some aspects of Optical Coherence Tomography

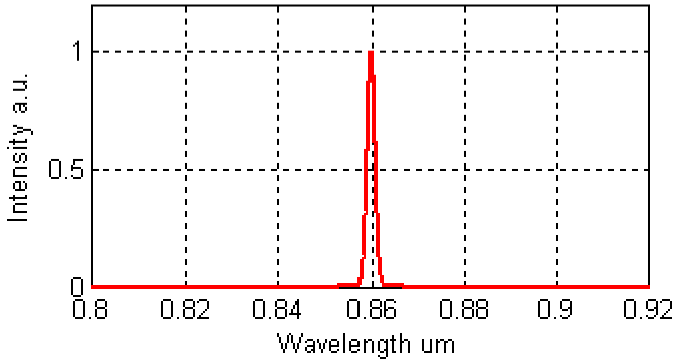
SSOM Lectures, Engelberg

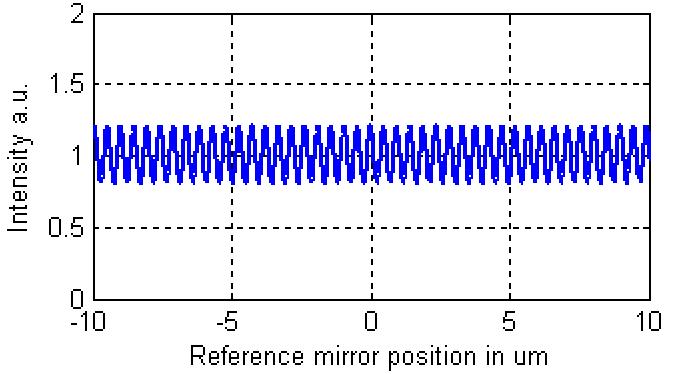
17.3.2009

Ch. Meier

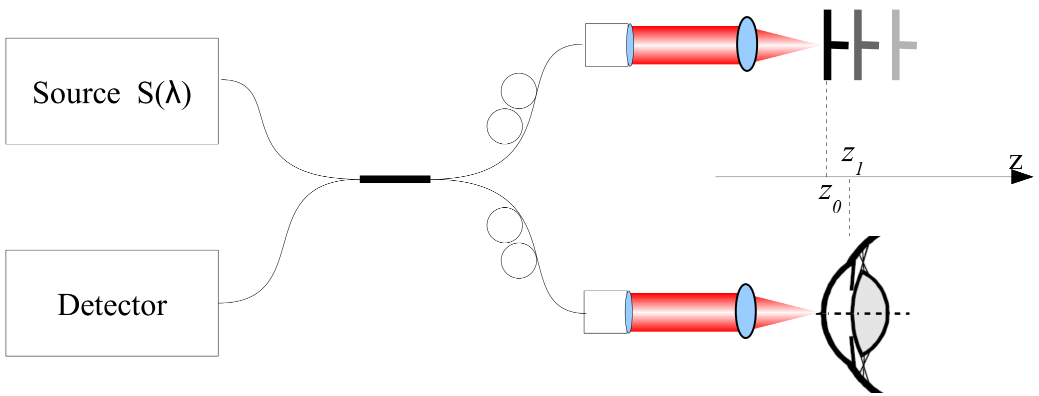
Contents

Time Domain OCT



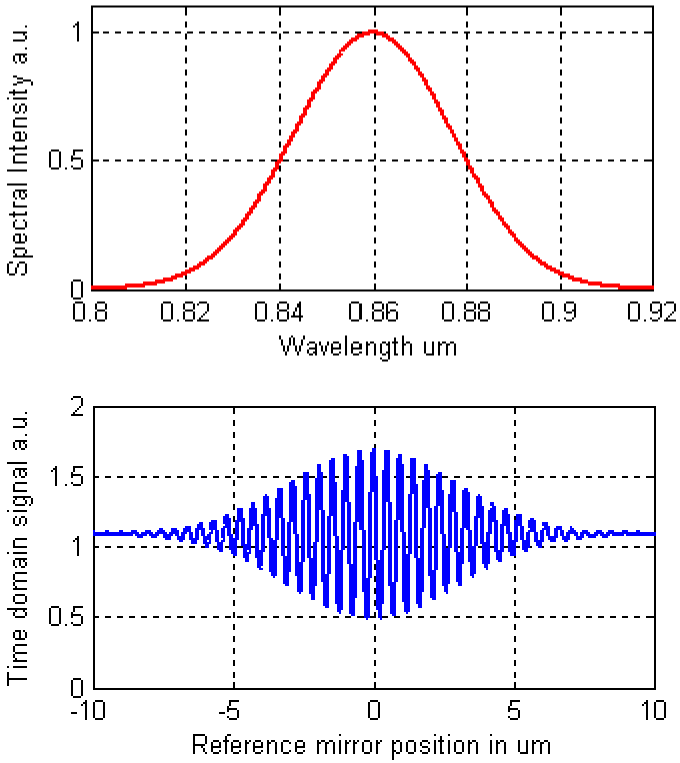


Michelson Interferometer setup with moving reference mirror

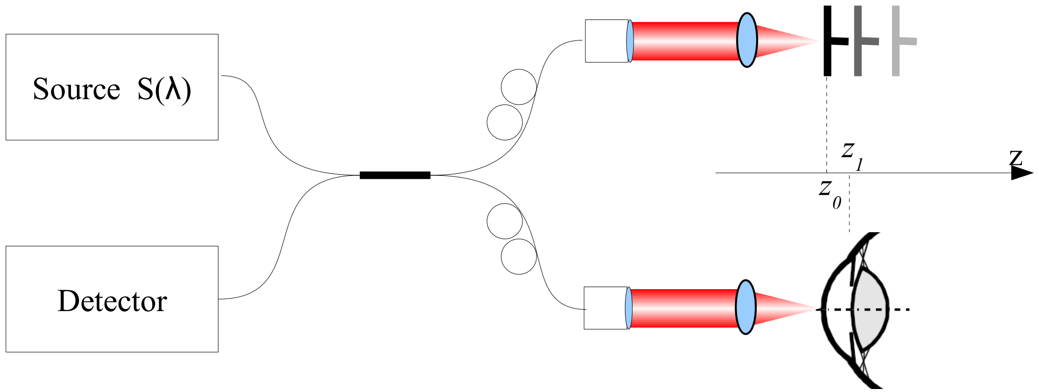


$$TD(z) = r_R^2 + r_s^2 + 2r_R r_s cos(2k(z_0 - z1))$$

Time Domain OCT

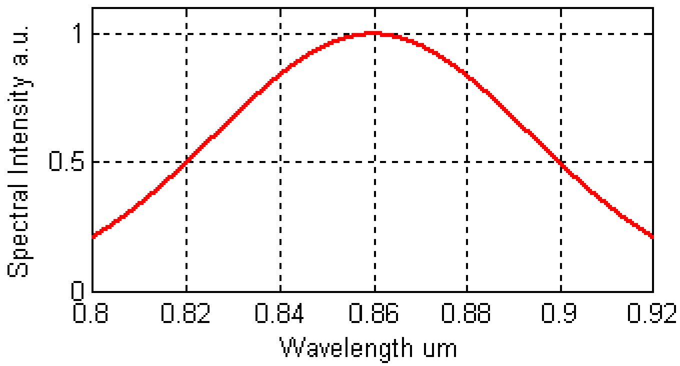


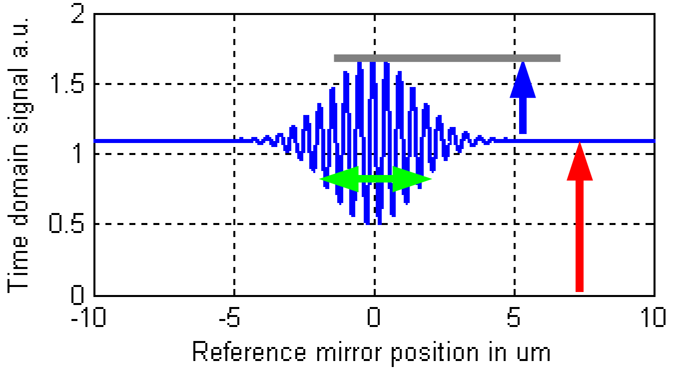
Broadband source = low coherence
Interferences are localized



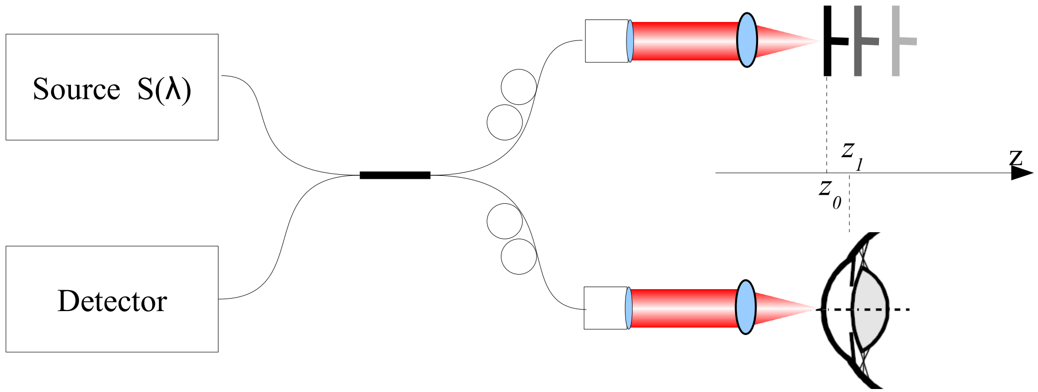
$$TD(z) = I_{DC} + I_{AC}|\gamma(z)|cos(2k\Delta z)$$

