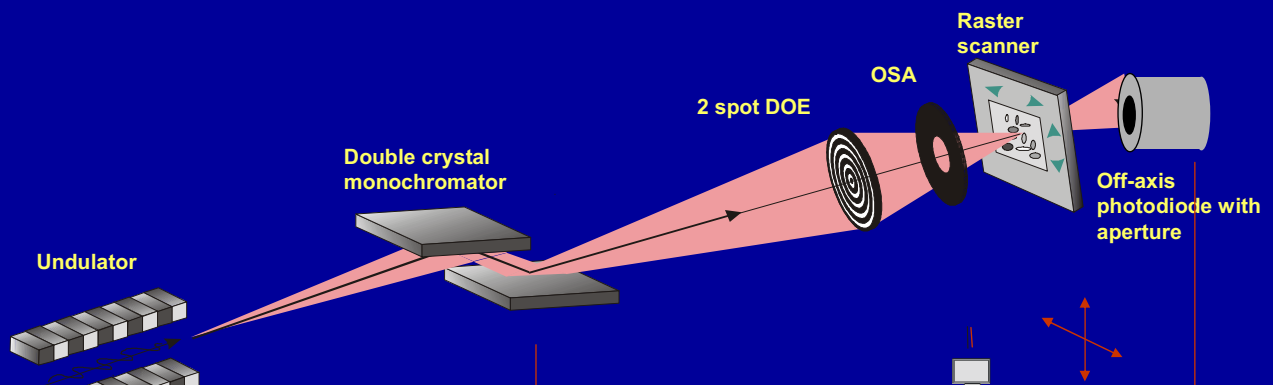
Development of multi-spot X-Ray DOE

SEM pictures showing an overview of the DOE (DOE area is $100 \times 100 \mu\text{m}^2$) and details of the outermost area whose resolution is below 100 nm



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Scanning X-ray microscope at ID21 beamline, ESRF



A Si photo diode with a $50 \mu\text{m}$ aperture in front was placed on one flank of an interference fringe in order to be highly sensitive to shifts of the fringes related to optical path differences introduced by the raster scanned specimen.

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2 spot DOE on SXTM at 4 KeV (February 2001)

2 μm thick PMMA test structures with a transmission of 99 % @ 4 keV

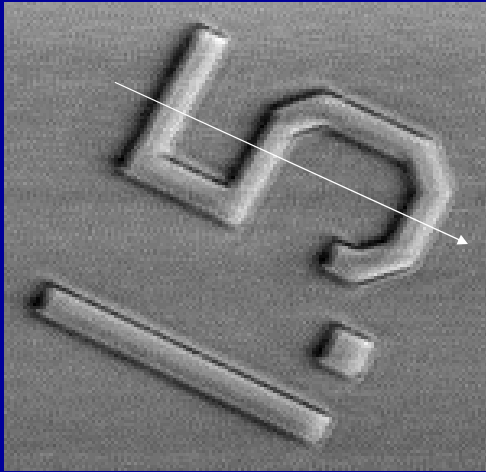


Image taken with the scanning X-ray microscope at the ID21 beamline, ESRF

Dwell time: 40ms / px with 200 x 200 px

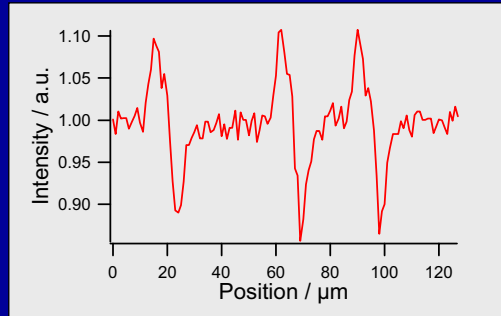
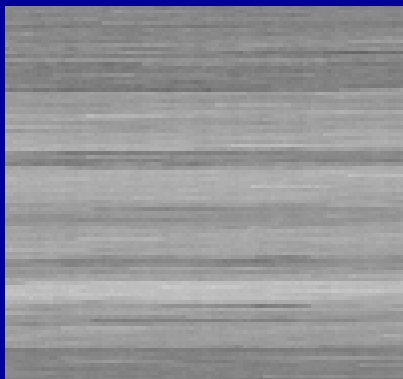
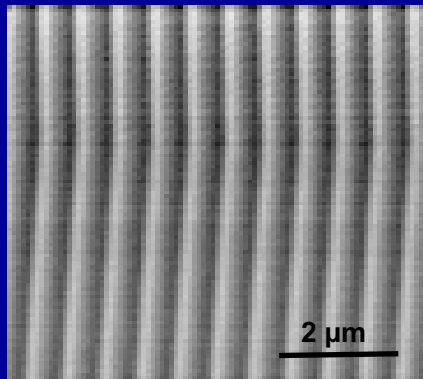


Image contrast: 25% in DIC

Scanning transmission X-ray microscopy in DIC mode using a 2-spot ZP



Brightfield (BF)

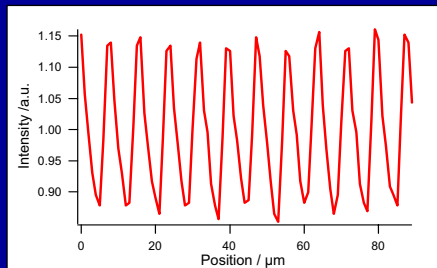
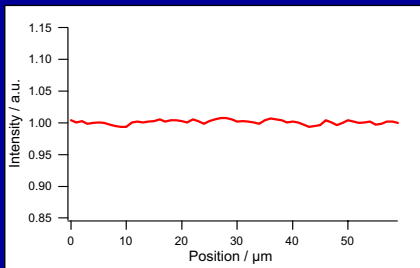


DIC

2 μm thick grating structures in PMMA

4 keV

200 x 200 px
40 ms/px dwell



Contrast:

BF: 1 %

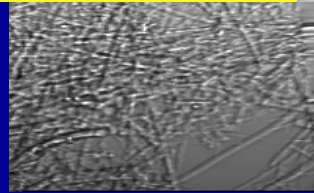
DIC: 25 %

Air Pollution SiO₂ fiber Filter(Trieste)
2 spot DIC&XRF measurements (July 2002)

