JOHANNES KEPLER UNIVERSITY LINZ | JKU

Strain mapping with Polarisation-Sensitive Optical Coherence Tomography

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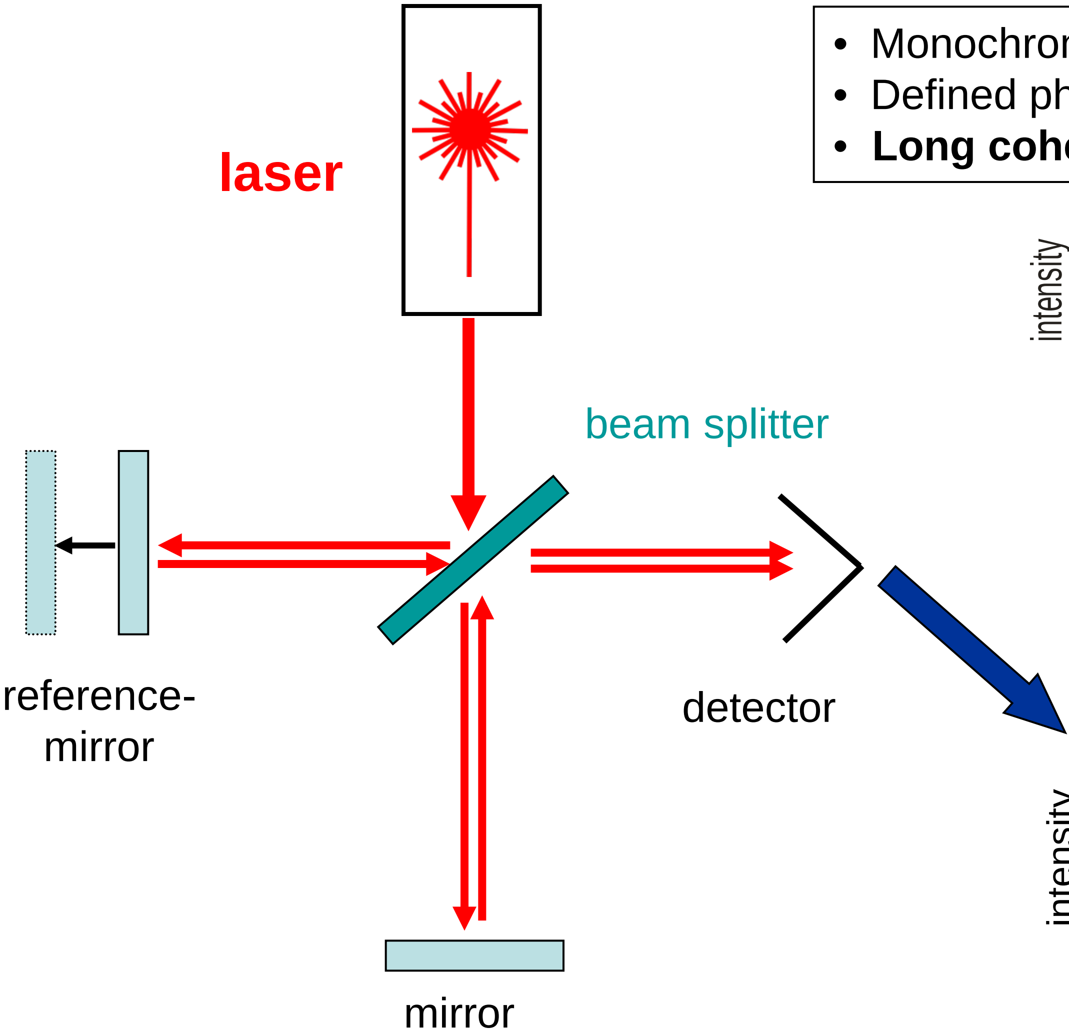
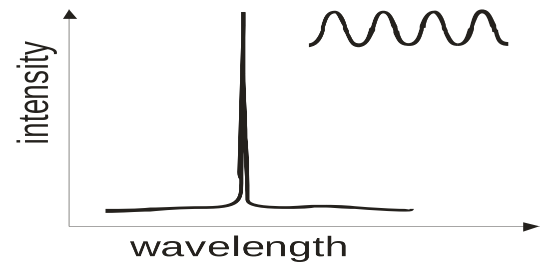
Outline

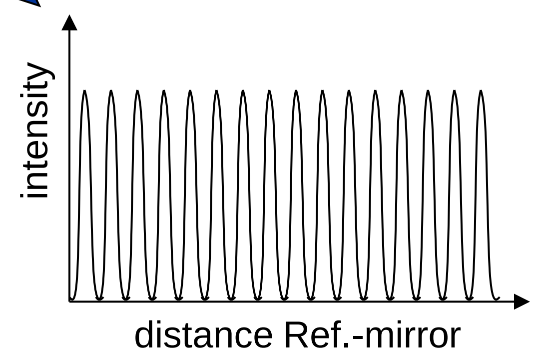
- Introduction to optical coherence tomography (OCT)
- Extension of OCT towards polarization-sensitive imaging (PS-OCT)
- Application of PS-OCT for strain mapping and dynamic material characterization
- Conclusion and outlook

Laser interferometry

- Monochromatic (single frequency)
- Defined phase relation over longer distances
- **Long coherence length L**



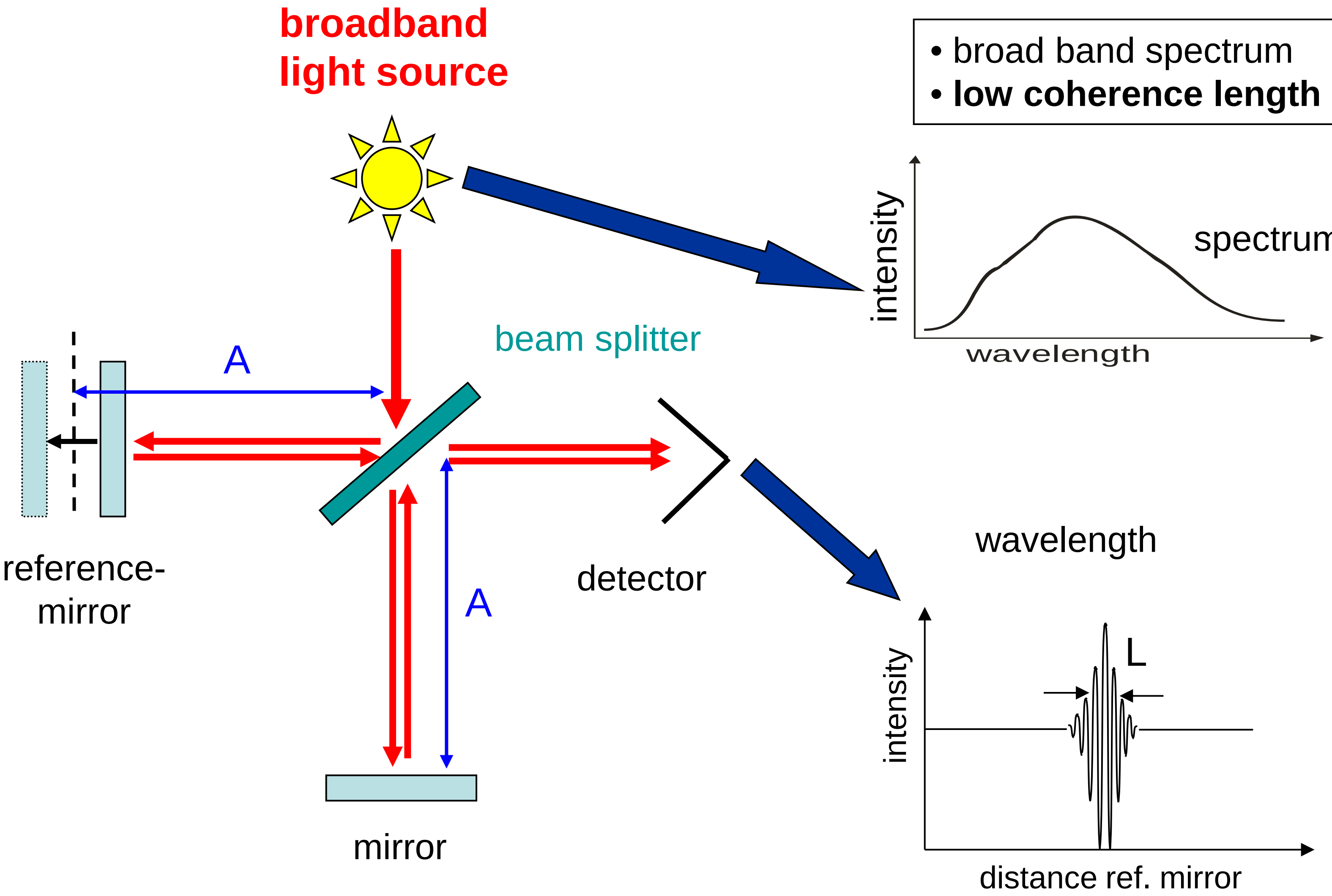




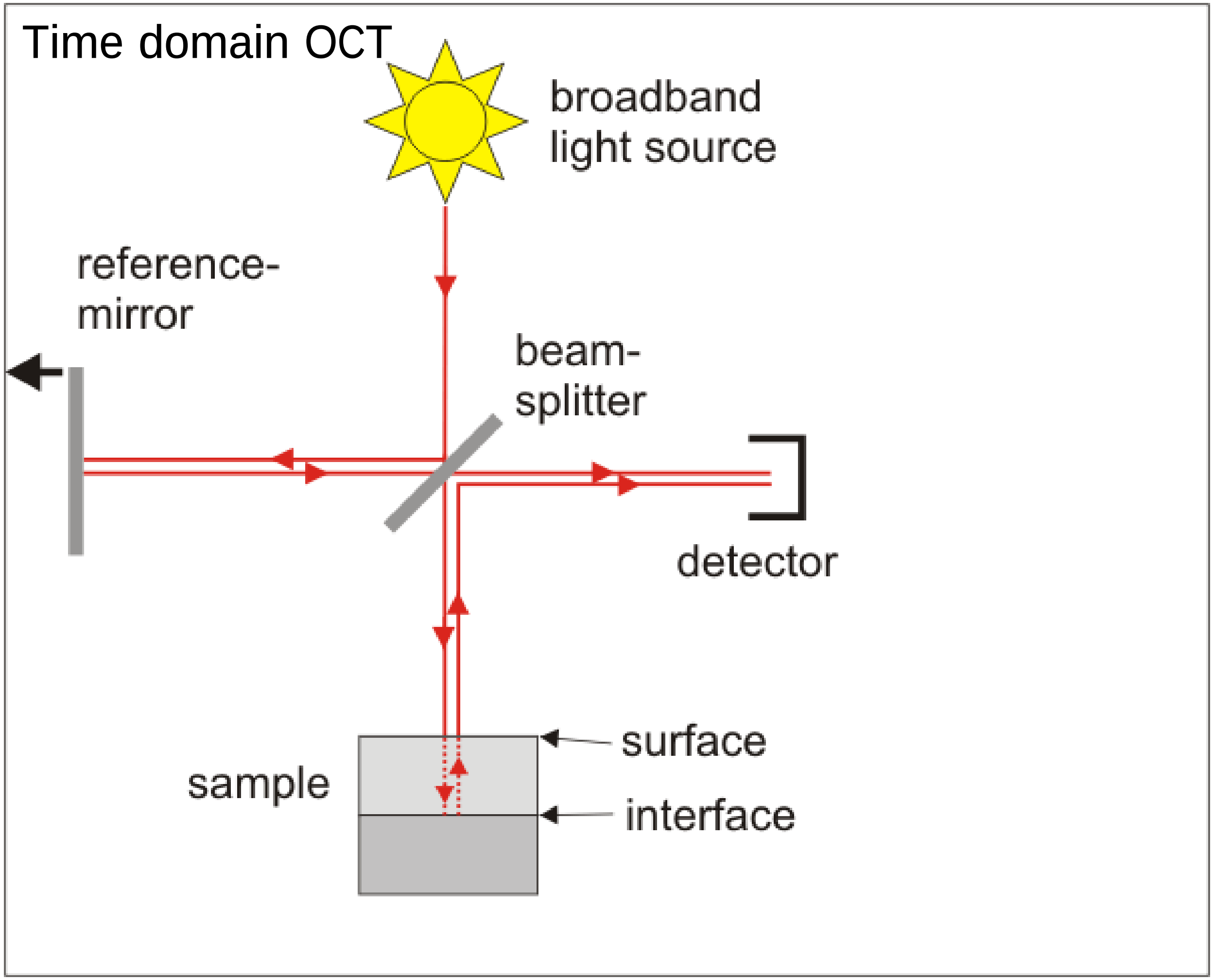
Michelson Interferometer

White light (low coherence) interferometry (WLI/LCI)

