Optical Metrology in Nanofabrication

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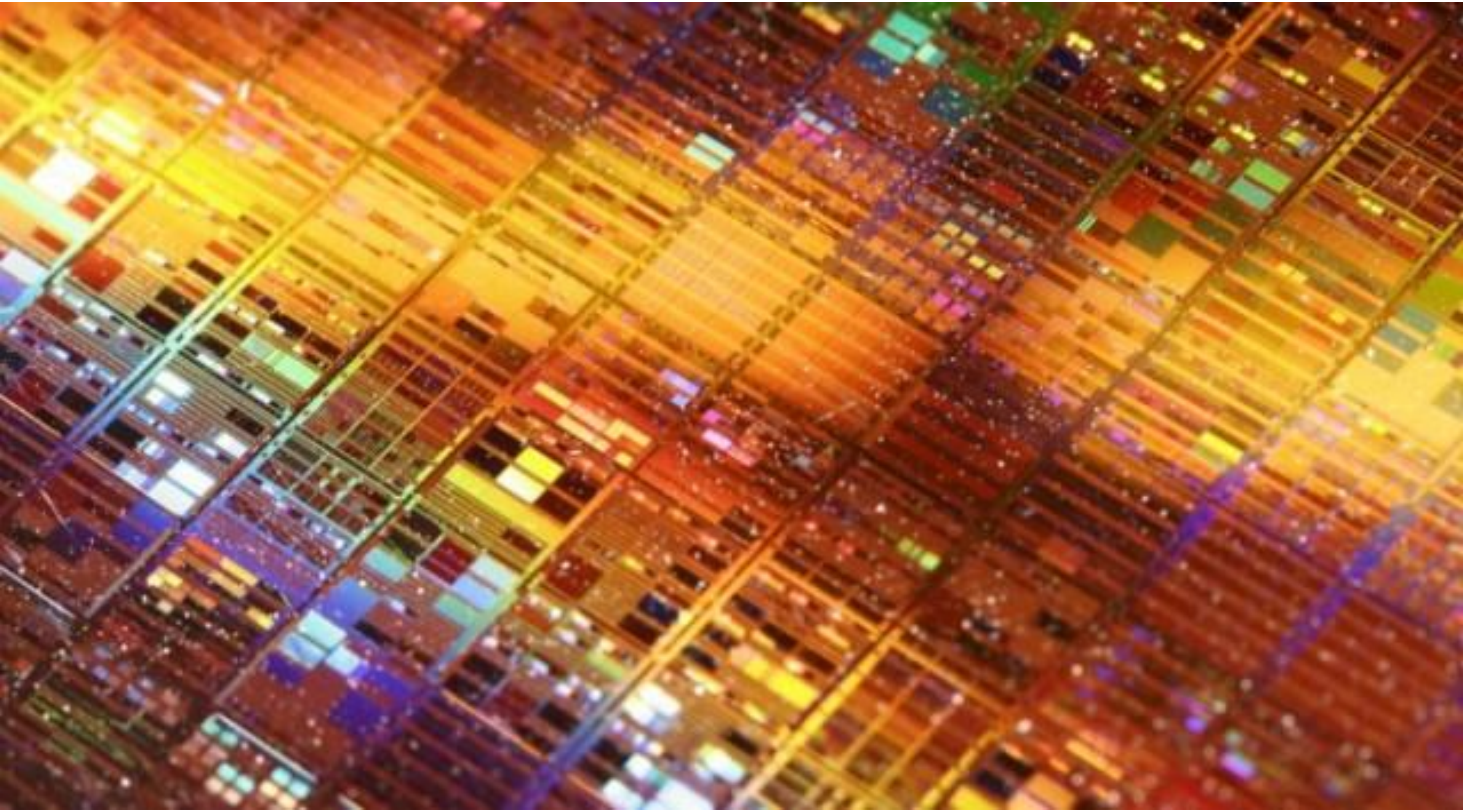
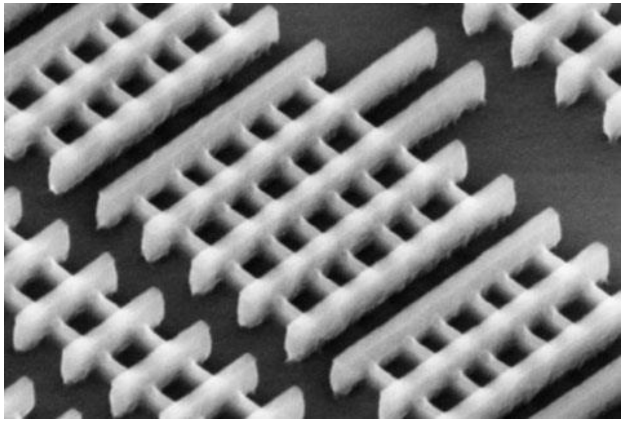
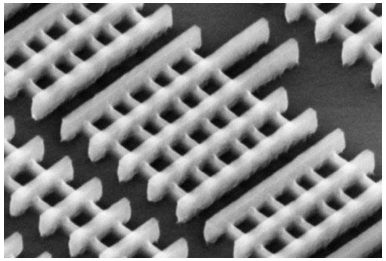
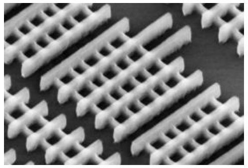
Patrons: Generalitat de Catalunya, CSIC, UAB Universitat Autònoma de Barcelona
Member of: BIST Barcelona Institute of Science and Technology, Institució CERCA Centres de Recerca de Catalunya



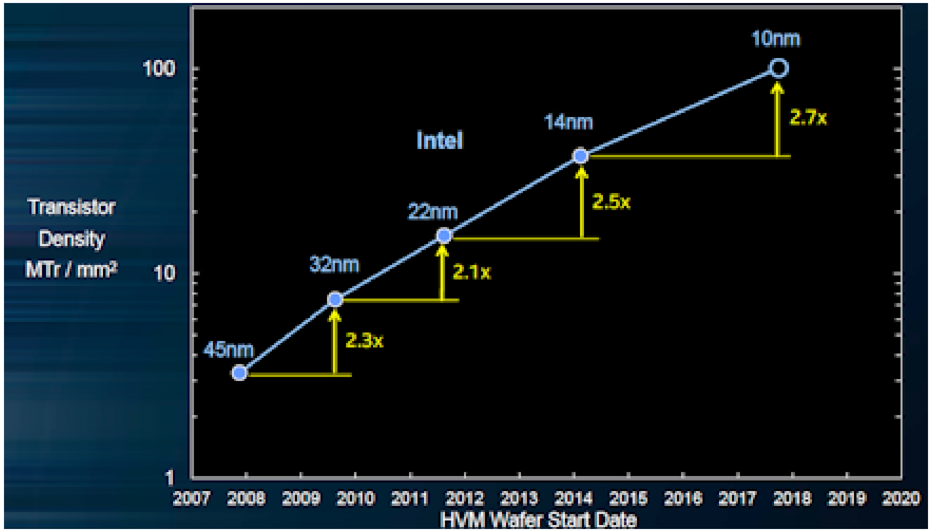
Why Metrology?

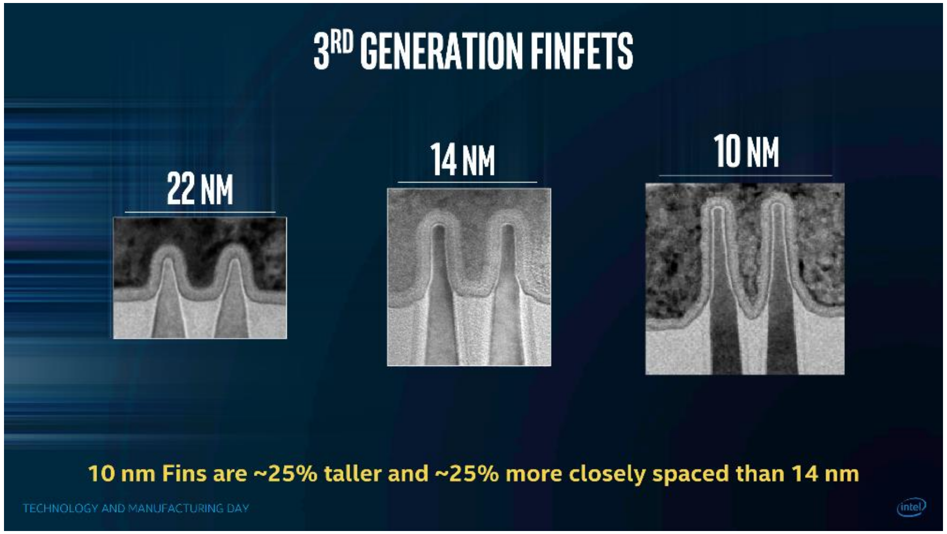






Logic Transistor Density



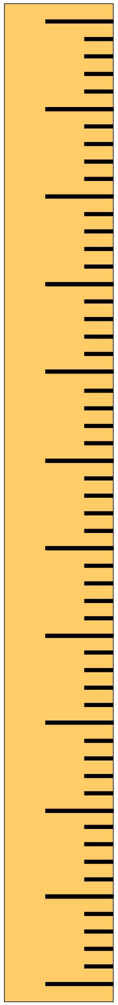


International Roadmap for Devices and Systems, Metrology (2017)

Overview

- Overview of Metrology
- Metrology in Nanofabrication
- Optical Scatterometry
- Inverse Problem Solving
- Case Study : Diffractometry for roll-to-roll microstructured films

Overview



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Metrology Introduction

“ When you can measure what you are speaking about and express it in numbers you know something about it; but when you can not express it in numbers your knowledge is of a meagre and unsatisfactory kind” – Lord Kelvin (1824 – 1907)

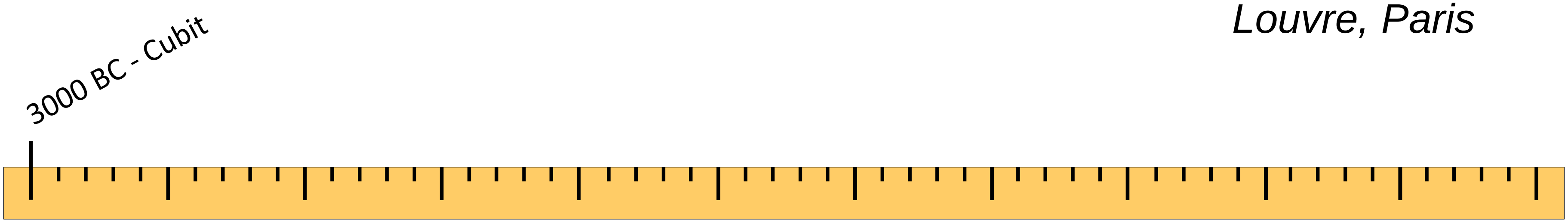
Metrology

- Defining of Standard Units (e.g. m, s, Kg etc.)
- Traceability
- Practical Measuring Devices (e.g. microscope, SEM, ruler etc.)

Measuring by the Body – The Cubit

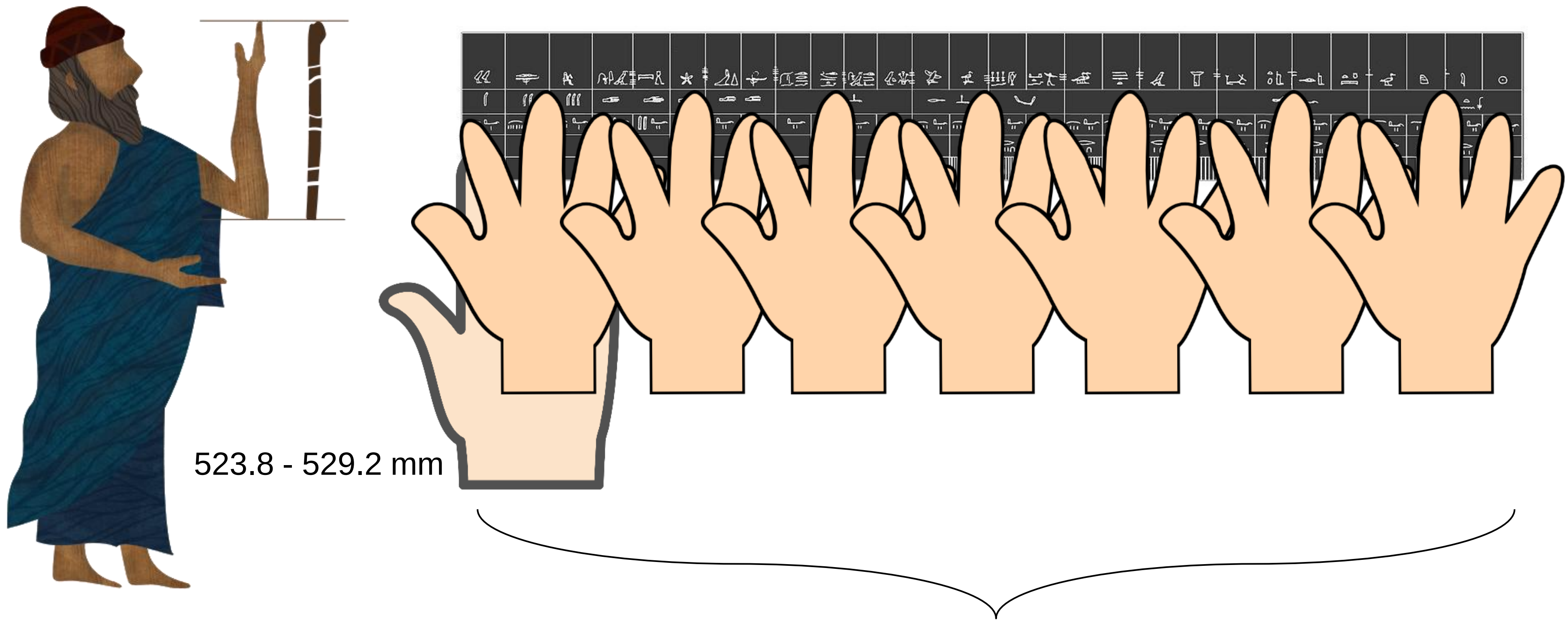
523.8 - 529.2 mm

Louvre, Paris

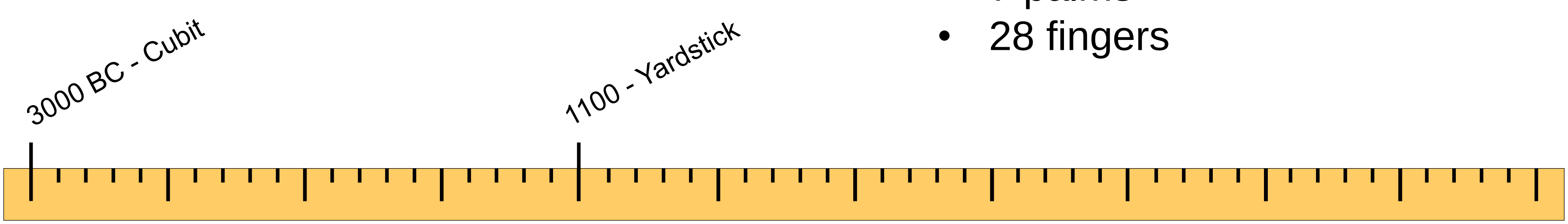


www.npl.co.uk/educate-explore/factsheets/history-of-length-measurement/

Measuring by the Body – The Cubit



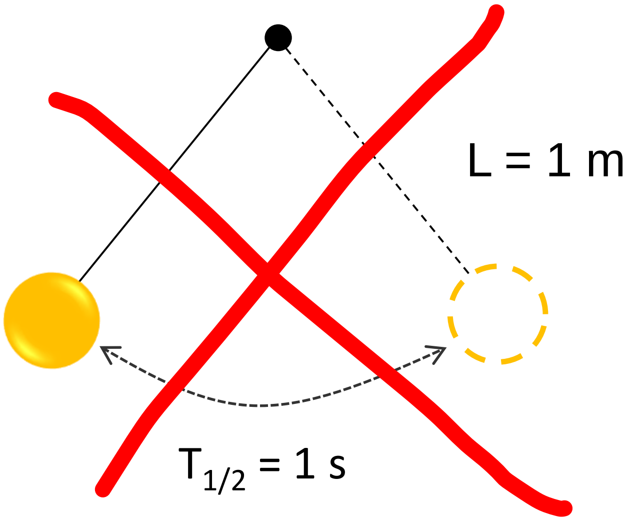
- 7 palms
- 28 fingers



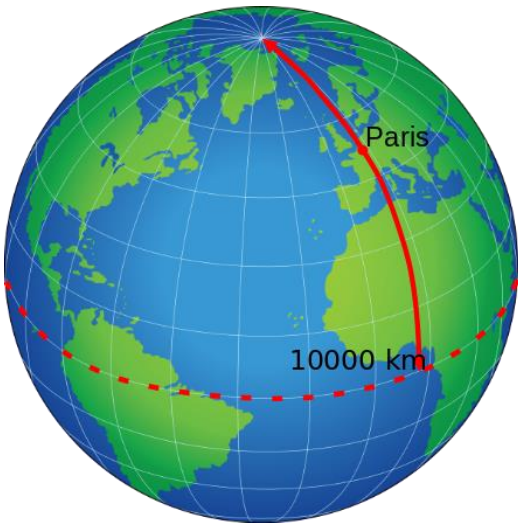
www.npl.co.uk/educate-explore/factsheets/history-of-length-measurement/

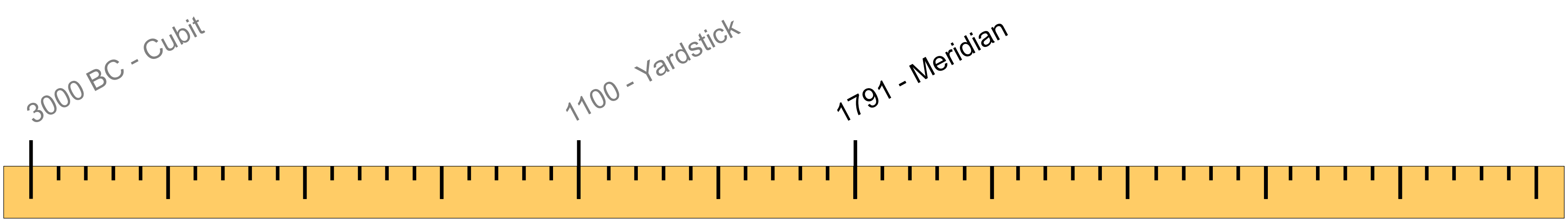
Meridian Definition

Pendular Definition



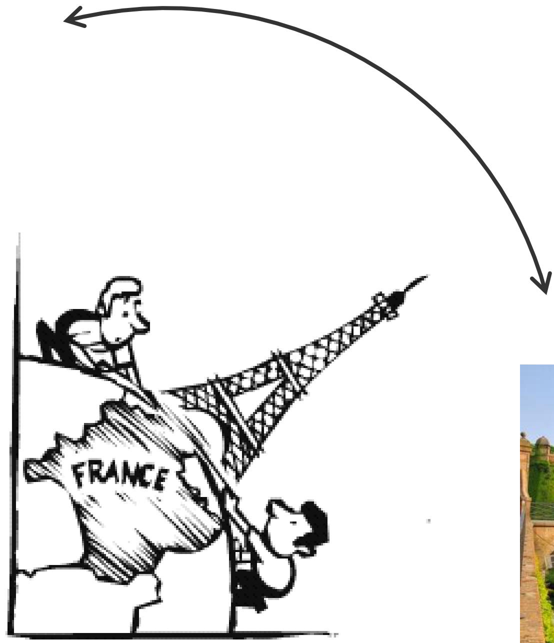
Meridian Definition



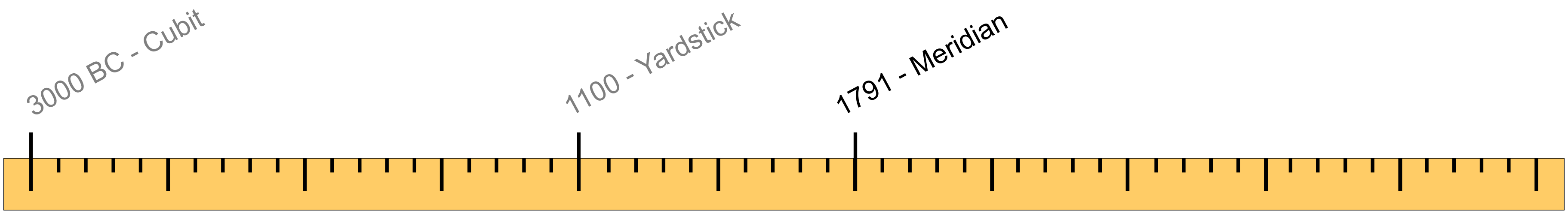


The Polar Quadrant Survey

Belfry of Dunkirk

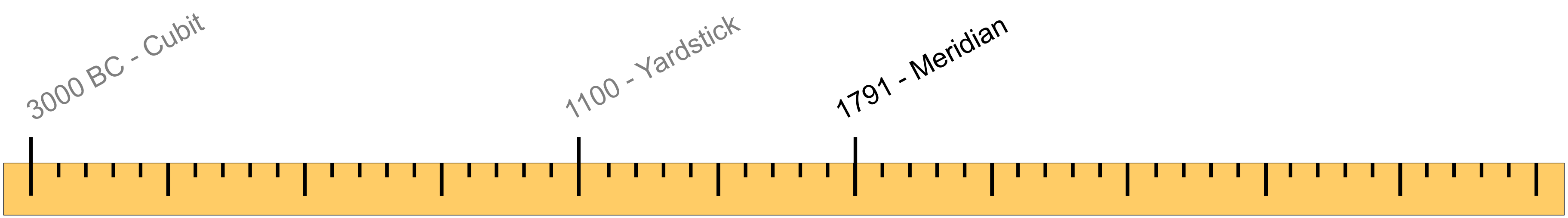


Castell de Montjuïc, Barcelona



www.npl.co.uk/educate-explore/factsheets/history-of-length-measurement/

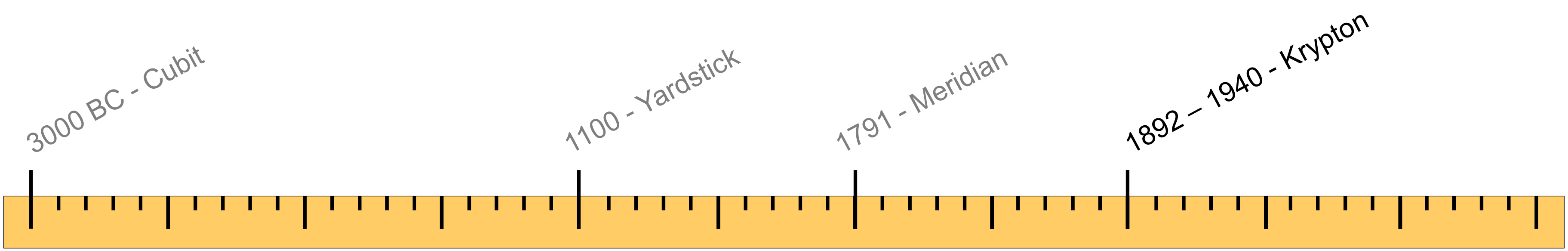
Mètre des Archives



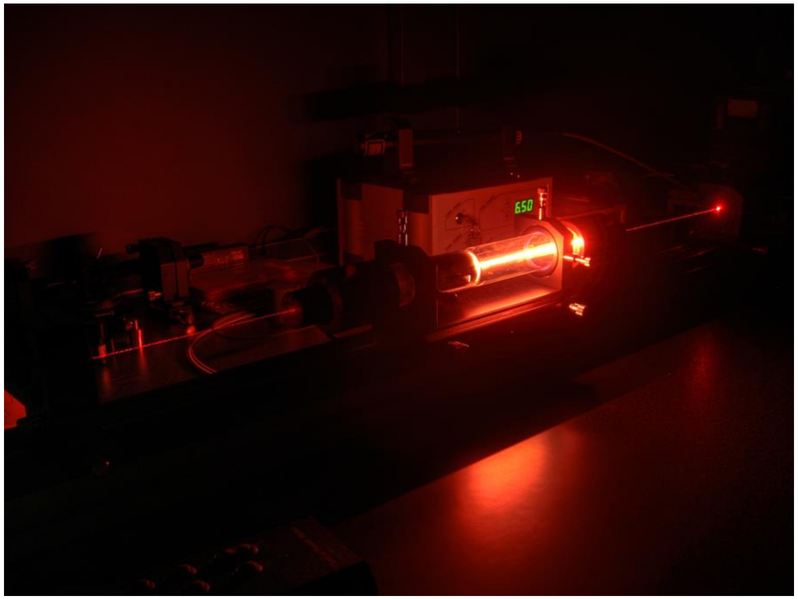
Krypton Lamp

Q: How many 605 nm wavelengths are in a metre?

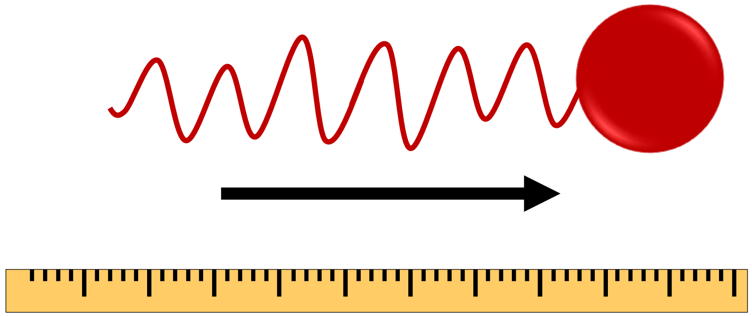
A: 1 650 763.73



Iodine-stabalised He-Ne Laser

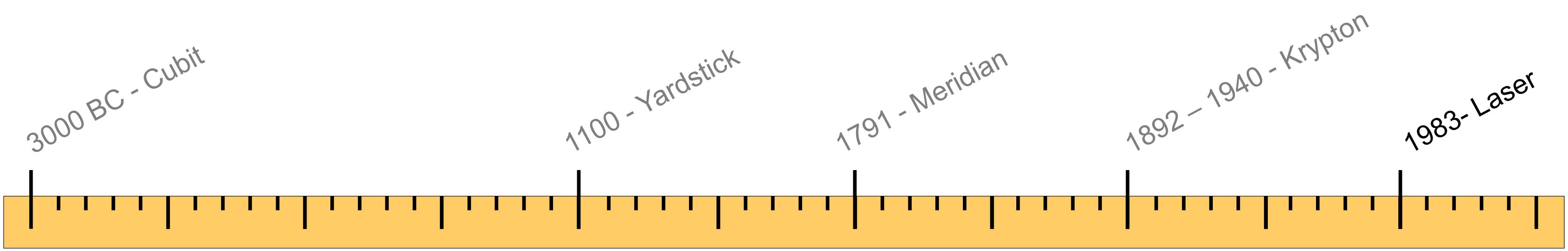


1 m =



t = 1/299 792 458 s

~ 3.33 ns



Metrology

Metrology

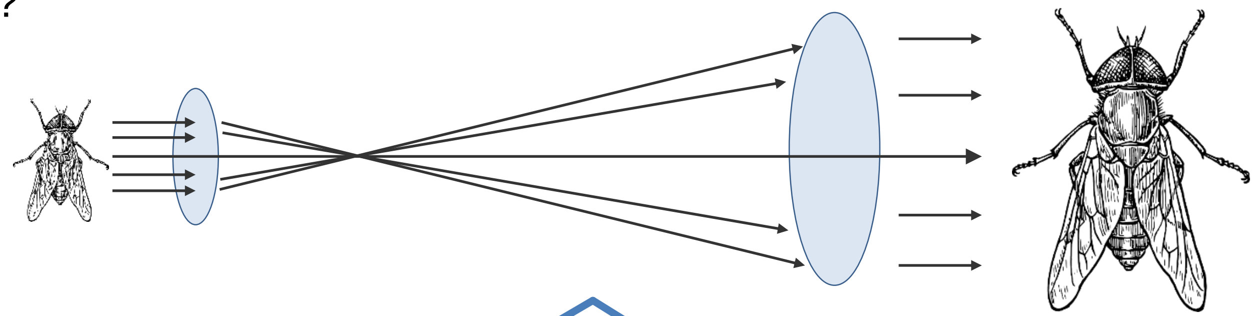
- Defining of Standard Units
- Traceability
- Practical Measuring Devices

What has been the most importnat invention?