Time Domain OCT





Broadband source = low coherence, interferences are localized



$$TD(z) = I_{DC} + I_{AC}|\gamma(z)|cos(2k\Delta z)$$

Degree of coherence

$$\gamma(z) = e^{-4ln(2)\left(\frac{z}{l_c}\right)^2}$$

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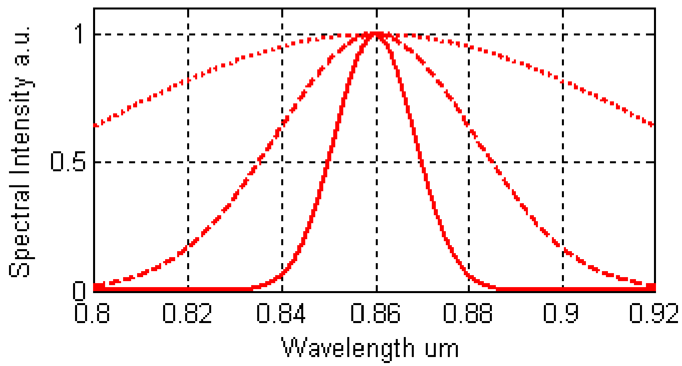
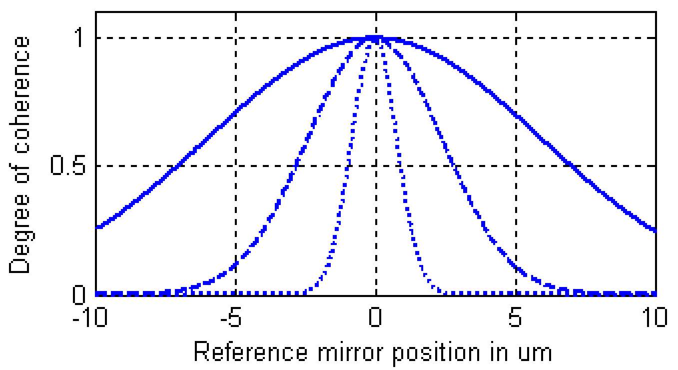
Source Spectrum - Degree of Coherence





$$l_c = \frac{2ln(2)}{\pi}\frac{\lambda_m^2}{\Delta\lambda}$$

Wiener – Khinchin theorem: The correlation function and the spectrum form a Fourier pair

$$\Gamma(\tau) = \mathfrak{F}^{-1}[S(\nu)]$$

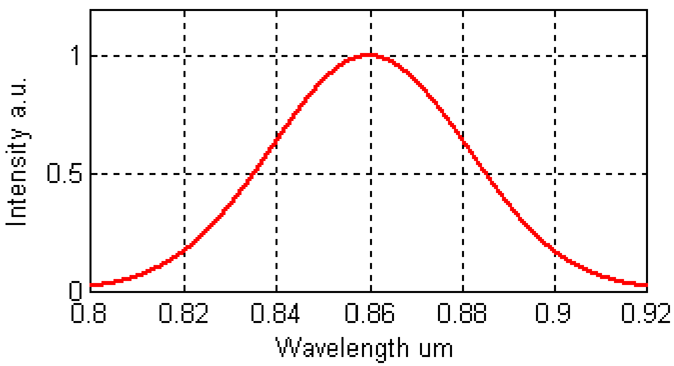
The normalized correlation function is the degree of coherence $\gamma(\tau)$. For a gaussian Spectrum

$$|\gamma(z)| = |\gamma(\tau c)| = e^{-4ln(2)\left(\frac{z}{l_c}\right)^2}$$

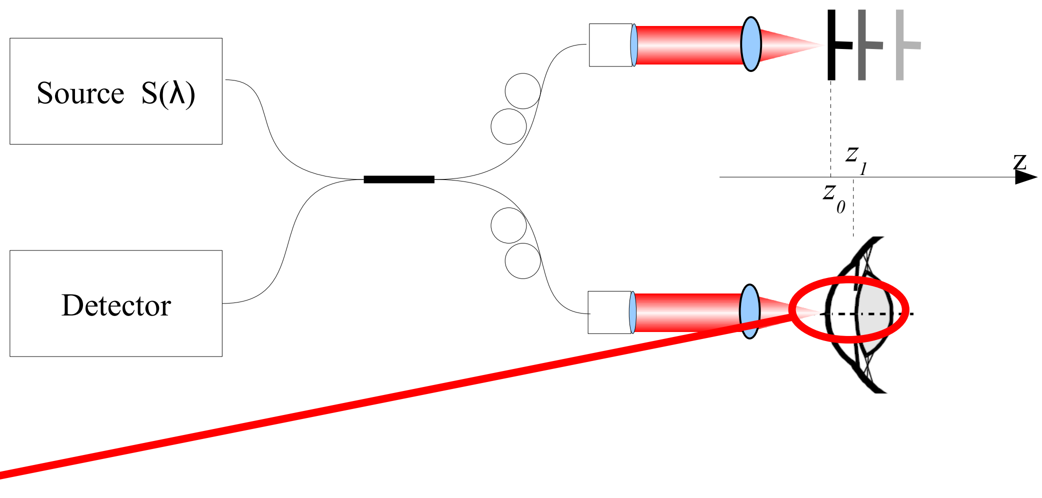
The coherence length (FWHM)

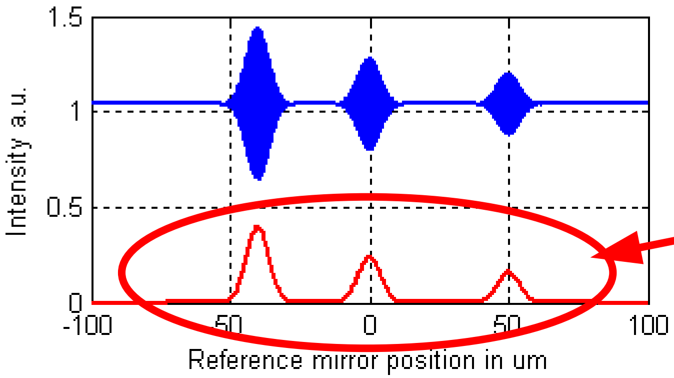
Bandwidth	Coherence length
20 nm	14 um
50 nm	5.6um
150 nm	1.9um

