Institute of Applied Physics
Friedrich-Schiller-Universität Jena

Metrology and Sensing

Lecture 12-2: Optical Coherence Tomography

2021-02-02

Herbert Gross

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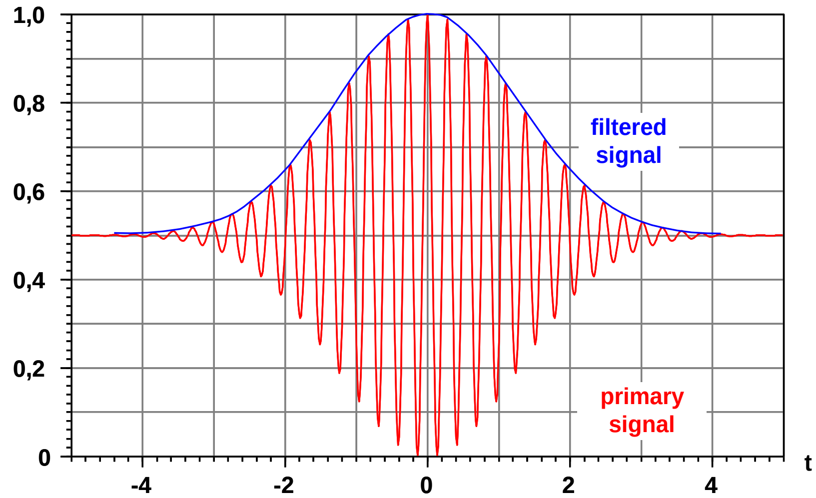
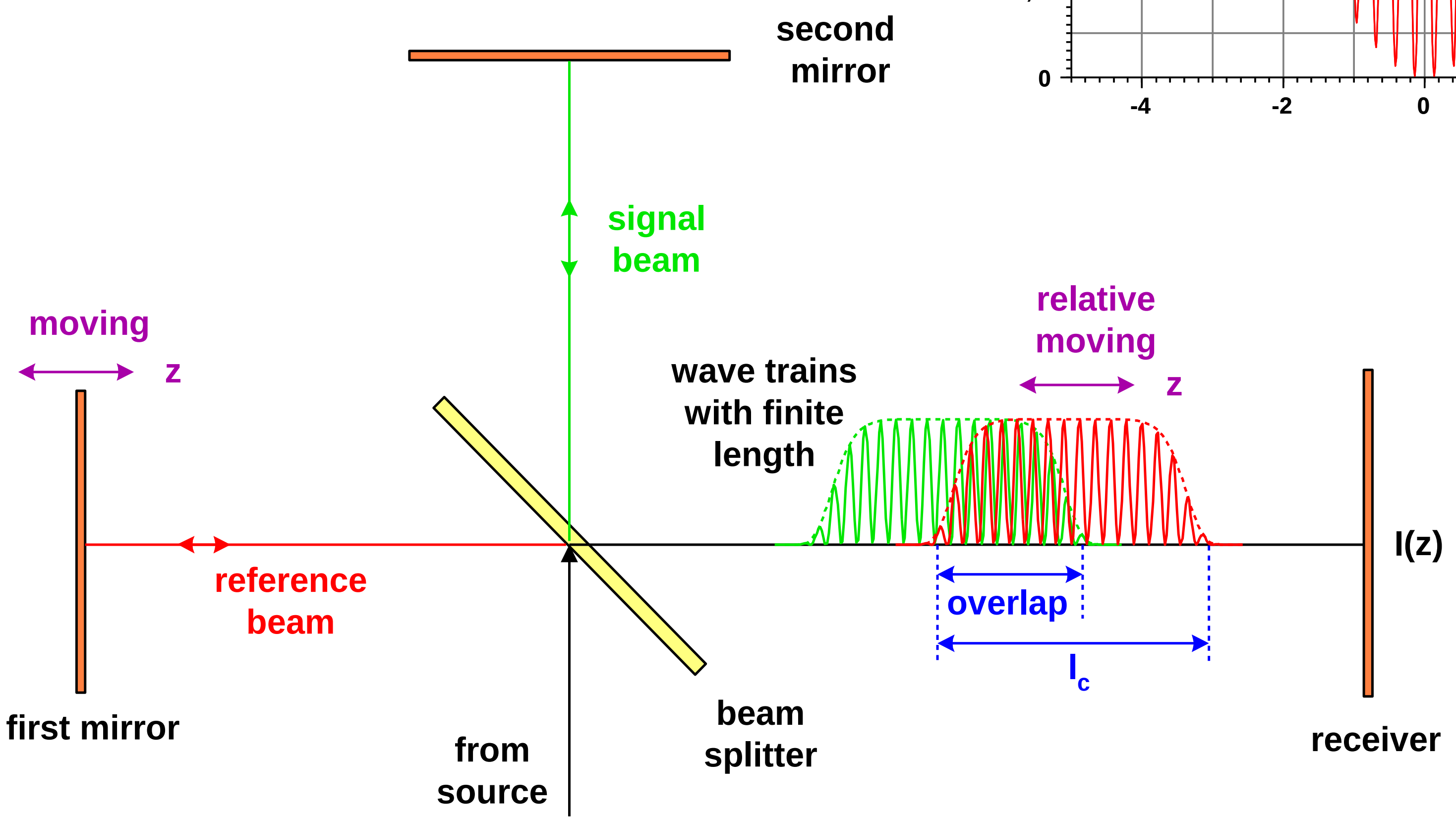
- Basic principle of OCT
- Michelson interferometer
- Time domain signal





Interference Contrast

- Superposition of plane wave with initial phase φ
  Intensity:

$$I = \sum_m I_m + 2\sum_{n<m} \sqrt{I_n \cdot I_m} \cdot \cos(\varphi_n - \varphi_m)$$

- Radiation field with coherence function Γ:

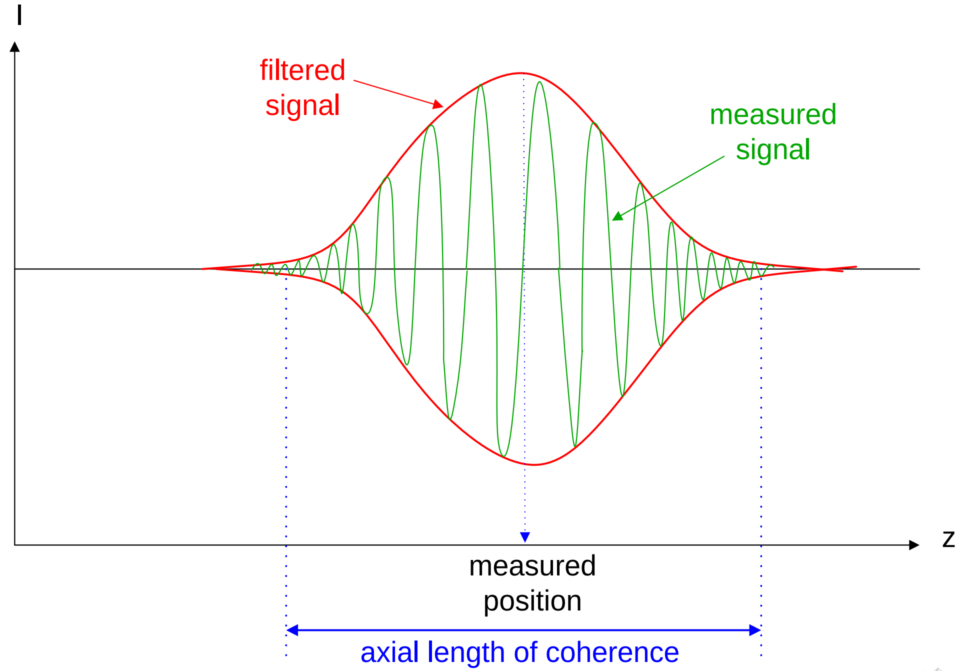
$$I(\vec{r}) = I_1(\vec{r}) + I_2(\vec{r}) + 2\cdot\Gamma(\vec{r}_1, \vec{r}_2, 0)$$

