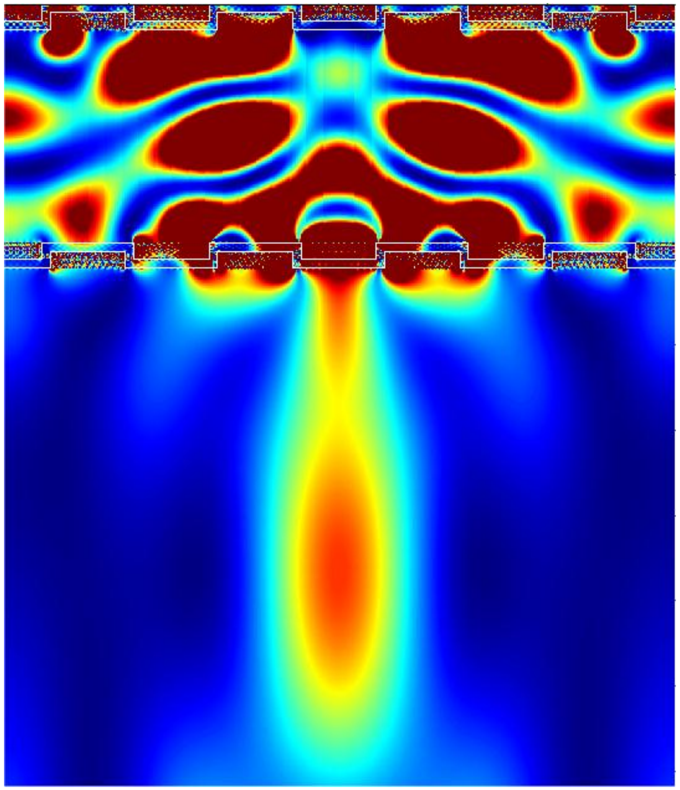
Model-based reconstruction of periodic sub-λ features



- ITO Stuttgart
- Optical Metrology: Advantages & Disadvantages (Challenge)
- Inverse Problems: Solving Strategy (Modelbased Feature Reconstruction)
- Outlook

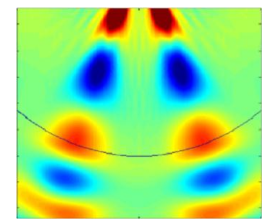
ITO Research Targets

3D-Surface Metrology

- scaled measurement systems
- sensor models & sensor fusion

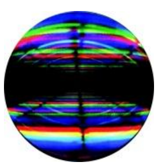
Active Optical Systems

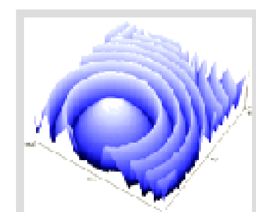
- computational imaging
- wavefront engineering



High-Resolution Metrology & Simulation

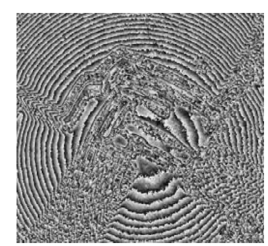
- CD-metrology & defectoscopy
- metamaterials & superresolution





Interferometry & Diffractive Optics

- asphere- and freeform metrology
- design, holograms & macro-/microoptics



Coherent Metrology

- digital holography, ESA & HNDT
- phase retrieval & remote laboratories

Optical Metrology:

Advantages

& Disadvantages

Optical Metrology

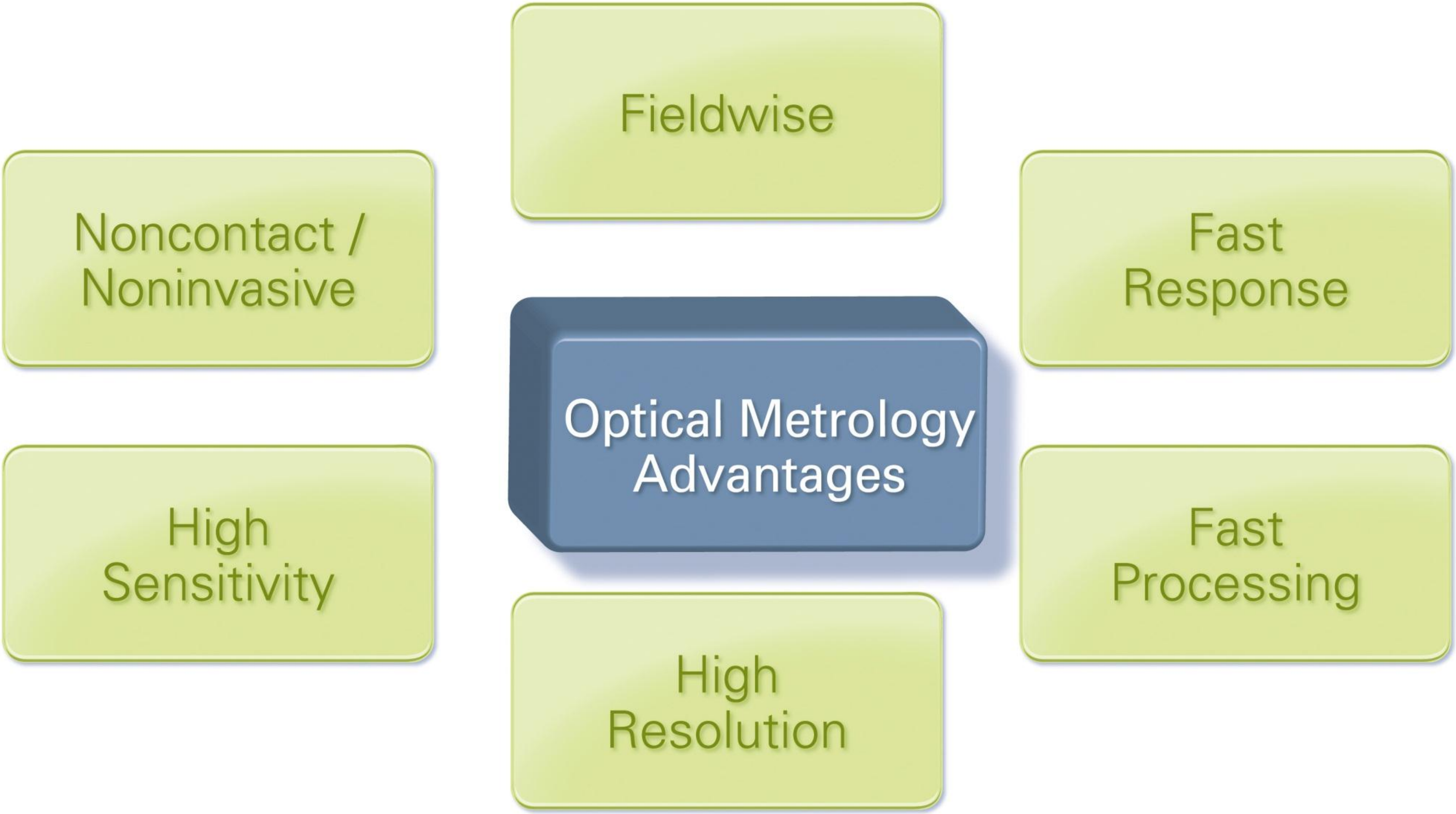
Working range: >10 orders of magnitude

AFM & SNOM	White Light & confocal Microscopy	Holographic & Speckle-Metrology	Fringe Projection

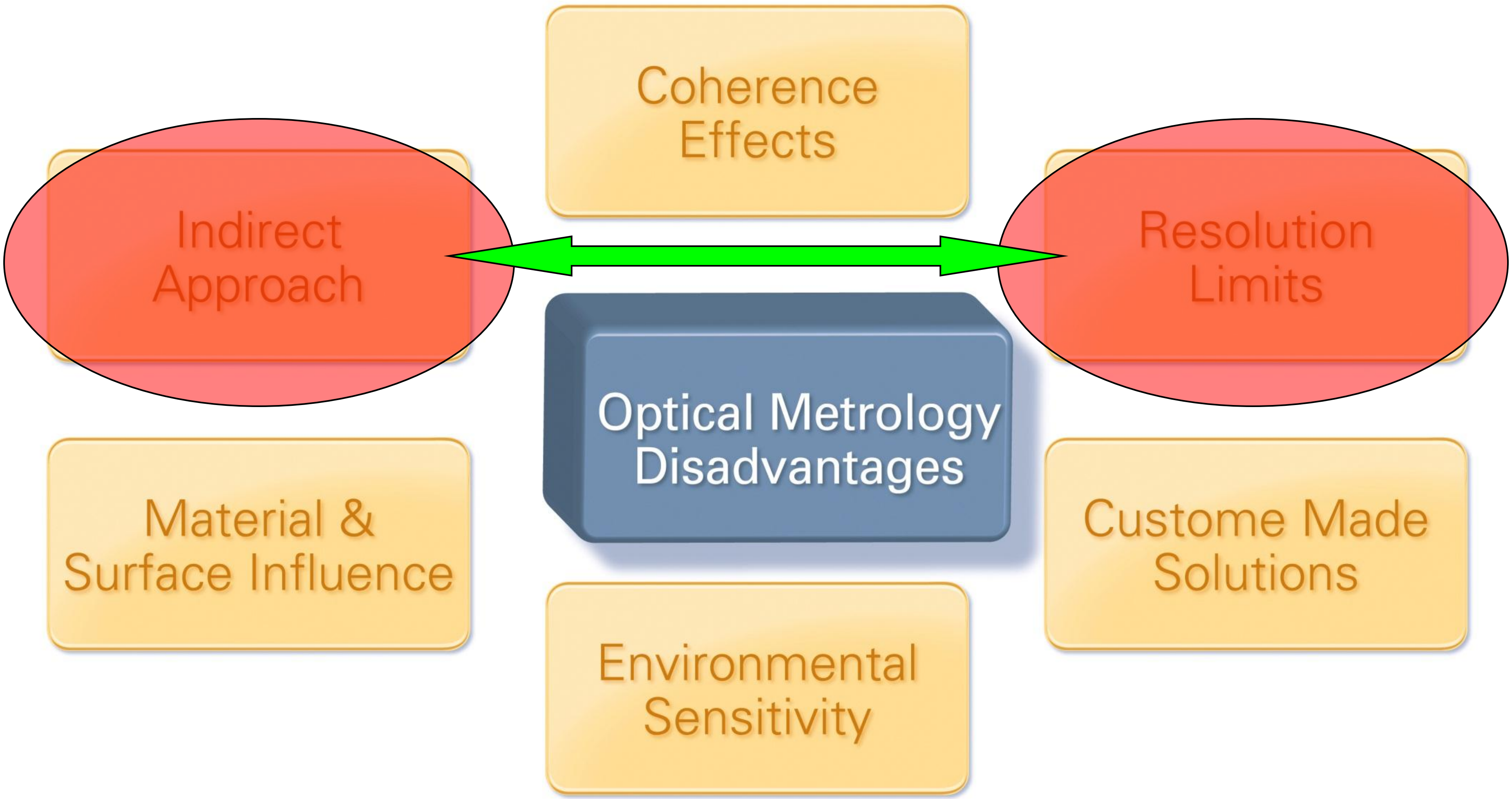
Quantities: - geometric data (coordinates, shape, microtopography)

- changes of geometric data (displacements, strain)
- material parameters (youngs modulus, poisson ratio, …)
- material faults (cracks, voids, delaminations, ...)