Time Domain OCT



The signal envelope represent the reflectivity depth profile $r_s(z)$





Resolution

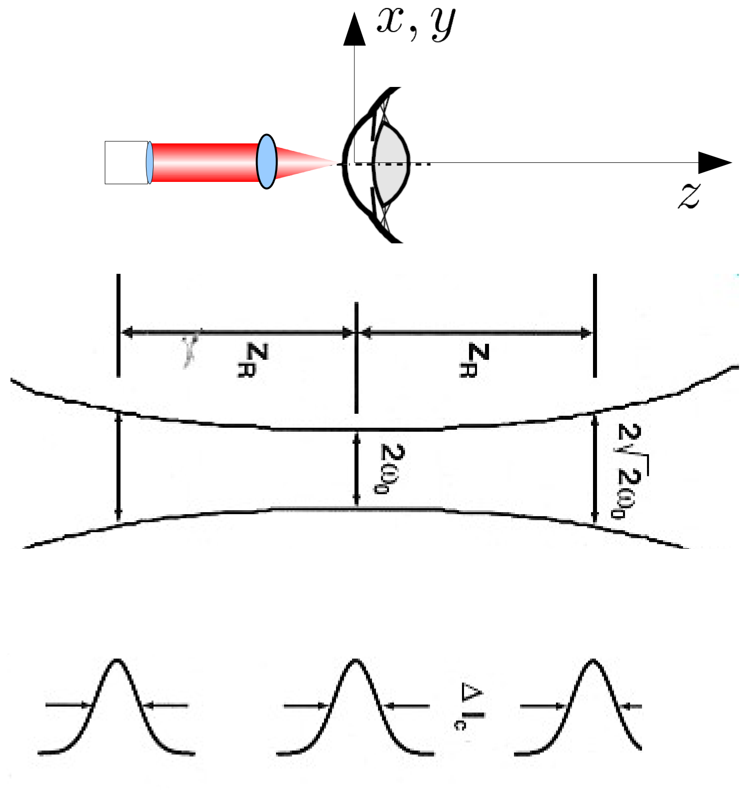
Lateral resolution = spot diameter

$$\Delta x = \frac{4\lambda}{\pi}\frac{f}{d} \sim \frac{1}{N_A}$$

Beam diameter d and focal length f

Axial resolution = coherence gate

$$\Delta z = l_c = \frac{2ln(2)}{\pi}\frac{\lambda_m^2}{\Delta\lambda}$$

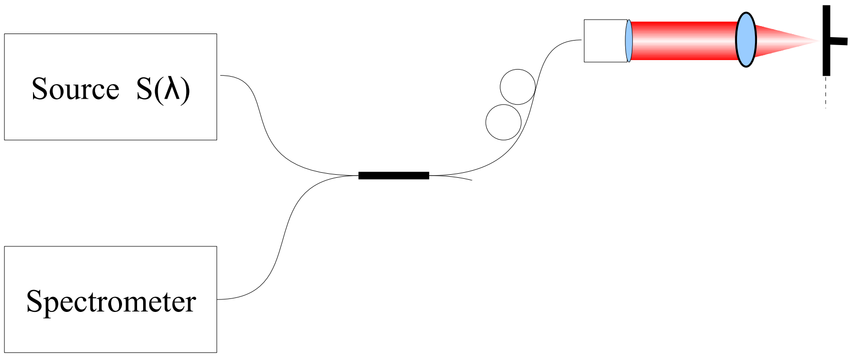


In OCT Systems axial resolution

- is independent of Numerical Aperture NA !
- depends on source spectrum

Frequency/Fourier – Domain OCT

Broadband source coupled to SM fiber



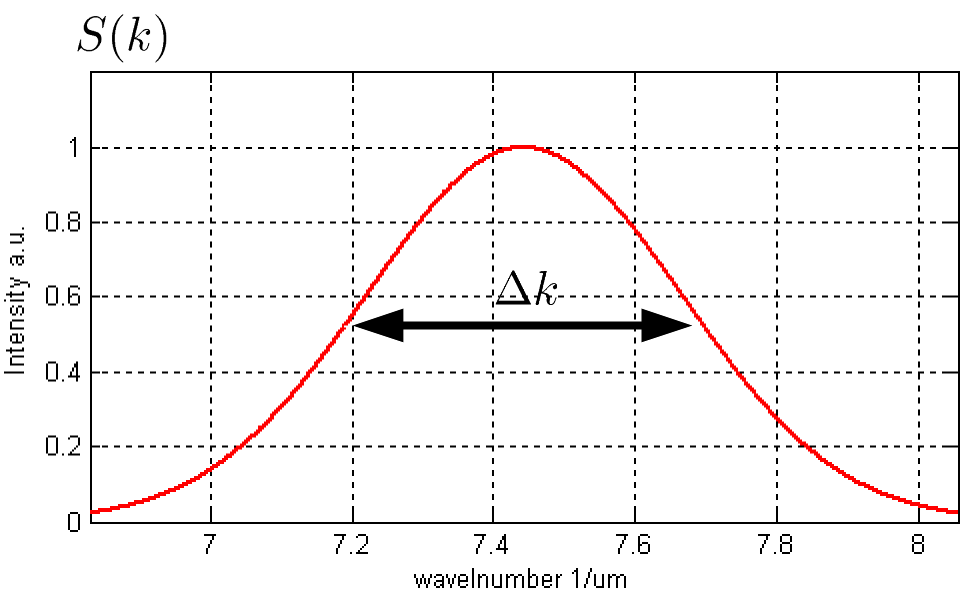
Suppose gaussian Spectrum with bandwidth

$$\Delta\lambda$$

In wavenumber:

$$k = \frac{2\pi}{\lambda}$$

$$\Delta k = 2\pi \frac{\Delta\lambda}{\lambda_m^2}$$



Frequency/Fourier – Domain OCT

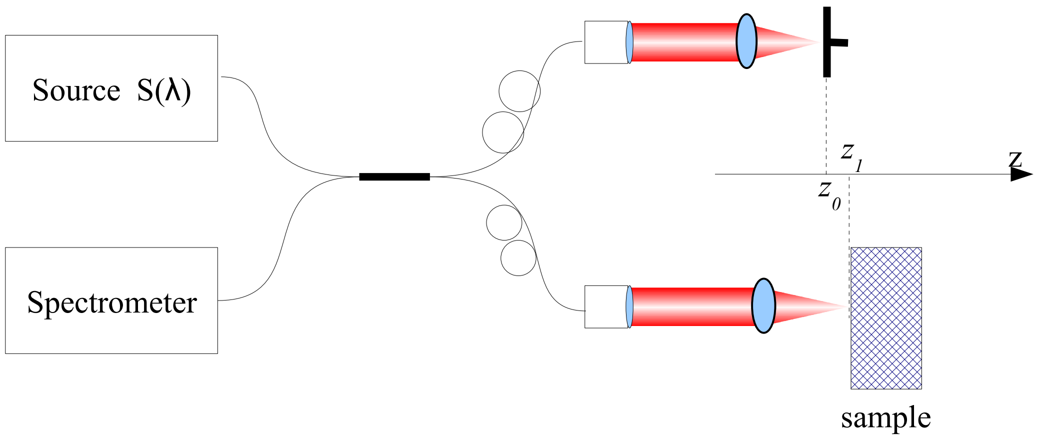
Interferences due to optical path difference