Eric Betzig

Brief History of Optics

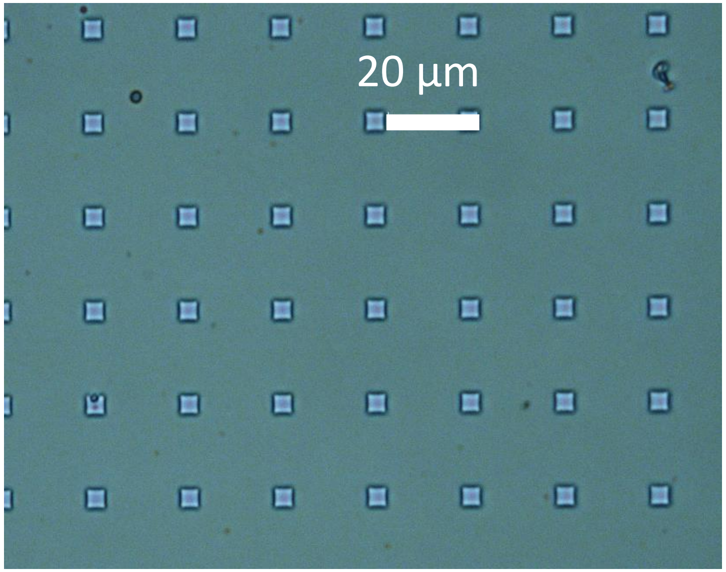
Compound Lens System ~ 1600
Inventor = ?

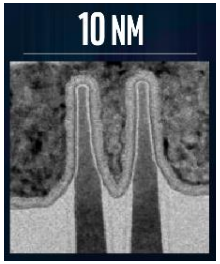


Microscopes

Telescopes

Modern Microscopy



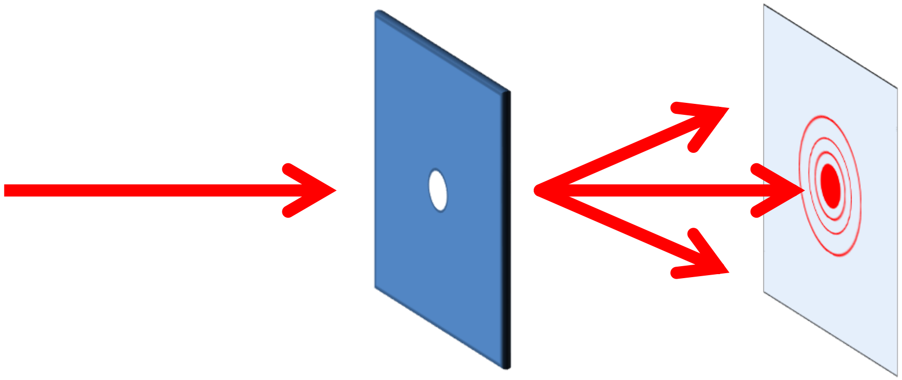


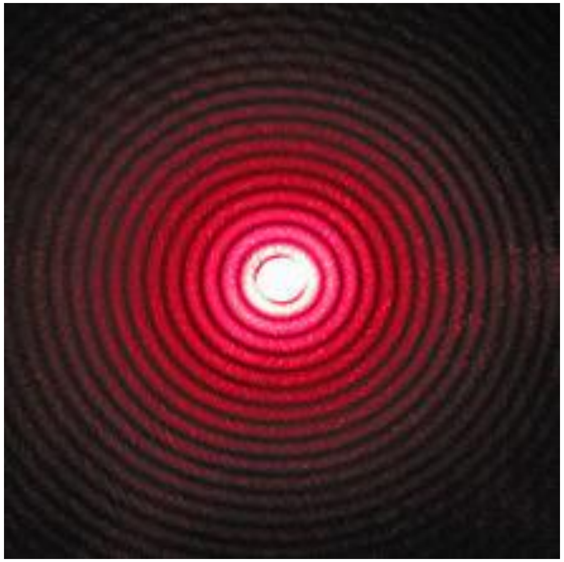
Virus ~ 100 nm
Proteins ~ 10 nm

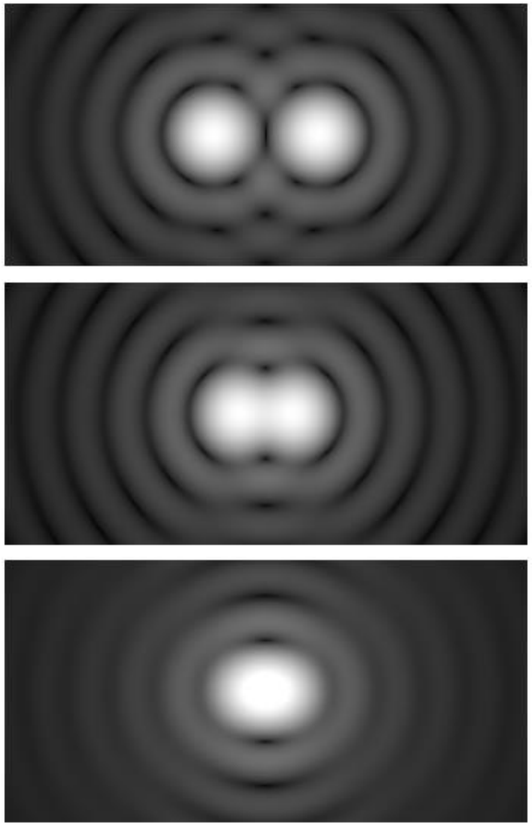
Modern Transistors ~ 20 nm

Diffraction Limit

Airy Disk





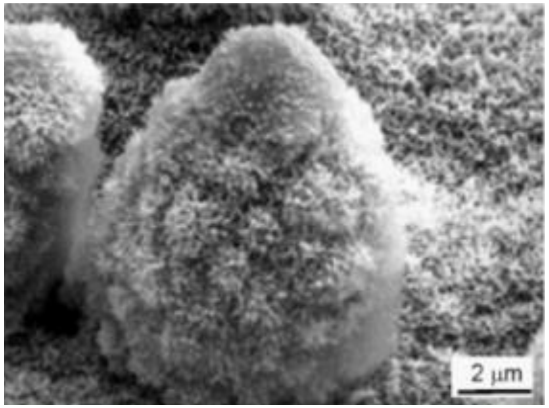


$$r = \frac{0.61\,\lambda}{NA} \approx \frac{\lambda}{2}$$

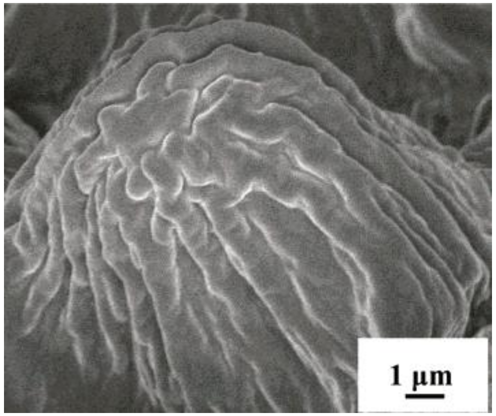
Scanning Electron Microscope (SEM)

Bio Hydrophobic Surfaces

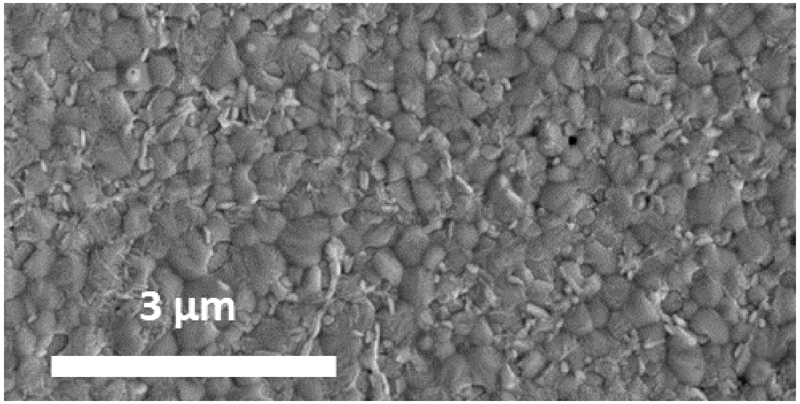
Lotus Leaf

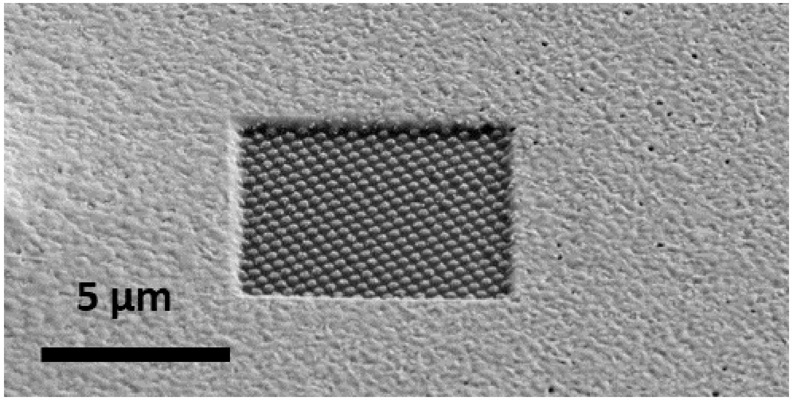


Rose Petal

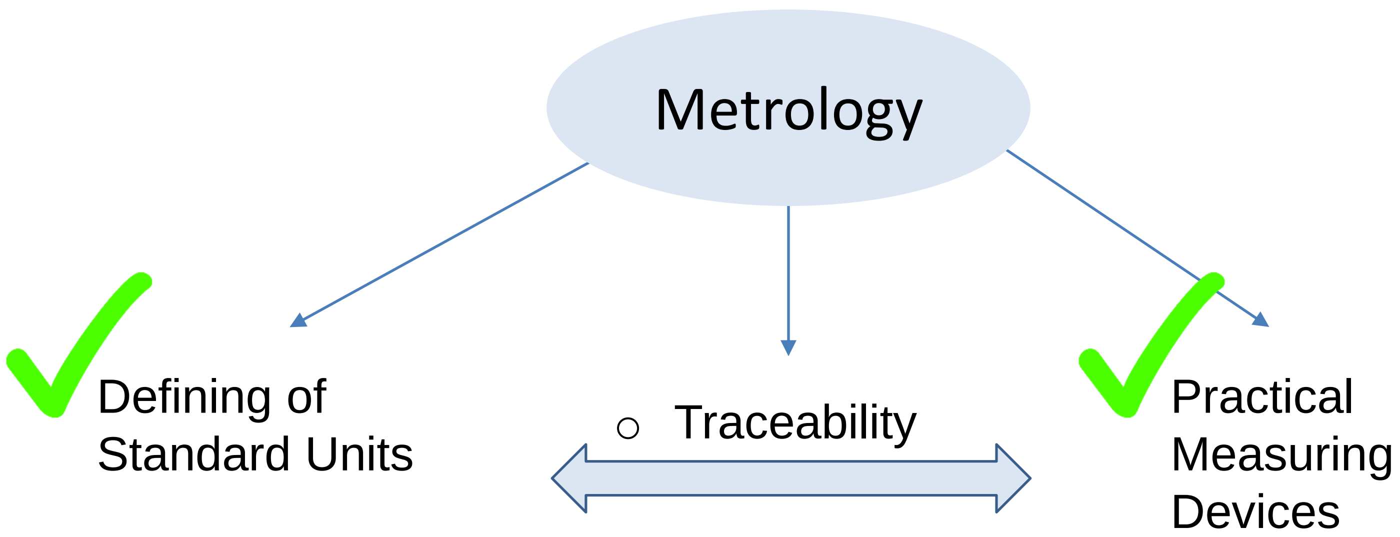


Perovskite DFB Lasers





Metrology



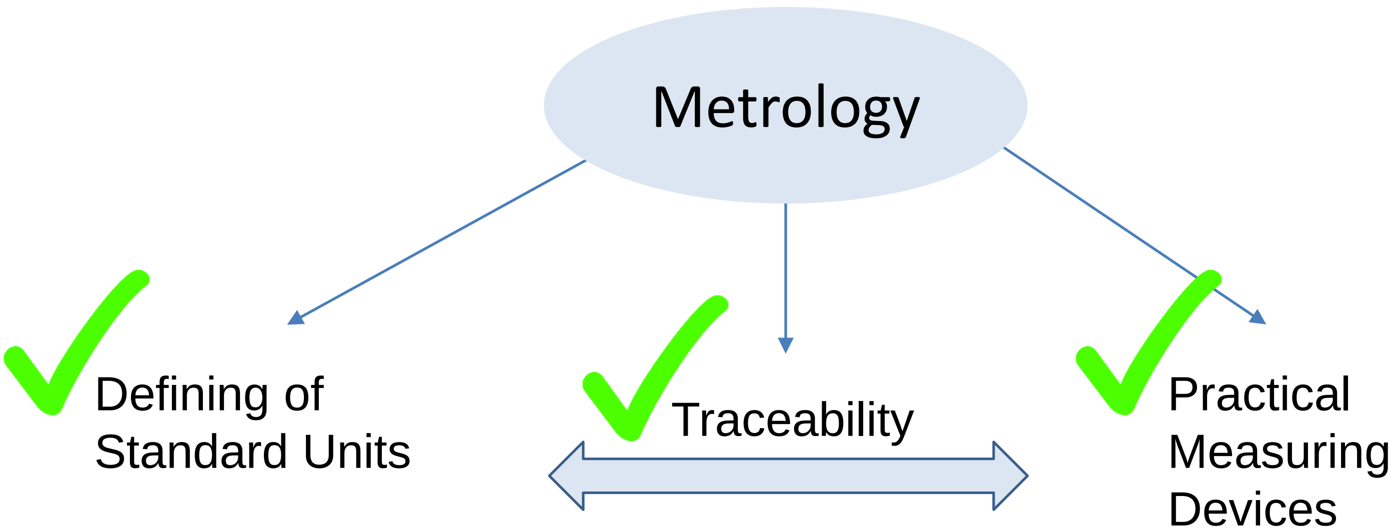
Metrology
Defining of Standard Units
Traceability
Practical Measuring Devices

Traceability

SI Unit		m
International/National Standard	0.001 %	$\frac{1}{299\,792\,458}\ s$
Calibration Laboratory/ Reference Standard	0.01 %	Micrometer Dial (Primary)
In-house Calibration/ Working Standard	0.05 %	Micrometer Dial (Secondary)
Company´s Equipment	0.1%	Calibration Step
Final Product	1%	Microscope

www.npl.co.uk/educate-explore/factsheets/traceability-and-uncertainty/

Metrology


Metrology
Defining of
Standard Units
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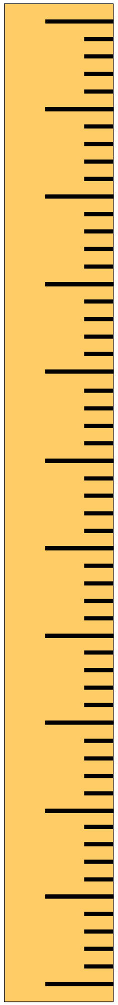
Measuring
Devices

Overview



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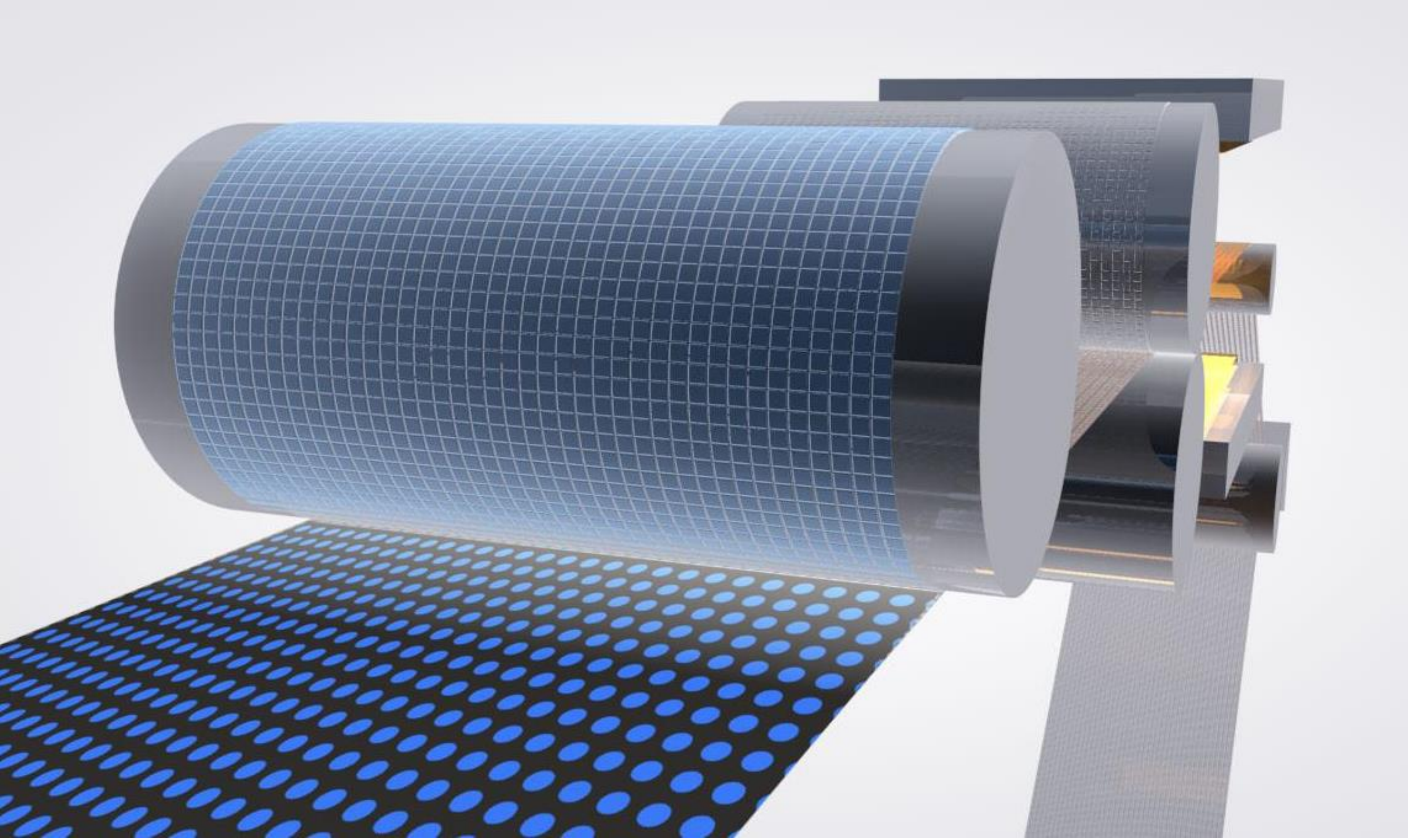
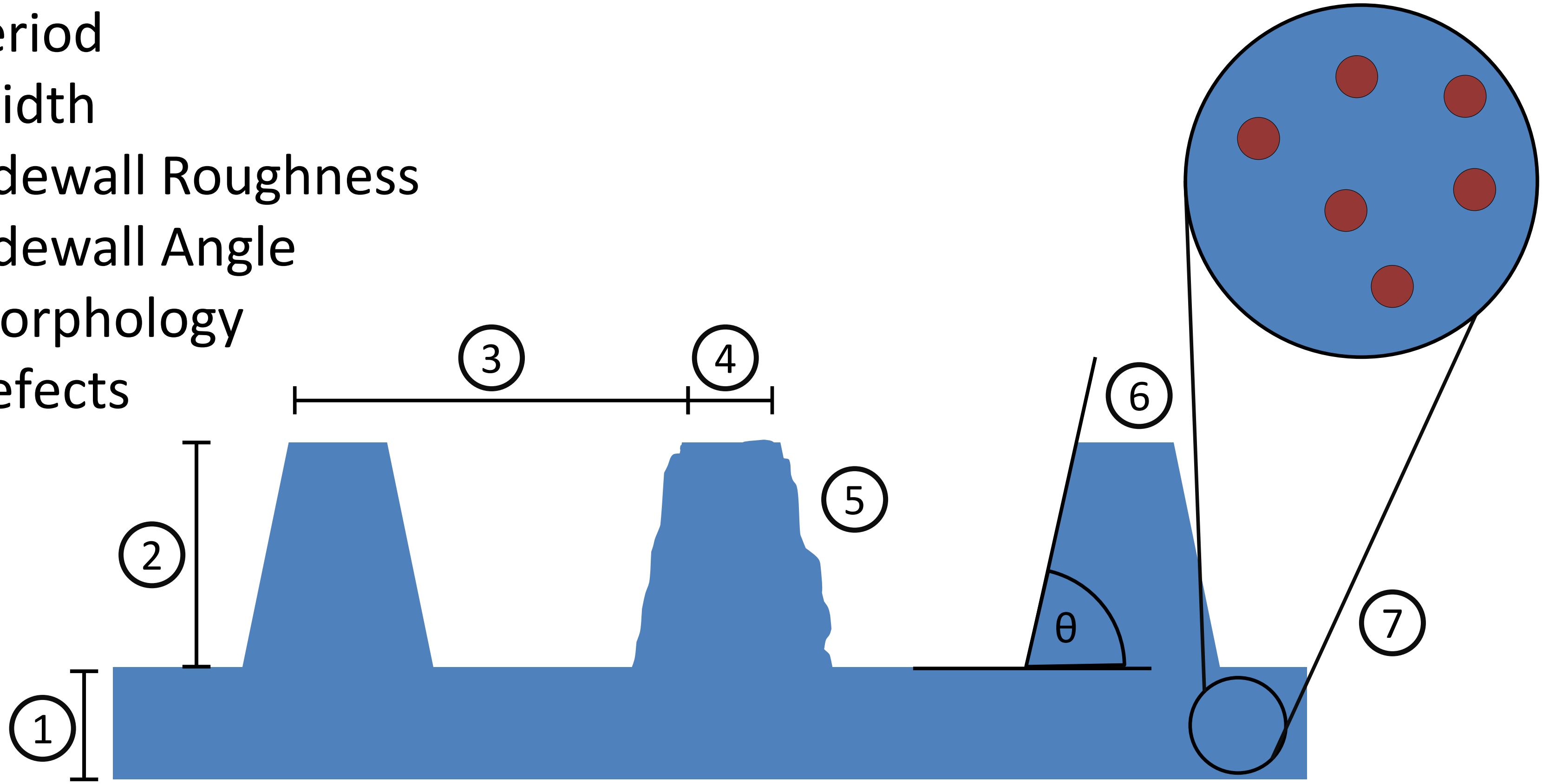
High Throughput Roll-to-Roll Printing



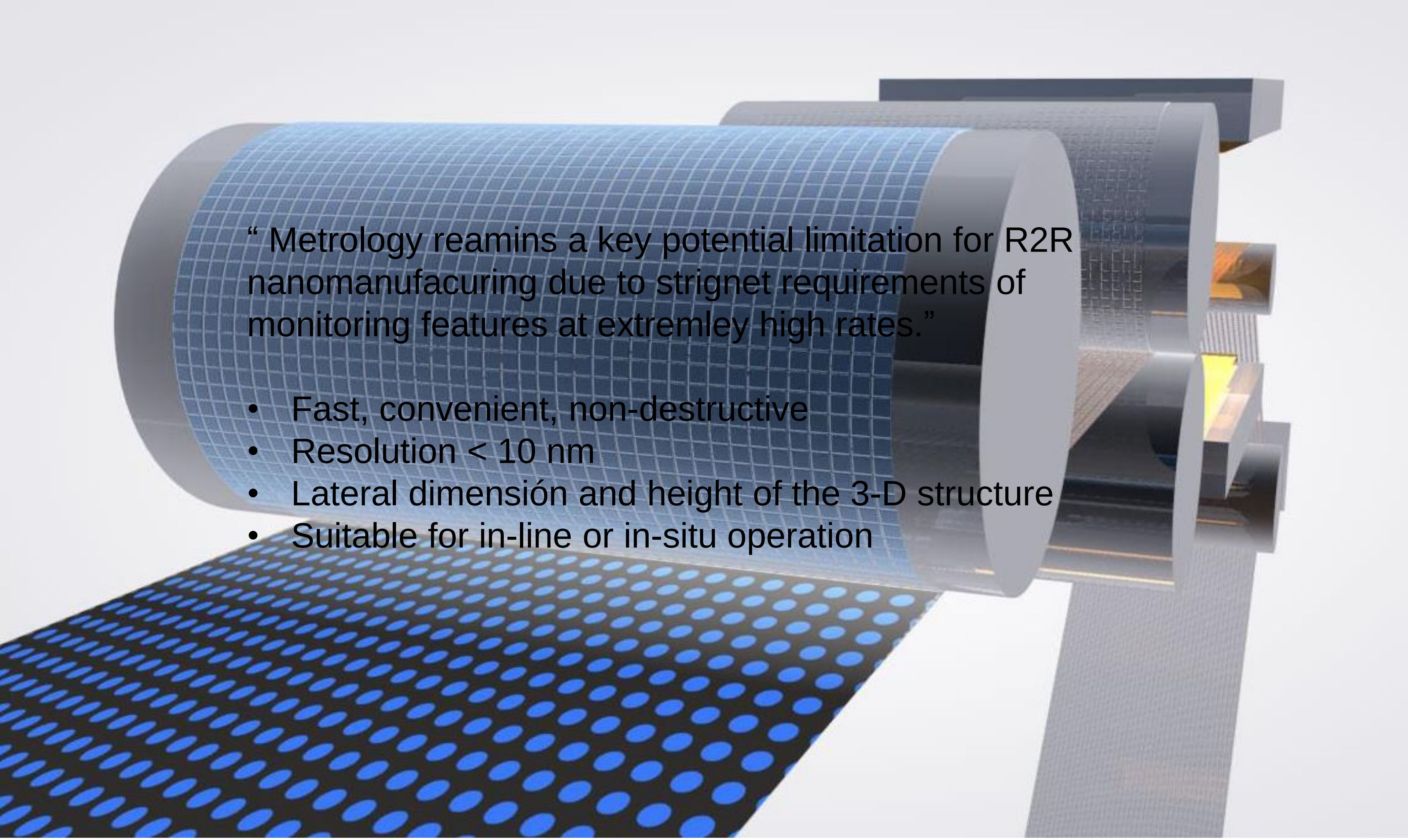
Nanofabrication technologies for Roll-to-Roll Processing, NIST-NNN Workshop, 2011

What to Measurere?

(1) Film thickness
(2) Height
(3) Period
(4) Width
(5) Sidewall Roughness
(6) Sidewall Angle
(7) Morphology
(8) Defects



Wish List of Metrology



“ Metrology reamins a key potential limitation for R2R nanomanufacuring due to strignet requirements of monitoring features at extremley high rates.”