- Reduced contrast for partial coherence

$$K = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \left| \frac{\Gamma(\vec{r}_1, \vec{r}_2, \tau)}{\sqrt{I(\vec{r}_1) I(\vec{r}_2)}} \right|$$

- Measurement of coherence in Michelson interferometer:
  phase difference due to path length difference in the two arms
  (Fourier spectroscopy)

$$\Delta\varphi = 2\Delta k \cdot z = \frac{4\pi \cdot \Delta\lambda \cdot z}{\lambda^2}$$



Principle of OCT

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- Basic method of optical coherence tomography:
  - short pulse light source creates a coherent broadband wave
  - white light interferometry allows for interference inside the axial coherence length
- Measured signal:
  - low pass filtering
  - maximum of envelope gives the relative length difference between test and reference arm

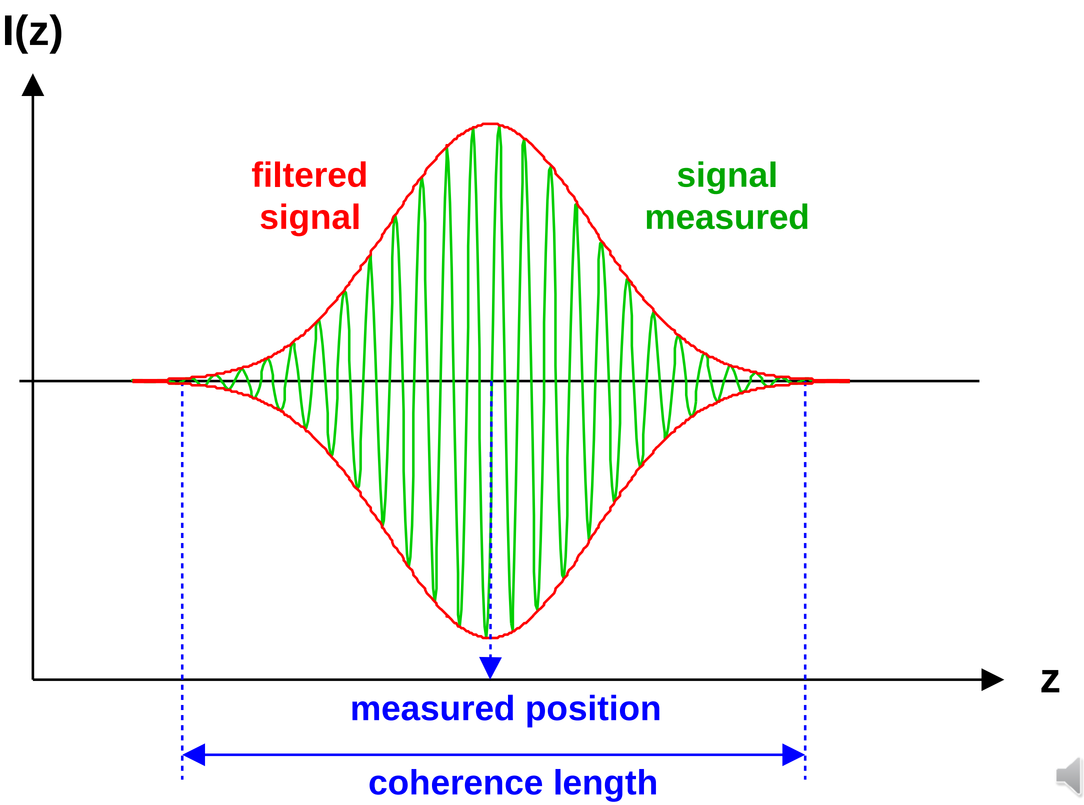
$$\Delta l \approx \frac{\lambda_o^2}{\Delta\lambda}$$

- For Gaussian beam

$$\Delta l = \frac{4\ln 2}{\pi} \cdot \frac{\lambda_o^2}{\Delta\lambda}$$

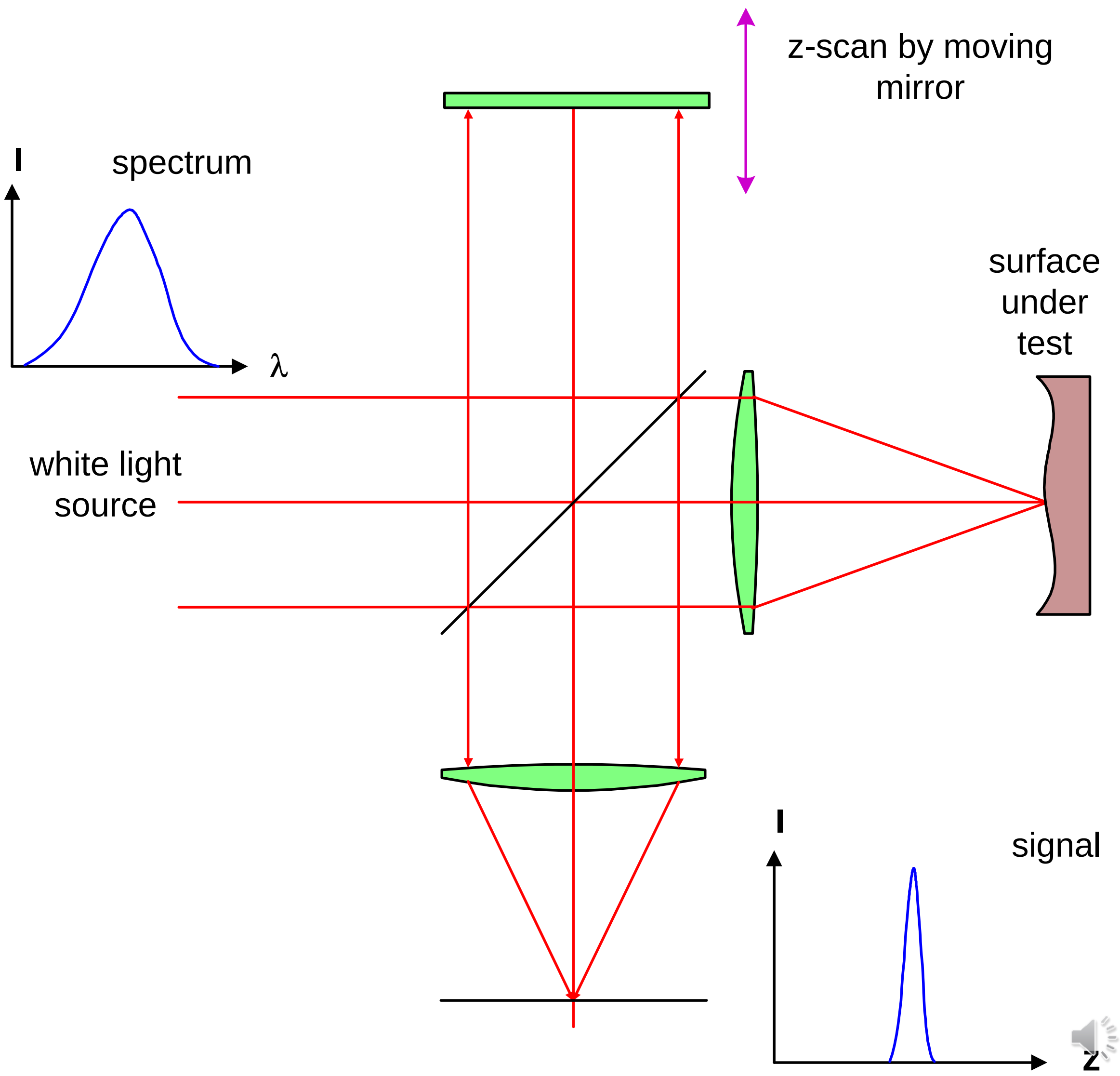
- High frequency oscillation depends on z

$$\Delta\varphi = 2\Delta k \cdot z = \frac{4\pi \cdot \Delta\lambda \cdot z}{\lambda^2}$$