Far Field Optics: many advantages

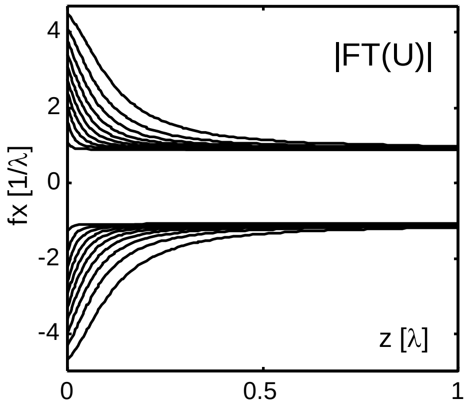


Far Field Optics: 2 obvious disadvantages



Information Lost

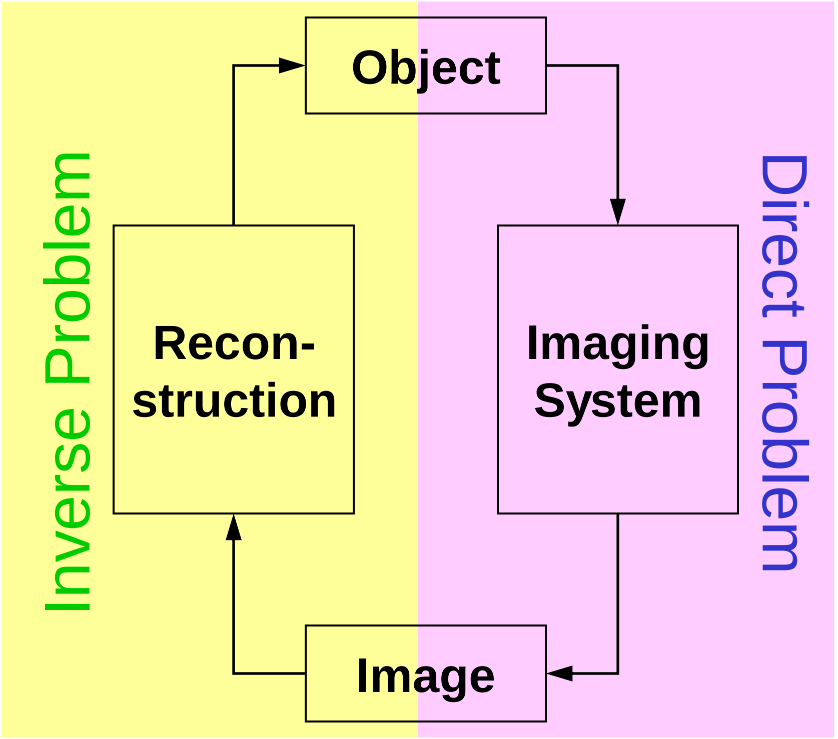
- Free space is a low-pass filter!
- Spatial frequency content decreases with distance



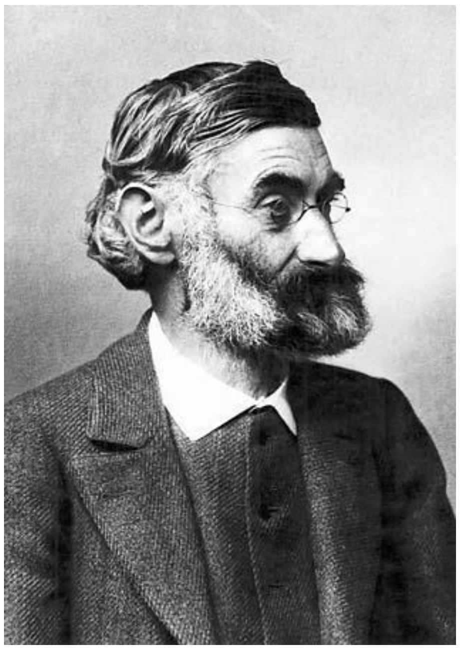
$$\Rightarrow \quad u_{max} = \frac{1}{\lambda}$$

Inverse Problem

- The measurement results are only „**Images**"!



Ernst Abbe (1840-1905): „*Theory of Image Formation*“



Archiv für Mikroskopische Anatomie
9(1873), pp. 413-468

Beiträge zur Theorie des Mikroskops und der mikroskopischen Wahrnehmung.

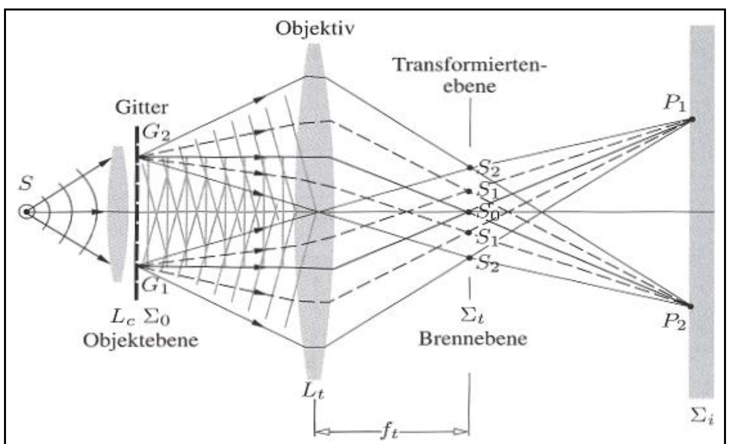
I. Die Construction von Mikroskopen auf Grund der Theorie. II. Die dioptrischen Bedingungen der Leistung des Mikroskops. III. Die physikalischen Bedingungen für die Abbildung feiner Structuren. IV. Das optische Vermögen des Mikroskops.

Von

Dr. E. Abbe,
ao. Professor in Jena.

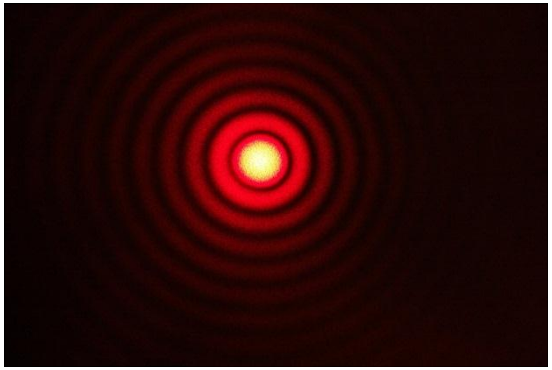
I. Die Construction von Mikroskopen auf Grund der Theorie.

1. In den Handbüchern der Mikrographie findet man gelegentlich die Thatsache berührt, dass die Construction der Miksroskope und ihre fortschreitende Verbesserung bisher fast ausschliesslich Sache der Empirie, geschickten und ausdauernden Probirens von



$$d = \frac{\lambda}{2\sin\alpha}$$

Lateral Resolution Limit

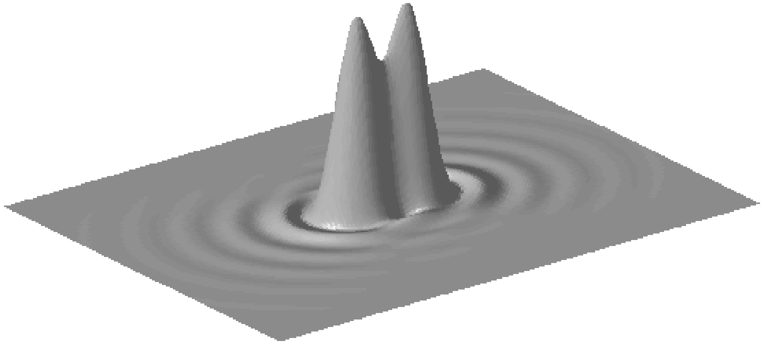


$$\delta x = \kappa_1 \cdot \frac{\lambda}{n \cdot \sin\alpha}$$

Example: n=1,7, σ=45° ➞ $\delta x \approx 0{,}5\lambda$

Point Image (Airy Spot)

2 Adjacent Point Images



➡ Structure Width < $\lambda/2$ not resolvable

Inverse Problems: Solving Strategy

Modelbased Feature Reconstruction

1. Use all (*useful*) **information that is available!**

(Evaluation of the whole Information Content of the Light Field)

2. Combine the direct with the indirect Problem

- Active Metrology

- Modelbased Metrology

- Sensor Fusion

1. Use all (*useful*) information that is available!

(Evaluation of the whole Information Content of the Light Field)

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- Active Metrology

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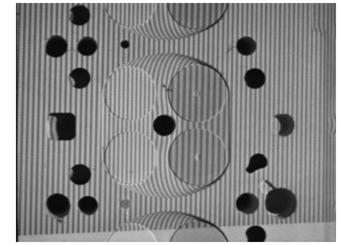
Evaluation of the whole Information Content of the Light Field

Information Channels:

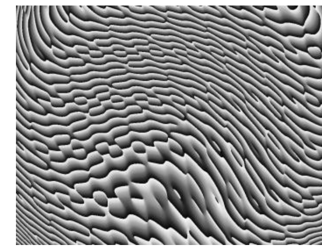
$$\mathbf{E}(\mathbf{r},t)=\mathbf{a}(\mathbf{r})\cdot e^{i(-\mathbf{k}\cdot\mathbf{r}+\omega t)}$$

- Intensity



- Phase

$\mathbf{k}\cdot\mathbf{r}$



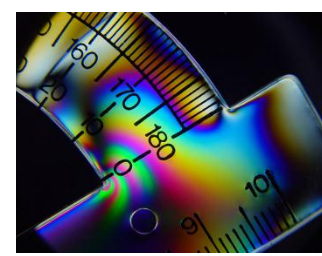
- Direction

(Angular Spectrum)

$\mathbf{k}$

- Polarization

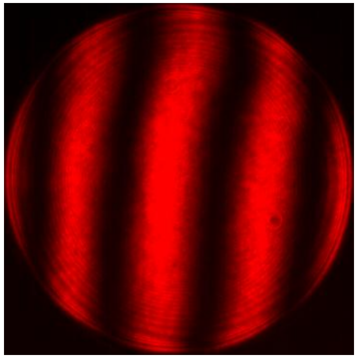
$\mathbf{E}$



Field Properties: Coherence (Correlation)

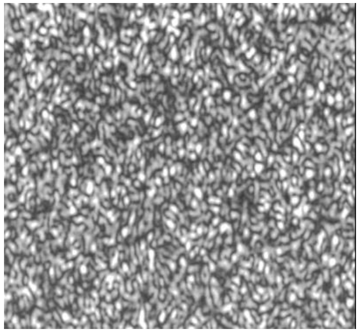
- Temporal Coherence

$\Gamma(\tau)$



- Spatial Coherence

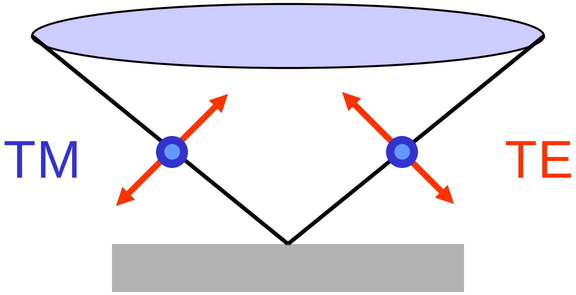
$\Gamma(\mathbf{r}_1,\mathbf{r}_2,0)$



Information Channels:

$$\mathbf{E}(\mathbf{r},t) = \mathbf{a}(\mathbf{r})\cdot e^{i(-\mathbf{k}\cdot\mathbf{r}+\omega t)}$$

<u>Example</u>: The Role of Polarization in Imaging



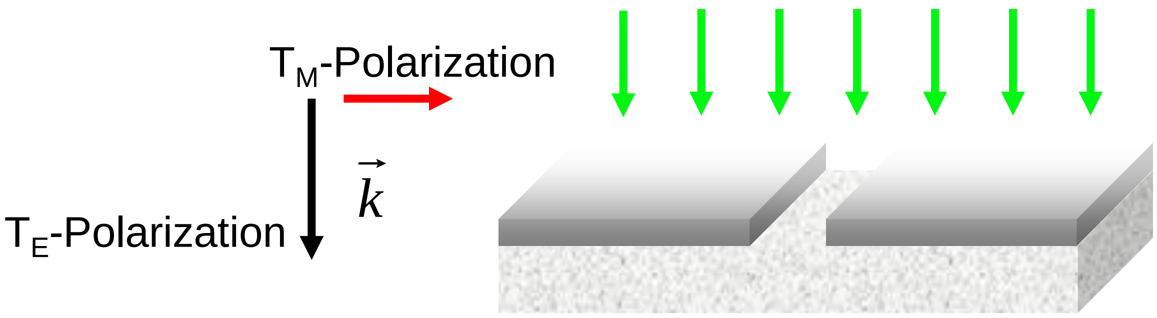
- Differences between orthogonal states of linear polarization (TE & TM)

- **small** for NA<0,7 (25°) **but** **large** for NA≈1 (90°)

- image contrast caused by TE drops to zero

- the diffraction at microstructures shows a complex polarization dependence

Role of Polarization: Simulation Example

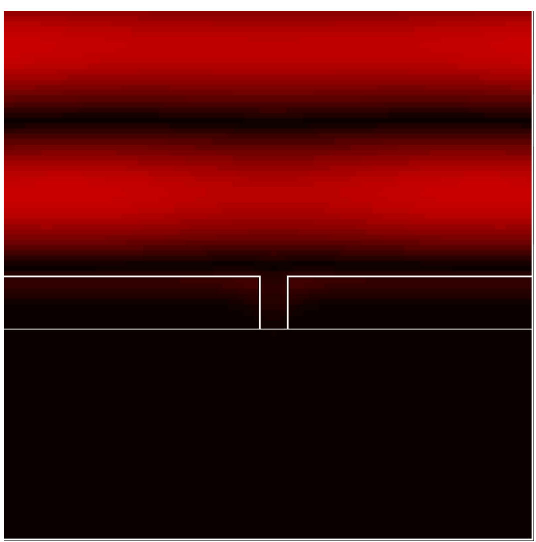


Trench-width: 50nm (sub-λ !!!)

