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Winter College on Optics and Photonics
7 - 25 February 2000

1218-14

"Micro-Optics & Optical Nanostructures"

H.P. HERZIG
Institut de Microchnique
Univ. Neuchâtel
Switzerland

Micro-Optics & Optical Nanostructures

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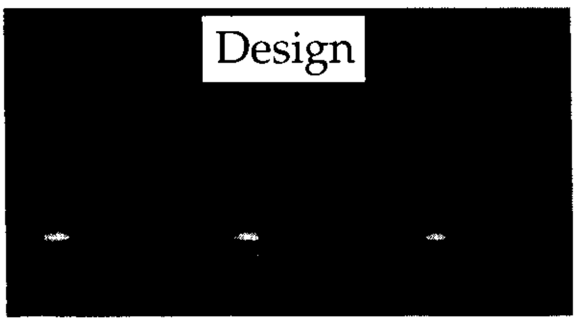
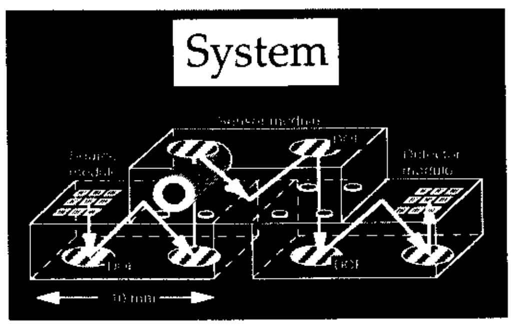
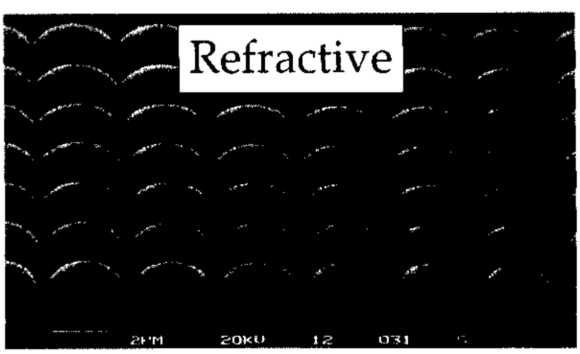
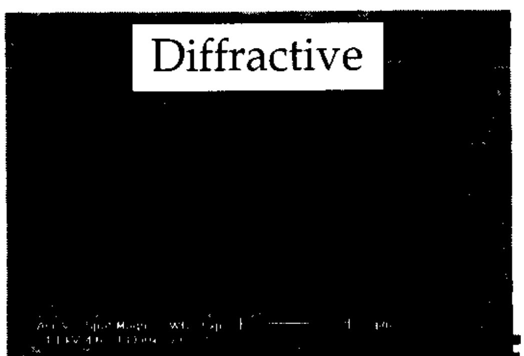
IMT-Uni NE

optics.unine.ch/research/Microopt/microopt.html









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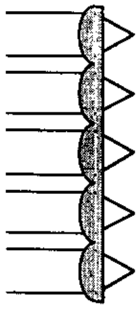
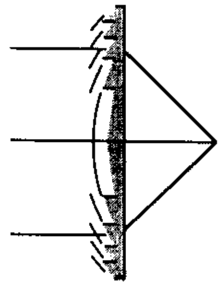
Micro-optical elements

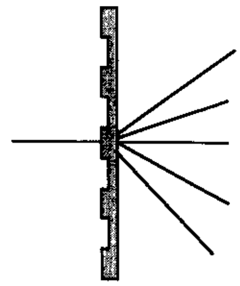
Free-space



microlens array

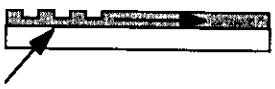


diffractive optical element



optimized grating

Integrated



grating coupler

integrated optics

fiber optics

Definition of micro-optics

- Optical elements with structures in the sub-mm and sub-μ range, which are fabricated mainly by lithographic methods
- Systems based on these elements

Realization of micro-optical elements

- Computer generated data
- Conversion of data into an optical element by lithographic methods
- Transfer of the structure in a rigid or transparent material (etching)
- Replication

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Micro-Optics: contents

- Diffraction - refraction
- Design fundamentals of micro-optical elements
- Fabrication techniques
- Aperture modulated diffusers (AMDs)
- Color fan-out elements
- Grating spectrometer
- Fourier spectrometer
- Lab on chip

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Refractive and diffractive micro-optics: theory

- Fundamentals of refraction and diffraction
- Complex amplitude transmittance
  $t(x,y) = \exp[\Phi(x,y)]$
- Implementation of phase function $\Phi(x,y)$
- Optimum design
- Diffraction elements - refractive elements

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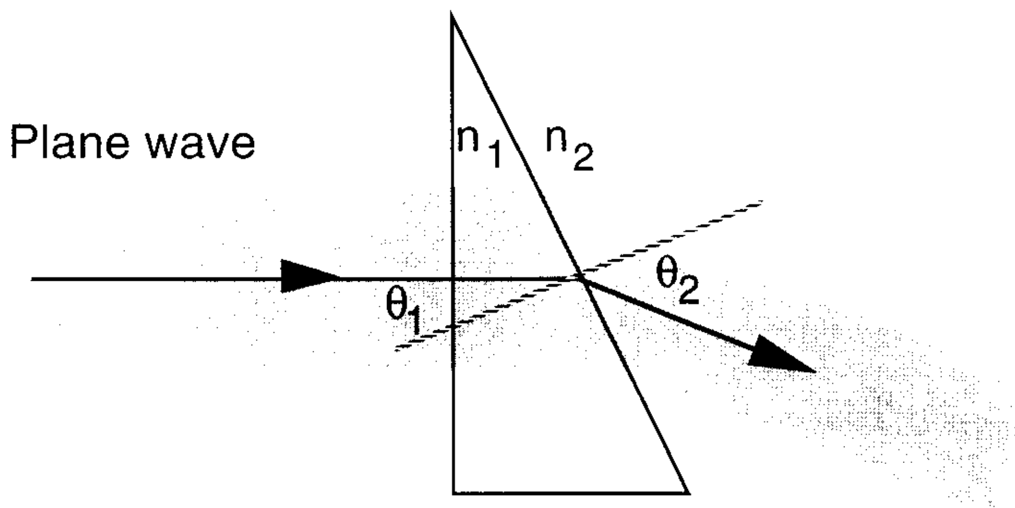
Refraction

$$n_1(\lambda)\ \sin\theta_1 = n_2(\lambda)\ \sin\theta_2$$



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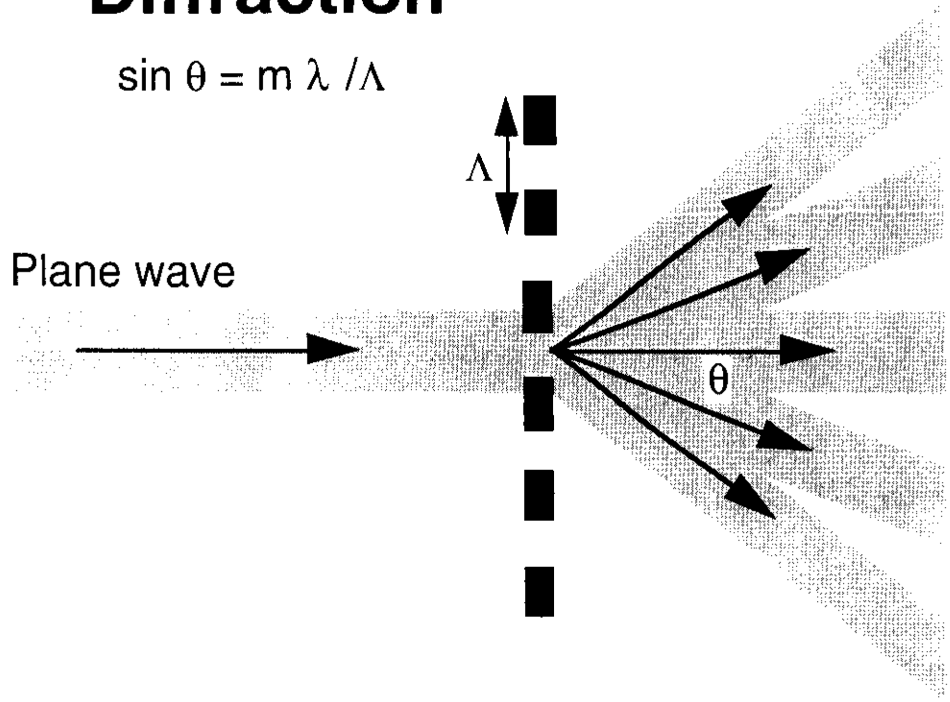
Diffraction

$\sin\theta = m\,\lambda/\Lambda$



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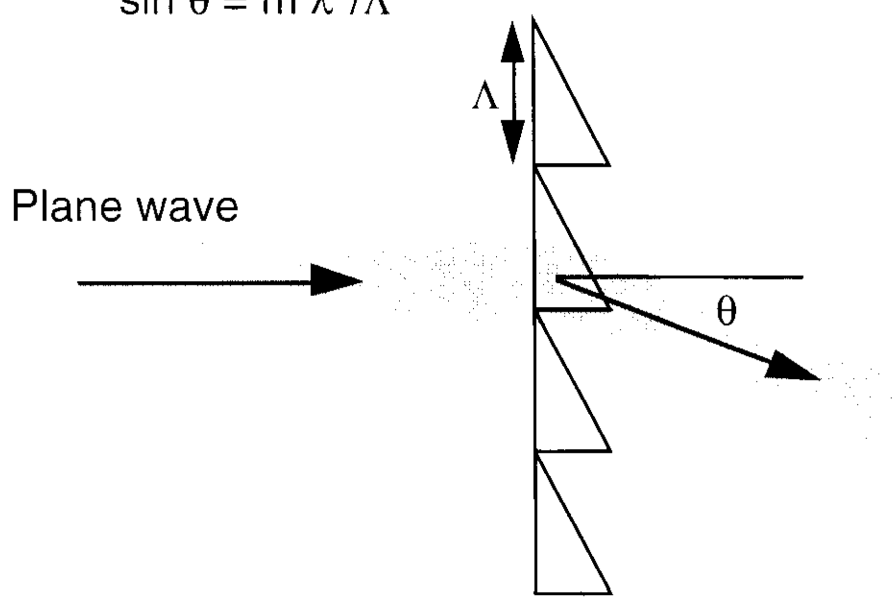
Diffraction

$\sin\theta = m\,\lambda/\Lambda$



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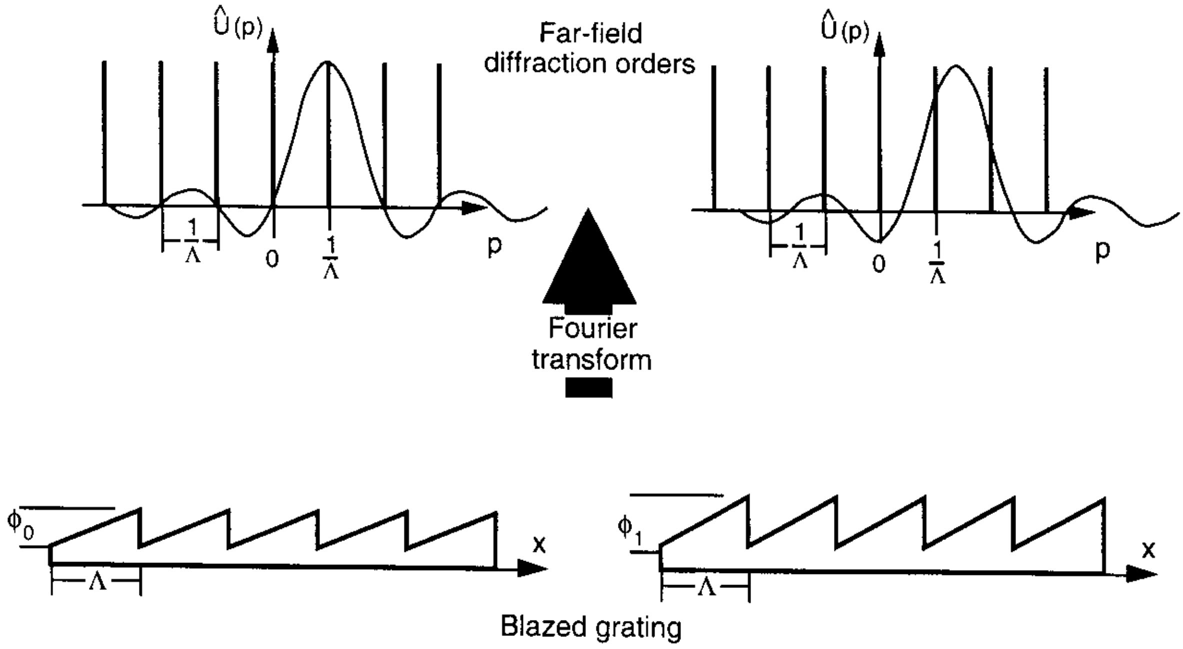

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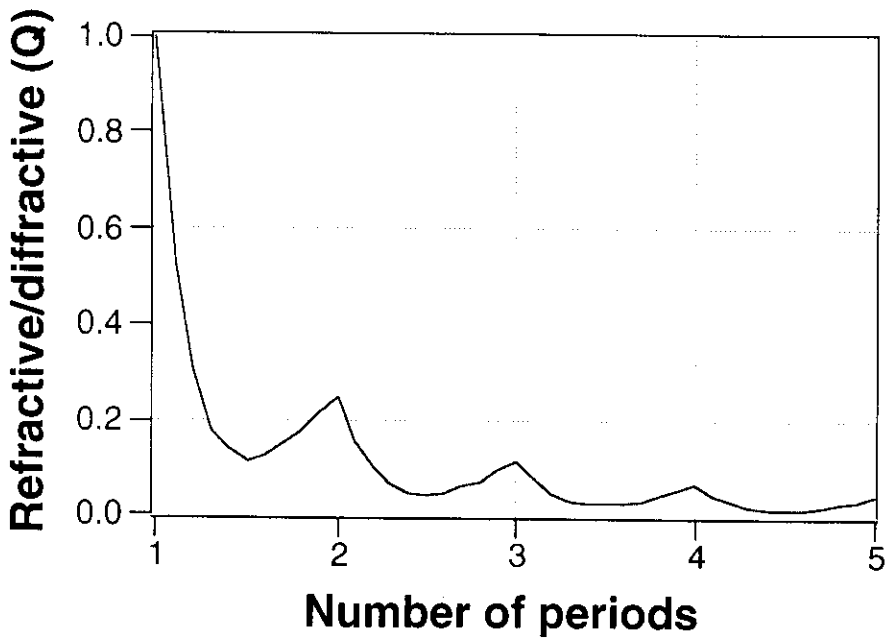
Refractive-diffractive properties of blazed grating (shrinkage error 10 %)



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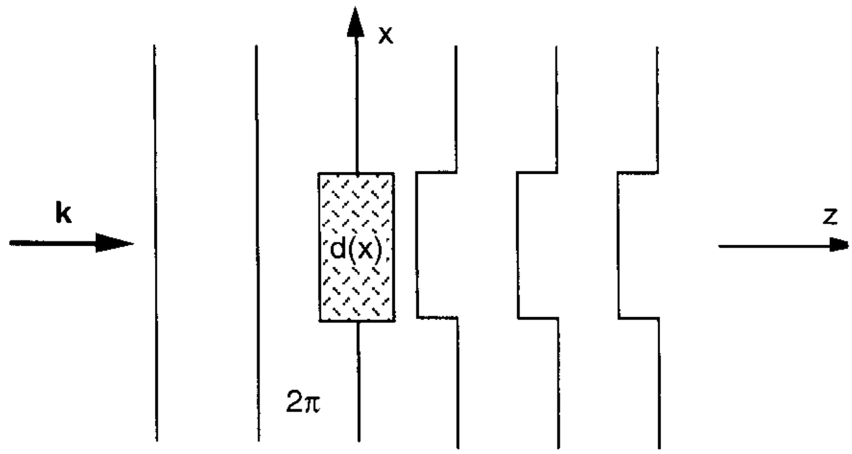
Complex amplitude transmittance



$U_2 = U_1 \exp[i\Phi(x)]$ with $\Phi(x) = d(x)\,(n-1)\,(2\pi/\lambda)$

$U_2 = t(x)\,U_1$ transmittance: $t(x) = \exp[i\Phi(x)]$

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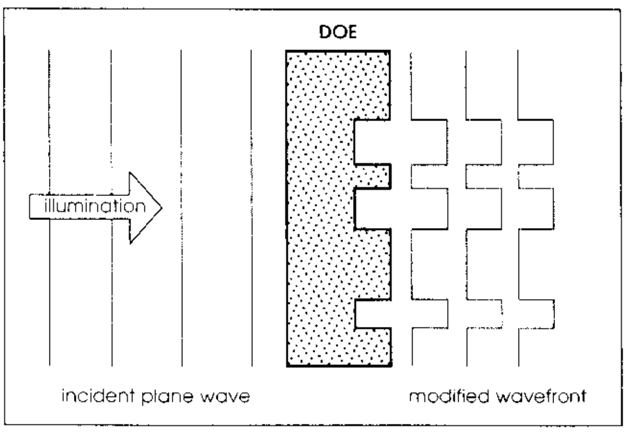
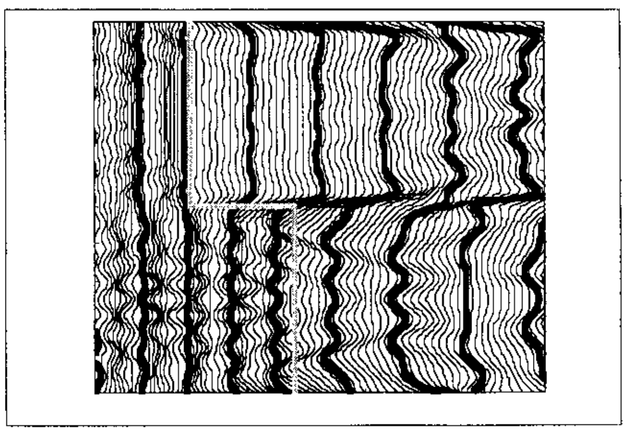
Why rigorous diffraction theory?

The interaction of light with structures having geometrical features in the order of the wavelength can not be described with classical scalar (thin-) diffraction models, but ask for .



thin diffraction theory



rigorous diffraction theory

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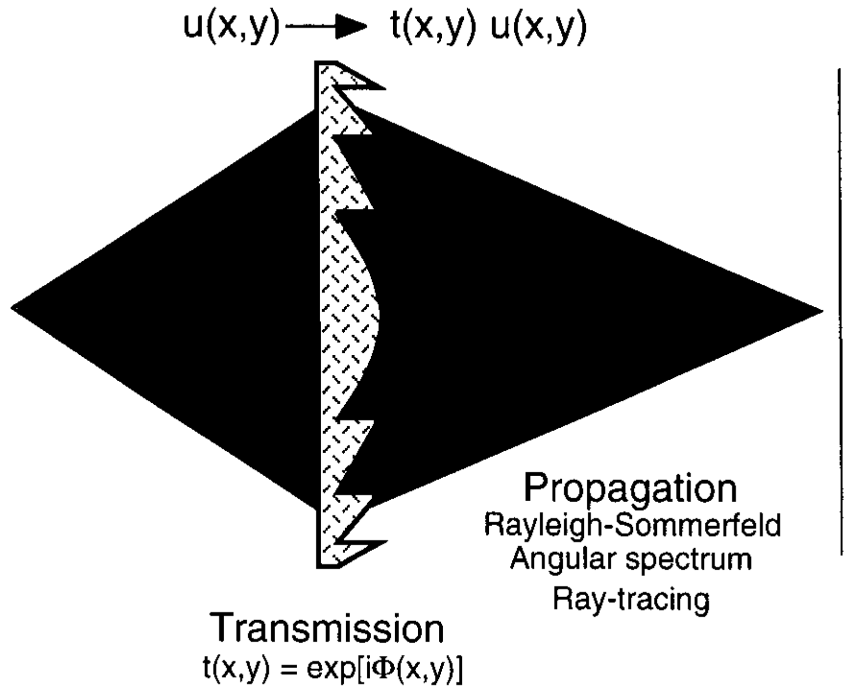
Transmission and propagation



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Calculation of the phase function

A thin phase element that is illuminated by an incident wave $\Phi_{in}(x,y)$ generates an output wave $\Phi_{out}(x,y)$. The wavefront conversion is described by

$$\Phi_{out}(x,y) = \Phi_{in}(x,y) + \Phi(x,y)$$

$$\Phi(x,y) = \Phi_{out}(x,y) - \Phi_{in}(x,y)$$

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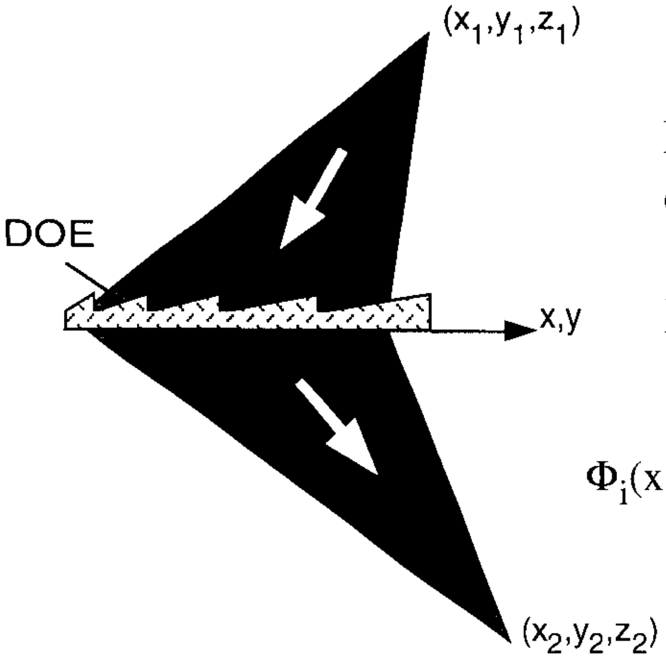

Diffractive lens which connects an object point (x_1,y_1,z_1) with an image point (x_2,y_2,z_2).

$$\Phi_i(x,y) = \frac{2\pi}{\lambda_0}\sqrt{(x-x_i)^2+(y-y_i)^2+(z_i)^2}$$

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In general, the optical task is more complex, e.g., if an extended object has to be imaged. In that case, the DOE phase function Φ(x,y) is typically described by a polynomial:

$$\Phi(x,y) = \frac{2\pi}{\lambda}\sum_{m,n} a_{mn}x^m y^n$$

The DOE is then optimized by optimizing the polynomial coefficients $a_{m\,n}$.

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Implementation of the phase function as DOE

In order to realize a diffractive element, the phase function Φ is wrapped to an interval between 0 and an integer multiple of 2π.

Phase profile: $\Psi(x,y) = [\Phi(x,y) + \varphi_0] \bmod 2\pi$

Relief profile: $h(x,y) = [\Psi(x,y)/2\pi][\lambda_0 \ /(n(\lambda_0)-1)]$

φ_0 constant phase offset.

n refractive index of the grating material

λ_0 design wavelength.