7.2 KeV X-ray

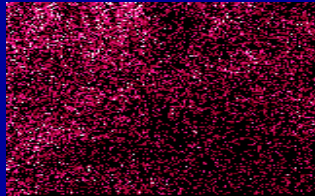


Absorption contrast

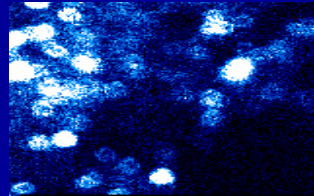


Diff. Interf. contrast

20 μm

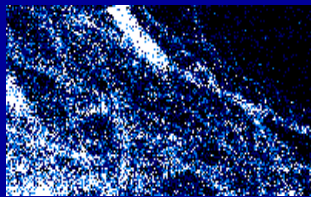


Cr XRF map

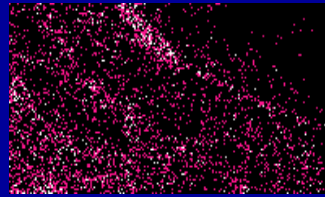


Fe XRF map

4 KeV X-ray

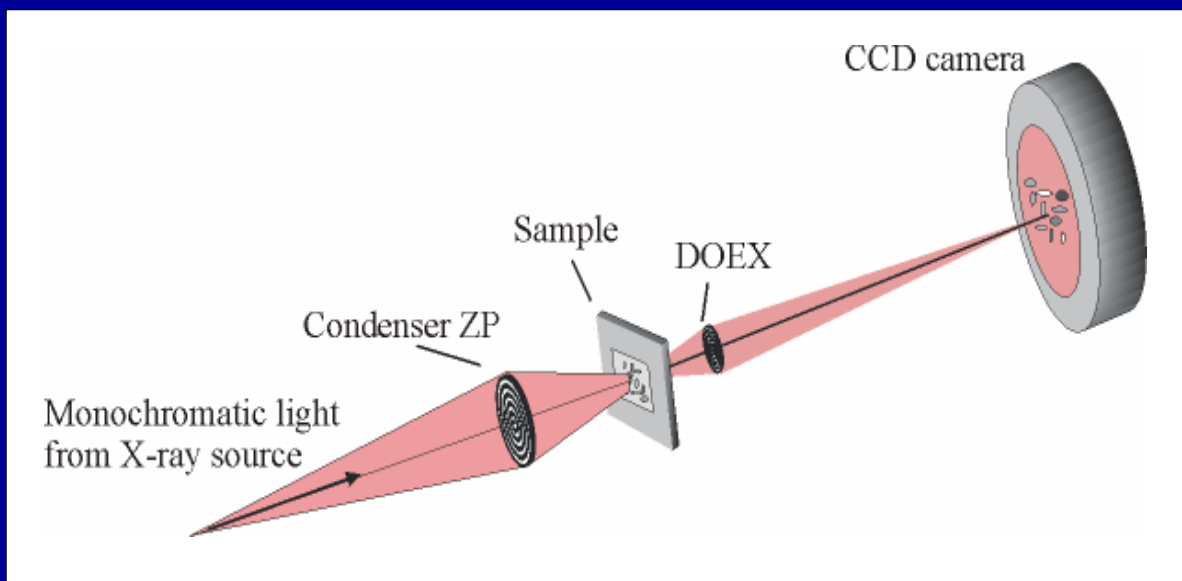


Ca XRF map



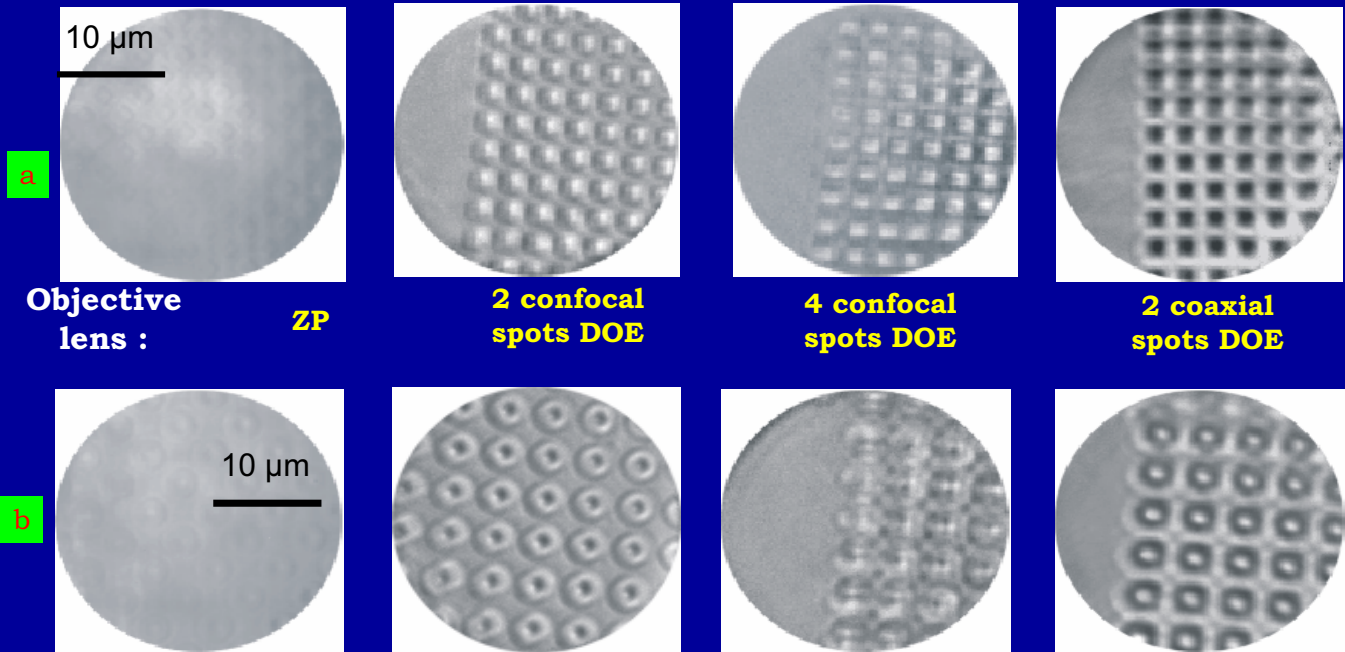
K XRF map

Optical setup of DIC full field microscope



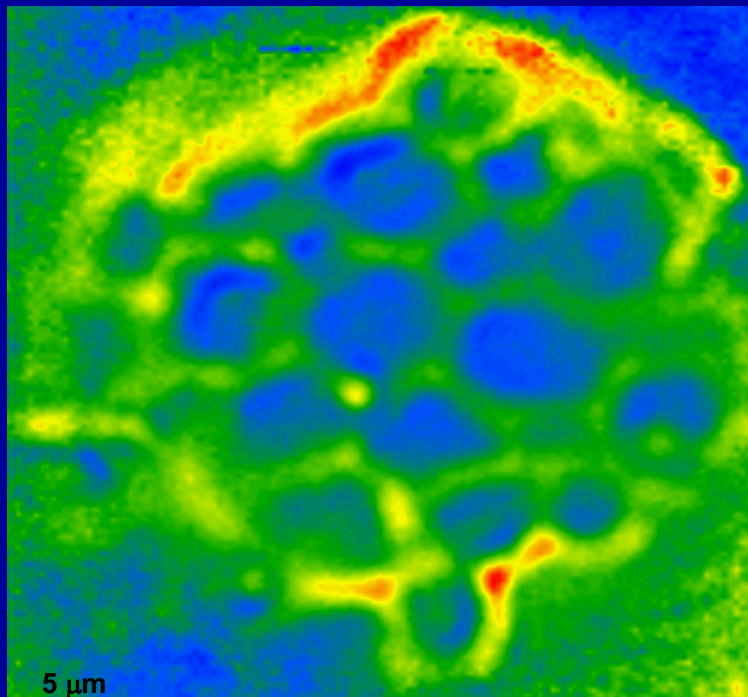
PMMA test structures (June 2001)

test structures (a=squares, b=toroids) 1 μm thick with a transmission of 99.99 % @ 4 keV



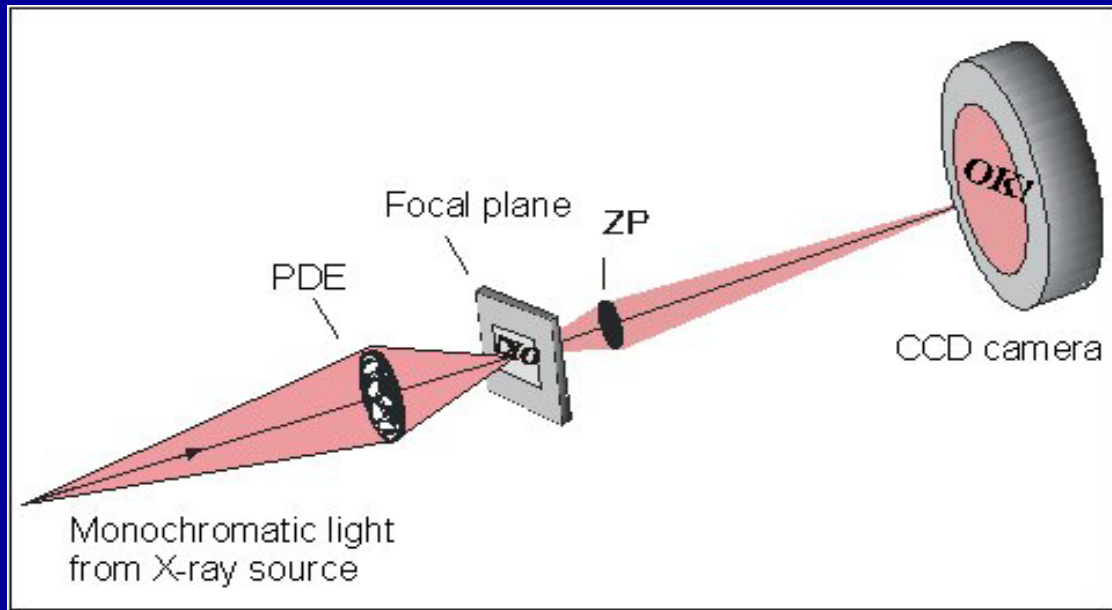
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Yeast cells: imaging in TXM at 4 keV by using diffractive optics



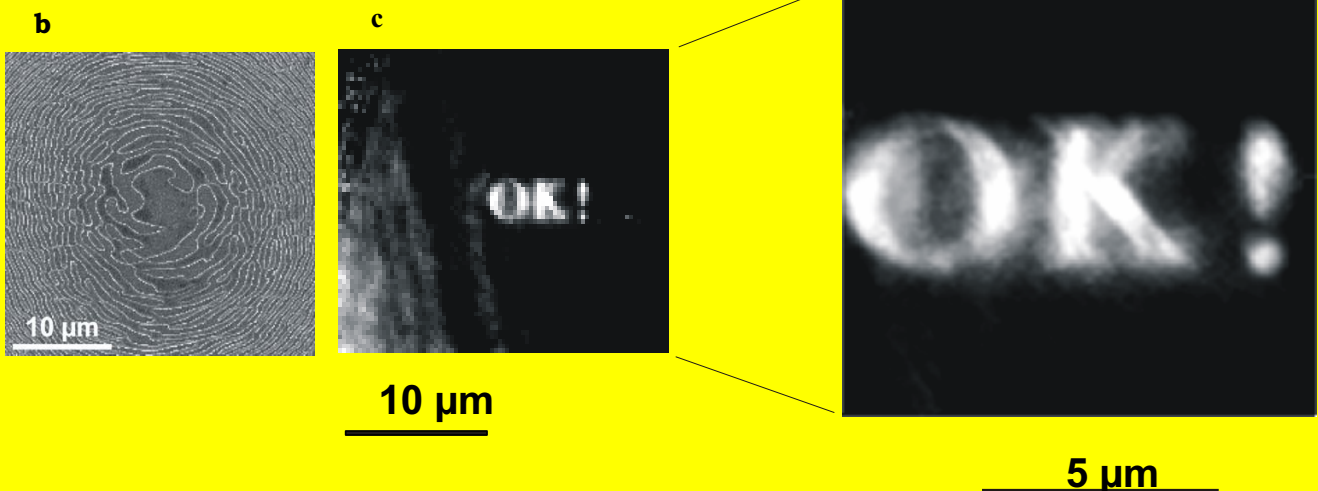
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Complete X-ray- beam shaping Optical setup of DIC full field microscope



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Complete X-ray- beam shaping (June 2001)



b - SEM image of the fabricated OK! DOE

c - The intermediate image formed by the DOE at the focal plane located at 50 mm is magnified 150 times on a CCD detector by a ZP that acts as an objective lens

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DIC Image formation with coherent illumination

$$i(\mathbf{x}) = a_1 \left| \int_{-\infty}^{+\infty} f(\mathbf{x}_o) h(\mathbf{x} - \mathbf{x}_o) d\mathbf{x}_o \right|^2$$

$$f(\mathbf{x}) = \exp(-j\phi(\mathbf{x})) \quad \text{Transmission function of the phase object}$$

$$h(x, y) = 0.5 \exp(-j\Delta\theta)\delta(x - \Delta x, y) - 0.5 \exp(j\Delta\theta)\delta(x + \Delta x, y)$$

$$h(x, y) = \quad \text{Ideal PSF from ray-tracing (geometrical optics)}$$

$$\Delta x \quad \text{=Shear in x direction}$$

$$\Delta\theta \quad \text{=constant phase bias}$$

C. Preza et. al. *J. Opt. Soc. Am. A*/Vol. 16, No. 9. 1999

Field Intensity in the DIC image

$$i(x, y) = a_1 \sin^2 [0.5 \{ \phi(x - \Delta x, y) - \phi(x + \Delta x, y) \} + \Delta\theta]$$

If the shear Δx very small (differential) compared to the size of the details of the specimen (or the resolution of the ZP) ==> the phase difference can be written as a phase gradient:

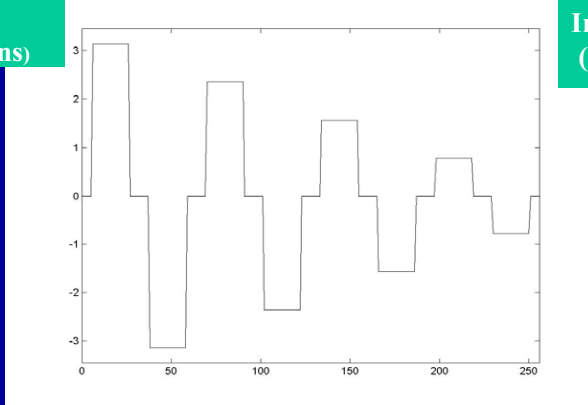
$$i(x, y) = a_1 \sin^2 \left(\Delta x \frac{\partial \phi(x, y)}{\partial x} + \Delta\theta \right)$$

With DOE is possible to control the contrast through the bias $\Delta\theta$

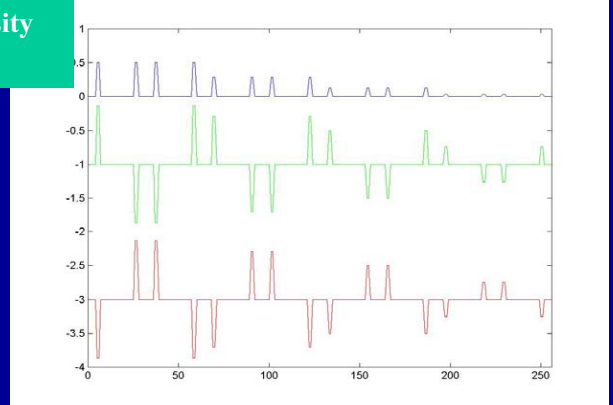
Bias retardation in DIC

$$i(x, y) = a \sin^2 \left(\Delta x \frac{\partial \phi(x, y)}{\partial x} + \Delta \theta \right)$$

Phase
(radians)



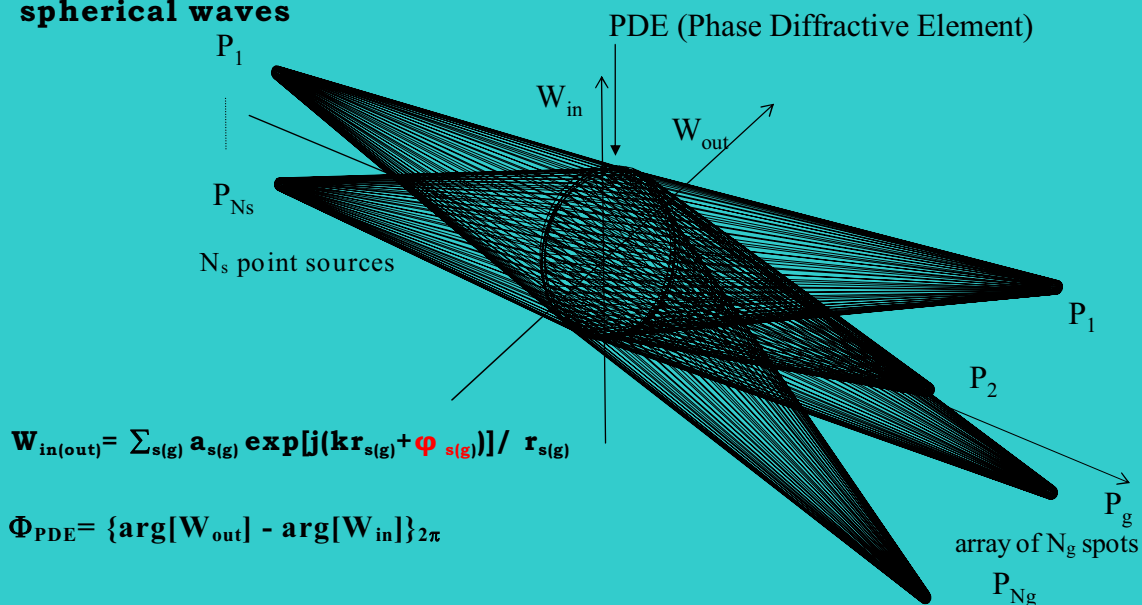
Intensity
(a.u.)



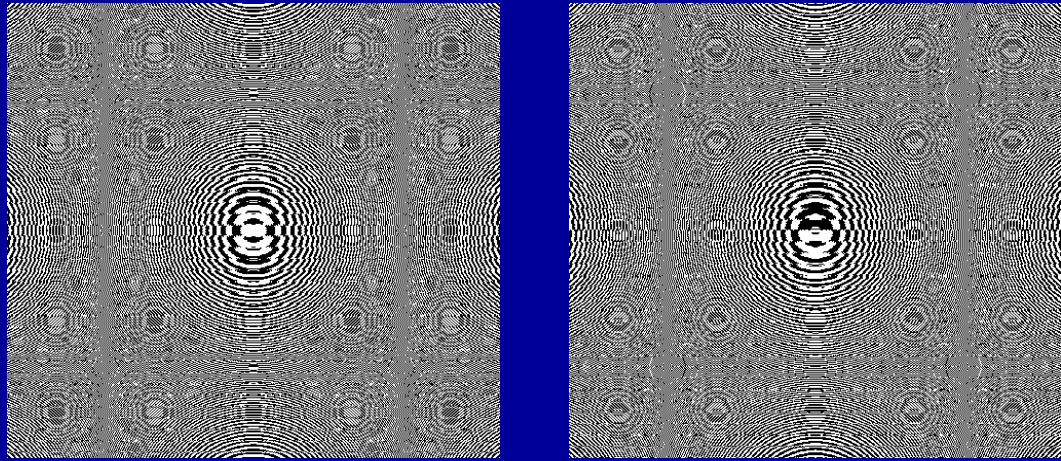
- (a) The phase function of a one dimensional object described in 250 pixels;
- (b) Intensity distributions obtained with the same shear $\Delta x = 2$ but different bias values:
 $\Delta \theta = 0$ - first line, $\Delta \theta = \pi/4$ - second line, and $\Delta \theta = 3\pi/4$ - third line;
 the signals are offset by 2 a.u. for a clear representation

Spherical wave propagation approach

To calculate the phase function Φ_{PDE} , we assume that the light source which illuminates the PDE and the intensity distribution produced by the PDE can be described by point sources generating spherical waves

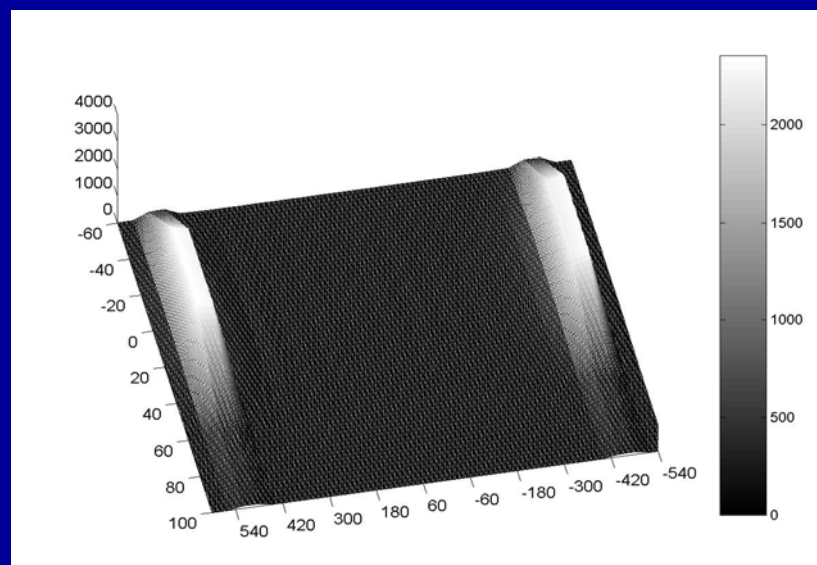


DOEs producing the same beam shearing (1 mm) but different bias: a) no bias, b) bias = π at 1 m from the DOE (DOE size= 2 cm, described in 480 pixels)

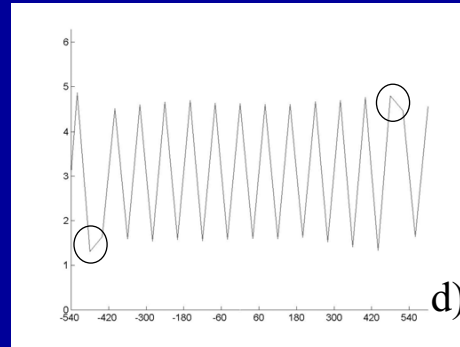
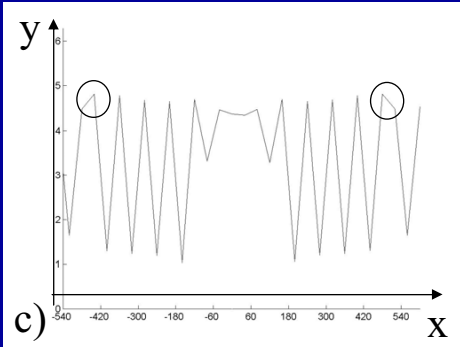
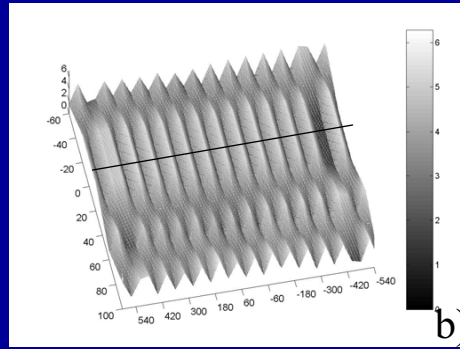
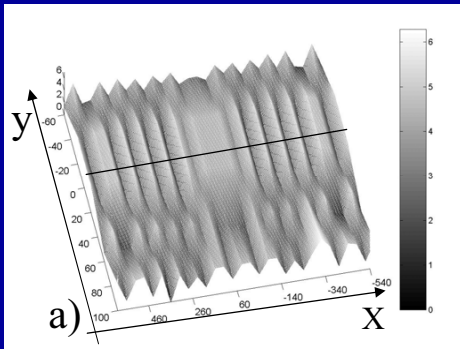


