Optical Coherence Tomography OCT

Optische 3D Tomographie

SLN Seminar  2. Dez. 2010

Ch. Meier
www.ti.bfh.ch/OptoLab
Outline

1. Introduction

2. History and technological Basics
   Time Domain TD-OCT, Frequency Domain FD-OCT, Full Field OCT

3. OCT Applications
   Ophthalmology, Cardiology, Dermatology

4. Some Projects @ OptoLab, BFH-TI, Biel

5. OCT-Future: Speed, Spectral, Doppler, Phase, Polarization
Tomographic Methods in Medicine

Tomography = 3D image by sections
Greek word tomos = slice, section

- CT  X-ray
- MRI Magnetic Resonance Imaging
- PET Positron Emission Tomography
Tomographic Methods in Medicine

- UST  Ultra Sound Tomography
- DOT  Diffuse Optical Tomography
- PAT  Photoacoustic Tomography

3D-image-reconstruction

(tumor
(increased vascular density)
imaging of inhomogenities)
Tomographic Methods in Medicine

- Confocal Microscopy

- OCT
  Optical Coherence Tomography

Cardiac myocytes | Bar = 10µm.
Dr. Robert Ross, UCLA Medical School.

Drexler W., Fujimoto J. Science Direct 2007
Tomographic Methods in Medicine

<table>
<thead>
<tr>
<th>Name</th>
<th>Speed</th>
<th>Hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT</td>
<td>-</td>
<td>+++</td>
</tr>
<tr>
<td>MRI</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PET</td>
<td>-</td>
<td>+++</td>
</tr>
<tr>
<td>UST</td>
<td>++</td>
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<tr>
<td>DOT</td>
<td>-</td>
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</tr>
<tr>
<td>PAT</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>OCT</td>
<td>+++</td>
<td>-</td>
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</table>
3D Imaging by lateral scanning

- Depth profiles are constructed by measuring the time delay of backscattered or back reflected light by interferometric measurements.

- Similar to ultrasonic time of flight measurements.

- Cross sectional images are obtained by scanning in x and y direction.
OCT: wavelength range

Hemoglobin and water have low absorption in near infrared

Diagnostic window

Absorption
Scattering
Absorption

Absorption Coefficient

Wavelength [μm]

HbO₂
Melanin
H₂O
Windows of interest

J.L. Boulnois

0.4 0.6 0.8 1 2 4 6 8
Basic principle: Time Domain OCT

Michelson Interferometer setup with moving reference mirror

The signal envelope represents the reflectivity depth profile

From: Sarunic, Optics Letter 2006
OCT History, the beginnings

1991  First medical application of Time Domain OCT in vitro (Huang, Fujimoto, Science )

1993  Demonstration of OCT on eye in vivo (Fercher)

1996  First commercial application In Ophthalmology.
      STRATUS, ZEISS

- Zeiss hold monopole on ophthalmic market thanks to strong patents.
- Glaucoma, AMD, Diabetic Retinopathy.
- 2006 are 6000 Stratus in use.
OCT Market development

What happens here?

FIGURE 1.3 OCT products and revenue 1996–2008
OCT History, second generation

1995  First Publication of a new method: Fourier Domain OCT
      (Fercher, J. of Optics Communication, 1995)

1998  Application to Dermatology
      (Häusler, J. of biomedical Optics)

2000  Several papers to Fourier Domain OCT
      The new method is faster, has better
      contrast and image quality

2002  First instrument on market

The ideas to the second generation OCT systems
were published before patents were deposed

The technique is free !!
FD-OCT, basic principles
FD-OCT, basic principles

Interferences due to optical path difference

\[ F D(k) = S(k) \left( r_R^2 + r_s^2 + 2r_R r_s \cos(2kz) \right) \]

Frequency in k-space is proportional to OPD

Reflectivity profile is obtained by a Fourier transformation
FD-OCT, basic principles, swept source

\[ F D(k) = S(k)(r_R^2 + r_s^2 + 2r_Rr_s\cos(2kz)) \]

\[ SD(z) = \mathcal{F}^{-1}[S(k)] \otimes \mathcal{F}^{-1}[2r_Rr_s\cos(2kz)] \]
## Resolution: OCT and Microscopy

<table>
<thead>
<tr>
<th></th>
<th>Lateral resolution</th>
<th>Axial resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Confocal Microscope</strong></td>
<td>$\Delta x \sim \frac{1}{N_A}$</td>
<td>$\Delta z \sim \frac{1}{N_A^2}$</td>
</tr>
<tr>
<td><strong>OCT</strong></td>
<td>$\Delta x \sim \frac{1}{N_A}$</td>
<td>$\Delta z = \frac{4\ln(2)}{\Delta k}$</td>
</tr>
</tbody>
</table>

\[ N_A = \frac{d}{2f} \]
Scanning FD OCT

Source $S(\lambda)$

Spectro

Swept Source

Detector

$z$

Cam

Full Field OCT

Source $S(\lambda)$

Swept Source

Cam
State of the art, retina imaging

From OptoPol, soct_HR

From Zeiss cyrrus

From: Drexler W., Fujimoto J. Science Direct 2007
State of the art, retina imaging

From: Drexler W., Fujimoto J. Science Direct 2007
Anterior segment of the eye

From: Grulkowski., Optic Express, march 2009
Endoscopic OCT and cardiology

From LightLab

Kume, Assessment of coronary calcification by OCT, PCR online 2010
Optical Biopsy

Tissue investigation without extraction

Fig. 7. (a) In vivo endoscopic OCT image of rabbit colon with (b) corresponding histology. Delineation of upper colonic mucosa (cm), muscular mucosa (mm), submucosa (sm), and muscularis externa (me) is possible. Enlarged images show the capability to visualize crypt structure. Tissue separations seen in the lower part of the histology images are due to a histology processing artifact.