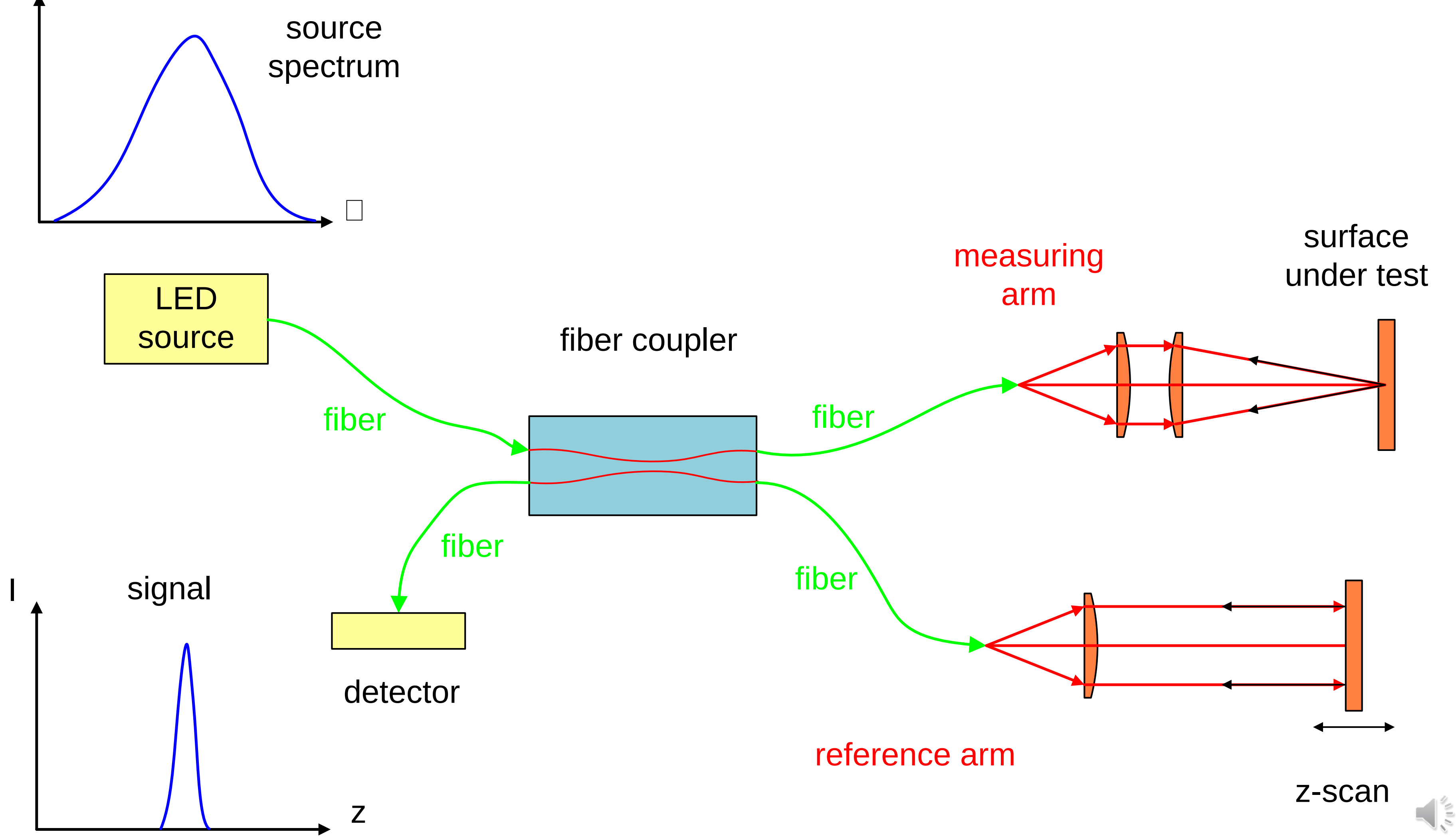
OCT - White Light Interference

- Signal
  spectral profile
- Basic setup:
  Michelson interferometer



Fiber Based OCT Interferometer

Basic setup



OCT Measurement of Distances

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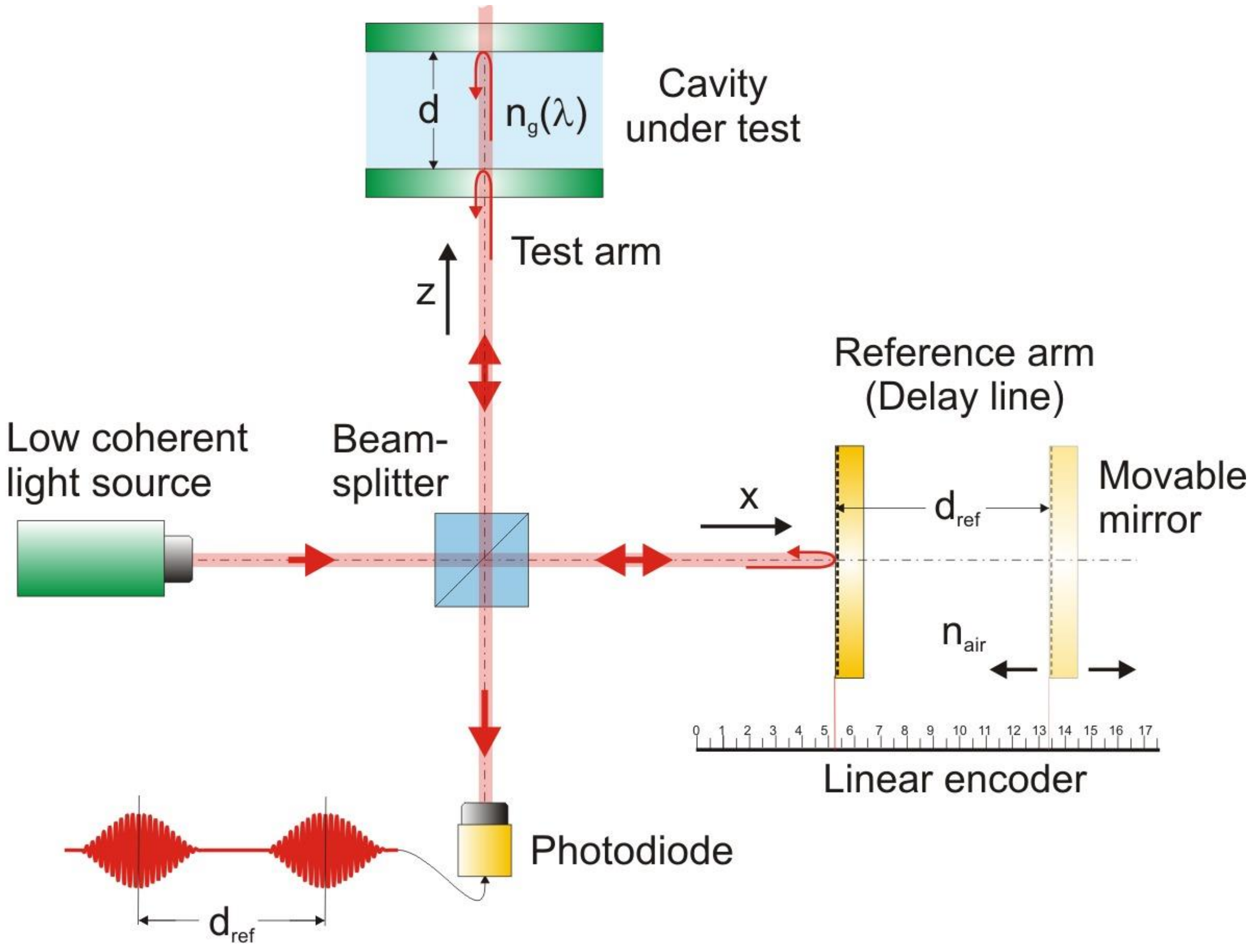
- Technical application of white light interferometry



