Optical coherence tomography

Peter E. Andersen

Optics and Plasma Research Department
Risø National Laboratory
E-mail peter.andersen@risoe.dk

Outline

- Part I:
  - Introduction to optical coherence tomography (OCT).
- Part II:
  - Modeling the light propagation in the OCT geometry.
- Part III:
  - Biomedical applications,
  - Extracting optical properties.

Introduction to optical coherence tomography (OCT)

Part I

Outline – Part I

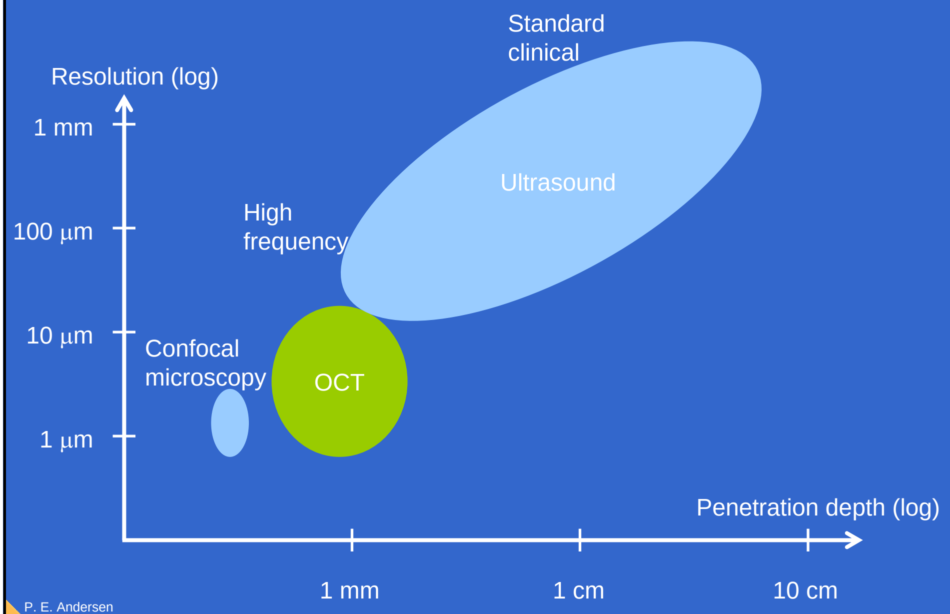
- Physical principle behind OCT
  - based on interference,
  - tomography comes about by scanning.
- Components and systems

Optical biopsy – definition

- The in situ imaging of tissue microstructure with a resolution approaching that of histology, but without the need for tissue excision and processing

Optical coherence tomography

- Three-dimensional imaging technique with ultrahigh spatial resolution even in highly scattering media
- Based on measurements of the reflected light from tissue discontinuities
  - e.g. the epidermis-dermis junction.
- Based on interferometry
  - involves interference between the reflected light and the reference beam.



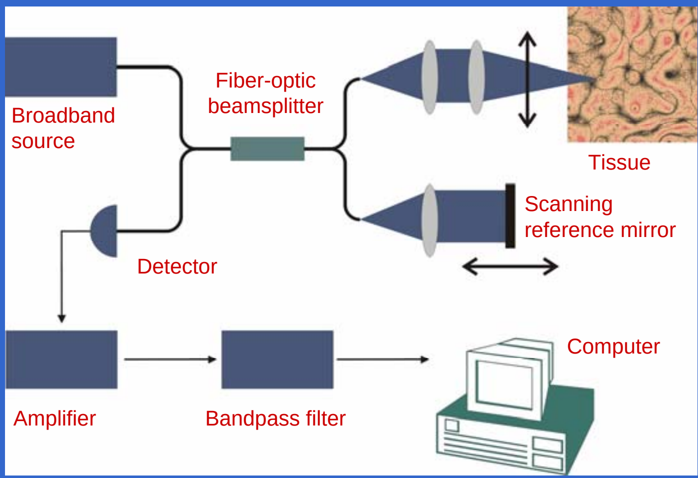
OCT in non-invasive diagnostics

- Ophthalmology
  - diagnosing retinal diseases.
- Dermatology
  - skin diseases,
  - early detection of skin cancers.
- Cardio-vascular diseases
  - vulnerable plaque detection.
- Endoscopy (fiber-optic devices)
  - gastrology,
  - …

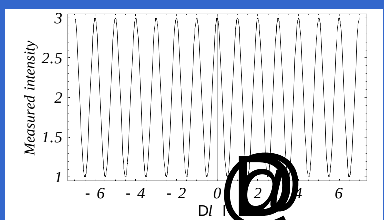
- Functional imaging
  - Doppler OCT,
  - spectroscopic OCT,
  - optical properties,
  - PS-OCT.