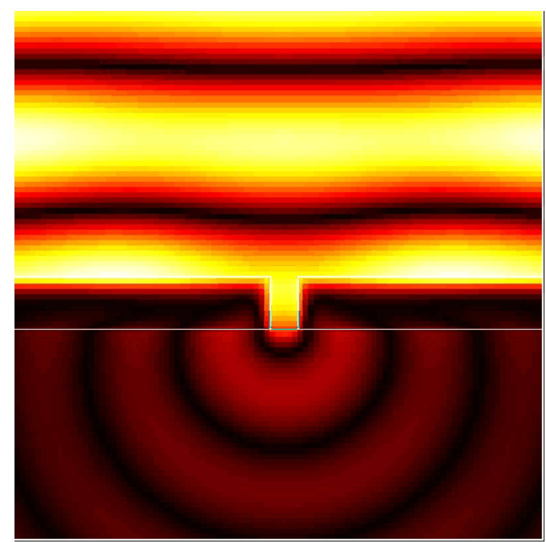
Chromium (100nm) on Glass

wavelength: 550nm

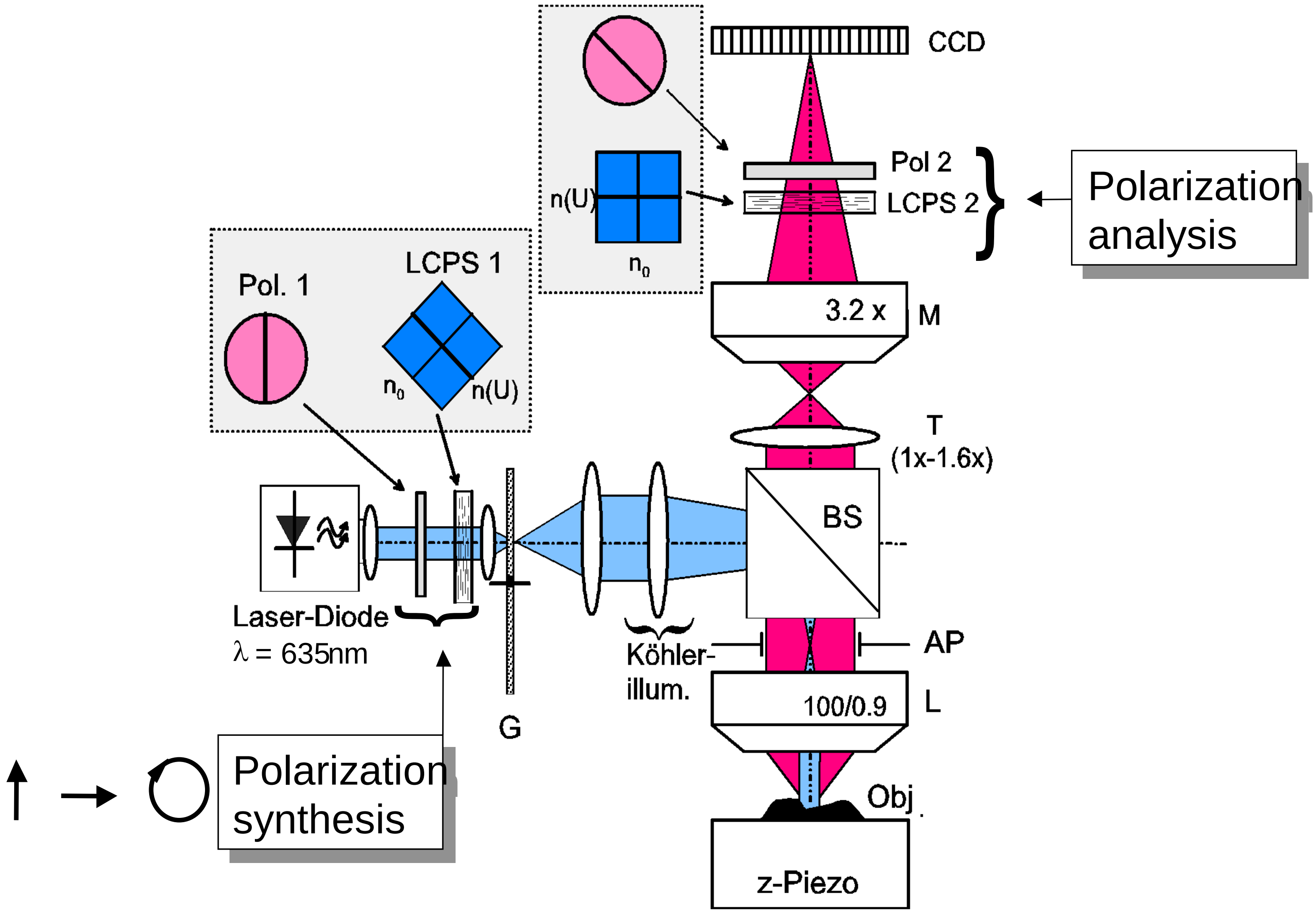
T_E-Polarization



T_M-Polarization

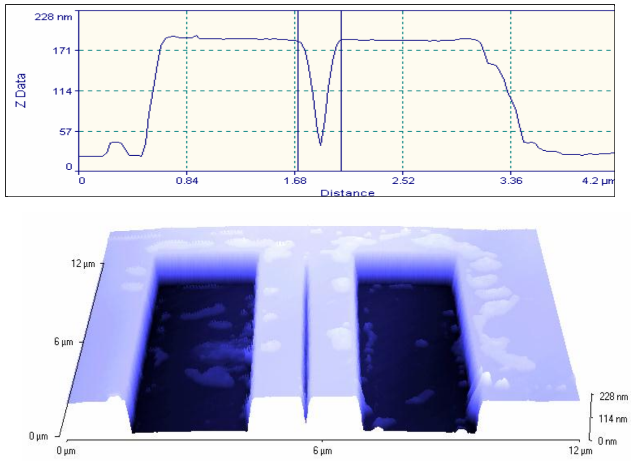


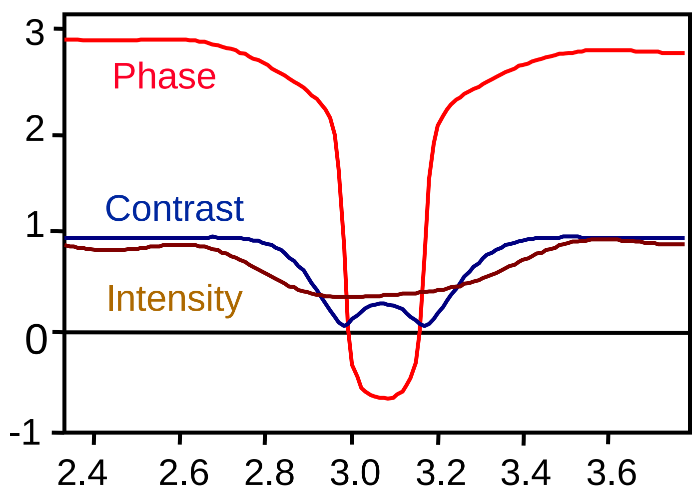
Setup for PSPI for microstructure inspection

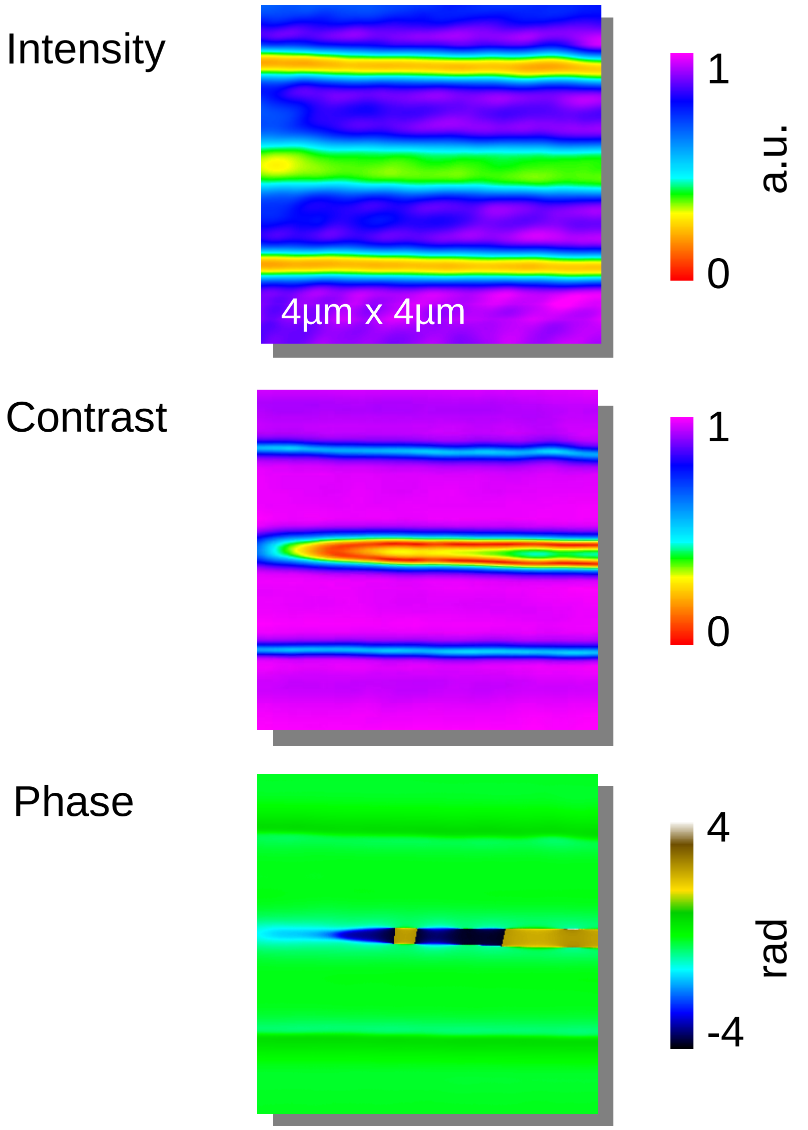


PSPI for sub-λ microstructure inspection

Sub-λ Groove: 330 nm (λ=635nm)

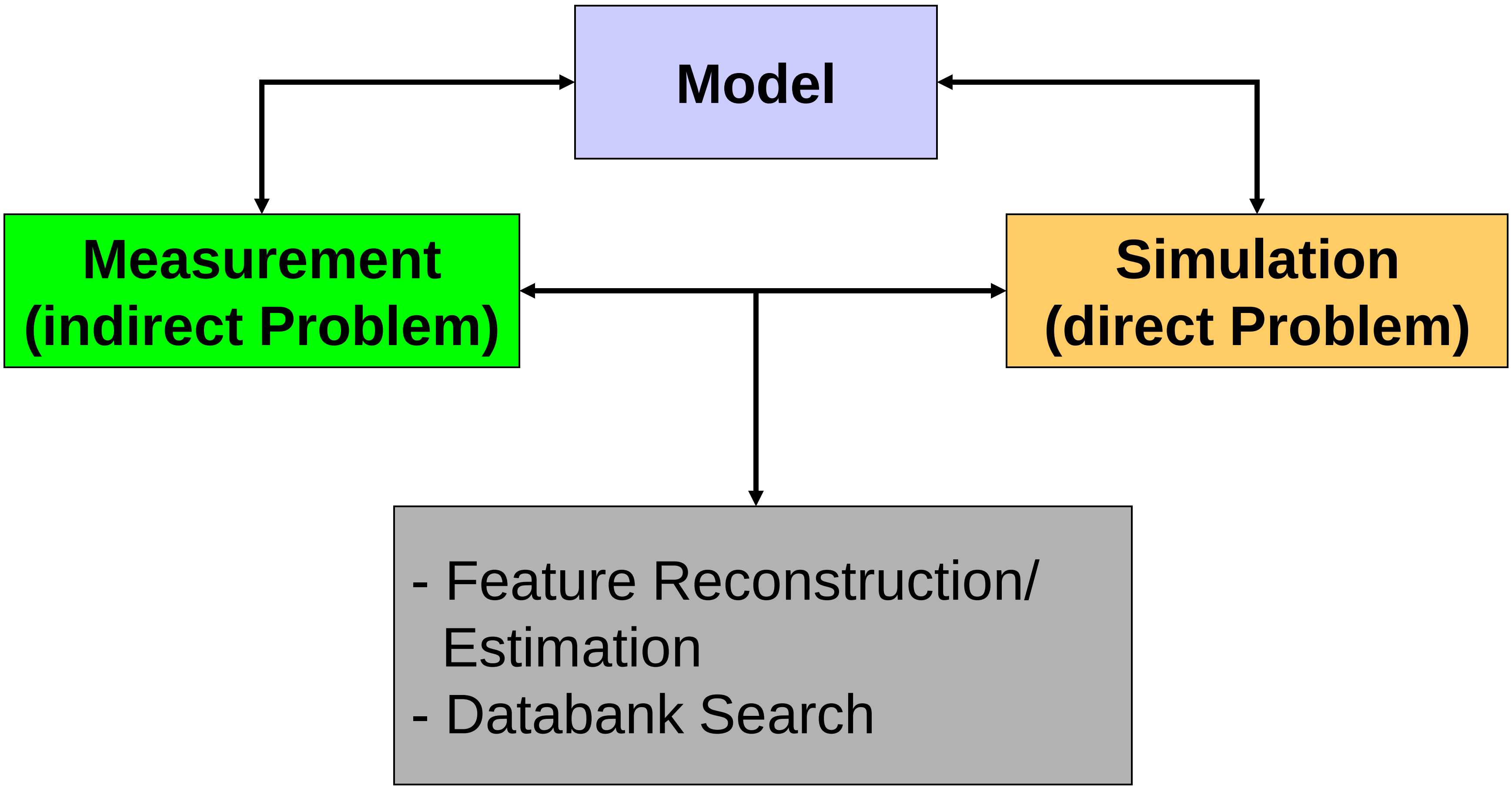






Model Based Metrology

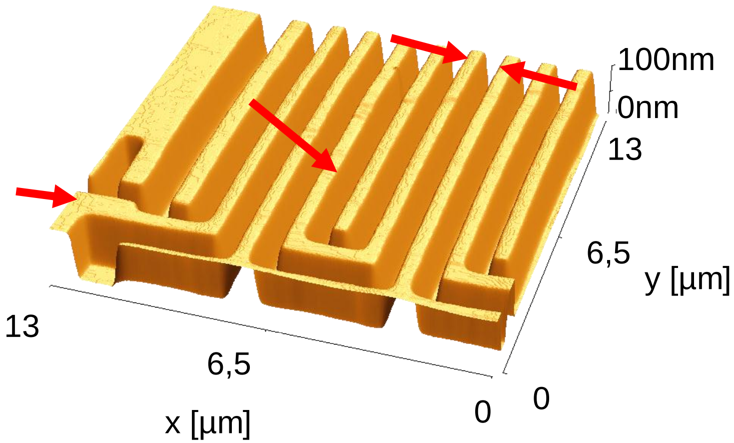
General Solution Strategy

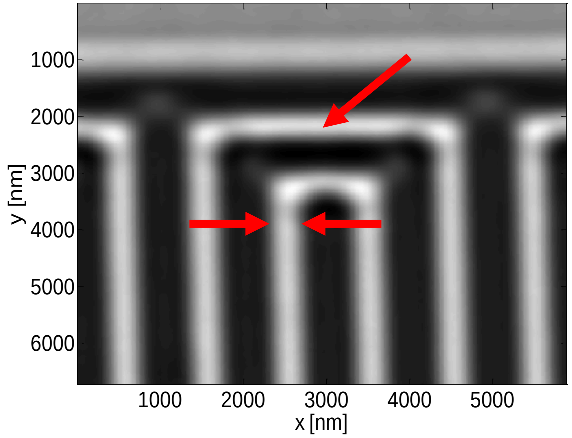


Example

Reconstruction of sub-λ Features in Photolithography

CD-Metrology: Evaluation of the Structure Quality of tiny (sub-λ) Structures





Typical Tasks:

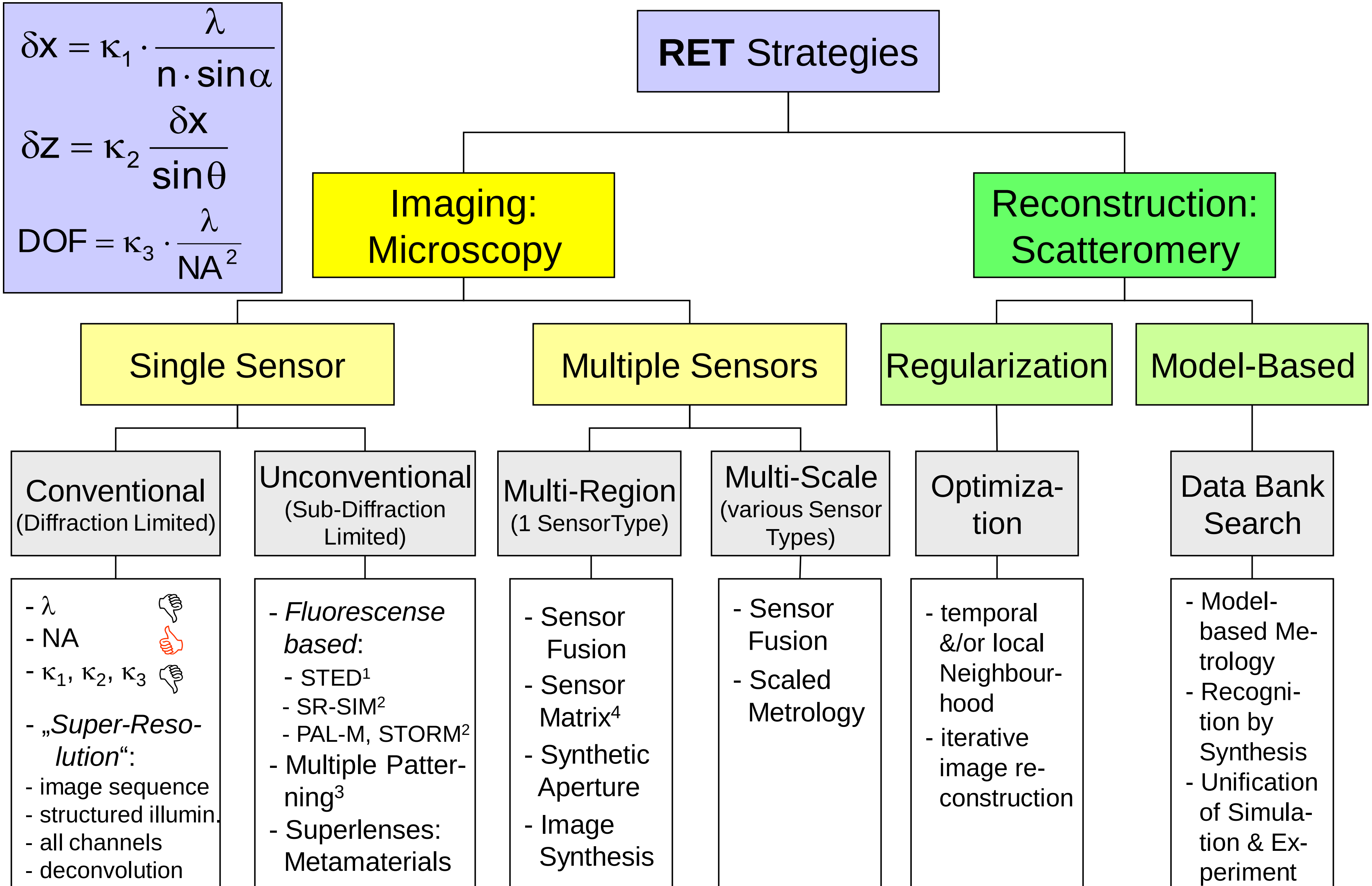
- Dimensional Quantities: Depth, Width, ...
- Structure Shape: Profiles, Curvature, Angle, Roughness,...
- Defects
- Phase

Resolution Enhanced Technologies RET

$$\delta x = \kappa_1 \cdot \frac{\lambda}{n \cdot \sin\alpha}$$

$$\delta z = \kappa_2 \frac{\delta x}{\sin\theta}$$

$$DOF = \kappa_3 \cdot \frac{\lambda}{NA^2}$$



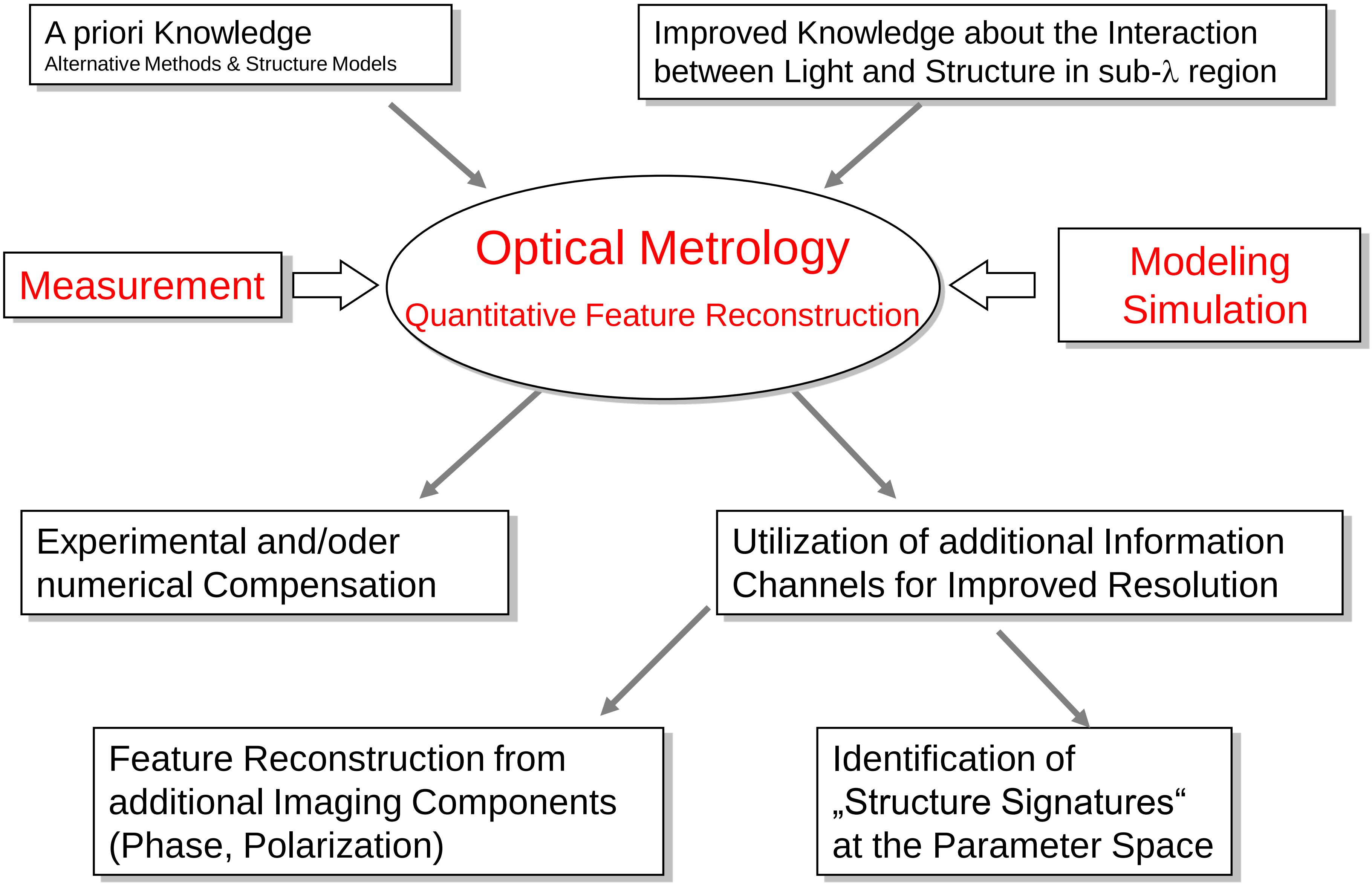
[1]http://en.wikipedia.org/wiki/STED_microscopy, [2]http://www.zeiss.de/highres_visual_d, [3]http://en.wikipedia.org/wiki/Multiple_patterning, [4]SMARTIEHS-Project

Resolution Enhanced Technologies RET

RET Strategies

- **Imaging: Microscopy**
  - **Single Sensor**
    - **Conventional** (Diffraction Limited)
      - λ
      - NA
      - κ_1, κ_2, κ_3
      - „*Super-Resolution*“:
      - image sequence
      - structured illumin.
      - all channels
      - deconvolution
    - **Unconventional** (Sub-Diffraction Limited)
      - *Fluorescense based*:
        - STED[1]
        - SR-SIM[2]
        - PAL-M, STORM[2]
      - Multiple Patterning[3]
      - Superlenses: Metamaterials
  - **Multiple Sensors**
    - **Multi-Region** (1 SensorType)
      - Sensor Fusion
      - Sensor Matrix[4]
      - Synthetic Aperture
      - Image Synthesis
    - **Multi-Scale** (various Sensor Types)
      - Sensor Fusion
      - Scaled Metrology
- **Reconstruction: Scatteromery**
  - **Regularization**
    - **Optimization**
      - temporal &/or local Neighbourhood
      - iterative image reconstruction
  - **Model-Based**
    - **Data Bank Search**
      - **Model-based Metrology**
      - Recognition by Synthesis
      - Unification of Simulation & Experiment

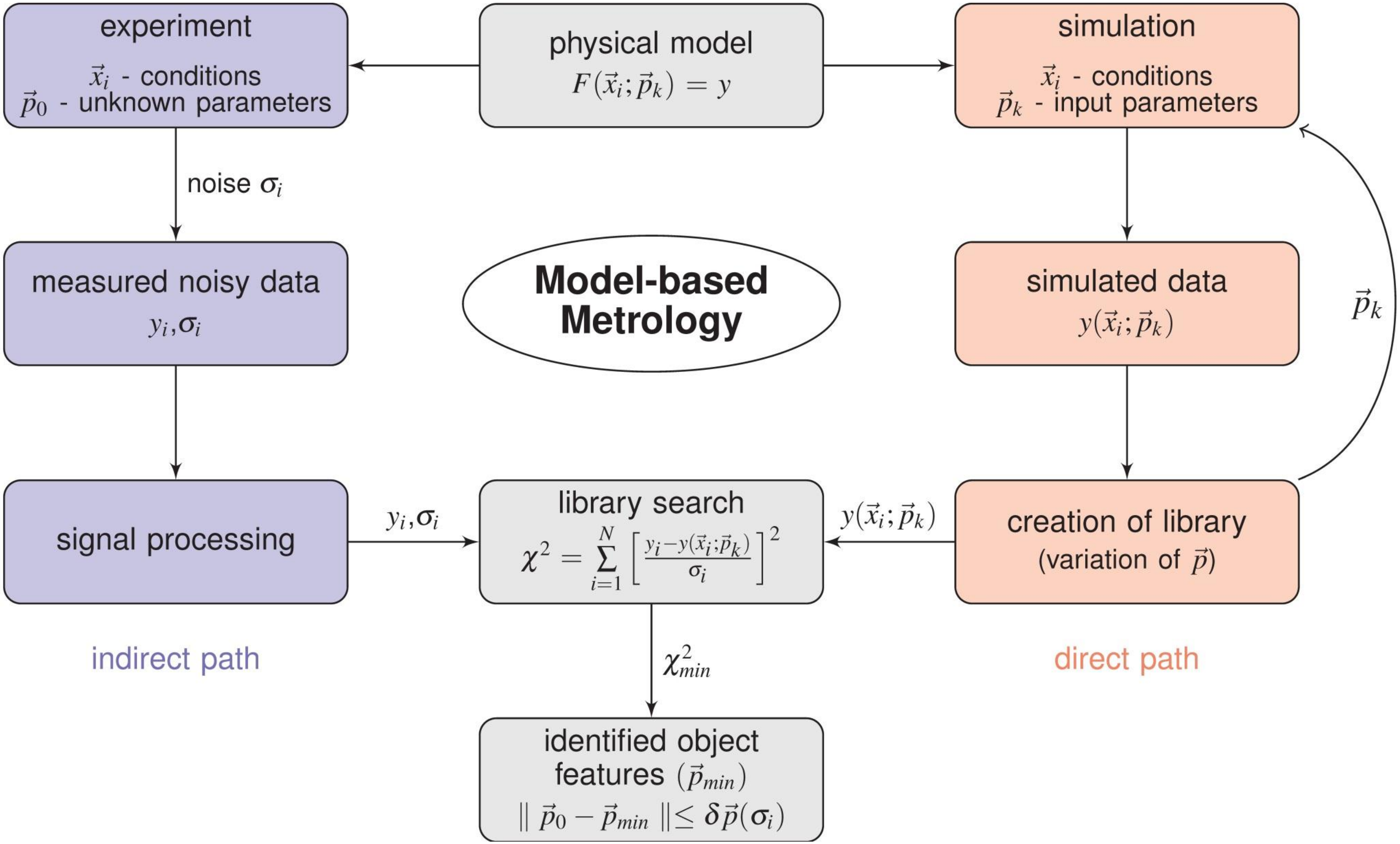
Model-Based Approaches: „*Hybrid Metrology*“