OCT Modes

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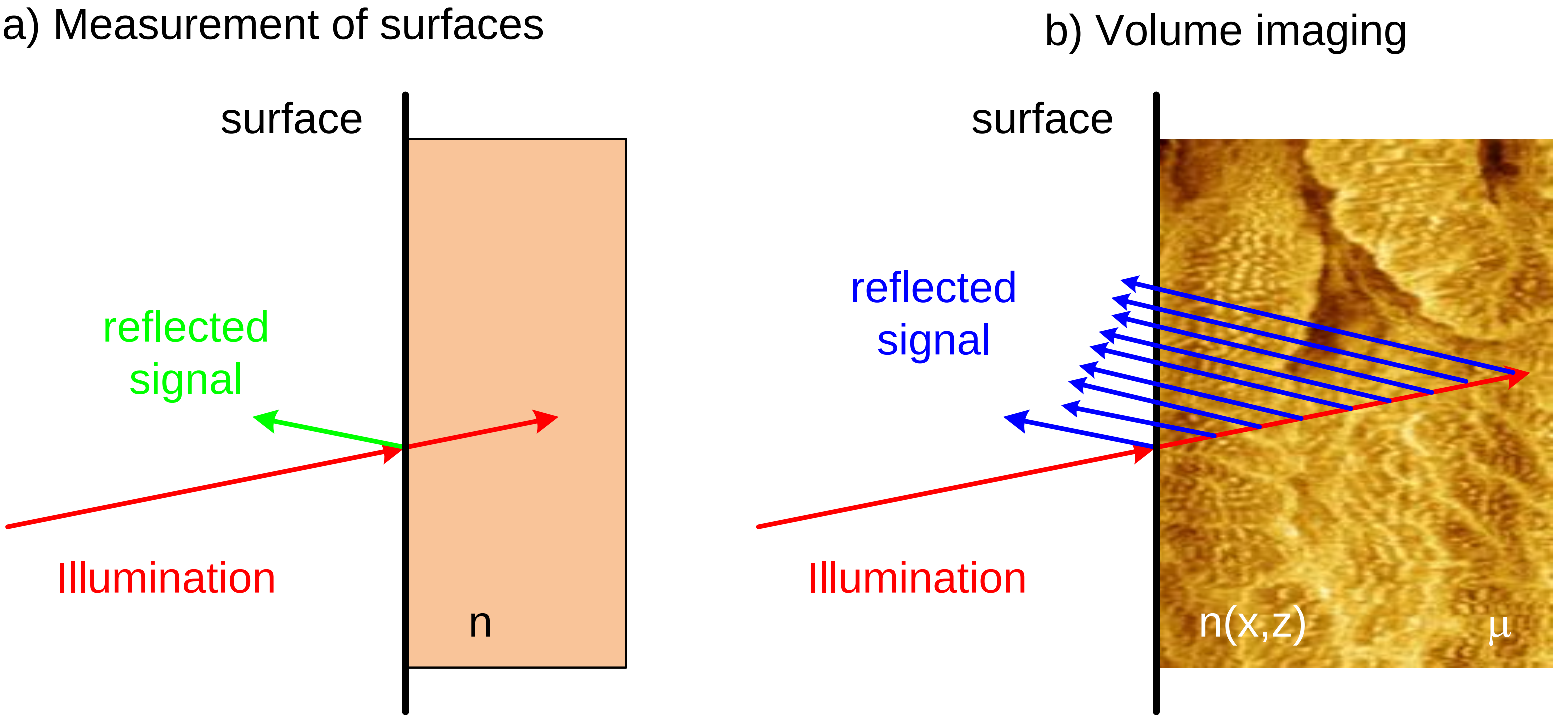
- Possibilities of the usage of OCT:

  - measureing of surfaces
    reflected light at n-interface

  - volume imaging
    reflected light or back scattered light in inhomogeneous medium n(x,z), μ



Optical Coherence Tomography

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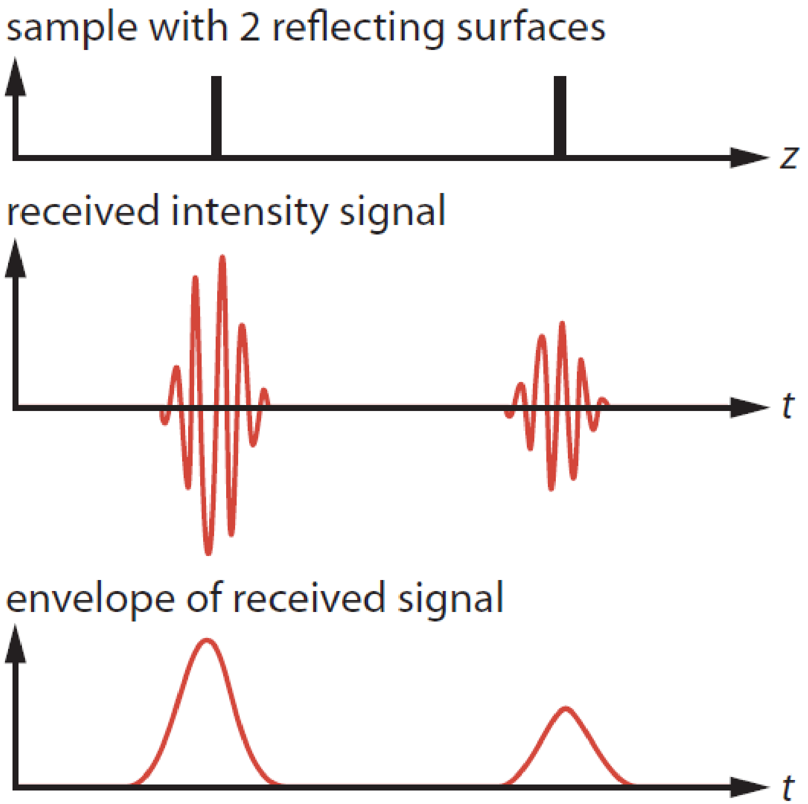
- Example:
  sample with two reflecting surfaces
- 1. Spatial domain