- Guided surgery
  - delicate procedures
    - brain surgery,
    - knee surgery,
    - …

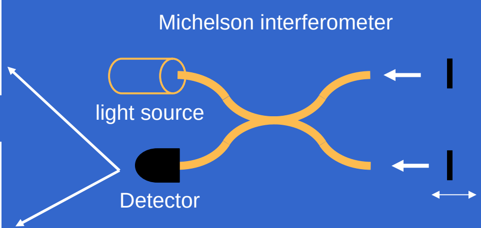
The OCT setup

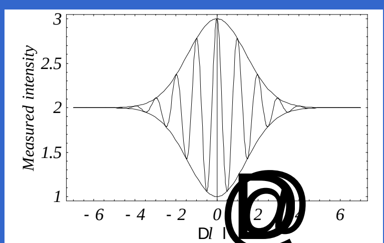


Interference



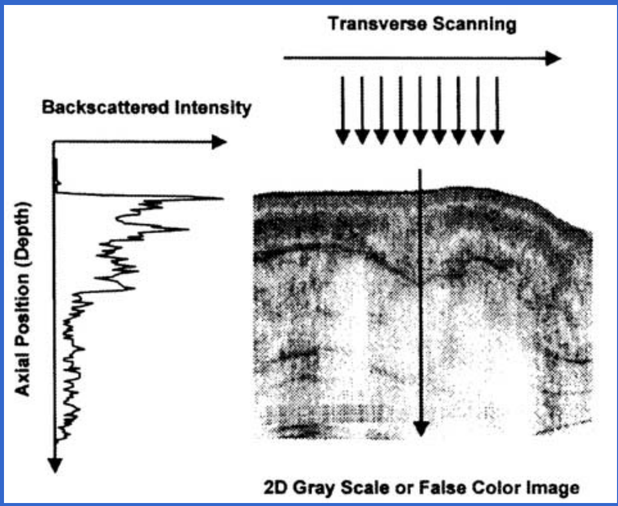
Coherent source





Partially coherent source

Construction of image



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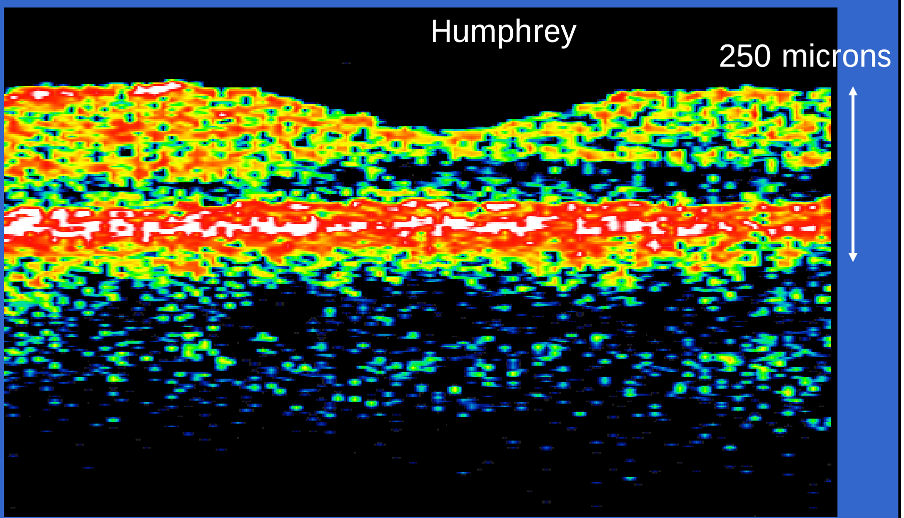
Normal Eye