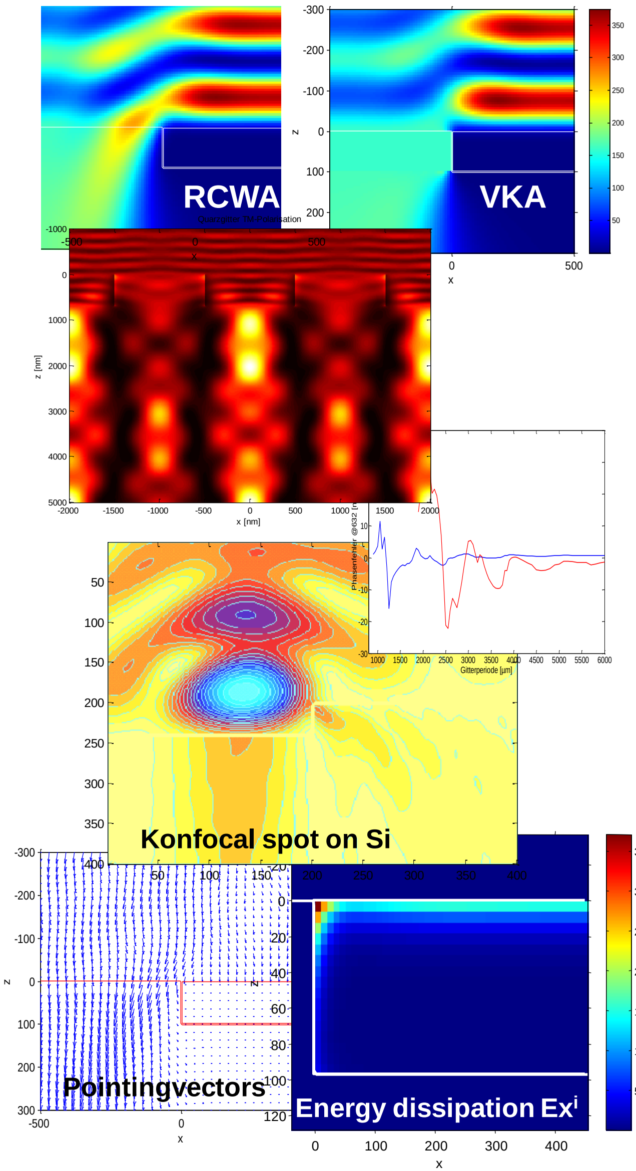
Measurement Strategy

Inverse Problem

Direct Problem



ITO Simulation Tool: MicroSim



Rigorous Computing of the Light-Object-Interaction

- RCWA, VKA, FDTD, FEM
- Rigorous Scattering Theory
- Diffractometry, Scatterometry, Digital Holography

Visualization of Near- and Farfield in 2D and 3D

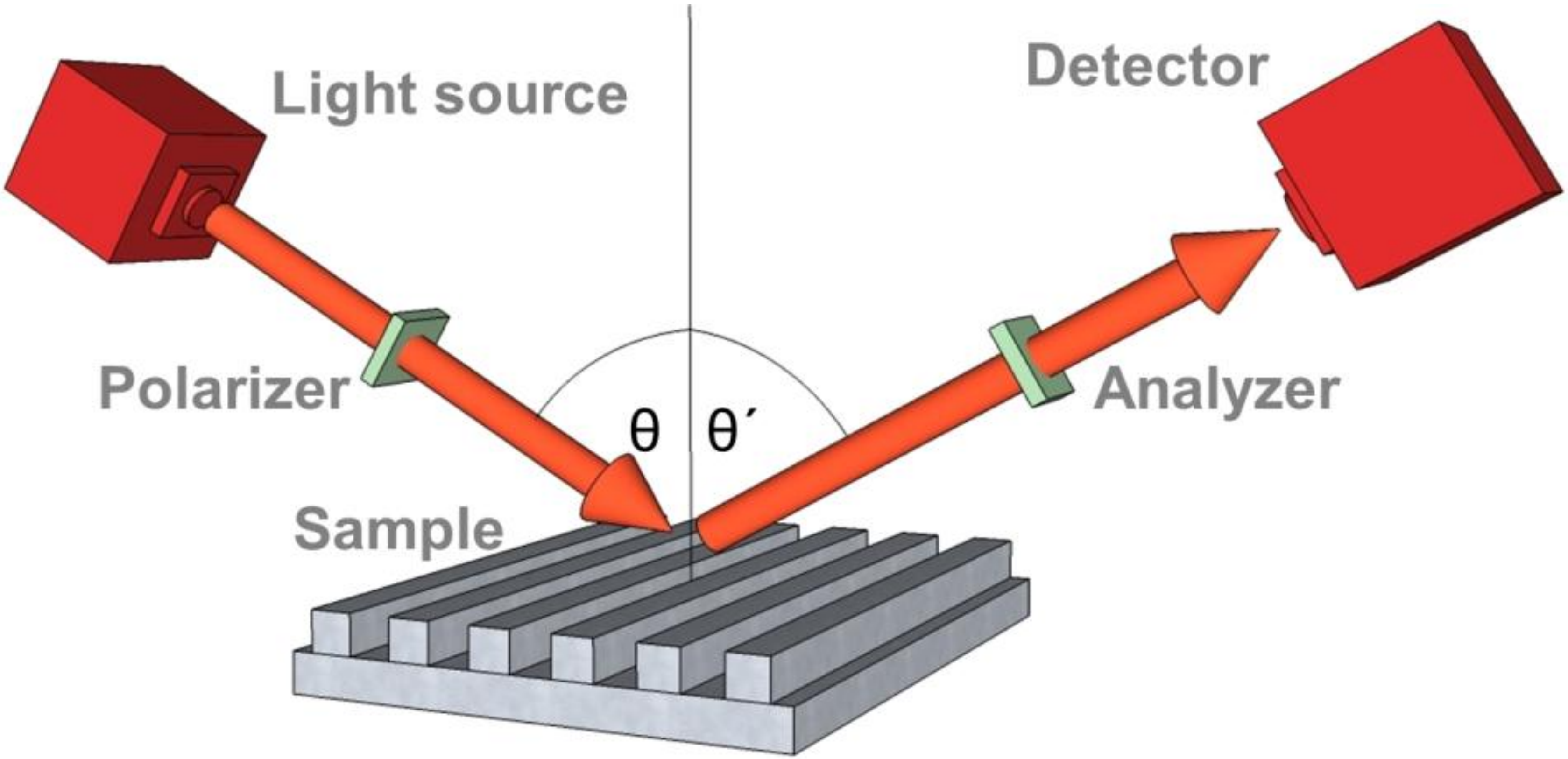
- Amplitude, Phase
- Vector Components
- Energy Dissipation, Pointing-Vectors

Simulation of Microscopic Imaging Process

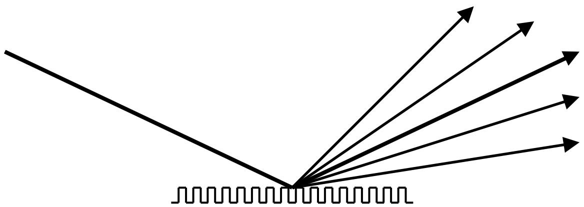
- Brightfield-Microscopy, Darkfield-Microscopy
- Interference Microscopy, Polarization Microscopy
- Quantitative Phase Contrast, DIC

Measurement Tool: Scatterometry

(polarization sensitive)

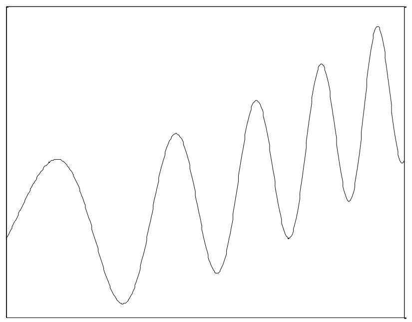


Measurement Principle



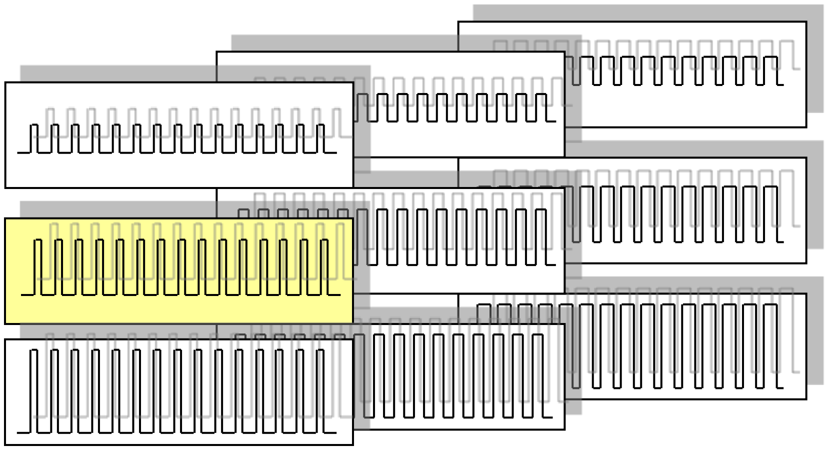
Diffraction (”Scattering")
with Polarization Signatures

Direct Problem

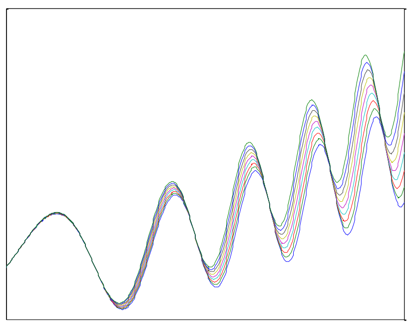


Spectra Simulation

Modeling of Structures
(having LER!)



Inverse Problem



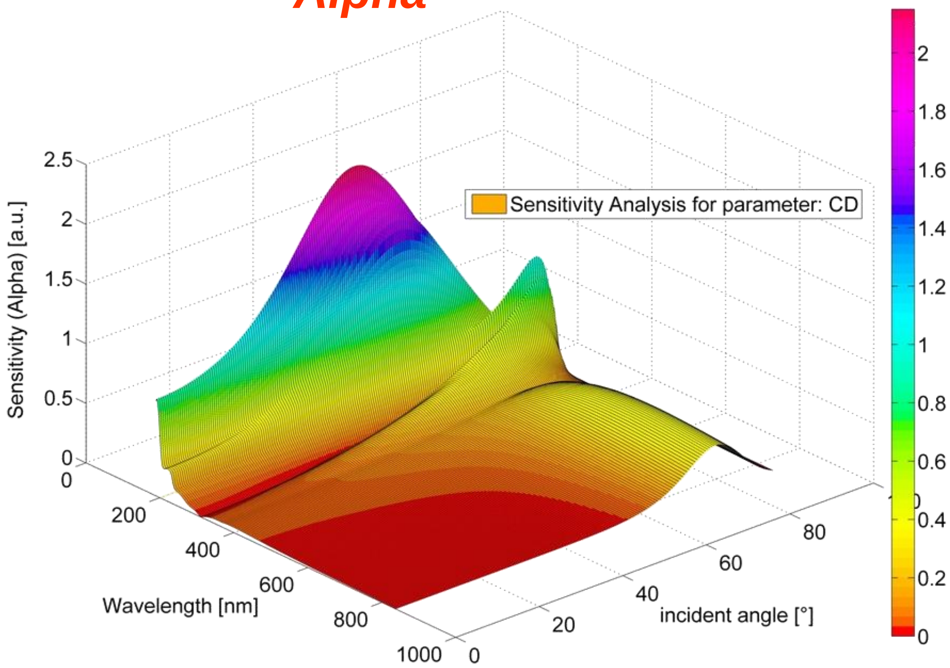
Parameter Influence/
Parameter Sensitivity