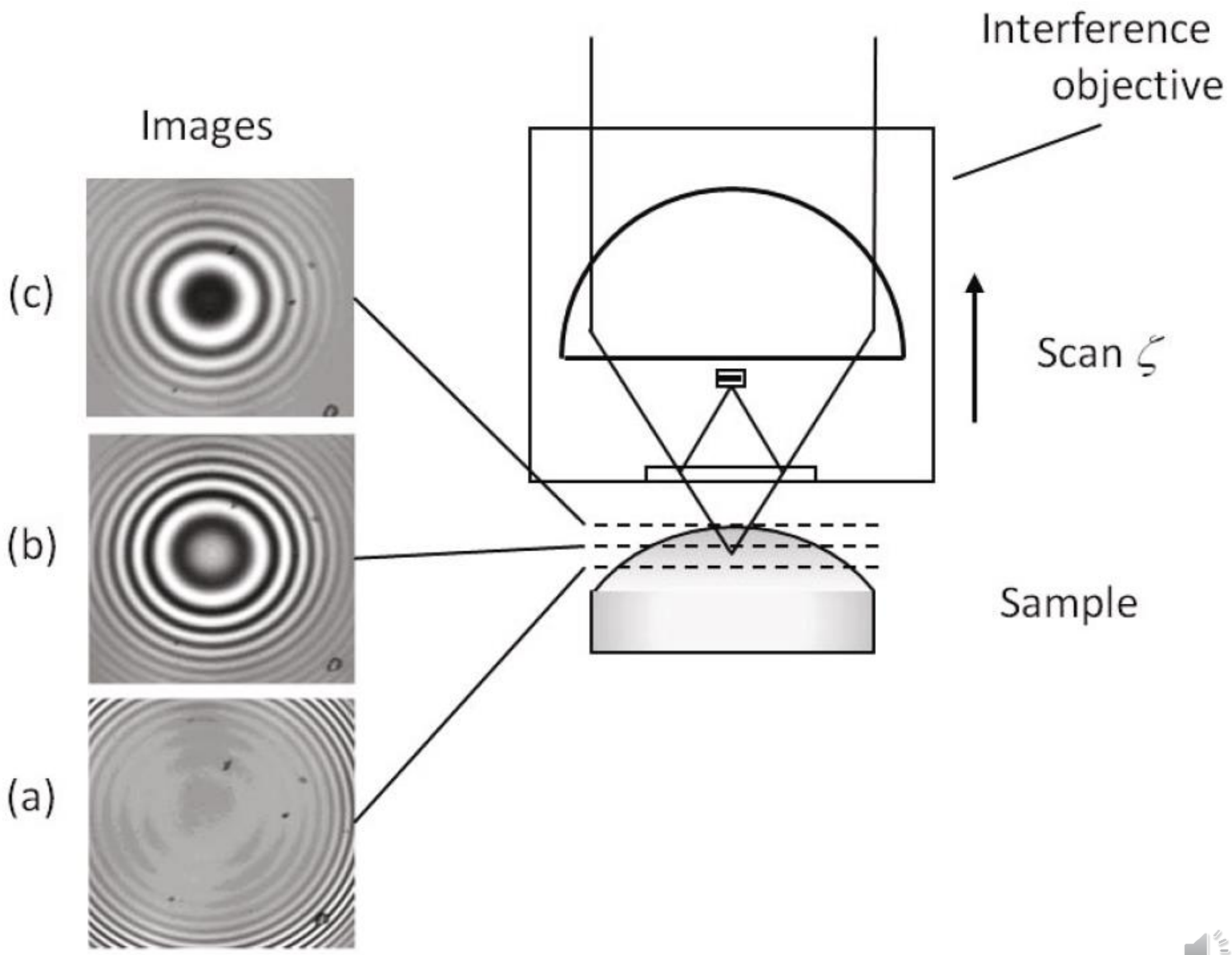
  2. Complete signal

  3. Filtered signal
     high-frequency content removed



Ref: M. Kaschke

1. Decrease of contrast as a result of the coherence gating



Ref: R. Leach

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Properties of OCT

- Reference arm:
  - allows for z-scan in the depth
  - z-discrimination by axial length of coherence, defined by the bandwidth (coherence gating)
  - Large spectral width of illumination source: good time/spatial z-resolution
- Measured signals:
  - reflected light and scattered light
  - SNR above 10^{-10} can be resolved
- Problems:
  - refractive interfaces are dispersive
  - group refractive index is important
- Typical:
  - fast axial scan by moving mirror or rotating cube (A-scan)
  - slow lateral x-y-scans (B-scans)

Optical Coherence Tomography

- Achronyms in literature

Acronym	Term
CPM	Coherence probe microscope
CSM	Coherence scanning microscope
CR	Coherence radar
CCI	Coherence correlation interferometry
HSI	Height scanning interferometer
MCM	Mirau correlation microscope
RSP	Rough surface profiler
RST	Rough surface tester
SWLI	Scanning white light interferometry
TD-OCT	Time-domain optical coherence tomography (full field)
VSI	Vertical scanning interferometry
EVSI	Enhanced VSI
HDVSI	High-definition VSI
WLI	White light interferometry
WLSI	White light scanning interferometry
WLPSI	White light phase shifting interferometry