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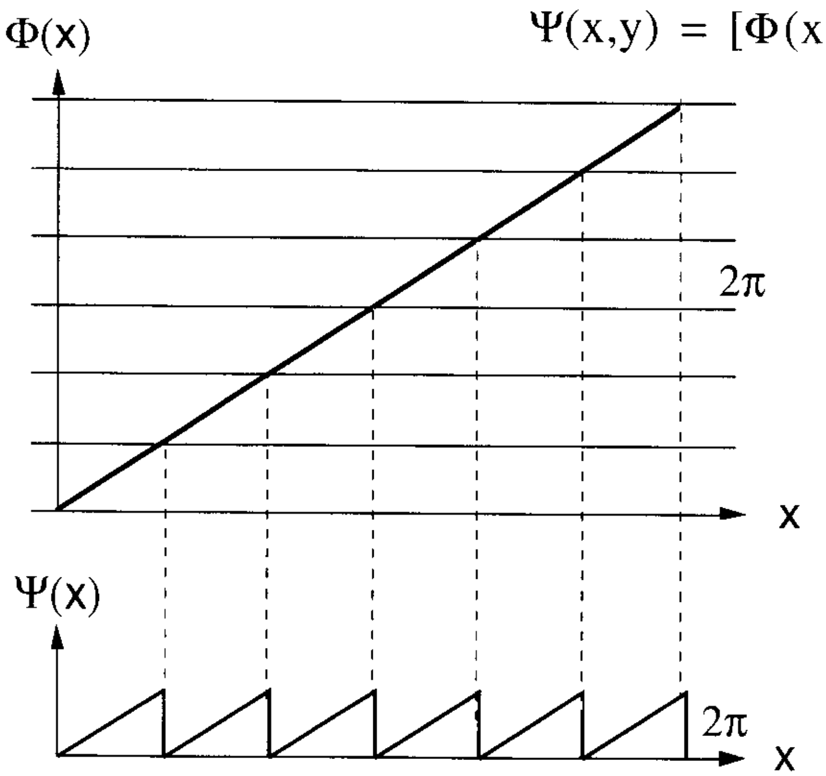
$\Psi(x,y) = [\Phi(x,y) + \varphi_0] \bmod 2\pi$



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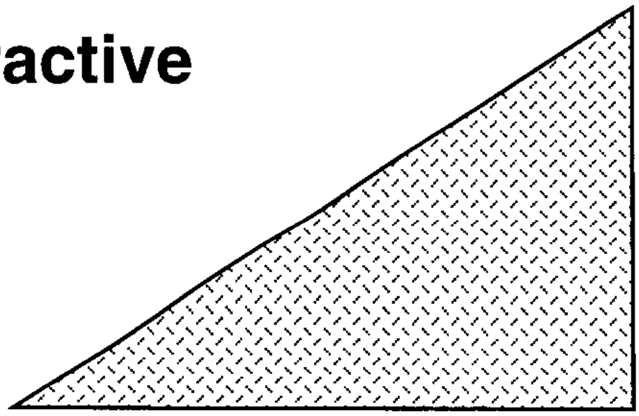
refractive



diffractive

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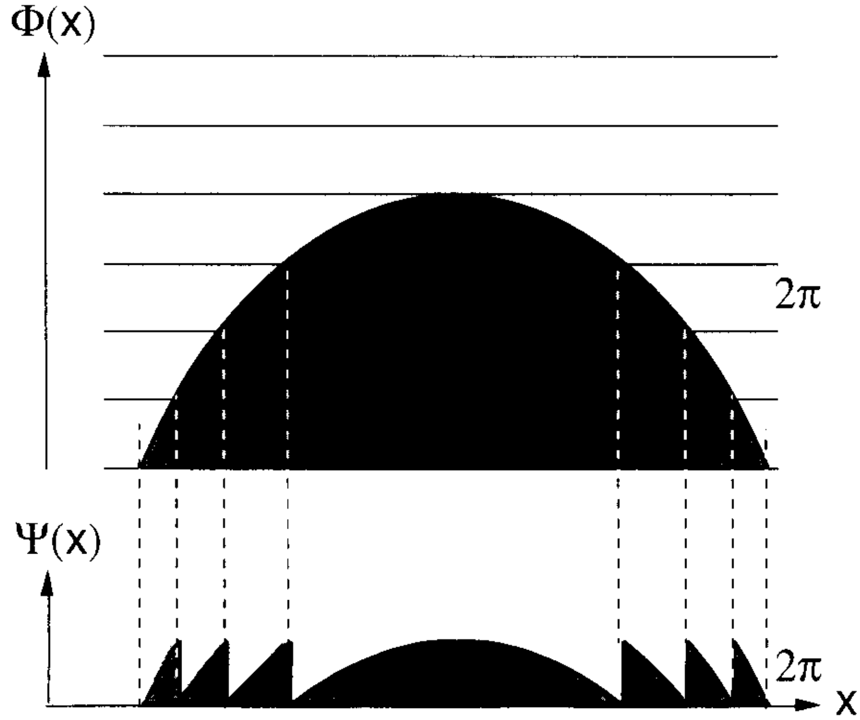

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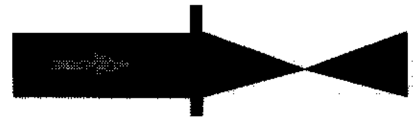
Design of continuous-relief DOEs

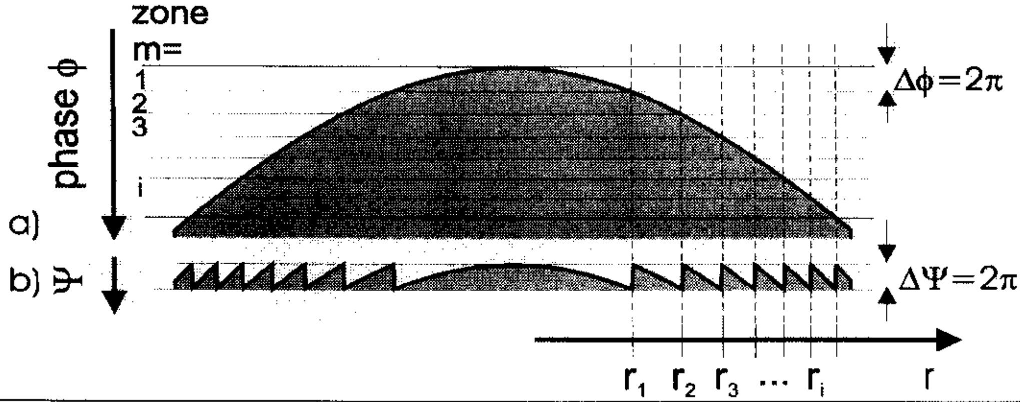
I) Calculate DOE phase function ϕ

analytical, custom or commercial (ray-trace) program.

$$\phi_{in}(x,y)+\phi(x,y)=\phi_{out}(x,y)$$



II) Wrap phase

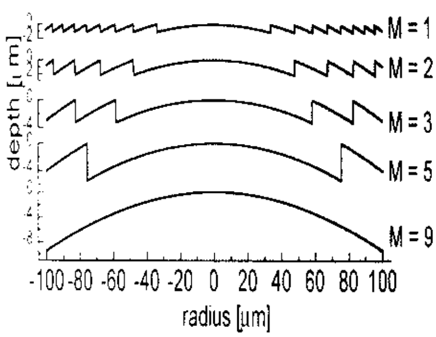


III) Transform wrapped phase into surface relief

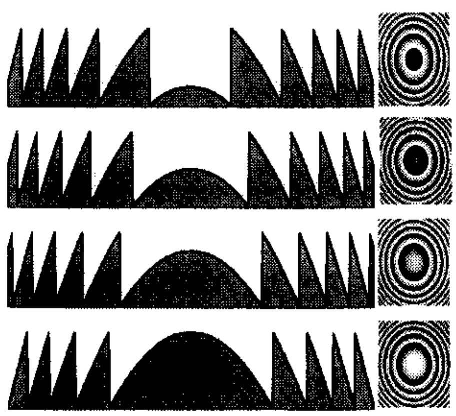
Design freedoms

Wrapped phase function Ψ: $\Psi(r)=\left[\phi(r)+\varphi_m+\varphi_0\right] \bmod \left(M_m\, 2\pi\right)-\varphi_m$

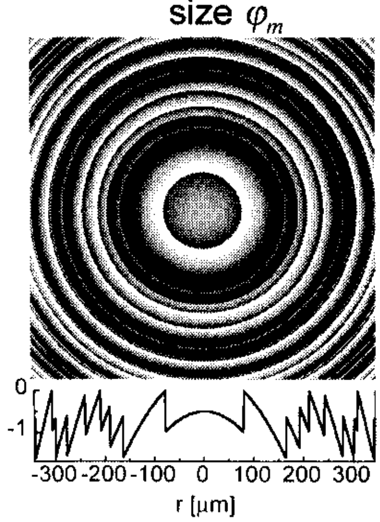
Phase-matching number M_m



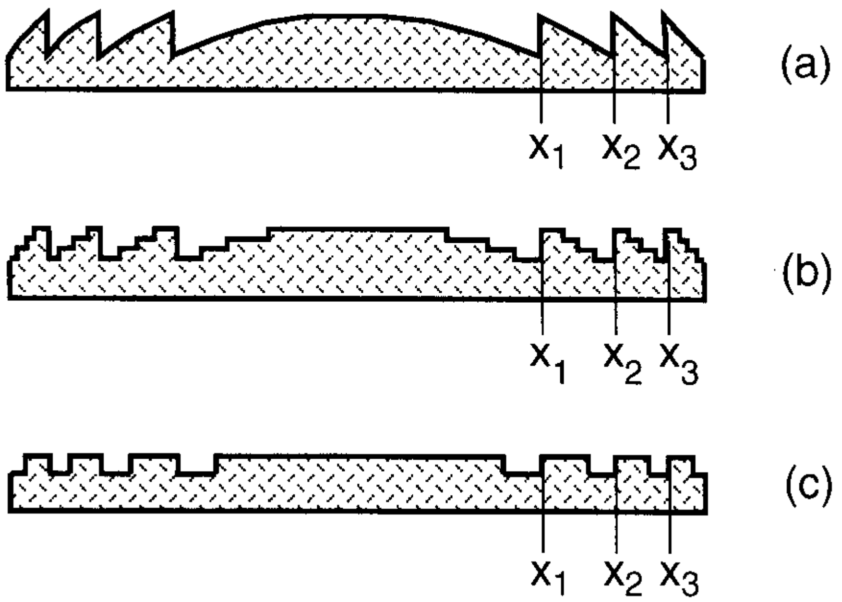
Phase offset φ_0



Zone position and size φ_m



Binary and continuous-relief DOEs



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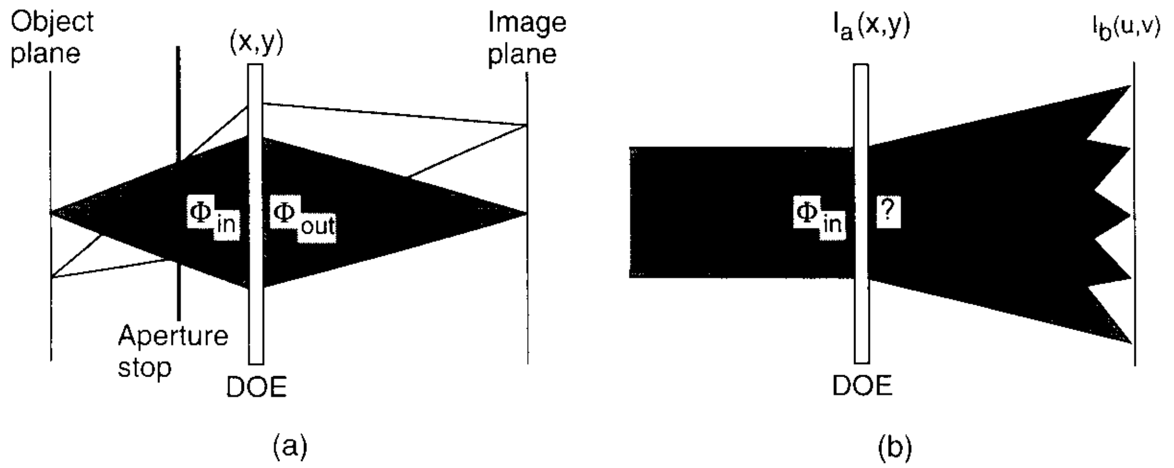
Optimum design



(a) Imaging (b) Beam-shaping

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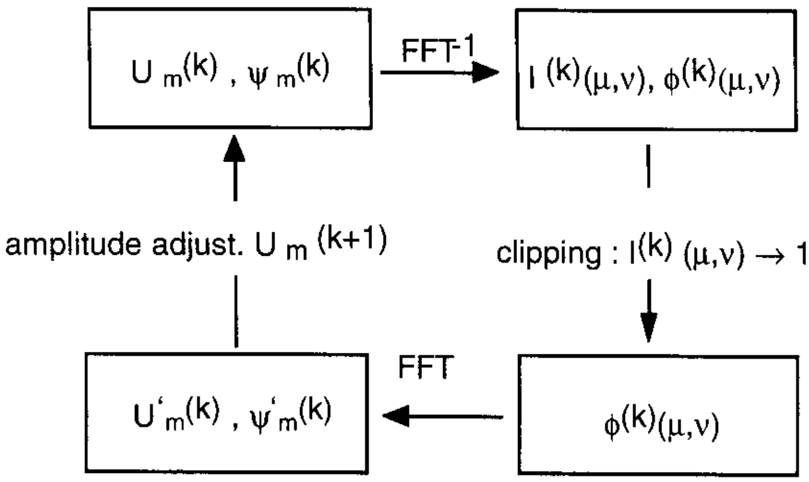
Iterative Fourier algorithm (IFTA)

Image plane **DOE plane**

input : $A_m(0) = 1$

$\psi_m(0)$ = random



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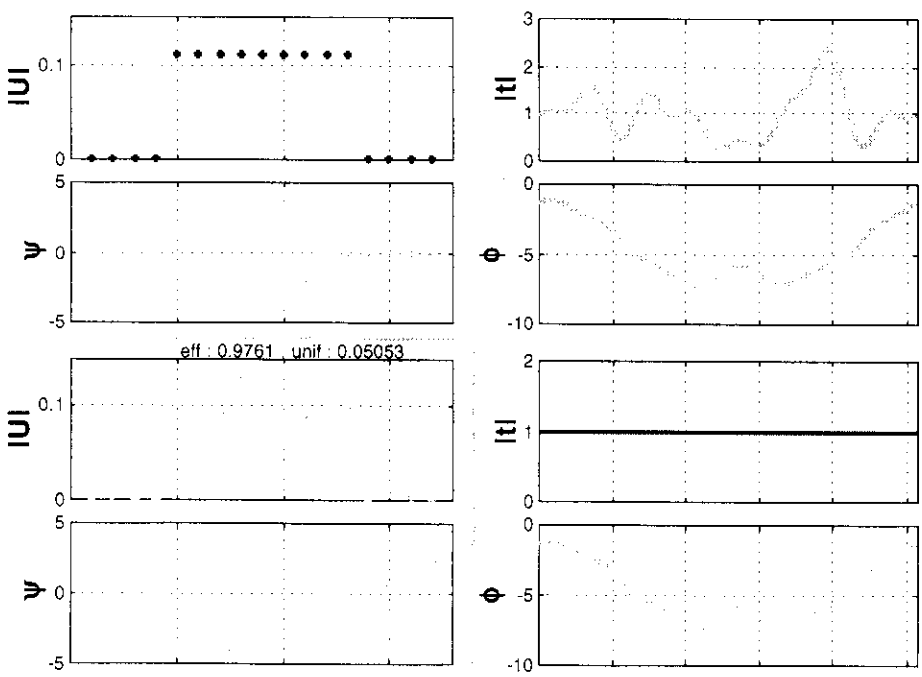
Example: fan-out 9x1



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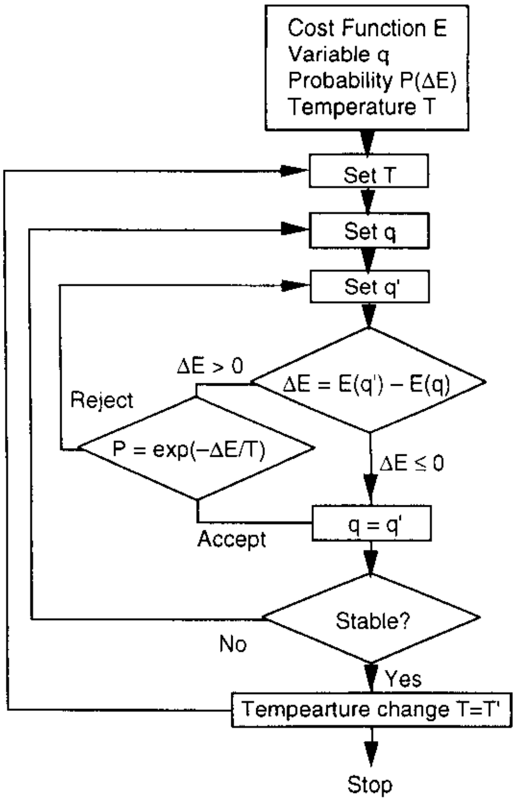
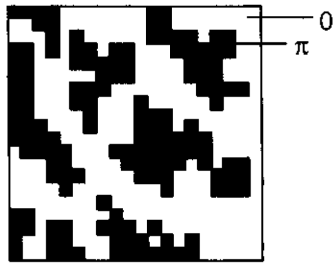
Simulated annealing





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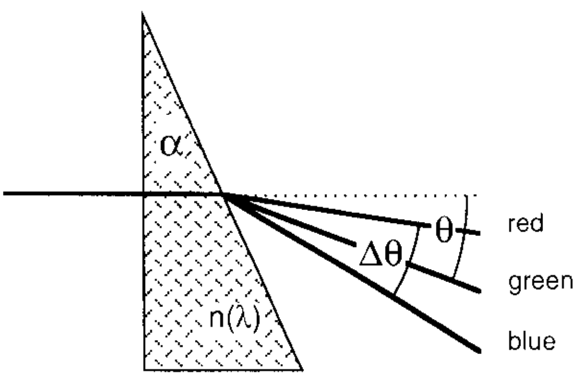
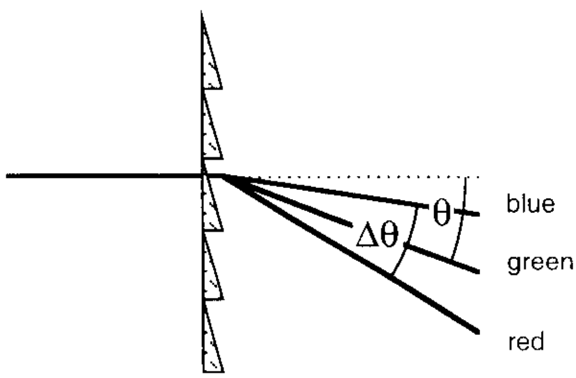
Dispersion

Refraction



$$\nu_r = \frac{\theta}{\Delta\theta} = \frac{n_d - 1}{n_F - n_C}$$

Diffraction



$$\nu_r = \frac{\theta}{\Delta\theta} = \frac{\lambda_d - 1}{\lambda_F - \lambda_C}$$

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Dispersion

	Refractive	Diffractive
Abbe number:	$\nu_r = \frac{n(\lambda_1) - 1}{n(\lambda_2) - n(\lambda_3)}$	$\nu_d = \frac{\lambda_1}{\lambda_2 - \lambda_3}$
$\lambda_1 = 587.6$ nm $\lambda_2 = 486.1$ nm $\lambda_3 = 656.3$ nm	$\nu_r = 80$ to 20	$\nu_d = -3.45$

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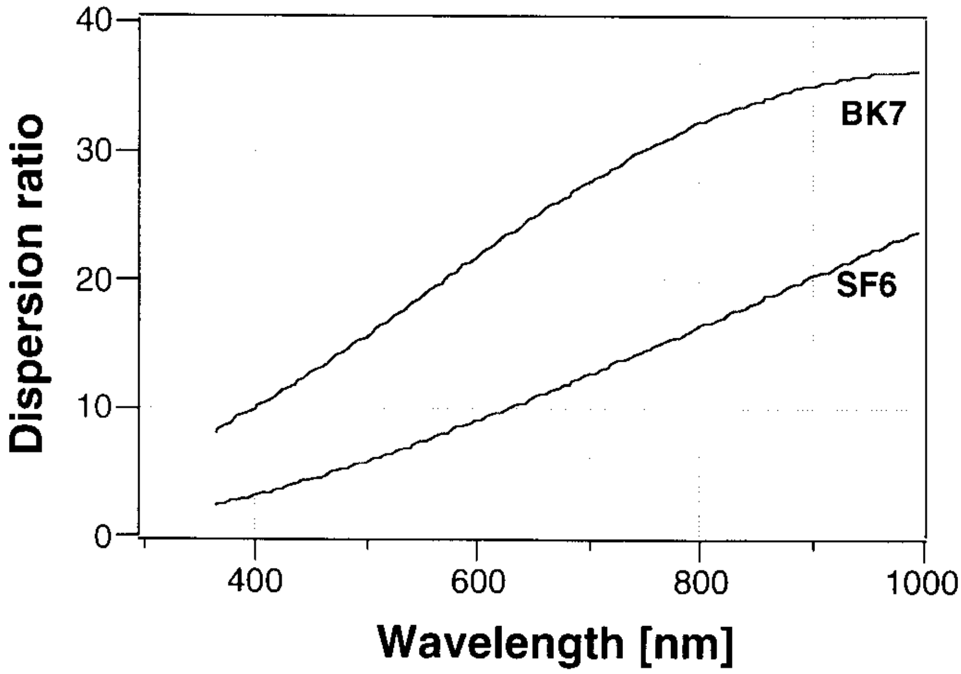
Dispersion ration $D_r = \nu_{refractive}/\nu_{diffractive}$



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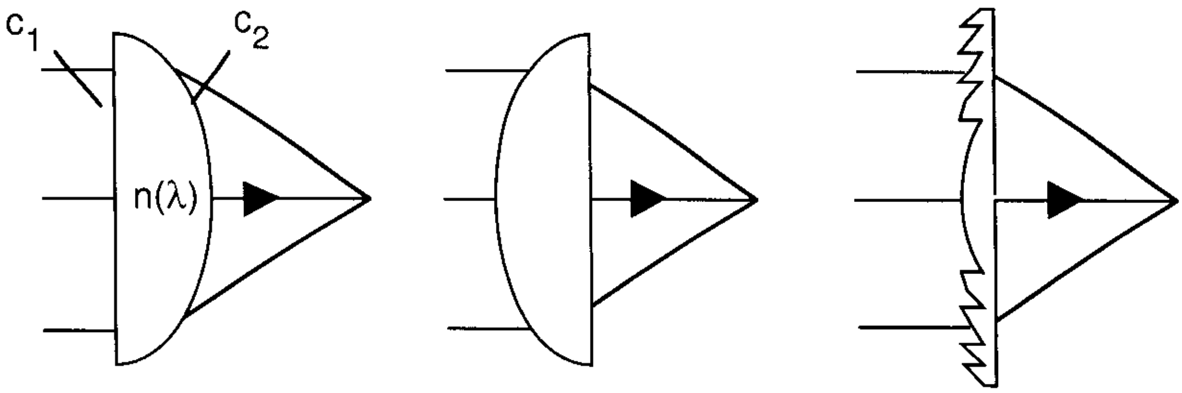
Paraxial properties of lenses



$$f_r(\lambda) = \frac{1}{n(\lambda) - 1} \, \frac{1}{c_1 - c_2} \qquad f_d(\lambda) = f_0 \frac{\lambda_0}{\lambda}$$

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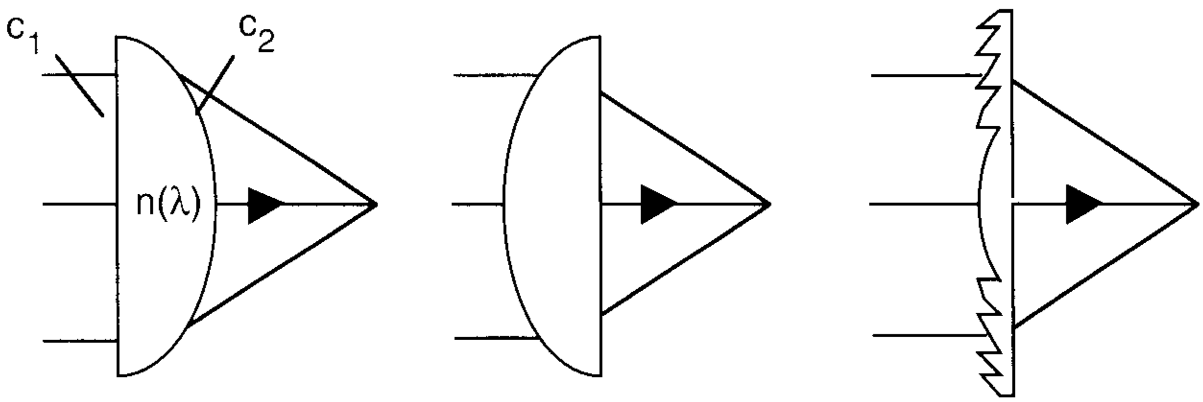
Spherical aberration $S_I = (NA)^4 f C_i$



$$C_a = \frac{n^2}{(n-1)^2} \qquad C_b = \frac{n^3 - 2n^2 + 2}{n(n-1)^2} \qquad C_c = 1 - \left(\frac{l_0}{l}\right)^2$$