- broad band spectrum
- **low coherence length L**

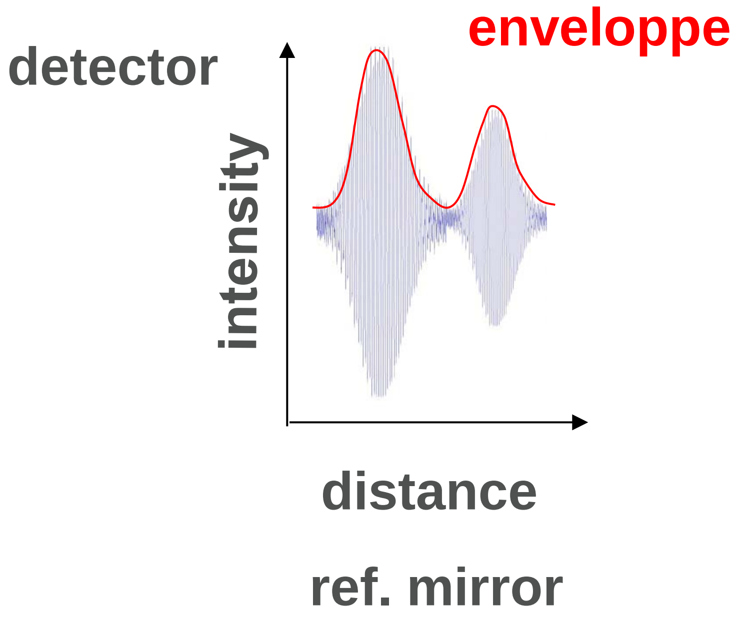


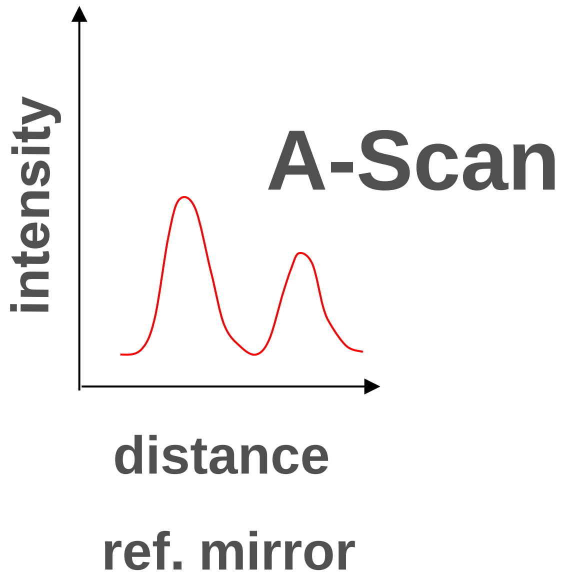
Principle of OCT



→ D. Huang et al., Science 254, 1178 (1991)

OCT depth profile: A-Scan

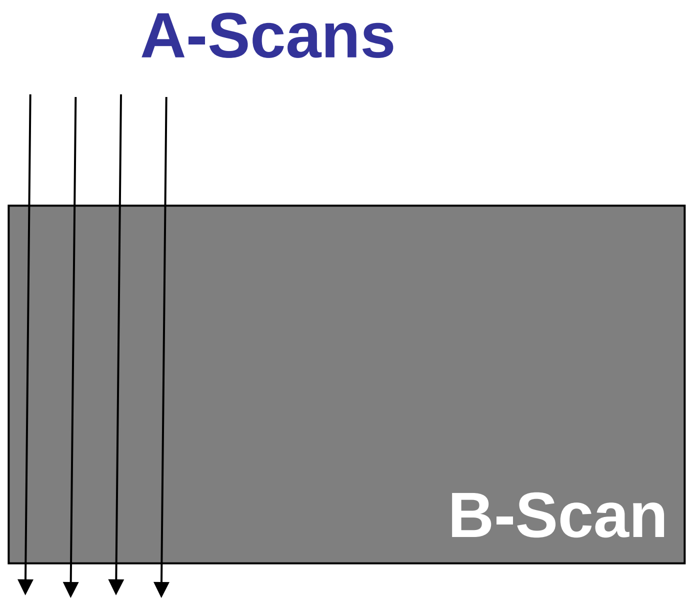




OCT cross-section: B-Scan

Sequence of A-Scans leads to:

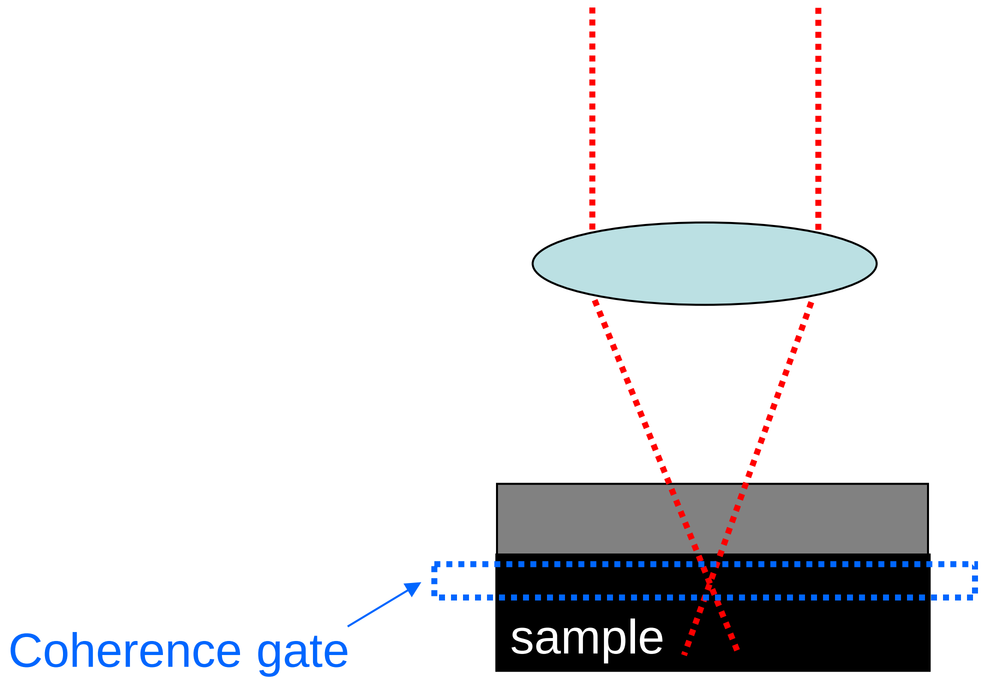
cross-sectional image (B-scan)



OCT: lateral resolution

→ decoupled from axial (depth) resolution

→ determined by spot size



OCT depth (axial) resolution

Axial resolution δz (decoupled from lateral resolution):

$$\delta z = \frac{l_C}{n_{Medium}} = \frac{2\ln 2}{n_{Med}\pi}\frac{\lambda_C^{\ 2}}{\Delta\lambda}$$

l_c...coherence length, λ_c...central wavelength, Δλ...spectral width, n…refractive index

→ Demand for broadband light sources

OCT: high sensitivity

→ Incident power ~ 1 mW

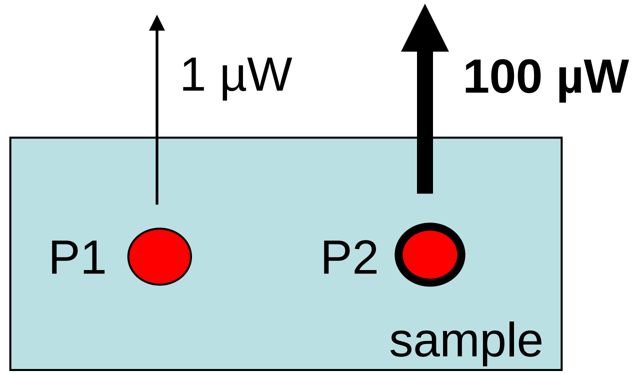
→ 5-15 scattering events

→ High dynamic range

→ High sensitivity (~100 dB, femtoWatt detectable)

→ Penetration depth in scattering media ~ mm range (depending on wavelength and material)

OCT: high sensitivity



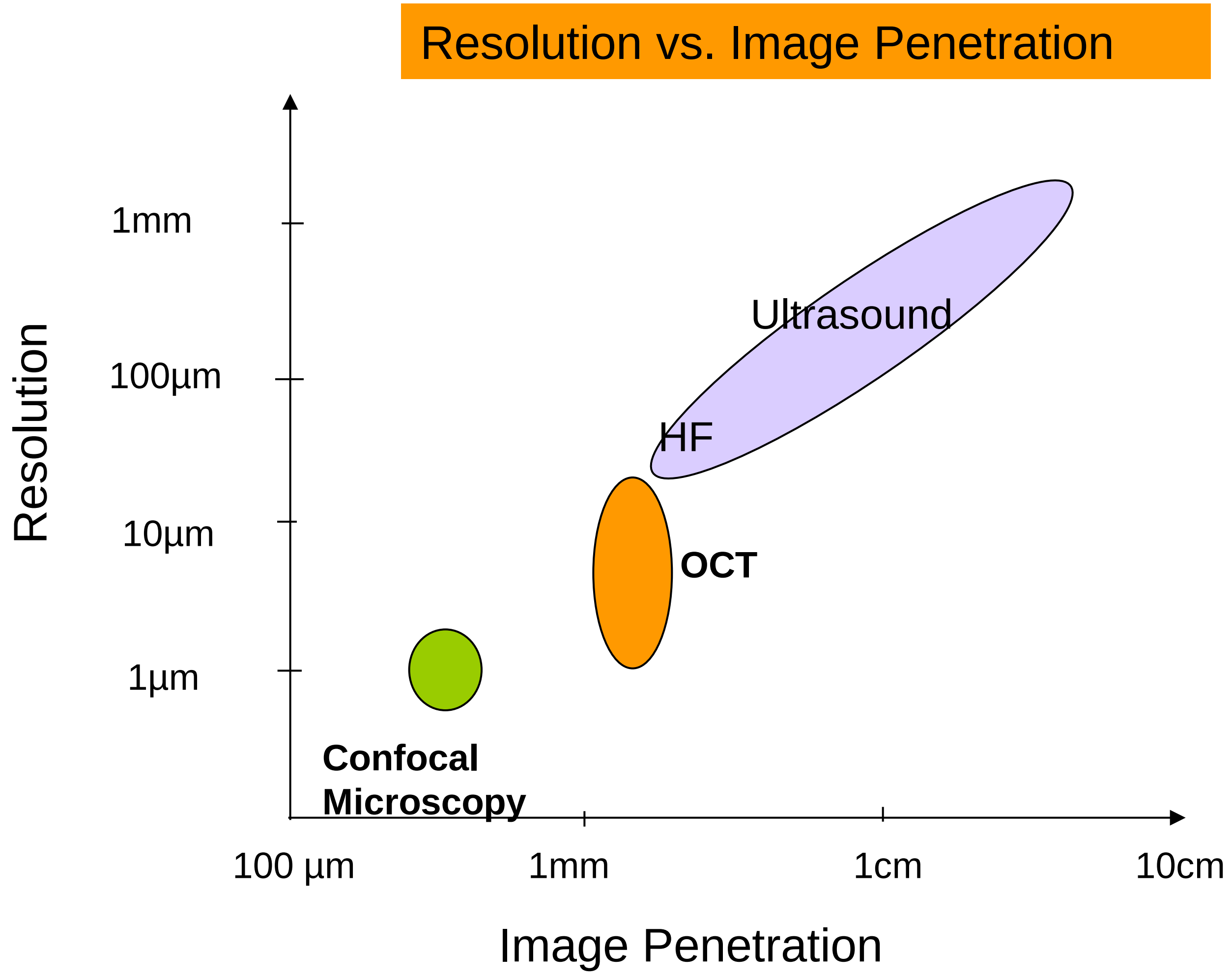
Intensity-based measurement method (e.g. fluorescence microscopy):

- Detector: P1/P2 = 1:100

OCT:

- Signal ~ E_{ref} * E_{sample} → P1/P2 = 1:10 !
- Signal E_{sample} multiplied with reference field → coherent amplification

Micro-imaging techniques



Origin of OCT: biomedical diagnostics

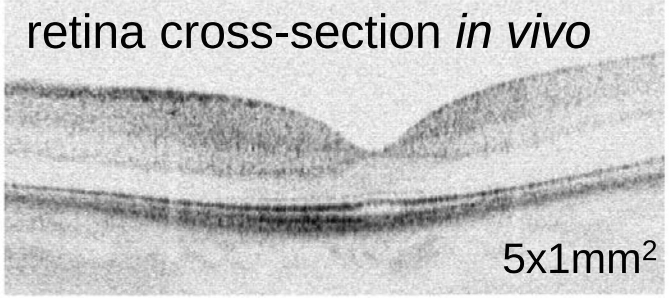
Ophtalmology:

- Diseases of retina (glaucoma)

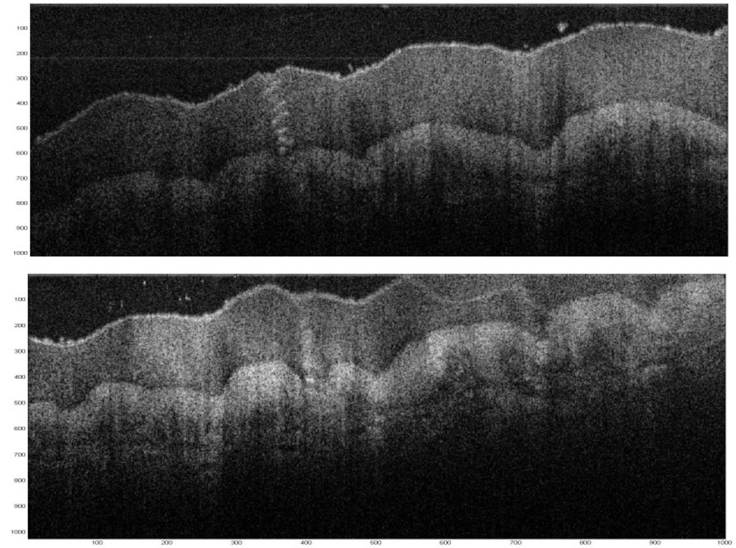
Dermatology:

- Skin cancer, melanoma detection

OCT:
retina cross-section *in vivo*



Pircher et. al., OPT. EXPRESS 12, 5940 (2004)



OCT for material characterization

Main applications: **bio-medical** (retina, skin, arteries, teeth, ...)

