Signal Processing and data acquisition in Optical Coherence Tomography (OCT)

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From TOMO 3D Project
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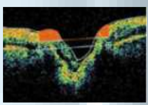
A few about OCT

What 's OCT ?

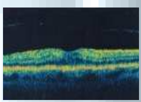
Below, some OCT scan Images

The optical coherence tomography is a non-invasive and non-destructive technique of three-dimensional imaging with micrometer resolutions.



OCT image of optic nerve head

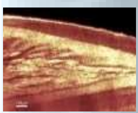
This is an interferometric method which exploits the temporal coherence properties of light.



OCT Scan of macula

Thus, she requested laser sources delivering a large bandwidth spectrum and therefore a low temporal coherence.

The vast majority of applications is in the biomedical field (specially Ophthalmology and Tissue diseases domain), although some applications in the industrial field also exist.

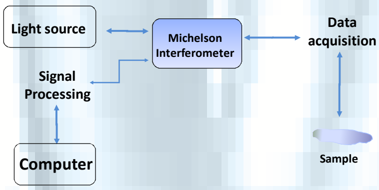


OCT image of the human skin adjacent to a finger-nail.

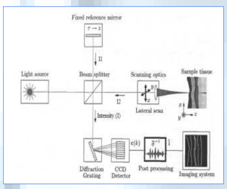
Our aim is to design a 3D Tomograph able to fight against counterfeiting and detect them, furthermore reveal the defects in the glass.

How OCT works ?

OCT uses interferometry which is basically a technique of interfering beams, like the Michelson interferometer, to create an output beam that is different than the input beam and then compare the differences or similarities between the beams to view samples.



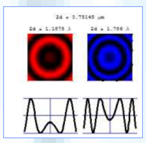
Michelson Interferometer



$$Intensity = I_1 + I_2 + 2\sqrt{I_1 I_2}\,\text{Cos}\left[\frac{2\pi}{\lambda}\left(2d\,\text{Cos}\left[\frac{\sqrt{x^2+y^2}}{f}\right]\right)+\pi\right]$$

where I_1 and I_2 are the intensities of the two beams, λ is the wavelength, and d is the path length difference between the two interferometer arms. x and y are coordinates in the focal plane of a lens of focal length f.

The fringes for wavelengths λ = 632.8 nm and 420 nm are shown against

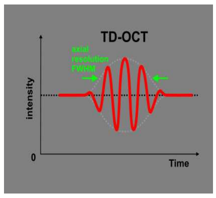


What about the signal Processing ?

Time Domain OCT

In time domain OCT , the pathlength of the reference arm is translated longitudinally in time.

A property of low coherence interferometry is that interference, i.e. the series of dark and bright fringes, is only achieved when the path difference lies within the coherence length of the light source.



This interference is called auto correlation in a symmetric interferometer (both arms have the same reflectivity), or cross-correlation in the common case.

The envelope of this modulation changes as pathlength difference is varied, where the peak of the envelope corresponds to pathlength matching.

The interference of two partially coherent light beams can be expressed in terms of the source intensity, I_S, as

$$I = k_1 I_S + k_2 I_S + 2\sqrt{(k_1 I_S)\cdot(k_2 I_S)}\cdot Re[\gamma(\tau)] \qquad (1)$$

Where $k_1 + k_2 < 1$ represents the interferometer beam splitting ratio, and γ(τ) is called the complex degree of coherence, i.e. the interference envelope and carrier dependent on reference arm scan or time delay τ, and whose recovery of interest in OCT.

Due to the coherence gating effect of OCT, the complex degree of coherence is represented as a Gaussian function expressed as

$$\gamma(\tau) = \exp\left[-\left(\frac{\pi\Delta\nu\tau}{2\sqrt{\ln 2}}\right)^2\right]\cdot\exp(-j2\pi\nu_0\tau) \qquad (2)$$

Where Δν represents the spectral width of the source in the optical frequency, and ν0 is the centre optical frequency of the source.

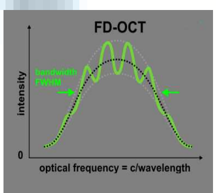
The Gaussian envelope is amplitude modulated by an optical carrier, that is due to the Doppler effect resulting from scanning one arm of the interferometer, and the frequency of this modulation is controlled by the speed of scanning.

Therefore, translating one arm of the interferometer has two functions: depth scanning and a Doppler-shifted optical carrier are accomplished by pathlength variation. In OCT, the Doppler-shifted optical carrier has a frequency expressed as

$$f_{Dopp} = \frac{2\cdot\nu_0\cdot v_s}{c} \qquad (3)$$

Frequency Domain OCT

In frequency domain OCT, the broadband Interference is acquired with spectrally separated detectors (either by encoding the optical frequency in time with a spectrally scanning source or with a dispersive detector, like a grating and a linear detector array).



Due to the Fourier relation (Wiener-Khintchine theorem between the auto correlation and the spectral power density) , the depth scan can be immediately calculated by a Fourier-transform from the acquired spectra, without movement of the reference arm.

This feature improves imaging speed dramatically, while the reduced losses during a single scan, improve the signal to noise proportional to the number of detection elements.
The parallel detection at multiple wavelength ranges limits the scanning range, while the full spectral bandwidth sets the axial resolution.

Spatially Encoded Frequency Domain OCT (aka Spectral Domain or Fourier Domain OCT)

SEFD-OCT extracts spectral information by distributing different optical frequencies onto a detector stripe (line-array CCD or CMOS) via a dispersive element .

There, by the information of the full depth scan can be acquired within a single exposure.

However, the large signal to noise advantage of FD-OCT, is reduced due the lower dynamic range of stripe detectors, in respect to single photosensitive diodes, resulting in an SNR (signal to noise ratio) advantage of ~10 dB at much higher speeds.

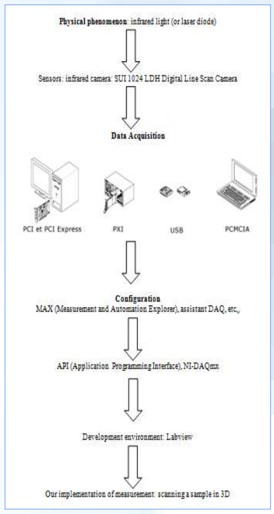
Time Encoded Frequency Domain OCT (also swept source OCT)

TEFD-OCT tries to combine some of the advantages of standard TD and SEFD-OCT. Here, the spectral components are not encoded by spatial separation, but they are encoded in time.

The spectrum either filtered or generated in single successive frequency steps and reconstructed before Fourier-transformation.

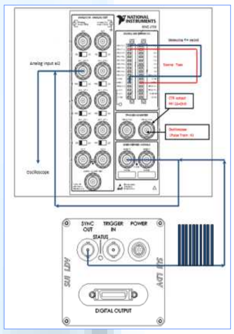
And what about Data Acquisition?

Labview and data flow

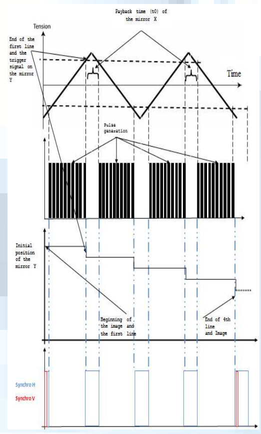


Data in real time

Real time board



Simulation



Experimental results