Ref: R. Leach

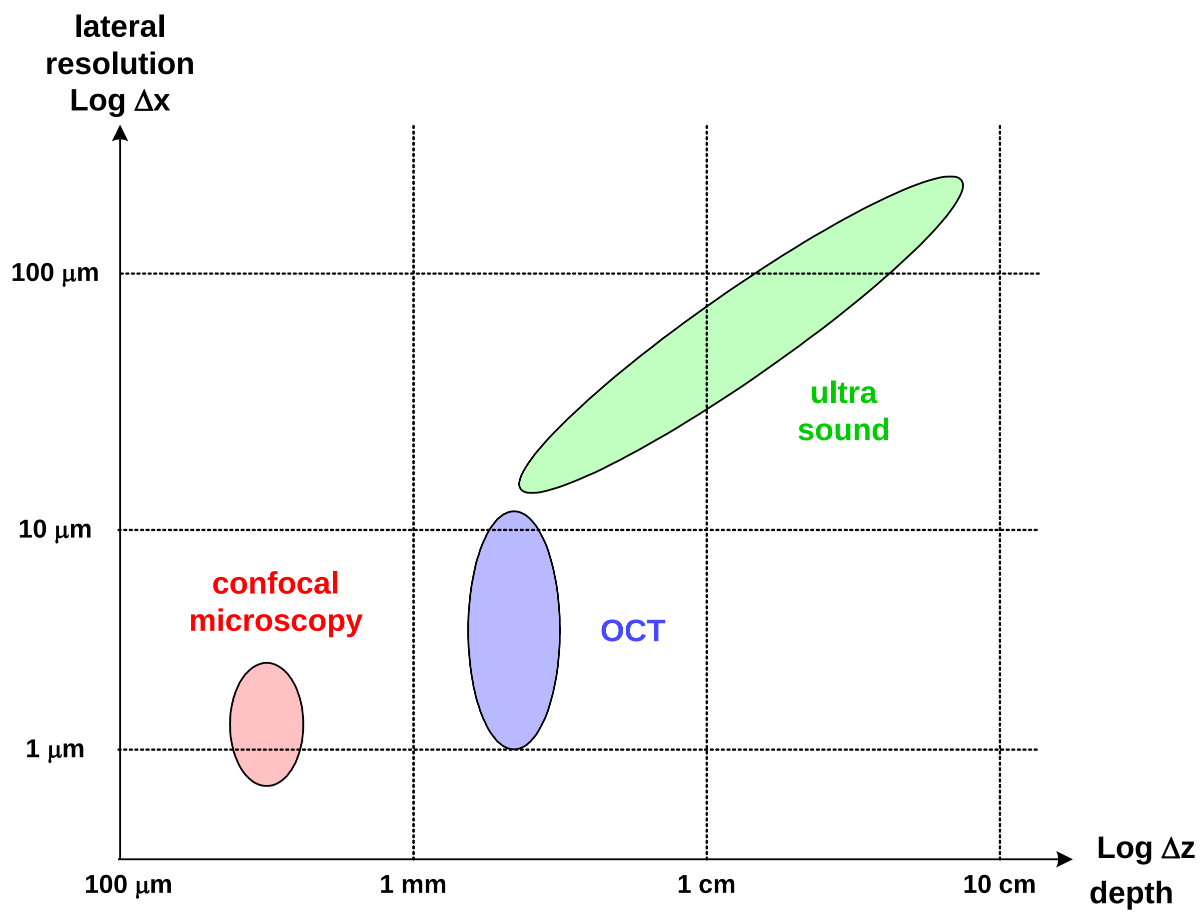
Resolution of OCT

- Lateral resolution:
  Airy profile

$$\Delta x = \frac{4\lambda \cdot f}{\pi \cdot \varnothing} = \frac{2\lambda}{\pi \cdot \sin u}$$

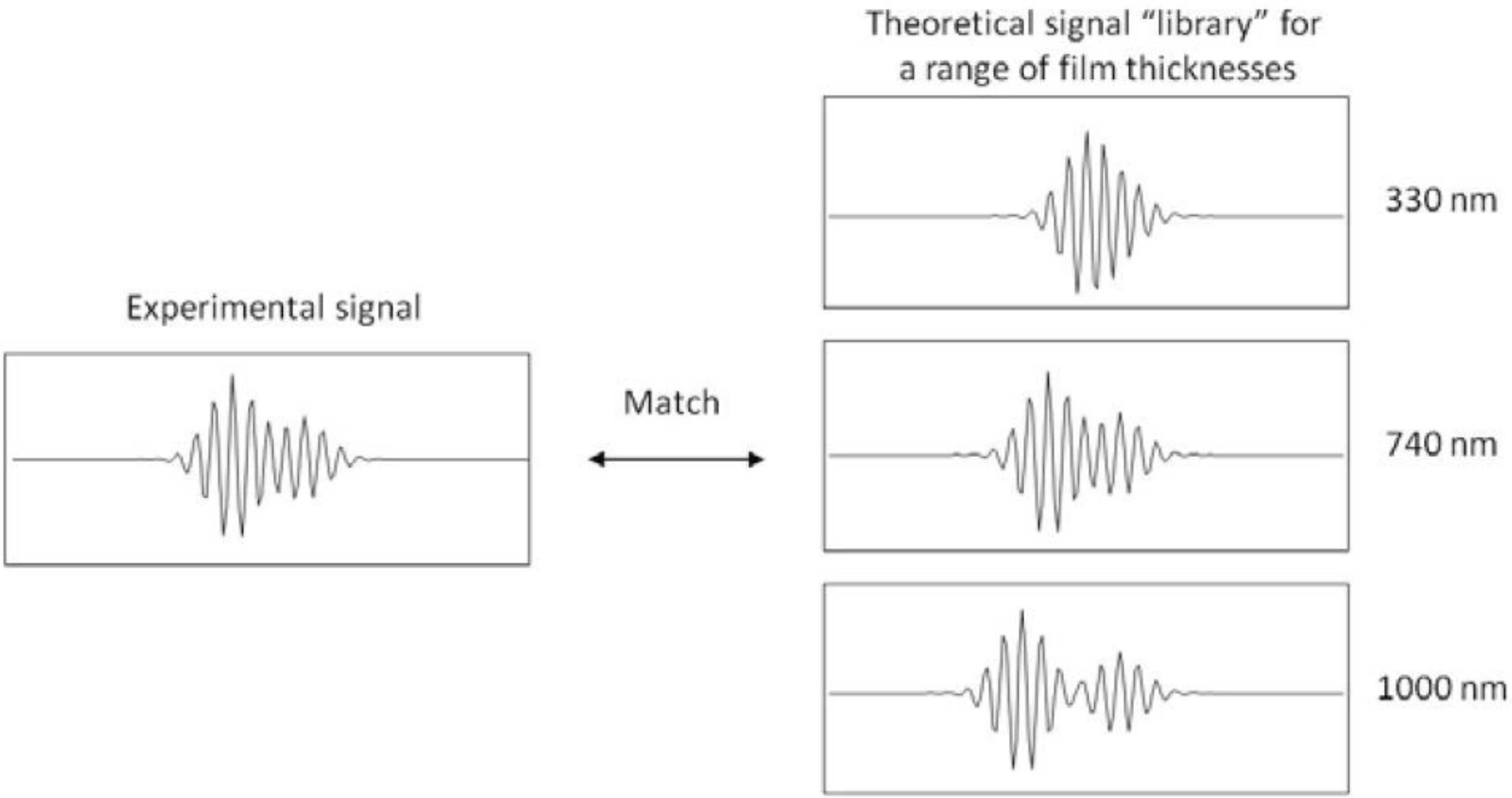
- Penetration depth:
  axial resolution

$$\Delta z_{res} = \frac{2\ln 2}{\pi} \cdot \frac{\lambda^2}{\Delta\lambda}$$



Optical Coherence Tomography

- Signature of OCT signale for thin layer measurements at the resolution limit



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Theory of Time Domain OCT

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- Basic assumption: Michelson interferometer
- Coherent field of the reference arm
  factor 2: double pass in the arm
  $$E_r(\omega) = E_{ro}(\omega) \cdot e^{2ik_r(\omega)z_r - i\omega t}$$
- Coherent field of the sample/test arm
  $$E_s(\omega) = E_{so}(\omega) \cdot e^{2ik_s(\omega)z_s - i\omega t}$$
- The spectral distributions E(ω) correspond to a low coherence light source (ultra short pulses)
- Simplification: only a single mirror is assumed as sample
- Interference signal
  $$I(\omega) = |E_r(\omega)|^2 + |E_s(\omega)|^2 + 2 \cdot \mathrm{Re}\left[E_r(\omega) E_s^*(\omega)\right]$$

  integrating over all spectral components
  of the modulated signal part
  $$I_{TD} = 2\,\mathrm{Re}\left[\int E_r(\omega) E_s^*(\omega)\, d\omega\right]$$
  $$= 2\,\mathrm{Re}\left[\int E_{ro}(\omega) E_{so}^*(\omega) \cdot e^{i\Delta\varphi(\omega)}\, d\omega\right]$$
- Phase difference determines the fast
  oscillating signal
  depends on z-difference and on dispersion
  $$\Delta\varphi(\omega) = 2\left[k_s(\omega) z_s - k_r(\omega) z_r\right]$$

Theory of Time Domain OCT

- With expansion of the dispersion functions

$$k_s(\omega) = k(\omega_0) + (\omega - \omega_o)\left.\frac{dk}{d\omega}\right|_{\omega_o}$$