Material investigation?

- **Polymers, compound materials, ceramics, glasses...**

- Sizes in the range of a few microns
  (diameters of fibres, size of inclusions, thickness of layers)

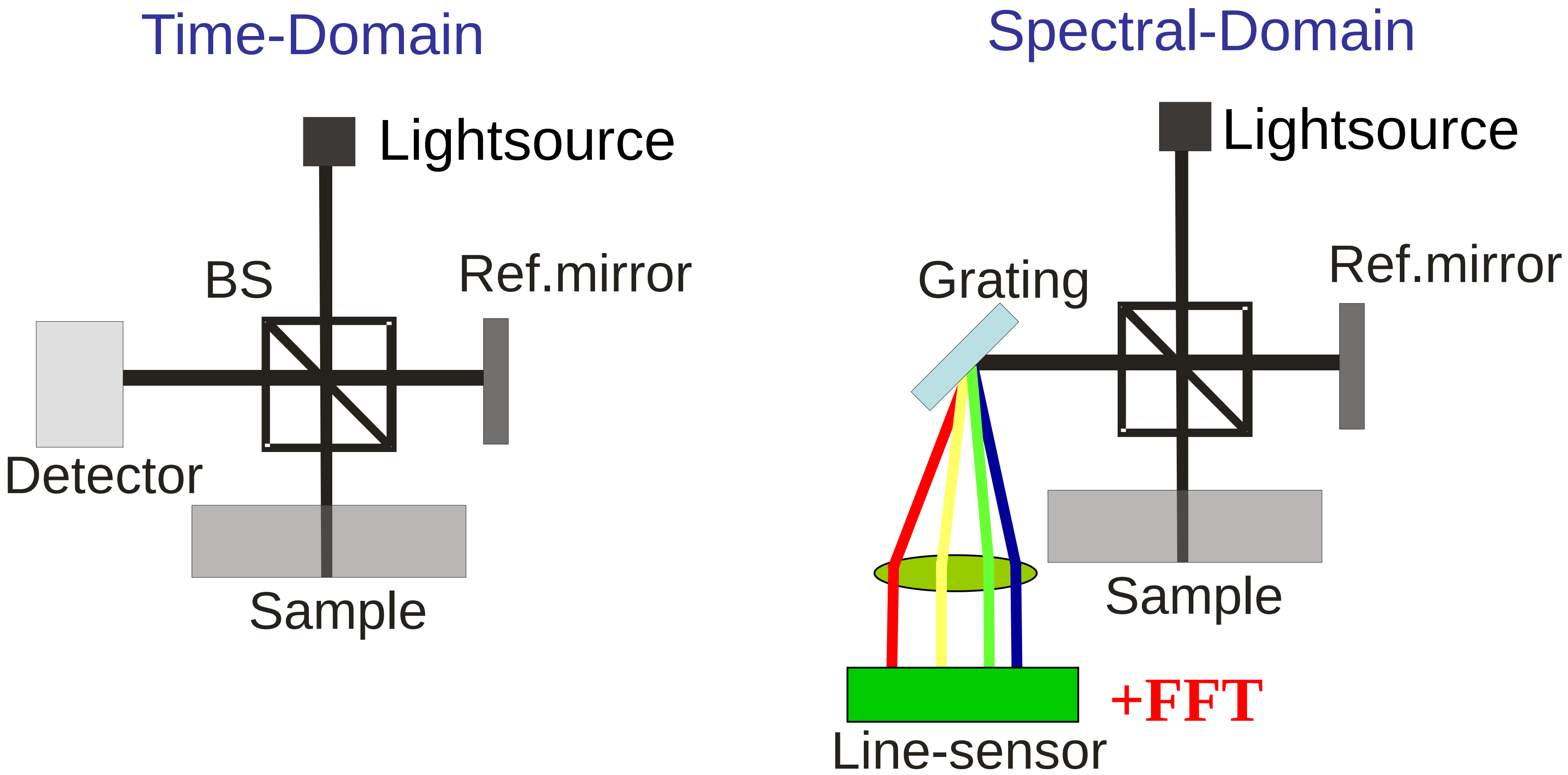
→**Ultra-high resolution OCT**

- Additional information and contrast: e.g. internal strain

→**Polarization-sensitive OCT**

- On-line inspection: **short measurement times (FD-OCT)**

Time-Domain versus Fourier-Domain (Spectral-Domain (SD))



1-1000 A-scans/s

20.000-100.000 A-scans/s

Time-Domain versus Fourier-Domain (Spectral-Domain (SD))