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Airy disk radius

Refractive	Diffractive
$r(\lambda) = 1.22 \frac{\lambda f}{D}$	$r(\lambda) = 1.22 \frac{\lambda_0 f_0}{D} \approx \text{const}$

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Diffractive elements

- Arbitrary shape
- Accurate focal length
- High functionality
- High dispersion (<0)
- Problems:
  - low NA (< 0.2)
  - diffraction efficiency (80% - 95%)
  - stray-light

Refractive elements

- Spherical and cylindrical shape
- High NA (> 0.1)
- Low dispersion (>0)
- High efficiency
- Low stray-light
- Problems:
  - fill factor
  - arbitrary shapes

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Fabrication of micro-optical elements

- Fabrication of diffractive optical elements
- Gray-tone lithography
- Melting resist technology
- Profile shaping by RIE

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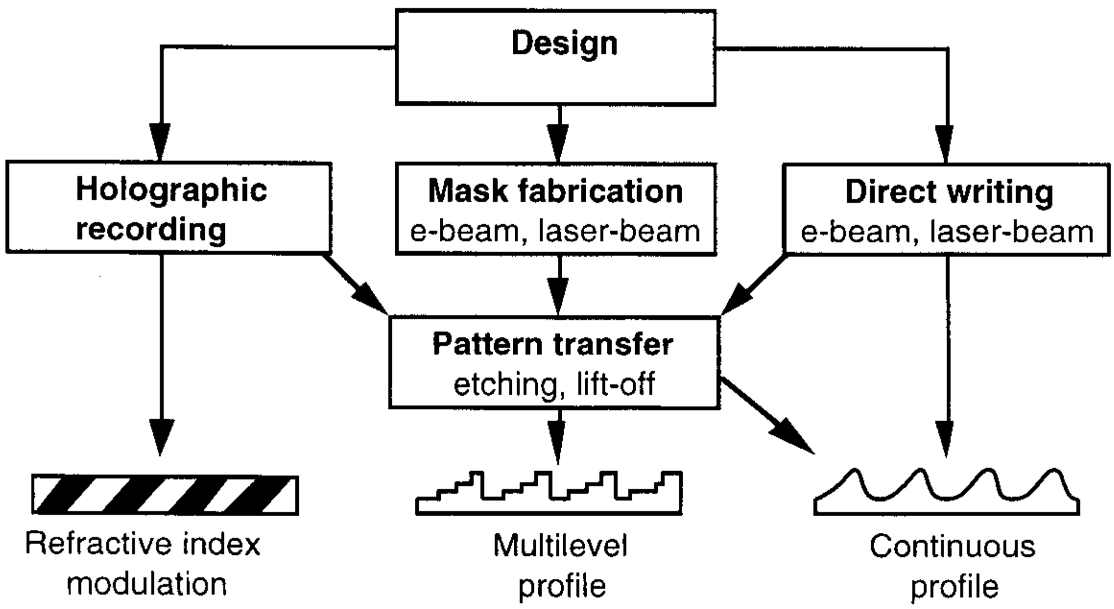
Fabrication methods



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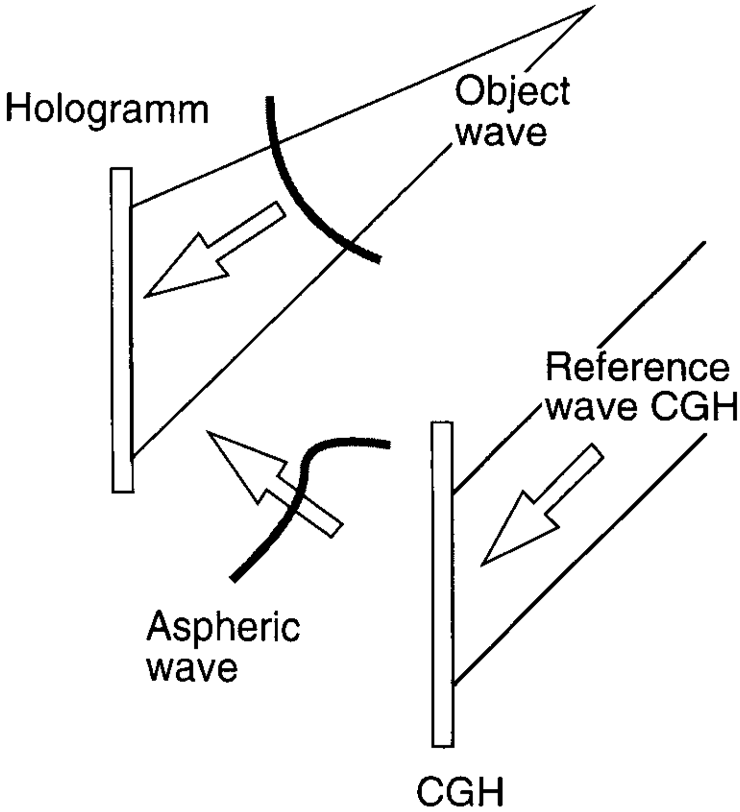
Holographic recording



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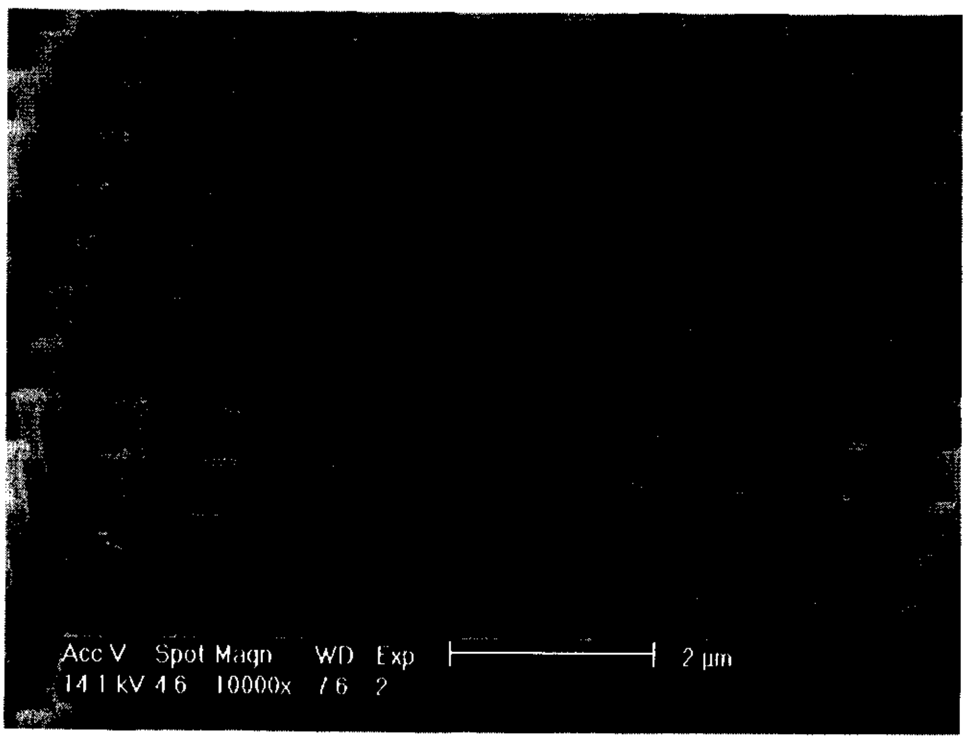
Crossed gratings (Λ = 1 μm)



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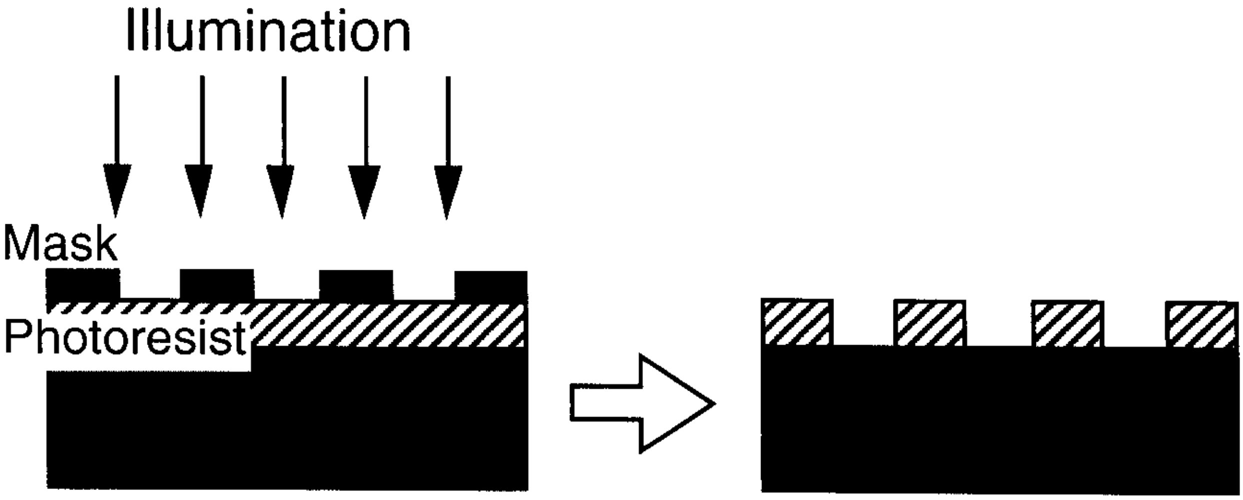

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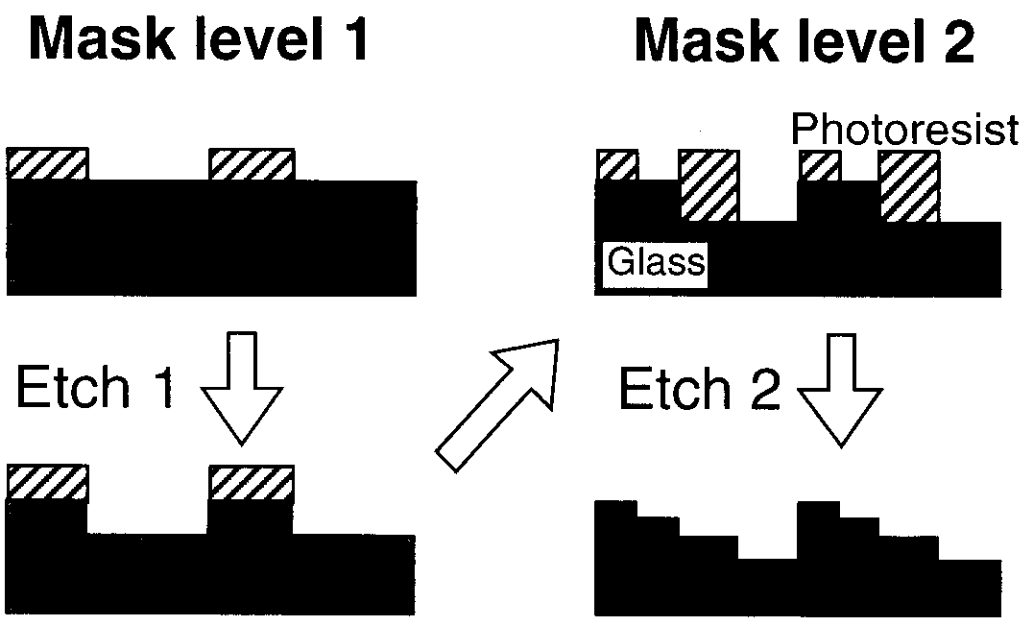

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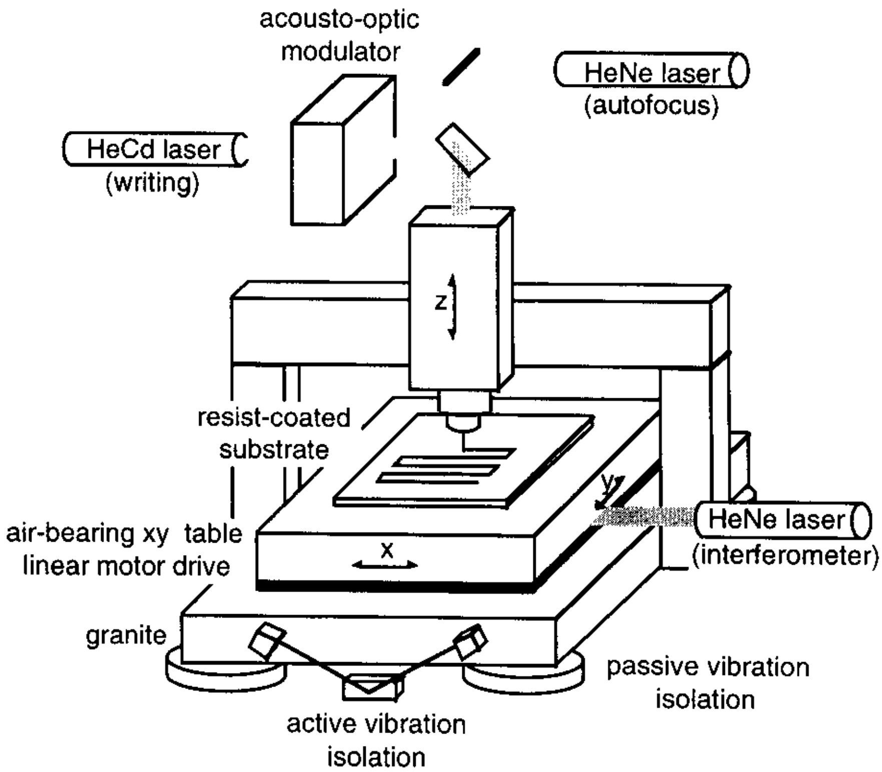
Laser-beam writing



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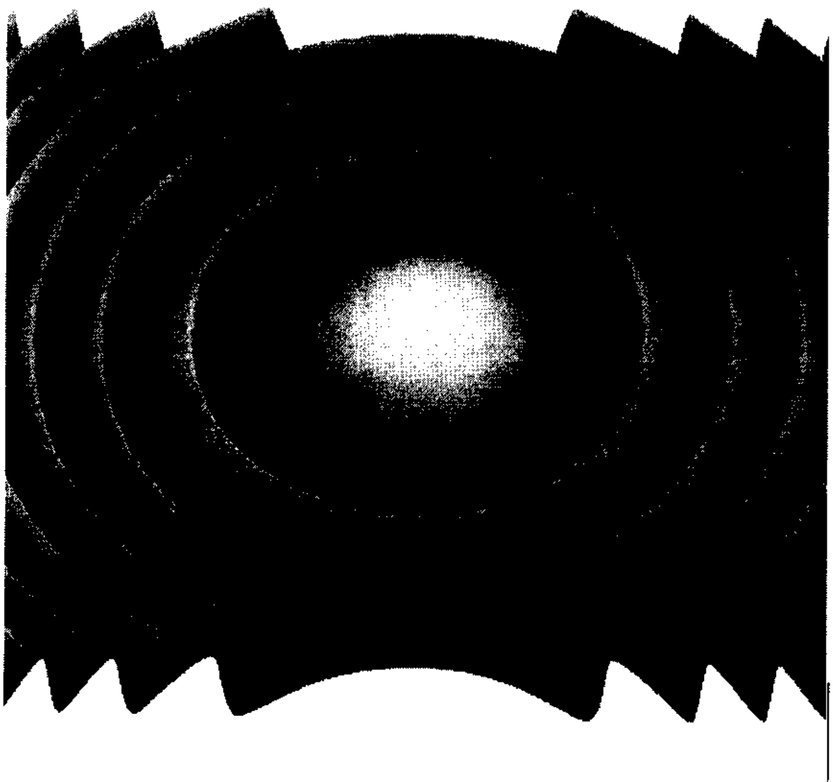
Diffractive optical element (DOE)



Direct laser writing at CSEM Zurich

(M. T. Gale, M. Rossi)

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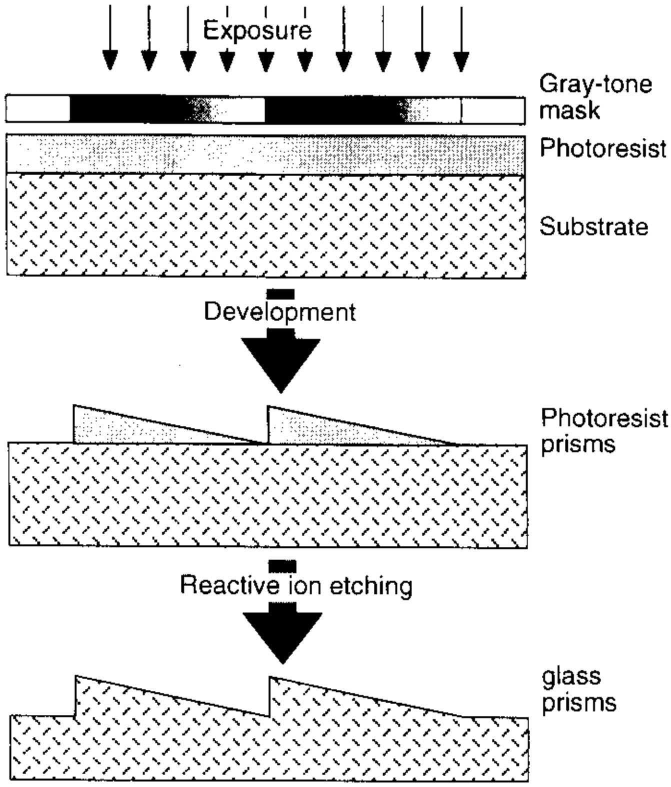
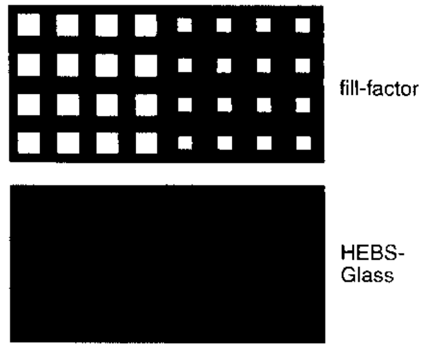
Gray-tone mask





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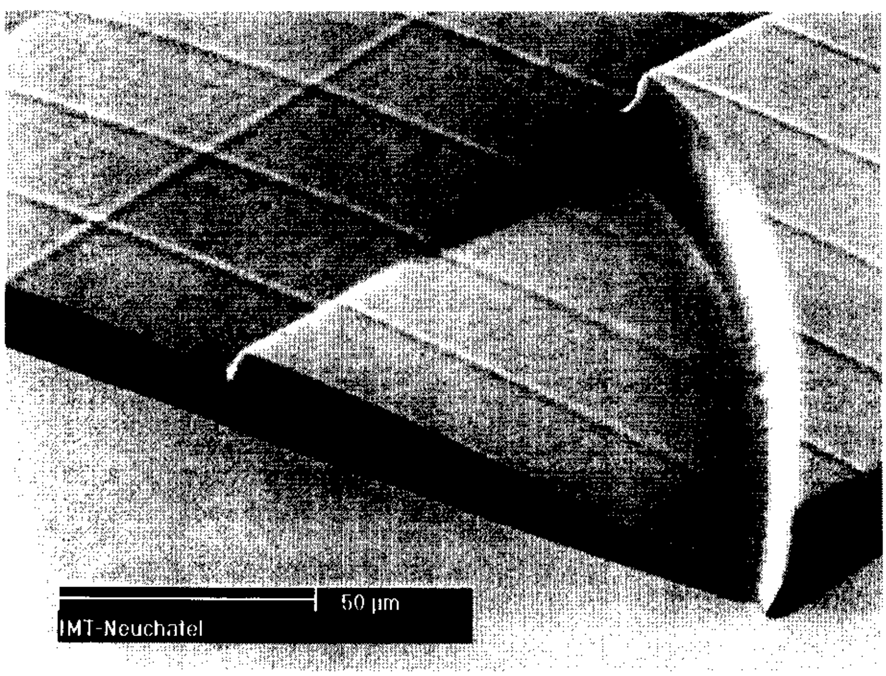
Gray-tone technology: structure in photoresist



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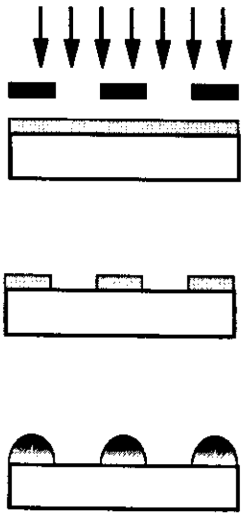
MELTING RESIST TECHNOLOGY

Fabrication of microlens arrays



light
mask
resist
substrate

Photolithography

resist cylinders
substrate

Resist cylinders

micro lenses
substrate

Melting (~150°C)

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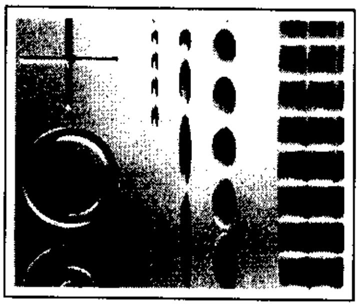
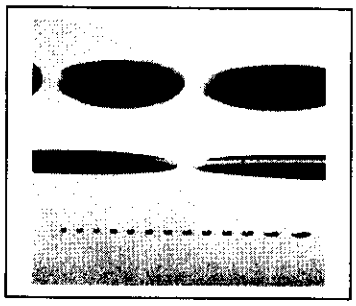
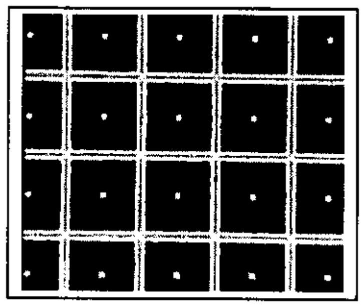
Melting resist microlenses



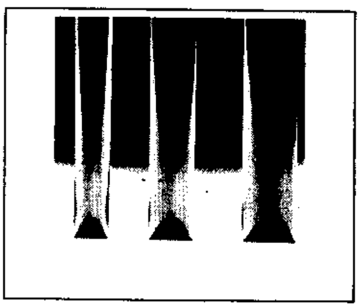
Non-spherical lenses



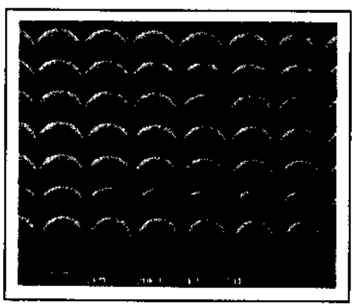
Elliptical lenses for off-axis imaging



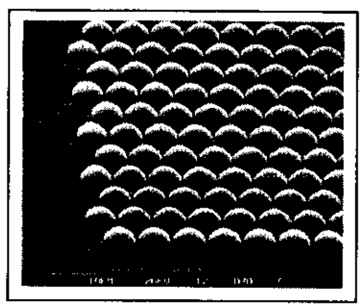
Square lenses



Cylindrical lenses



close packaging (0.2μm gap)



5μm lens diameter

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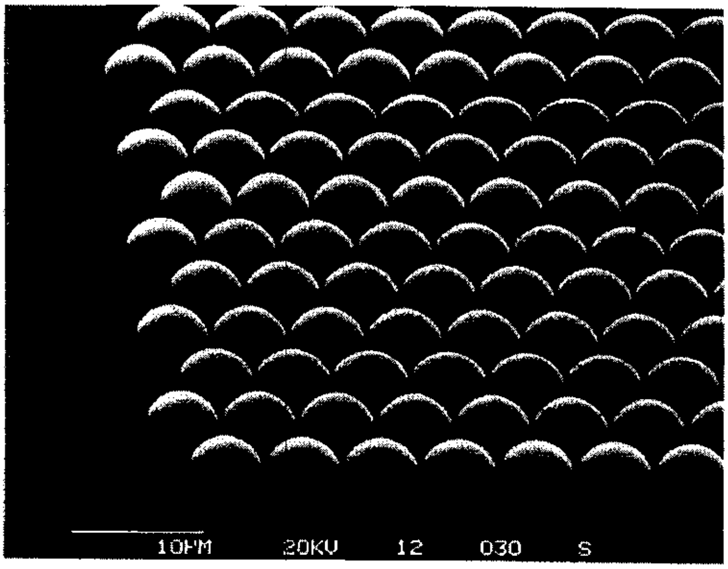
MELTING RESIST MICROLENSES