- Definition of the spectral cross correlation S(ω) between reference and sample arm assumed to be symmetrical
  R_s: reflectivity in sample arm

$$R_s S(\omega) = E_{ro}(\omega) E_{so}^*(\omega)$$

- Phase difference with phase and group velocity

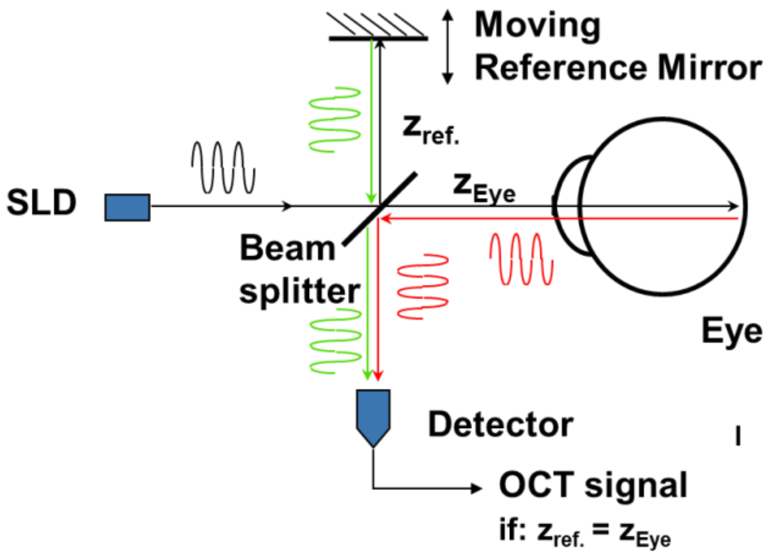
$$\Delta\varphi = 2\Delta z \cdot \left(\frac{\omega_o}{c_p} + \frac{\omega - \omega_o}{c_g(\omega)} \right) = \omega_o \Delta t_p + (\omega - \omega_o)\Delta t_g$$

- Final result of TD-OCT signal

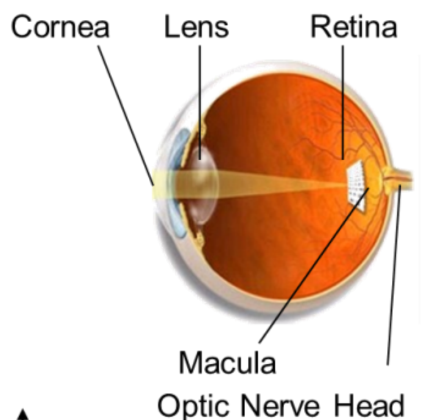
$$I_{TD}(\Delta z) = R_s \cos(\omega_o \Delta t_p) \cdot \int S(\omega) \cdot e^{-i(\omega - \omega_o)\Delta t_g}\, d\omega$$

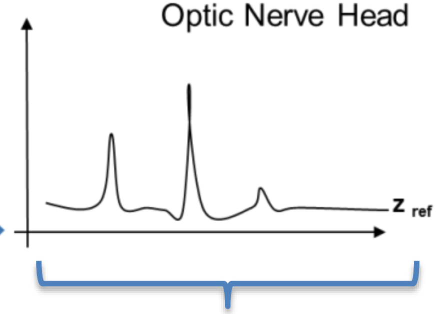
- Interpretation:
  - cos-prefactor: high oscillating term, proportional to time difference
  - integral term: envelope of signal, depends on dispersion
    is determined by the light source spectrum bandwidth

OCT Enables 3D Imaging in Ophthalmology



Measuring OCT-signals at known positions $z_{ref.}$ of the reference mirror → A-scan





within Rayleigh range of imaging optics

OCT combines unique resolution with high sensitivity

- axial resolution is independent of the numerical aperture (pupil) with NA = 0.05
- by heterodyne detection a photon-noise limited sensitivity is achieved ($R \geq 10^{-10}$)

$$\Delta z = l_c \approx 0.44\, \lambda/\Delta\lambda \approx 5\ \mu m$$

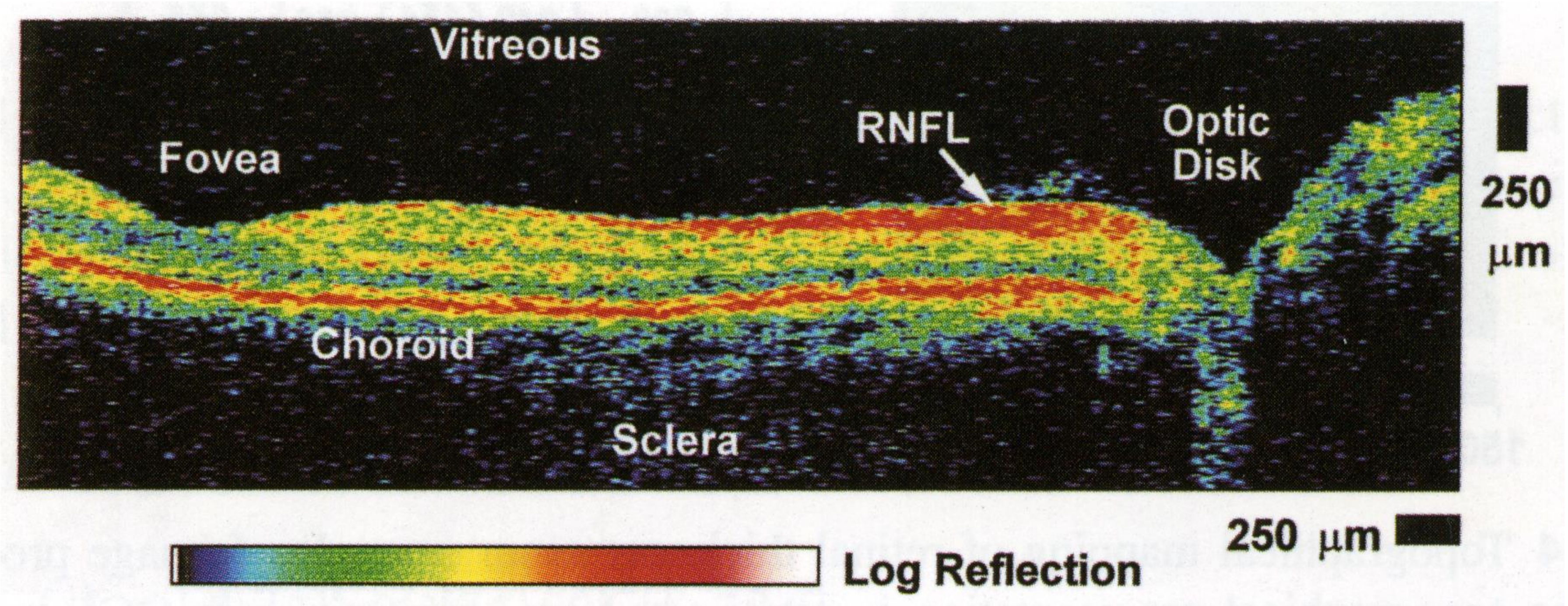
optical resolution

$$\Delta z \approx 2\lambda/NA^2 \approx 1.7\ \mu m\ (1.33 \cdot 1/24)^{-2} \approx 555\ \mu m$$