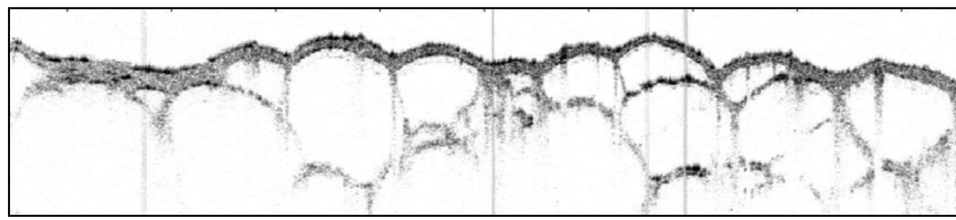
Image-size: 1 Mpxl

Polyolefin foam

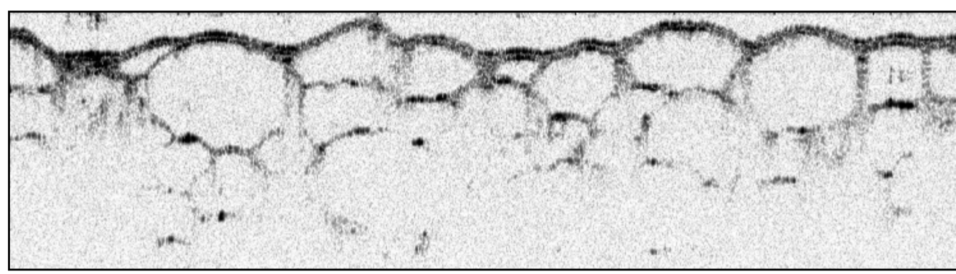
500 µm

First TD-OCT (with SLD):
500 seconds

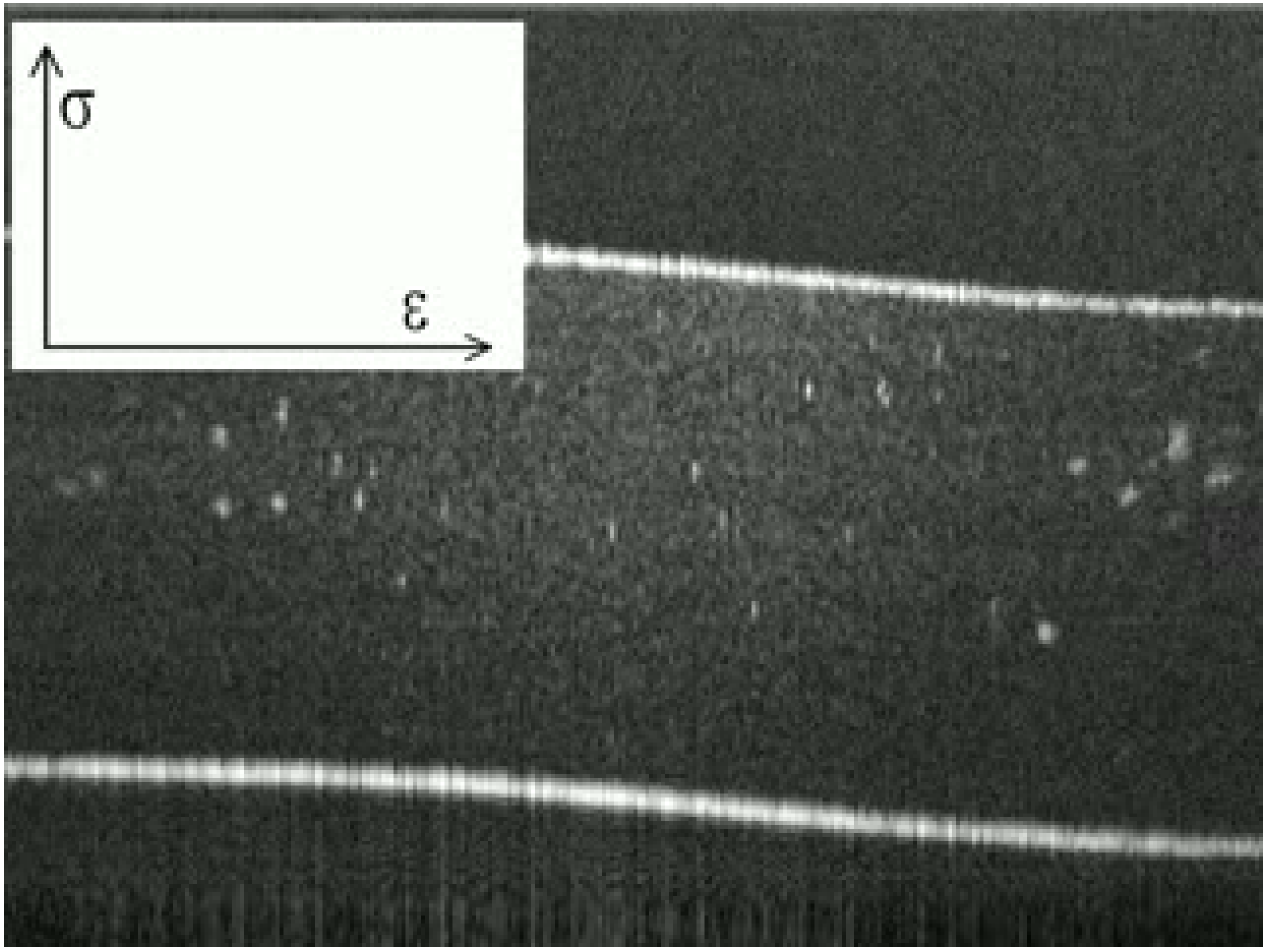
TD-OCT (UHR):
2 seconds



SD-OCT (UHR):
0.036 seconds

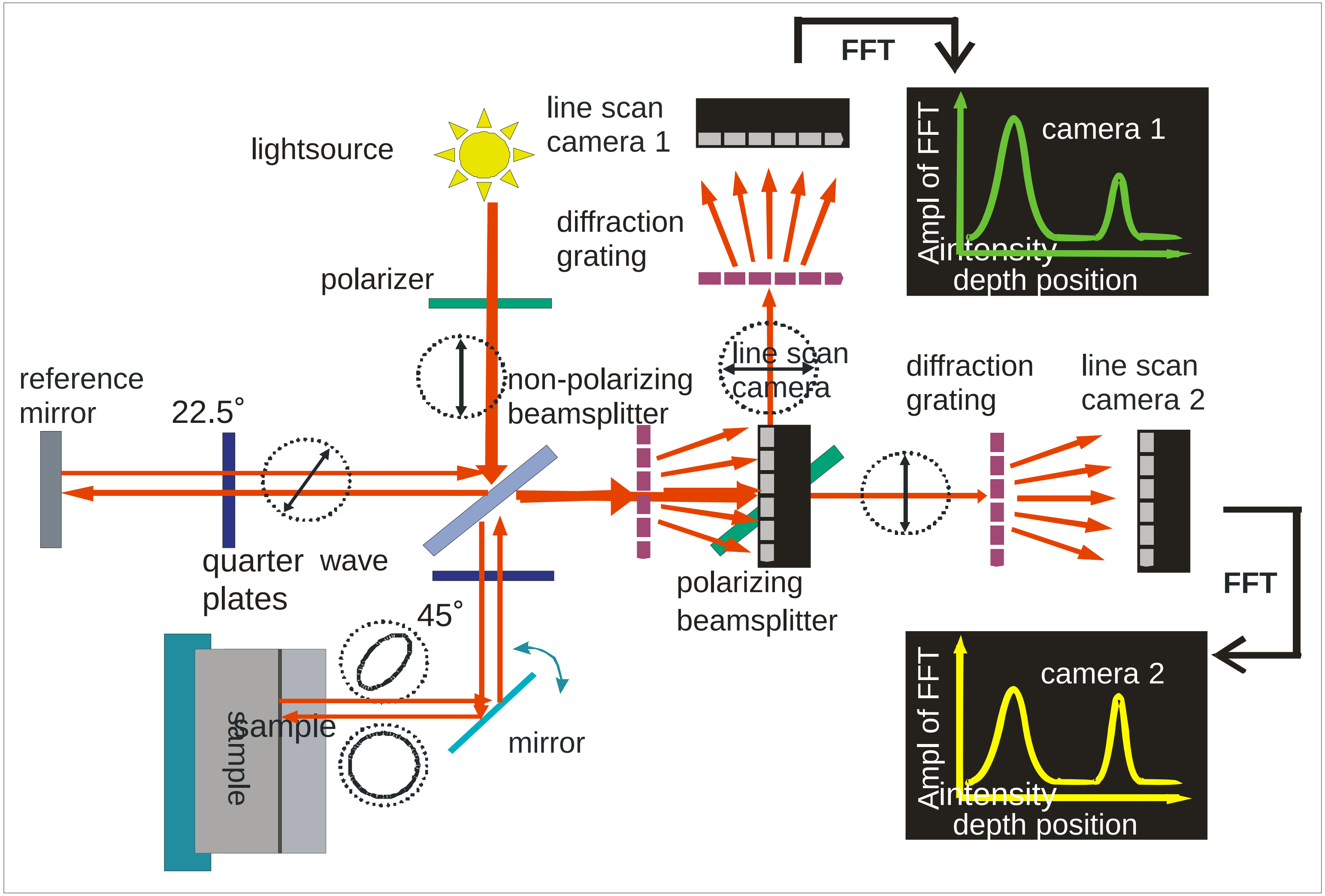


SD-OCT: tensile testing

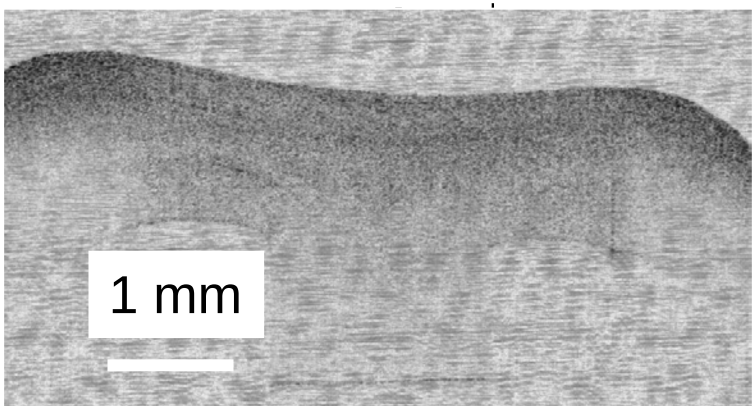


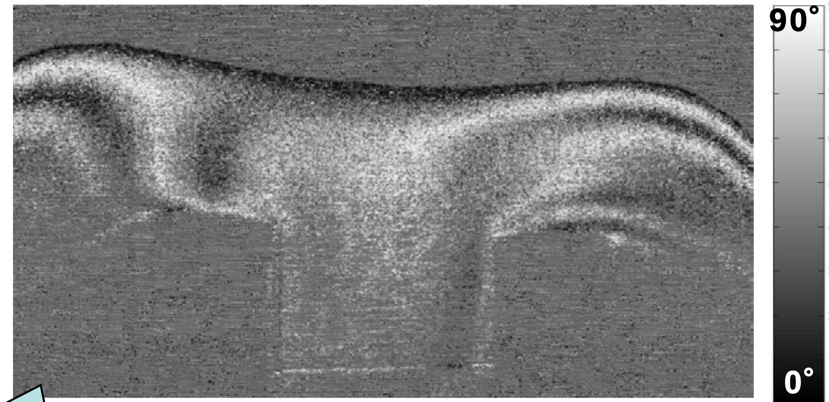
Polypropylene with elastomer particles

Polarization-sensitive SD-OCT



PS-OCT: 3 images (injection moulded polymer part)

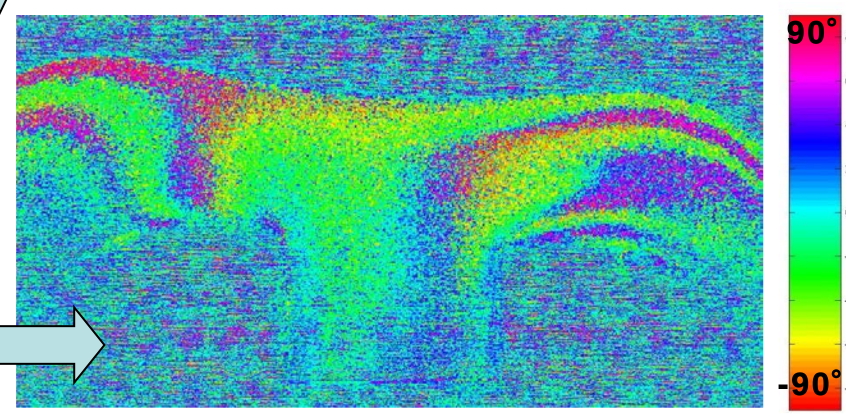




1. **<u>Intensity image:</u>** $\sim (A_1^2 + A_2^2)^{1/2}$

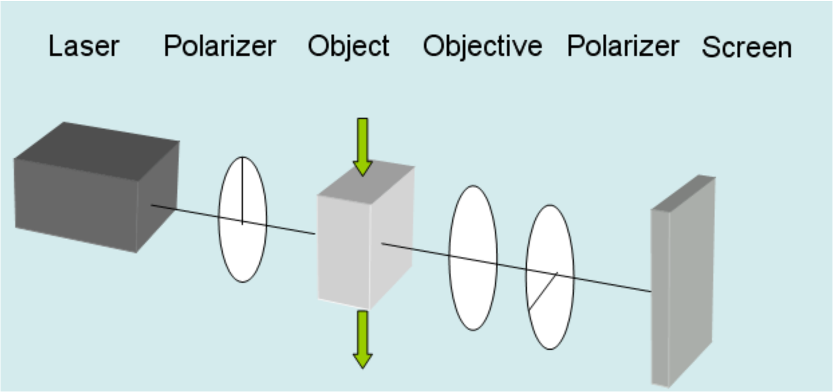
2. **<u>Retardation image:</u>** $\sim \mathrm{atan}(A_1 / A_2)$

3. **<u>Image of orientation of optical axis:</u>**
$\sim \phi_1 - \phi_2$

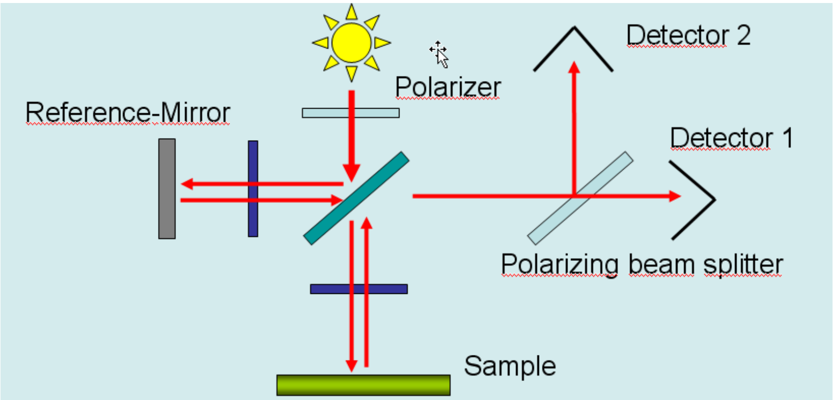


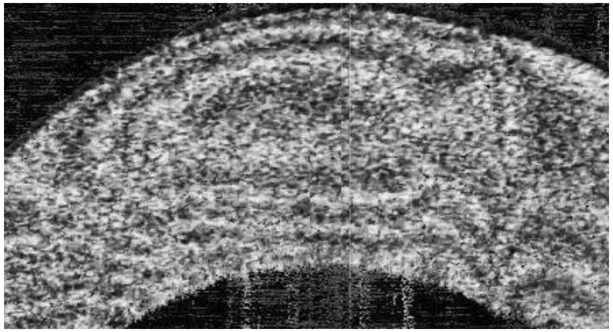
Stress & Retardation Images

Photoelasticity



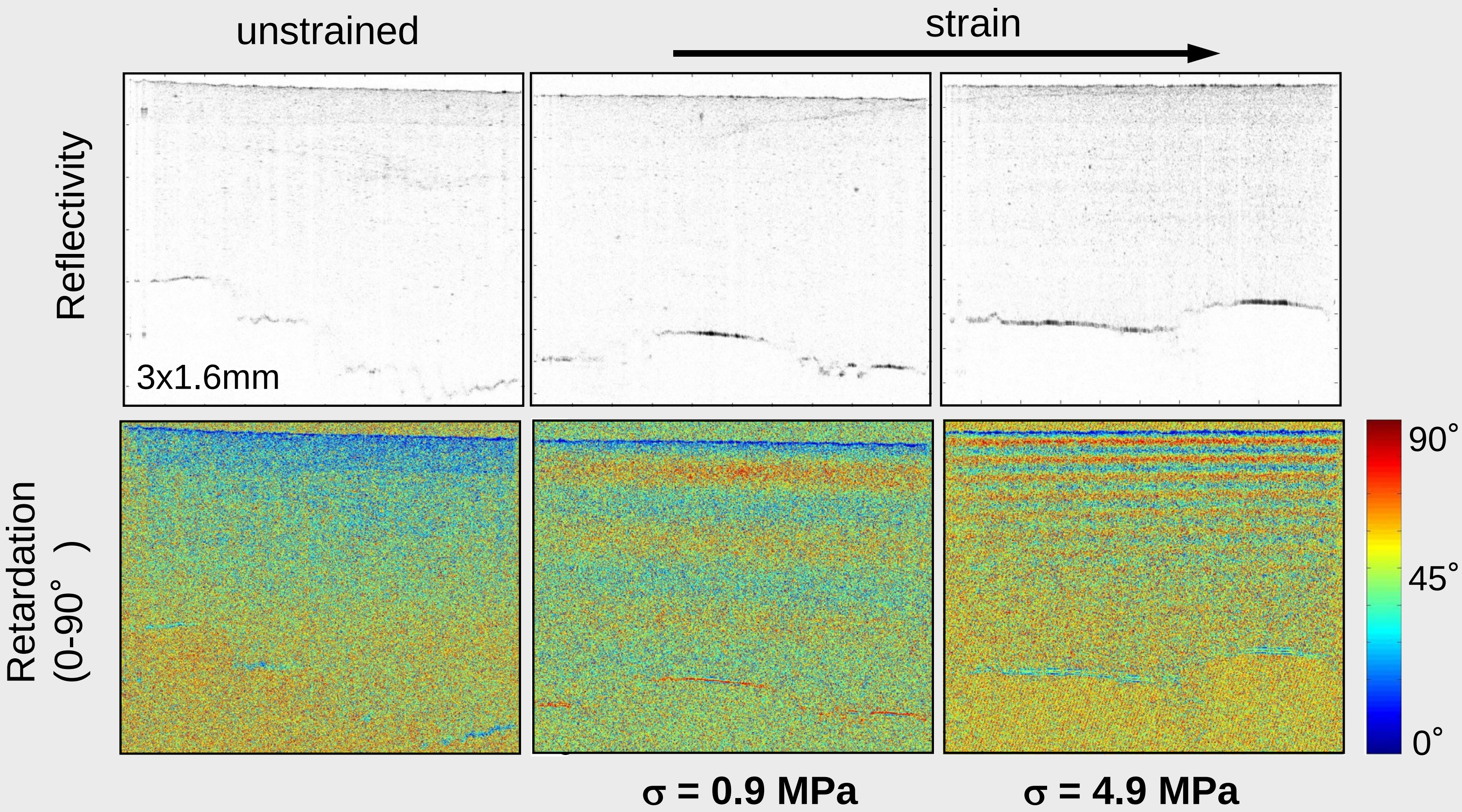
PS-OCT





Bended polymer structure imaged by PS-OCT (Retardation image)