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The intensity distribution obtained in the focal plane ($\Delta x=1$ mm $\lambda=532$ nm DOE made by Hamamatsu SLM)

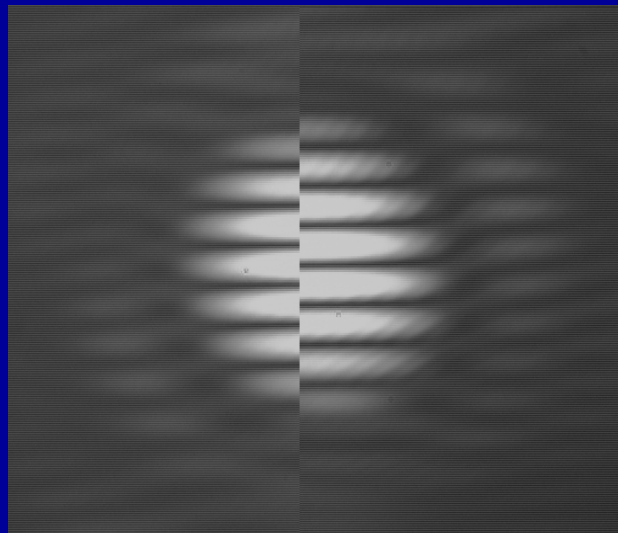


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Phase distributions obtained in the focal plane of the DOE. For the 3D graphics (a,b) the phase is represented in radians on the z axis, the distances represented on x and y axes being expressed in microns. The phase distributions along the lines indicated in a) and b) are represented in the second line c) and d) clearly showing the presence of the π bias

The interference patterns obtained after the focal plane of the DOEs implemented on the phase SLM Hamamatsu; the left pattern corresponding to the DOE without bias is shifted with half of a fringe with respect to the right pattern which corresponds to the DOE with bias π

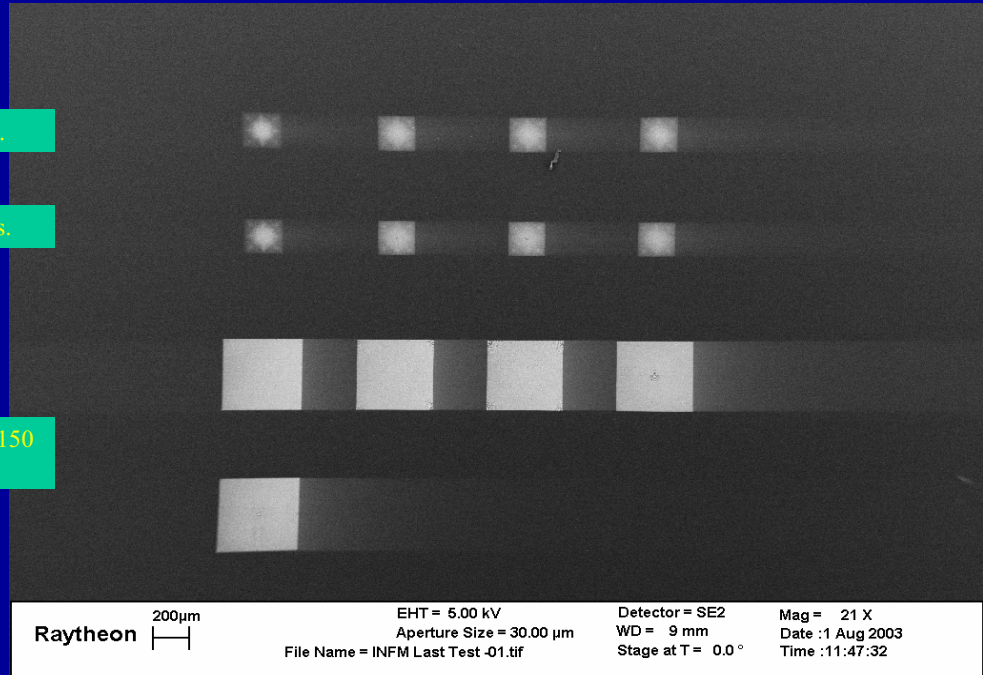


Complete set of objectives and condenser lens fabricated By e-beam lithography

2 spots at 6.5 KeV 50 nm res.

2 spots at 2.5 KeV 50 nm res.

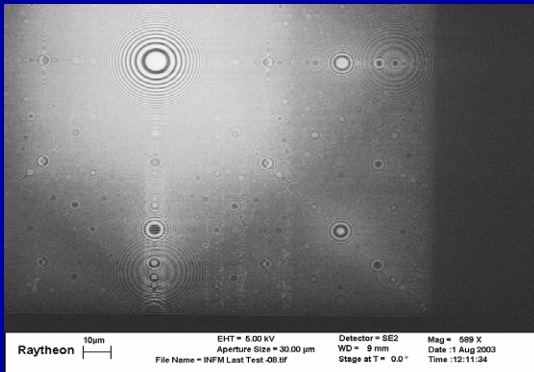
Top hat condenser at 4 KeV 150 and 200 nm res.



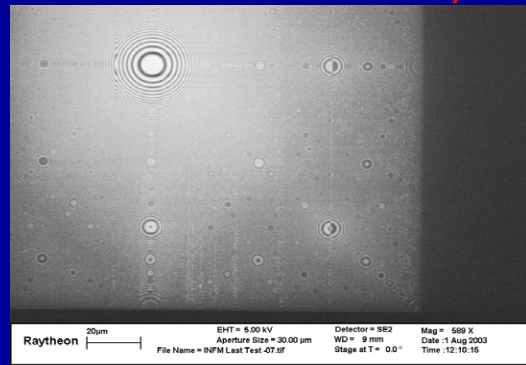
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DOE for Bias control