Performed Sensitivity Analysis

- **wavelength**: 190 nm – 840 nm in 1 nm steps
- **incident-angle:** 0° – 90° in 0.5° steps
- ellipsometric angles (alpha, beta)
- for all 3 structure types (dense lines: resist, etched, STI)
- parameters (CD, pitch, height, SWA,…)
- nodes: CD 75 nm ... CD 18 nm, in max. 6 nm steps

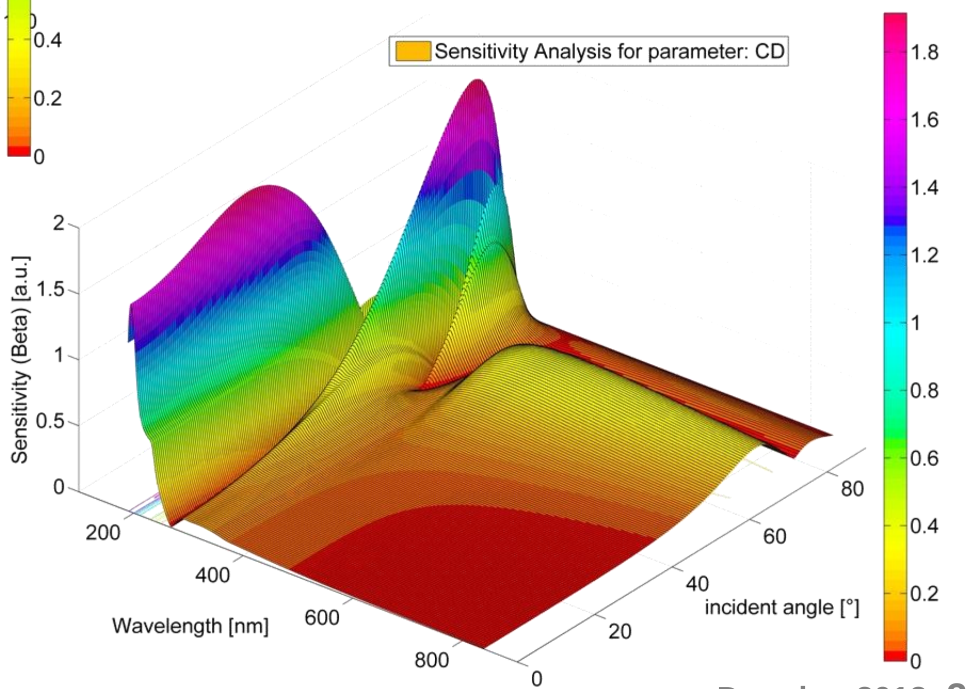
Sensitivity Analysis: Results

Alpha

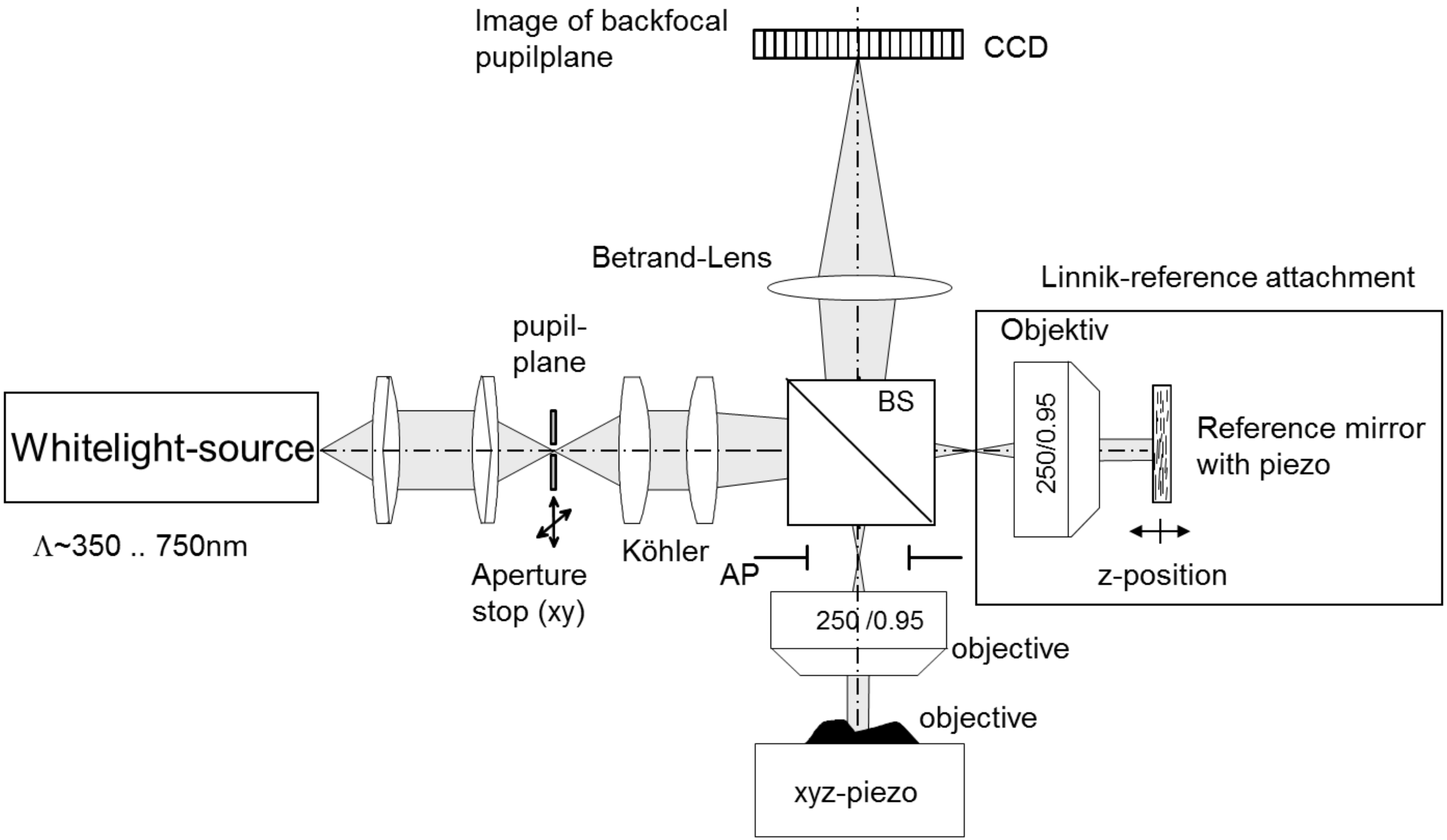


Example:
Resist Structures CD 36 nm

Beta

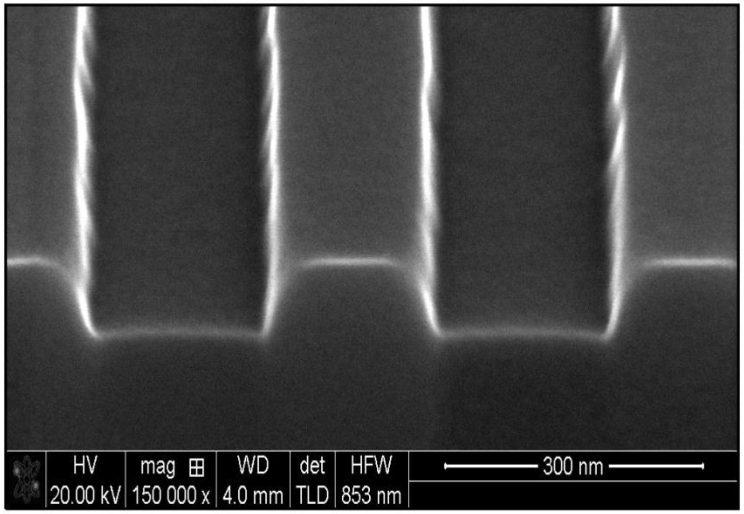


Scatterometry & Phase Sensitive Depth Measurement (White-Light-Interference-Fourier-Scatterometry)