Herz,... Fujimoto, OpticsExpress 2004
**Full Field OCT**

- sub um resolution
- geometrical height

- phase image
- Refractive index meas.
- Identifying live cancer cells

Choi, *Full-field optical coherence microscopy ...*, *Opt. Express* (2010),
Full Field Swept Source OCT

- No real swept source available in Si-camera range (300 – 1000 nm)

- fast NIR cams are very expensive

Red blood cells
Sarunic, Full Field Swept Source Phase Microscopy, Optics Letters 2006
Full Field OCT, made in Switzerland

Phase–Sensitive Parallel
Optical Coherence Tomography

Number of pixels 144 x 90
Vertical resolution 200nm
Lateral resolution 2 um
Some Projects @ OptoLab

Linear $k$-Spectrometer for OCT

$$FD(k) = S(k) \left( r_R^2 + r_s^2 + 2r_Rr_sc \cos (2kz) \right)$$

- Sensitivity: 93 dB @ 40 µs integration time
- Camera speed: 28’700 A-scans/s
- Measuring range: 6 mm

Collimator  Grating  Prism  Lens  Camera
Linear K-Spectrometer for OCT

- Human finger @ 835 nm
  - 3 x 10 mm
  - 1024 x 1024 pixels
  - Integration time: 0.111 ms

- Pig cornea @ 830 nm
  - 1 x 3 mm
  - 1024 x 1024 pixels
  - Integration time: 0.250 ms
Internal Fingerprint Identification with OCT

- Secure and reliable identification
- Use of the internal structures of the finger (region around the papilla layer)
- Compatible with algorithm for fingerprint identification

OCT Callisto

OCT Box Callisto
Includes: - Source
- Spectrometer
- Reference arm
- Interferometer

Dimensions: 200 x 150 x 70
Axial Scan Resolution: 6.5 μm
Measurement range 6.6 mm
Spectroscopic OCT

• System developed to analyze spatial resolved spectral absorption of substances using OCT

• Possible ability to determine physiological parameters (e.g. in blood) non-invasively

• Distinguishable levels of ICG (*indocyanine green, near-infrared absorber*) in micromolar (μM) concentrations

P. Steiner, Ch. Meier, V.M. Koch, „Influence and compensation of autocorrelation terms in depth resolved spectroscopic Fourier-Domain optical coherence tomography”, Applied Optics 2010
Coherence Length Measurement

- System development to measure the instantaneous coherence length.

- Crucial performance indicator for swept laser sources

- Setup is based on a Mach-Zehnder interferometer with variable delay length

- Application in the development process of rapidly swept laser sources

- Measurements at sweeping rates up to 120 kHz possible
Outlook

• **Speed**
  Example: $1024 \times 1024 \times 1024 = 1\text{Gvoxel}$
  with $20\text{kHz}$ A-scan rate acquisition time $= 52\text{ s}$ too long!

• **Data Processing**
  De-noising, segmentation, 3D representation
  Data reduction -> compressive sampling

• **Sources**
  Stable broad band laser sources @ affordable cost,
  Miniaturized high speed swept source

• **Functional OCT**
  Polarization, Spectroscopic, Phase, Doppler,
  Combination with Fluorescence Microscopy, or Raman Spectroscopy
Speed

• 3D images in vivo: speed minimize motion artifacts

Gora, M.;…Wojtkowski, M. OpticExpress, Aug. 2009, (up to 200kHz A scan rate)
Ultra High Speed OCT

• 325 kHz FDML frequency
• 2.6 MHz effective sweep rate after 8x buffer
• More than 10 MHz depth scan rate with 960 samples per depth scan
• 4.5 GVoxel/ s

Miniaturized Swept sources

EXALOS
50 kHz sweep rate

AXSUN

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength Range</td>
<td>1250 – 1360 nm</td>
</tr>
<tr>
<td>Output Power</td>
<td>20 mW</td>
</tr>
<tr>
<td>Sweep Rate</td>
<td>50 kHz</td>
</tr>
<tr>
<td>Coherence Length</td>
<td>12 mm</td>
</tr>
</tbody>
</table>

Sweeping due to tunable Fabry-Perrot filter
Functional OCT, Doppler

Bachmann, ... Leitgeb. OpticExpress,. 2007
3D Polarization sensitive OCT

- Images sub-surface vocal fold tissue non-invasively
- Useful information in guiding surgeons during phonomicrosurgery

K.H. Kim, *In vivo 3D human vocal fold imaging… OpticsExpress 2010*
OptoLab
BFH TI Biel
www.ti.bfh.ch/OptoLab

Master Thesis available

Biomedical Master or
MSE Master Laser + Photonics

Thank you for your attention

S. Gloor, P. Steiner, B. Moser, T. von Niederhäusern,
F. Andronico, P Stalder, D. Trivun, D. Ernst
R. Lehmann, A. Bossen, Ch. Meier