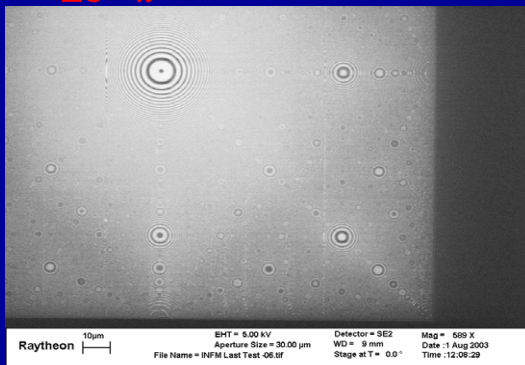
$\Delta\theta = 0$



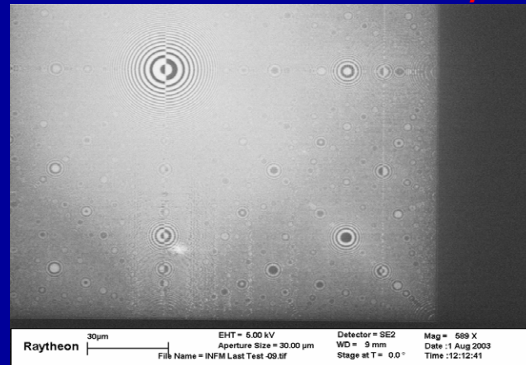
$\Delta\theta = \pi/2$



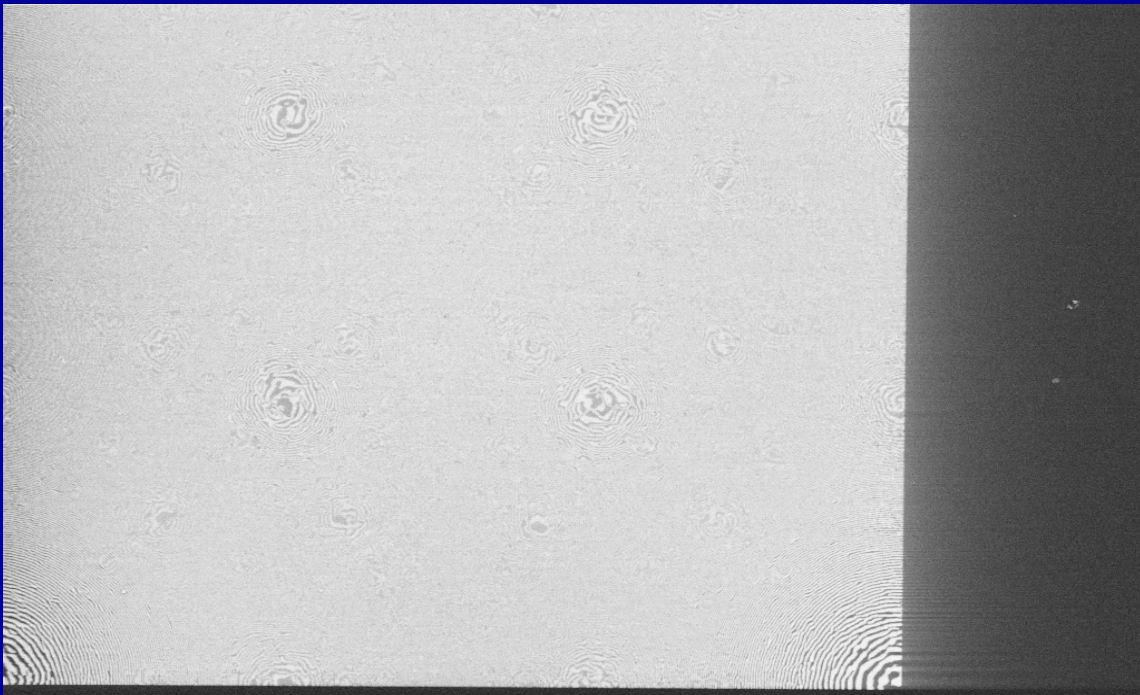
$\Delta\theta = \pi$



$\Delta\theta = 2\pi/3$



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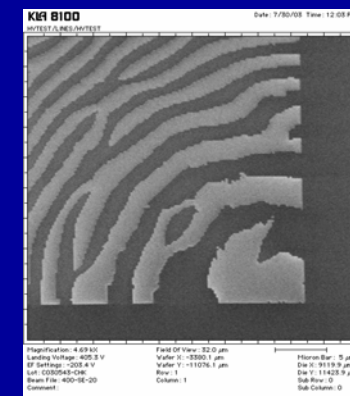
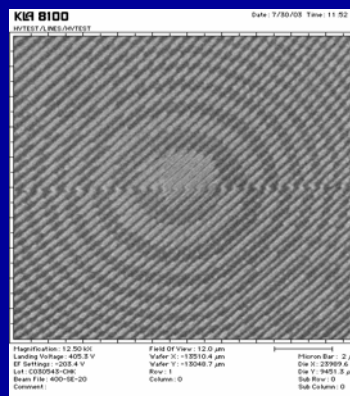
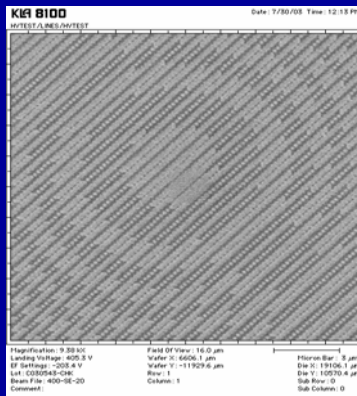
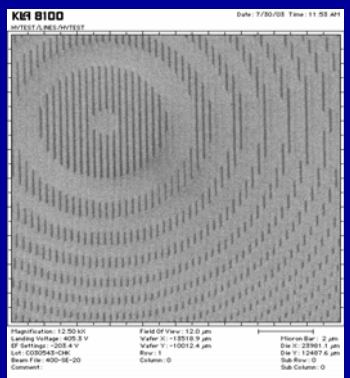
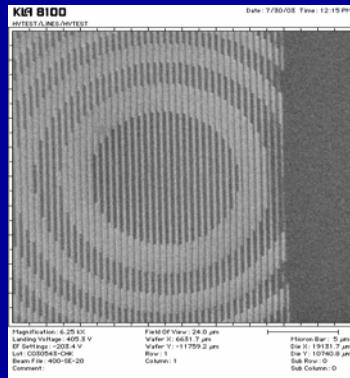
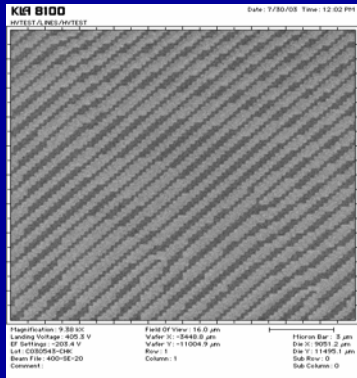
Raytheon 

EHT = 5.00 kV
Aperture Size = 30.00 μm
File Name = INFM Last Test -13.tif

Detector = SE2
WD = 9 mm
Stage at T = 0.0 $^\circ$

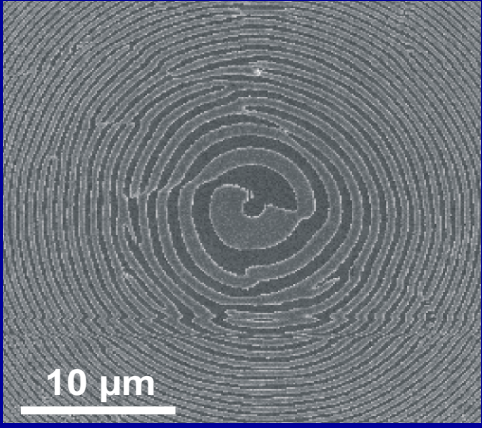
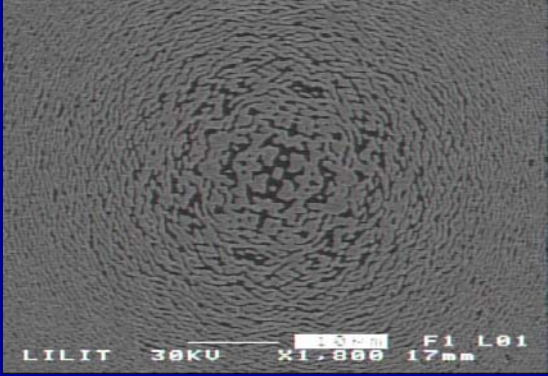
Mag = 225 X
Date :1 Aug 2003
Time :12:18:06

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Further DOE already fabricated to be tested



- Top Hat for TXM microscope (to replace the condenser lens)
- New annular distribution for DIC microscopy
- Sub micron Intensity pattern for maskless lithography and CVD induced by X-rays

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50 nm smaller pixel size with 30 nm details

KLA 8100 Date: 7/30/03 Time: 11:46 AM
HVTEST/LINES/HVTEST

Magnification: 300.00 kX
Landing Voltage: 405.3 V
EP Settings: -205.4 V
Lot: G030543-CHK
Beam File: 400-SE-20
Comment:

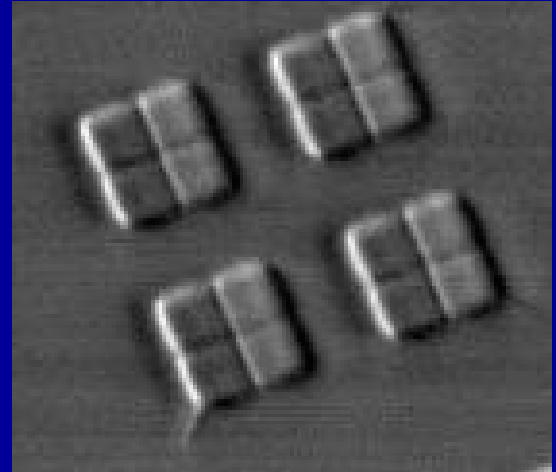
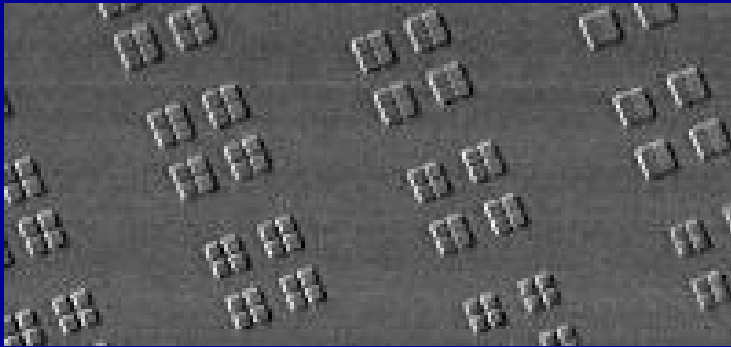
Field Of View: .5 μm
Wafer X: -13524.6 μm
Wafer Y: -7108.6 μm
Row: 2
Column: 0

Micron Bar: 0.1 μm
Die X: 23975.4 μm
Die Y: 391.4 μm
Sub Row: 0
Sub Column: 0

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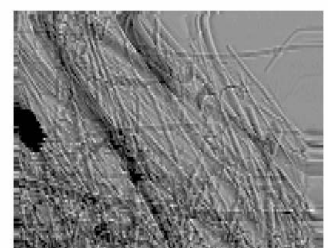
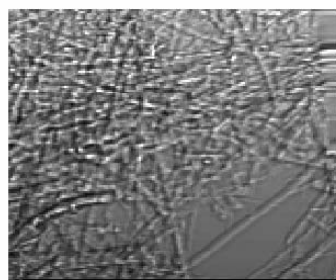
From the report
DOE Experiment
O. Dhez and M.Salomé
7/10/2003

Experiment performed on ID21 SXM
branch, in 16 bunch mode, under
vacuum at 6.5keV. The
sample used is the PMMA test object.



7.2 KeV X-ray

4 KeV X-ray

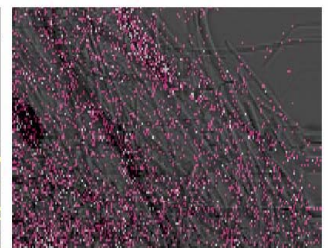
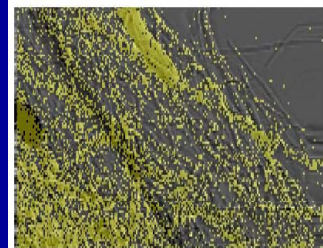
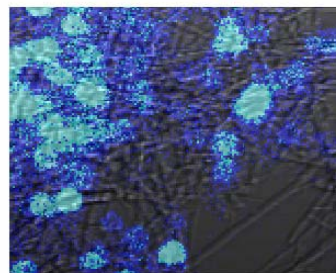
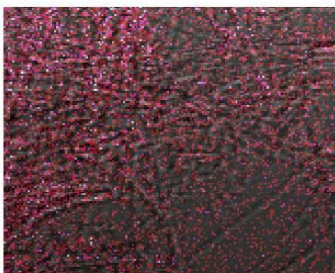