$$OPD = 2k(z_1 - z_0)$$

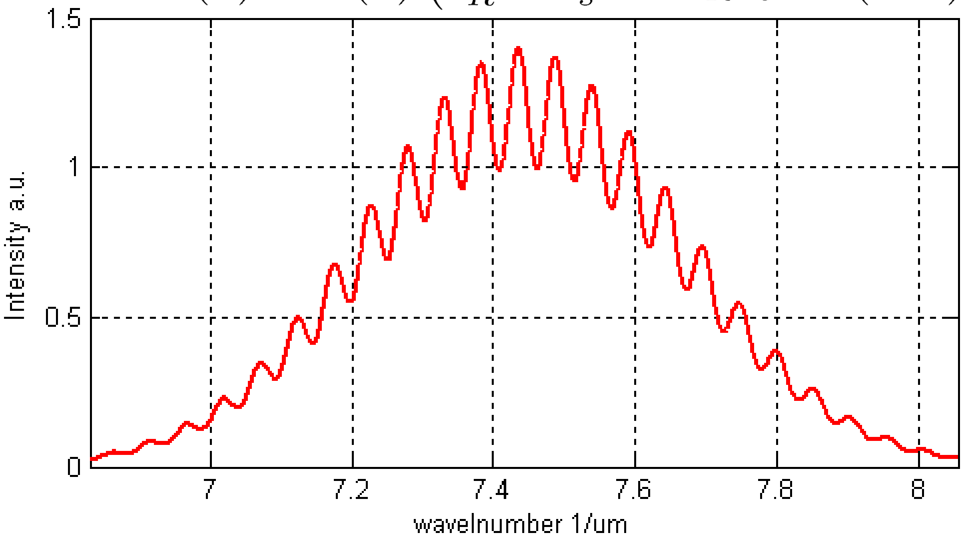
Amplitude reflectivities

$$r_R \quad , \; r_s$$

Frequency in k-space is proportional to OPD



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



Frequency/Fourier – Domain OCT

Interferences due to optical path difference

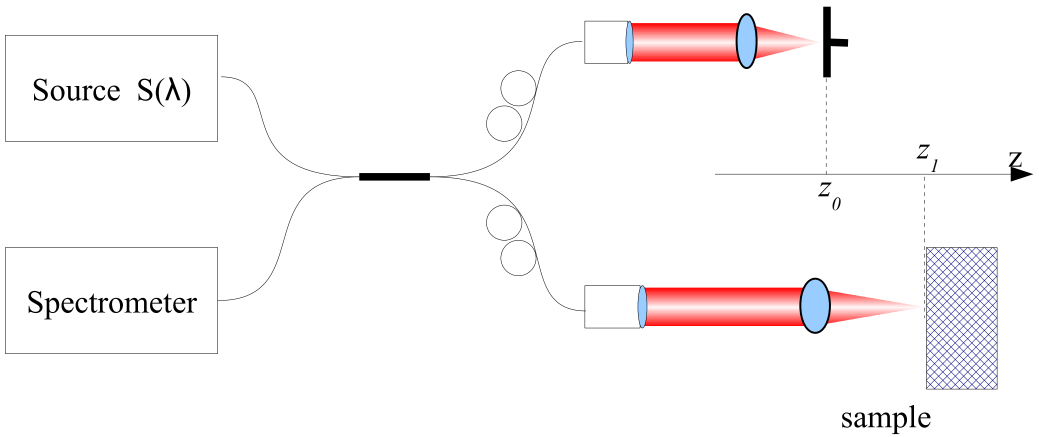
$$OPD = 2k(z_1 - z_0)$$

Amplitude reflectivities

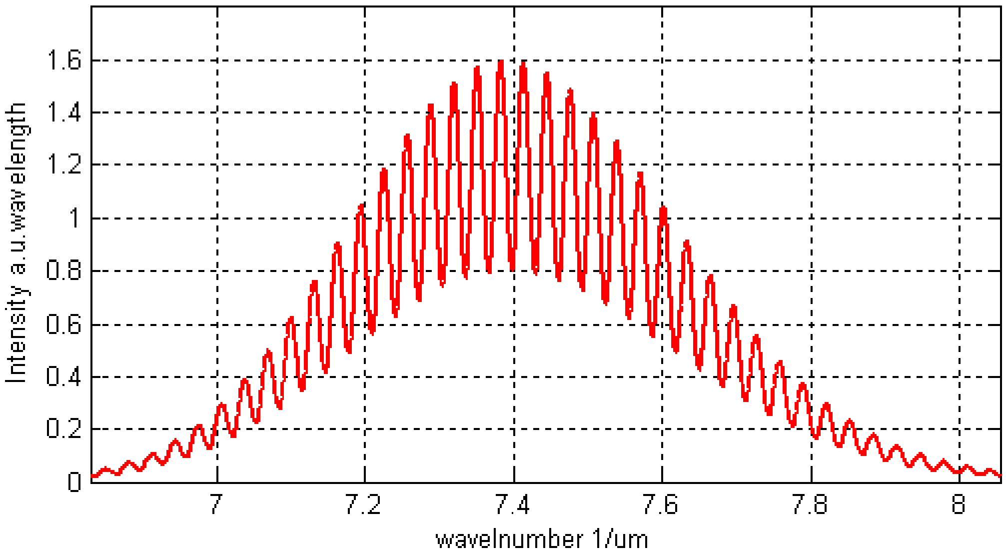
$$r_R \quad , \; r_s$$

Frequency in k-space is proportional to OPD

Time domain signal is obtained by a Fourier transformation



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

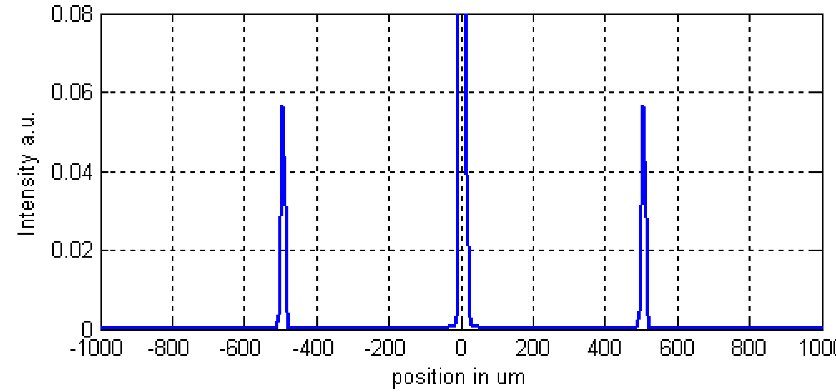


FD OCT, post processing

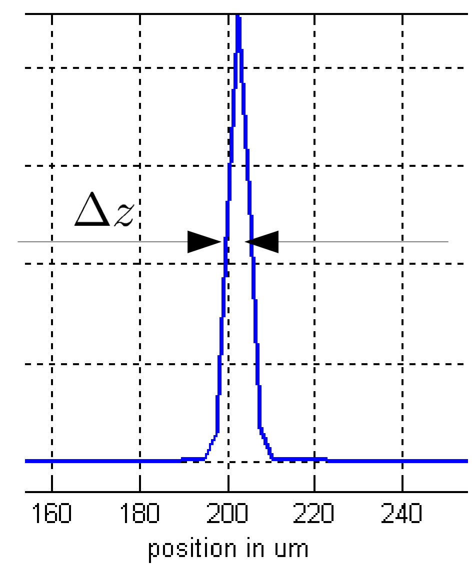
Signal after Fourier Transformation

$$TD(z) = \mathfrak{F}^{-1}\left[FD(k)\right]$$

$$TD(z) = \mathfrak{F}^{-1}\left[S(k)\right] \otimes \mathfrak{F}^{-1}\left[2r_R r_s cos(2kz)\right]$$



Axial resolution $$\Delta z = \frac{2\ln(2)\lambda_m^2}{\pi\Delta\lambda} = \frac{4\ln(2)}{\Delta k}$$



The Fourier transformation of a real signal is symmetric.

Only the half measuring range is usable

FD OCT, post processing

Signal power drops for higher OPD due to finite spectrometer resolution.

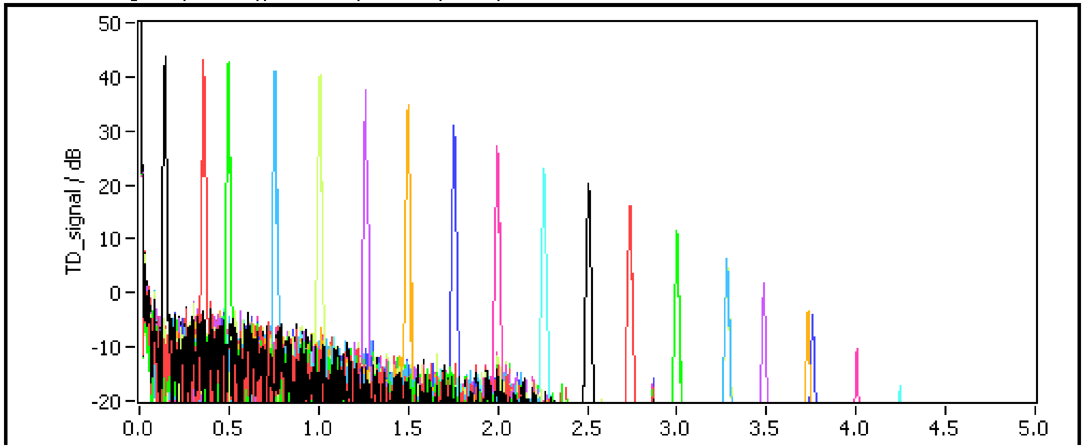
Scanning range or measuring range

$$z_{max} = \frac{1}{4}\frac{\lambda_m^2}{N\delta\lambda} = \frac{1}{2}\frac{\pi}{\delta k}$$

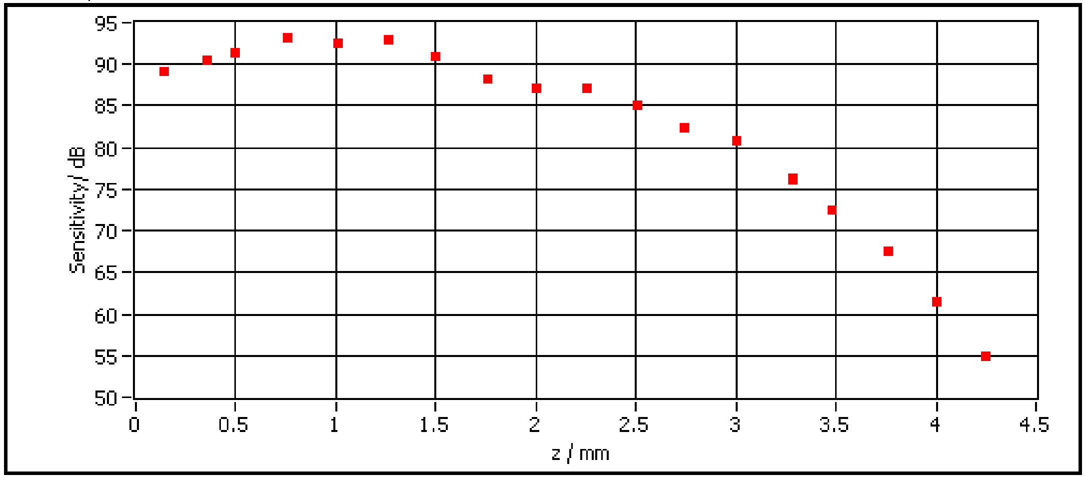
δk Spectral resolution

Measurement from home build FD System (12.3.09)

Reflection on glass (R=0.04), ND Filter(T=0.086) in smple arm.



Sensitivity



Time Domain vs Frequency Domain

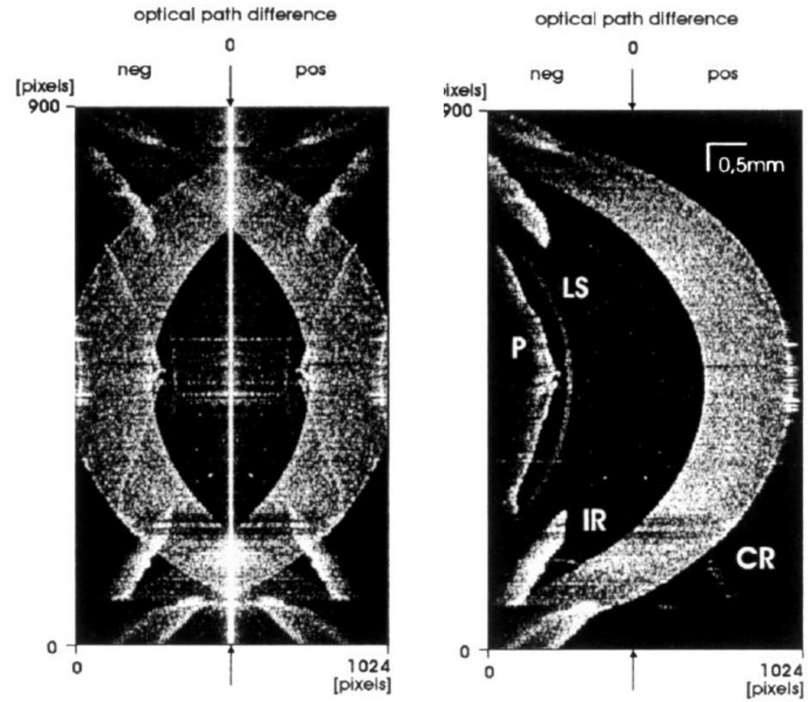
	Time Domain	Frequency Domain
Scan rate	Slow (< 1kHz)	Fast (50 kHz, >100 kHz with swept source and CMOS cameras)
Mechanics	Mechanical scanning reference arm	no mouvable parts
SNR	$\backsim r_S^2$	$\backsim r_S^2 \frac{N}{2}$
Scan range	Limited by reference arm	Signal power decreases with depth Mirror ambiguity bisect scanning depth

FD OCT, post processing

The symmetry property of the Fourier Transform can produce image artifacts.

How to overcome the mirror ambiguity in FD-OCT ?