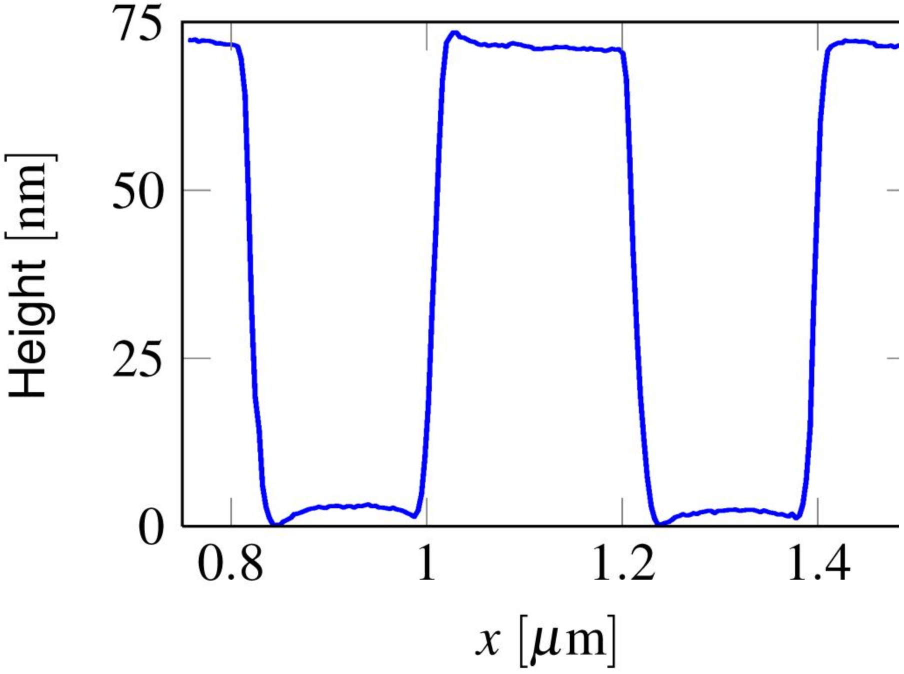


Structure measured with SEM & AFM

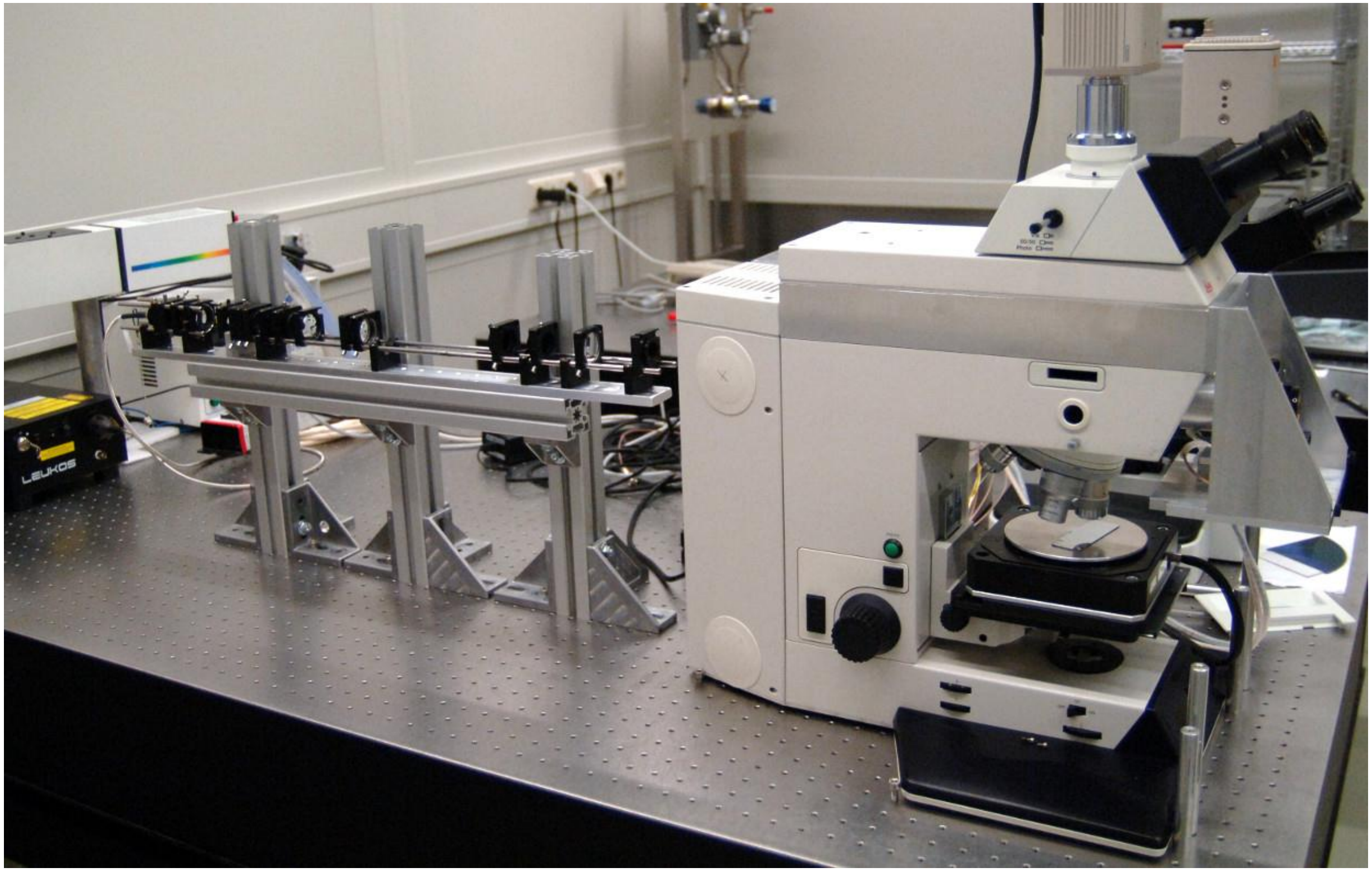
SEM



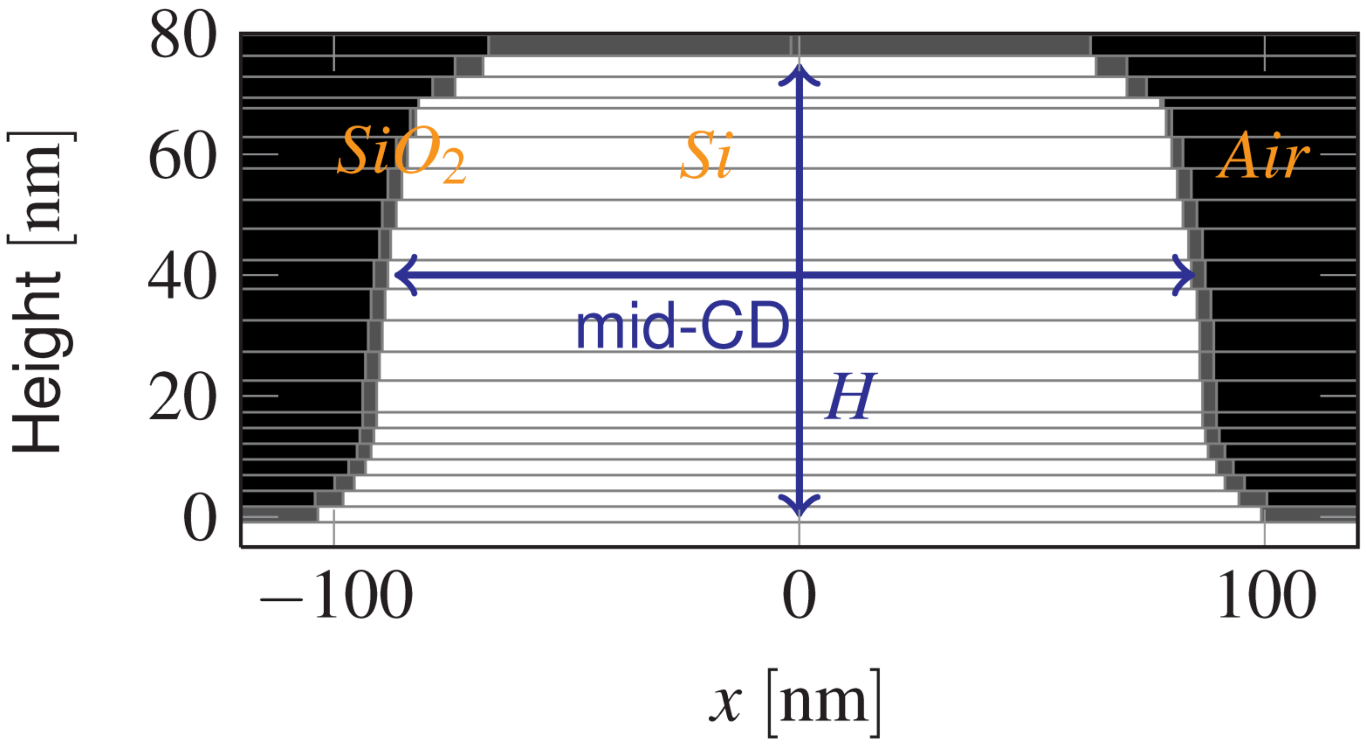
AFM



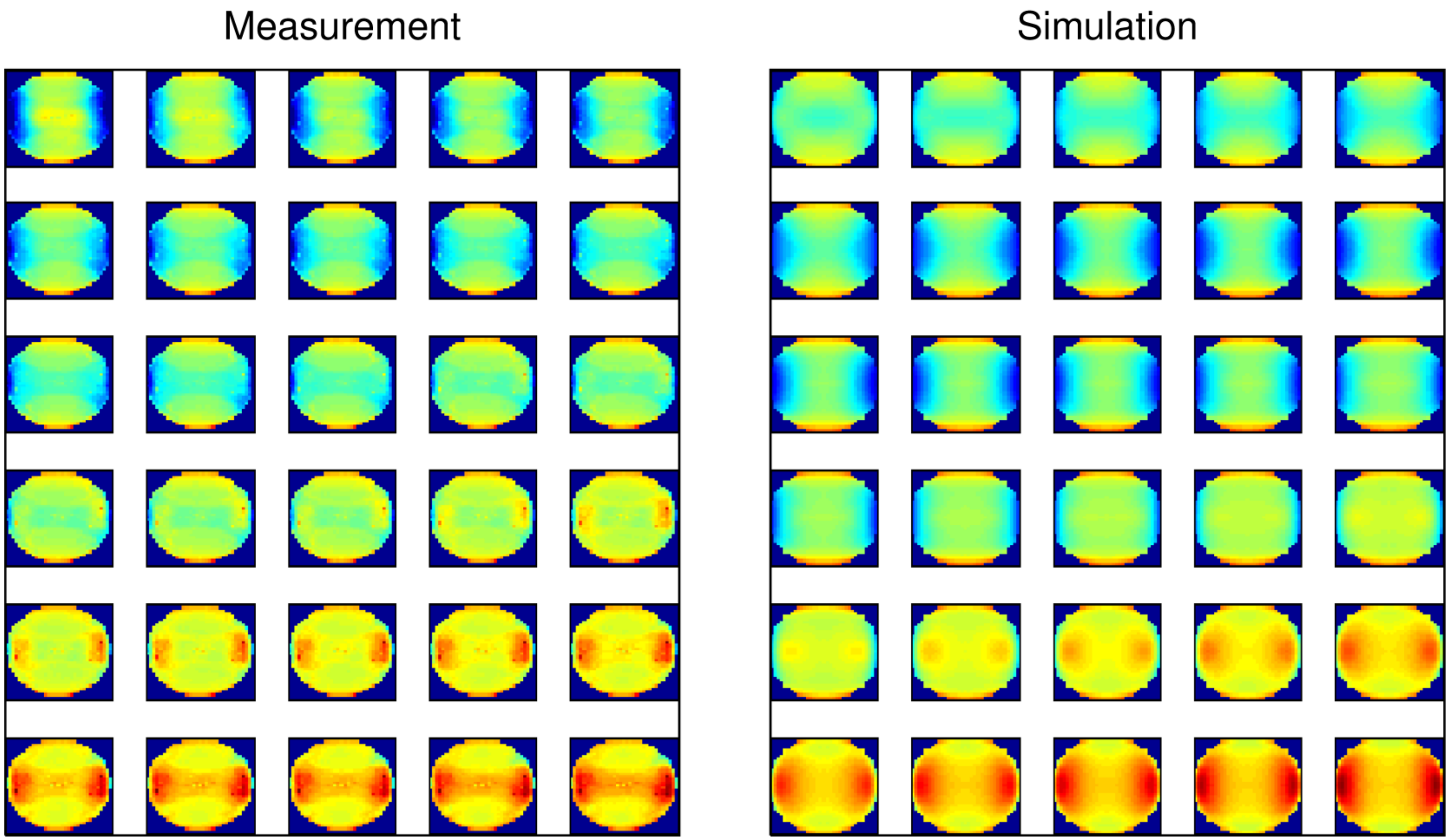
Experimental Setup



Structure Simulation



Measurement versus Simulation (Pupil images)



Example: Feature Reconstruction

Silicon Grating: CD=200nm

Parameter	Value SEM	Value AFM
Mid-CD	182±7 nm	-
Pitch	400±2 nm	400±2 nm
Height	76±9 nm	72±7 nm
SWA	77±3 nm	-

Reconstructed Parameters

Parameter	Reconstructed Value
Mid-CD	182 nm
Height	85 nm
SWA	77,5 nm

Outlook

Resolution Enhanced Technologies RET

- **RET Strategies**
  - **Imaging: Microscopy**
    - **Single Sensor**
      - **Conventional** (Diffraction Limited)
        - λ
        - NA
        - κ1, κ2, κ3
        - „*Super-Resolution*“:
        - image sequence
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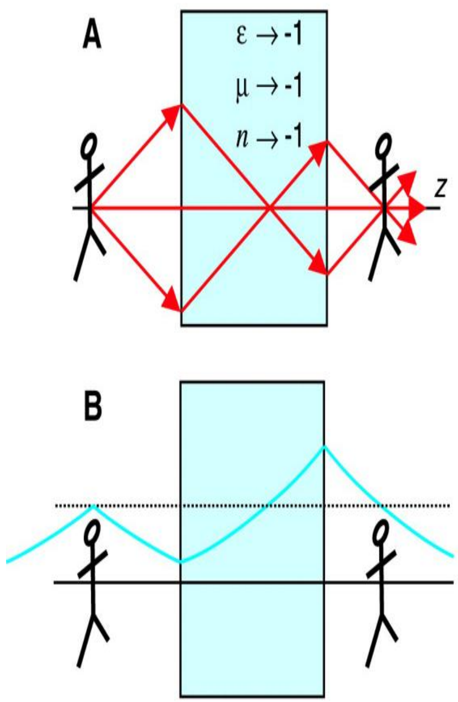
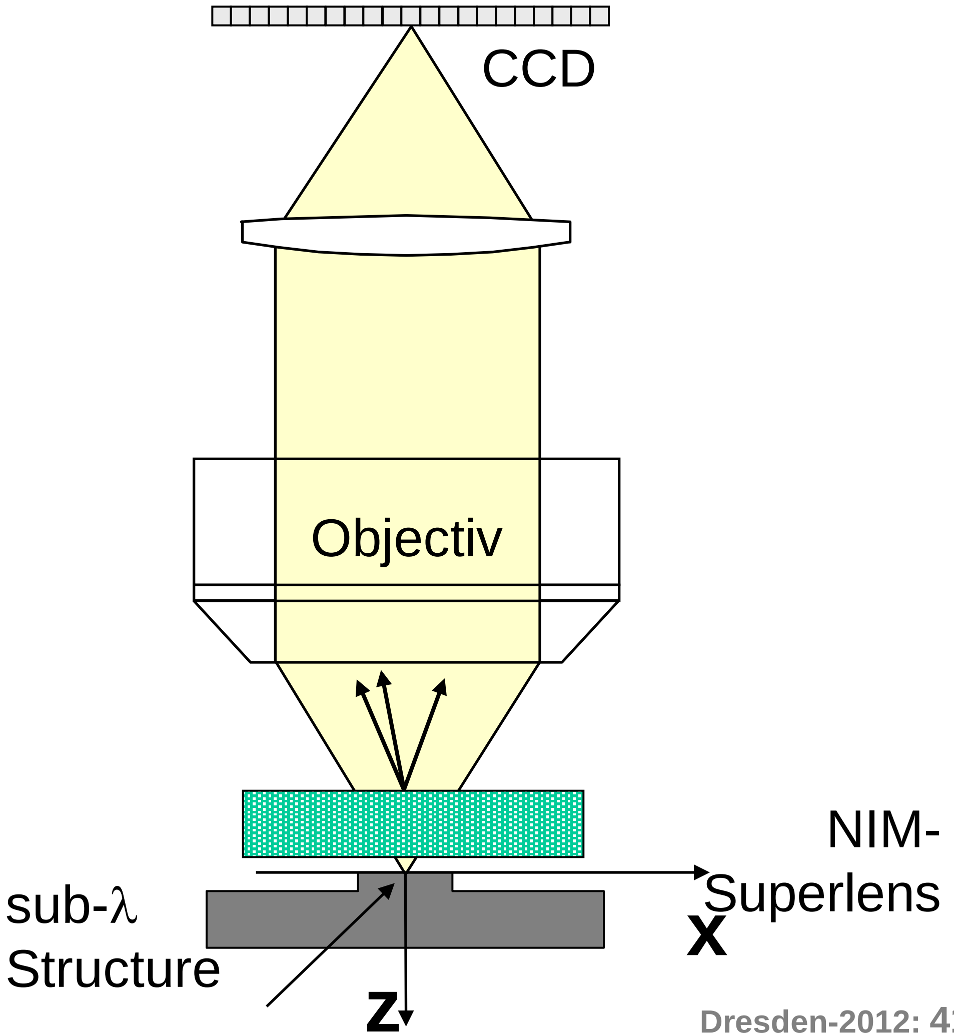
    - **Model-Based**
      - **Data Bank Search**
        - Model-based Metrology
        - Recognition by Synthesis
        - Unification of Simulation & Experiment

Resolution Enhancement of Imaging Systems using a „Superlense“ made of Metamaterials (NIM)