Absorption contrast

Diff. Interf. contrast

Absorption contrast

Differential interference contrast



Cr XRF map

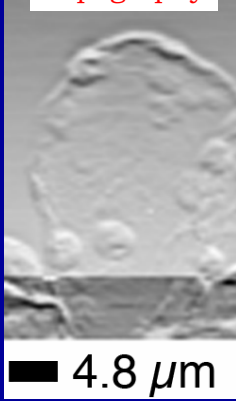
Fe XRF map

Ca XRF map

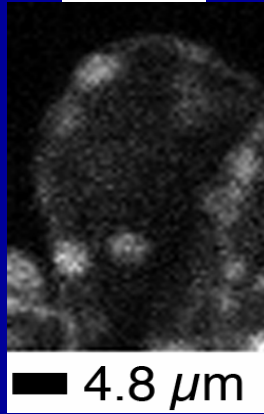
K XRF map

Id21, ESRF, M1578, 7.2 keV, 160 x 145 (?) px, 100 x 100 μm
thin sample

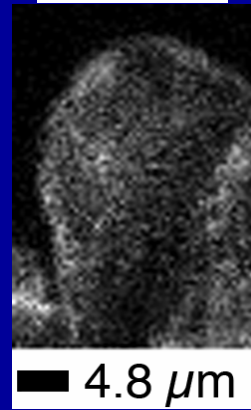
Topography



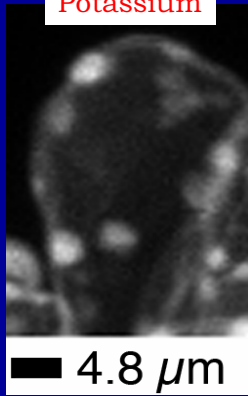
Chlorine



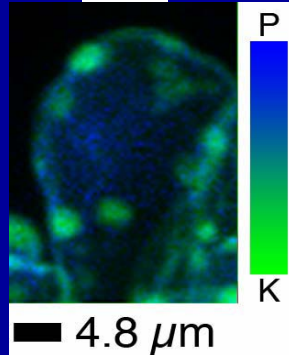
Phosphorus



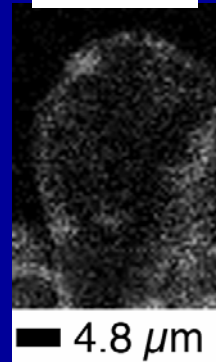
Potassium



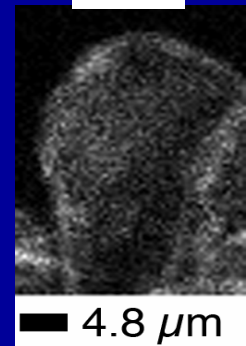
K&P



Scandium



Sulfur



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LEO 1540XB CrossBeam

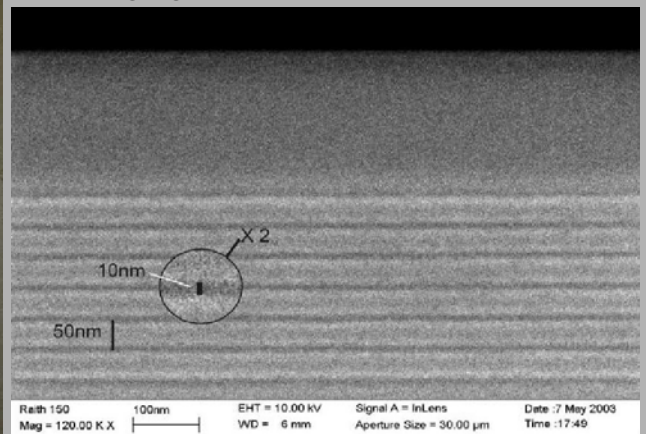


System Features:

- Super Eucentric 6-axis stage
X 102 mm, Y 102 mm
- Gas injection system
- 4" Airlock (optional)
- Automated aperture change on
FIB column
- Enhanced vacuum system

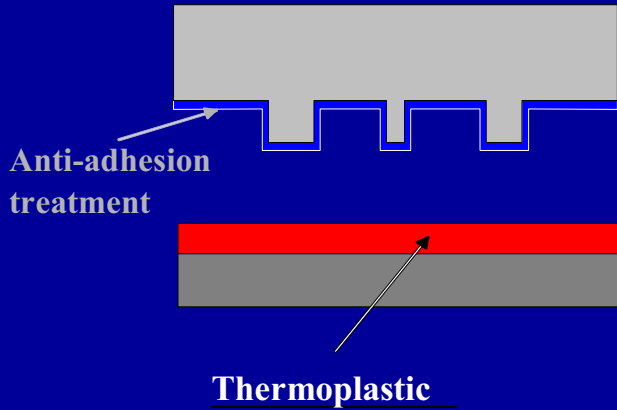
Optional included:

- EDS
- CAD
- Lithography
- SIMS



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Stamp materials : Si, Si oxide,
Si nitrate, Ni, W, quartz, sapphire

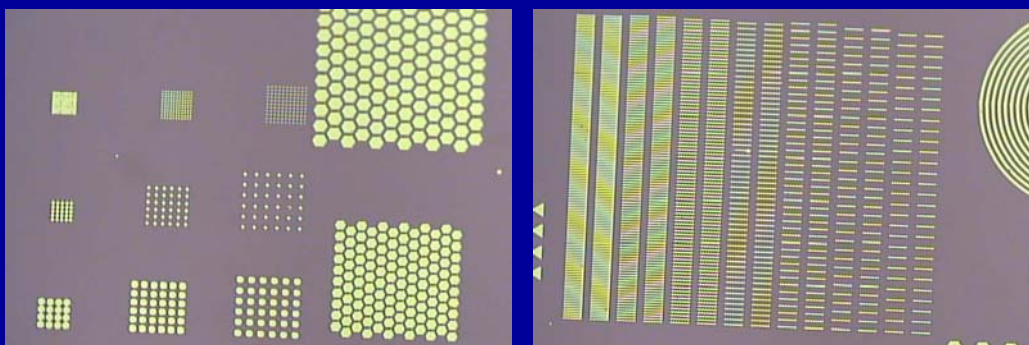


Embossing conditions

pressure: 50-100 bar

temperature: $T \sim T_g + 90^\circ$

Master: Gold on Silicon



Imprinted structures: PMMA (plexiglass) on Silicon



- ✓ **Two different DIC techniques using ZP doublet and X-Ray DOE**
- ✓ **Spatial resolution according to the design**
- ✓ **Technique has no limitation in spectral range as far as ZPs can be applied**
- ✓ **Full beam shaping achieved at X-ray wavelength**

Future investigations:

- **Extension of experiments to soft and harder X-rays**
- **Resolution limit toward state-of-art- fabrication technique**
- **Theoretical investigations and simulations (transfer function)**
- **Combination with spectro-microscopy for biological sample**

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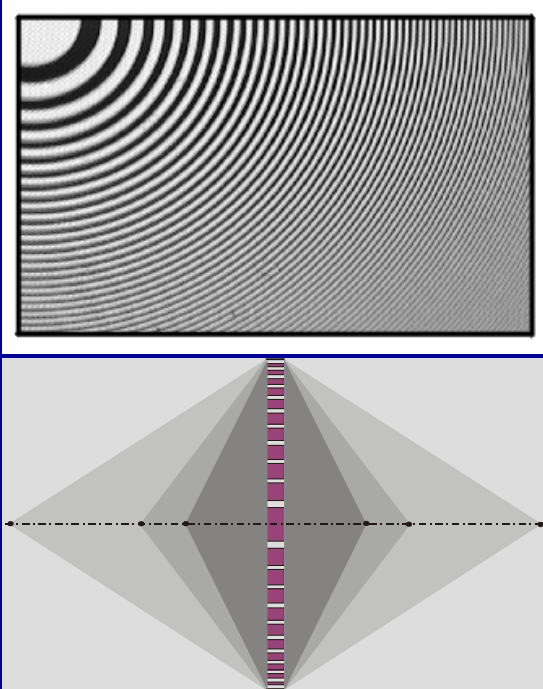
Lisa Vaccari, Matteo Altissimo, Luca Businaro
TASC-INFN at ELETTRA, Lilt

B. Fayard, U. Neuhaeusler, M. Salome, R. Baker
ESRF, ID21, Grenoble, France

F. Polack, D. Joyeux,
Lure& Universite Paris-Sud, Orsay, France

Alexei Barinov, Maya Kiskinova
ELETTRA

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Focusing, circular diffraction grating with radially increasing line density

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{q} \quad \text{if } n > 100$$

In terms of ZP parameters:

$$f_m = \frac{2}{m} D dr_m / \lambda$$

To avoid chromatic aberrations:

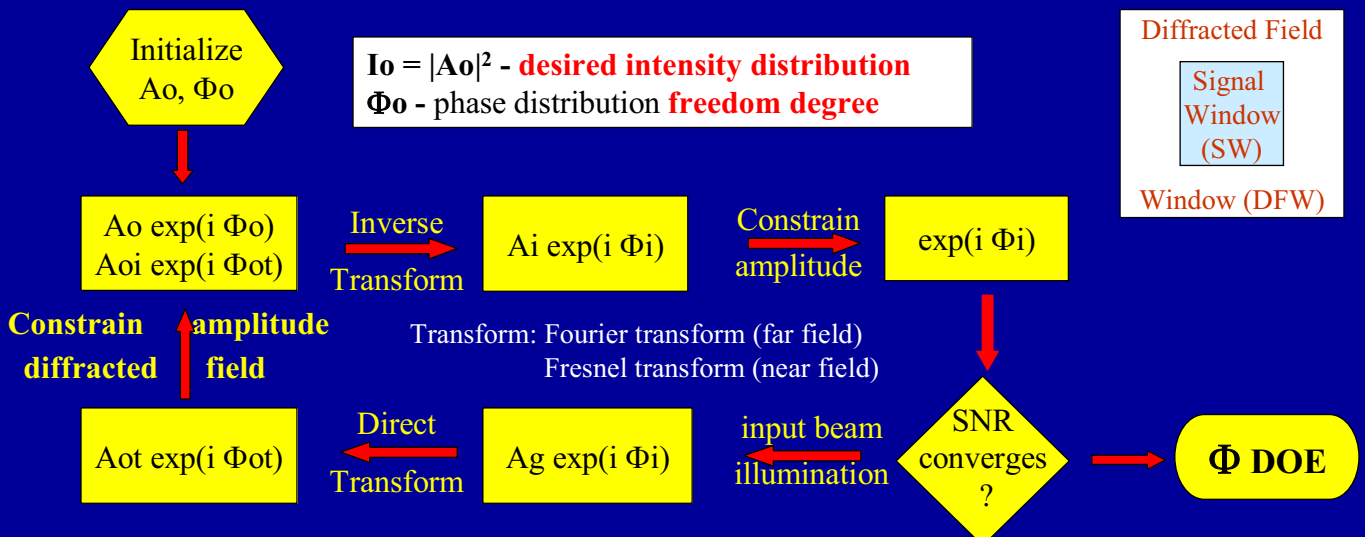
$$\frac{E}{\Delta E} \geq n m$$

$$\delta_m = [\delta_{i,m}^2 + \delta_r^2 + \delta_c^2]^{1/2} = [(1.22 \cdot dr_n / m)^2 + \delta_r^2 + (D \cdot \Delta E / E)^2]^{1/2}$$