IMT Neuchâtel - IBM ZRL - SUSS KG



Ø = 5μm*
1μm gap

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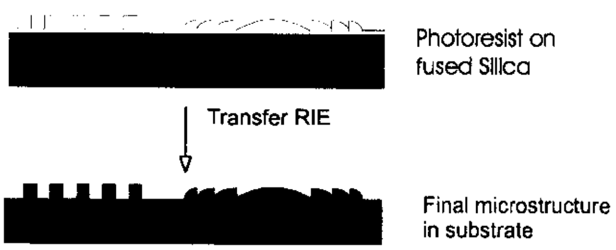
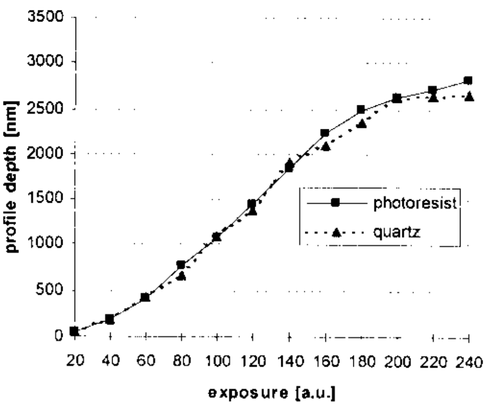
Transfer of laser beam written structures

(In cooperation with CSEM, Zürich, Switzerland)





- Transfer diffractive lenses with continuous-surface relief profiles of up to 3 μm depth
- 1:1 selectivity transfer to maintain the elements dimensions
- Possibility to correct depth errors of the photoresist structure
- Depth variations of less than 5 % for depths of 0 - 3 μm

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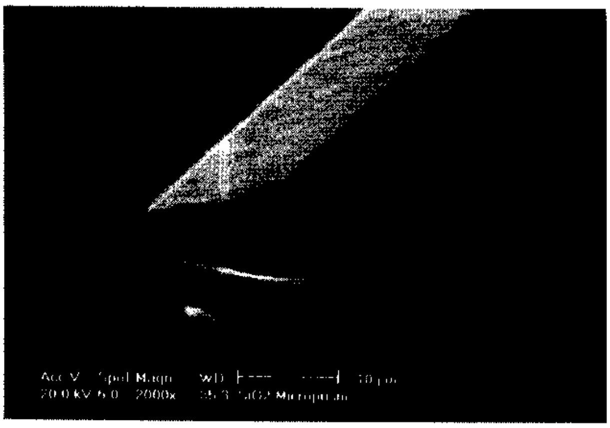
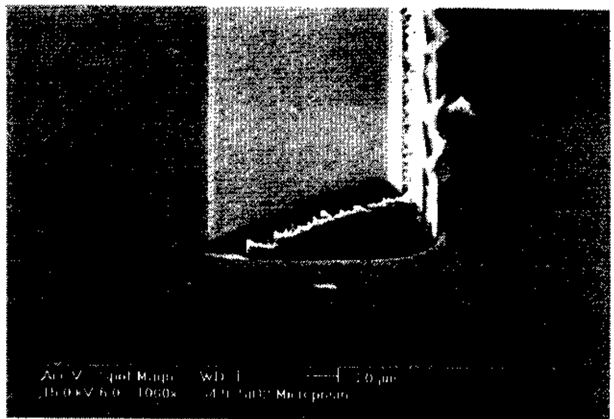
Fused silica microprisms

(In cooperation with Friedrich Schiller University, Jena, Germany)

- SiO2 microprisms realized by dry etching of photoresist structures realized by using graytone masks (HEBS glass).





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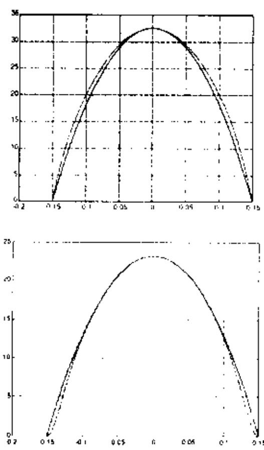
Profile shaping and low selectivity etching

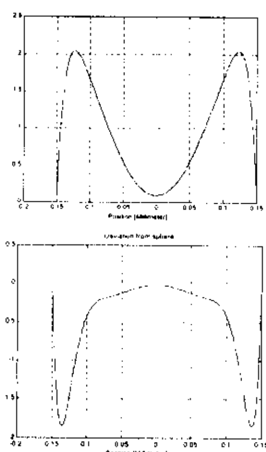
- Shape modification of micro-optical elements during the transfer process
  - Correction of eventual fabrication errors of photoresist master element
  - Dynamic of selectivity for shape correction from 0.8:1 o 1.2:1
- Low selectivity etching: e.g. height 30 μm (photoresist) ⇒ 3 μm (fused silica).

Photoresist refractive microlens
Diameter 300 μm, height 31.5 μm,
max. deviation from sphere + 2 μm

Fused silica refractive microlens
Diameter 300 μm, height 23 μm,
max. deviation from sphere -1.8 μm



Profile measured with Mach-Zender interferometer



Deviation from perfect sphere

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MICROLENS ARRAYS

- Melting resist technology
- Refractive plano-convex microlenses
- 2 μm to 5 mm diameter possible
- Photoresist: < f/5, Quartz: < f/30
- Diffraction limited resolution
- Replication techniques
- RIE transfer in fused silica

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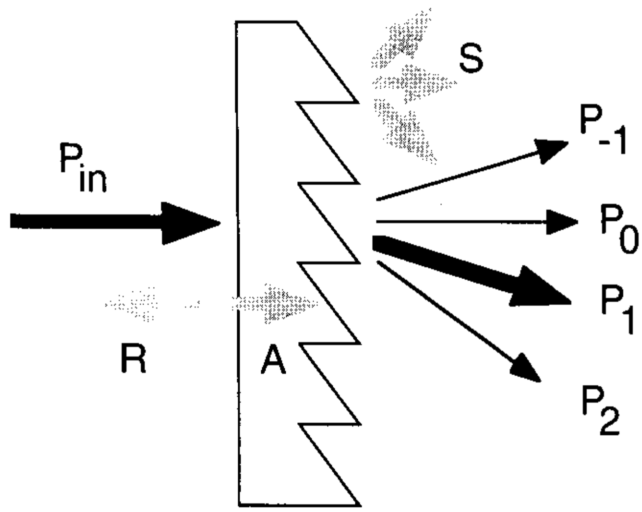
Diffraction efficiency η



$$\eta = \frac{P_1}{\sum P_m}$$

$$\eta_{overall} = \frac{P_1}{P_{in}}$$

R: reflection
A: absorption
S: scattering

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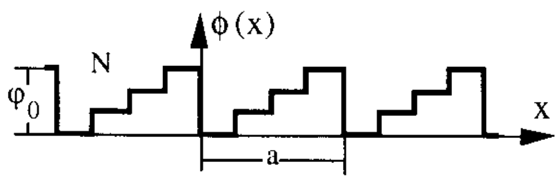
Diffraction efficiency (scalar theory, no losses)



blazed grating: $\varphi_0 = 2\pi$,

$$|A_n| = \frac{1}{N}\,\mathrm{sinc}\left(\frac{n}{N}\right)\frac{\sin[\pi(n-1)]}{\sin\left[\pi\left(\frac{n-1}{N}\right)\right]}$$

$$|A_1|^2 = \left[\frac{N}{\pi}\sin\left(\frac{\pi}{N}\right)\right]^2$$

N: number of phase levels
n: diffraction order

N =	2	4	8	16
$\|A_1\|^2$ =	40.5%	81,1%	95,0%	98,7%

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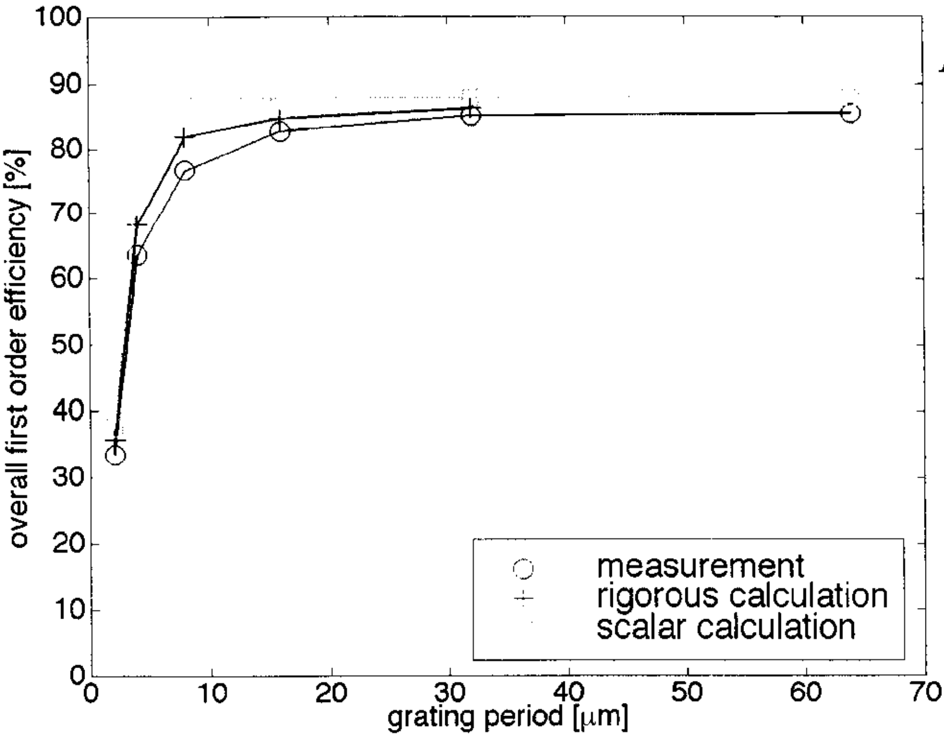
Diffr. efficiency: theory - experiment



A. Schilling

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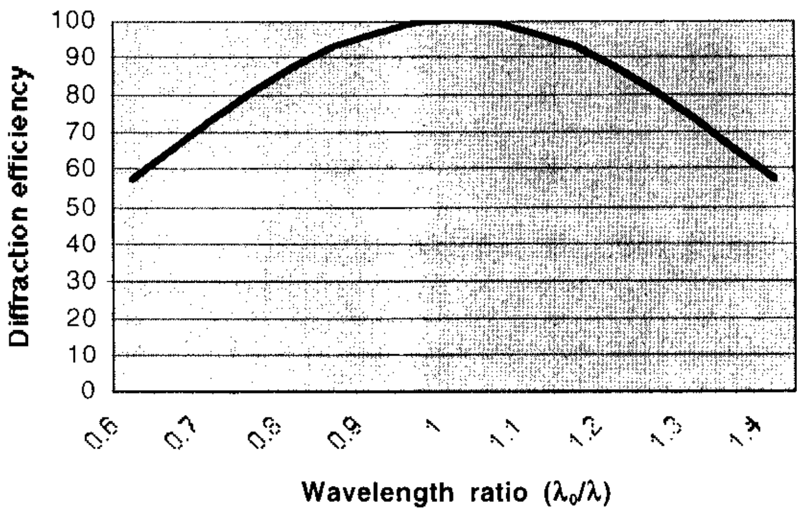
Diffraction efficiency versus wavelength



$$\eta(\lambda) = \left(\frac{\sin\{\pi[(\lambda/\lambda_0) - m]\}}{\pi[(\lambda/\lambda_0) - m]} \right)^2$$

Swanson, 1989

$$\eta_{poly} = \frac{\int_{\lambda_{min}}^{\lambda_{max}} \eta(\lambda) d\lambda}{\lambda_{max} - \lambda_{min}}$$

Buralli and Morris 1992

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Aperture modulated diffusers (AMDs)

H. P. Herzig

Institute of Microtechnology University of Neuchâtel

http://www-imt.unine.ch/

hanspeter.herzig@imt.unine.ch

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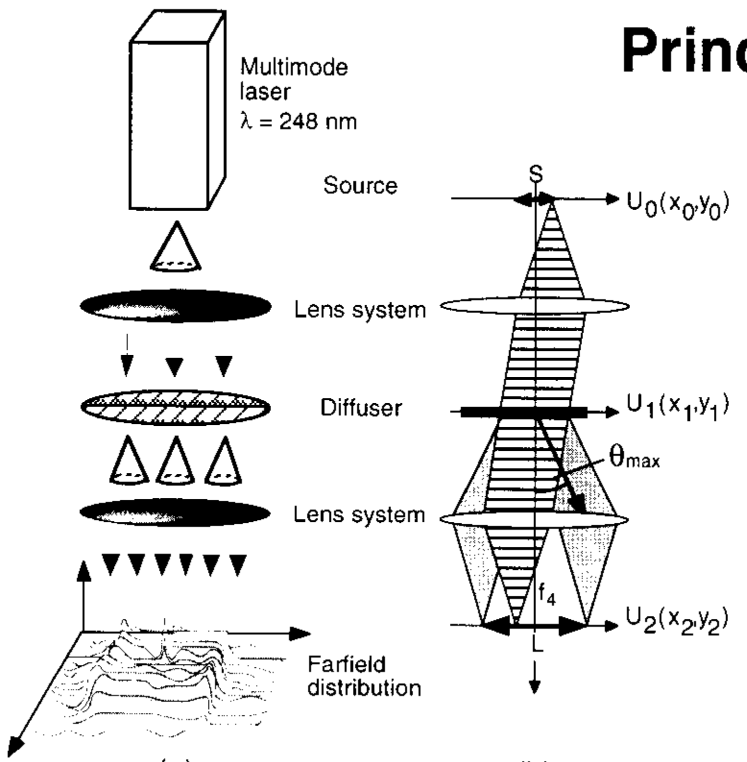
Principle of AMDs



(a) (b)

Aperture shape: $a(x_1, y_1)$

Transmission function:

$$t(x_1, y_1) = a(x_1, y_1)\exp[i\Phi(x_1, y_1)]$$

Coherent:

$$I_2(x_2, y_2) = |U_2(x_2, y_2)|^2 = |\mathrm{FT}\{U_1(x_1, y_1)\}|^2$$

$$= |\mathrm{FT}\{\mathrm{FT}^{-1}\{U_0(x_0, y_0)\} \cdot t(x_1, y_1)\}|^2$$

$$= |U_0(x_0, y_0) \otimes \mathrm{FT}\{t(x_1, y_1)\}|^2$$

Incoherent

$$I_2(x_2, y_2) = |U_0(x_0, y_0)|^2 \otimes |\mathrm{FT}\{t(x_1, y_1)\}|^2$$

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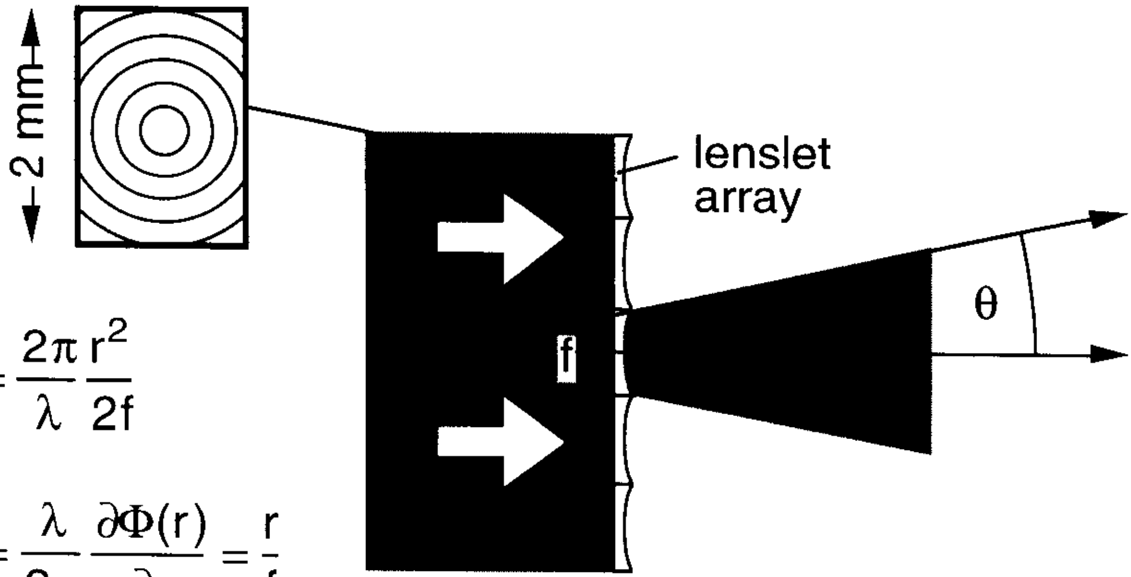
Design



$$\Phi(r) = \frac{2\pi}{\lambda}\frac{r^2}{2f}$$

$$\sin\theta = \frac{\lambda}{2\pi}\frac{\partial\Phi(r)}{\partial r} = \frac{r}{f}$$

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Specification of diffuser

- Flat-top with rectangular shape (e.g. 7 deg x 3 deg)
- Space invariant design
- Deflection angle of 7 deg at $\lambda = 248$ nm
  $\Rightarrow$ grating period $\Lambda = 2\ \mu m$ (mfs = 1 μm)
- High diffraction efficiency > 80 %
- Fabrication of elements in quartz

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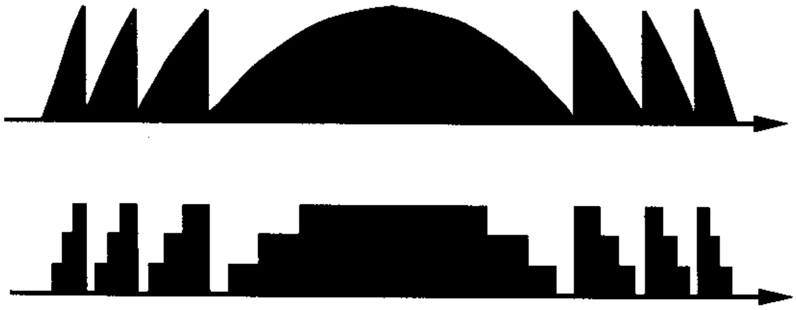
Diffraction efficiency



Diffraction efficiency:	2 phase levels	40.5 %
	4	81 %
	8	95 %
Problem:	Fabrication of a lens with smallest feature size of 1 µm	
Possible solutions:	- Binary lens - 8-4-2 level lens - Continuous-relief lens	

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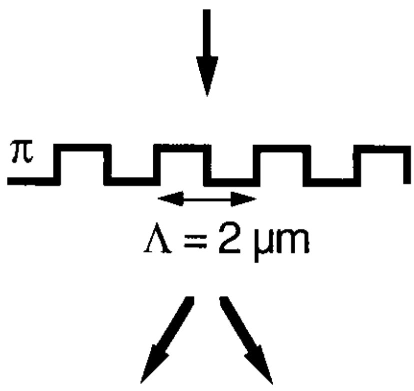
Diffraction efficiency of binary gratings



Binary lens	$\eta = 40.5\ \%$
Binary diffuser	$\eta \geq 81.0\ \%$

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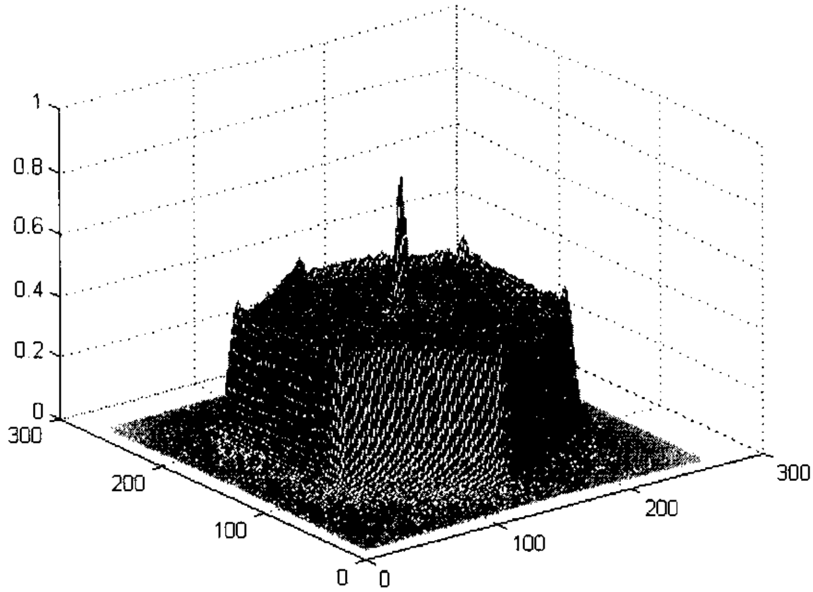
Far-field of a hexagonal diffuser



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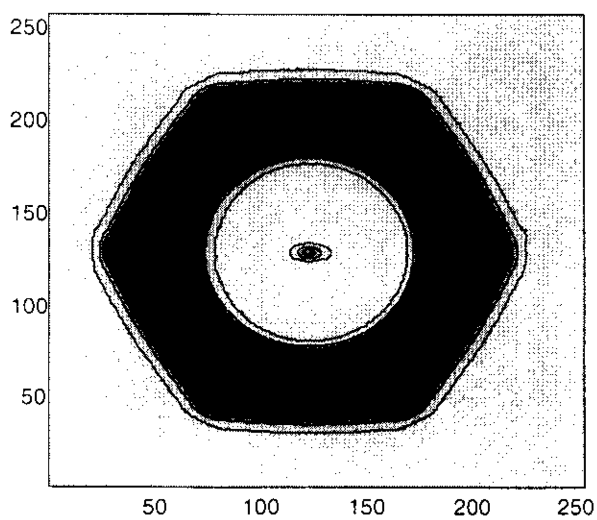
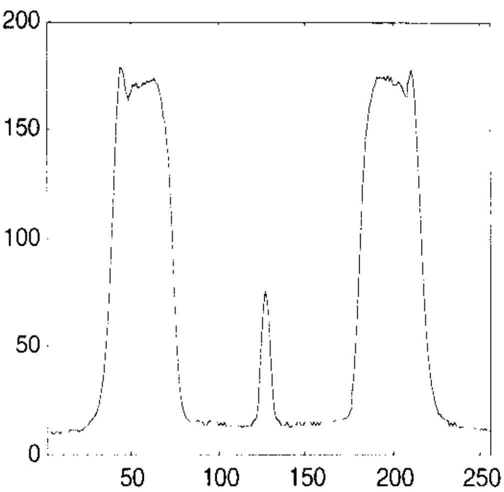
Annular Diffuser





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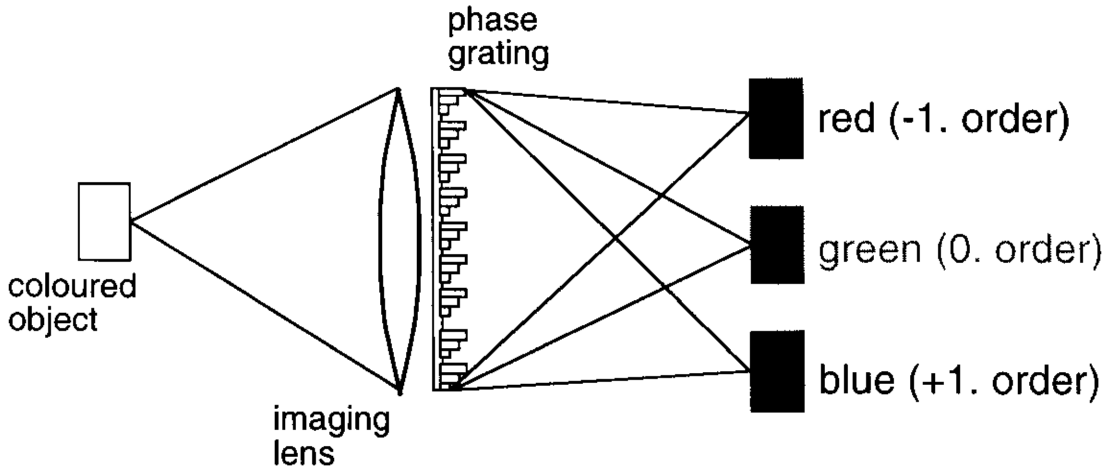
Color fan-out: principle

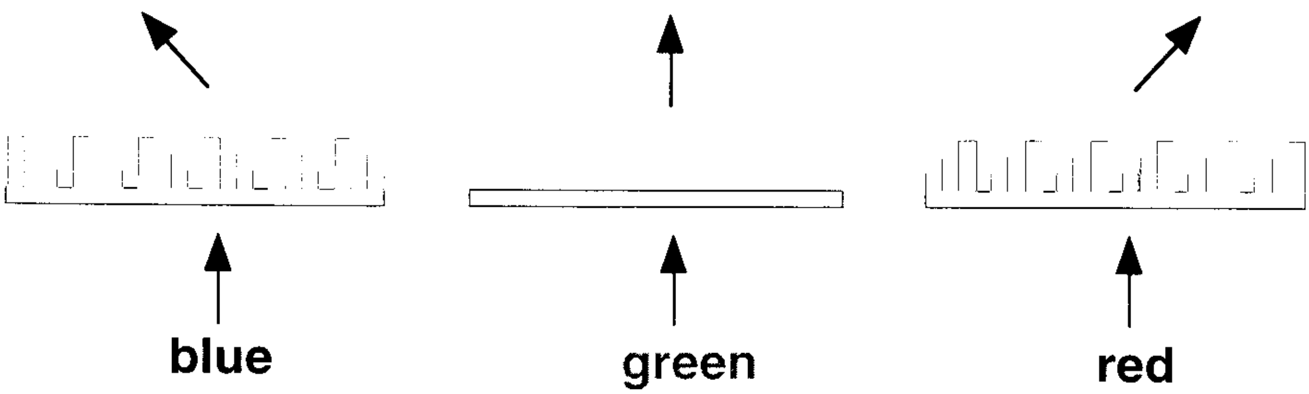
A. Schilling

Color fan-out elements are special phase gratings which project the three color components blue, green, and red into the three central diffraction orders.