Nominal width of scan: 2.8 mm

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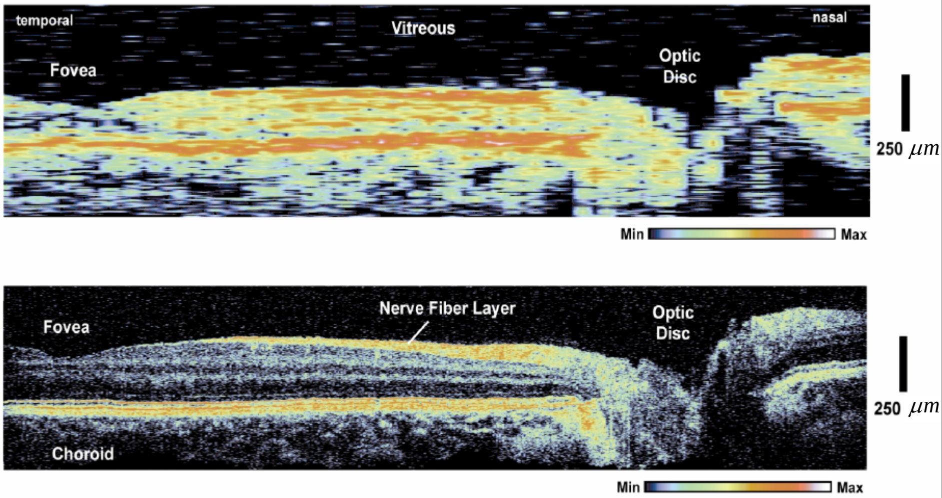
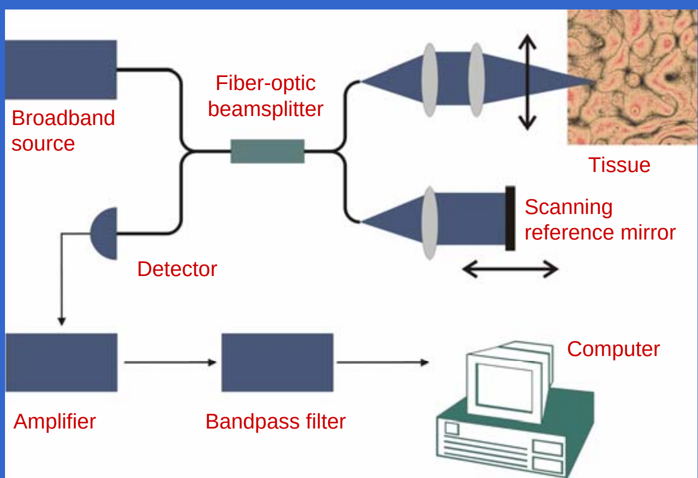
UHR-OCT versus commercial OCT



W. Drexler *et al*., “Ultrahigh-resolution ophthalmic optical coherence tomography”, Nature Medicine **7**, 502-507 (2001)

The OCT setup



System perspective

Light sources
- Superluminescent diodes
- Semiconductor amplifiers
- Femtosecond lasers
- …

Beam delivery and probes
- Hand-held probe
- Catheter
- Ophthalmoscope
- Microscope

OCT imaging engine
- Resolution
- Reference delay scanning
- Doppler/polarization/spectroscopy
- Detection
- Frequency domain

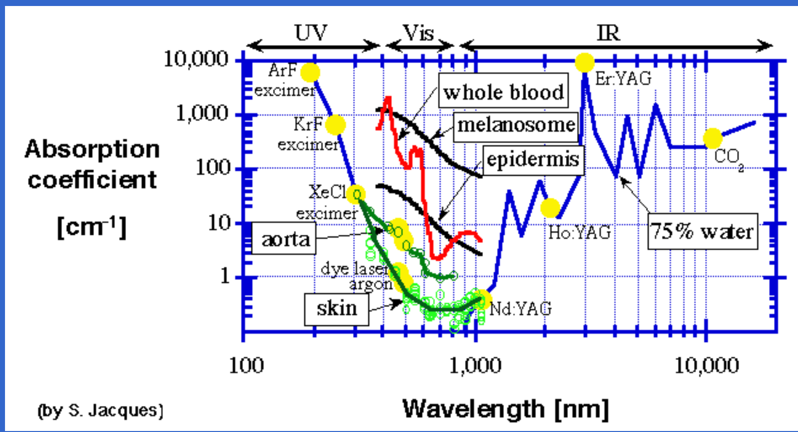
Computer control
- Drive system
- Real-time display
- Data management