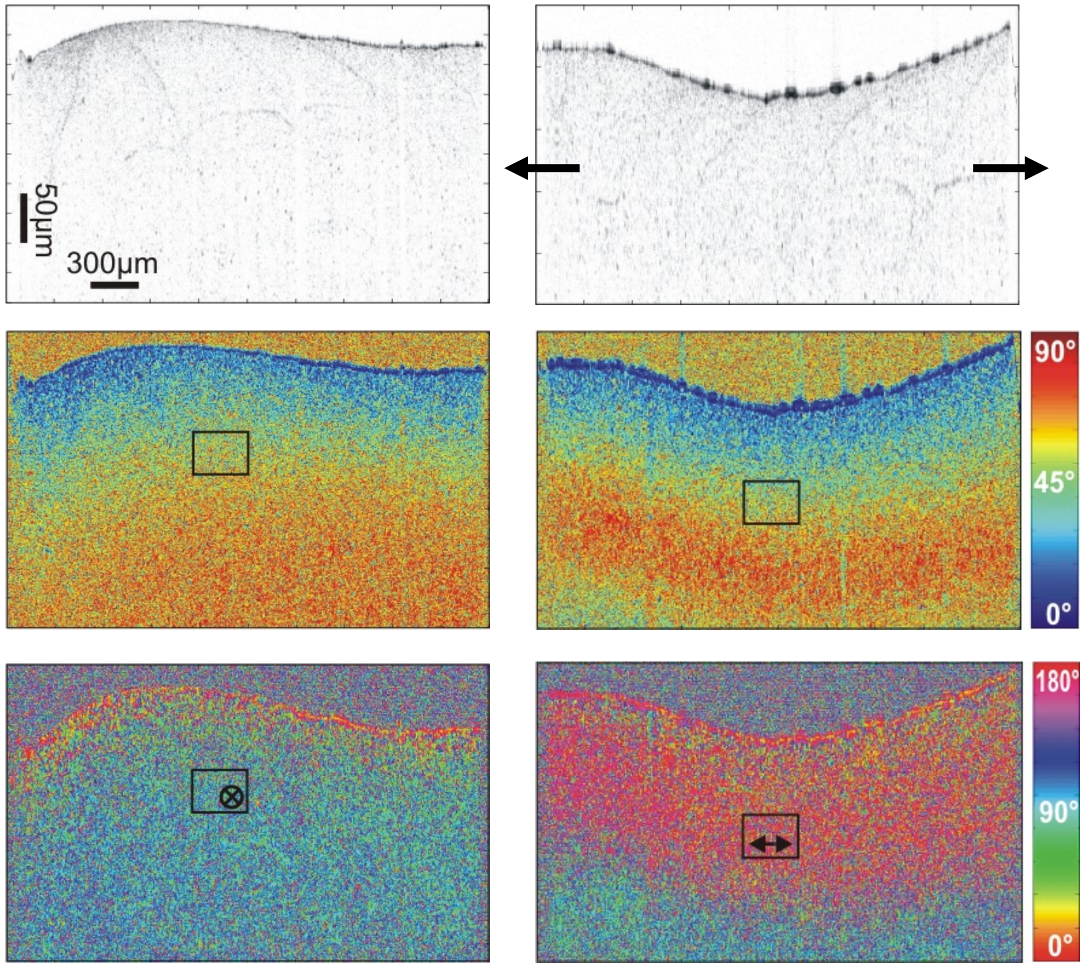
PS-OCT: strain/stress - birefringence



PS-OCT: orientation of optical axis

Elastomer sample

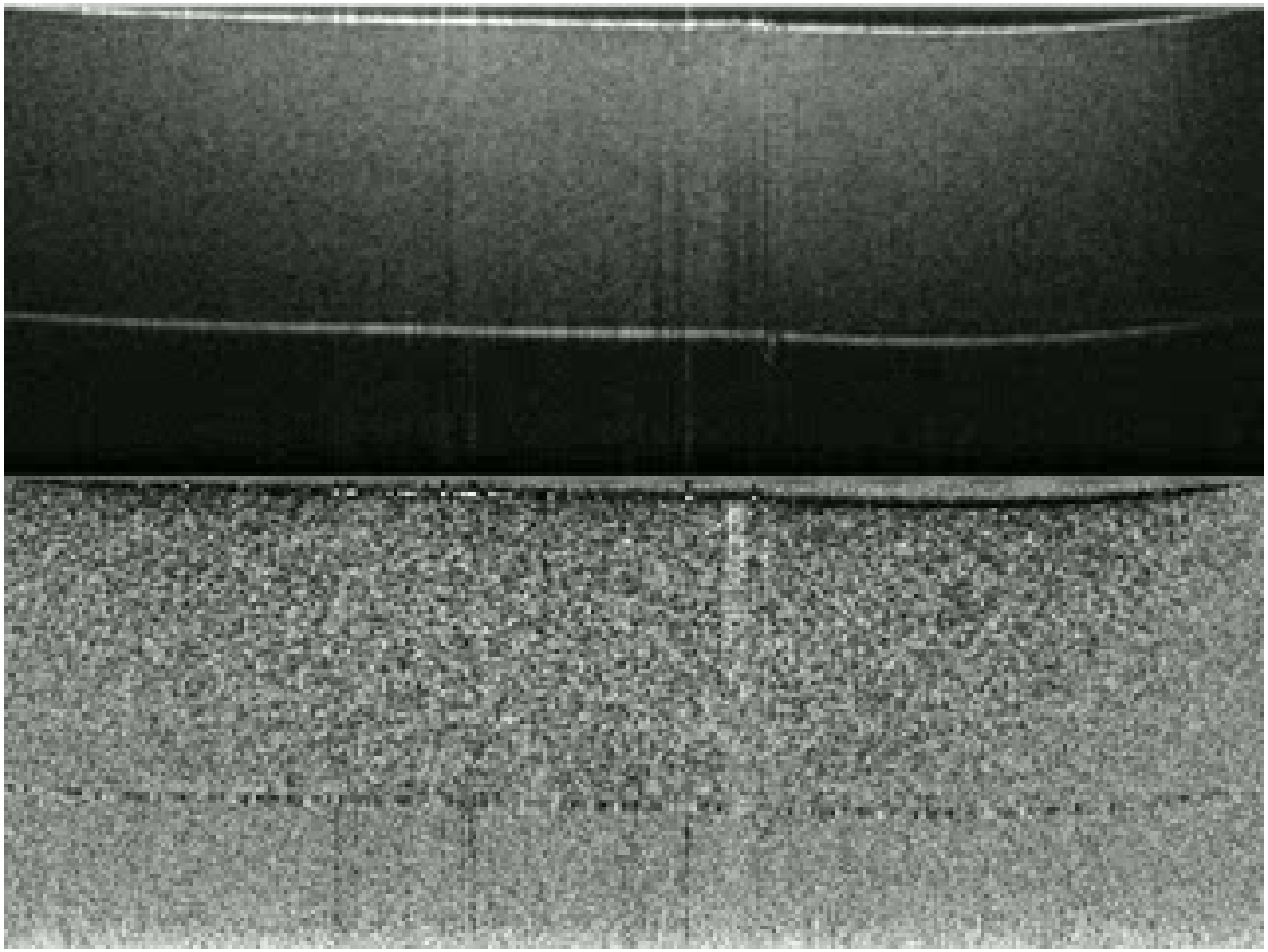
Unstrained | Stretched



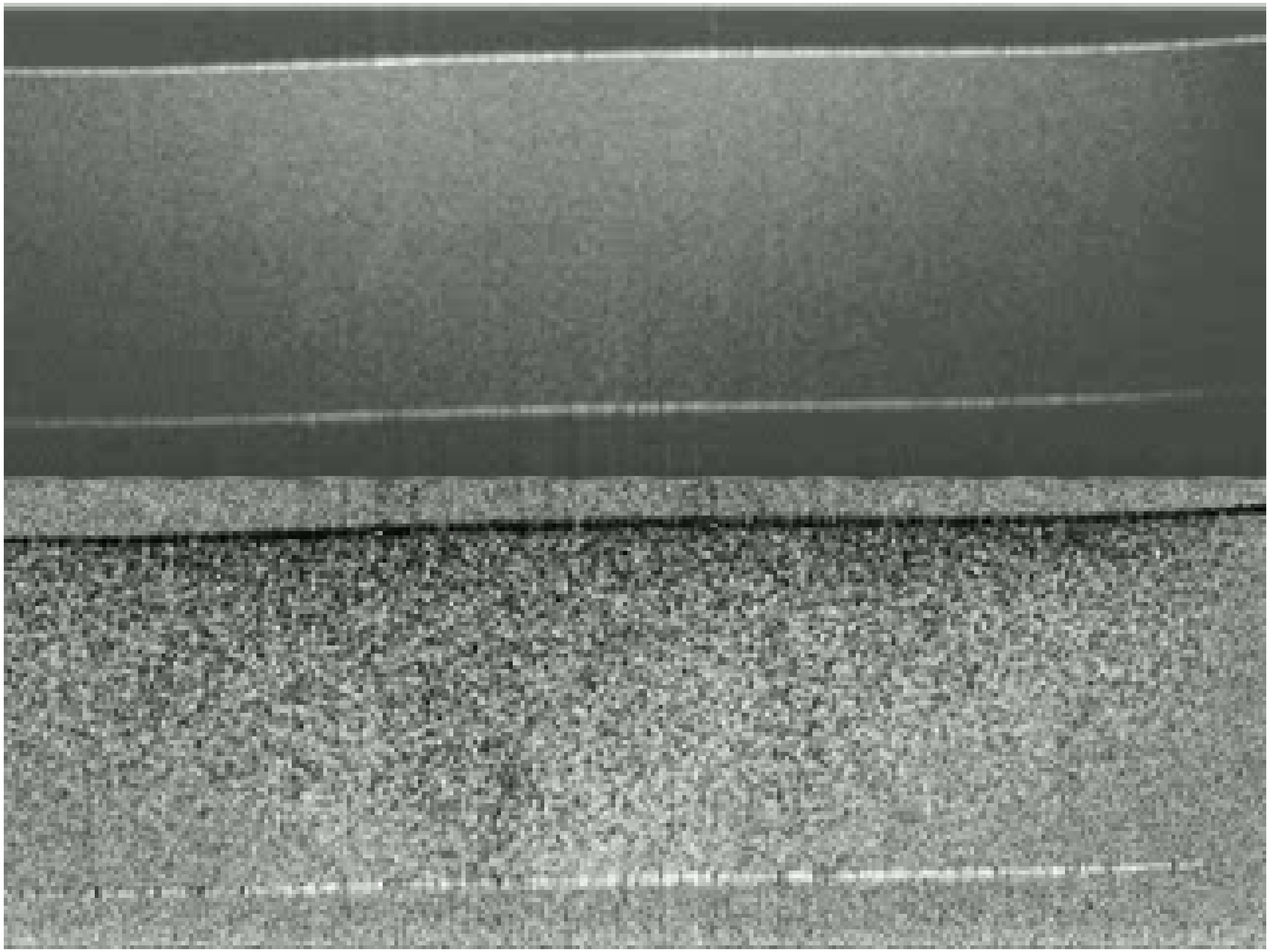
- Reflectivity
- Retardation
- Orientation of optical axis

- Structural imaging
- Birefringence – strain, anisotropies
- Orientation of strain fields

SD-PS-OCT: tensile testing (external defect)



SD-PS-OCT: tensile testing (internal defect)



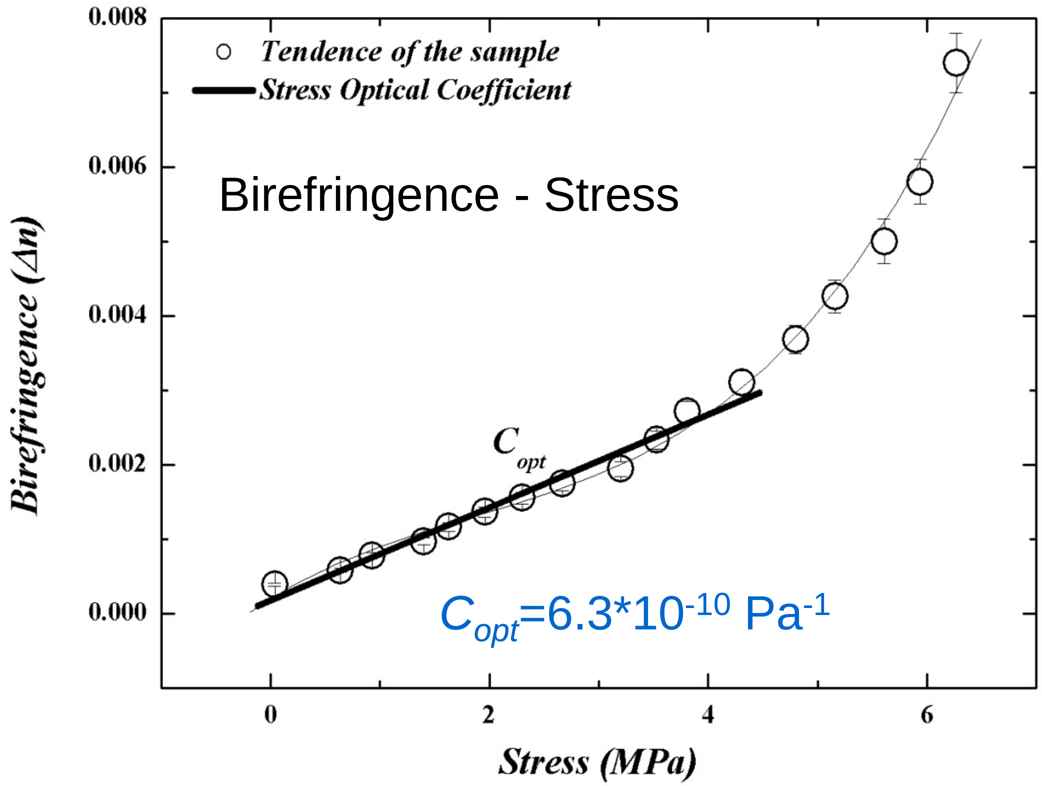
Quantification: Birefringence calibration

Birefringence Δn:

$$\Delta n = \frac{\lambda}{360} \frac{d(\textit{retardation})}{d(\textit{depth})}$$

Stress optical coefficient C_{opt}:

$$C_{opt} = \frac{\Delta n}{\sigma}$$



2D-image processing for PS-OCT

Reconstruction Procedure

(1) Pre-processing

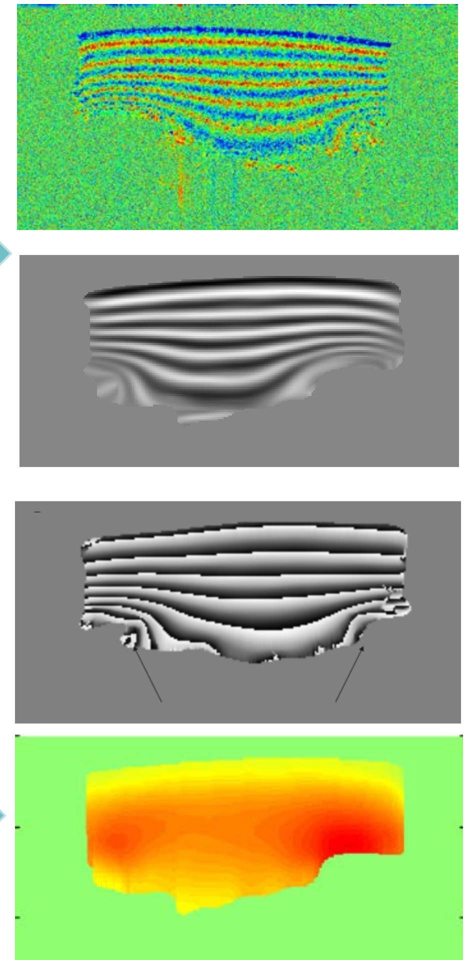
- Median filtering
- CED-based denoising
- Background correction