Color fan-out: principle

Desired phase profiles of the diffraction gratings for the three color components:

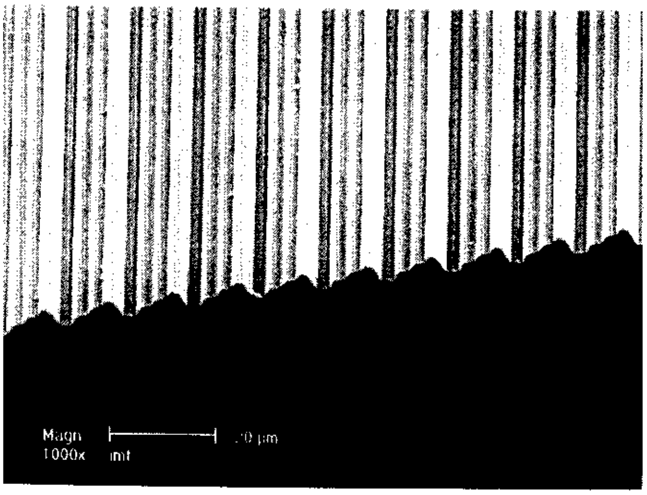


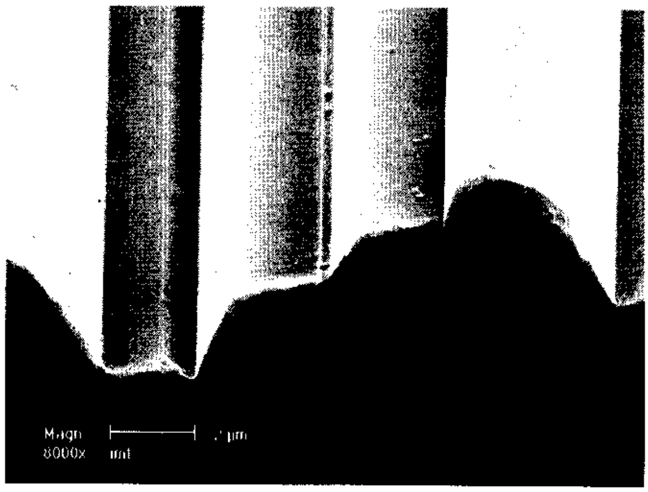
Solution: overphasing of phase structures (deep phase gratings)

Color fan-out elements: SEM images

Color fan-out elements etched in quartz:

- 12 µm grating period
- 3.3 µm profile depth





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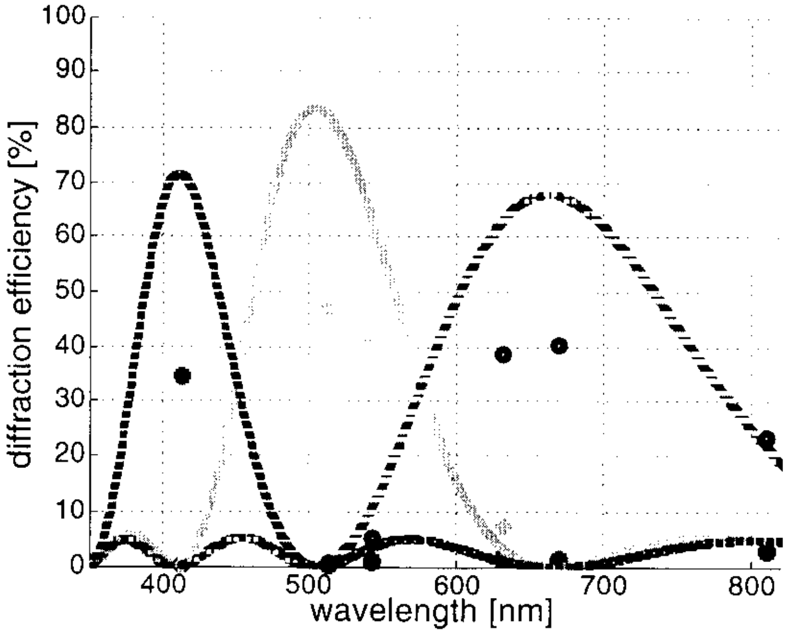
Color fan-out elements: efficiencies

Characterization of color fan-out elements (quartz):

- 4 phase levels
- 16 µm grating period
- 3.3 µm profile depth

rigorous theory (lines) and measurement (markers)



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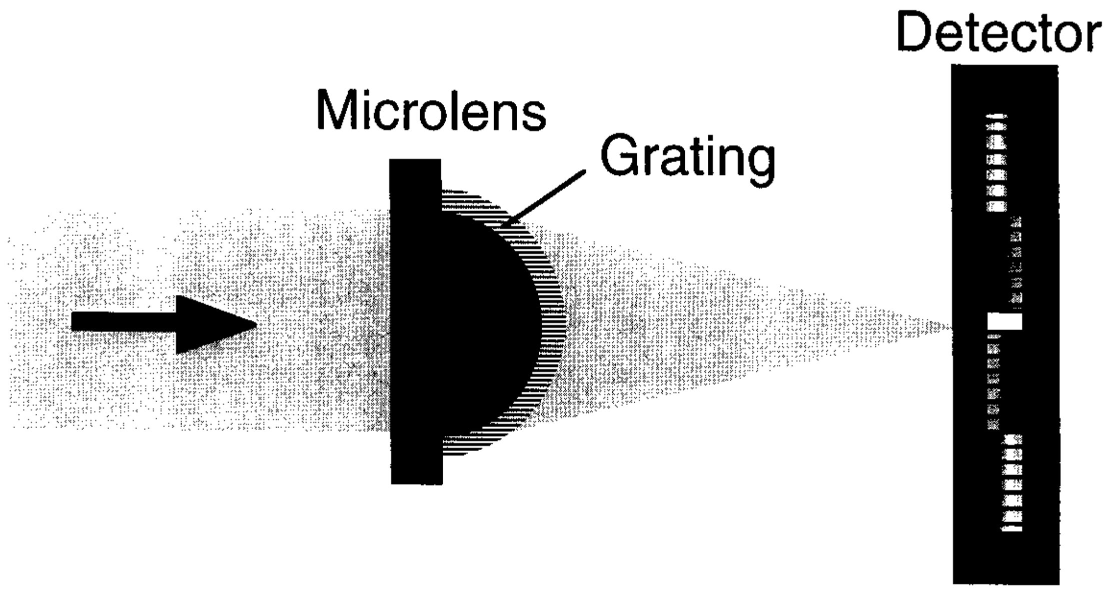
Application: µ-spectrometer

S. Traut

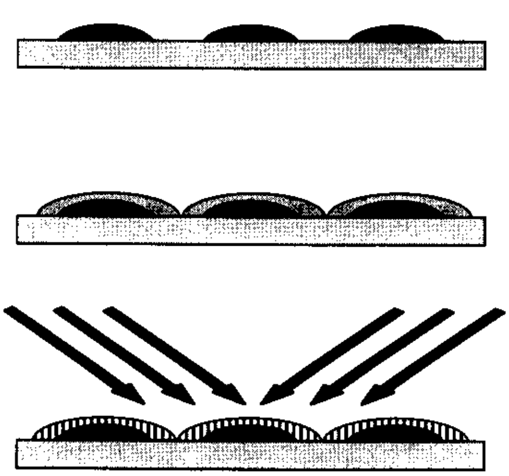


Holographic recording

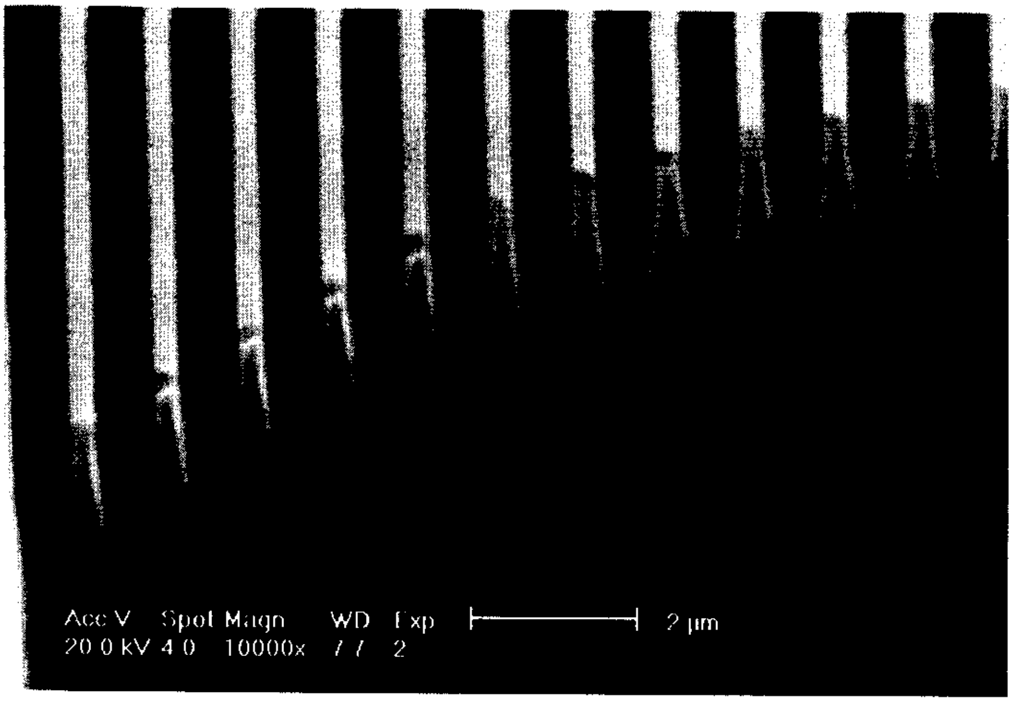
1) Fabrication of a microlens array

2) Photoresist coating of the array by spincoating

3) Holographic recording of the grating

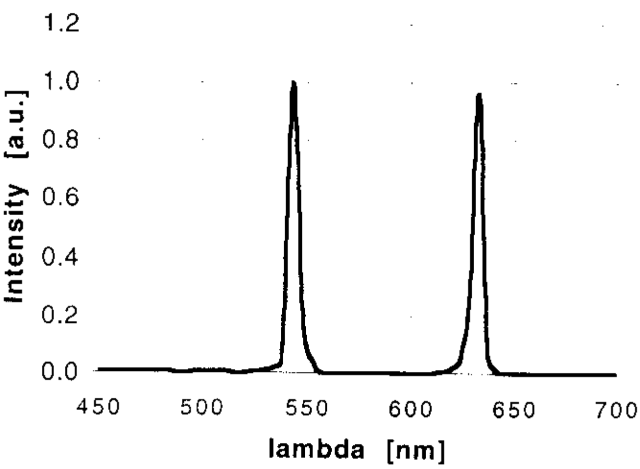


Grating on top of a refractive microlens



Resolution

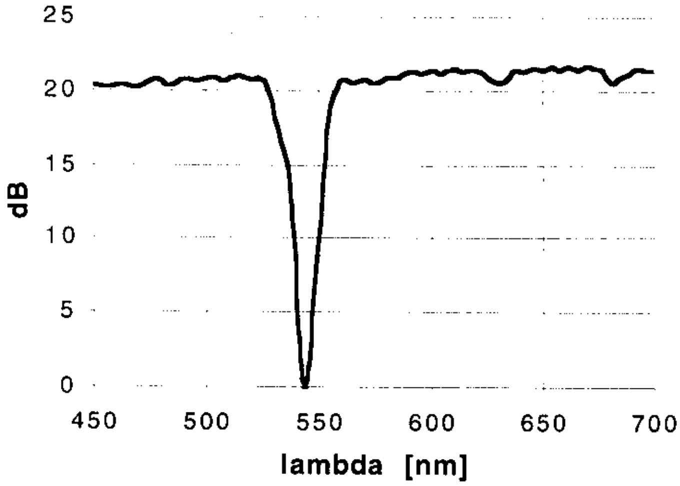
Resolution of µ-Spec610



lens diameter	measured resolution
350µm	11nm
610 µm	6 nm
990 µm	4 nm

Stray-light suppression

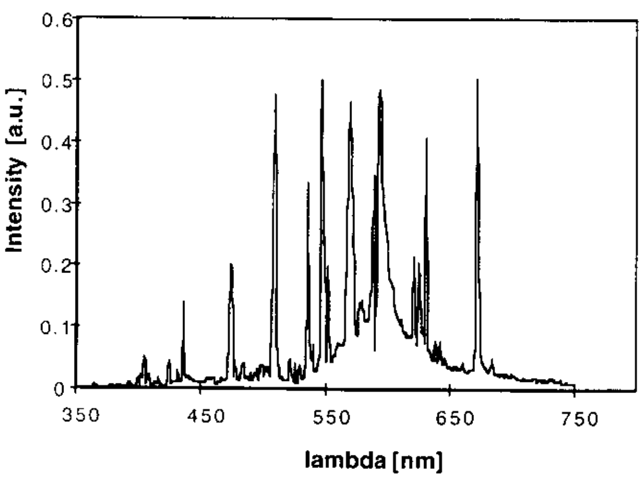
μ-Spec610 performance



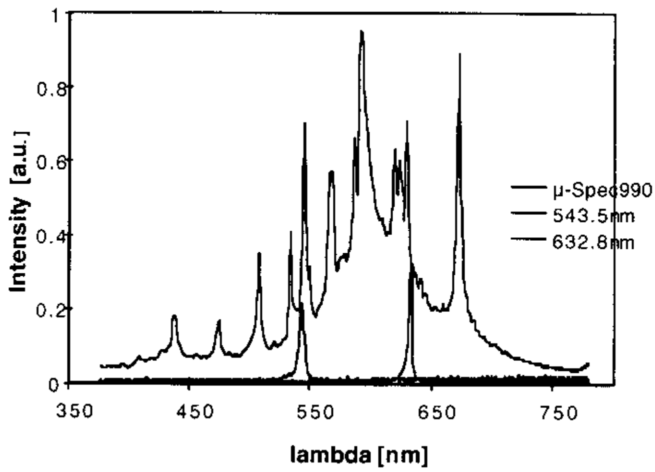
lens diameter	measured damping
350μm	6-9 dB
610 μm	20-22 dB
990 μm	18-20 dB

Spectrum of a Xenon lamp

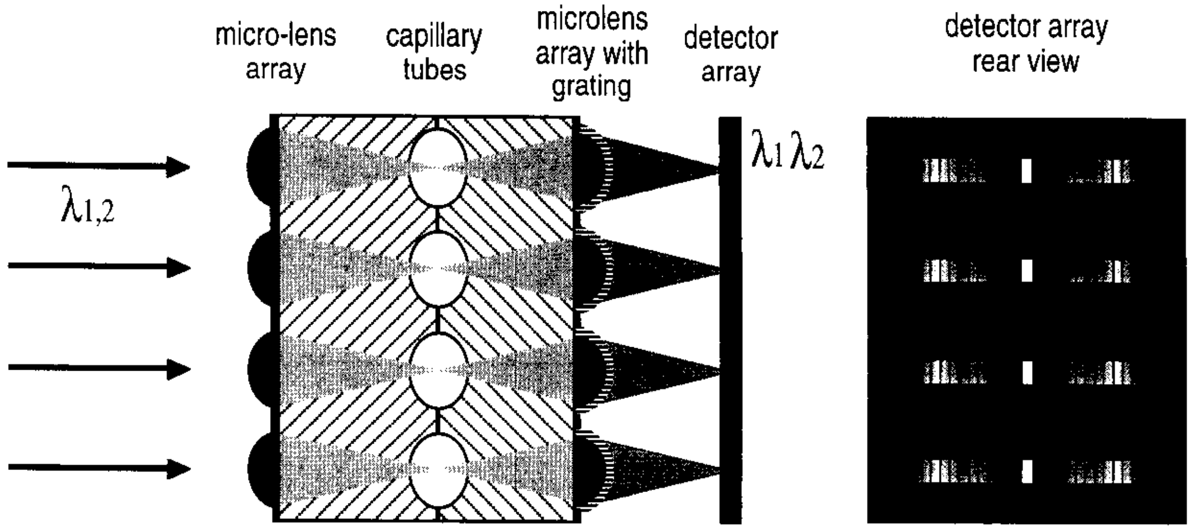
HR250 (1nm resolution)



μ-Spec99 0



Concept of a μ-Spec System



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Miniaturized
Fourier Transform Spectrometers

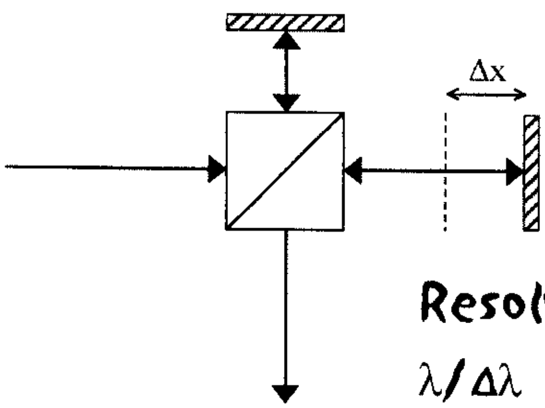
Hans Peter Herzig and Omar Manzardo

Institute of Microtechnology, University of Neuchâtel

www-optics.unine.ch

Acknowledgments: C. Marxer, IMT-Uni NE
H. Teichmann, CSEM Zurich

Fourier Transform Spectroscopy



Resolution:

$\Delta\sigma = 1/\delta_{max}$

$\Delta\lambda = \lambda^2/\delta_{max}$

$\lambda = 1/\sigma$

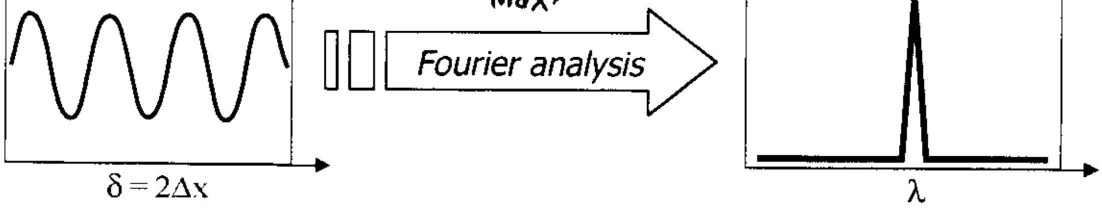
Resolving power

$\lambda/\Delta\lambda$ = no. of fringes

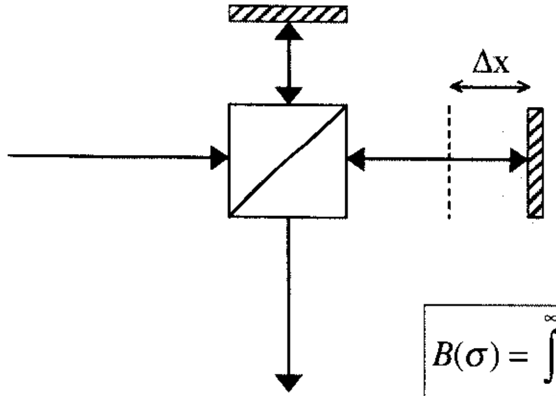
$= \delta_{max}/\lambda$

Detected intensity

Spectrum



Fourier Transform Spectroscopy



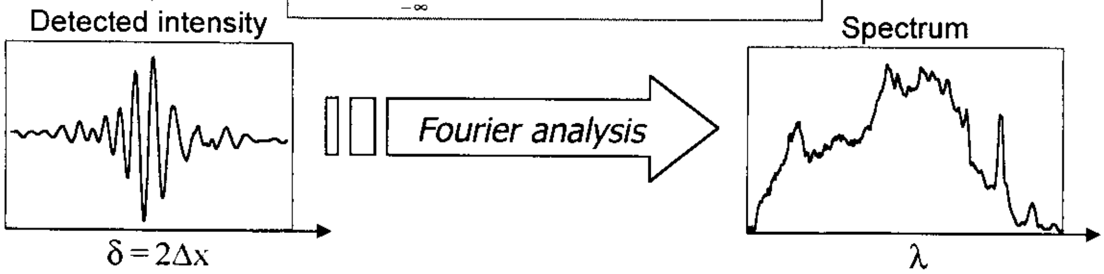
Resolution:

$\Delta\sigma = 1/\delta_{max}$

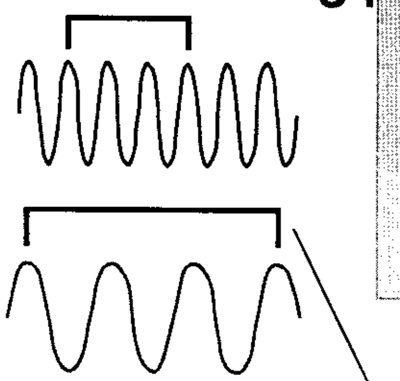
$\Delta\lambda = \lambda^2/\delta_{max}$

$\lambda = 1/\sigma$

$$B(\sigma) = \int_{-\infty}^{\infty} I(\delta)\exp[-i(2\pi\sigma\delta + \Delta\varphi)]d\delta$$