Image & signal processing
- Motion reduction
- Speckle reduction
- Image enhancement
- Rendering algorithms
- …

Choosing the light source

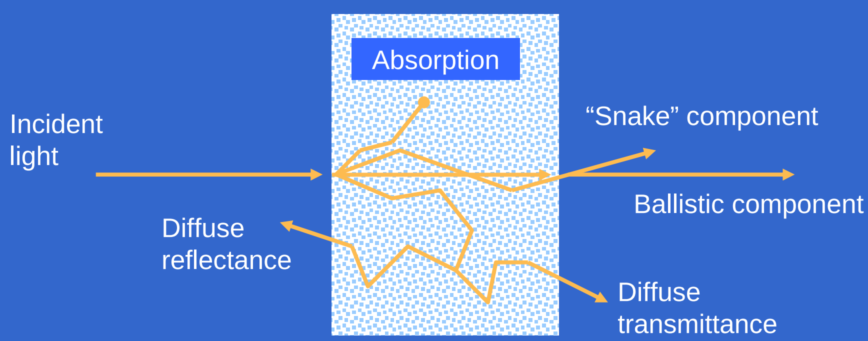
- Four primary considerations
  - wavelength,
  - bandwidth,
  - power (in a single-transverse-mode),
  - stability;
    - » portability, ease-of-use, etc.

Choose light source – wavelength

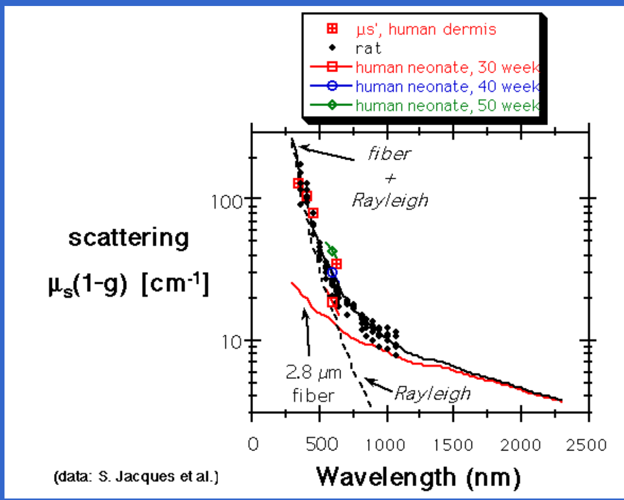


Choose light source – wavelength

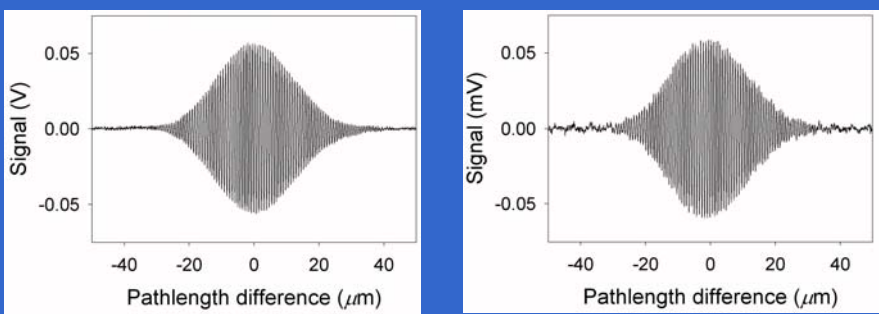
- Light propagation (Monte Carlo simulation)



Choose light source – wavelength



Raw signals



Light source spectrum

- Basic property
  - the temporal coherence envelope function G(τ) is related to the power spectral function S(ν) through G(τ) = FT{S(ν)}
    - » Wiener-Kinchine theorem
  - broadband source ⇔ high axial resolution