Several systems are proposed to achieve full range FD-OCT

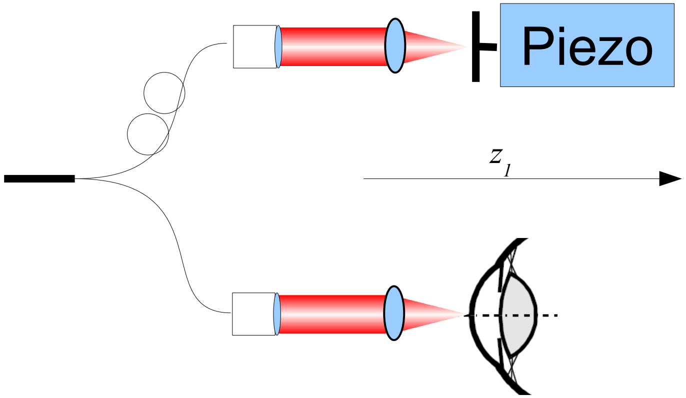


Bildquelle: Wojtkowski

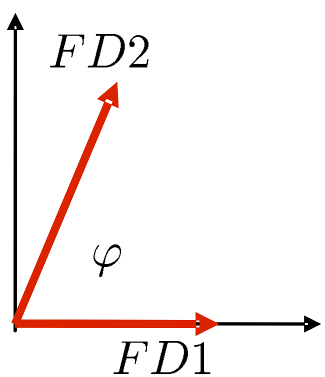
Full Range FD-OCT by Phase shifting

Consecutive acquisition of two ore more phase shifted signals

$$FDc(k) = FD1(k) + e^{j\phi} FD2(k)$$



- Time consuming
- Expensive



References

Wojtkowski, .. Optics Letters, 2002
Leitgeb,.. Optics Letters 2003

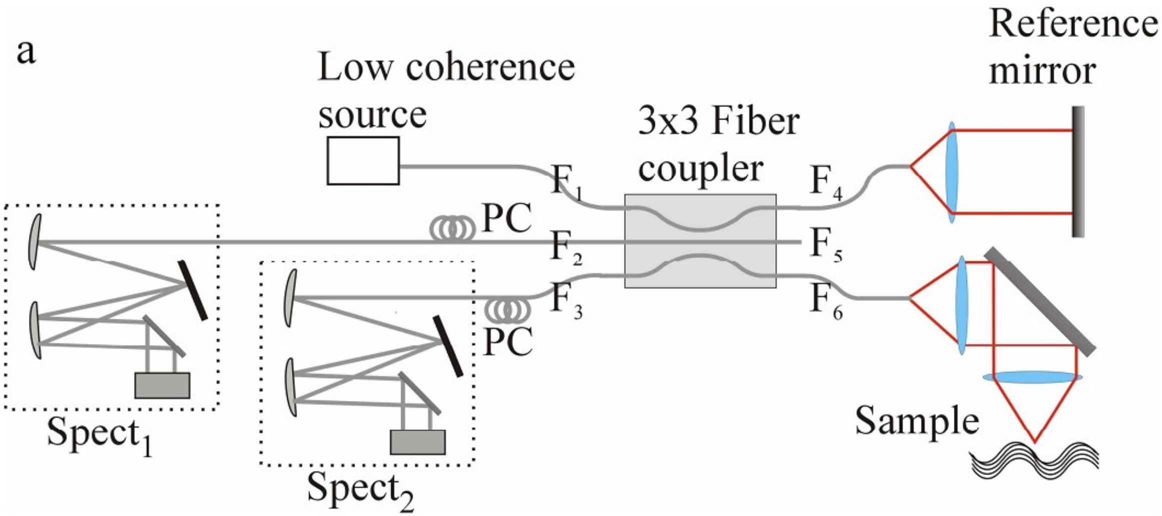
Full Range FD-OCT by 3x3 coupler

Parallel acquisition with a 3x3 fiber coupler

120° phase delay between output ports

(for even power splitting ration)