- Fast, convenient, non-destructive
- Resolution < 10 nm
- Lateral dimensión and height of the 3-D structure
- Suitable for in-line or in-situ operation

Nanofabrication technologies for Roll-to-Roll Processing, NIST-NNN Workshop, 2011

Standard Microscopy Limitations

Optical Microscopy

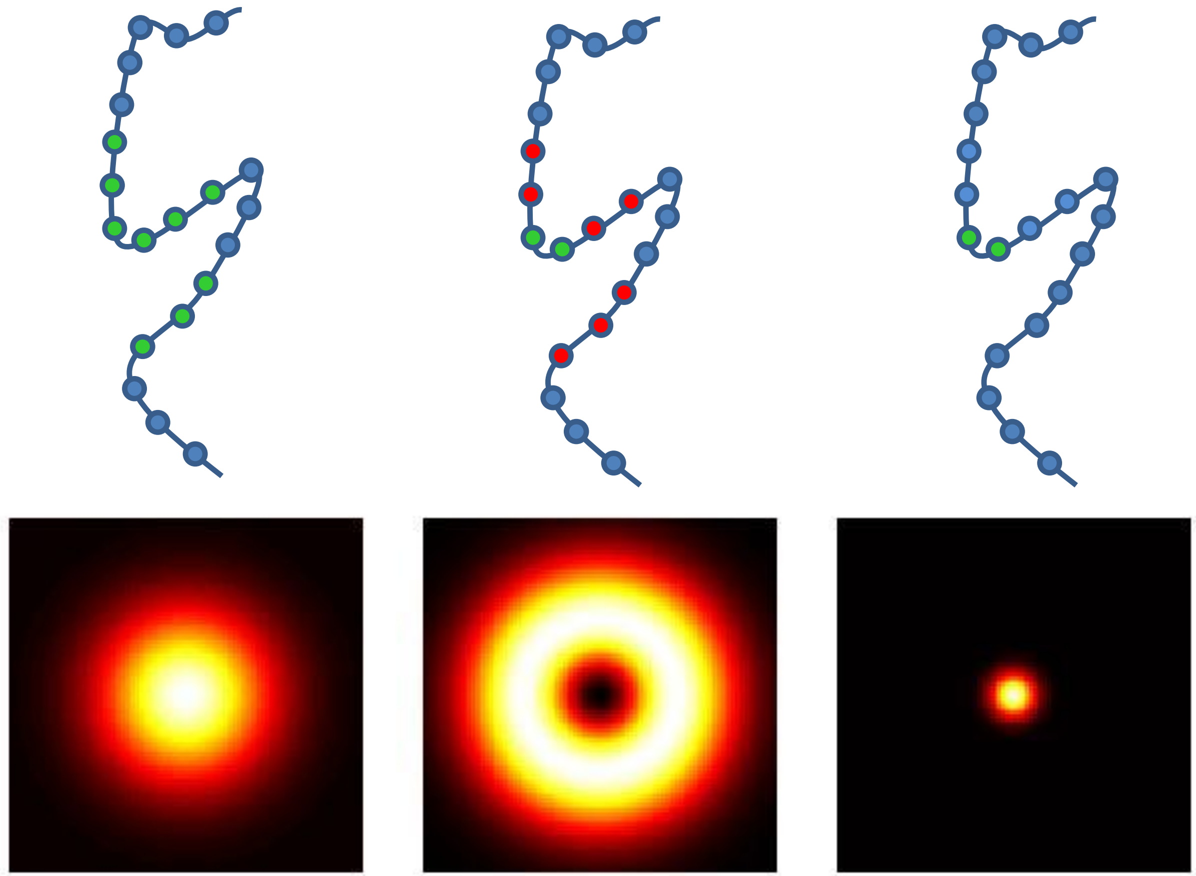
- Diffraction Limited?

SEM

- Requires Vacuum
- Sensitive Alignment
- Speed/resolution Trade-off

Super Resolution: Flourescence

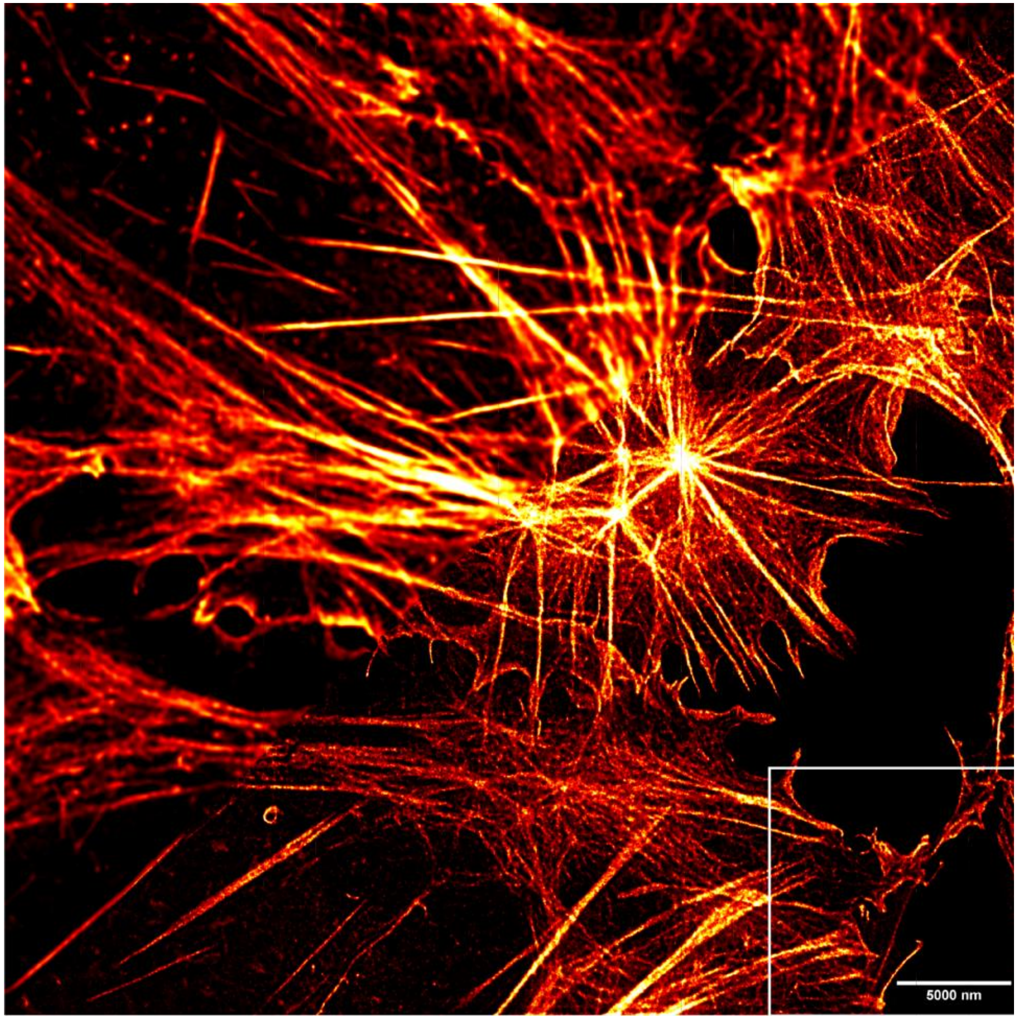
STED : Stiumulated Emission Depletion Microscopy



Super Resolution: Flourescence

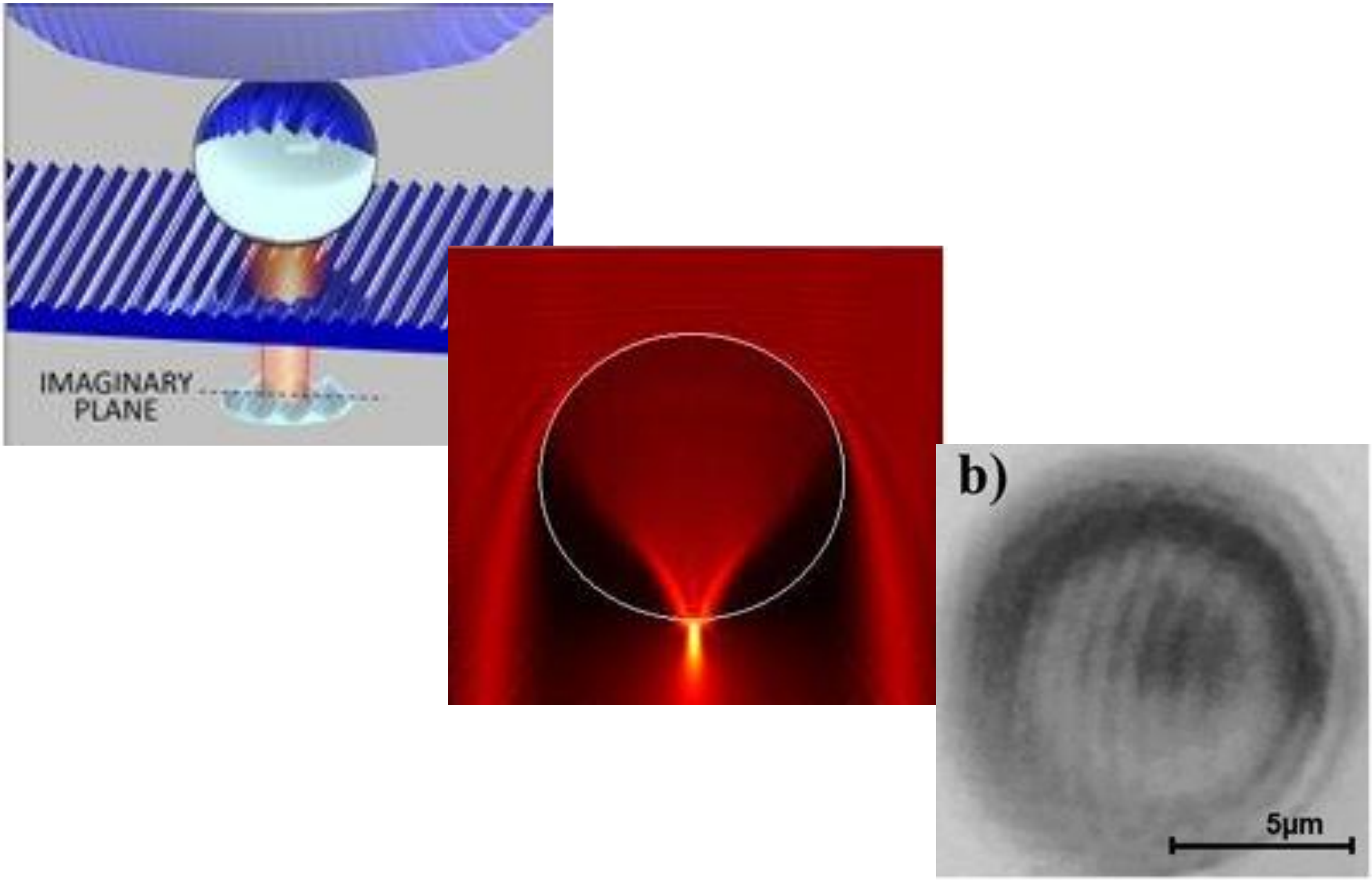
STED : Stiumulated Emission Depletion Microscopy

Confocal
Resolution = 200 nm



STED
Resolution = 50 nm

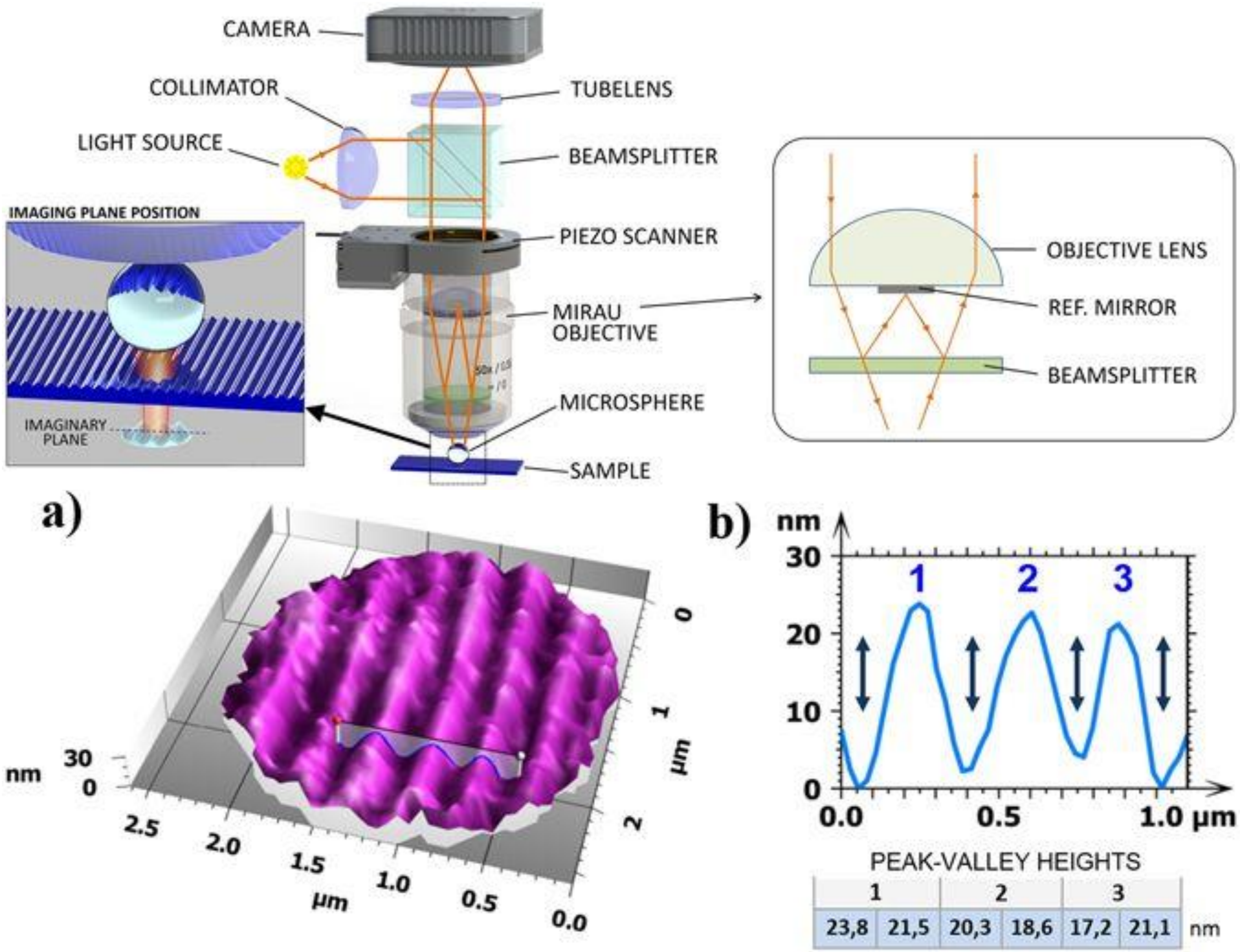
Microsphere-assisted Microscopy



Kassamakov et al, Scientific Reports **7**, 3683 (2017)

Microsphere-assisted Microscopy

3D Super-Resolution Optical Profiling Using Microsphere Enhanced Mirau Interferometry



Kassamakov et al, Scientific Reports **7**, 3683 (2017)

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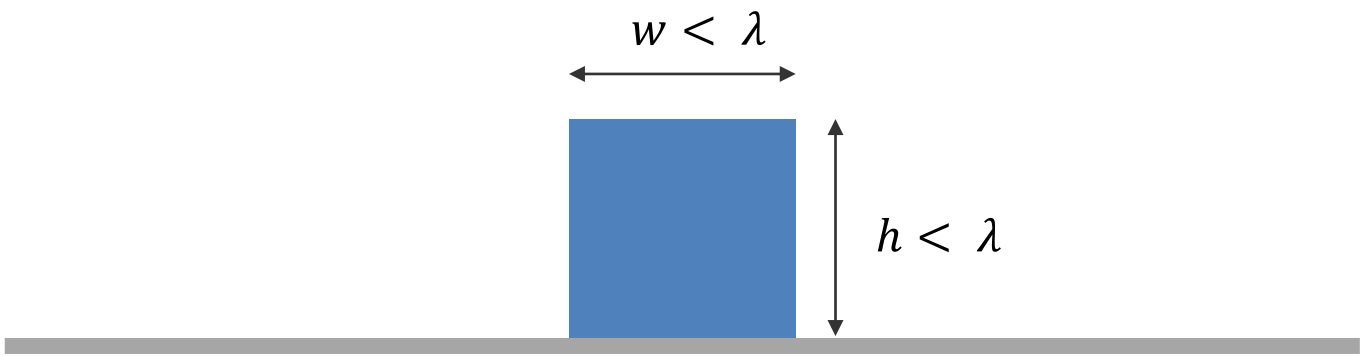
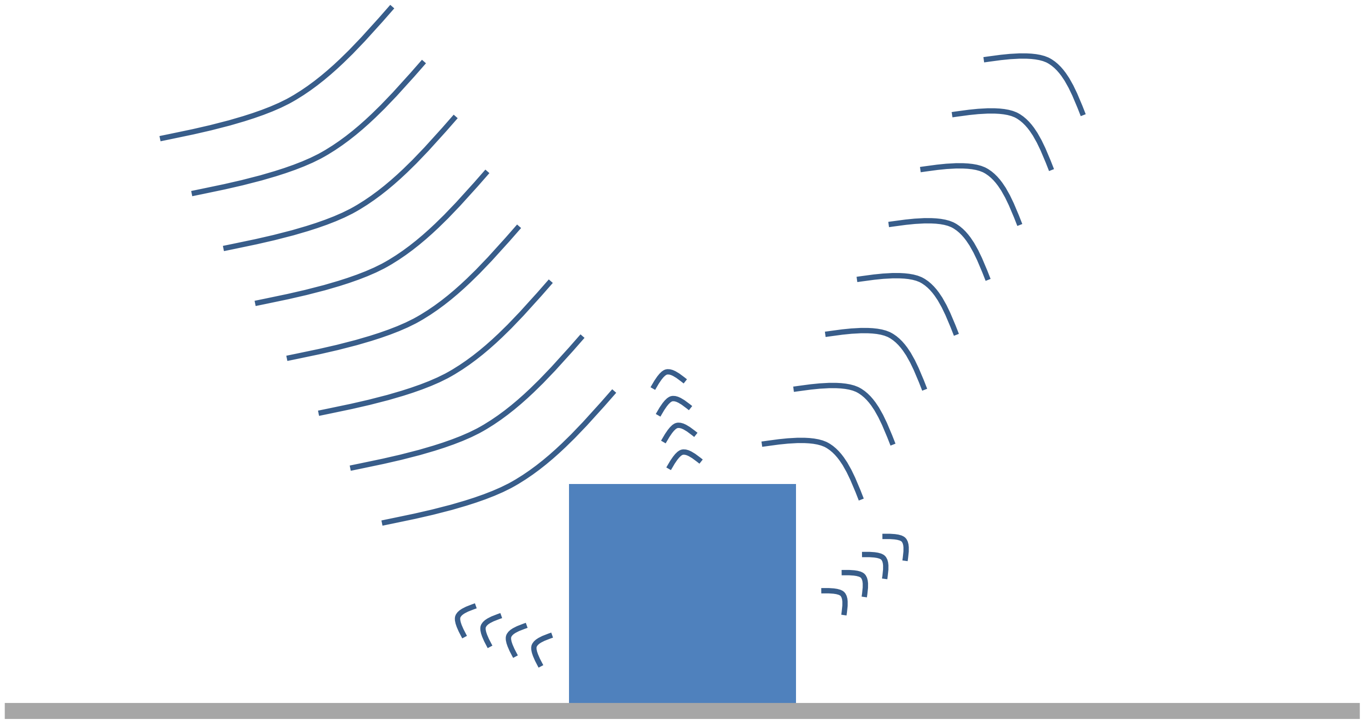
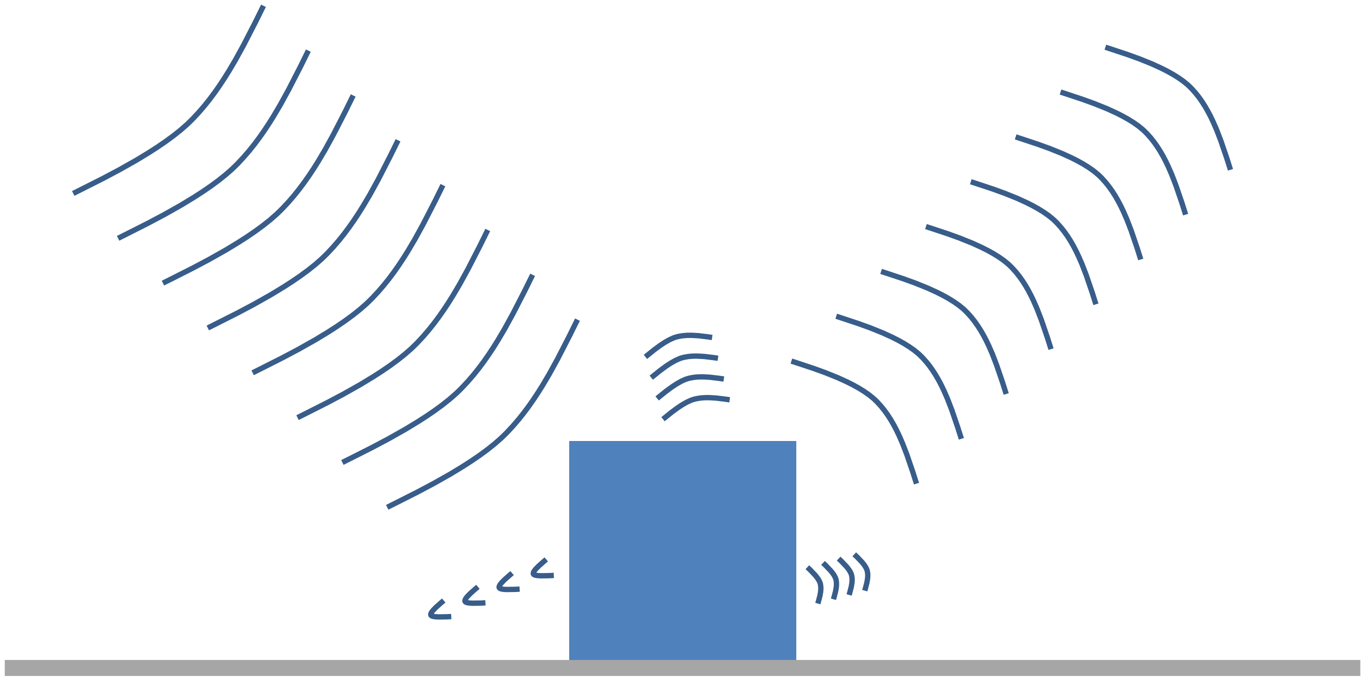
Scatterometry Schematic