(2) Demodulation

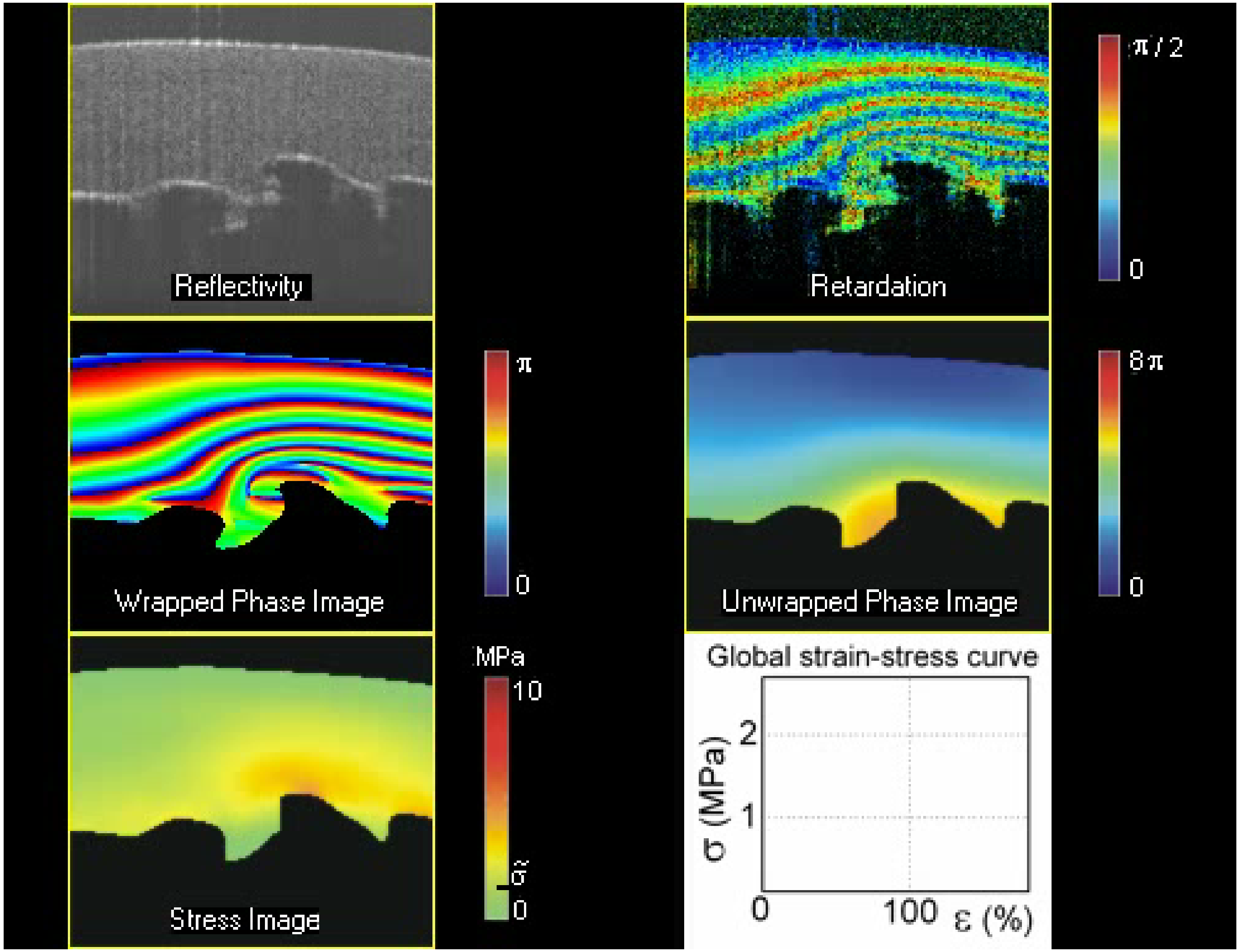
- Quadrature component (Radial HT)
- Orientation estimation
- Unwrapping

(3) Differentiation

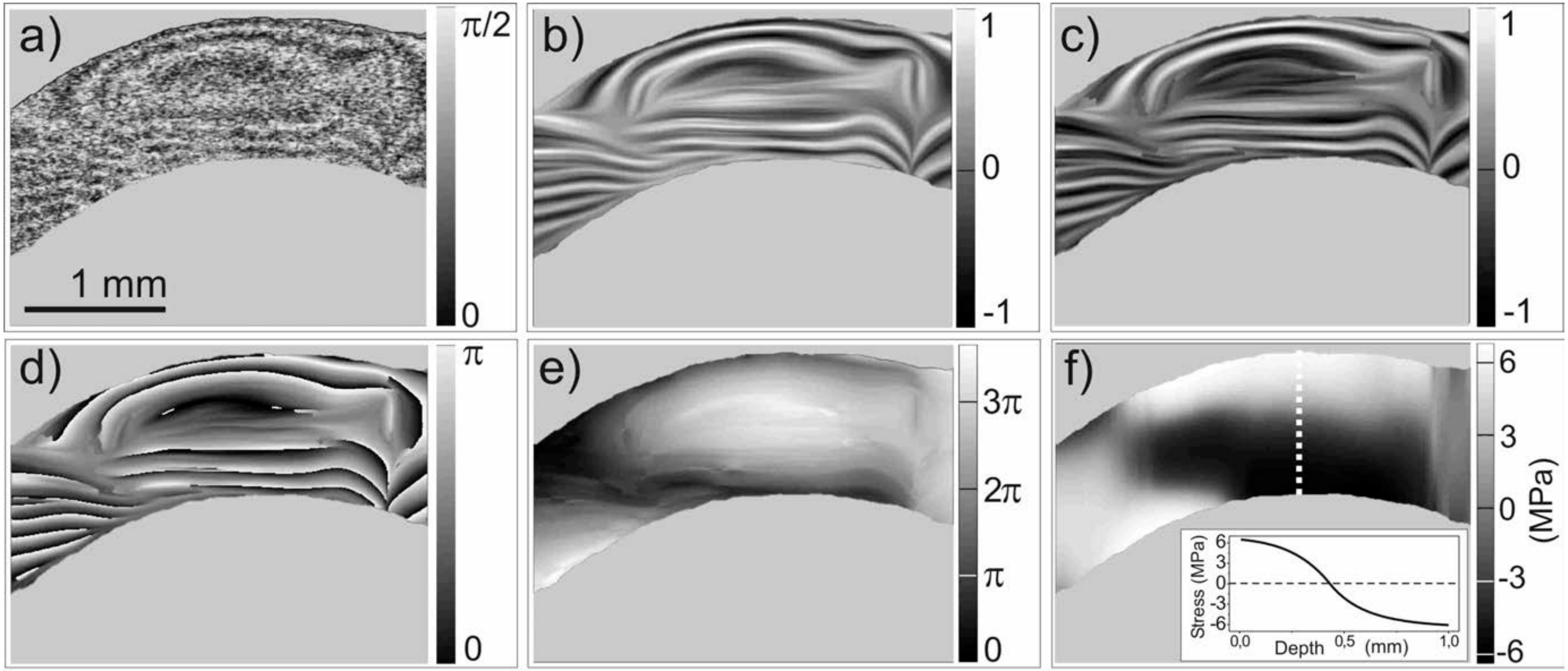
- Numerical differentiation
- Birefringence→Stress



Quantitative SD-PS-OCT: tensile testing



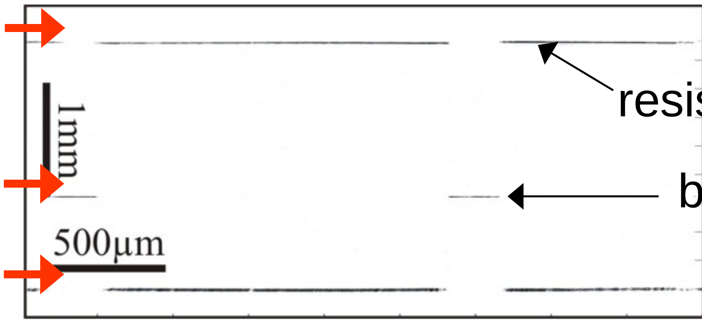
PS-OCT: bent polymer structure



a) Original retardation image
b) Denoising: Coherence enhancing diffusion (CED)
c) Quadrature image
d) Retardation: wrapped phase
e) Retardation: unwrapped phase
f) Stress image

Surface and interface stuctures

cross-sectional scan



resist surface

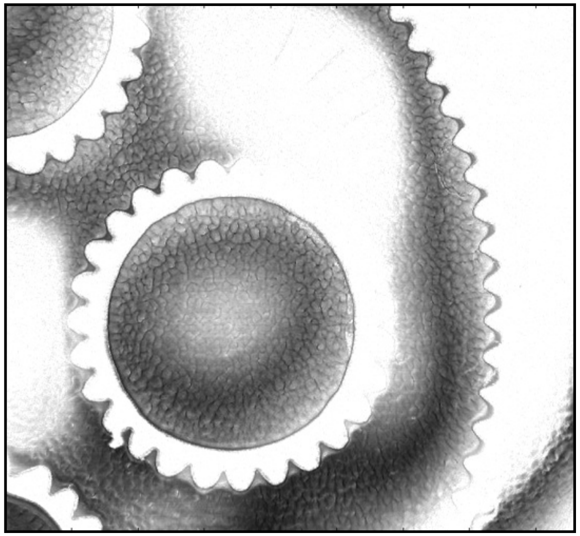
bare wafer

resist-wafer interface

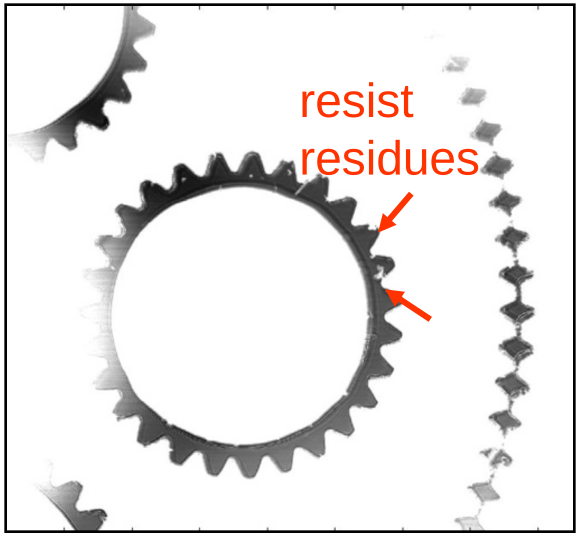
Photoresist moulds for miniature gear-wheels*

*Design of the wheel structures by Micromotion GmbH

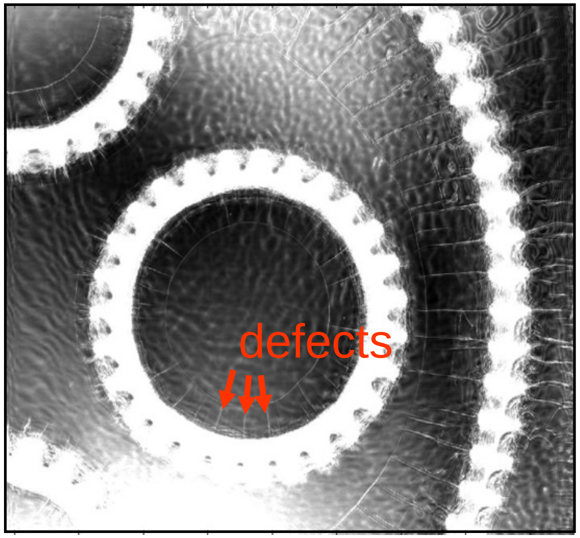
en-face scans (~3x3mm^2)