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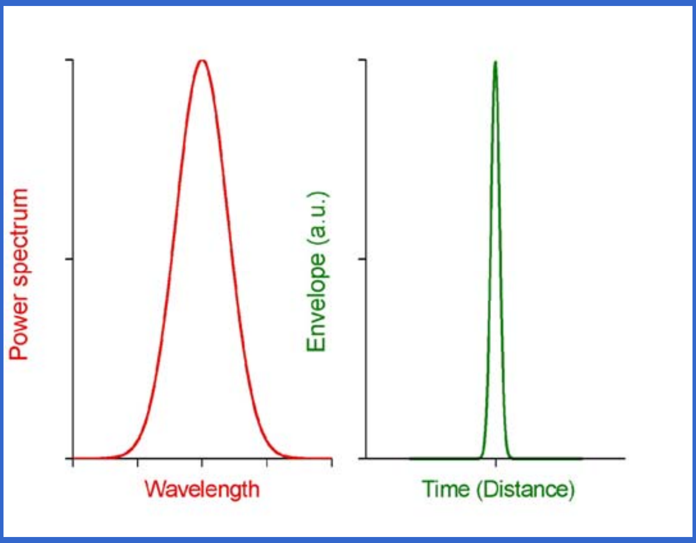
Source spectrum and envelope



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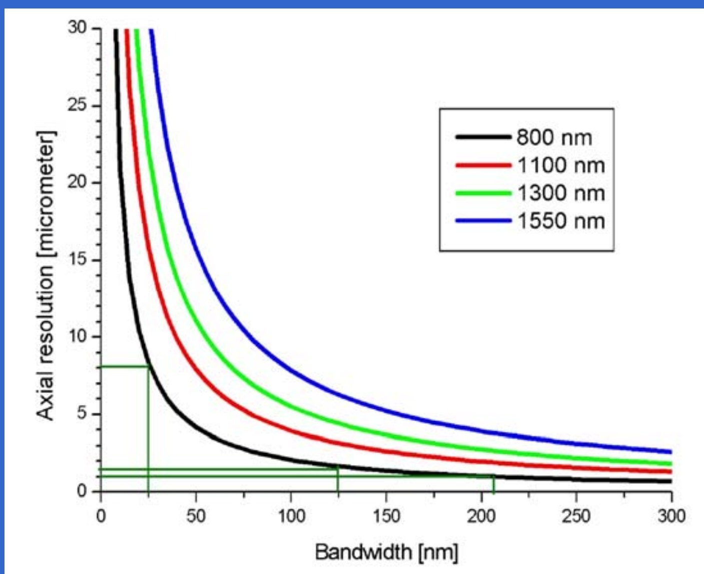
Axial resolution

- The axial resolution is

$$l_c = \frac{2c\ln 2}{\pi}\frac{1}{\Delta\nu} = \frac{2\ln 2}{\pi}\frac{\lambda_0^2}{\Delta\lambda} \approx 0.44\frac{\lambda_0^2}{\Delta\lambda}$$

  - notice that $\Delta\lambda$ is the 3dB-bandwidth!



Light sources for OCT (1/2)

- Continuous sources
  - SLD/LED/superfluorescent fibers,
  - center wavelength;
    - » 800 nm (SLD),
    - » 1300 nm (SLD, LED),
    - » 1550 nm, (LED, fiber),
    - » power: 1 to 10 mW (c.w.) is sufficient,
  - coherence length;
    - » 10 to 15 μm (typically),
- Example
  - 25 nm bandwidth @ 800 nm ⇒ ≈12 μm coherence length (in air).

Light sources for OCT (2/2)

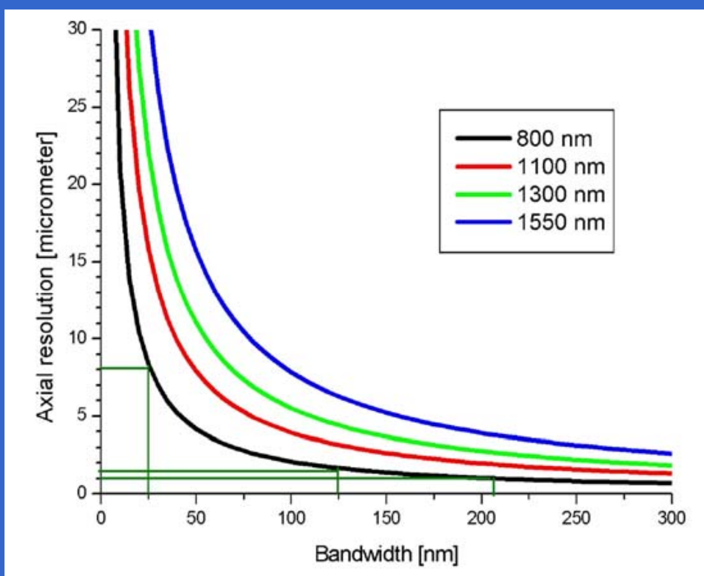
- Pulsed lasers
  - mode-locked Ti:Al_2O_3 (800 nm),
  - 3 micron axial resolution (or less).
- Scanning sources
  - tune narrow-width wavelength over entire spectrum,
  - resolution similar to other sources,
  - advantage that reference arm is not scanned,
  - advantage that fast scanning is feasible.