- Expensive

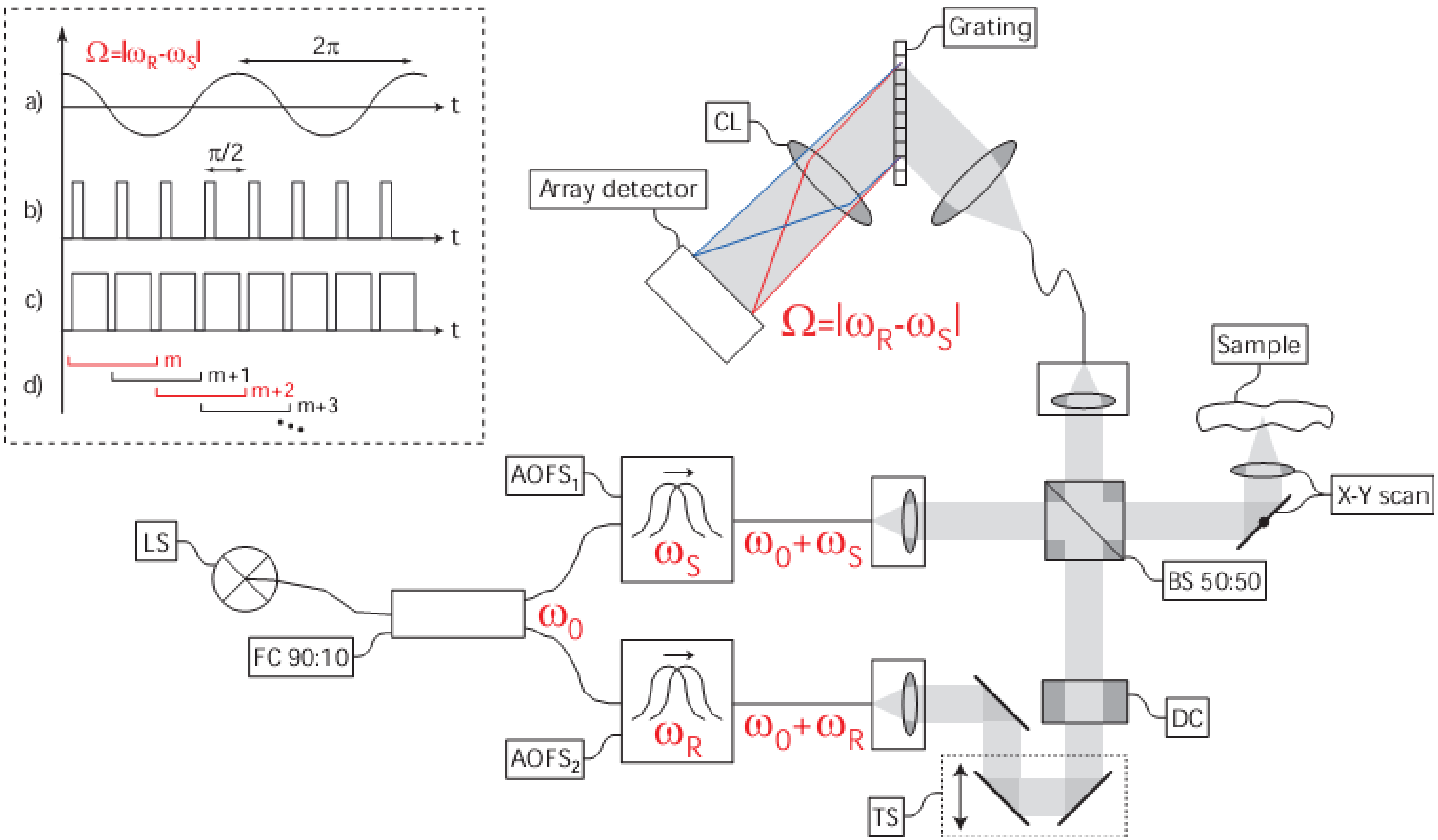


Bildquelle: Sarunic 2005

References

Sarunic, Optics Express, 2005

Full Range FD-OCT by heterodyne techniques



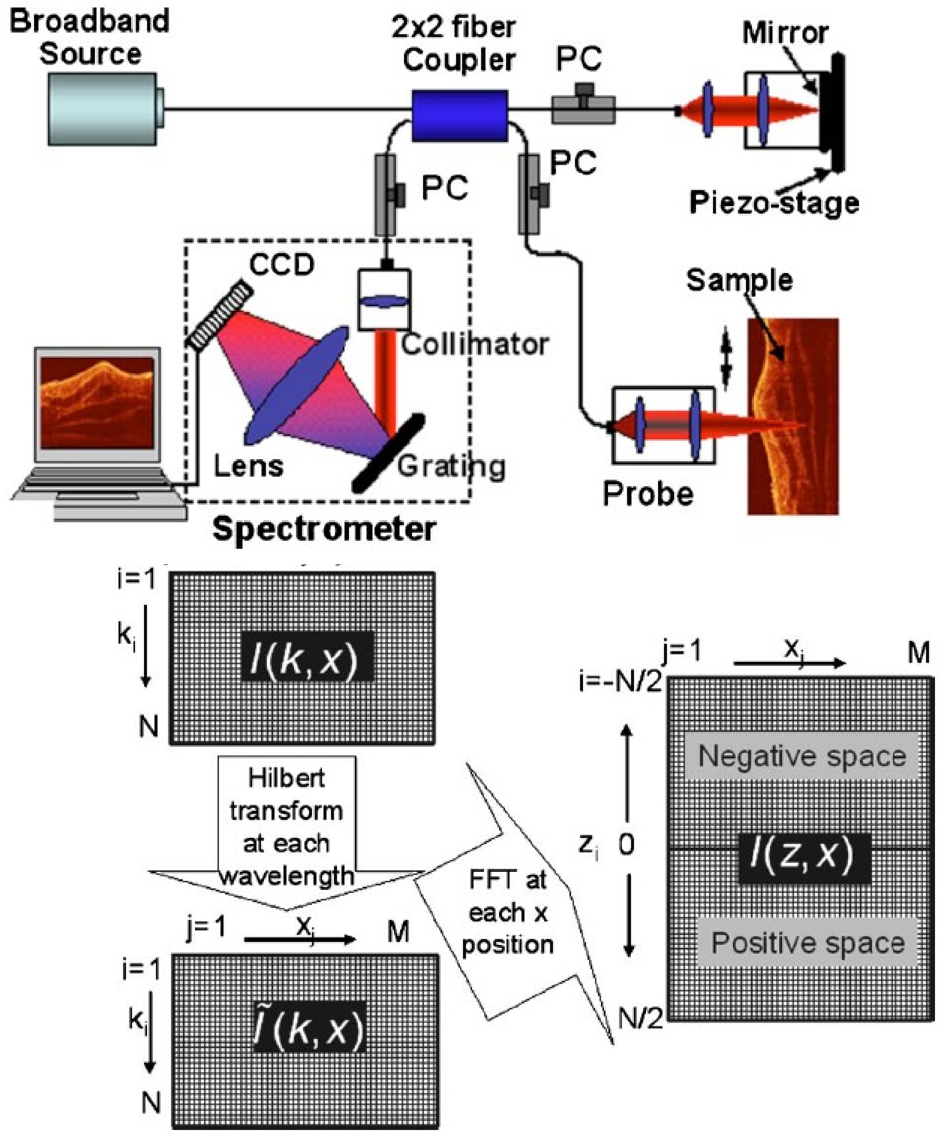
Reference

Bachmann, Optics Express 2006

Full Range FD-OCT

Phase shift by moving reference mirror over one B-scan

Construction of complex signal by Hilbert Transformation in x direction



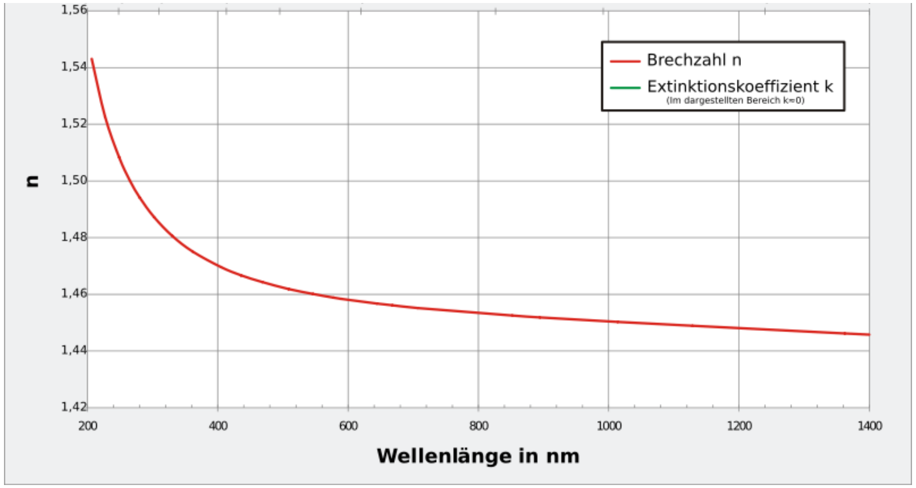
References

Wang, Applied Physics Letters, 2007

Full Range FD-OCT by Dispersion encoding

The dispersion mismatch in the interferometer can be used to

- Improve signal quality
- perform full range FD-OCT



The algorithm was recently published by B. Hofer, group of W. Drexler, Cardiff.

Bernd Hofer, Boris Pova\v{z}ay, Boris Hermann, Angelika Unterhuber,Gerald Matz, Wolfgang Drexler
Dispersion encoded full range frequency domain optical coherence tomography,
Opt. Express, 2009

Dispersion in OCT

The propagation constant depend on frequency $e^{j(2\beta(\omega)z-\omega t)}$
In a Taylor series expansion we have:

$$\beta(\omega) = \beta(\omega_0) + \frac{d\beta}{d\omega}(\omega - \omega_0) + \frac{1}{2}\frac{d^2\beta}{d\omega^2}(\omega - \omega_0)^2 + ...$$

The interpretation of the three terms are:

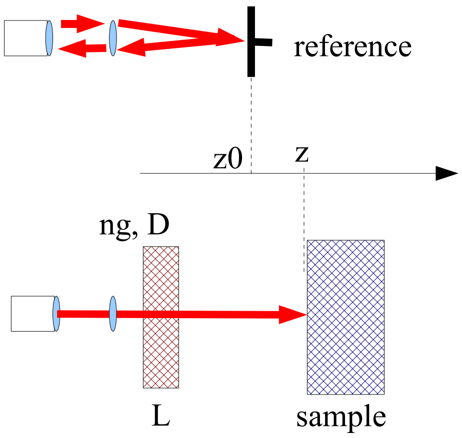
Wave number $$k = \beta(\omega_0) = n(\lambda)\frac{2\pi}{\lambda}$$

Group velocity $$\frac{1}{v_g} = \frac{d\beta}{d\omega} = \frac{1}{c}\left(n - \lambda\frac{dn}{d\lambda}\right)$$

Second Order Dispersion $$D = 2\pi\frac{d^2\beta}{d\omega^2} = \frac{\lambda^3}{c^2}\frac{d^2n}{d\lambda^2}$$

With c , λ vacuum speed of light and the vacuum wavelength

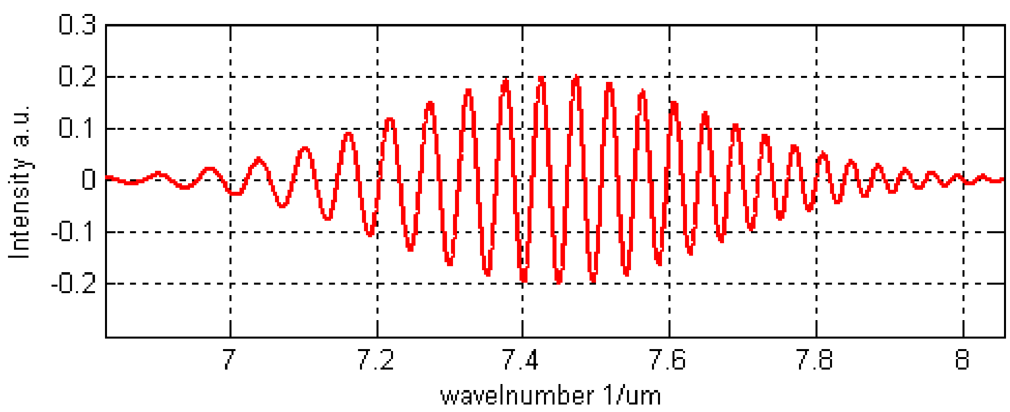
Dispersion in OCT



The dispersion mismatch is modeled by the element with thickness L , group index ng and second order dispersion D

$$FD(k) \backsim cos\left(\varphi_0 + 2\beta(\omega)z\right)$$

$$FD(k) \backsim cos\left(\varphi_0 + 2(z + n_g L)k + \frac{c^2 LD}{2\pi}k^2 + ...\right)$$



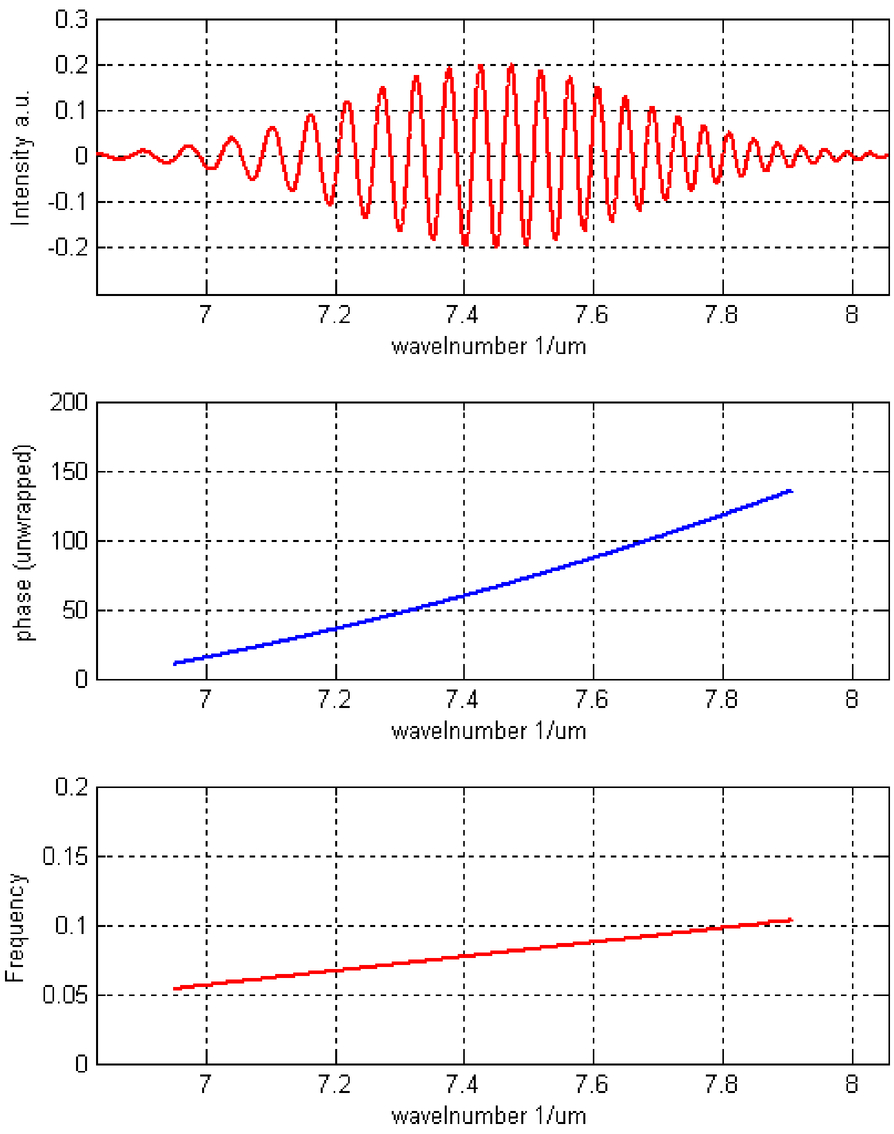
Dispersion mismatch

Signal without DC term

- one reflecting surface
- Positive Dispersion
- Positive OPD

Phase is determined by Hilbert transformation

- First derivative is prop. to frequency
- Second derivative is prop. to dispersion mismatch