resist surface

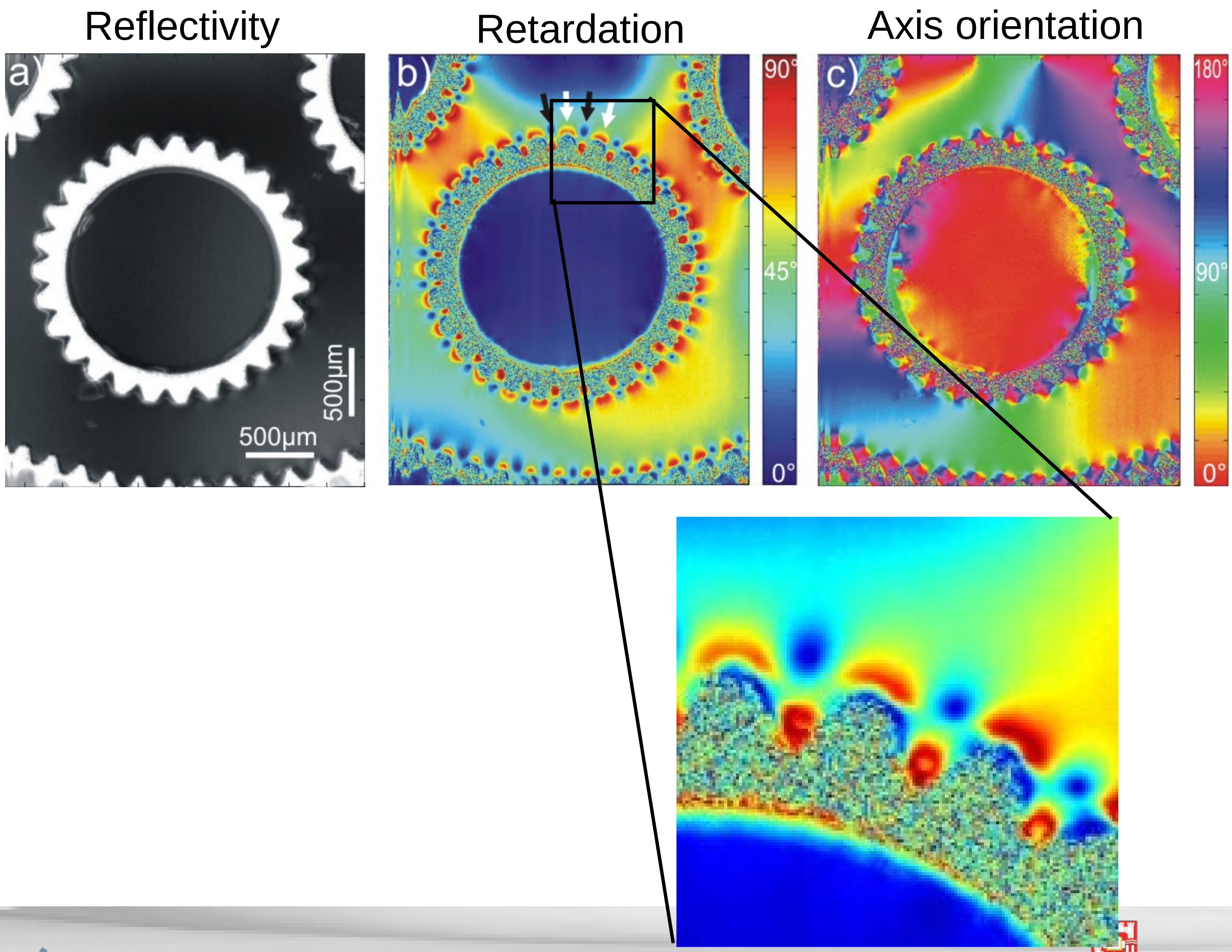


bare wafer

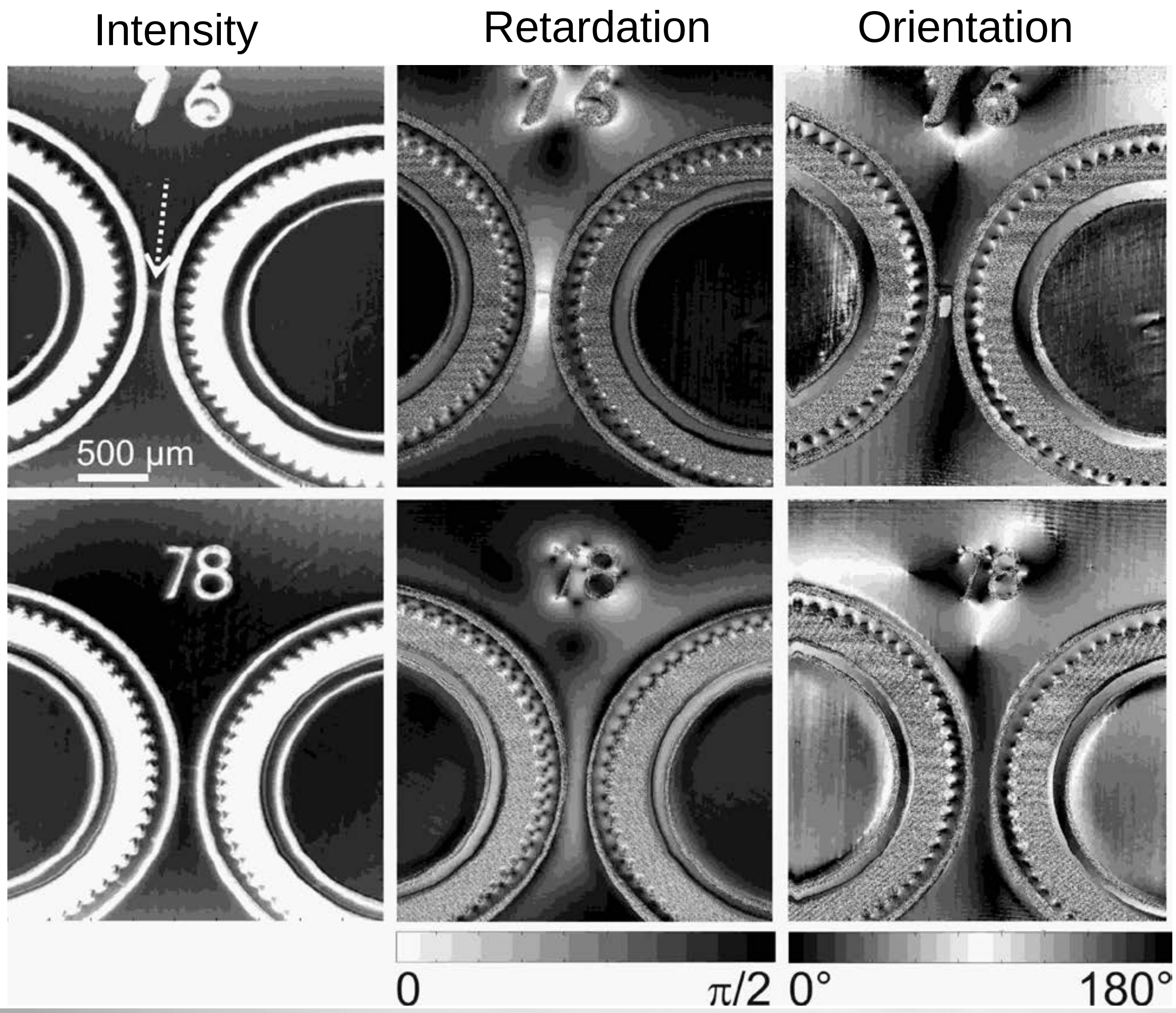


resist-wafer interface

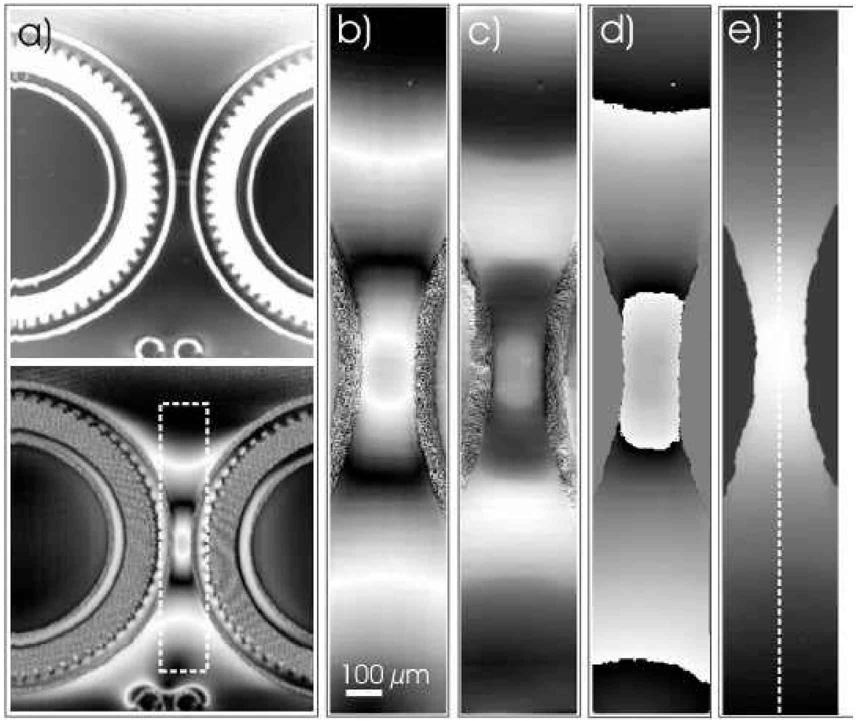
PS-OCT: strain mapping in micro-photoresist moulds

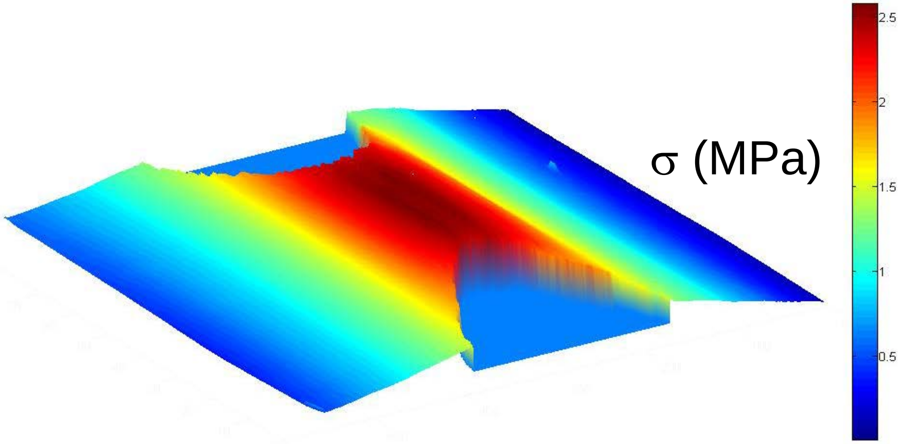


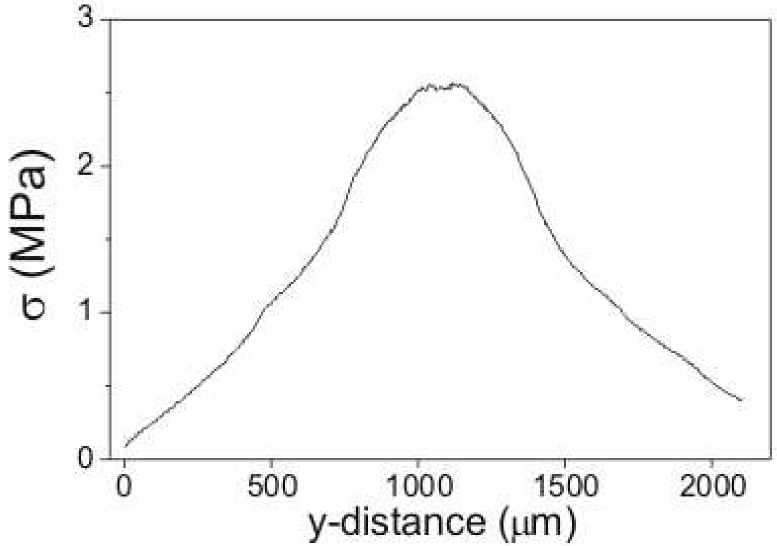
PS-OCT: process optimisation (minimizing strain)