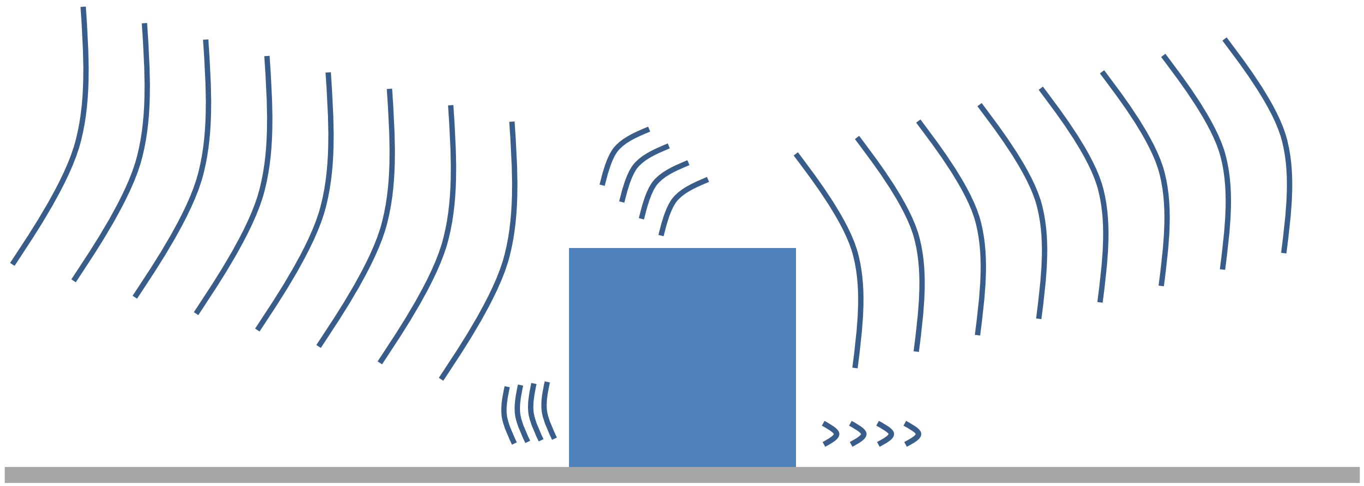
Scatterometry Schematic



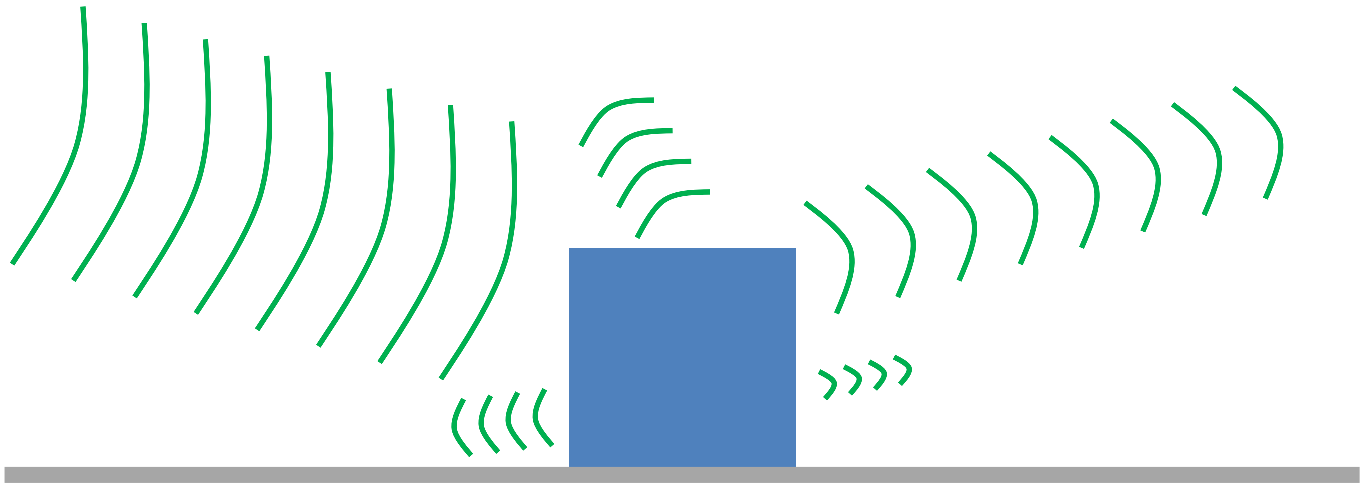
Scatterometry Schematic



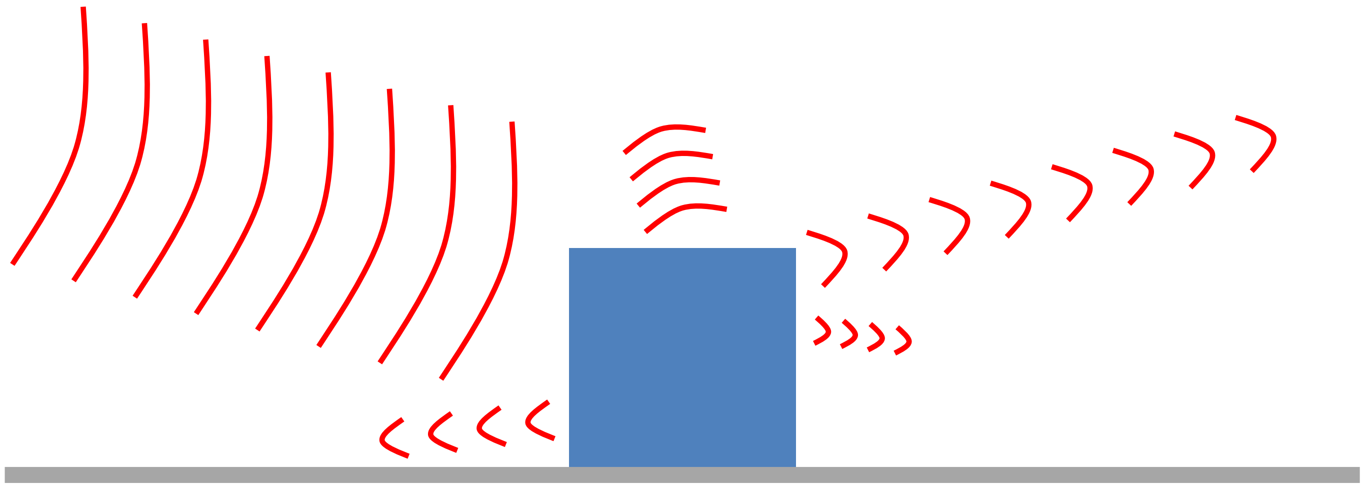
Scatterometry Schematic



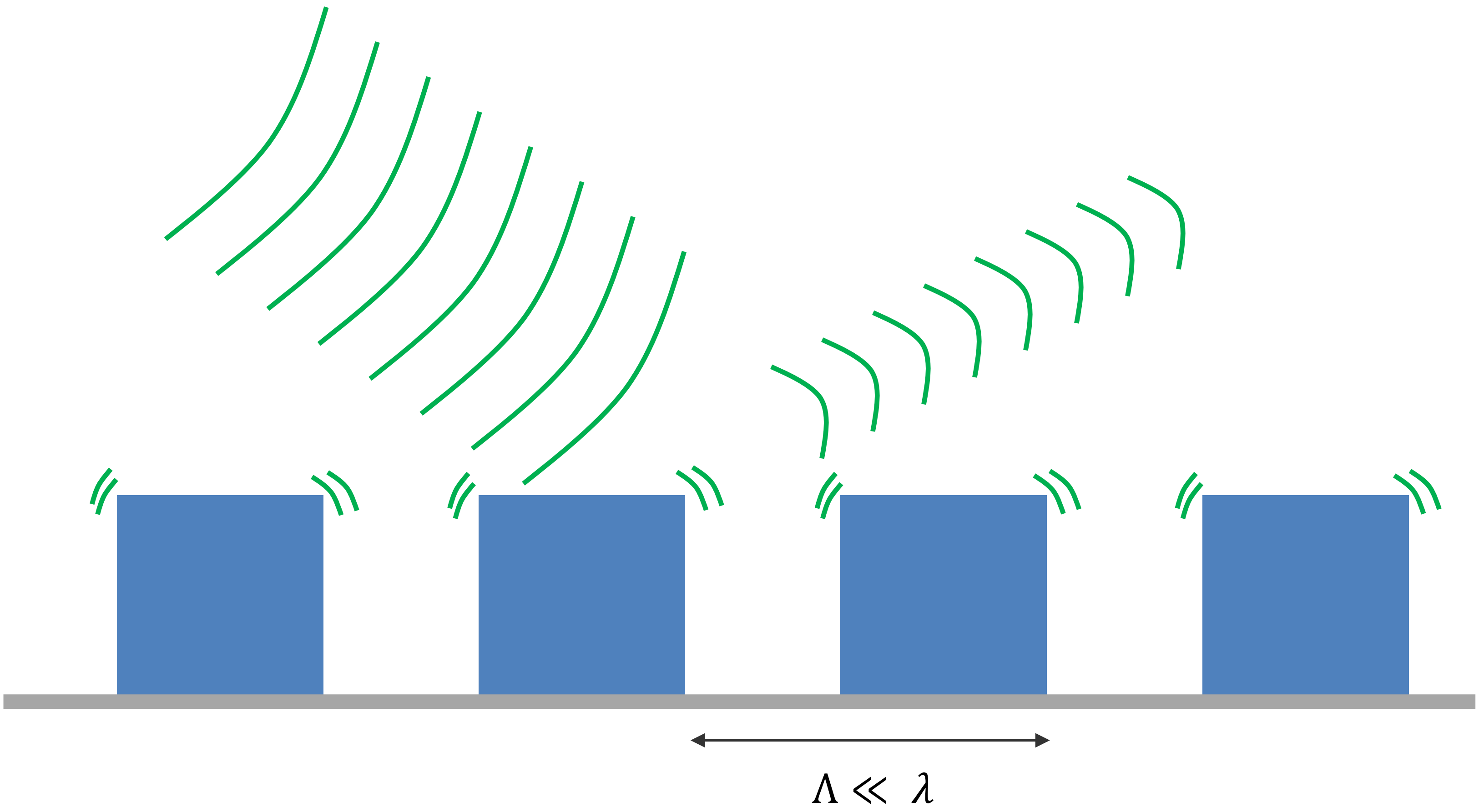
Scatterometry Schematic



Scatterometry Schematic



Scatterometry of a Periodic Structure



Optical Scatterometry Types

Optical Scatterometry

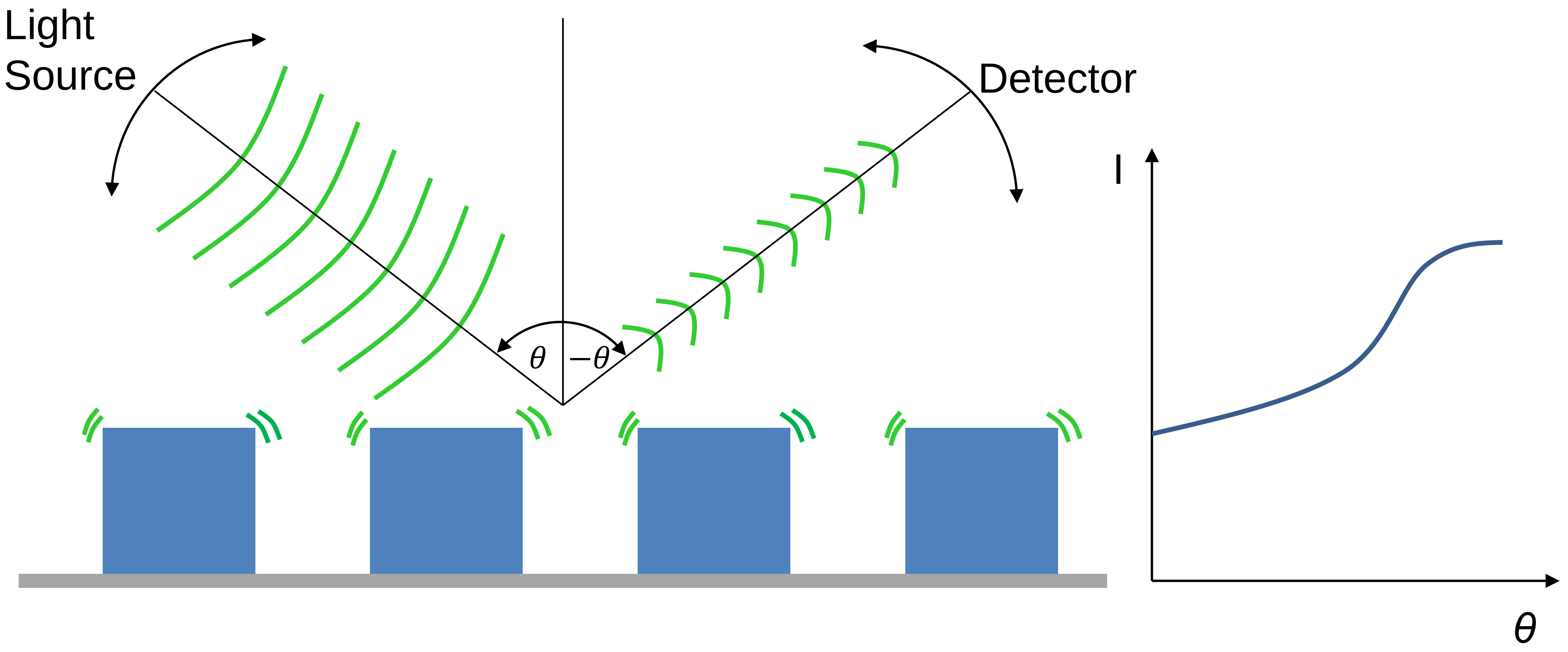
Reflectometry
Angle/Wavelength

Fourier
Scatterometry

Ellipsometry

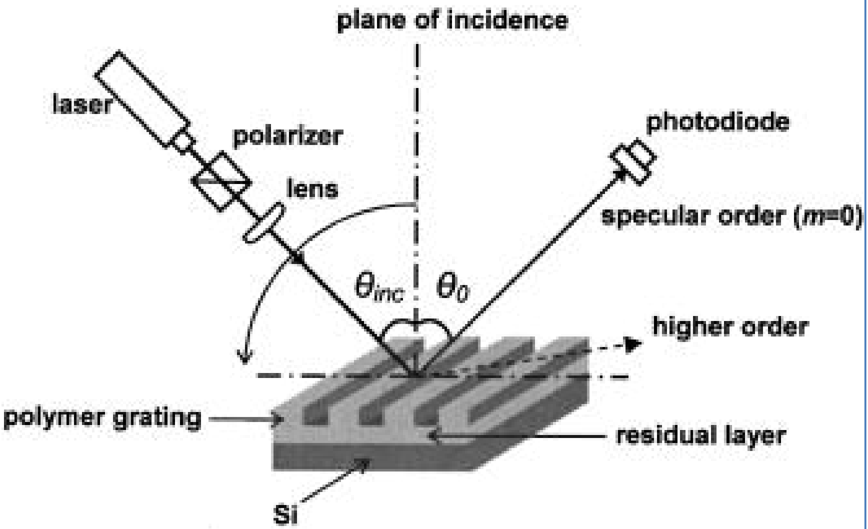
Diffractometry

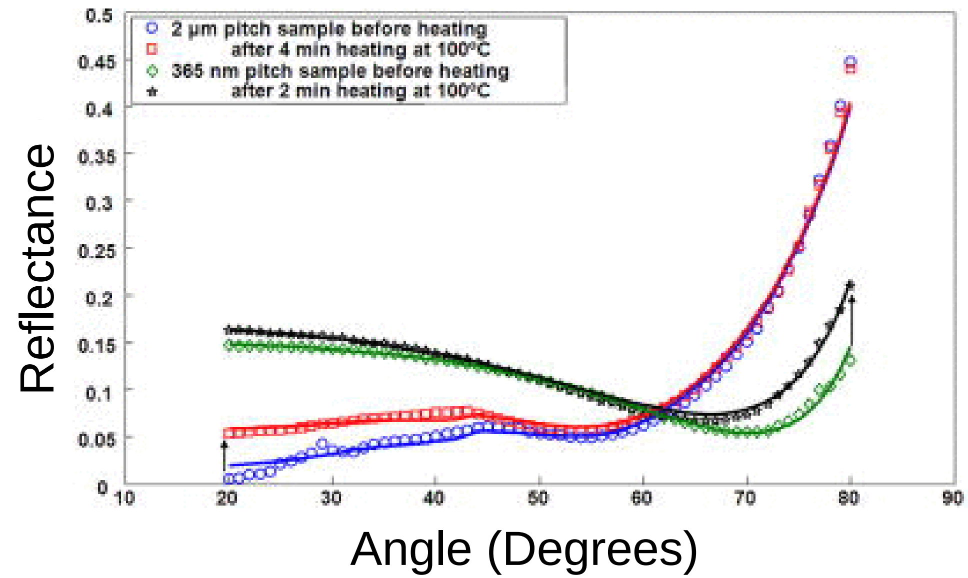
Reflectometry: Angle Dependance

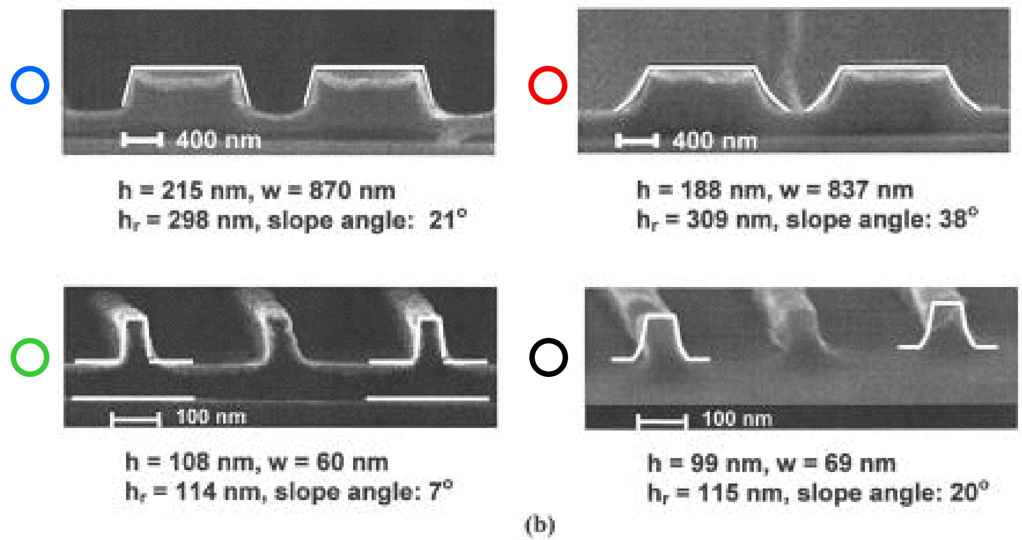


Reflectometry: Angle Example

Characterizing nanoimprint profile shape and polymer flow behavior using visible light angular scatterometry

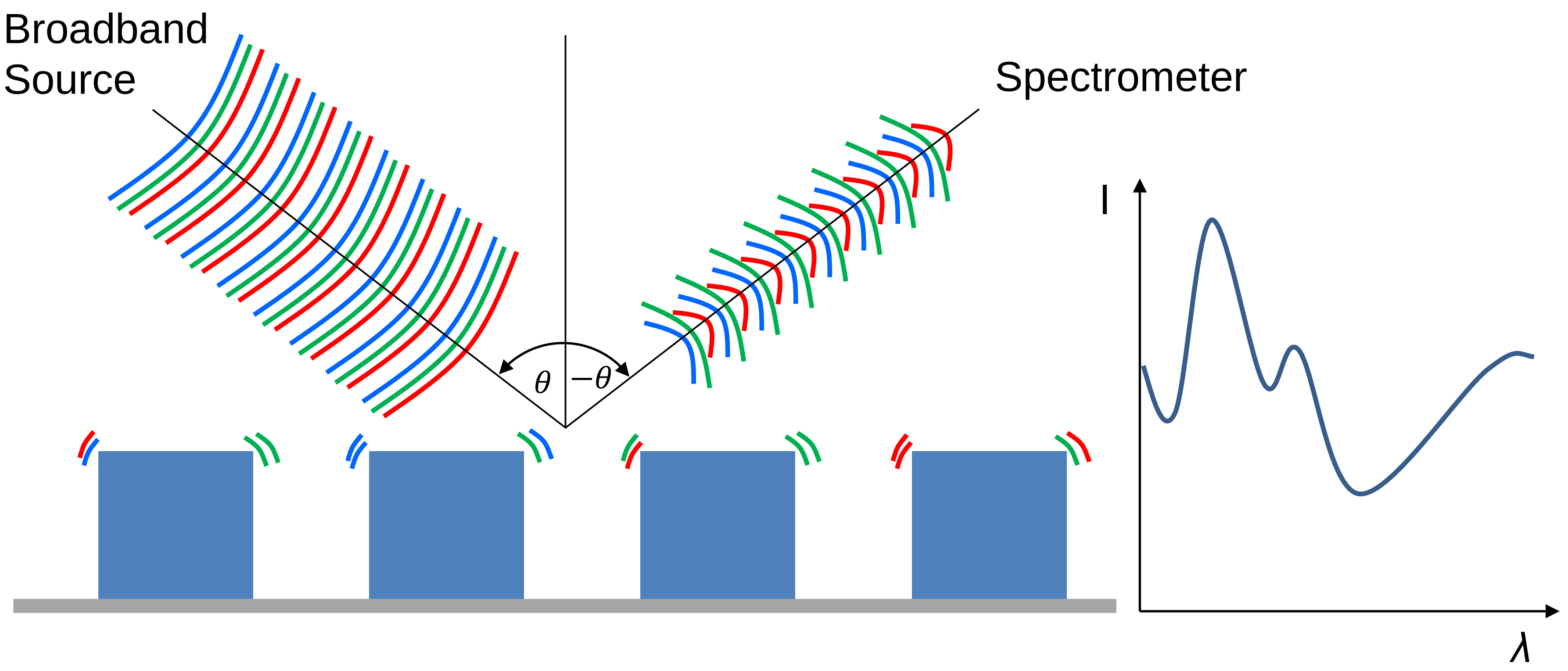






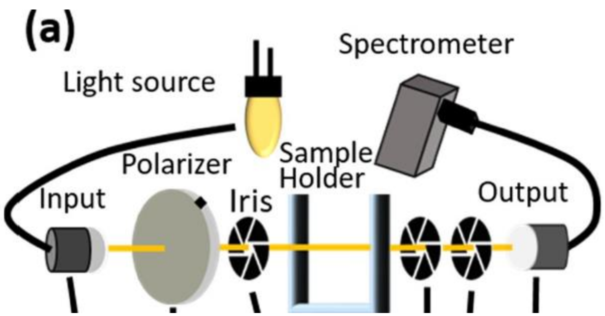
R. M. Al-Assaad et al, J. Vac. Sci. Tech. B. **25**, 6, 2007

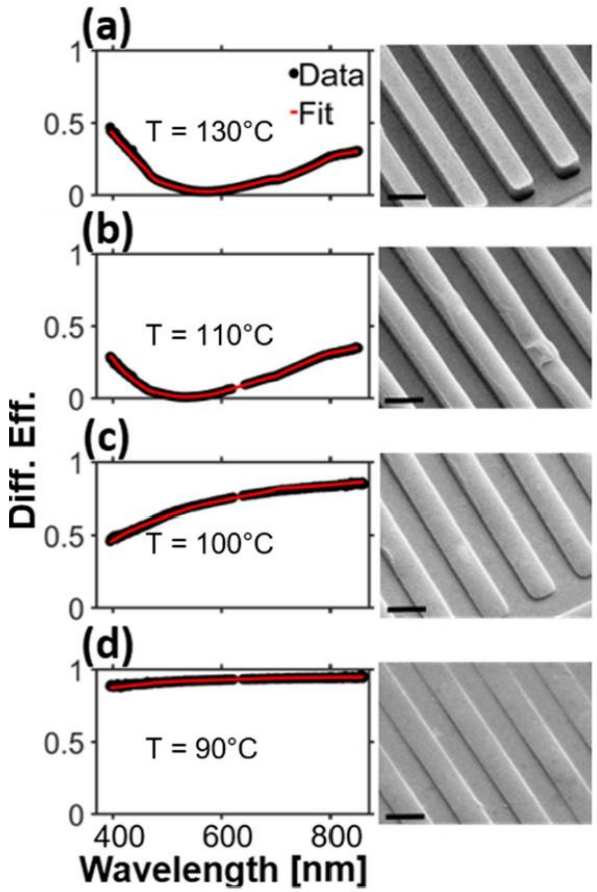
Reflectometry: Wavelength Dependance

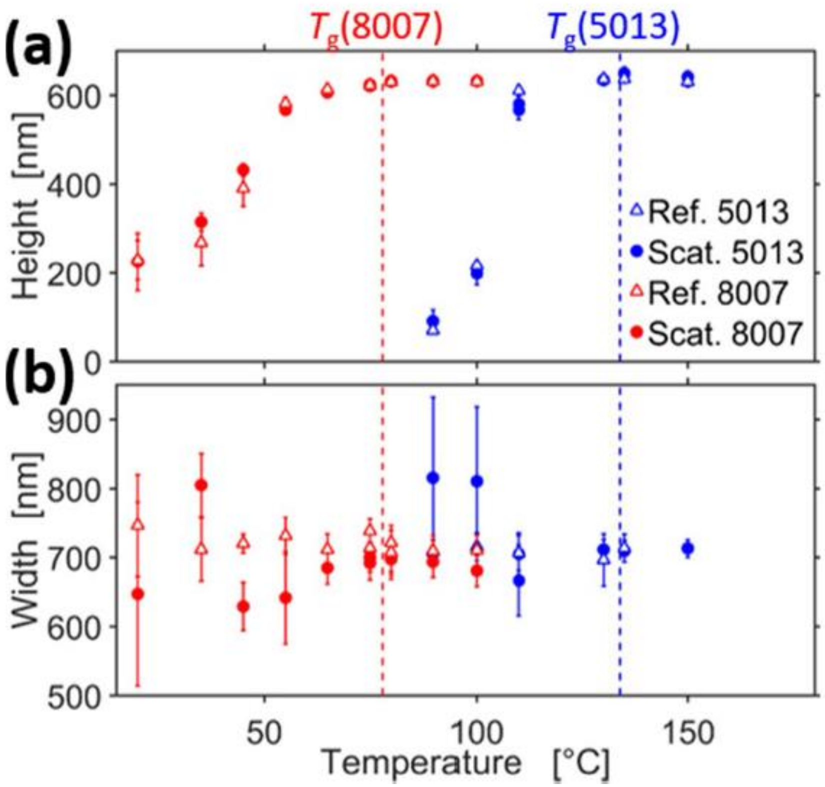


Reflectometry: Wavelength Example

In-line characterization of nanostructured mass-produced polymer components using scatterometry

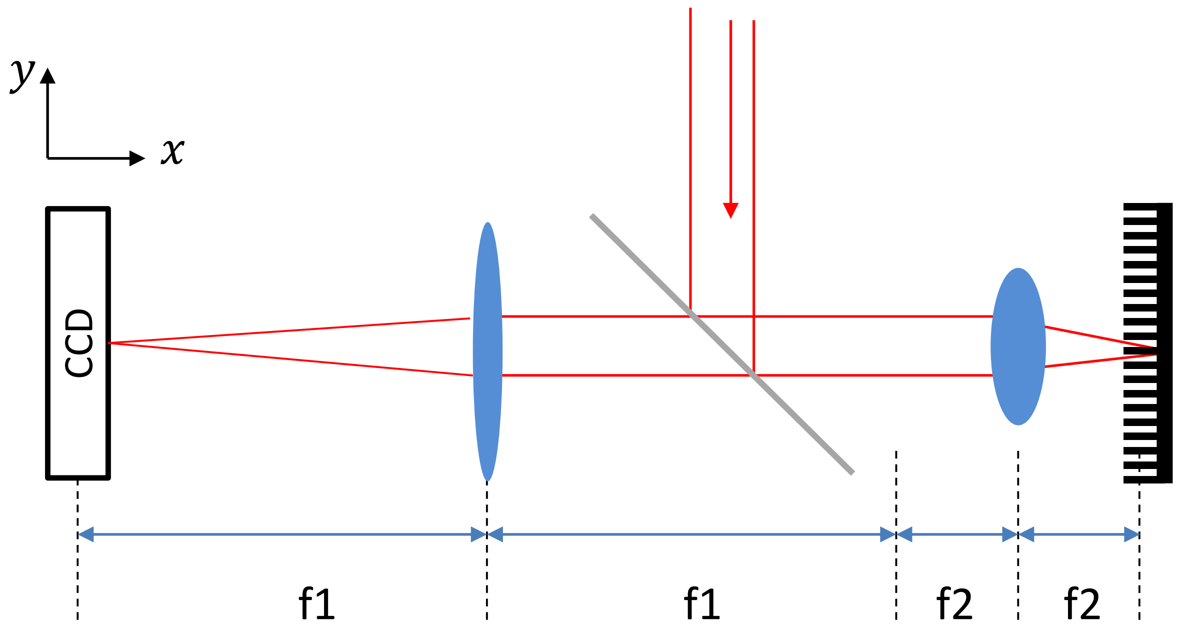






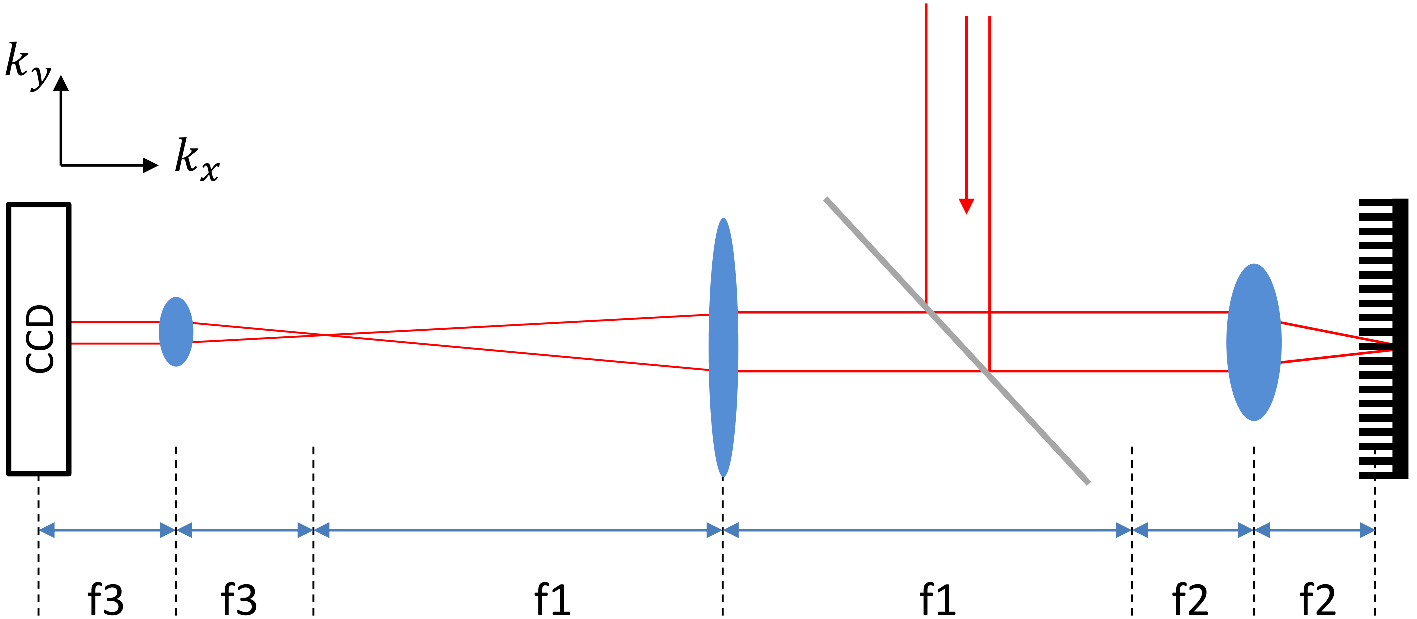
J. S. Madsen et al, J. Micromech. Microeng. **27**, 2396 (2017)

Real Plane Imaging



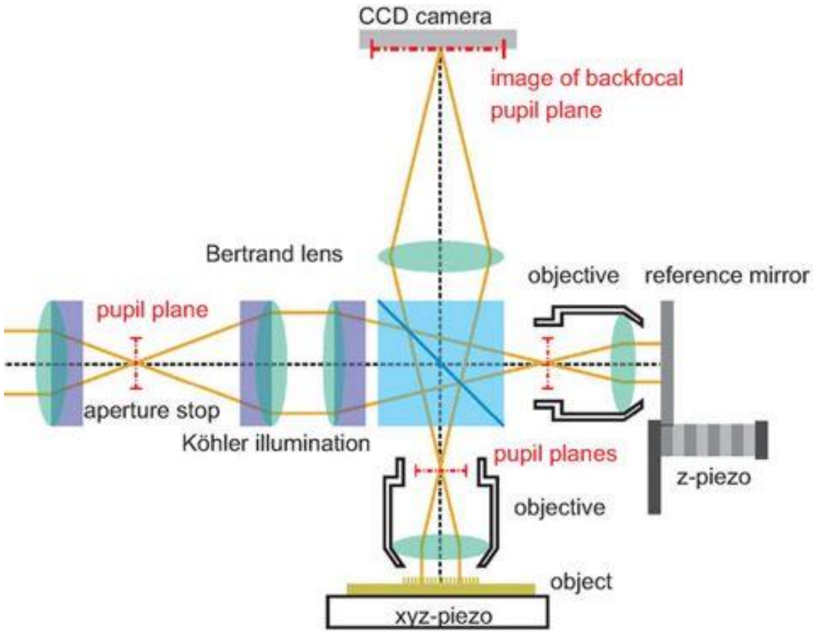
Fourier Scatterometry

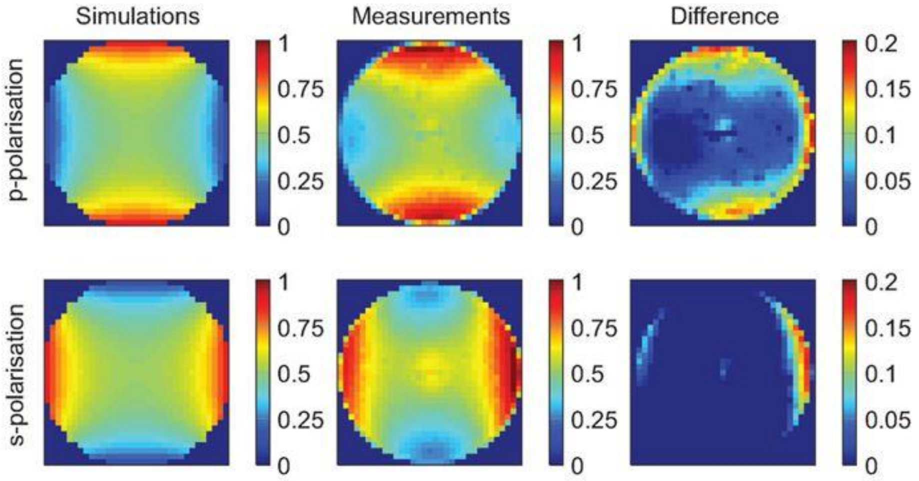
Fourier Plane Imaging

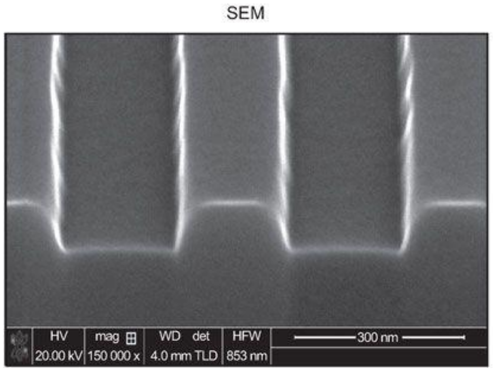


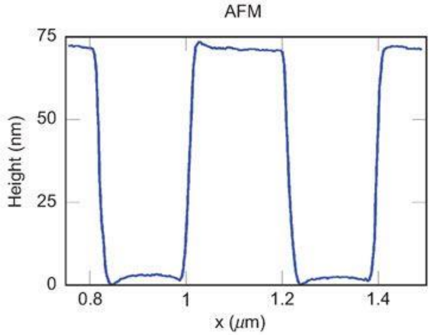
Fourier Scatterometry

Solving the inverse grating problem by white light interference Fourier scatterometry