Resolving power - filtering



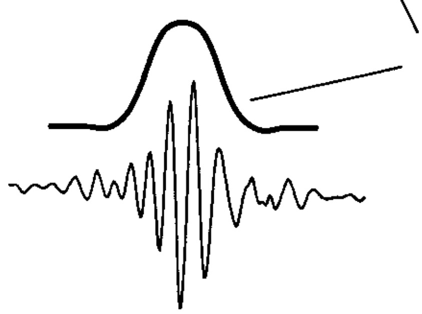
Resolving power

= number of periods

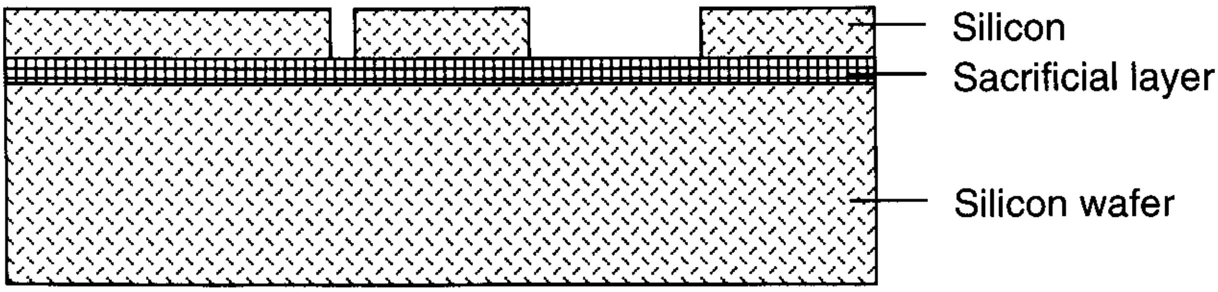
= $\lambda/\Delta\lambda$

= δ_{max}/λ

Variable filter functions

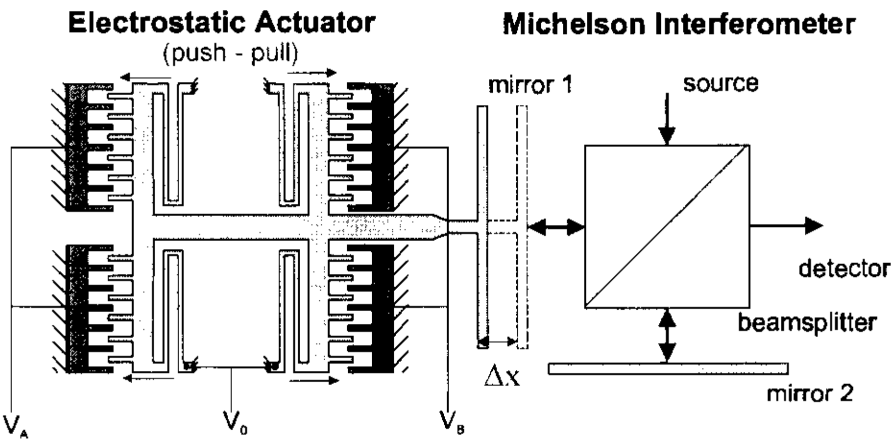


Surface micromachining



Setup

- Linear displacement of the mirror
- Free of hysteresis



Actuator

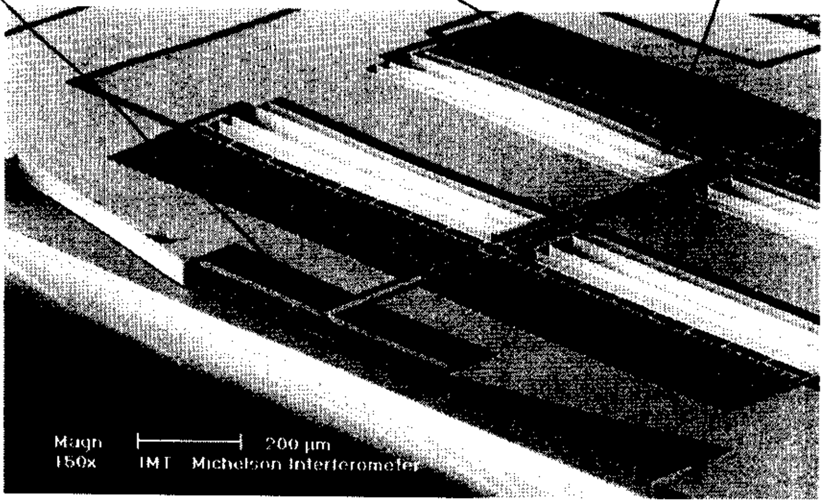
Mirror (Al coated)

Electrostatic comb - V_A, V_0, n, h, g

Spring - k

Mirror displacement

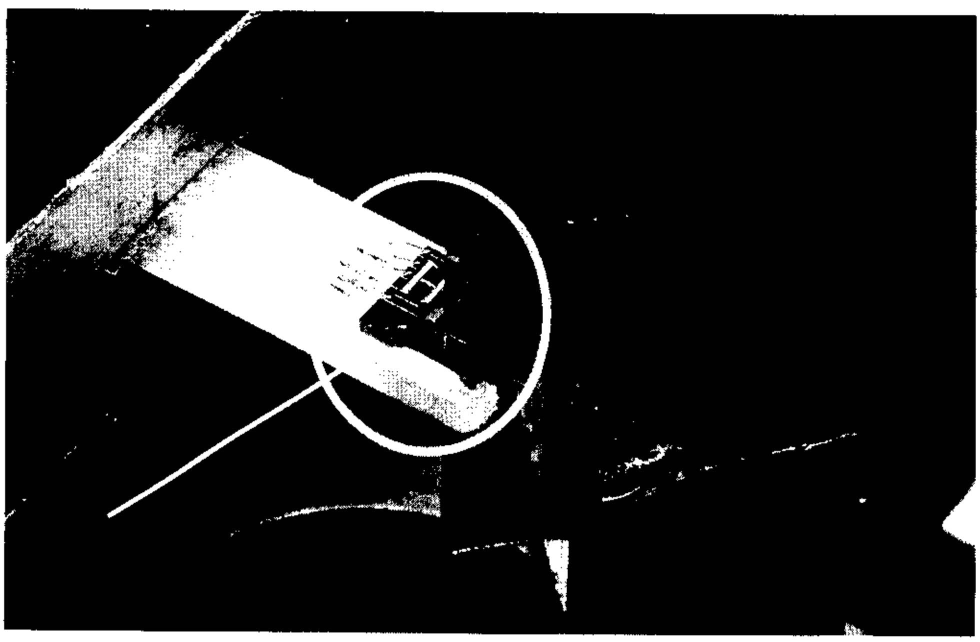
$$\Delta x = \frac{1}{k}\varepsilon_0 n \frac{h}{g} 2V_A V_0$$



$\Delta x_{max} = 40\ \mu m$

$\delta_{max} = 80\ \mu m$

Setup



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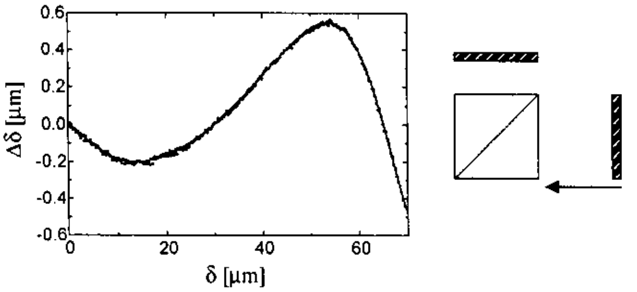
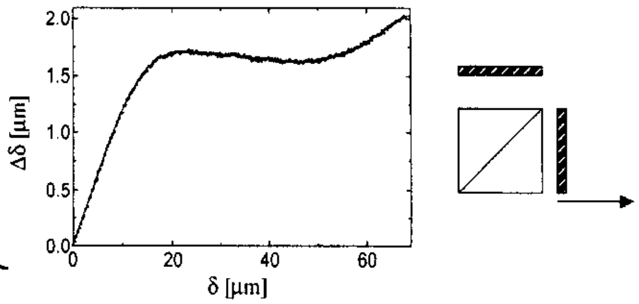
Linearity

Variation of the optical path difference: $\Delta\delta$
(interferometric measurement)

$\Delta V_0 = 20$ V
$\Delta x_{max} = 40$ µm



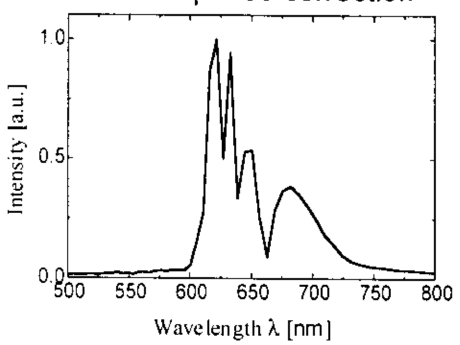
$\Delta\delta = \pm\ 0.5$ µm

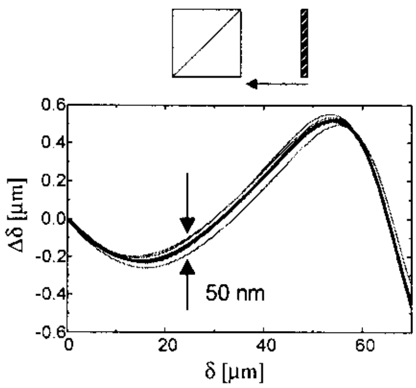


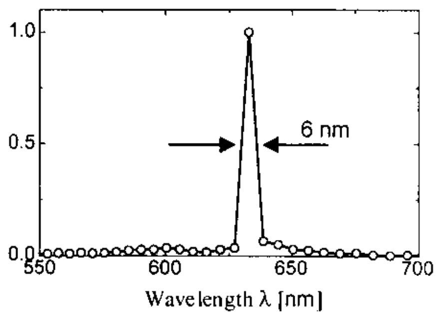
$\Delta\delta = \pm\ 1.0$ µm

Phase correction for calibrated mirror motion

Laser HeNe
without phase correction







$$B(\sigma) = \sum_{\delta} I_R(\delta) e^{-i2\pi\sigma\delta}$$

$$B(\sigma) = \sum_{\delta} I_R(\delta) e^{-i2\pi\sigma(\delta+\Delta\delta(\delta))}$$

Chemical chip

(for fluorscence detection)

J.-Ch Roulet

Institute of Microtechnology University of Neuchâtel

http://www-imt.unine.ch/

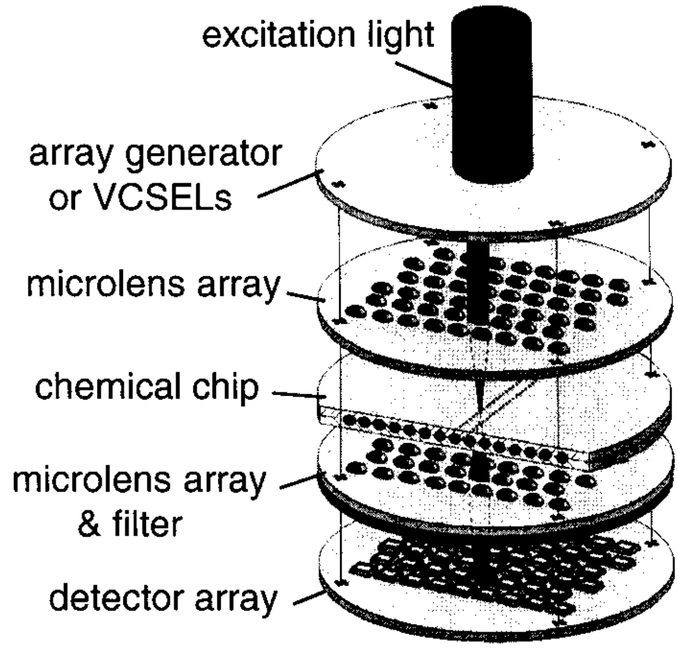
Achcknoledgment: K. Fluri, E. Verpoorte, R. Völkel, H. P. Herzig[1], N.F. de Rooij, R. Dändliker

Introduction

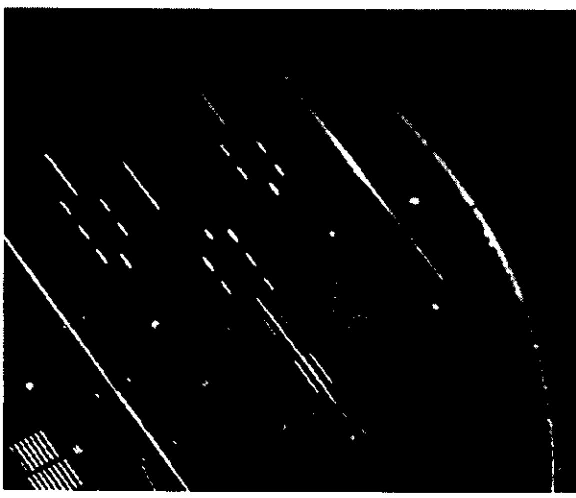
Fluorescence detection with micro-optics:

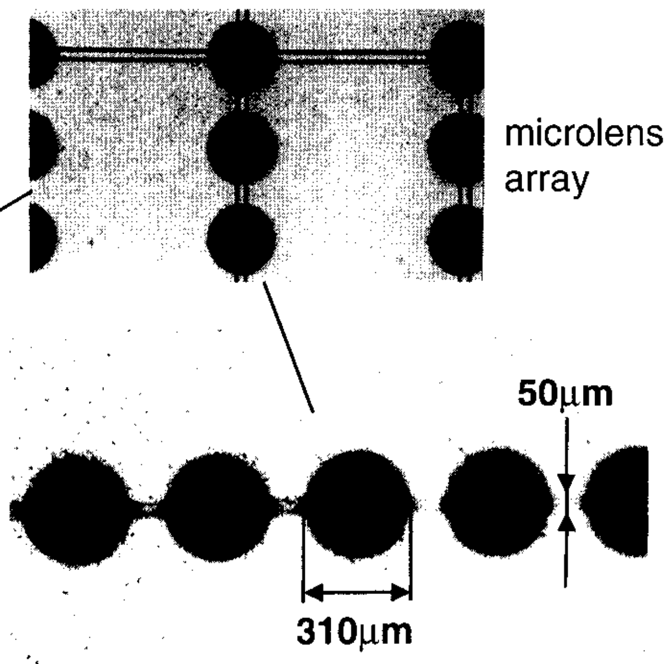
- Focusing excitation light into a detection volume (capillary, detection cell)
- Collection of the fluorescence
- Separation of the fluorescence (signal) from the noise (excitation light)

Stacked μTAS system



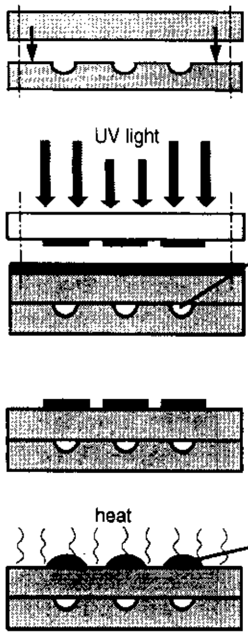
Microlenses on sealed capillary



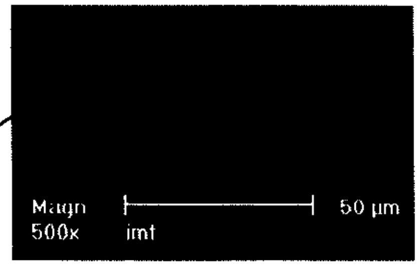


Chemical chip and microlens array fabrication

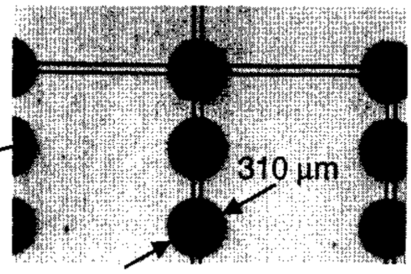
1. chemical chip bonding
2. photolithographic process for microlens layer
3. melting process



cross section of a capillary

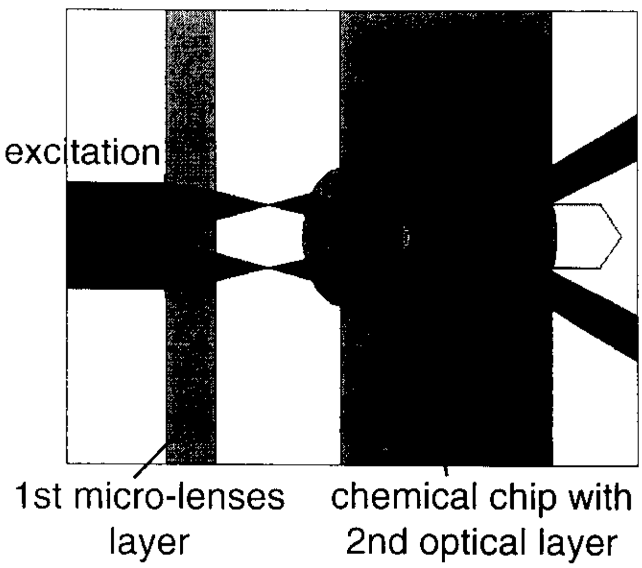


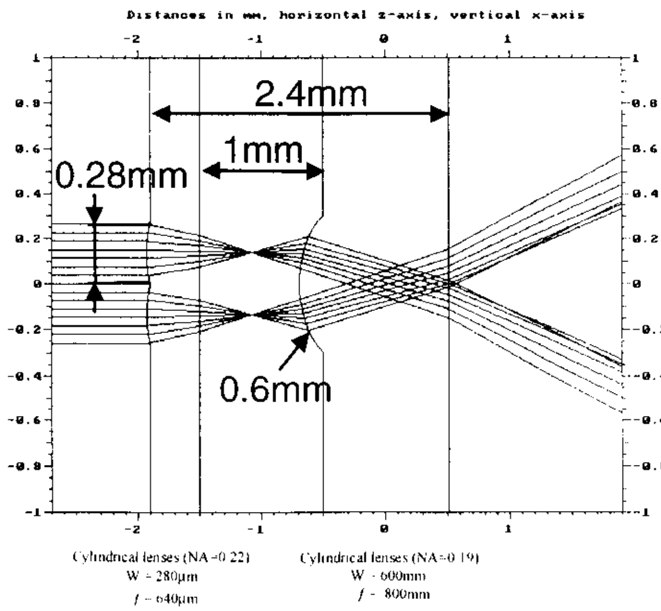
microlens array



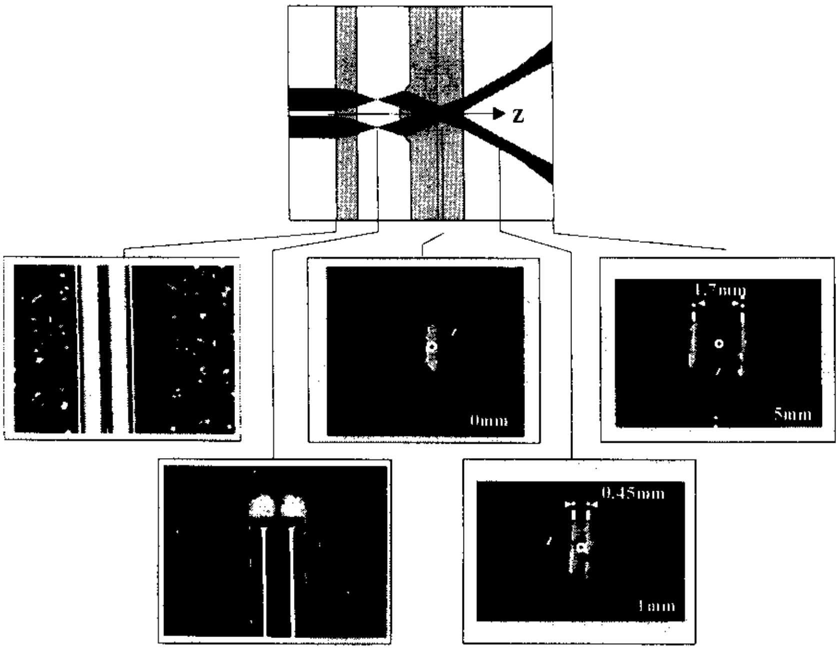
Beam splitting illumination system

Raytrace Simulation

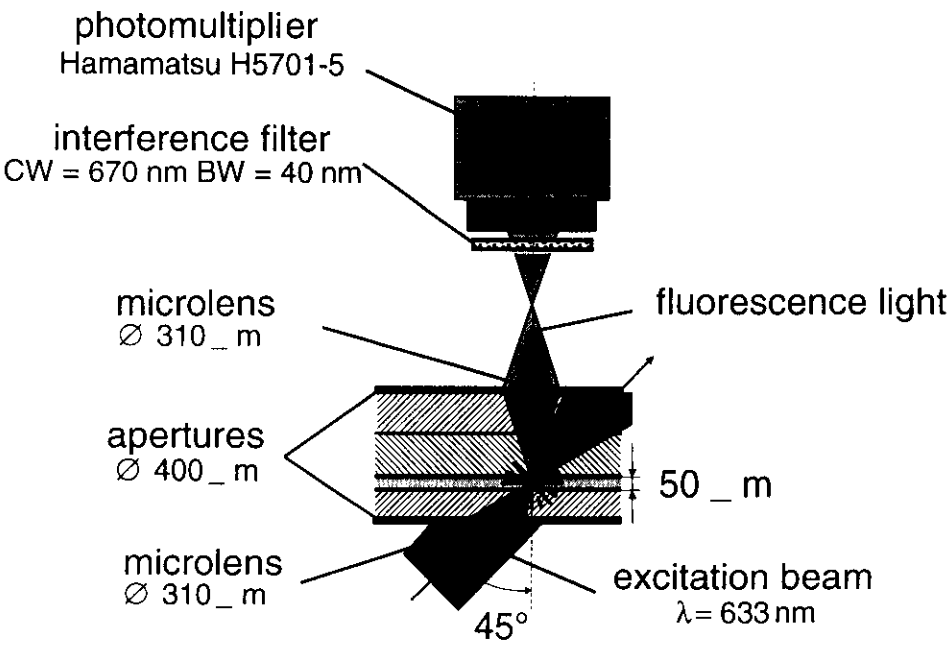




Beam splitting illumination system



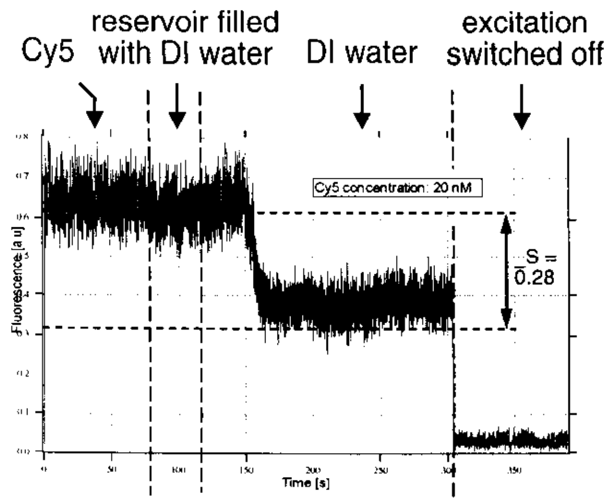
Detection using microlens array



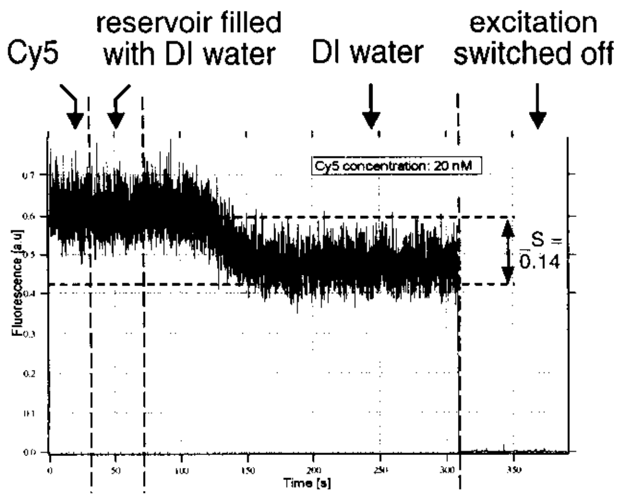
Measurement results

(Ti =1/10 s)

collection with microscope objective



collection with microlens



Conclusion

- chemical chip and optical system integration ⇨ route to detection in closely packed microchannels
- 20 nM dye solution detection ⇨ SNR = 20 dB/Hz
- integration of apertures and field stops possible ⇨ sensitivity improved
- versatile technology ⇨ integrated optical systems with different elements

Optical Nanostructures

- Zero-order gratings
- Fabrication of optical nanostructures
  - optical lithography
  - e-beam lithography
  - self-assembling
- SNOM (scanning near-field optical microscopy)
- HRIM (high-resolution interferometric microscopy)