Ref: M. Kempe

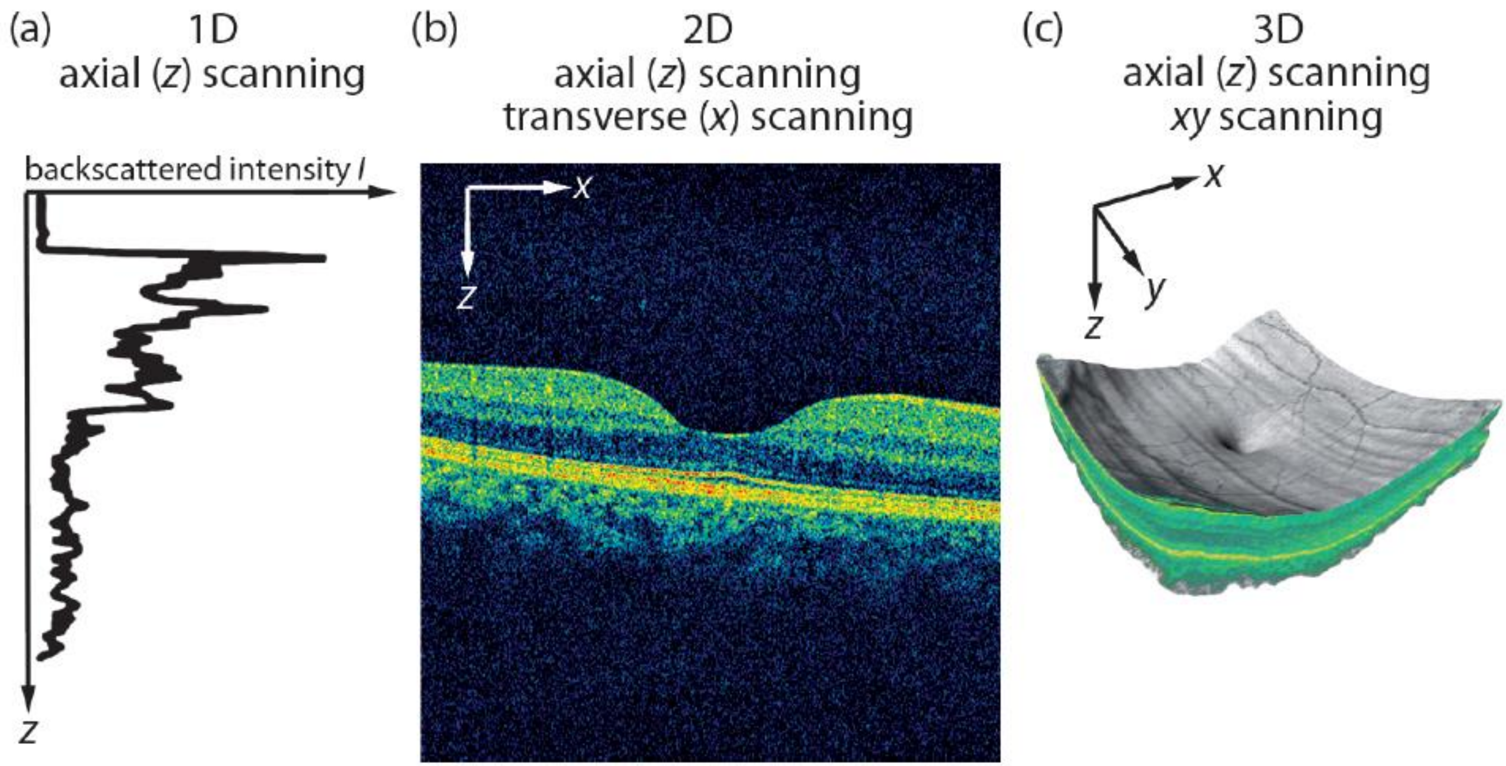
Example of OCT Imaging

Example:
Fundus of the human eye



Optical Coherence Tomography

- Dimensions of OCT imaging:
  a) only depth (A-scan), one-dimensional
  b) depth and one lateral coordinate (B-scan), two-dimensional
  c) all three coordinates, volume imaging



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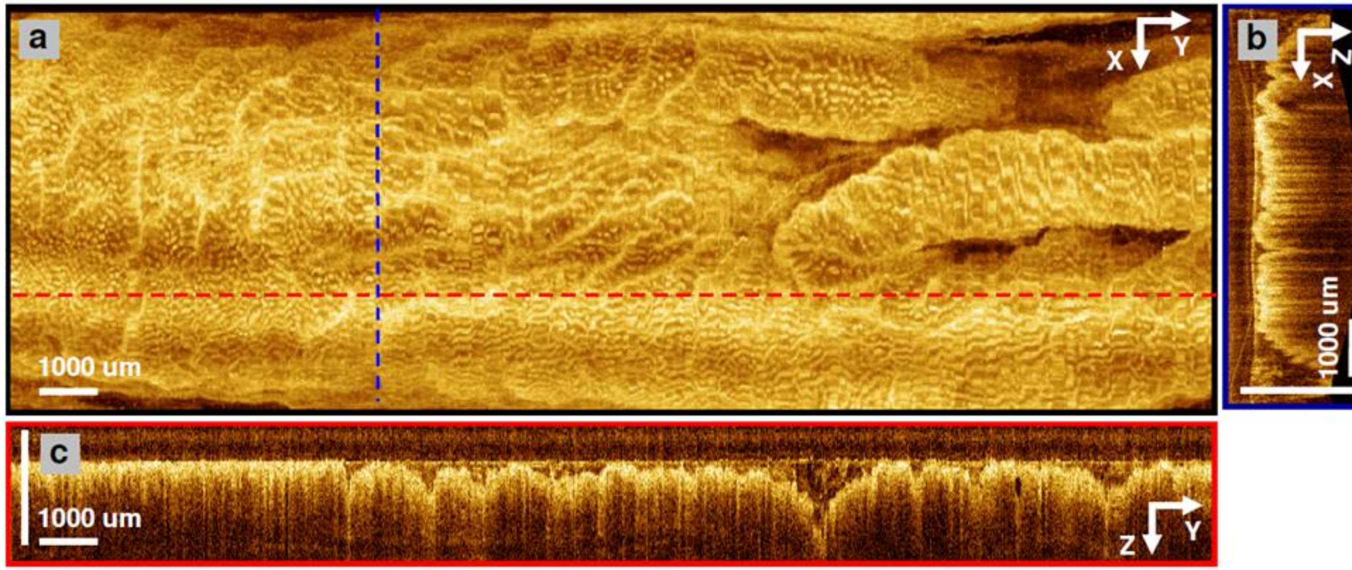
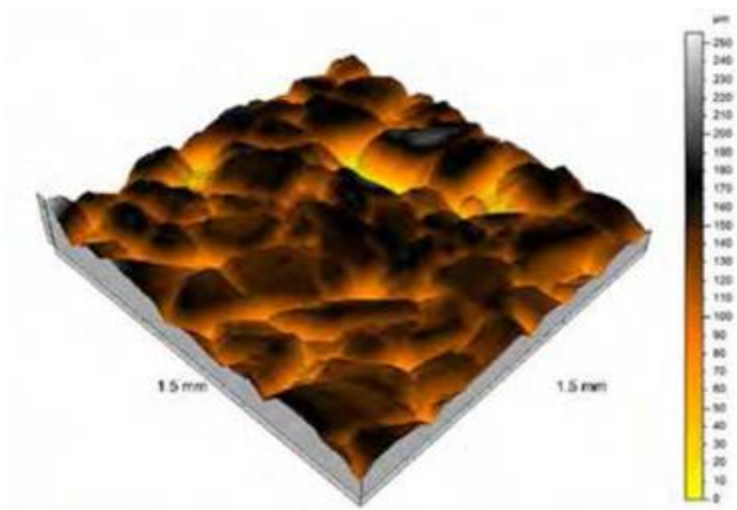
White Light Interferometry

- Examples





Ref: R. Kowarschik