ERA: Error **R**eduction **A**lgorithm, $A_{oi} = A_o$; DFW = SW

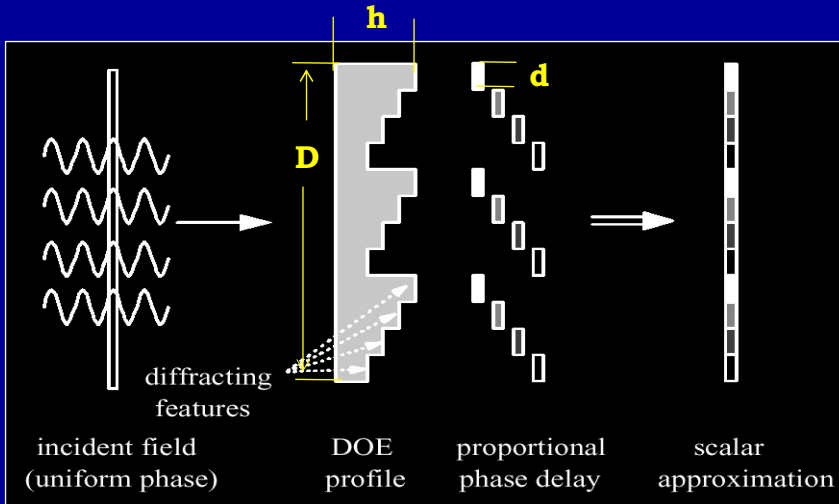
AAA: **A**daptive **A**dditive **A**lgorithm, $A_{oi} = \lambda A_o + (1 - \lambda) A_{ot}$ inside SW; DFW > SW

CEAA: **C**ombined **E**rror **A**daptive **A**lgorithm



scalar diffraction theory

$$d > 3\lambda$$



DOE's phase function:

$$\Phi_{\text{DOE}}(\mathbf{x}) = 2\pi (n-1) h(\mathbf{x}) / \lambda$$

Coherence considerations

Spatial coherence (Van Cittert-Zernike)

$$D = 0.61 \frac{L\lambda}{d/2} = 1.22 \frac{f\lambda}{\delta}$$

D: Diameter of coherently illuminated plane
d: Source diameter
L: Distance to observation plane

ZP shift $\Delta x < \delta = 1.22 dr_N$
Then:

If the separation (Δx) of the two superimposed images is below the resolution limit (δ) the two images will interfere without further restrictions to the spatial coherence of the source or, DIC works independent, of the spatial coherence of the illumination

Temporal coherence

$$l_{\text{coh}} = \frac{\lambda^2}{2 \Delta\lambda} > \frac{\lambda}{2} N = \Delta s_{\text{max}}$$

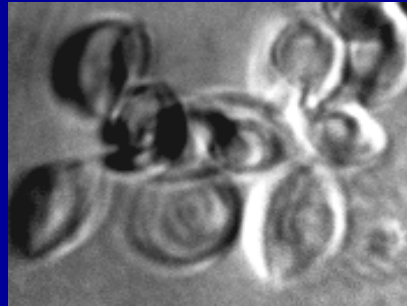
l_{coh} : coherence length
 Δs_{max} : path length difference
N: Number of zones

$$\frac{\lambda}{\Delta\lambda} > N \approx N_{\text{eff}} = \frac{(r+\Delta x)^2}{\lambda f}$$

ZPs have to be treated to be in the same plane (within their depth of focus) ($N > 100$)

Then:

No precautions to the source spectrum or other than for imaging with a single ZP

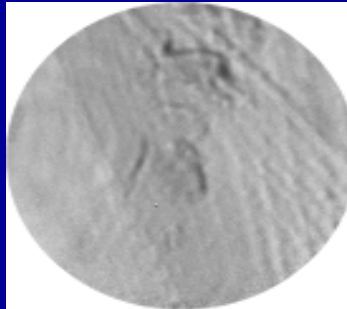
DIC X-ray microscopy
with a full-field imaging microscope @ 4 keVSpores of giant moss
"Dawsonia superba"

Exp. time: 20 s

5 μm

Wing of a moss

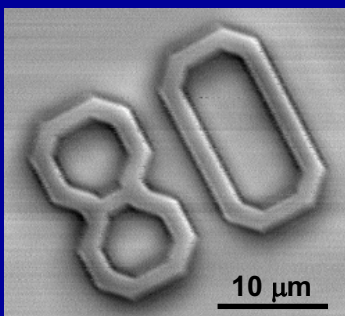
Exp. time: 30 s

10 μm 

B. Kaulich, T. Wilhein, E. Di Fabrizio, S. Cabrini, F. Romanato, M. Altissimo, J. Susini (Nov 2000)

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Summary of DIC with ZP doublets



- DIC contrast technique, which is applicable for photon energies where ZPs work successfully (0.1 – 30 keV)
- Increase in image contrast of up to 20x – 30x achieved
- Method can for the first time be applied in both transmission X-ray microscopy types (STXM and TXM)
- Alignment procedure not more complicated than for a single ZP

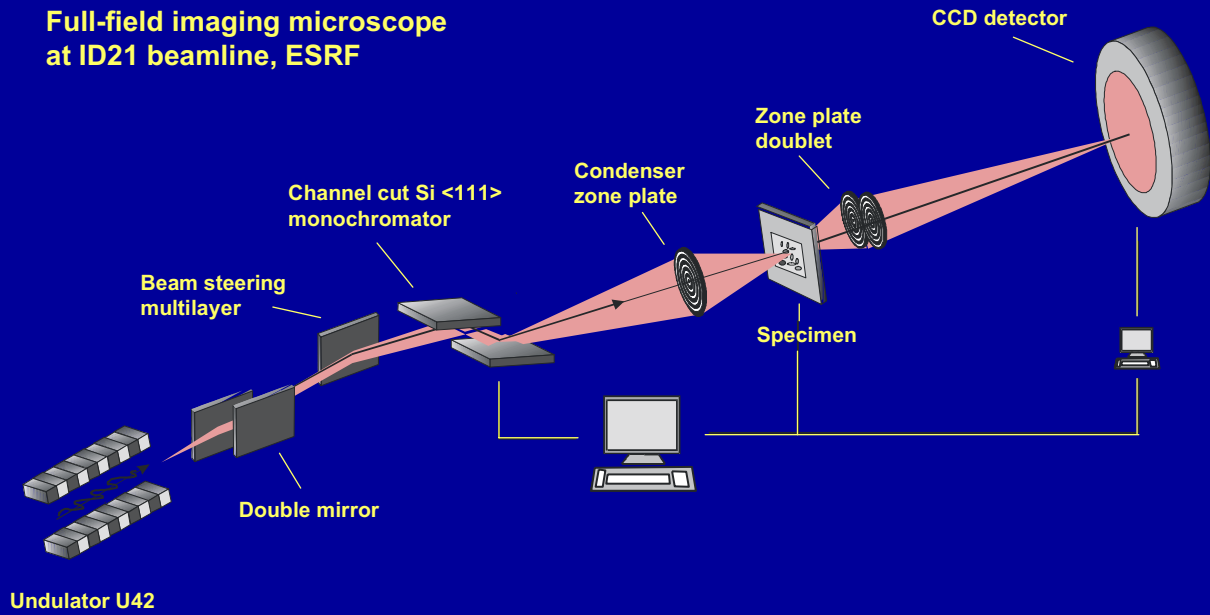
Improvements on ZP doublets fabrication:

- Simpler nanofabrication process (X-ray litho)
- Optimization in ZP diffraction efficiency (10 % @ 4 keV meas.)
- Improvement in spatial resolution
- higher energy range accessible > 10 keV

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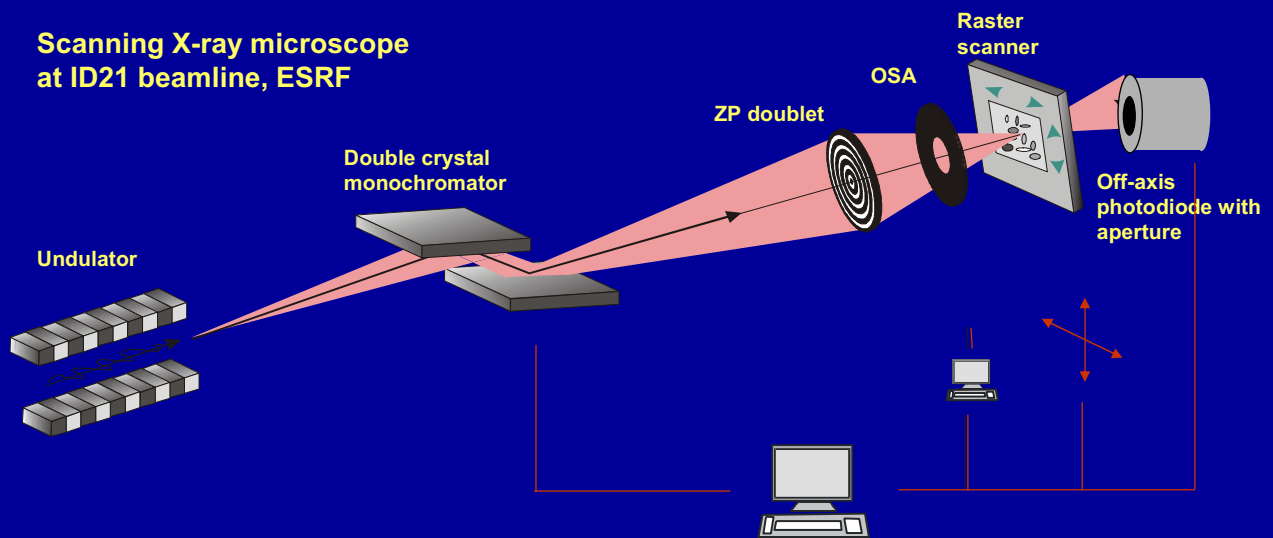
Full-field imaging microscope operating in DIC mode – Optical setup