OCT spatial resolution

- Axial and lateral resolutions are decoupled
- The axial resolution is

$$l_c = \frac{2c\ln 2}{\pi}\frac{1}{\Delta\nu} = \frac{2\ln 2}{\pi}\frac{\lambda_0^2}{\Delta\lambda} \approx 0.44\frac{\lambda_0^2}{\Delta\lambda}$$

  - notice that $\Delta\lambda$ is the 3dB-bandwidth!
- The lateral resolution is determined by the focusing conditions
  - optics
  - dynamic vs. static focusing



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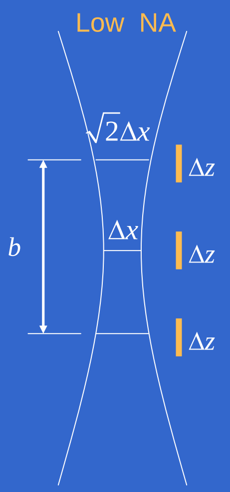
Lateral resolution (1/2)

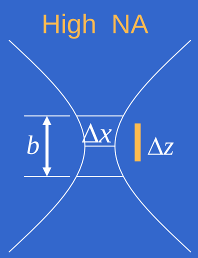


Lateral resolution

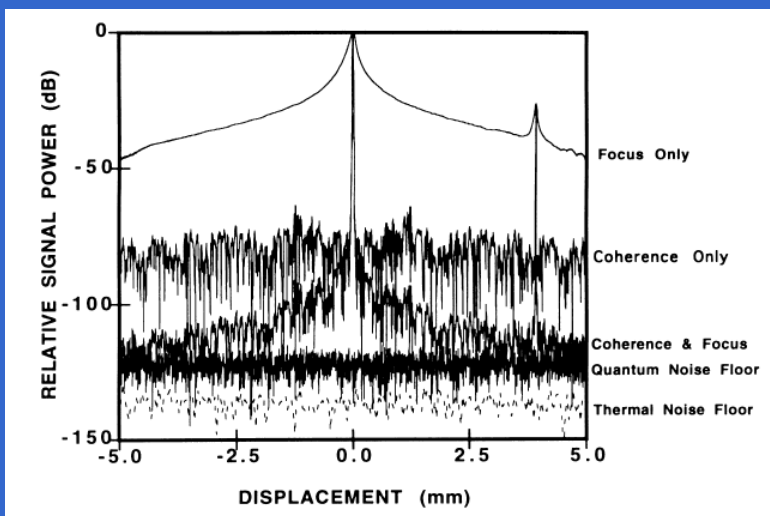
$$\Delta x = \frac{4\lambda}{\pi}\left(\frac{f}{d}\right)$$

Depth of focus

$$b = 2z_R = \pi\frac{\Delta x^2}{2\lambda}$$



Lateral resolution (2/2)



Ultra-high resolution OCT

- Broad bandwidth sources
  - solid-state lasers,
  - sub-5 fs pulse;
    - » Ti:Al_2O_3 (Spectral bandwidth: 350 nm demonstrated),
  - other lasers/wavelengths available or needed.
- Special interferometers and fiber optics
  - support for broad spectral range,
  - dispersion balanced,
  - current system used for OCT: 260 nm bandwidth, ~1.5µm resolution.
- Chromatically corrected optics
  - aberrations can decrease resolution and SNR.
- Broad bandwidth detectors and electronics
  - dual balance detection,
  - low noise circuitry necessary.