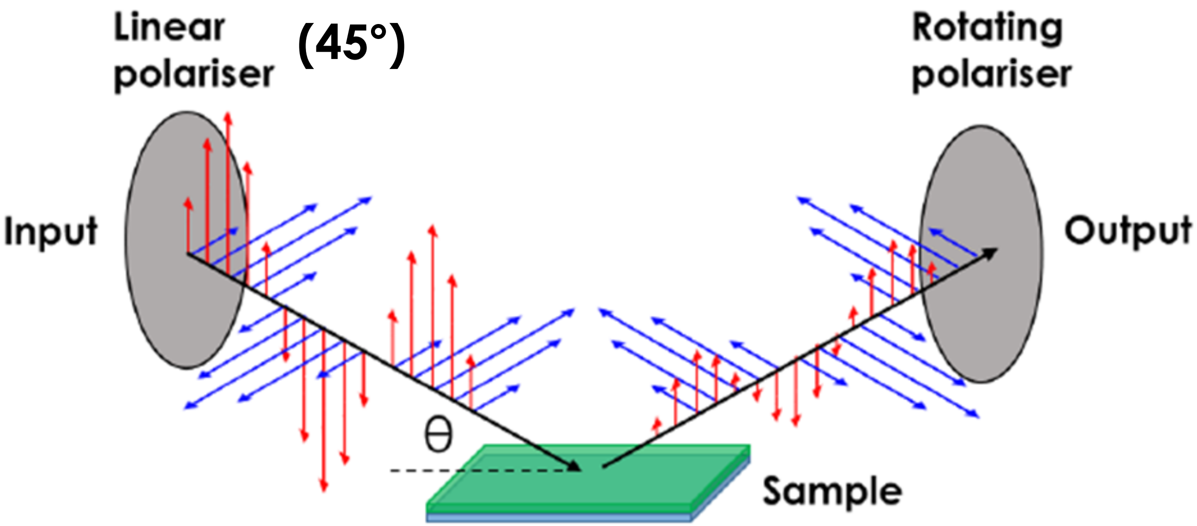






V. F. Paz et al, Light: Science & Applications volume 1, page e36 (2012)

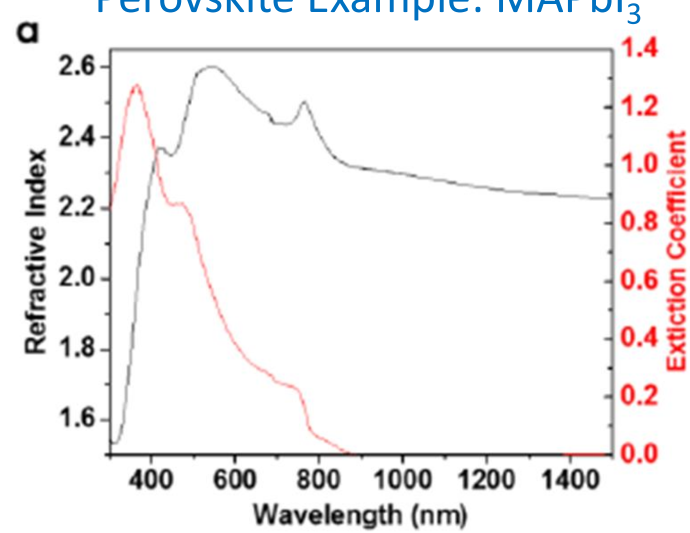
Ellipsometry



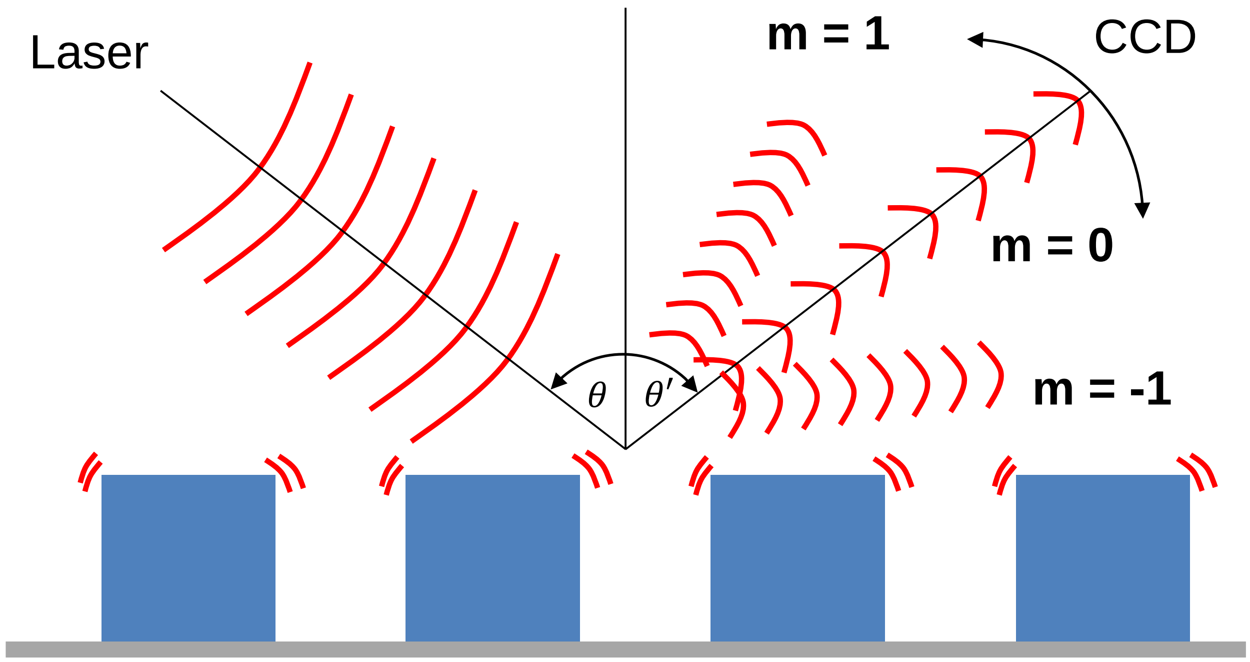
Measures the polarisation amplitude ratio and the dephasing of reflected light

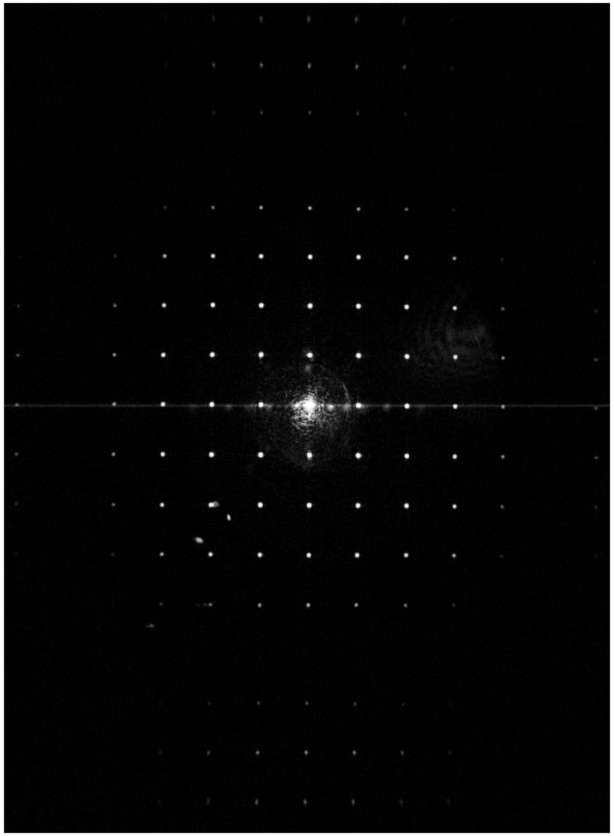
- Complex refractive index $\tilde{n} = n + i\kappa$
- Anisotropy
- Thicknesses of films or stacks of films (nms)
- (Grating Stucture)

Perovskite Example: $MAPbI_3$



Diffractometry

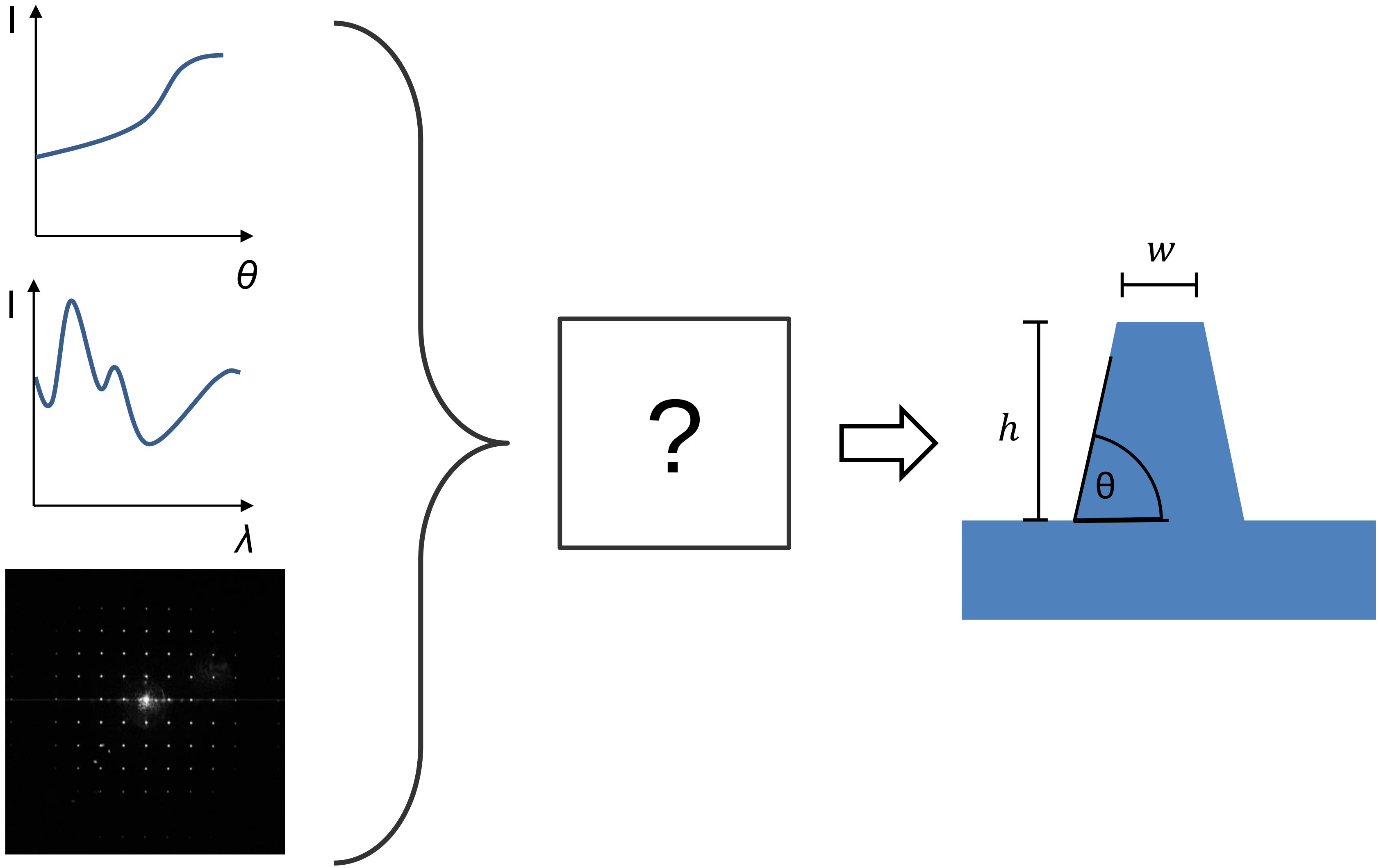




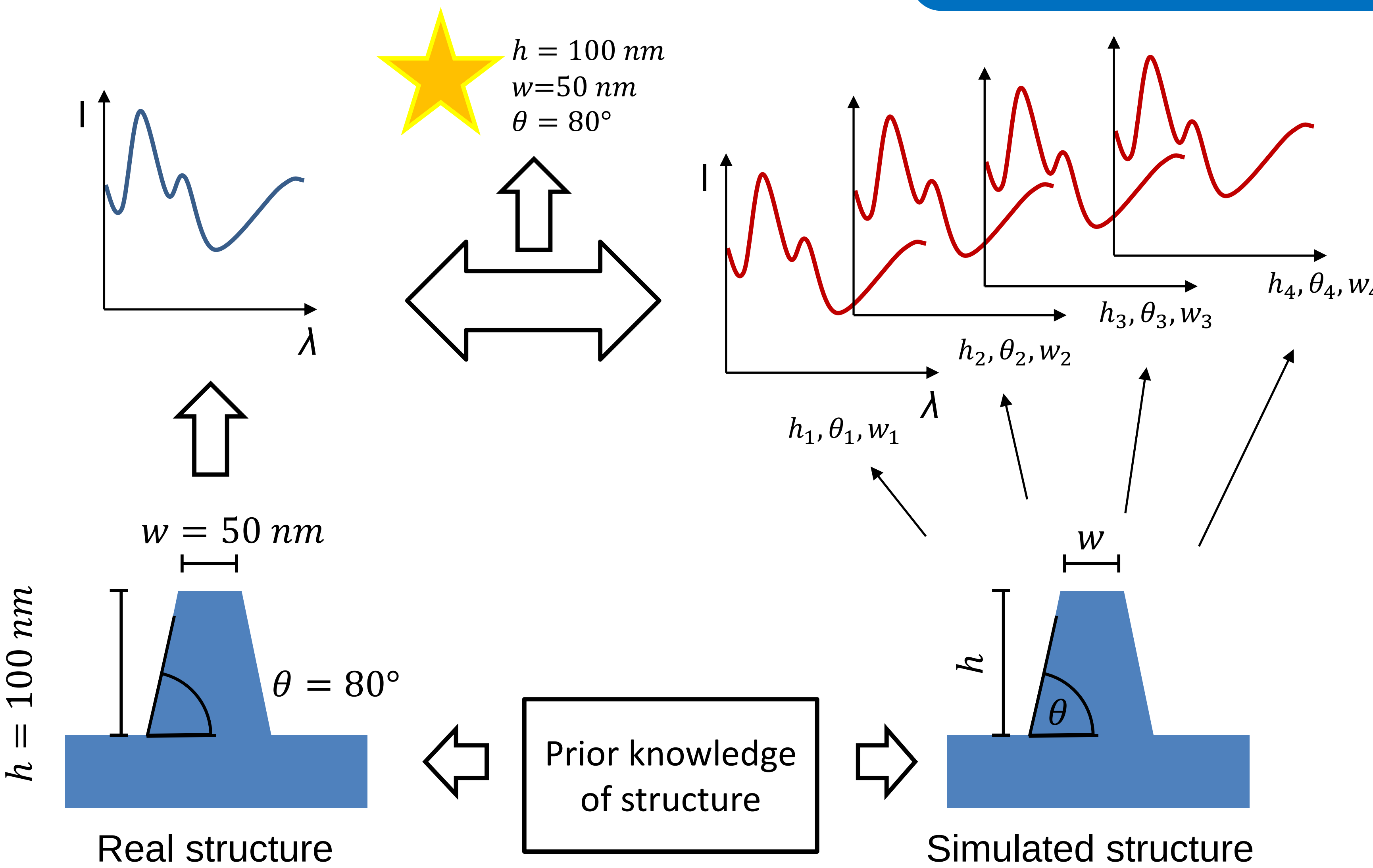
Overview

- Overview of Metrology
- Metrology in Nanofabrication
- Optical Scatterometry
- Inverse Problem Solving
- Case Study : Diffractometry for roll-to-roll microstructured films

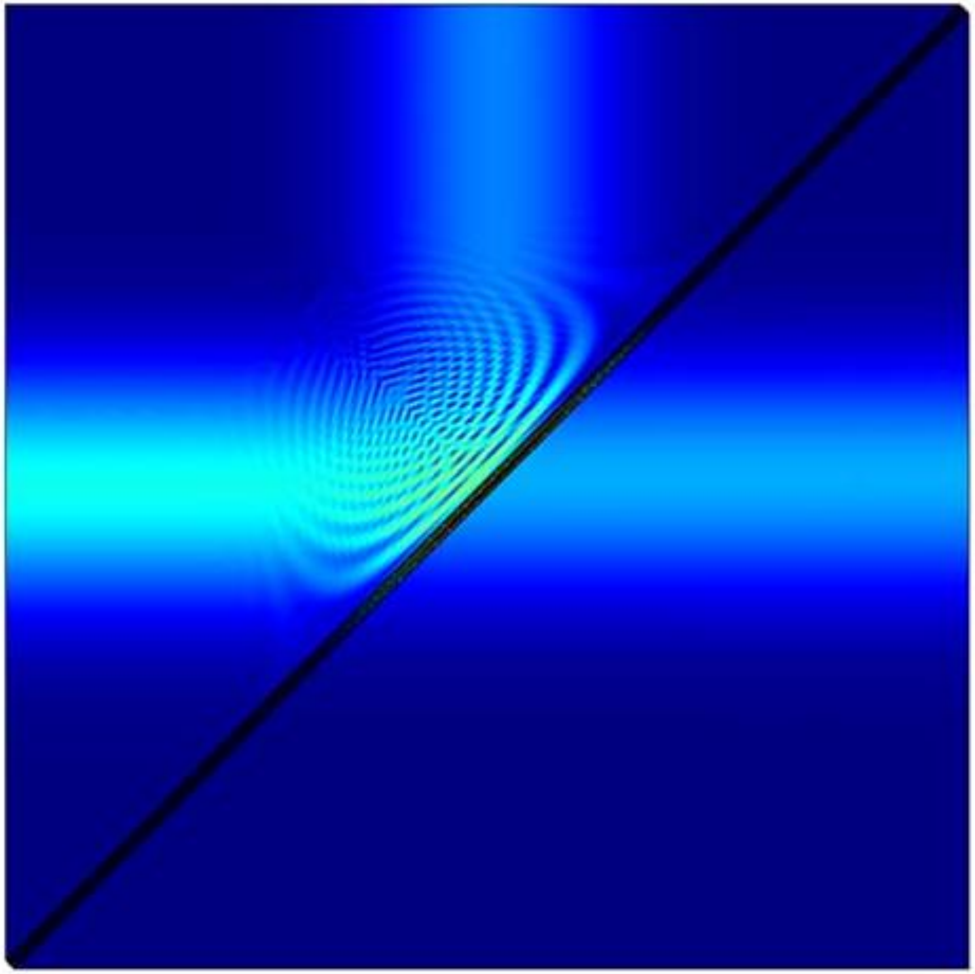
Inverse Problem Solving



Inverse Problem Solving



Solving Maxwell's Equations in 1D, 2D & 3D Computationally

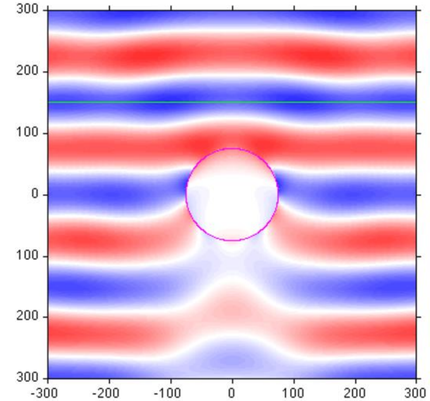


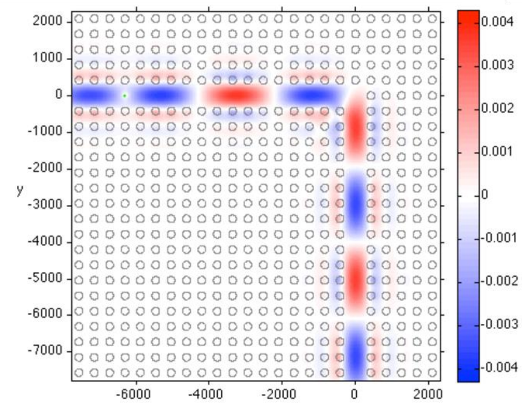
https://www.comsol.com/

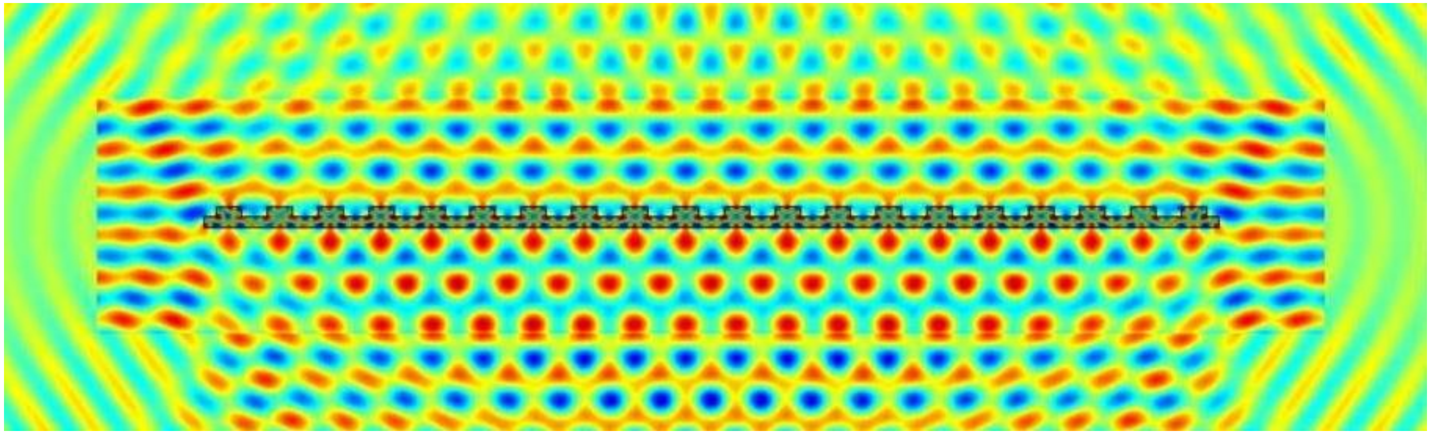
Finite-Difference Frequency/Time Domain

FDFD/FDTD

- Solves Maxells equations using finite-difference approximation
- Finite structures
- Can handle diffraction effects $\Lambda > \lambda$
- Semi-limited to 2D structures

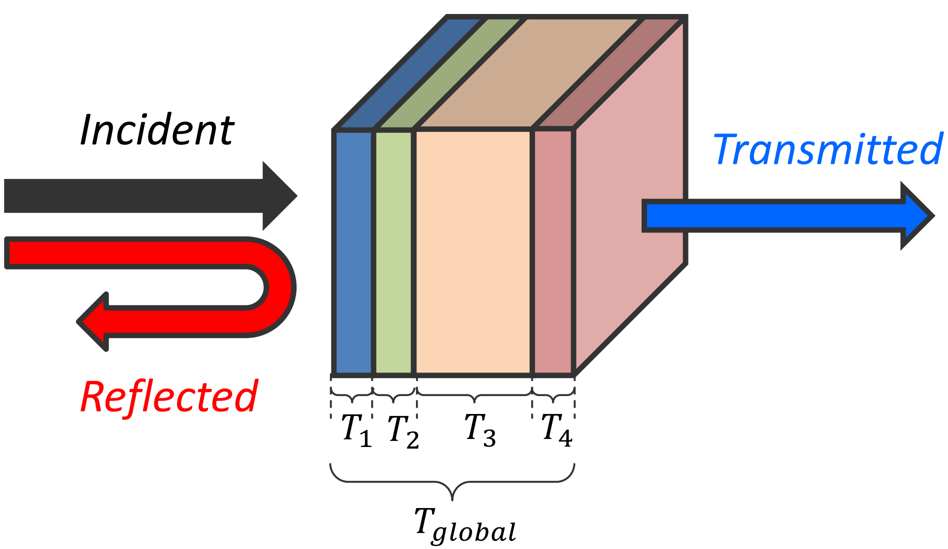






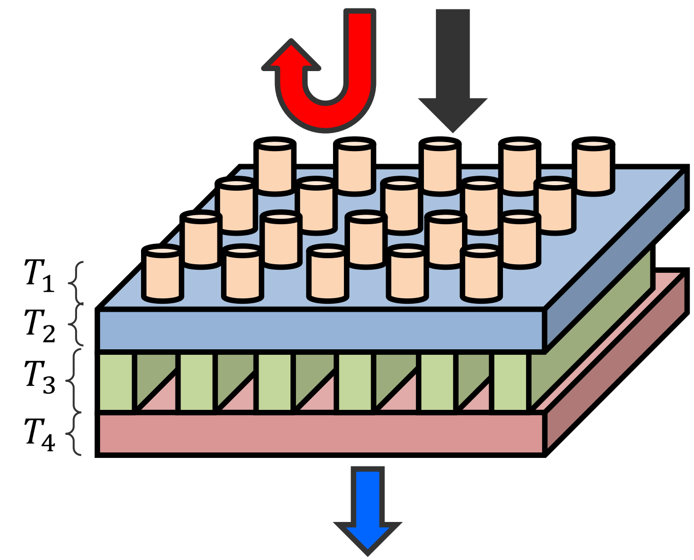
Rigourous Coupled-Wave Analysis

Transfer Matrix Method (TMM)



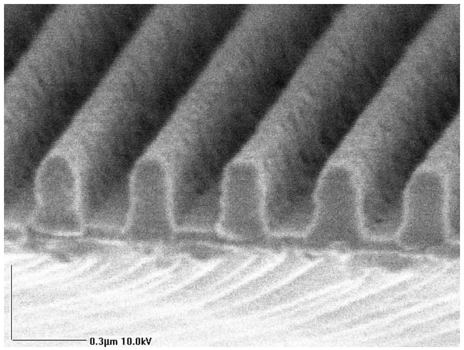
- Anaylitical Method
- 1D Dielectric Stacks

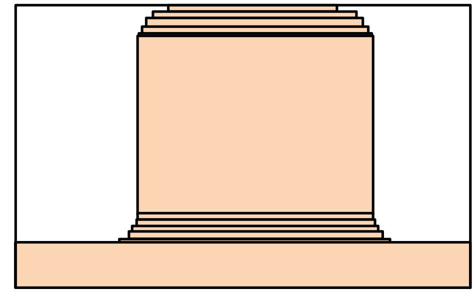
Rigourous Coupled-Wave Analysis (RCWA)

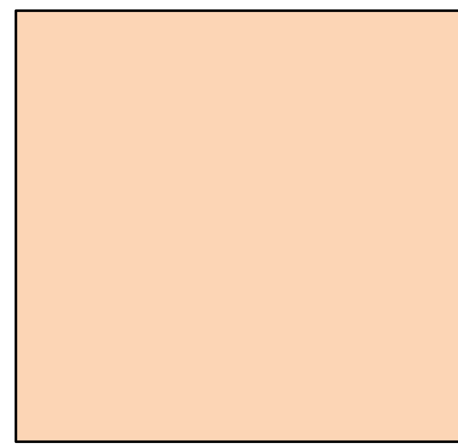


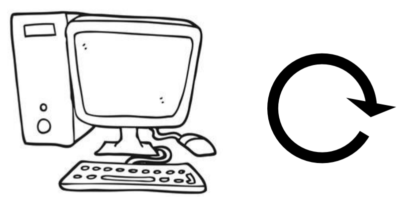
- Semi-Anaylitical Method
- 3D Structures
- Assumes Periodicity