Objective: Optical Microscopy of Nano-Structure

Pendrys ideal NIM-Lens

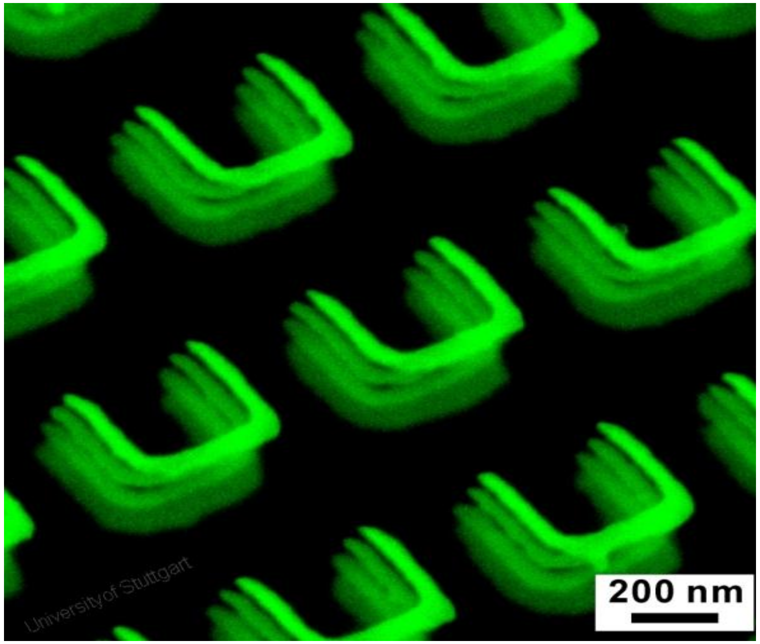




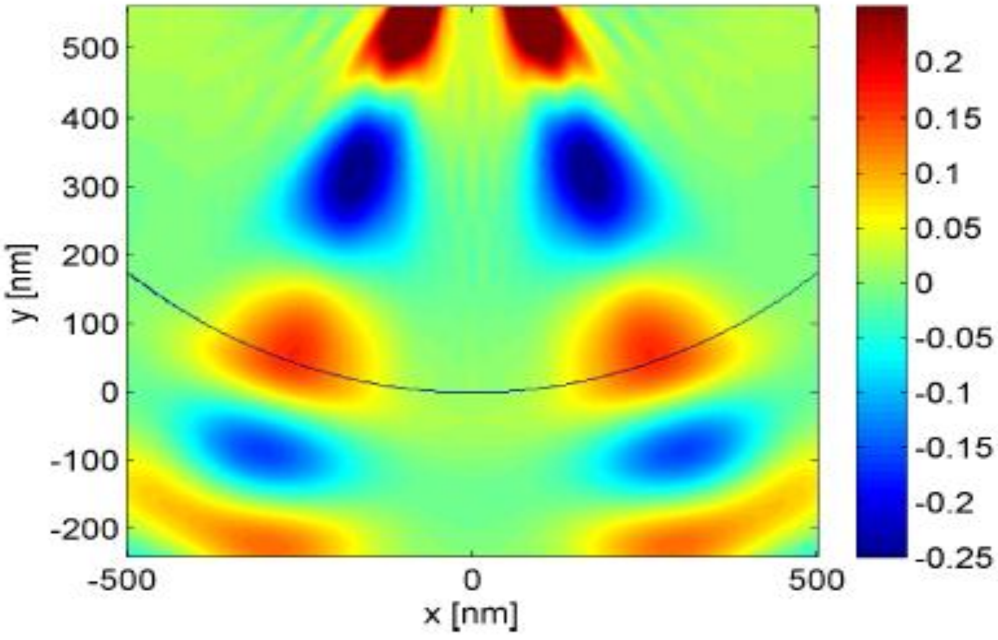
Meta-Material + Special Superlattice

Hyperlense-Imaging

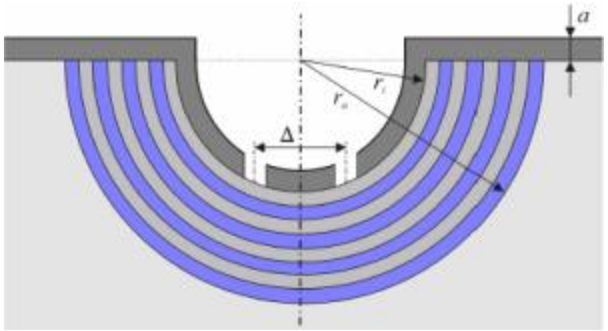
Negative Index (Meta-)Materials



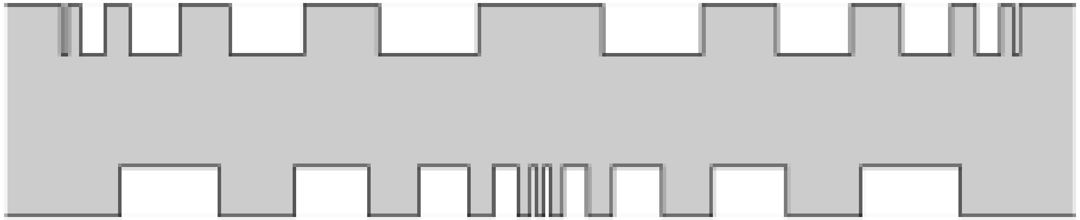
Far Field Propagation

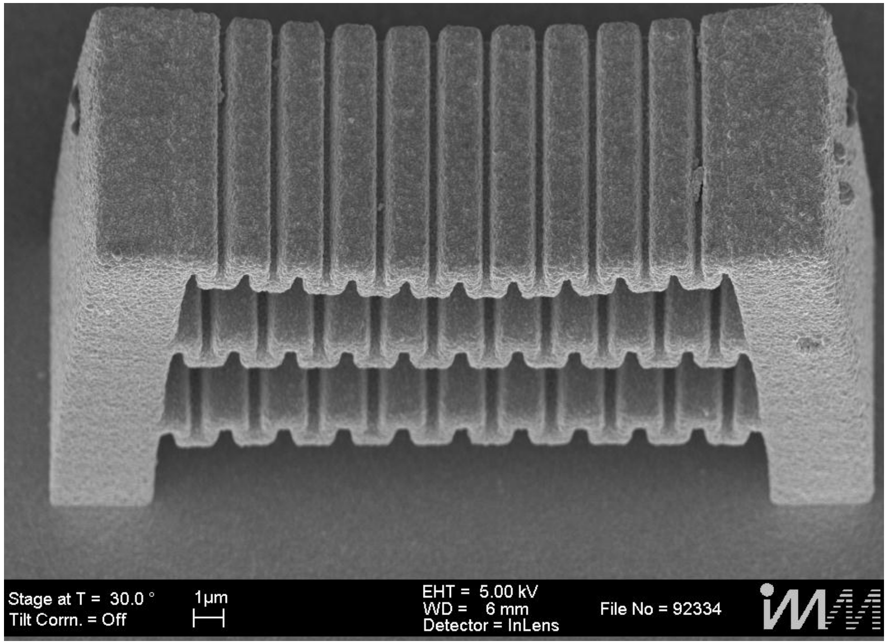


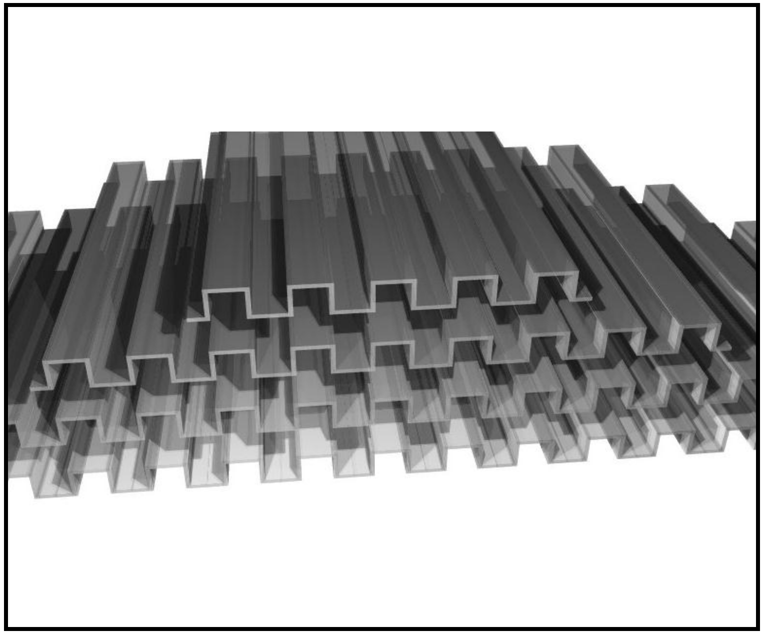
Special Superlattices



ITO & 4PI: Double-Meander Structures







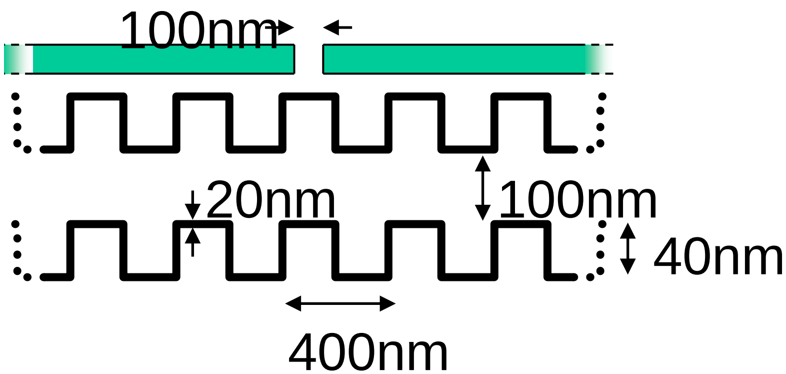
<u>Objective</u>: Realization of a **Perfect Lens**
(Propagat. of Modes with high Impulse, ‘Amplification’ of Evanes-zent Modes)

Step 1: Realization by ‘Waveguiding Structures’ for Surface Waves

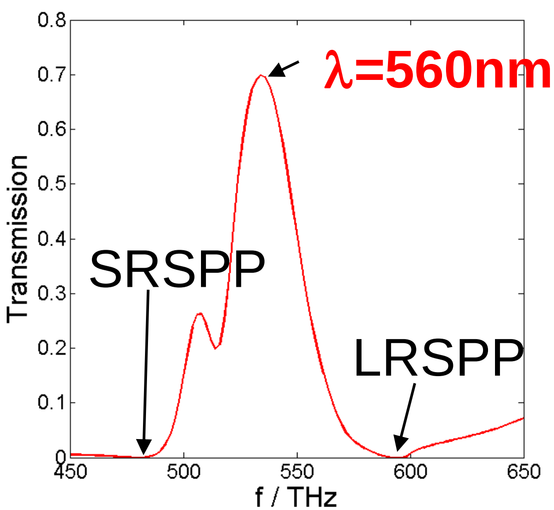
Step 2: Transformation into the Farfield,
Realization e.g. by Envelope-Structure/Surface of the **Hyperlense**

Imaging by Double-Meander-Structures:

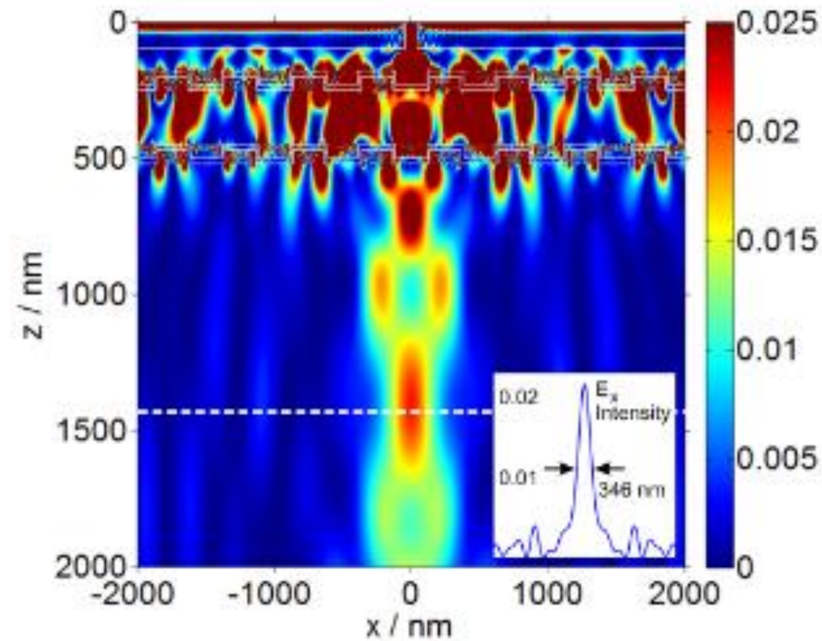
Simulated Structure:

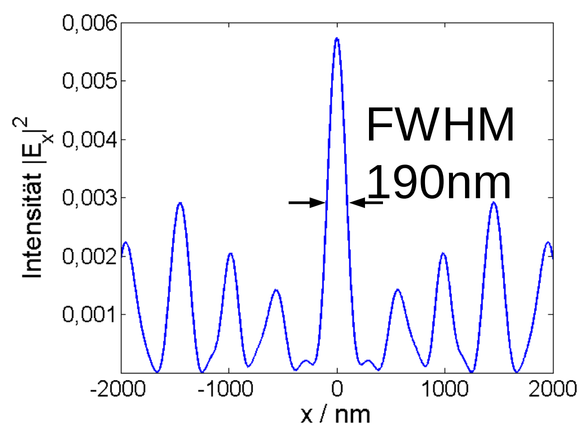


Bandpass:



sub-lambda imaging





Schau et al: Opt. Express, Jan. 2011