Scanning devices

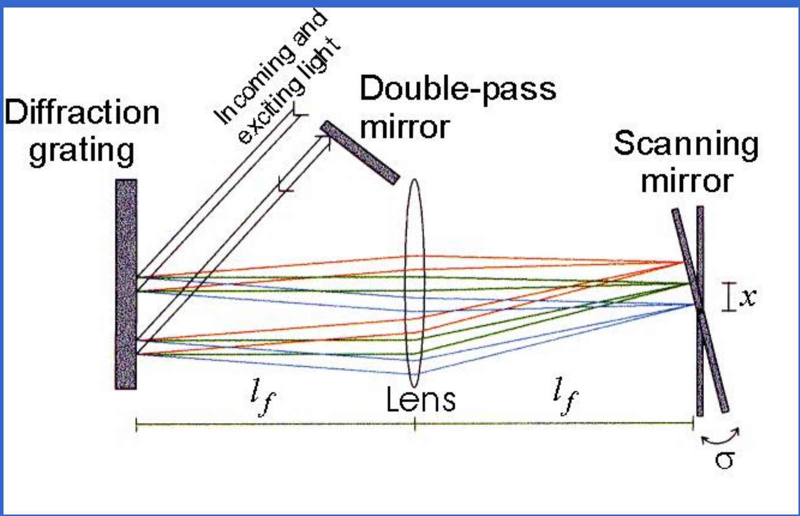
- Piezo or motorized scanning devices
  - ideal for both longitudinal and lateral scanning.
- Galvanic mirrors
- Resonance scanners
- Helical mirrors
  - longitudinal scanning.
- Fiber stretcher
  - longitudinal scanning.

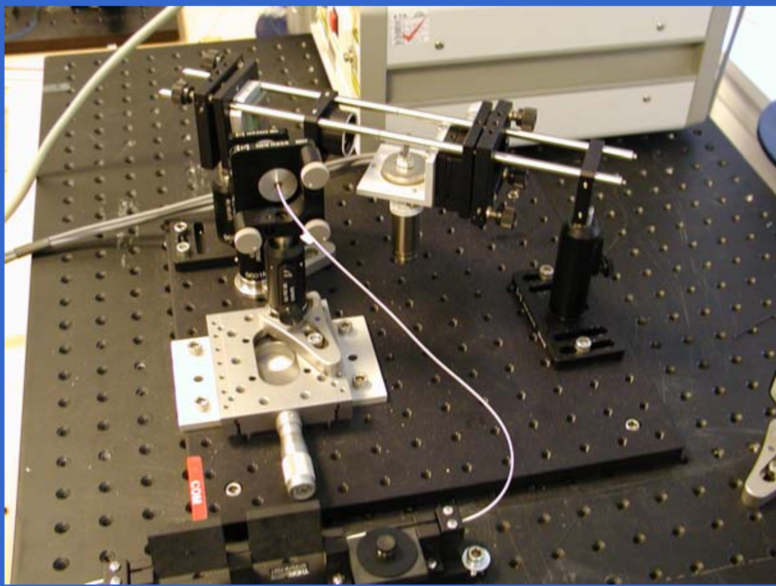
Fourier domain rapid scanning optical delay line (RSOD)

- The technique was originally developed for femtosecond pulse measurements
  - based on Fourier-transform pulse shaping techniques.
- Relies on the basic property of the Fourier transform
  - phase ramp in the Fourier domain corresponds to a group delay in the time domain.

$$x(t-t_0) \stackrel{\Im}{\longleftrightarrow} X(\omega)\exp\{-j\omega t_0\}$$

RSOD setup





RSOD characteristics

- Free-space group pathlength

$$\Delta l_g = 4\sigma x - \frac{4\sigma l_f \lambda_0}{p}$$

  - *p*: the grating pitch,
  - *f*: focal length,
  - σ: mirror angle.