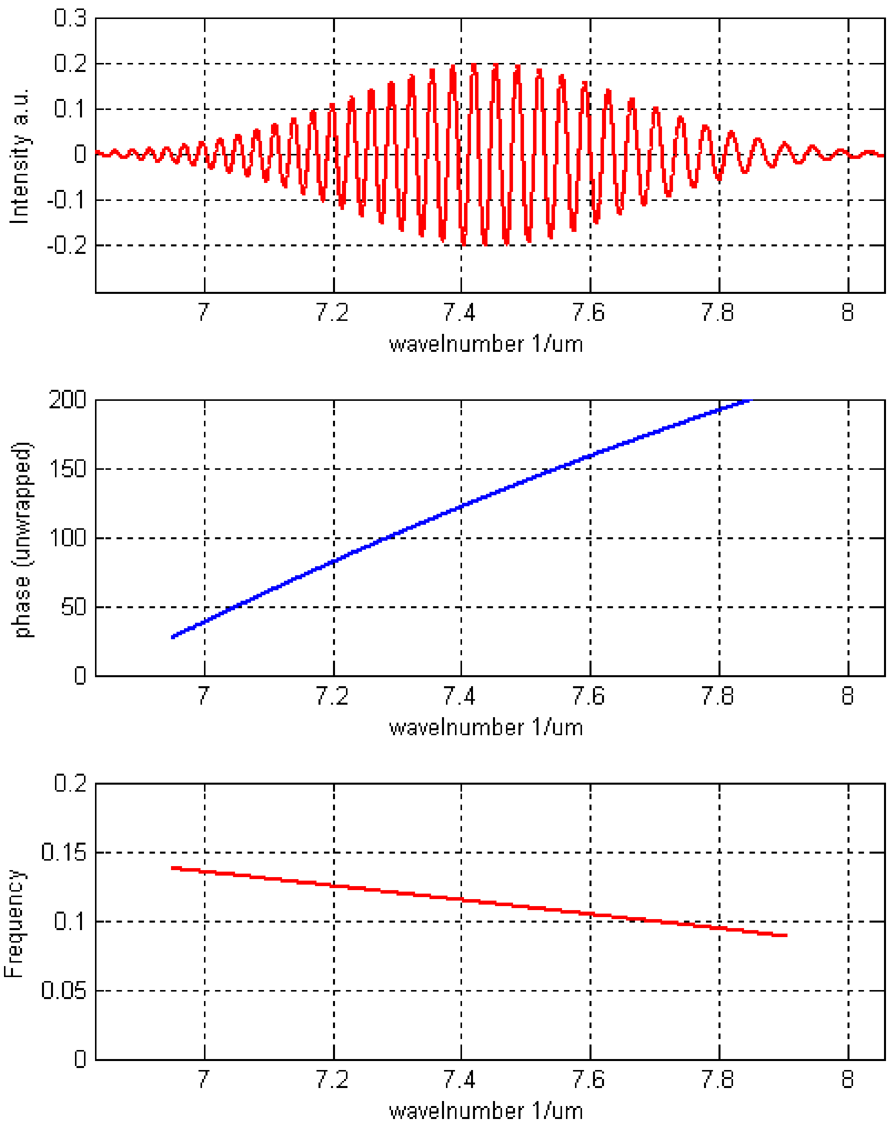


Dispersion mismatch

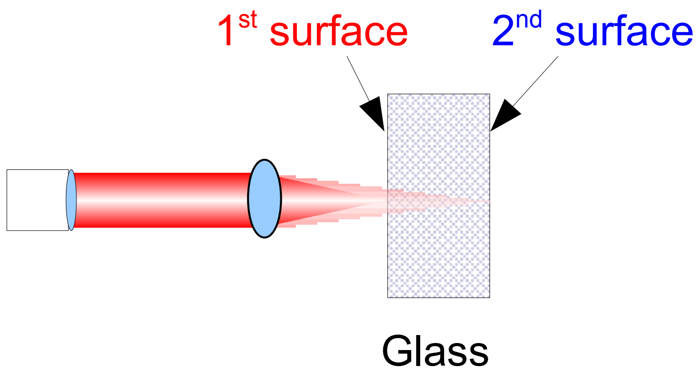
Signal without DC term

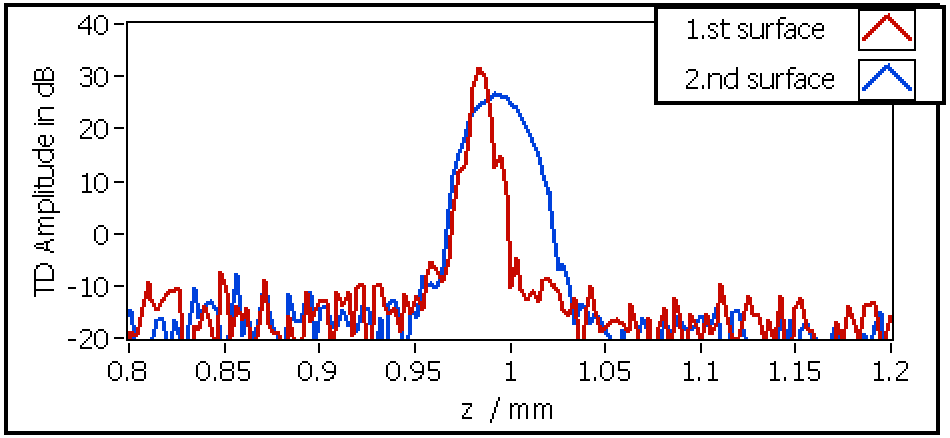
- one reflecting surface
- Positive Dispersion
- Negative OPD

The sign of OPD = sign of the measured dispersion



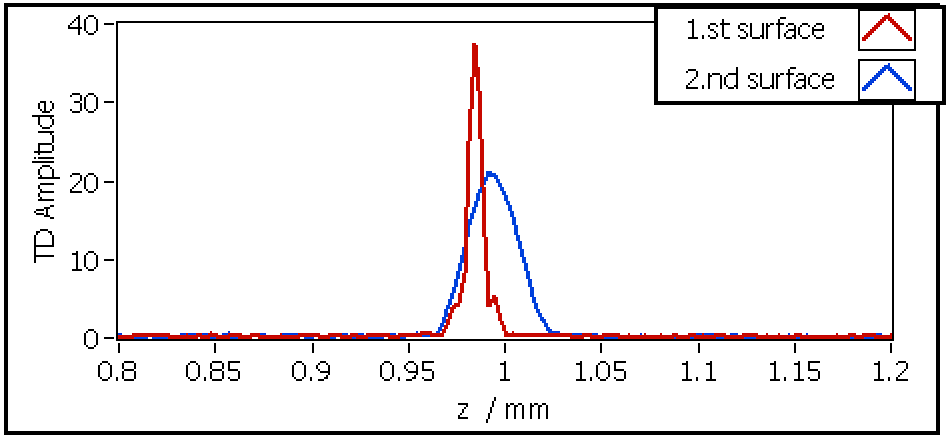
Dispersion Compensation





Dispersion in the interferometer degenerate:

- axial resolution
- SNR

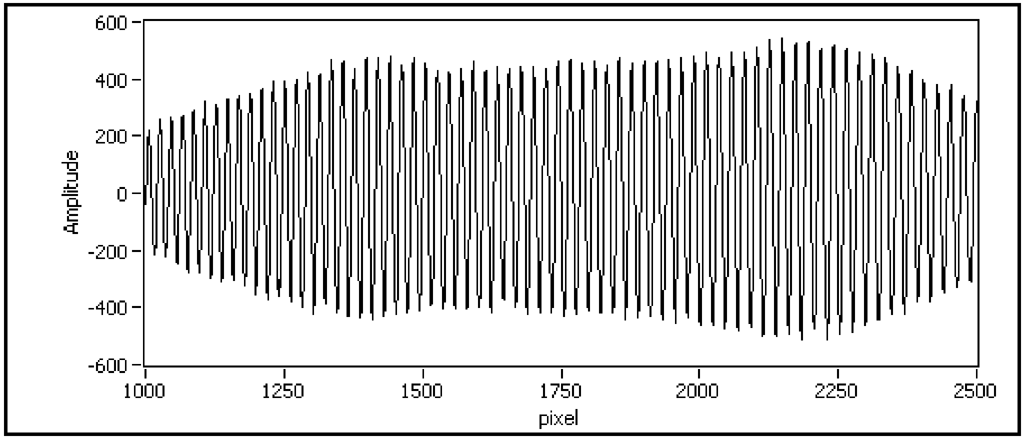


Dispersion Compensation

The FD-signal is multiplied by a complex phase factor

$$FDc(k) = e^{-j\psi(k)} FD(k)$$

$$\psi(k) = a_2 k^2 + a_3 k^3 + \ldots.$$



The factors a2, a3, … are determined by the second derivative of the phase function.