PS-OCT: stress quantification

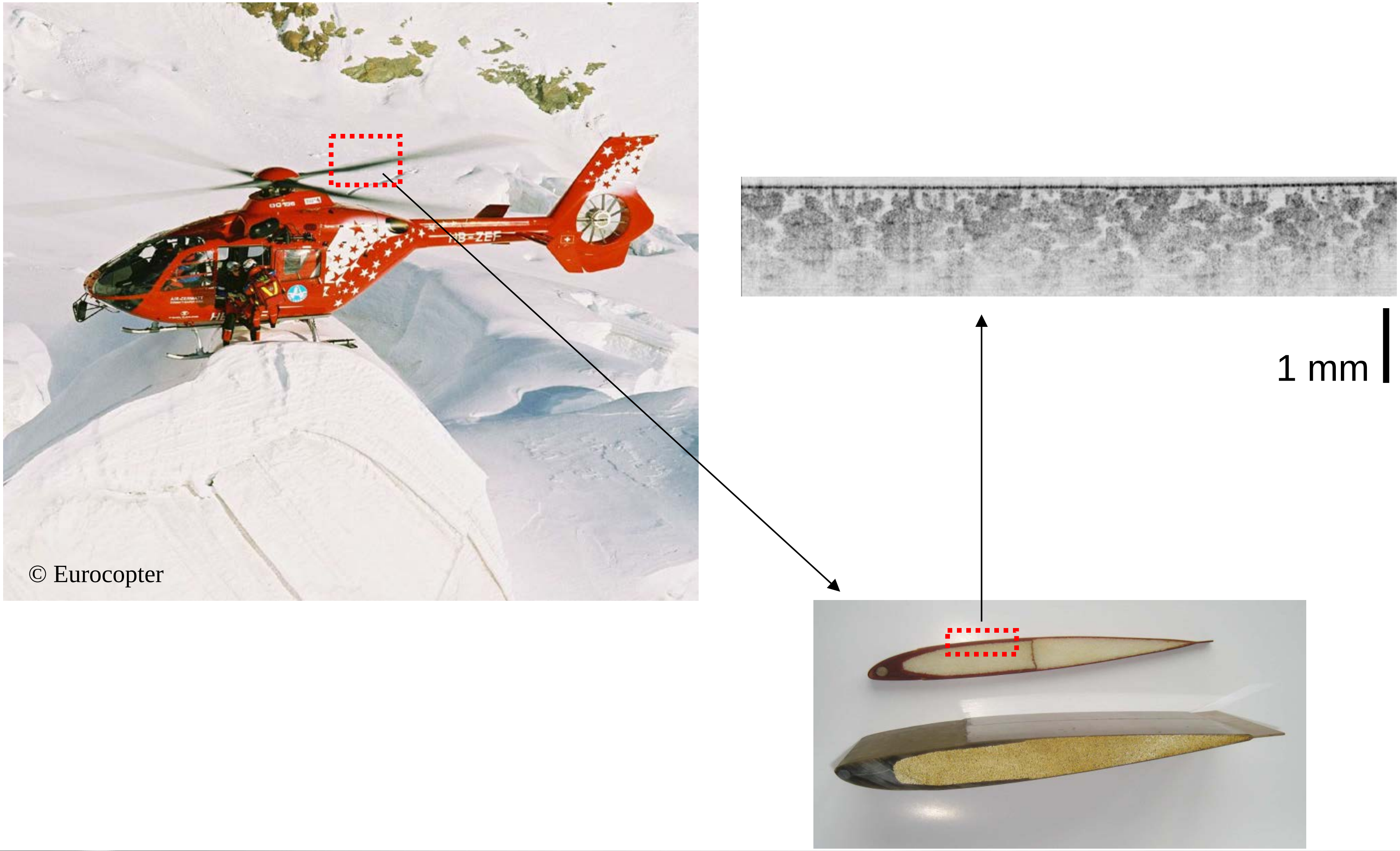






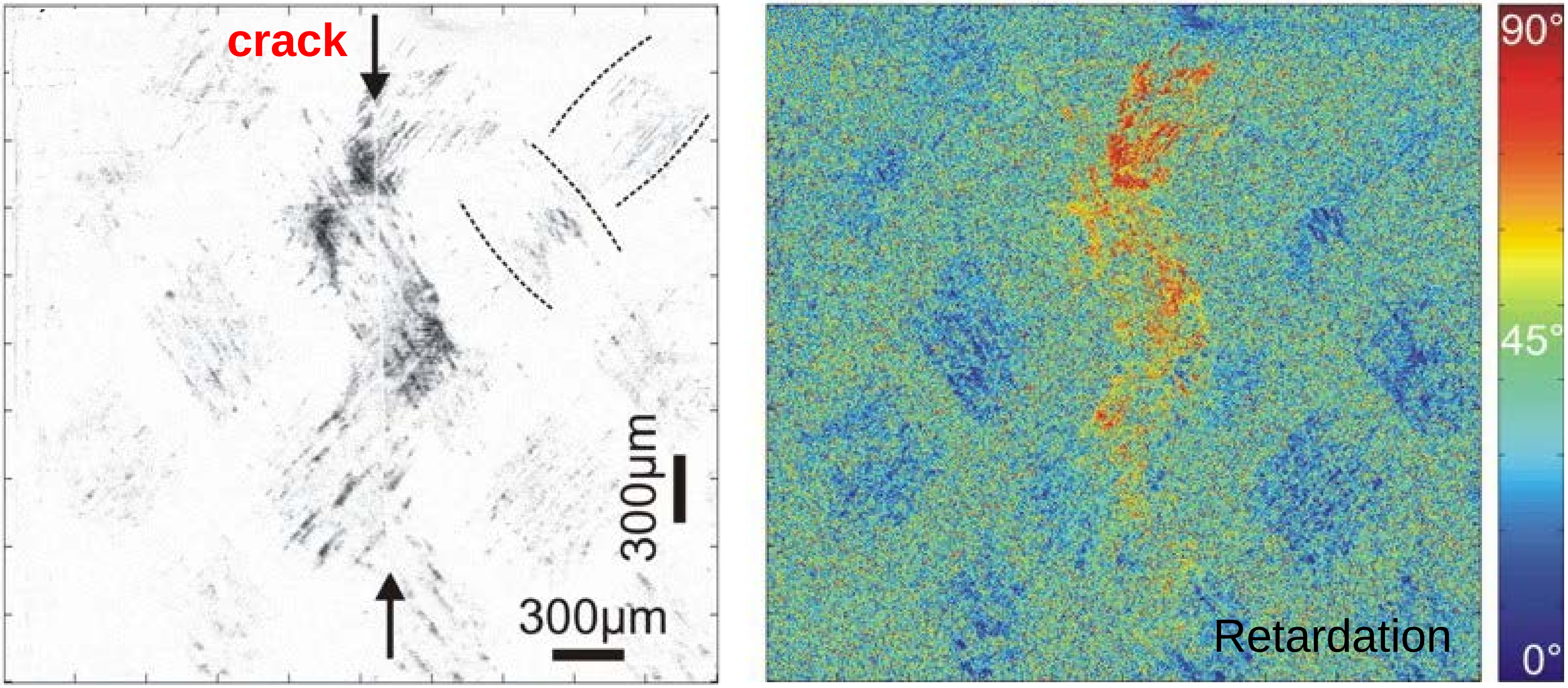
a) Original retardation image
b) Retardation image: region of interest
c) Quadrature image
d) Retardation: wrapped phase
e) Retardation: unwrapped phase
f) Stress image

Observation of damage formation



Glass-fibre composites (GFCs)

→ **crack-formation** due to loading tests

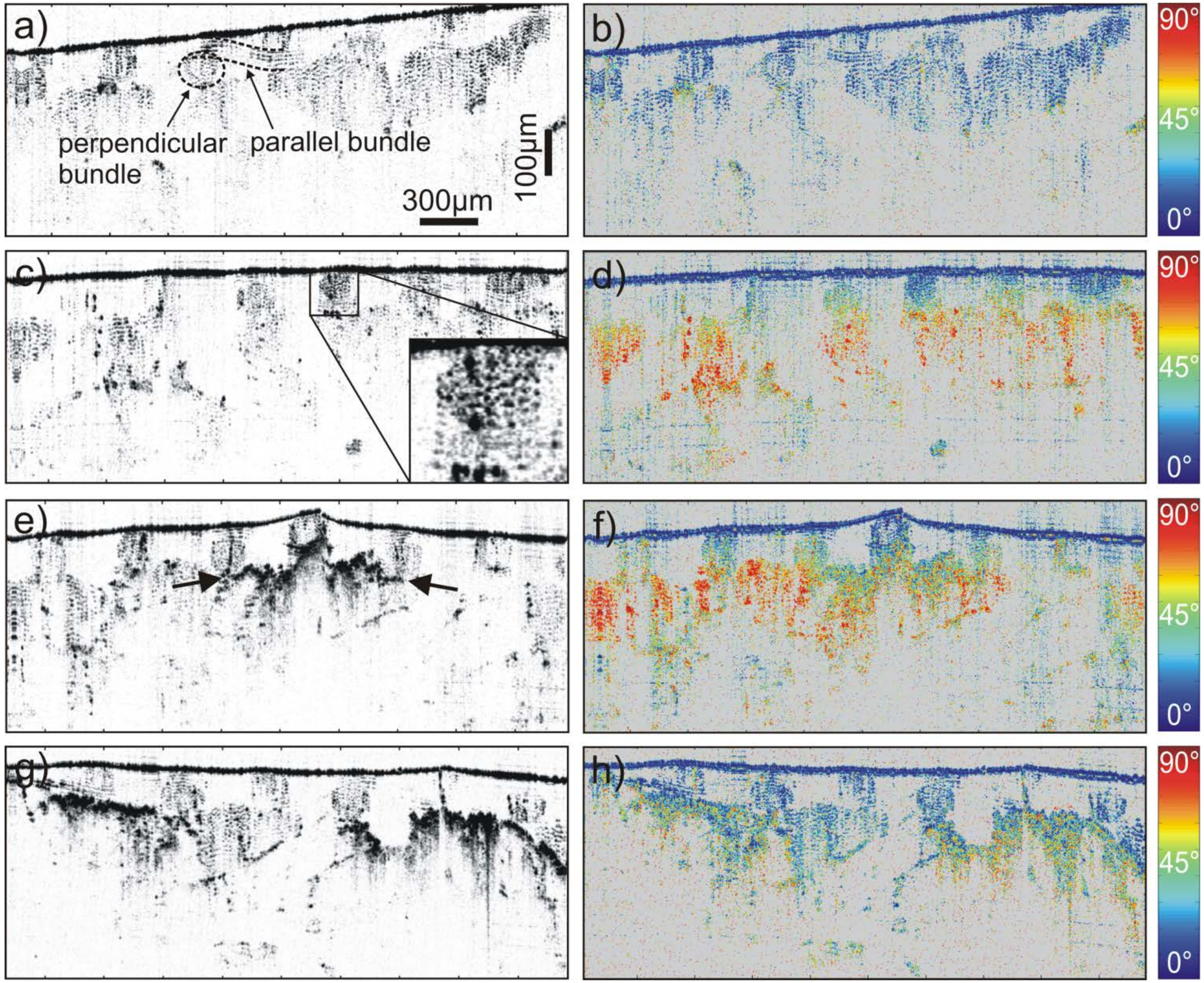


Increased birefingence in fibre bundles near crack

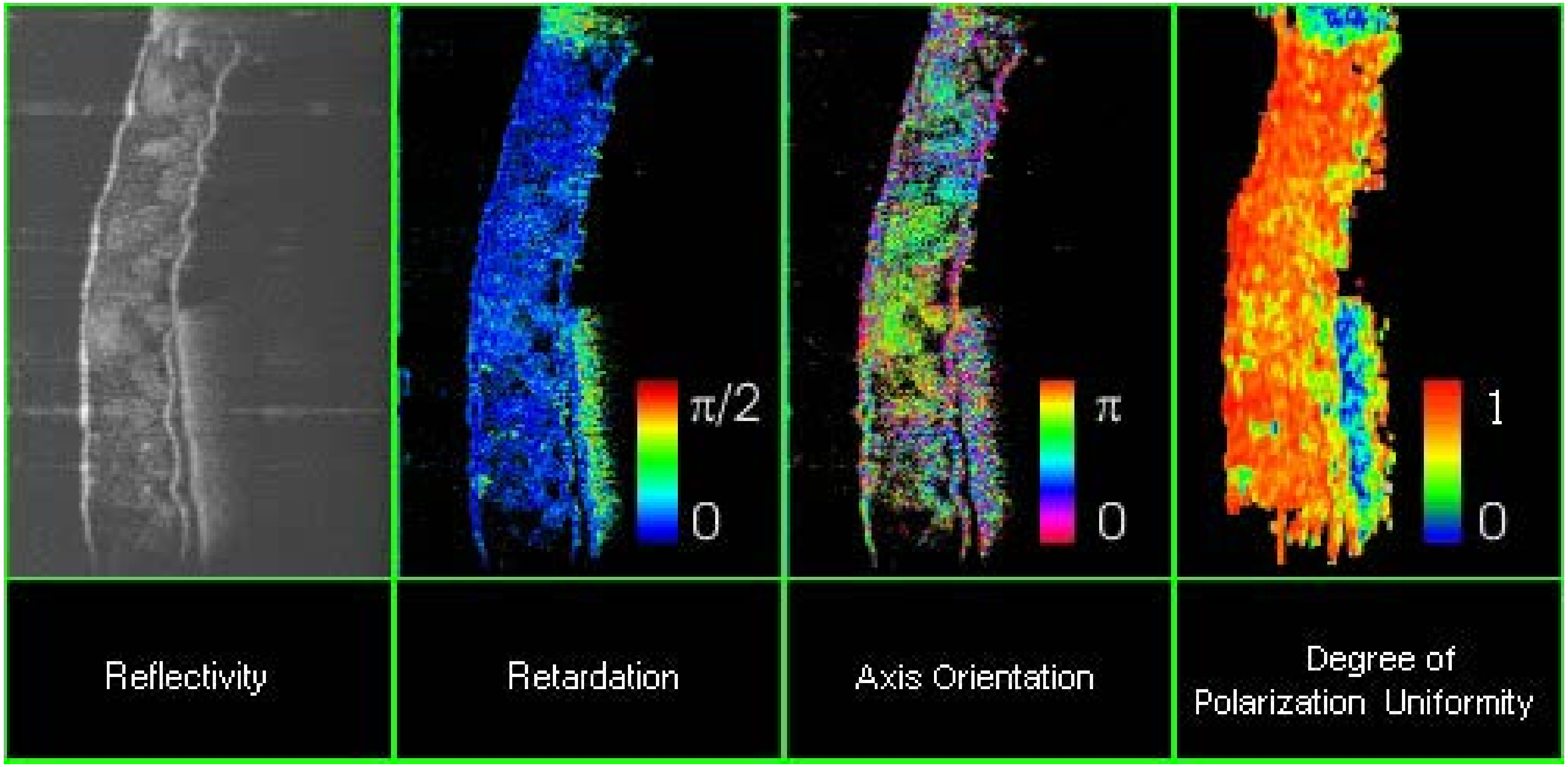
Glass-fibre composites (GFCs)

Increasing stress (bending)

released



Dynamic fracture test (glass fiber composite)



Conclusion

- Application to different types of materials and parts:
  - Bulk polymer parts, fibre composite materials, laminates and multilayer systems,...
- PS imaging for
  - PS – additional contrast
  - Depth resolved strain/stress – mapping
- SD-OCT for
  - High-speed imaging
- in progress:
  - Improvement of quantification