Full-field imaging microscope
at ID21 beamline, ESRF

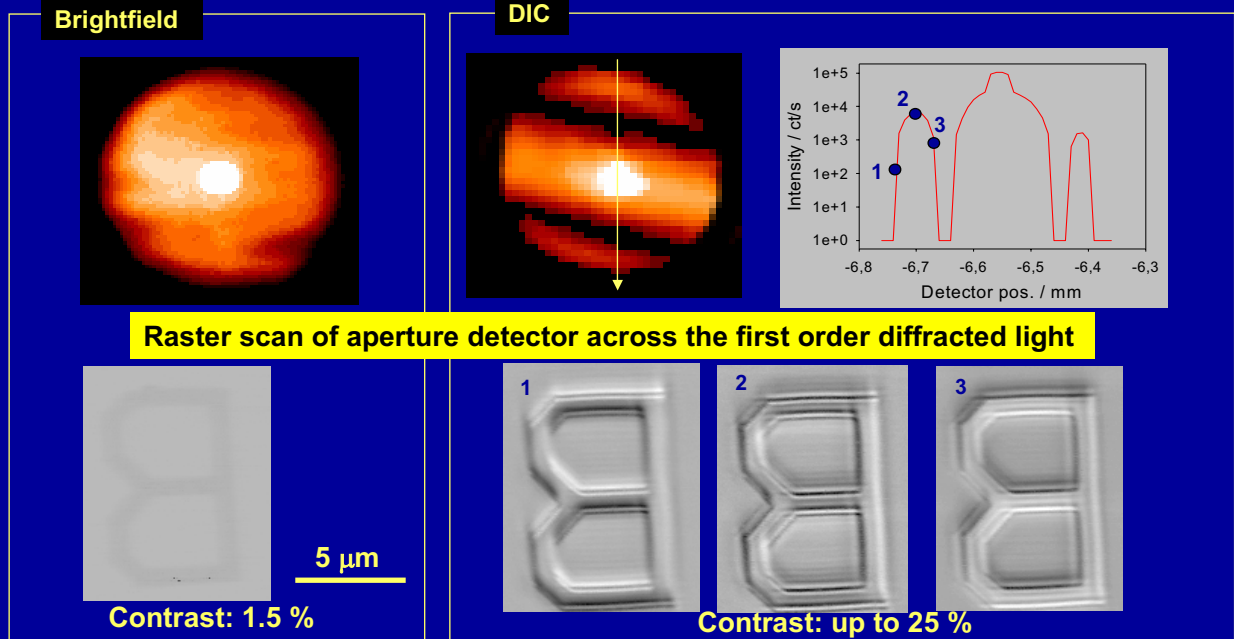


DIC with the scanning X-ray microscope: Optical setup

Scanning X-ray microscope
at ID21 beamline, ESRF



DIC with a scanning microscope (4 keV) using a ZP doublet



B. Kaulich, T. Wilhein, E. Di Fabrizio, F. Romanato, S. Cabrini, B. Fayard, J. Susini (Feb 2000)
B. Kaulich, B. Fayard, U. Neuhaeusler, M. Salome, J. Susini (March 2000)

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Scalar versus Vectorial diffraction based models

Scalar based models

- ray tracing, spherical wave propagation + superposition
- phase retrieval iterative algorithms (PRIA)
- global optimization methods: genetic algorithms, simulated annealing

Vectorial based models

- Finite element method (FEM)
- Boundary element method (BEM)
- Method of moments (MOM)
- Finite-difference method (FDM)
- Finite-difference time-domain (FDTD)

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- 1** Fraunhofer (far field); propagation operator: Fourier transform

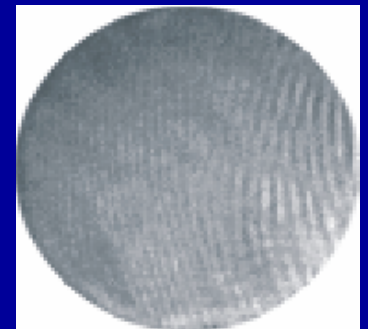
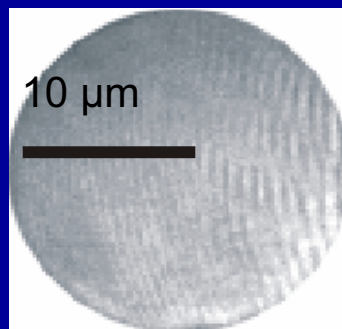
$$z > \pi D^2 / 4\lambda$$

- 2** Fresnel (near field); propagation operator: Fresnel transform

$$\sqrt[3]{\pi D^4 / 64\lambda} \leq z \leq \pi D^2 / 4\lambda$$

- 3** very near field; propagation operator: the Fresnel-Kirchoff integral

$$\lambda \ll z < \sqrt[3]{\pi D^4 / 64\lambda}$$

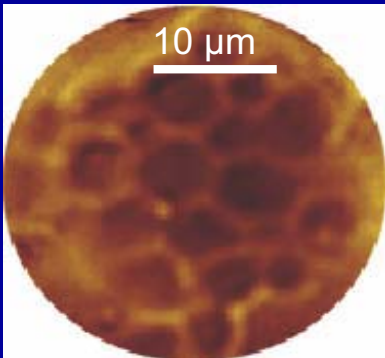


Objective lens: 2 confocal spots DOE

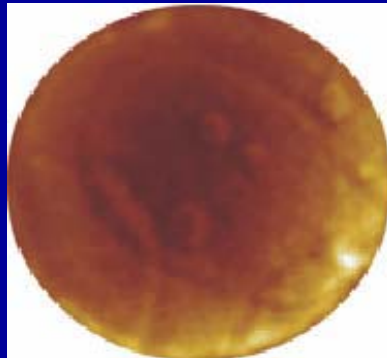
Sample: beamshaping DOE made by PMMA

Obs: the ultimate spatial resolution can be estimated being about 150 nm

Topography of biological samples @ 4 keV Measured with 2 coaxial spot DOE (June 2001)



array of yeast cells



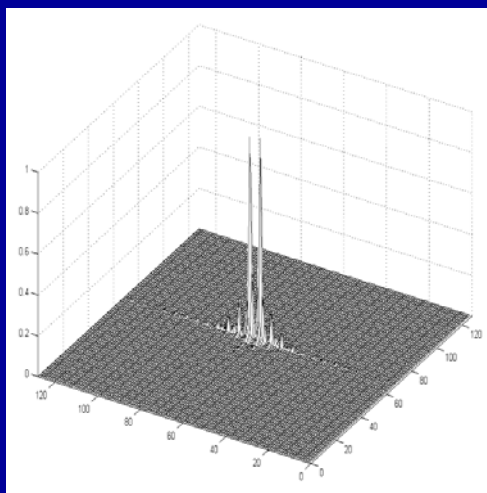
frog blood cells



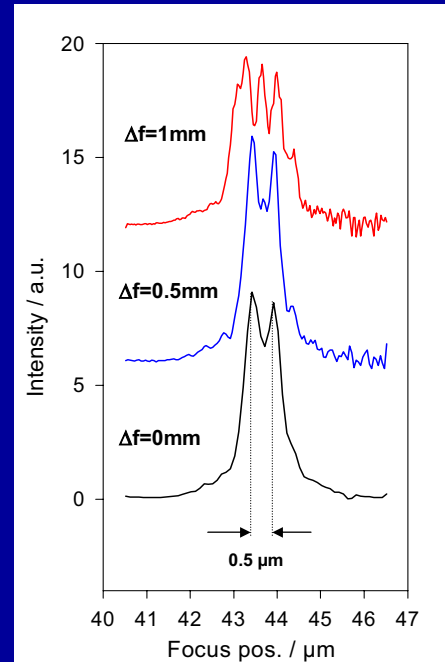
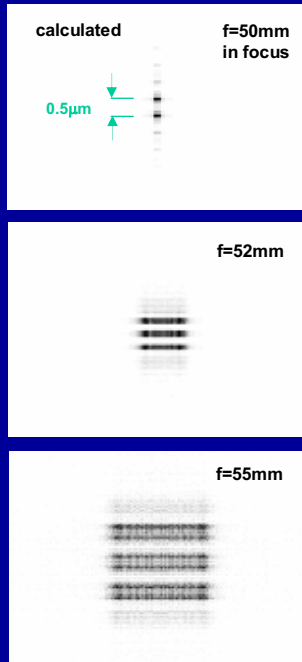
Iris flower fibers

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Simulation and measurements for multi-spot ZP



Simulation of 2-spot zone DOE
in / out focal plane



Comp. Simulations by: E. Di Fabrizio et al (Lilit)
Measurements by: B. Kaulich, T. Wilhein, S. Cabrini, A. Barinov, J. Susini (Feb 2001)

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$$R = A[\cos \omega t + \cos(\omega t + \phi) + \cos(\omega t + 2\phi) + \cdots + \cos(\omega t + (n - 1)\phi)], \quad (30.1)$$

$$A_R = A \frac{\sin n\phi/2}{\sin \phi/2}.$$

$$I = I_0 \frac{\sin^2 n\phi/2}{\sin^2 \phi/2}.$$

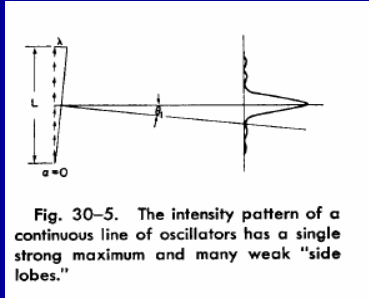


Fig. 30-5. The intensity pattern of a continuous line of oscillators has a single strong maximum and many weak "side lobes."

$$I = 4I_m \sin^2 \frac{1}{2}\Phi/\Phi^2.$$

are no higher-order maxima. If the scatterers are all in phase, we get a maximum in the direction $\theta_{\text{out}} = 0$, and a minimum when the distance Δ is equal to λ , just as for finite d and n . So we can even analyze a *continuous* distribution of scatterers or oscillators, by using integrals instead of summing.