- Interferogram central frequency

$$f_0 = \frac{4x}{\lambda_0}\frac{\partial \sigma}{\partial t}$$

- Bandwidth

$$\Delta f = \frac{2\Delta\lambda}{\lambda_0^2}\left(2x - \frac{2 l_f \lambda_0}{p}\right)\frac{\partial \sigma}{\partial t}$$

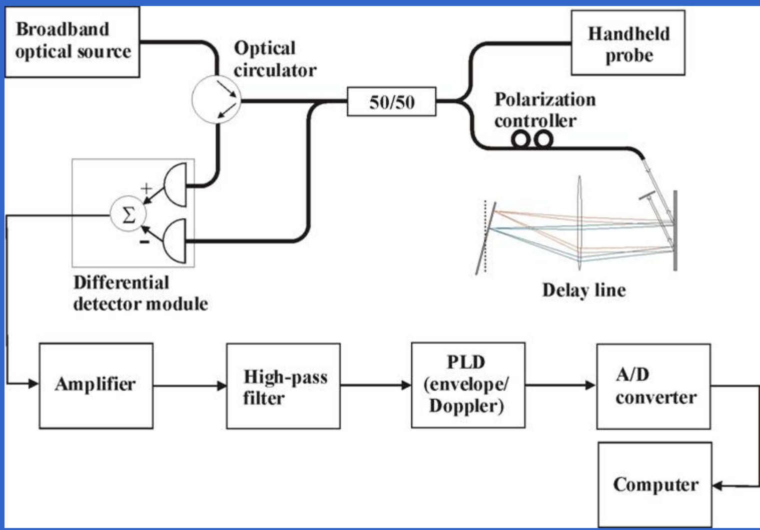
RSOD – figures-of-merit

- Scanning capabilities (galvo)
  - ~ 200 Hz,
  - ~ 5 mm.
- Scanning capabilities (resonant)
  - ~ 4-8 kHz,
  - ~ 5 mm.
- Advantages
  - dispersion compensation feasible since phase and group delays may be separated,
  - center frequency of interferogram is adjusted through axial position.

Light propagation in sample

- The sample
  - need to describe light-tissue interaction taking temporal and spatial coherence properties into account;
    - » can transport theory be used?
- Light-tissue interaction to be modelled using the extended Huygens-Fresnel principle
  - Part II of this lecture,
  - correlation between tissue, state of tissue (lesions) and optical properties?
    - » Part III of this lecture.

Our setup (mobile OCT unit)



Clinically adapted systems

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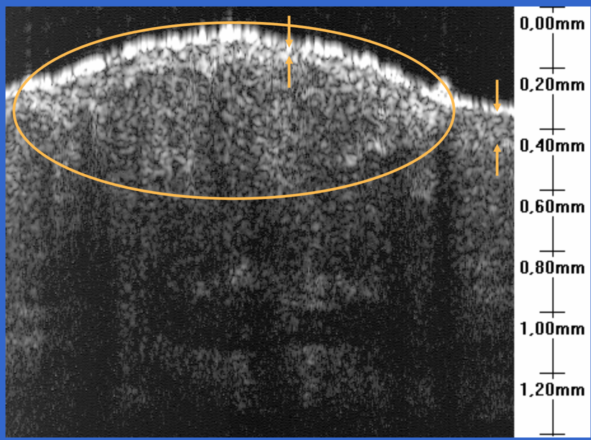
BCC II

- Layers
- Thinning of layers



OCT: Figures-of-merit – summary

- Dynamic range
  - 100 dB (or better).
- Resolution (typical)
  - 1-10 micrometers.
- Penetration depth
  - depending on wavelength/tissue,
    - » 1-2 mm (typically) for 1300 in skin tissue.
- Axial and lateral resolutions are decoupled
  - important for applications.
- Pixel density is related to spatial resolution and image acquisition time
  - $N_z=2*L_z/dz$,
  - $N_x=2*L_x/dx$,
  - image acq. time: $T=N_x*f_s$,
  - scan velocity: $v_s=L_z*f_s$.
- Image acquisition
  - seconds or less,
  - real-time OCT.
- Clinical adaptation
  - interfaced to standard equipment,
  - fiber-optic devices,
  - endoscopes.

OCT in non-invasive diagnostics

- Ophthalmology
  - diagnosing retinal diseases
- Dermatology
  - skin diseases
  - early detection of skin cancers
- Cardio-vascular diseases
  - vulnerable plaque detection
- Endoscopy (fiber-optic devices)
  - gastrology
  - …

- Functional imaging
  - Doppler OCT
  - spectroscopic OCT
  - optical properties
  - PS-OCT

- Guided surgery
  - delicate procedures
    - brain surgery
    - knee surgery
    - …