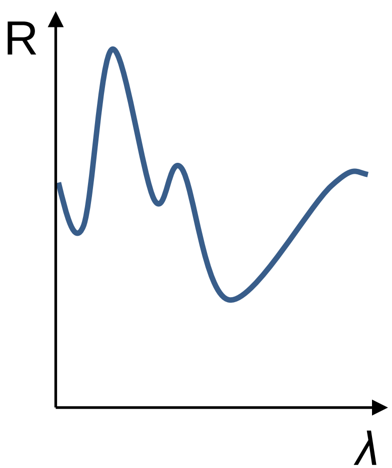
RCWA: Methodology





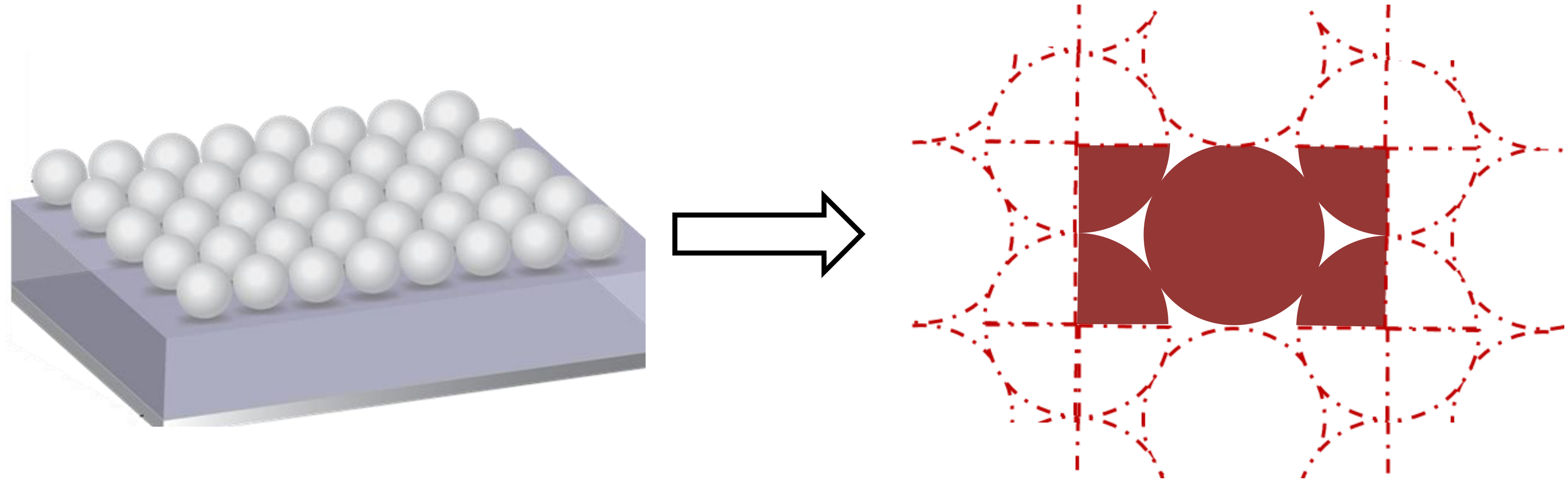


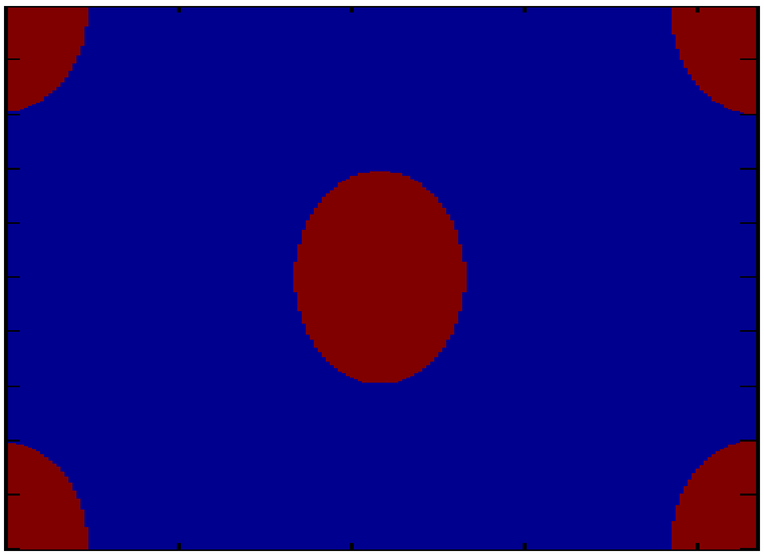


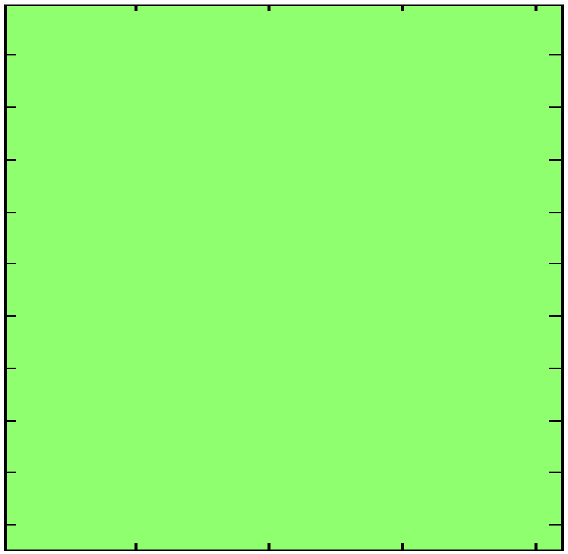


- Convert to Fourier Space (Spatial Harmonics)
- Sequentially Solve Maxwells Equations in Fourier Space

RCWA: Opal Example

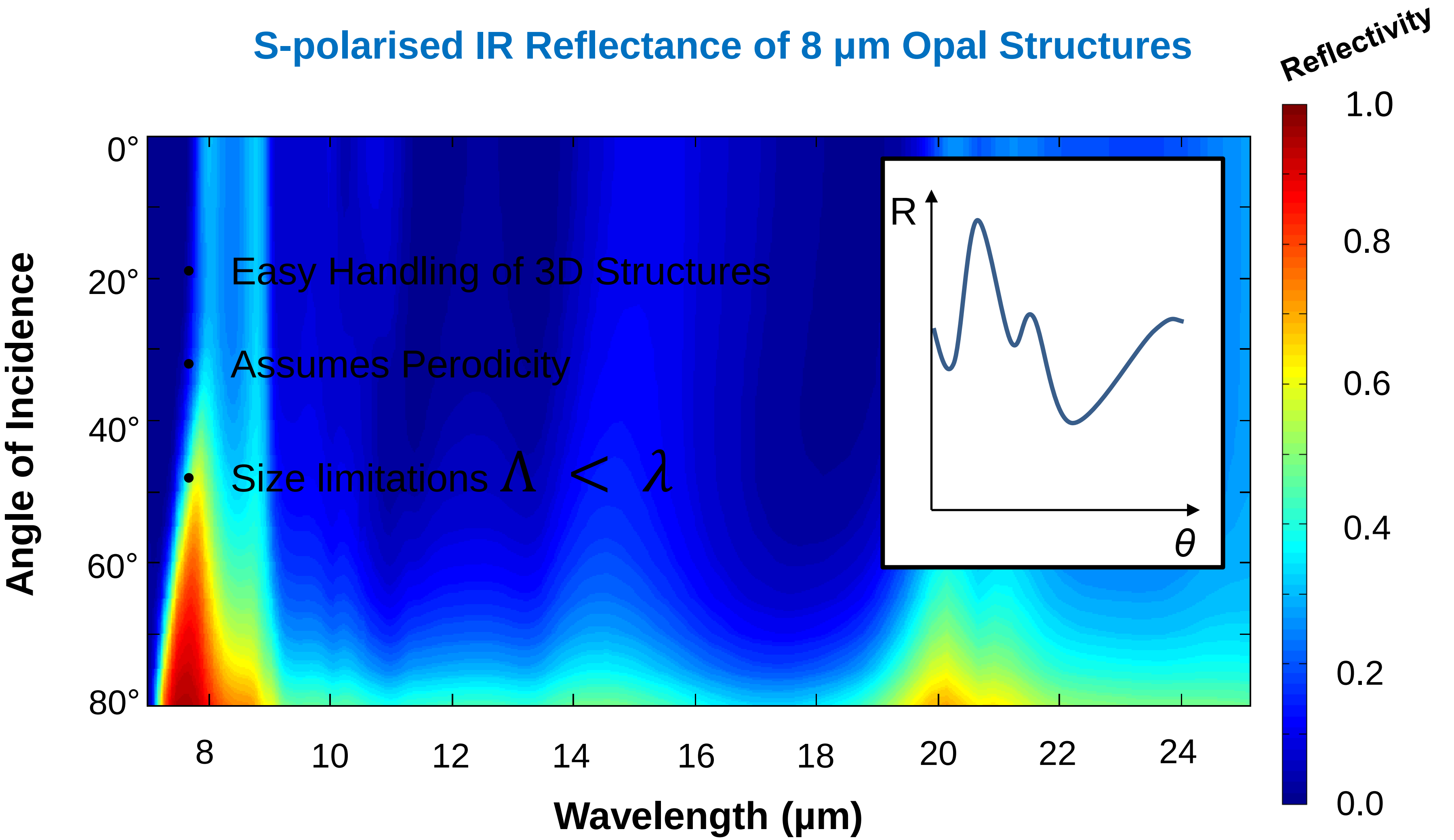






RCWA: Opal Example

- Easy Handling of 3D Structures
- Assumes Perodicity
- Size limitations $\Lambda < \lambda$



Overview

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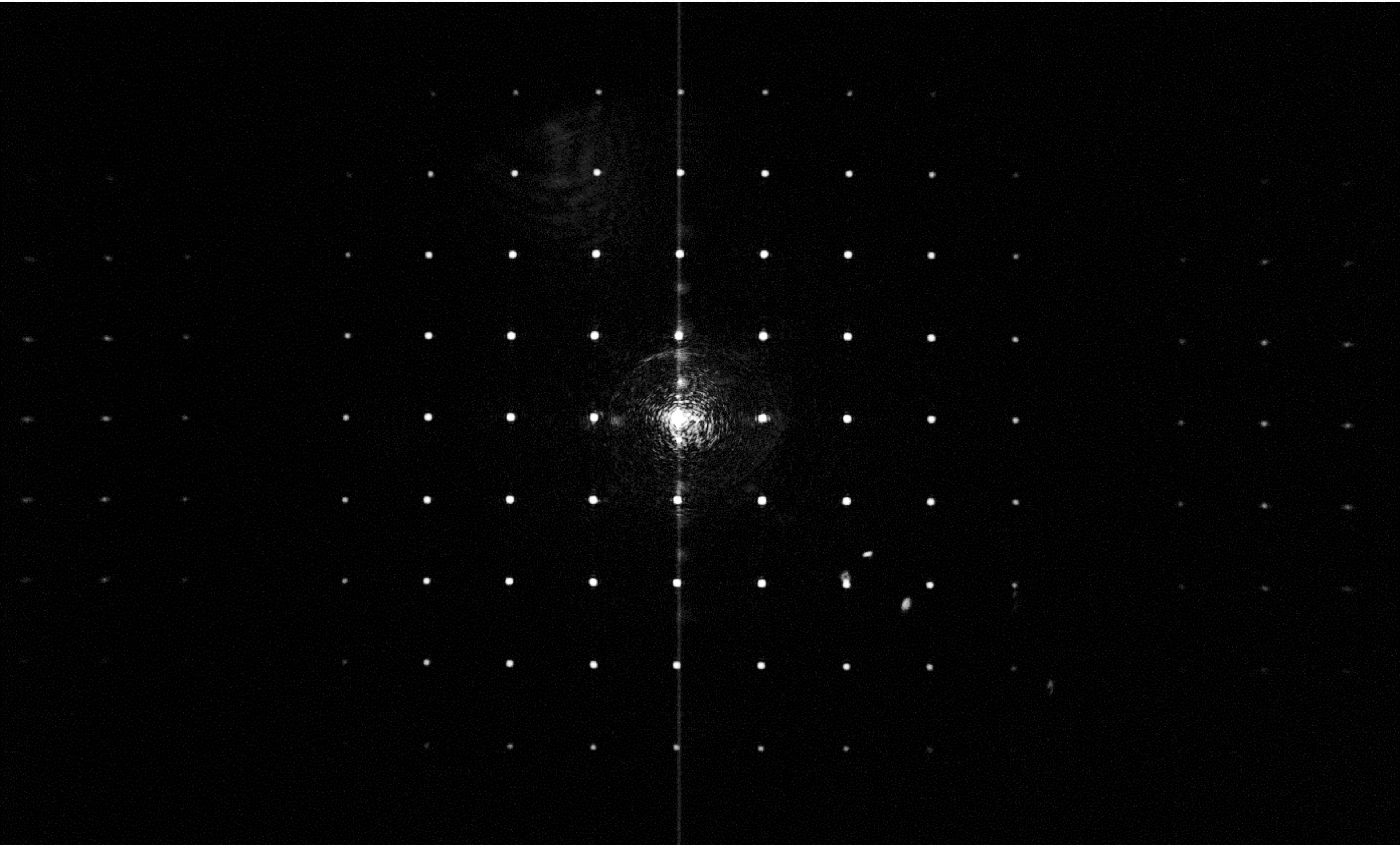
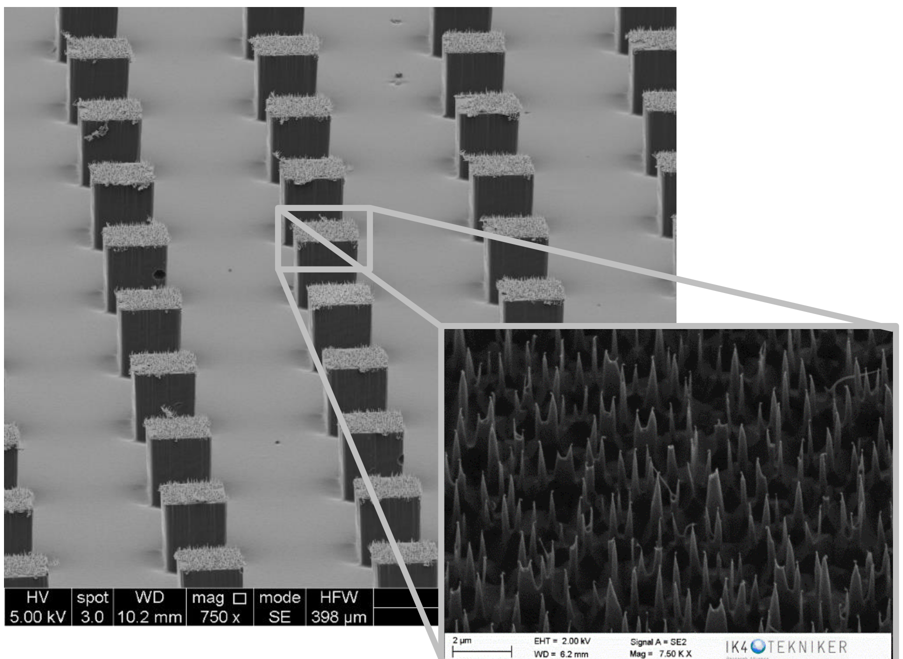
Case Study: Diffractometry @ ICN2

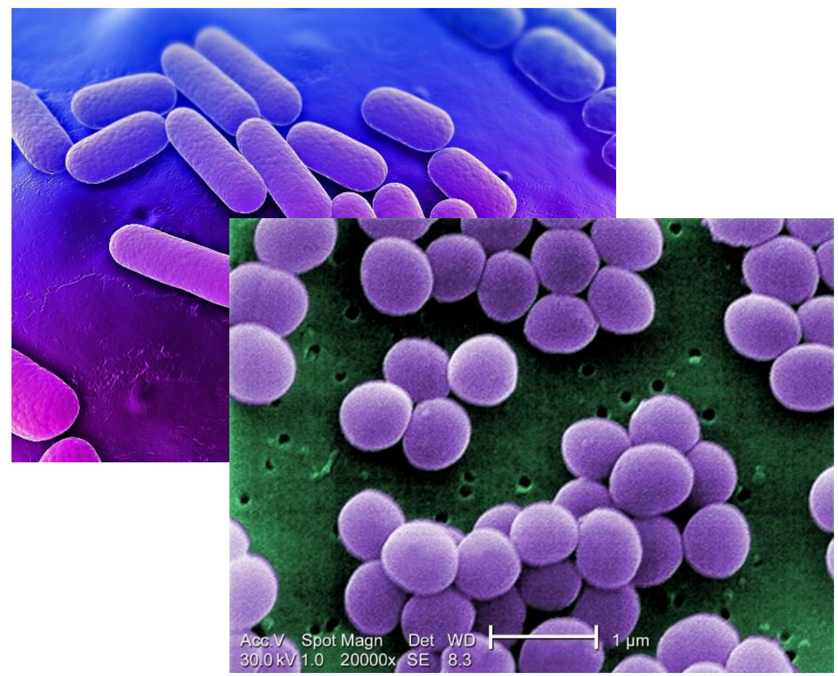


FLEXPOL: Antimicrobial FLEXible POLymers for its use in hospital environments

Materials processing & Nanostructuring | **Antimicrobial films** | **Product validation in laboraty & hospital**

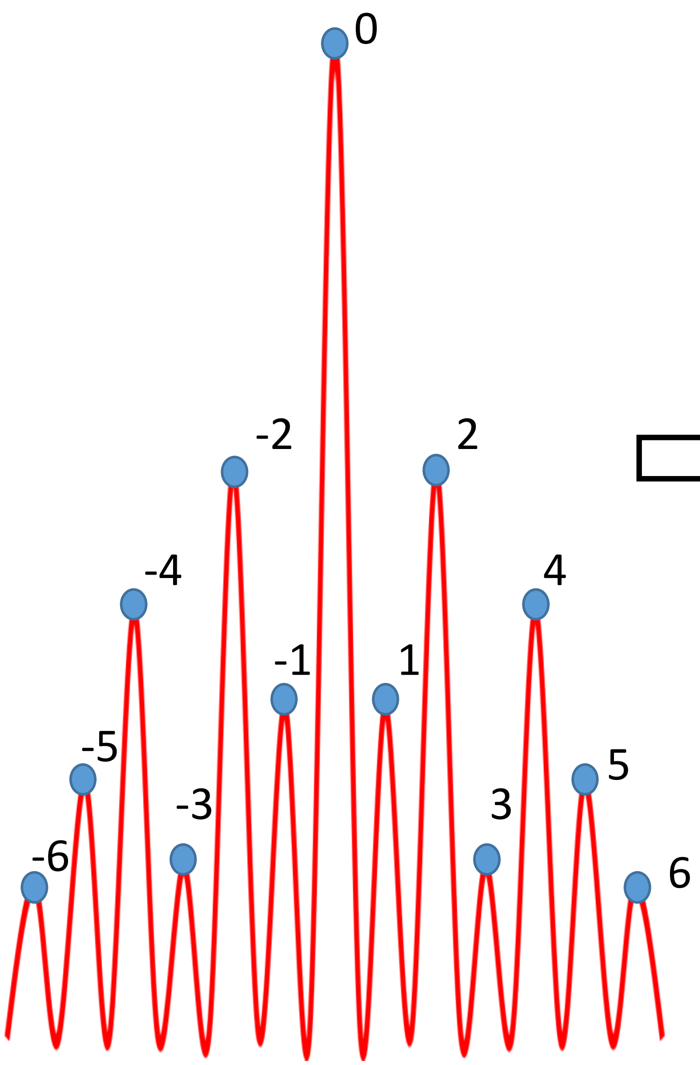
FlexPol

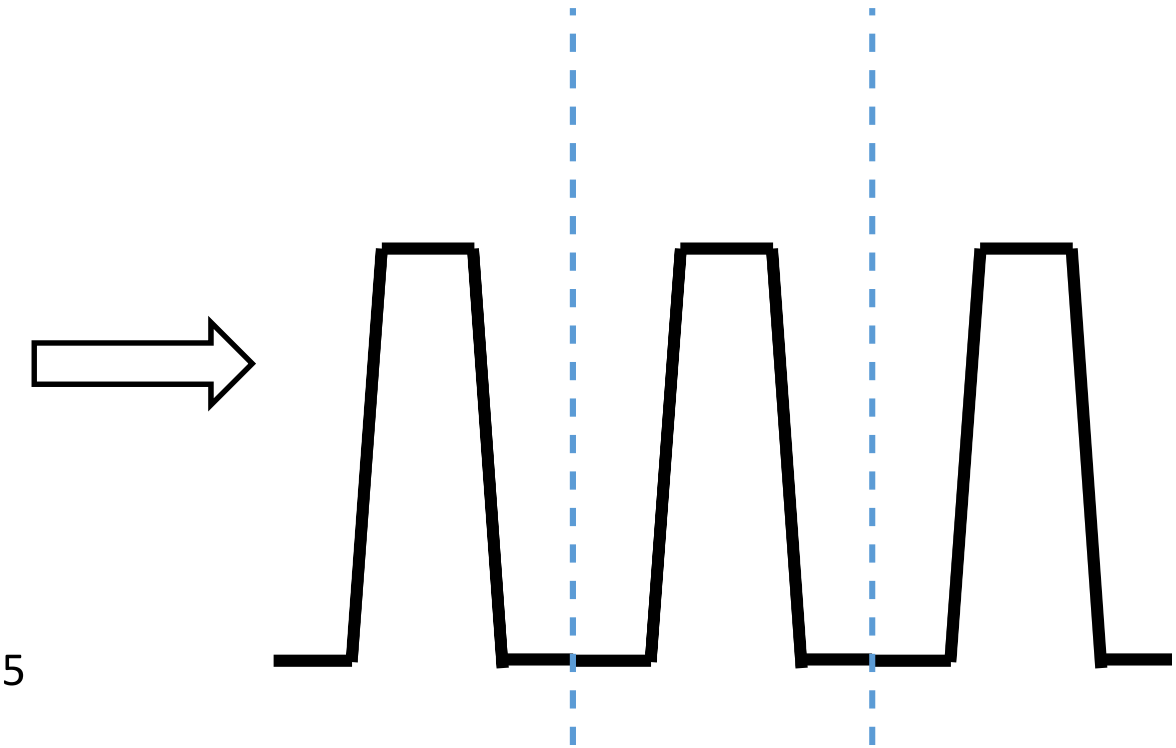




https://www.flexpol.eu/

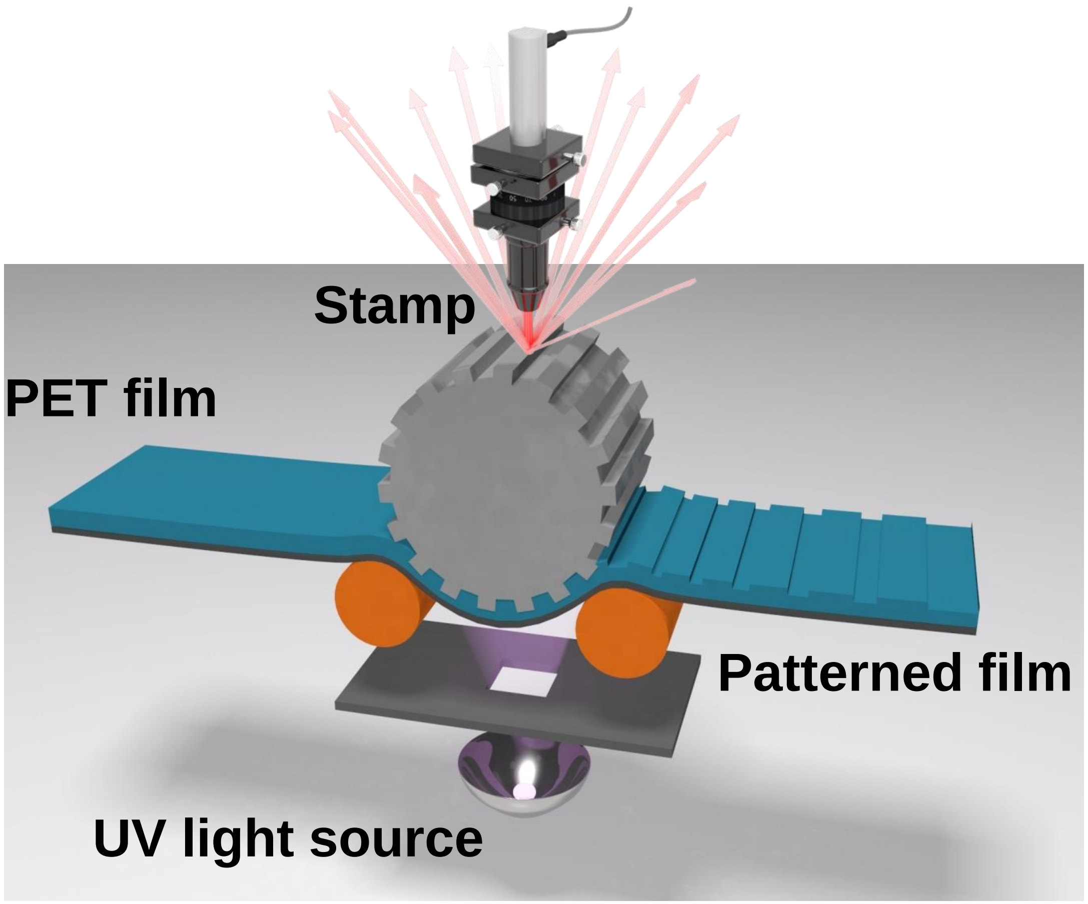
Hypothesis

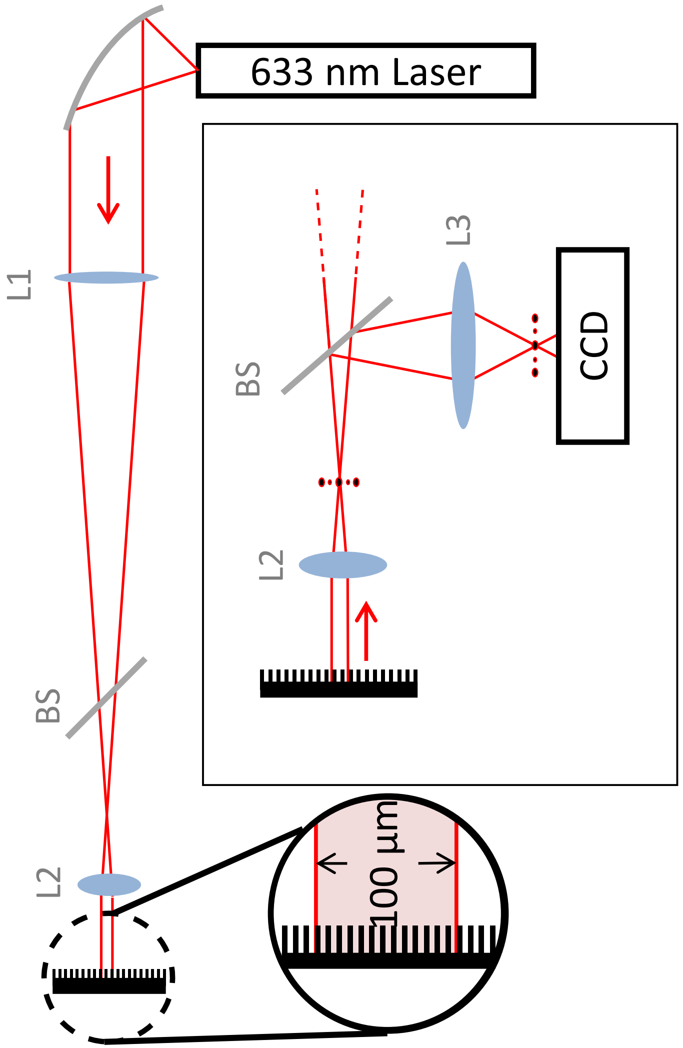




The realtive diffractive effeciencies of the diffraction pattern is indicative of the unit cell which created it