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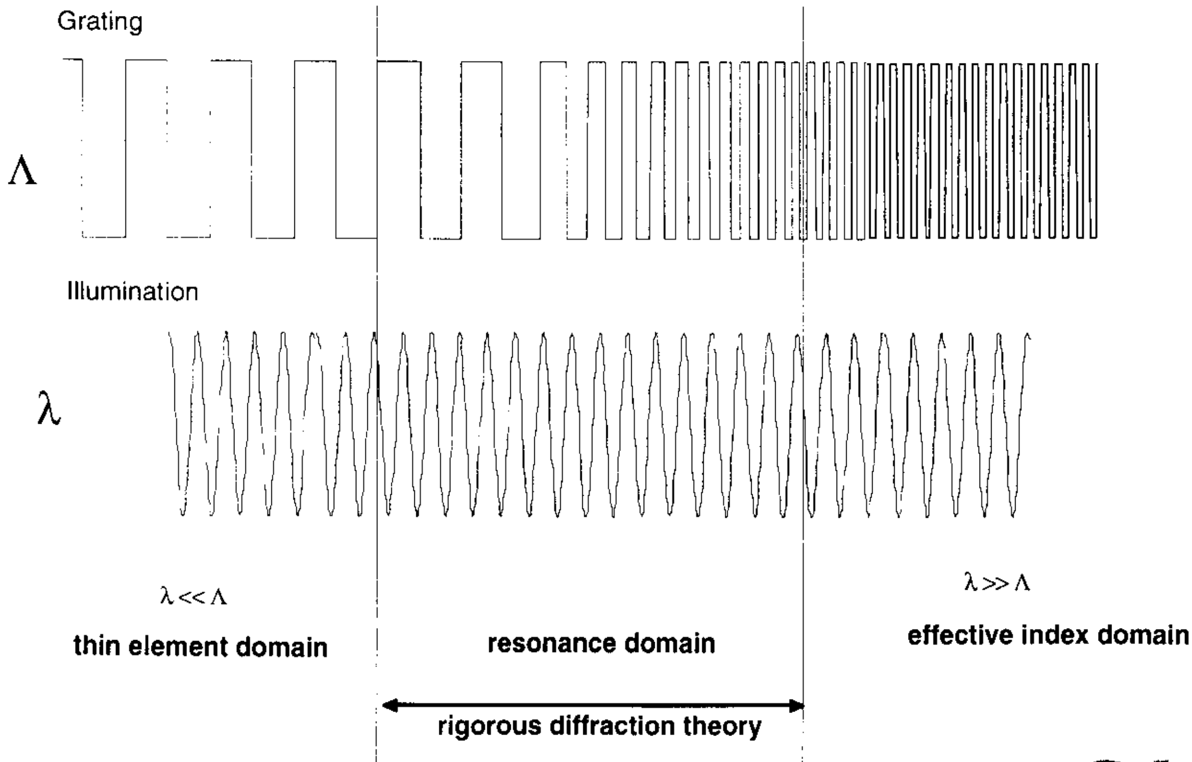
Diffraction theory for gratings



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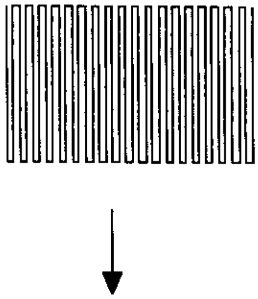
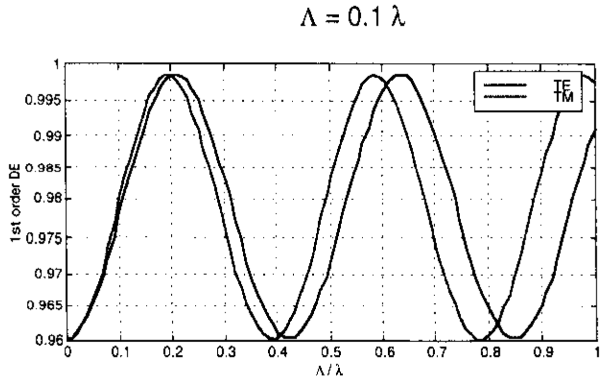
zero-order grating





ε_{eff}

TE-polarization $\varepsilon_{eff}^{TE} = t\varepsilon_1 + (1-t)\varepsilon_2$

TM-polarization $\dfrac{1}{\varepsilon_{eff}^{TE}} = \dfrac{t}{\varepsilon_1} + \dfrac{(1-t)}{\varepsilon_2}$

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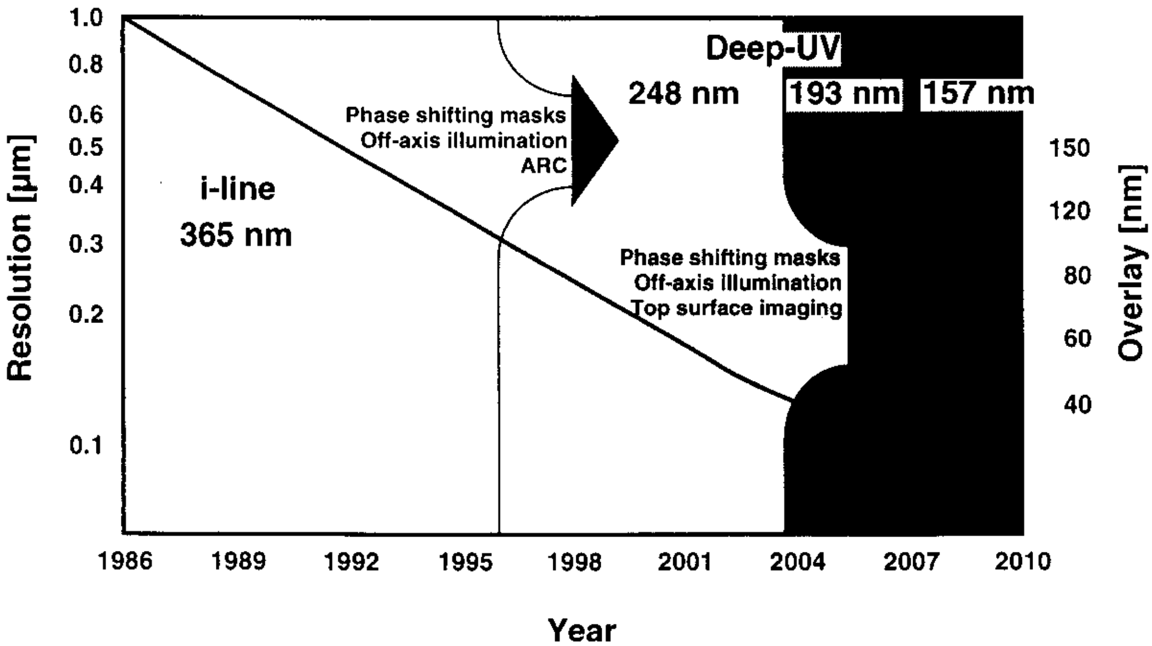
Optical lithography



S. Wittekoek, Microelectronic Engineering **23** (1994)

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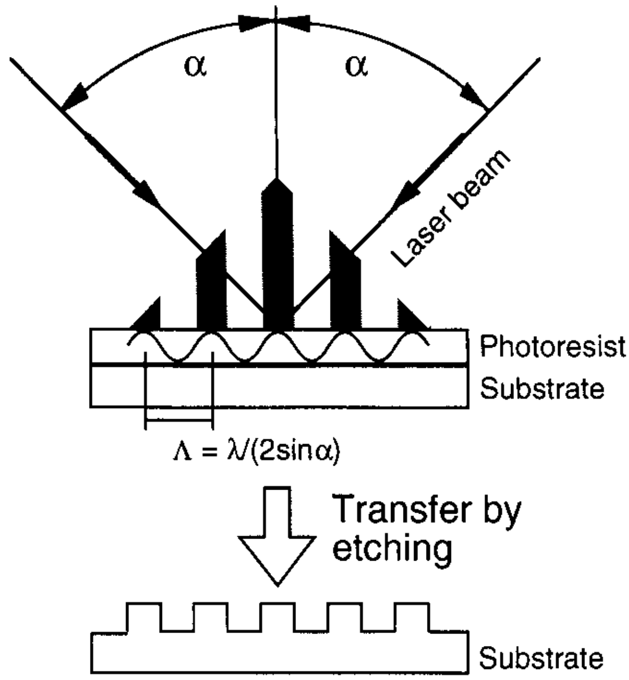
Interferometric recording



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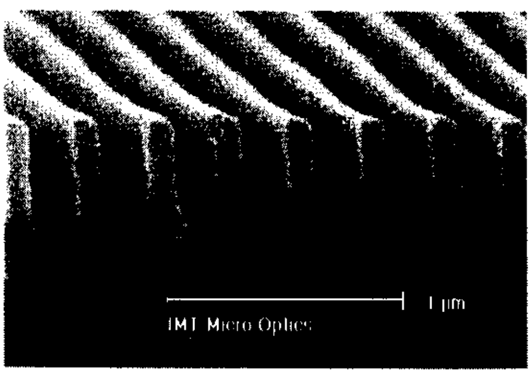
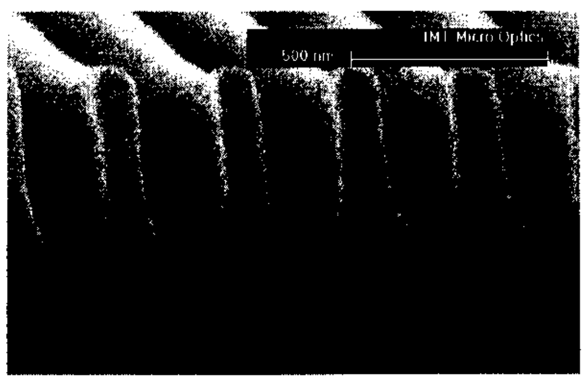
Gratings recorded in photoresist





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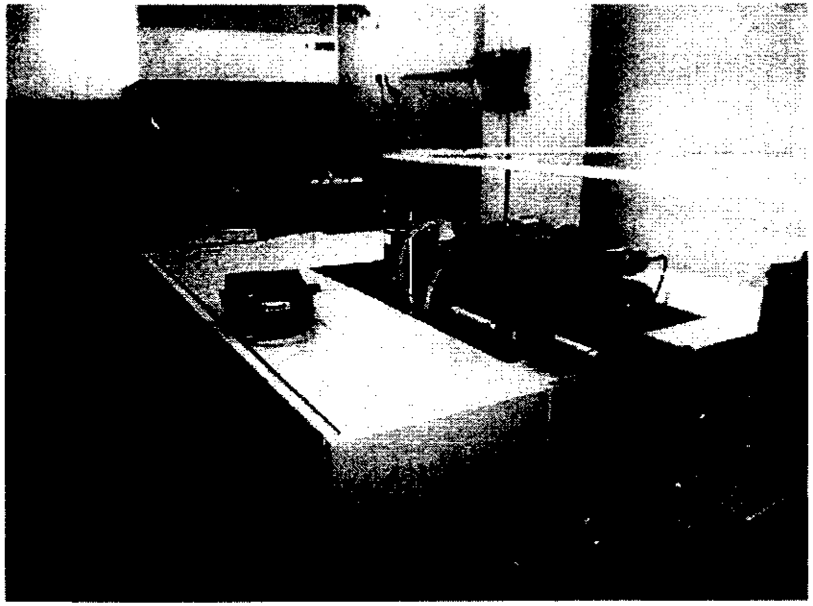
The LION LV-1 e-beam lithography tool



Lithography System for Integrated Optics and Nanostructures

Low Voltage 1 keV

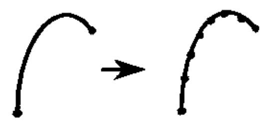
C. David

Laboratory for Micro- and Nanotechnology, Paul Scherrer Institute

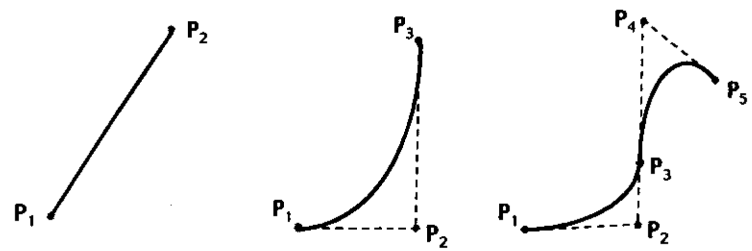
Exposure of Bézier-curves in continuous path control (CPC) mode

CPC mode:
- Sample stage moves along (curved or straight) path (max. 2 mm/sec)
- Beam deflection only compensates for stage misplacement
  => no field stitching required

Bézier curves:
- Curves are not described by polygons or primitives

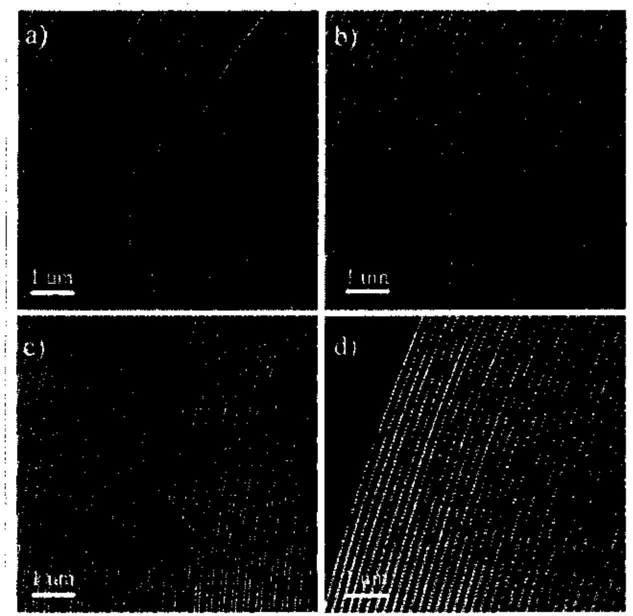


=> Optically smooth edges
=> Very efficient data compression



0th order Bézier curve | 1st order Bézier curve | 2nd order Bézier curve

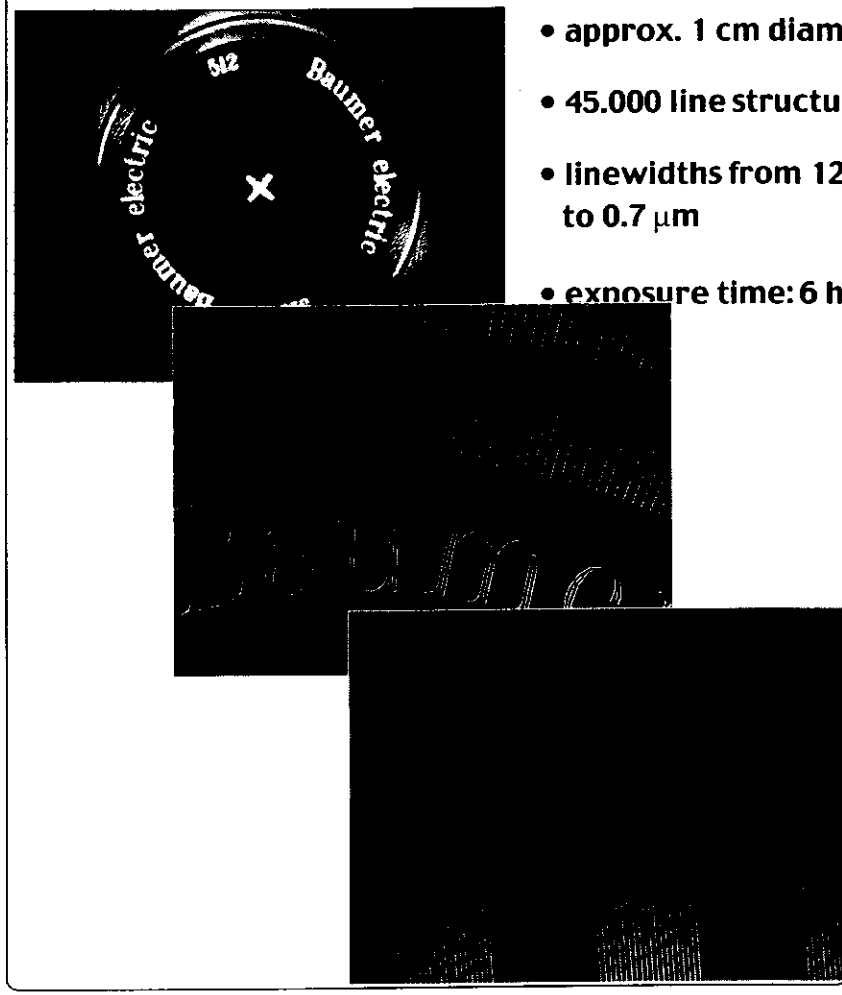
SEM micrograph of zone plate pattern



- Zone plate structures exposed at 2.5 keV in 50 nm PMMA etched into 20 nm Cr by RIE
- Each zone exposed as one single line in CPC-mode
- Good control of line width by defocusing down to 100 nm (duty cycle close to 0.5 for all line widths)

Applications: an angular encoder disk master

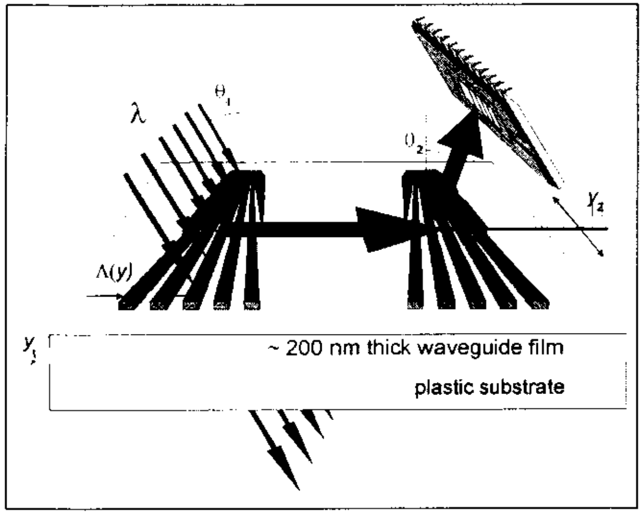
(patented by BAUMER electric, KTI-Projectpartner)



- approx. 1 cm diameter
- 45.000 line structures
- linewidths from 12 μm to 0.7 μm
- exposure time: 6 hours

Applications: chirped gratings for waveguide sensors

in collaboration with J. Söchtig and M.T. Gale, CSEM-Z

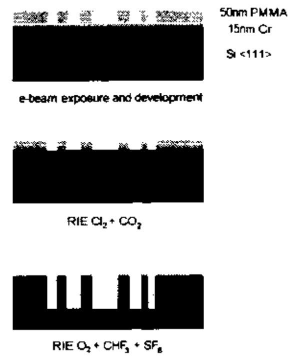


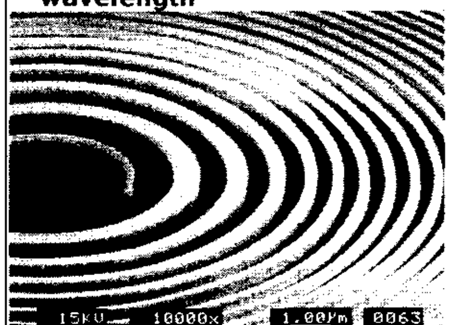
position y_2 of output signal depends on:

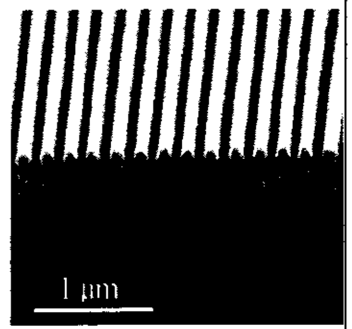
- wavelength => miniaturized spectrometer
- waveguide film => surface sensor for
  - immunosensors
  - ion detection in liquids

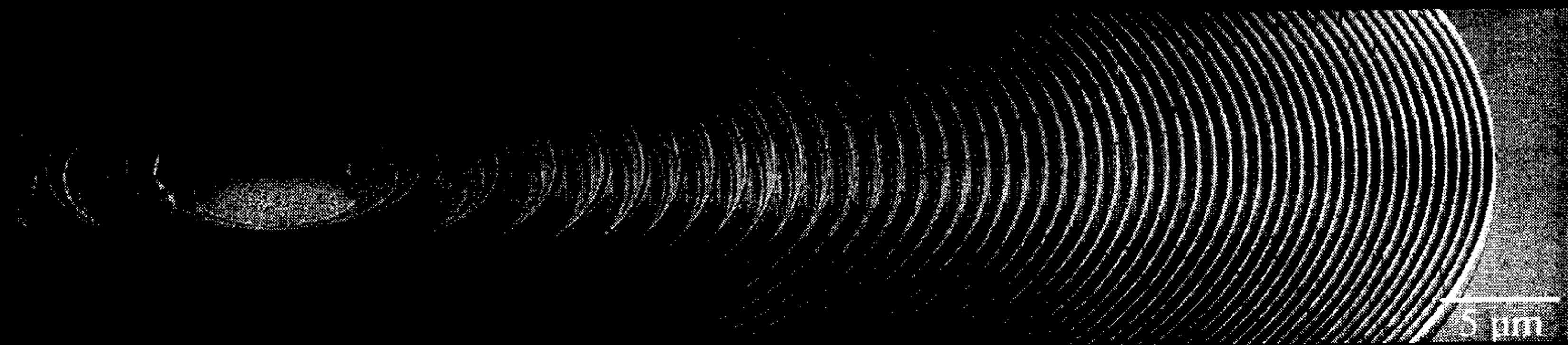
- zone plates made from Si <111> by e-beam lithography and RIE
- Smallest structures: 100 nm wide, 1000 nm deep
- Maximum size: 1 cm long, 1 mm wide, 2500 zone structures

=> focal length 1 m @ 0.1 nm wavelength

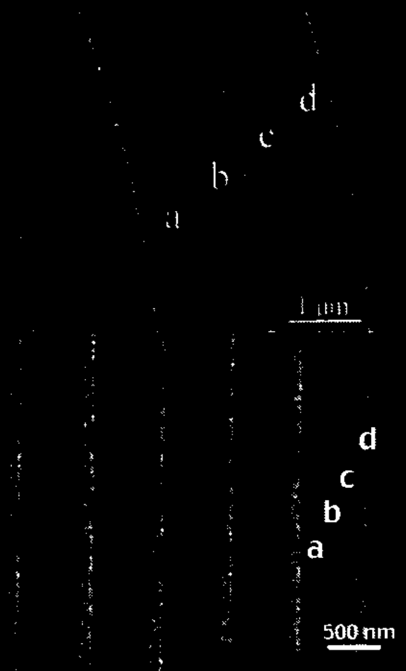




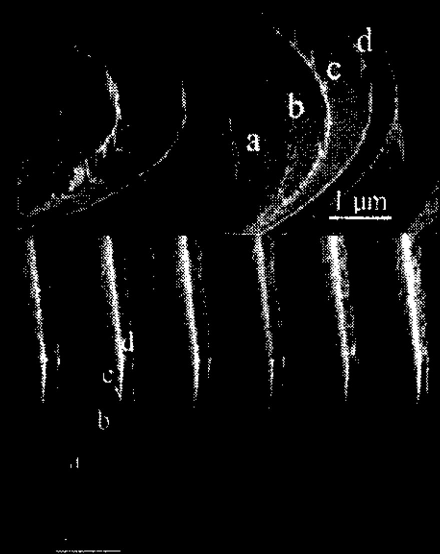




4-level x-ray lens with 1.5 mm structure height and 480 nm outermost pitch



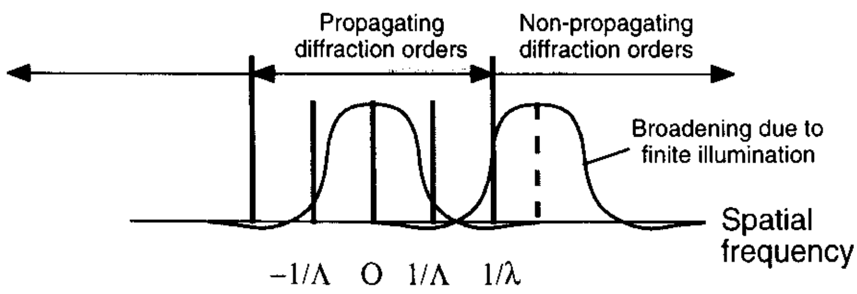
Al and Cr mask structures:
a: no metal, b: only *Cr*,
c: only *Al*, d: *Al* on *Cr*

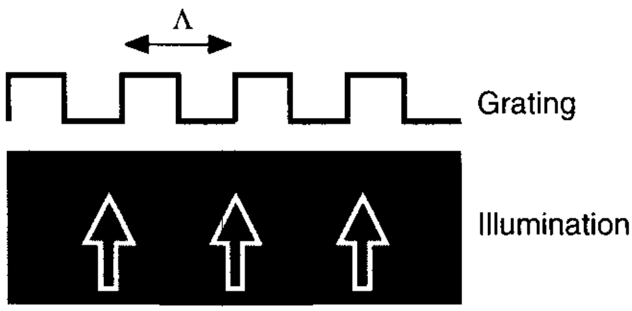


Resulting *Si*-structuren
after RIE in $CHF_3 : SF_6 : O_2$

Blazed grating in quartz with a 4-level profil
etched in a $CHF_3 : O_2$ plasma.

What can you see?





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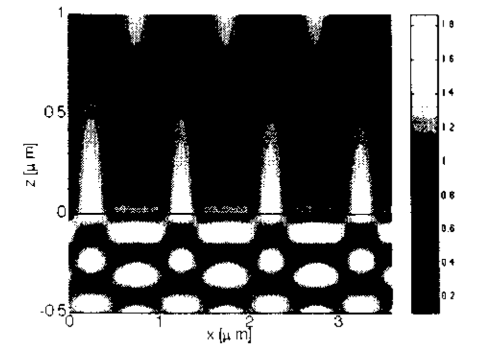
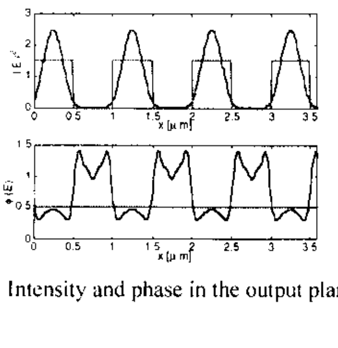
Optical near field

Amplitude

Example of calculated near-field intensity distribution



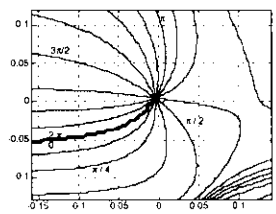
Chromium on glass mask: 50 nm layer, 1µm grating period, TE-pol., λ = 633 nm



Intensity and phase in the output plane

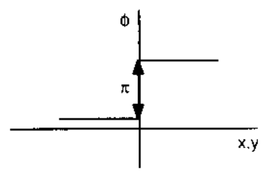
Phase

Example of phase dislocation

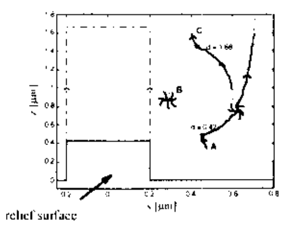


phase contour plot

Scan through the singularity



There is always a π phase jump scanning through a phase dislocation. The jump is sharp.



Position of the phase dislocation for different grating depths

path A Not yet a phase dislocation

[illegible]

path C Not anymore a phase dislocation

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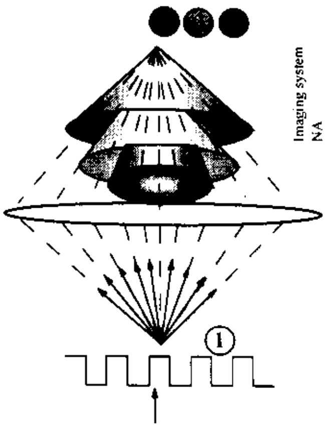
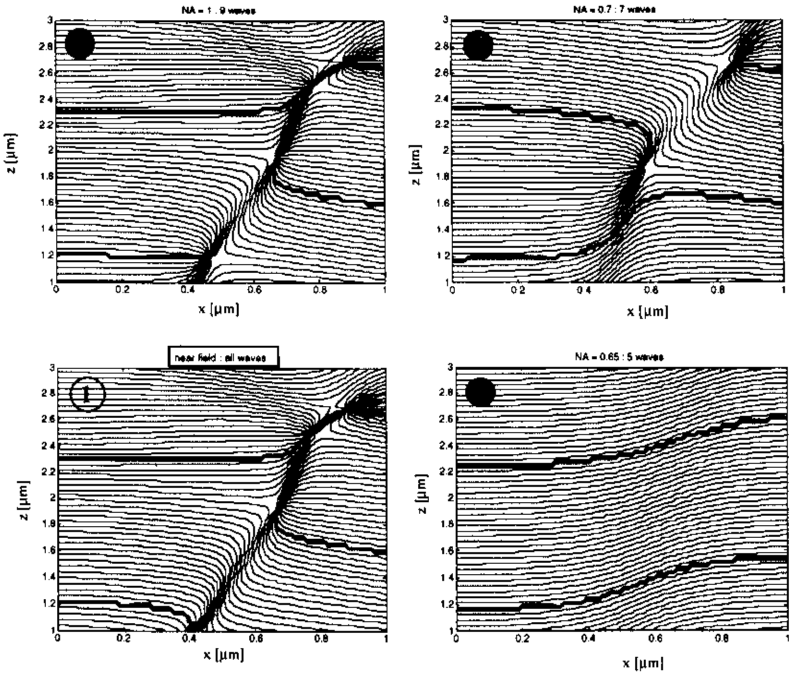
Far-field phase dislocations after low-pass filtering





Measuring the phase in the far field can give some information about the geometry of the structure!

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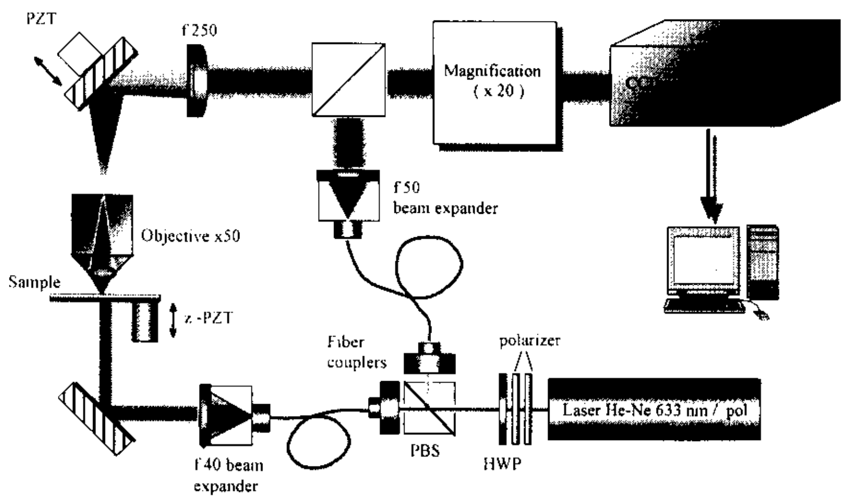
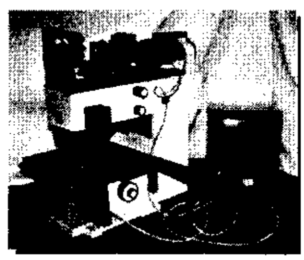
High Resolution Interference Microscope



HRIM based on a Mach-Zender interferometer



Mach-Zender interferometer

- CCD-pixel size: 10 µm
- Object-pixel size: 10 nm

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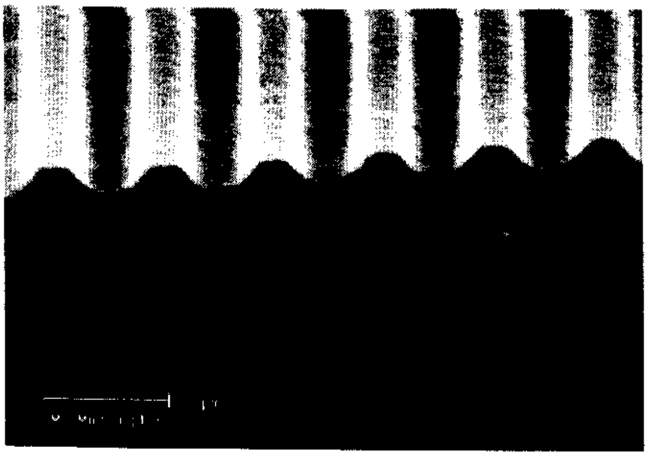
SEM pictures



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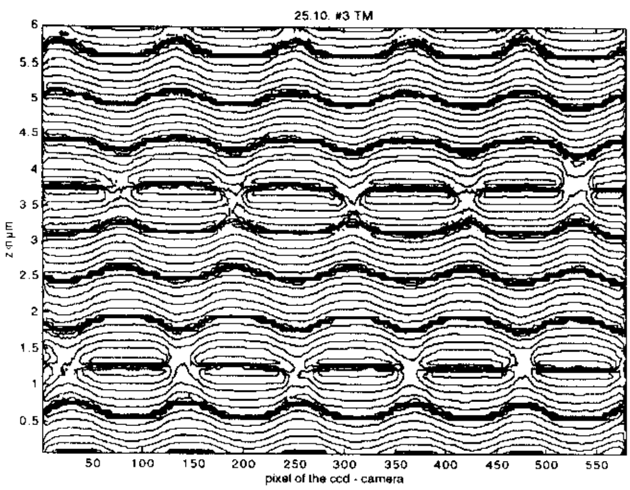
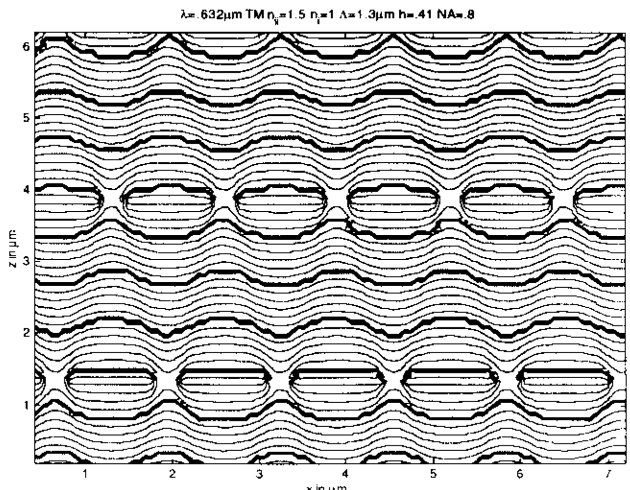
measurement / calculation





1pixel of the ccd-camera = 10nm

Λ =1. 3µm h=0.41µm TM

n_{ii}=1.5 n_i=1 λ=.632µm NA=0.8

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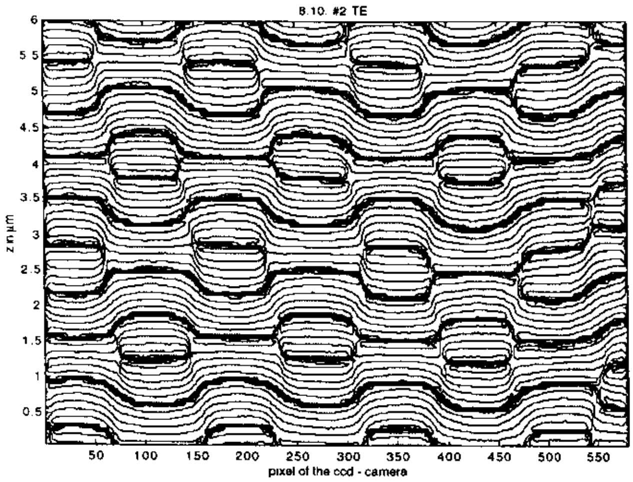
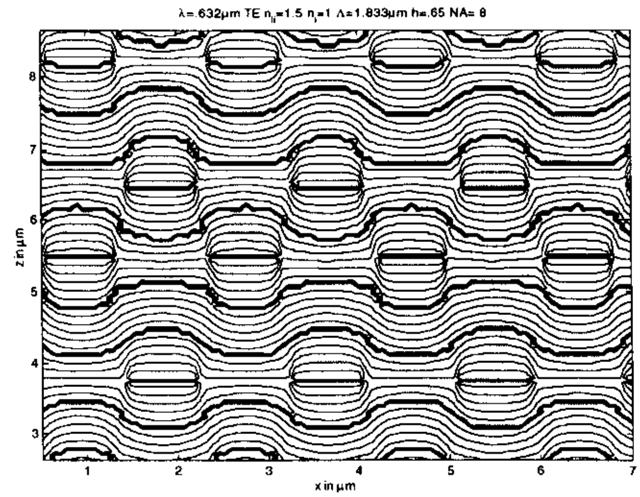
measurement / calculation





1pixel of the ccd-camera = 10nm

Λ =1.833µm h=0.65µm TE

n_{ii}=1.5 n_i=1 λ=.632µm NA=0.8

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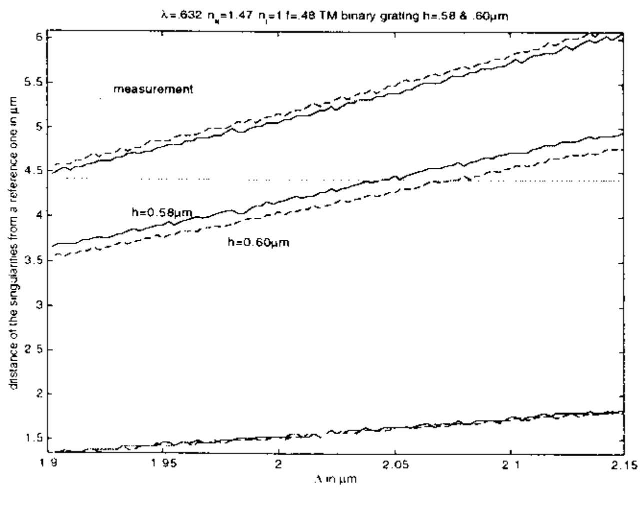
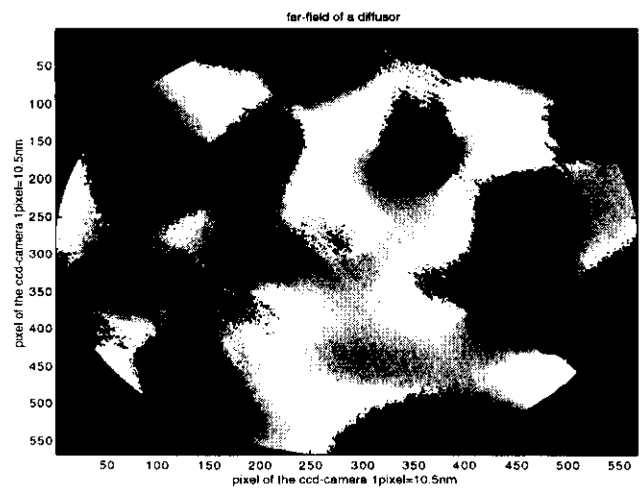
Resolution





distances of phase singularities
in the far field of a grating

$\Delta z \approx 60$nm

speckle

$\Delta x = \Delta y \approx 20$nm

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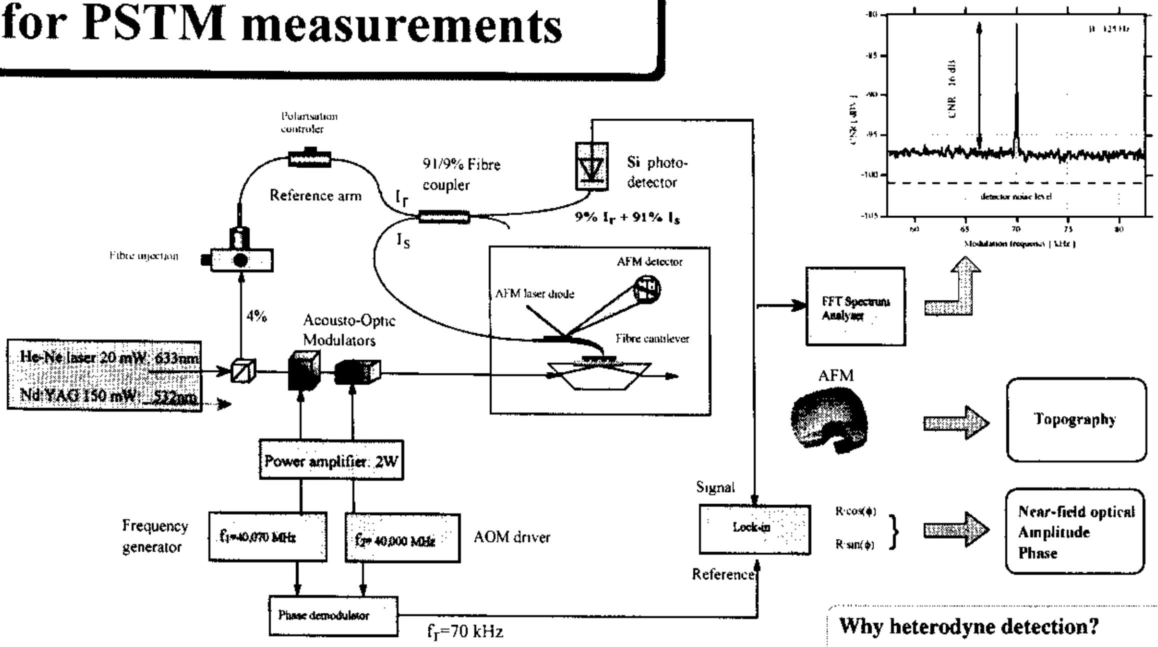
Heterodyne detection system for PSTM measurements



Bent coated fiber cantilever

Why heterodyne detection?

- Interferometry for phase measurements.
- Low signal detection.
- $P_{ref} >> P_{obj} \Rightarrow SNR = \frac{S}{q \cdot B} \cdot P_{obj}$
- Sensitive detection method. (more than an avalanche photodiode detection)

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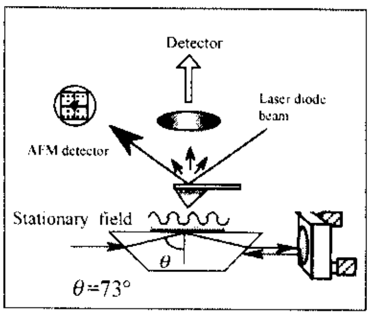
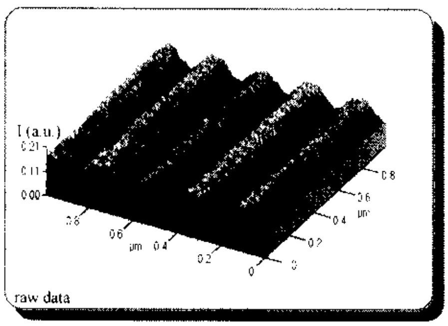
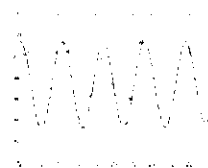
Measurements with transparent AFM probe

Evanescent standing wave field







Sinusoidal fitting

Smoothed data

$$\Lambda_{th} = \frac{\lambda / n_s}{2 \cdot \sin(\theta)} = 219.1 \ nm$$

$$\Lambda_{exp} = 220nm \pm 1nm \quad \leftrightarrow \quad \theta = 72° \pm 1°$$

λ= 633 nm

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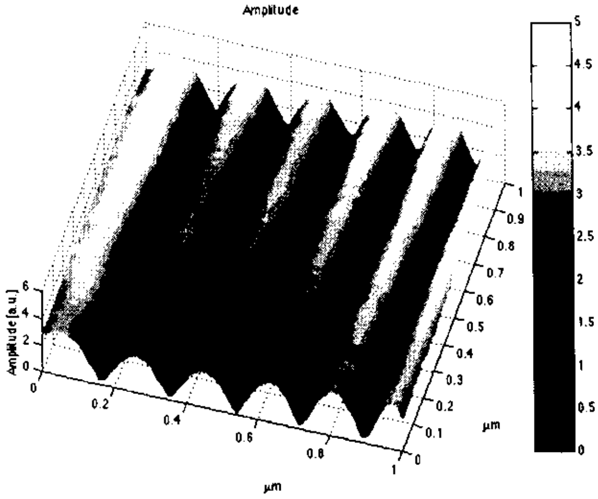
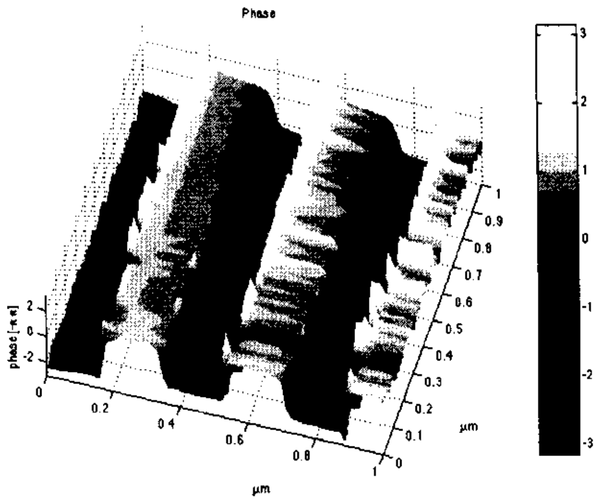
Amplitude and phase measurement of evanescent standing wave





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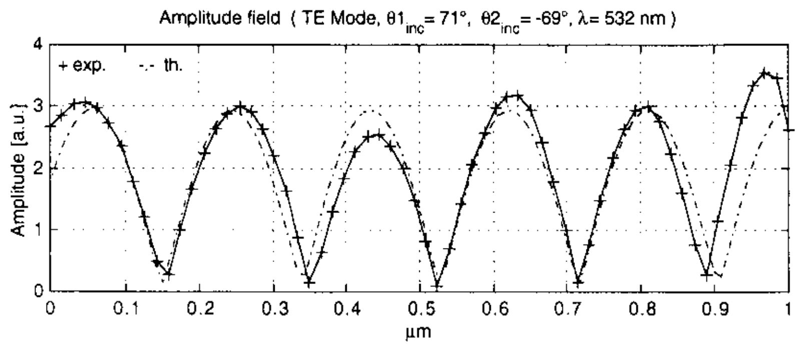
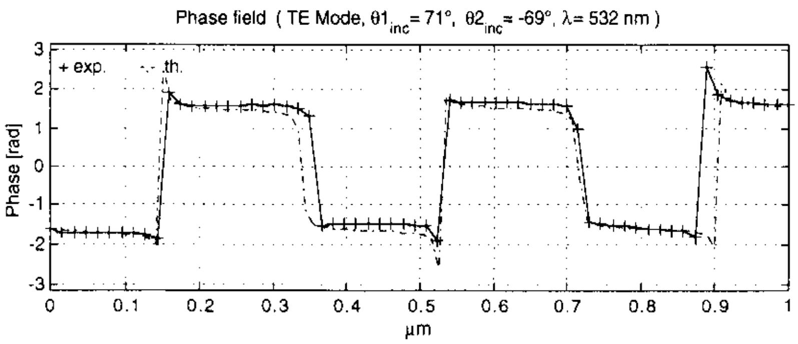
Amplitude and phase of evanescent standing wave





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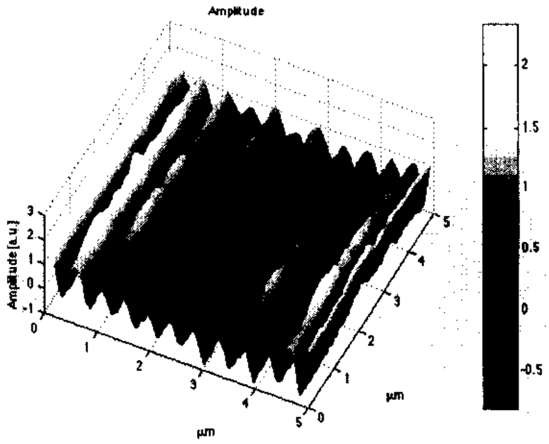
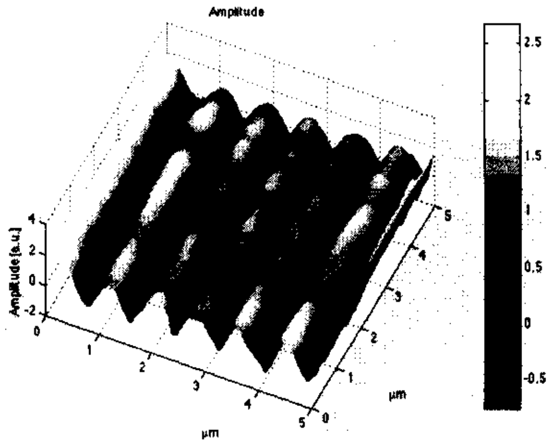
1 µm grating at normal incidence

TE-mode



TM-mode



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