Initial Device



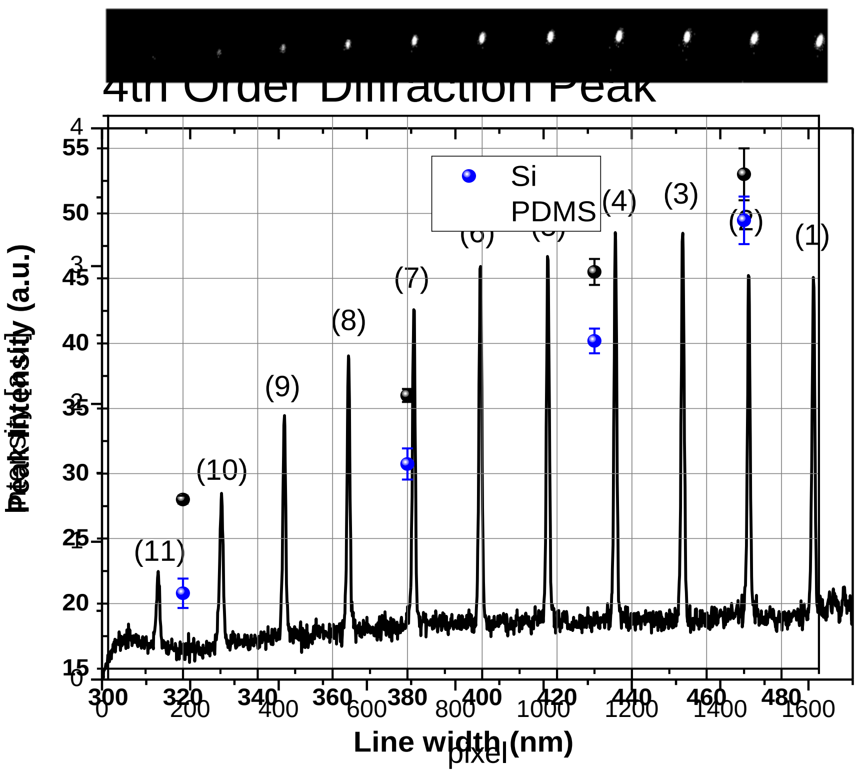


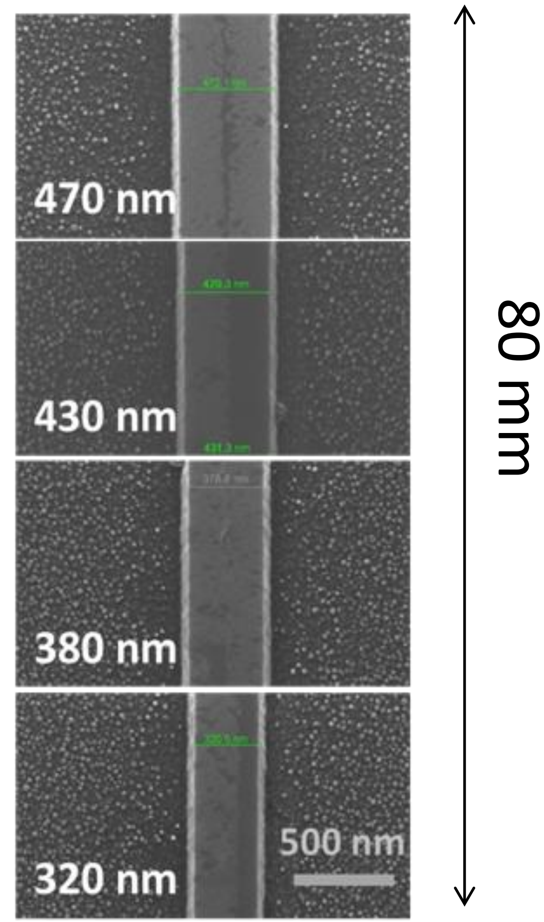
M. Kreuzer et al, APL Materials, **6**, 058502 (2018)

Initial Testing – Line Width Detection

Test Sample

- 80 mm long stripe with 4 distinct regions
- Periodicity 6 µm
- Each region varies line-width (320 – 470 nm)
- Silicon Master replicated in PDMS

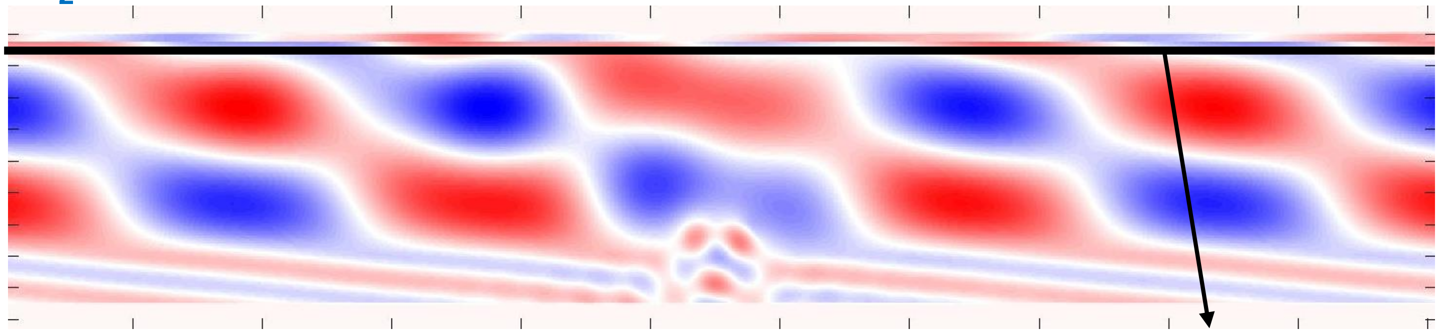




FDFD and The Diffraction Pattern

Device Structure

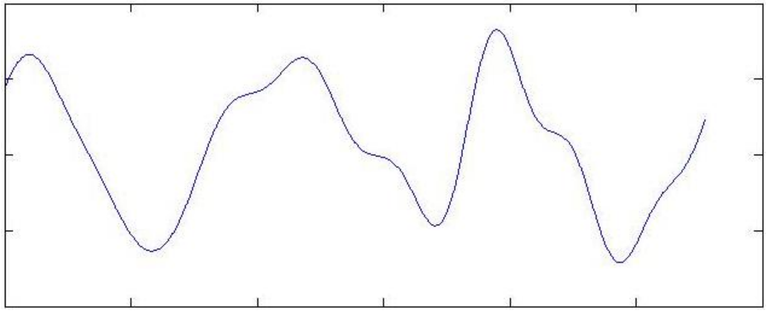
E_z Solution o the FDFD



$h = 115\ nm$ $\quad$ $\mathrm{SWA} = 90°$

$w = 320\ nm$ $\quad$ $\vartheta_{incident} = 18°$

$\mathrm{RC} = 60\ nm$



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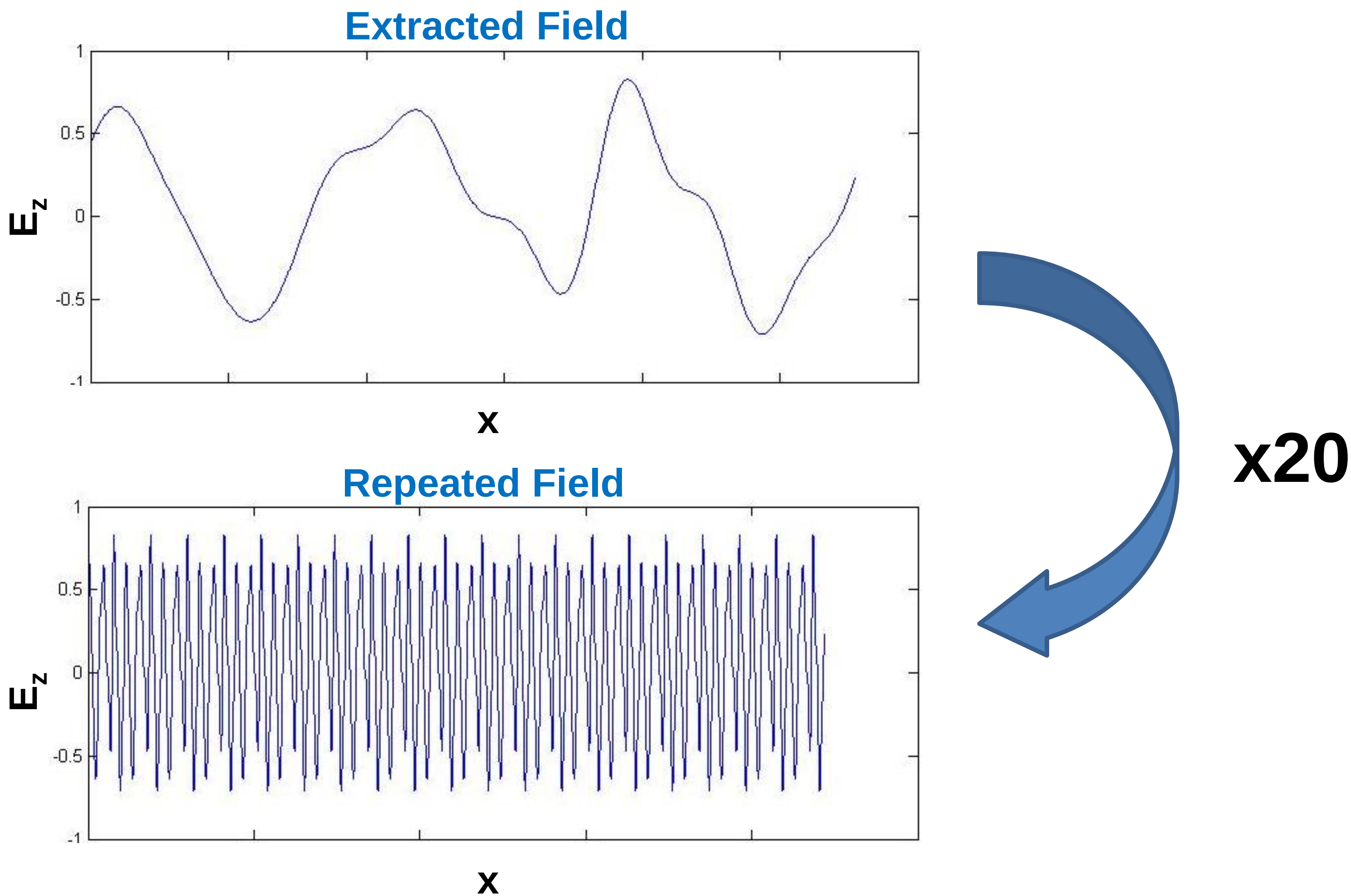
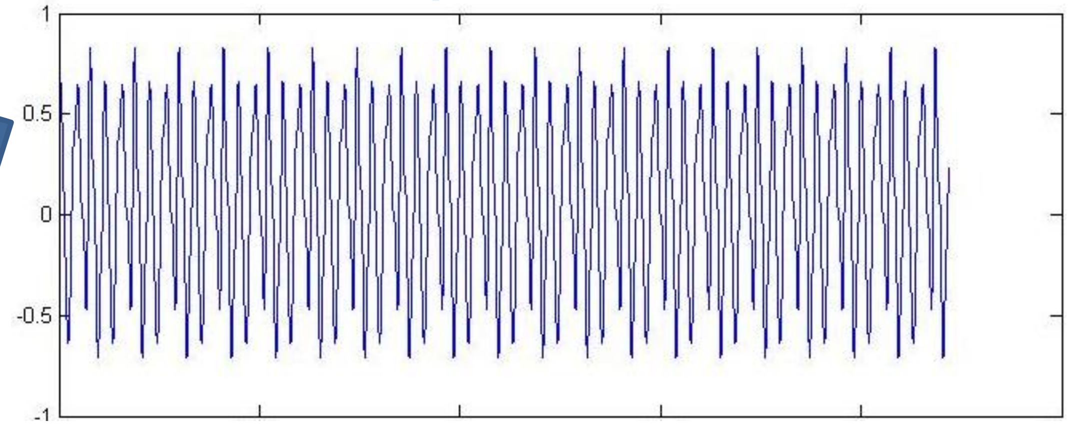
FDFD and The Diffraction Pattern



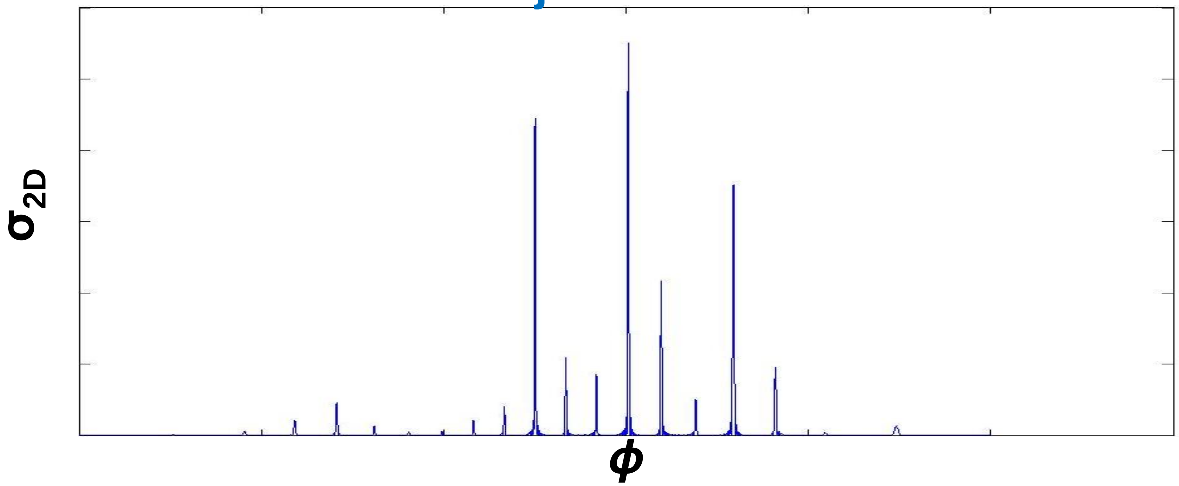
Far-Field Projection

Repeated Field

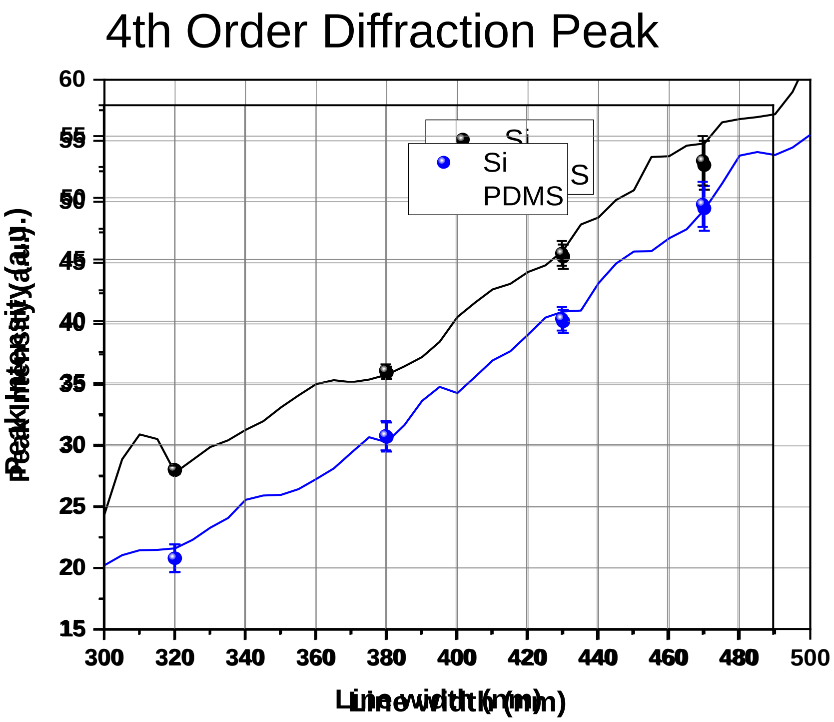


$$\sigma_{2D}(\phi) \propto \left| \oint_L \left\{ \eta_0 \left(n'_x H_y - n'_y H_x \right) - \left(n'_y \sin\phi + n'_x \cos\phi \right) E_z \right\} e^{ikr' \cos(\phi - \phi')} k\, dl' \right|^2$$

Projected Far-Field



Calibrating for Line-Width



Silicon

$h = 115 \pm 10\,nm$

$\vartheta_{incident} = 13 \pm 1°$

$\mathrm{RC} = 50 \pm 15\,nm$

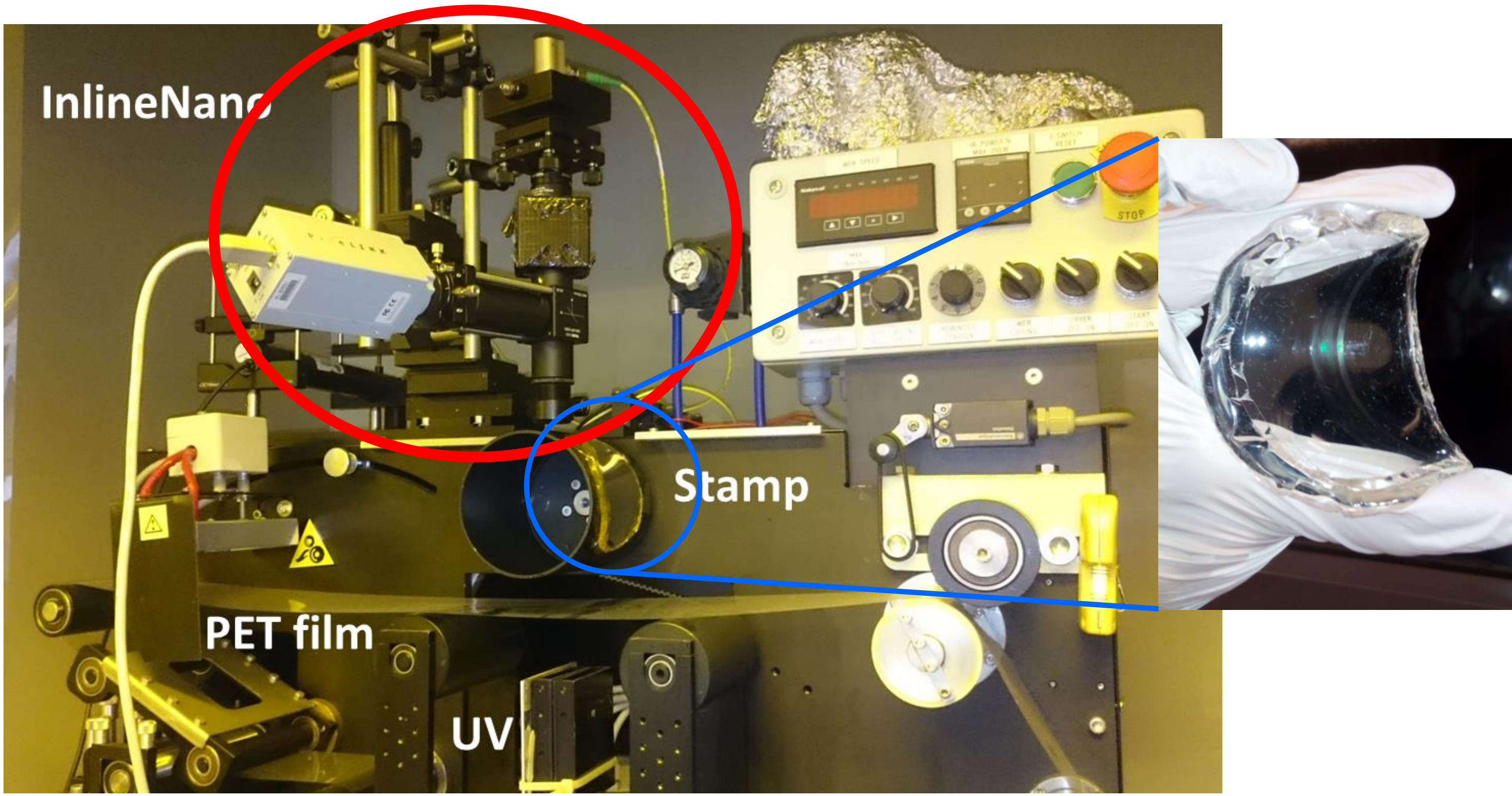
PDMS

$h = 120 \pm 5\,nm$

$\vartheta_{incident} = 11 \pm 1°$

$\mathrm{RC} = 40 \pm 15\,nm$

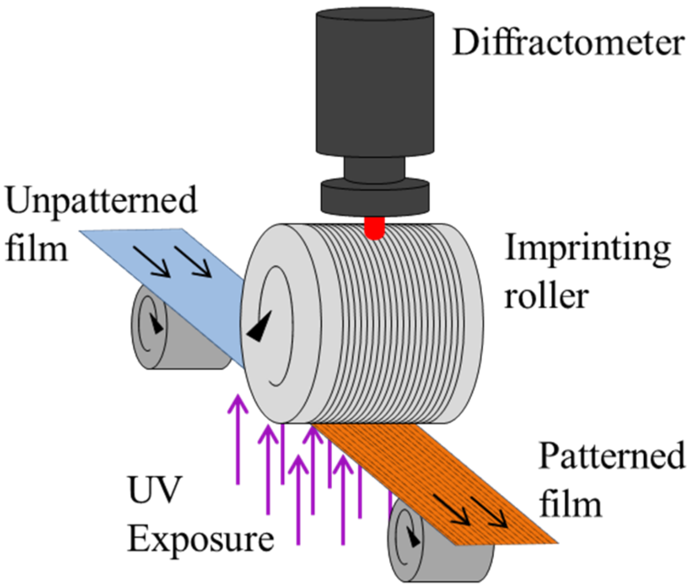
M. Kreuzer et al, APL Materials, **6**, 058502 (2018)

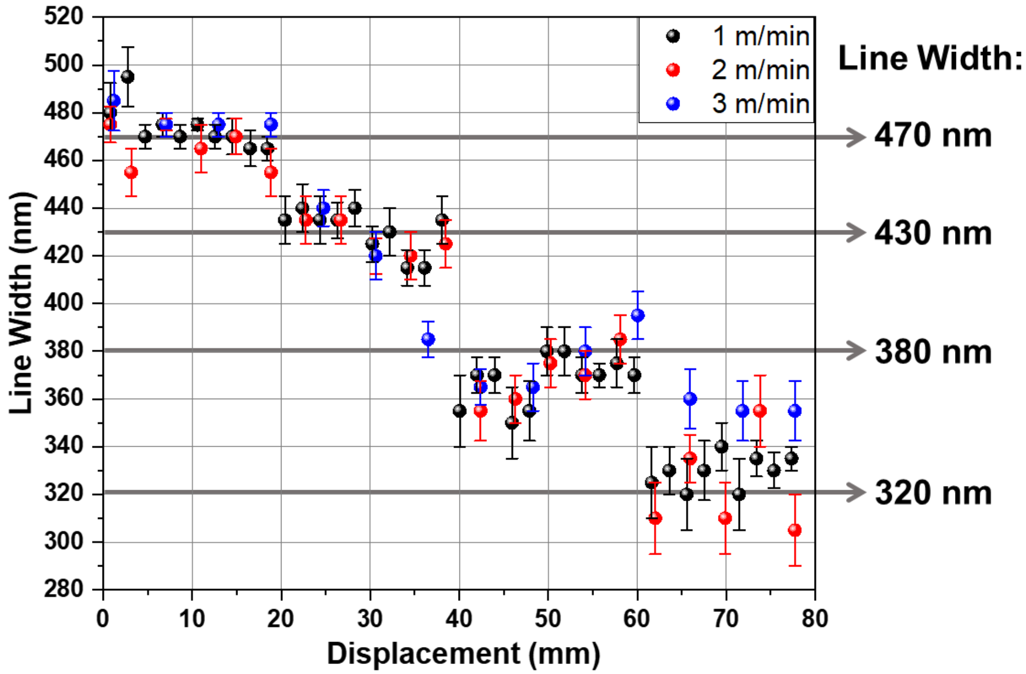


OFFLINE MEASURMENT

M. Kreuzer et al, APL Materials, **6**, 058502 (2018)

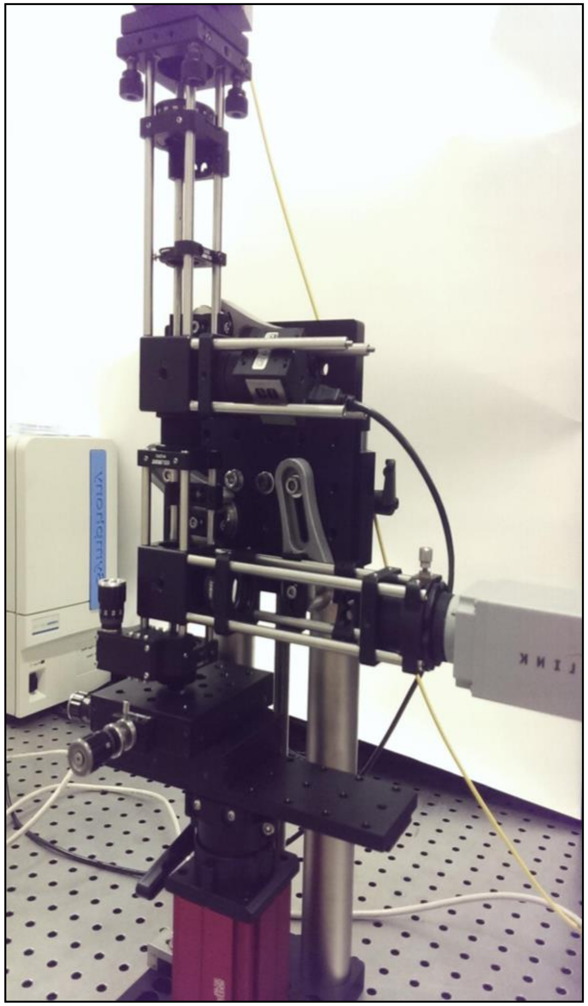
Roll-to-Roll Line Width Sensing

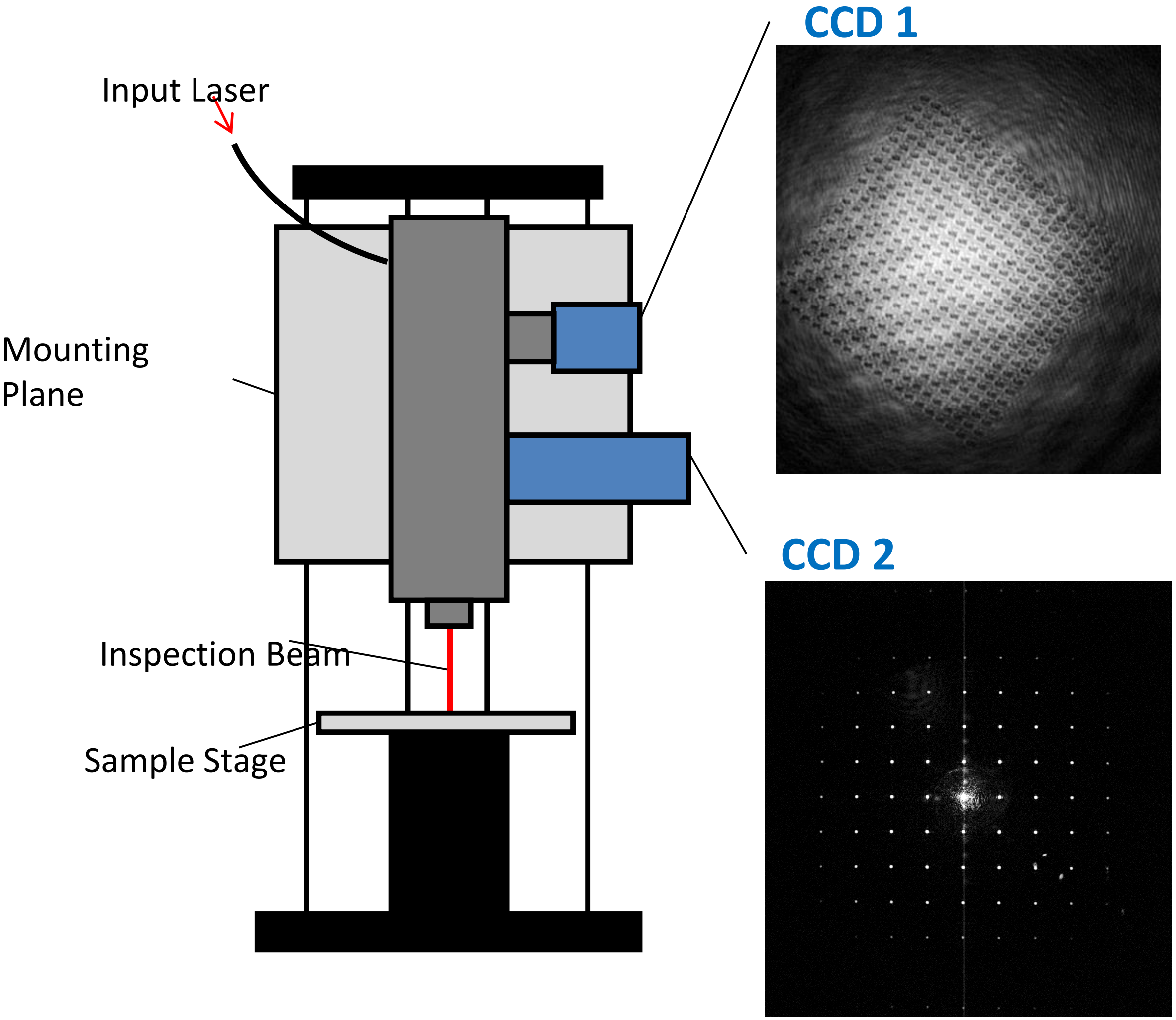




M. Kreuzer et al, APL Materials, **6**, 058502 (2018)

Diffractometry: System Update

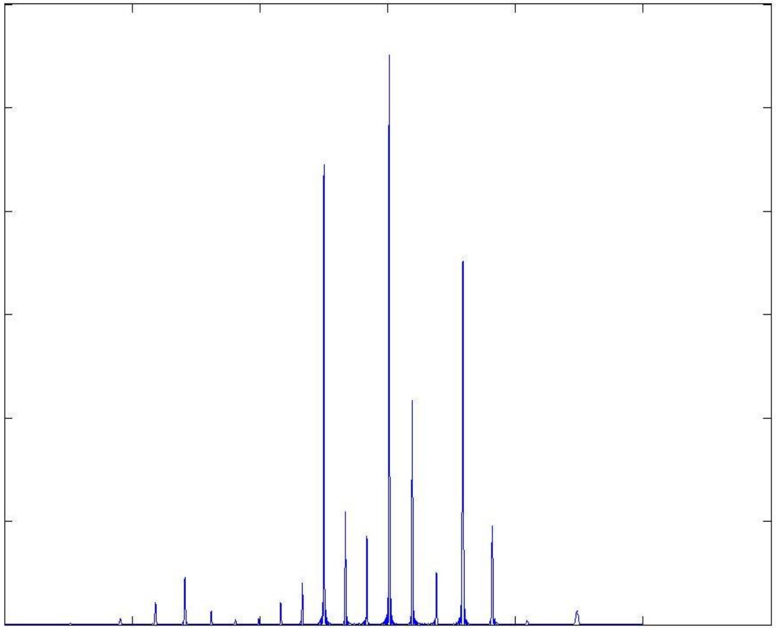




M. Kreuzer et al, APL Materials, **6**, 058502 (2018)

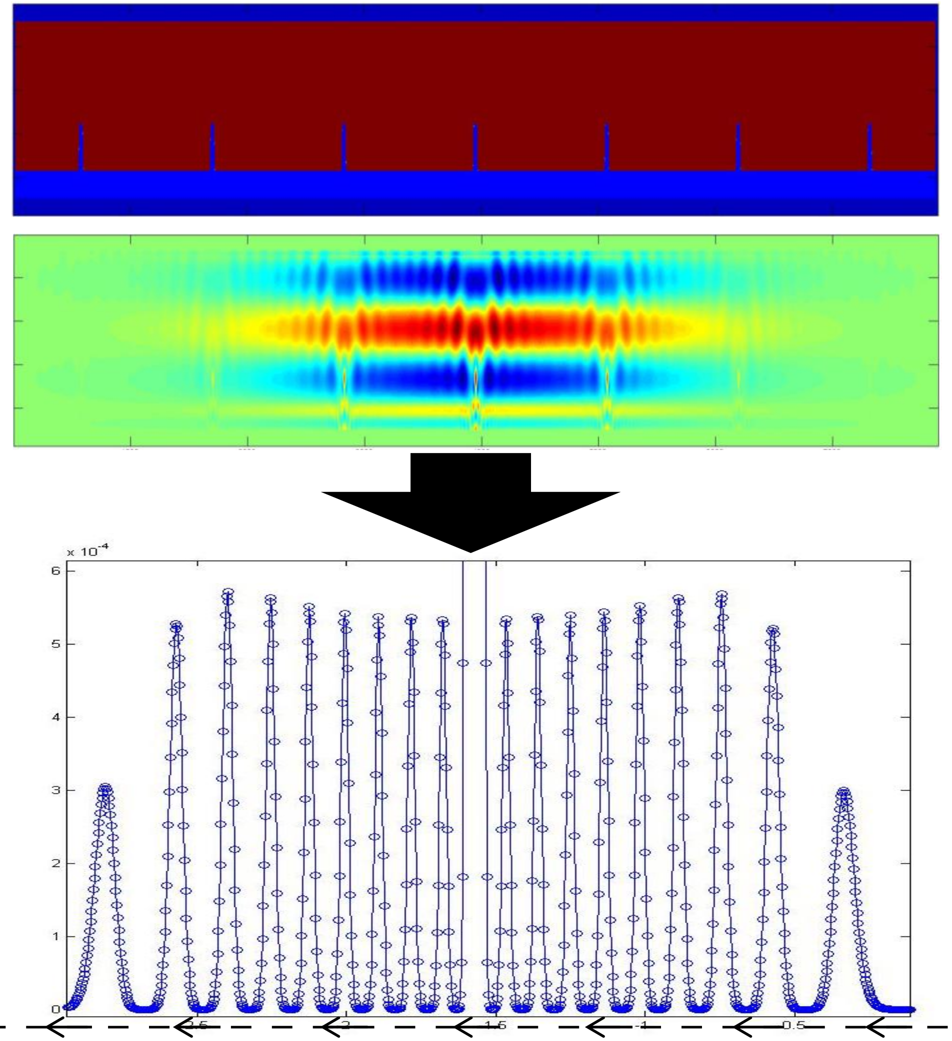
FDFD: Update Methodology

FDFD Old Method



Modelling finite, more realistic areas leads to smooth far-field diffraction patterns

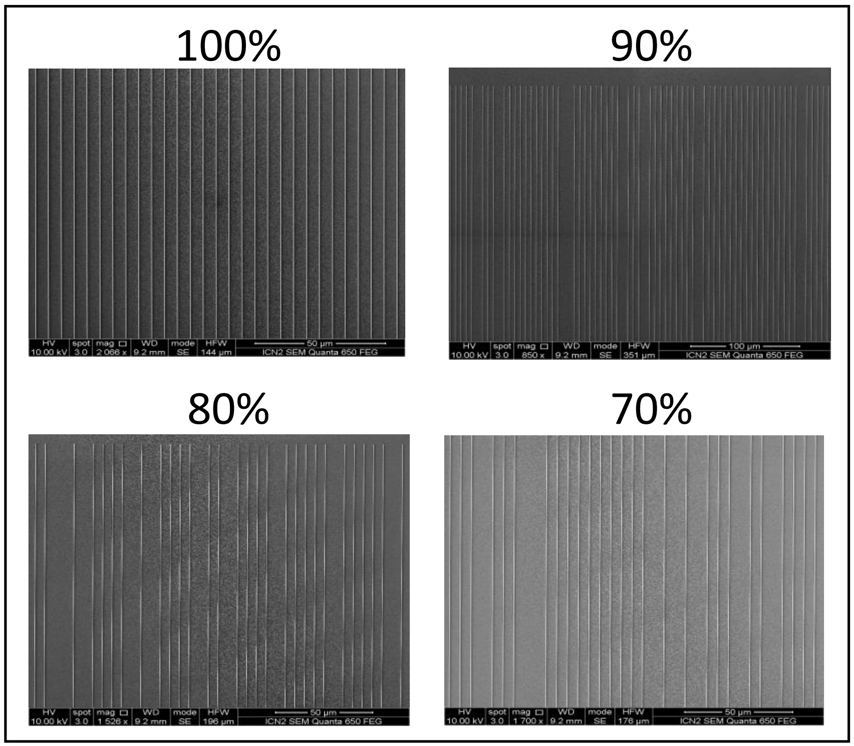
FDFD New Method

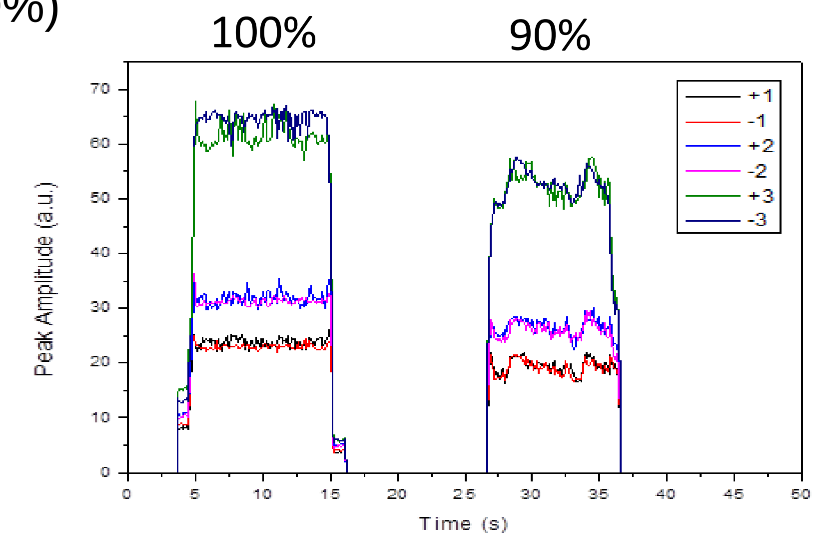


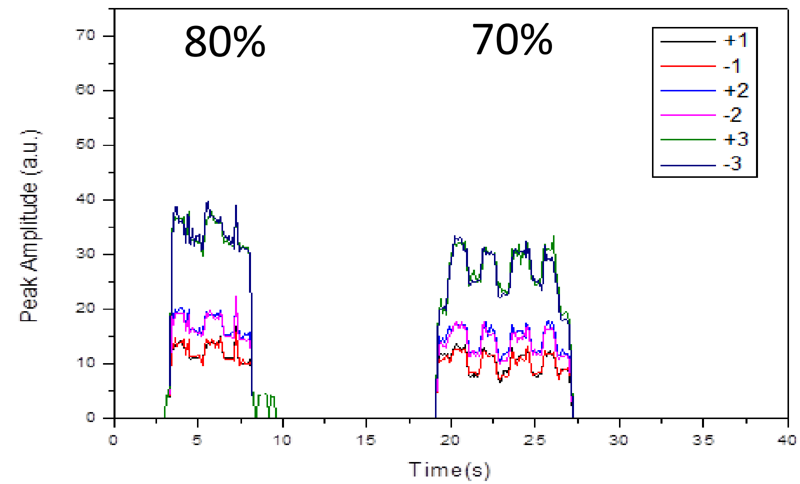
Defect Detection

Defect Gratings

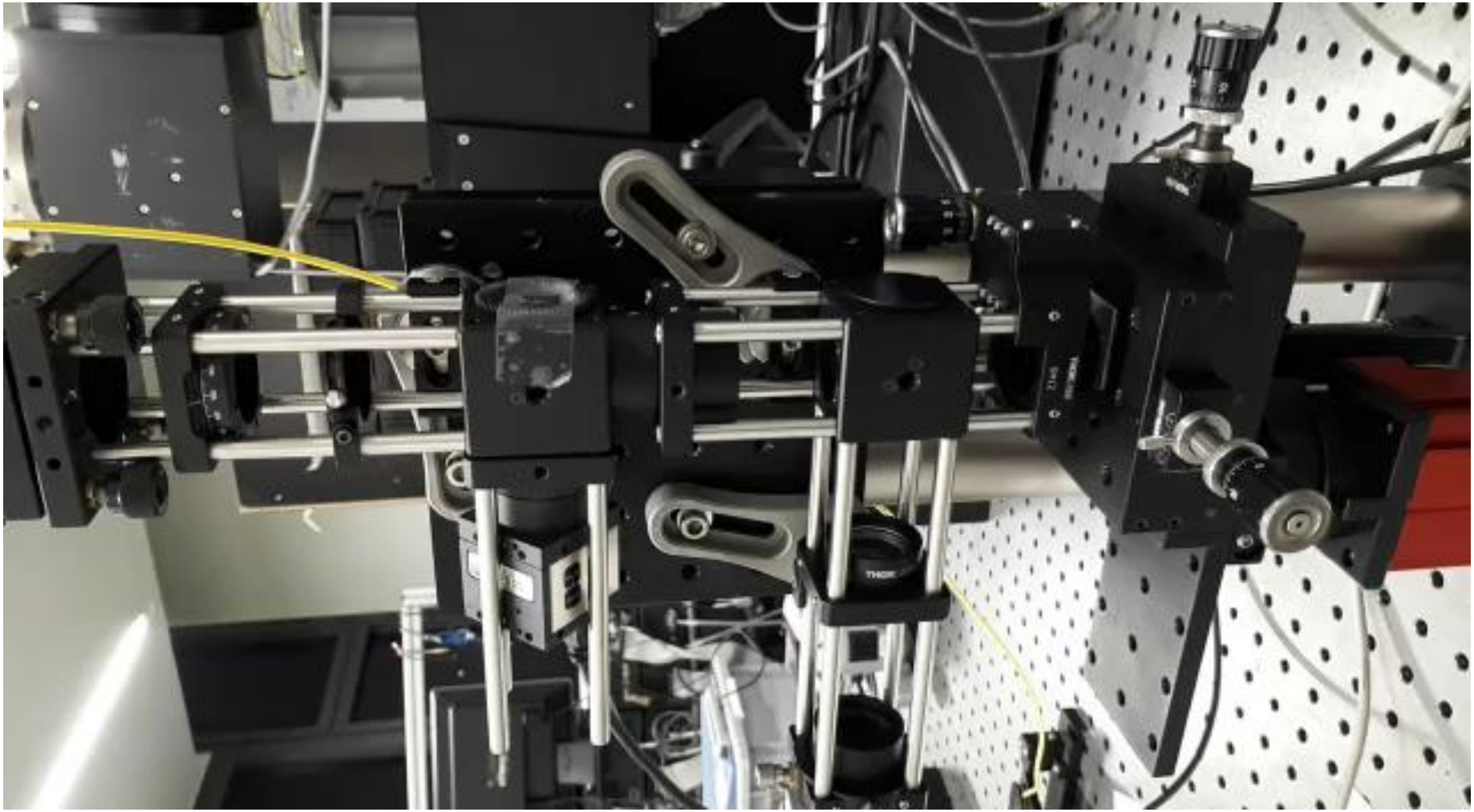
- Varying amounts of missing lines (100-70%)
- 5 μm pitch
- ~ 300 nm height
- ~ 200 nm width





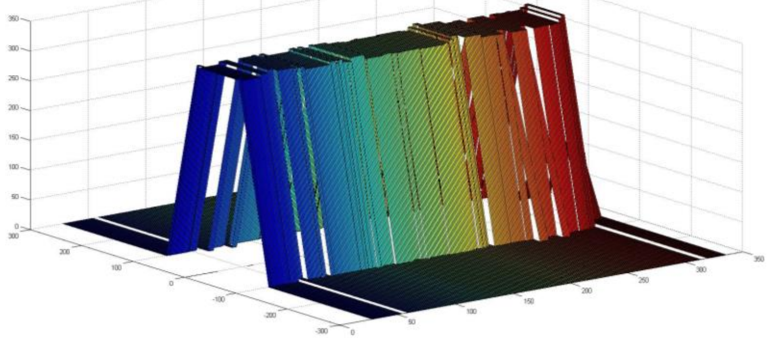


Live Diffractometry



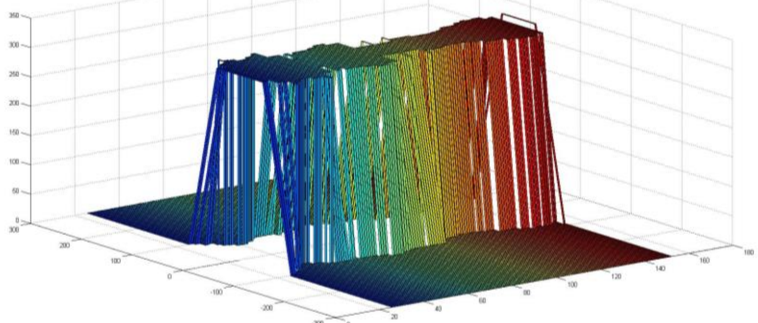
Diffractometry

Silicon Master



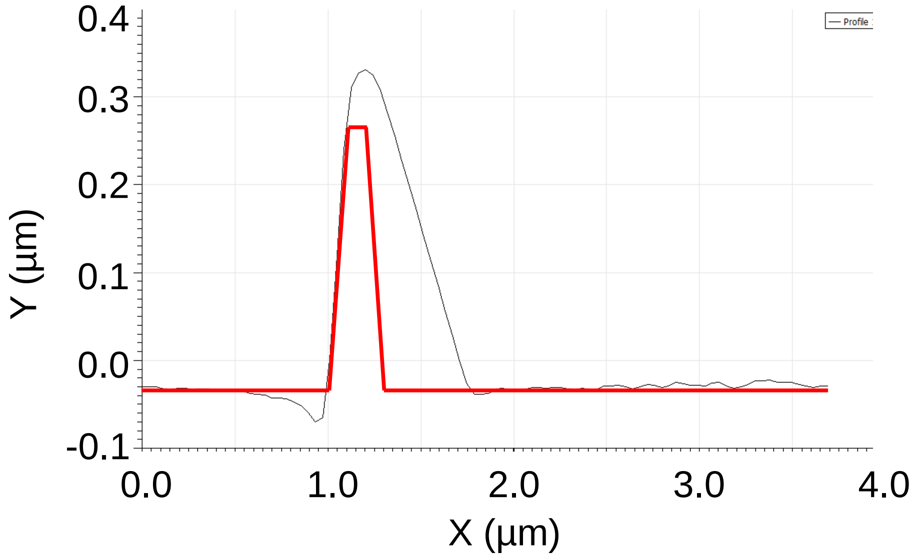
Height = 330 ± 5 nm, Width= 95 ± 5 nm, Slope = 78 ± 2 °

Ormocomp NI Replica



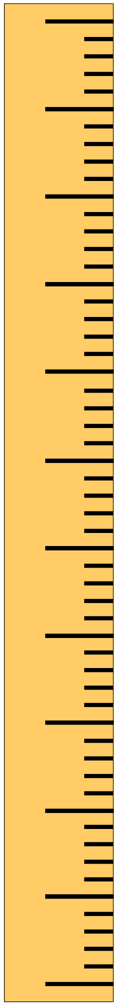
Height = 315 ± 5 nm, Width= 90 ± 10 nm, Slope = 72 ± 6 °

Ormocomp AFM Comparison



- Comparison shows reasonable agreement with AFM limitations
- Comparison with a FIB cross-section required

Conclusions



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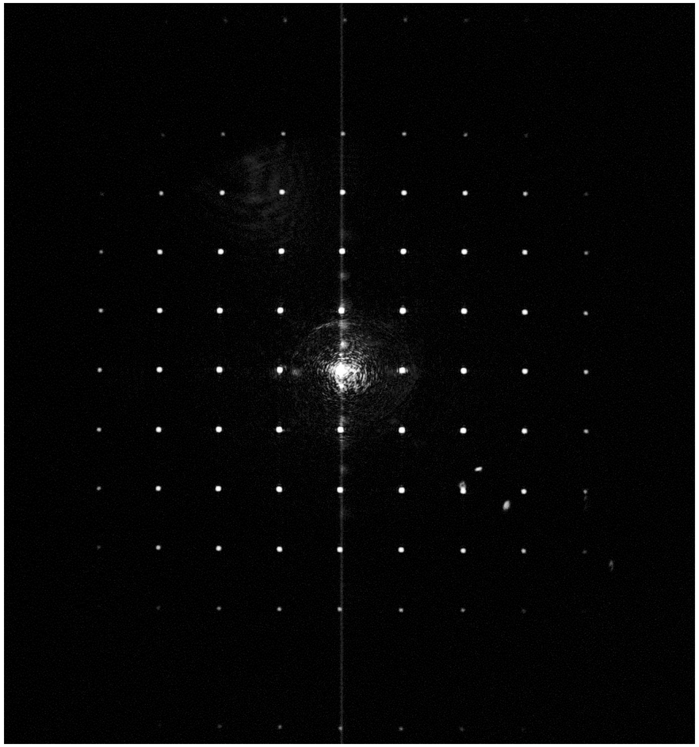
Future of Diffractometry

- Potential for high-throughput fast dimensional metrolgoy
- Nanoscale accuracy but limited to microscale periodicity
- Improvements required on traceability
- Move to 2D structures
- Possibility for other metrology for microscale phenomena (hydrophobicity, microlens)



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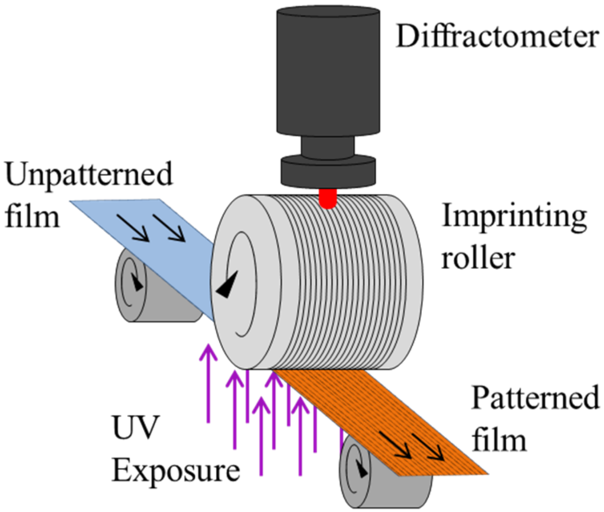
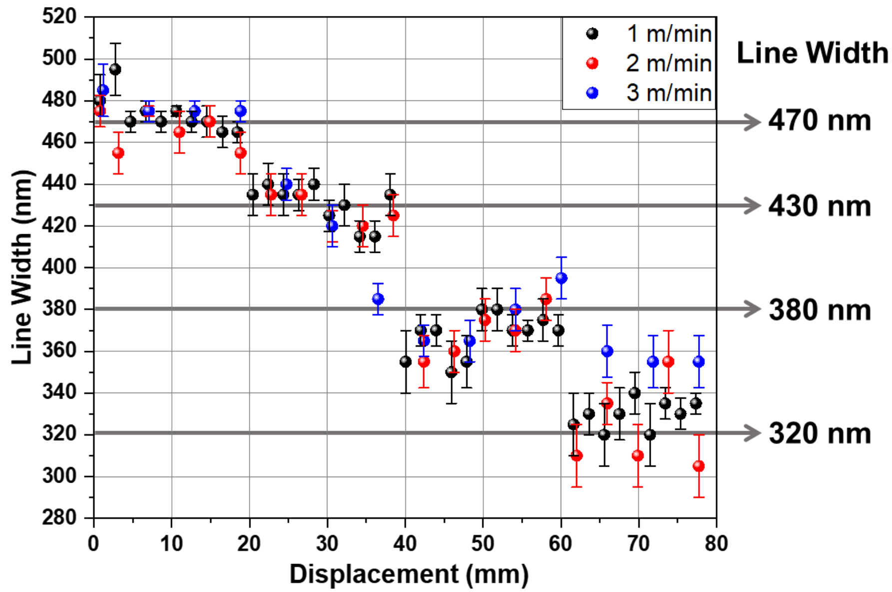
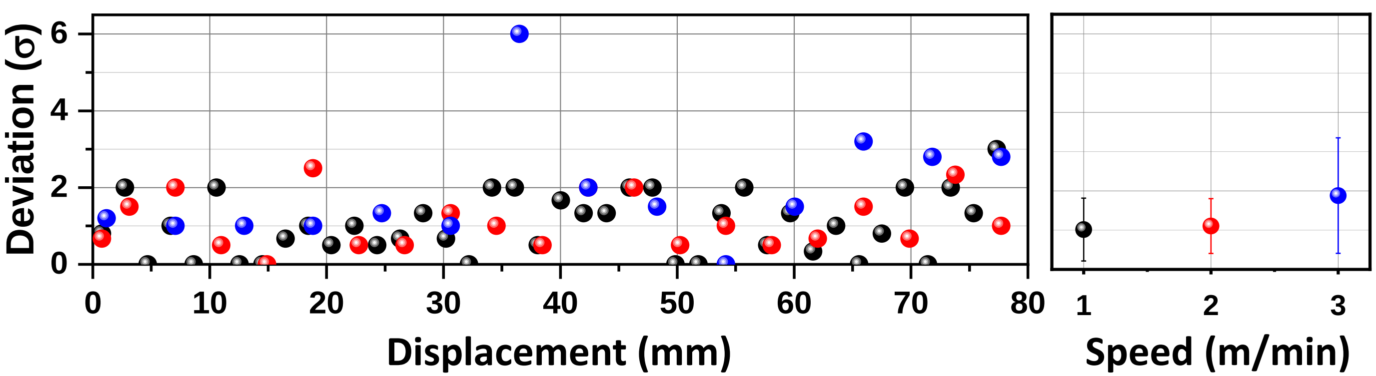


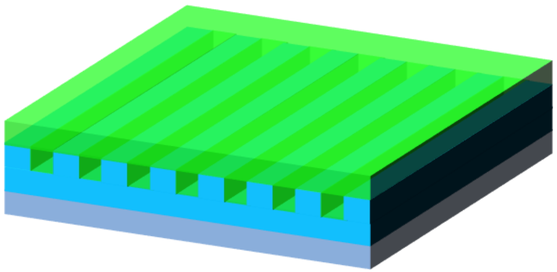




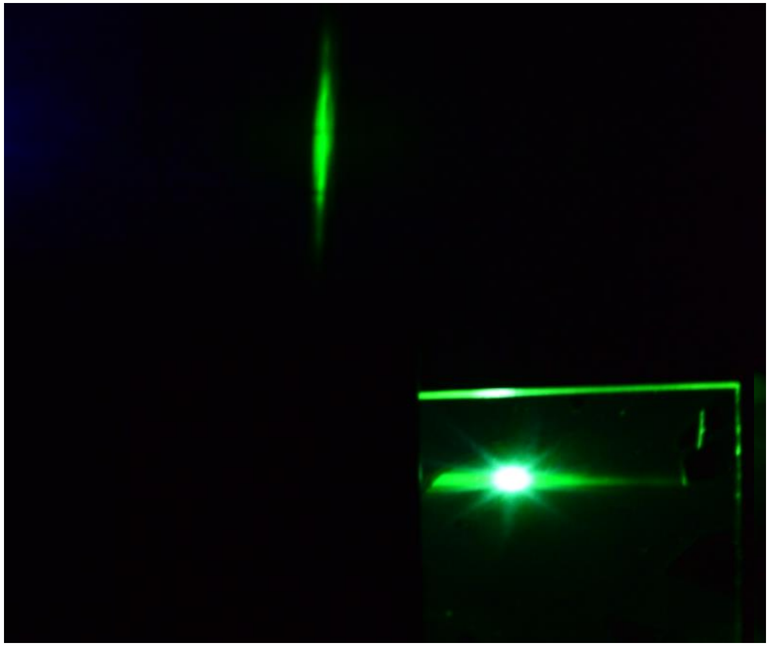
M. Kreuzer et al, APL Materials, **6**, 058502 (2018)

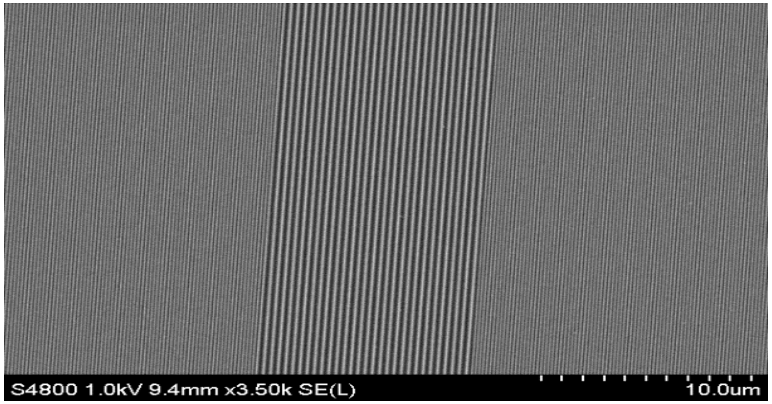
Example : Organic DFB Lasers

- Completely Solution Processable
- Wavelength Tuneable Laser
- Easy to Upscale?



$$\Lambda \propto \lambda_{laser}$$





Organic Semiconductor Lasers, I. D. W. Samuel*, and G. A. Turnbull, *Chem. Rev.*, 2007, *107* (4)