$$FD(k) \propto \cos\left(\varphi_0 + 2(z + n_g L)k + \left(\frac{c^2 L D}{2\pi} \right) k^2 + \ldots. \right)$$

Dispersion Compensation

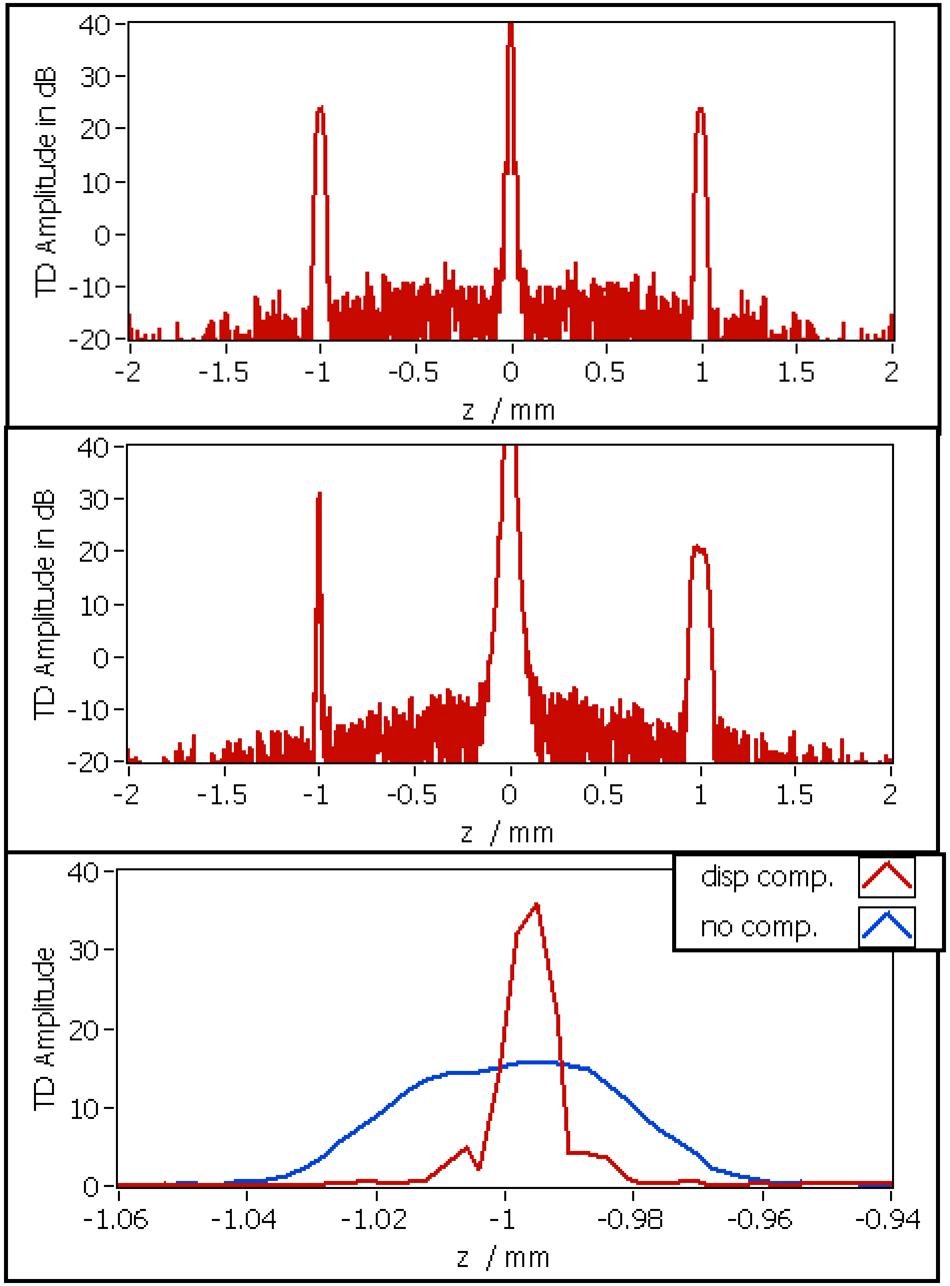
Signal before and after dispersion compensation

Dispersion of 25 mm glass in sample arm

SNR improvement 8 dB

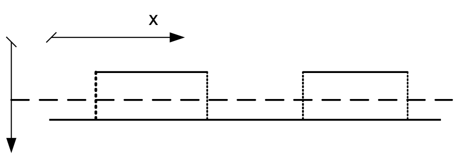
Axial resolution improvement factor 4.6

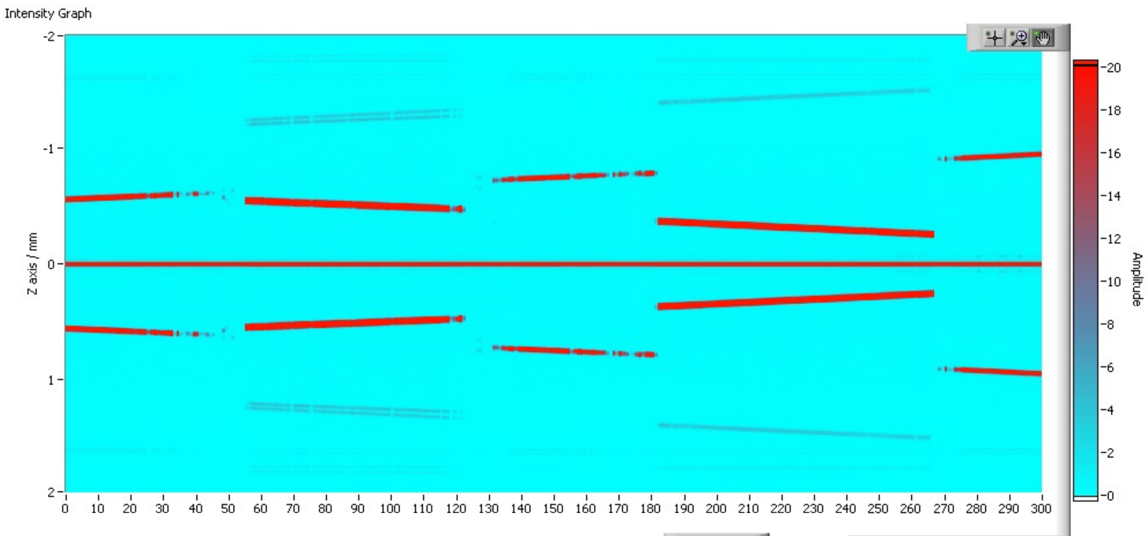
FWHM = 9 um compensated
= 44 um uncompensated

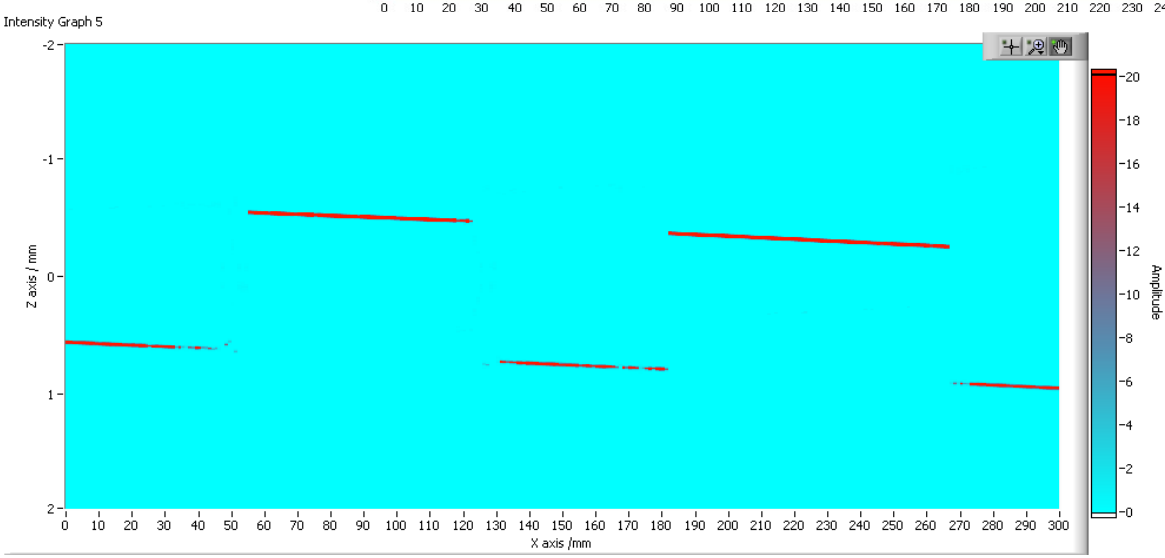


Dispersion encoded Full Range

The dispersion mismatch is used to identify the sign of OPD





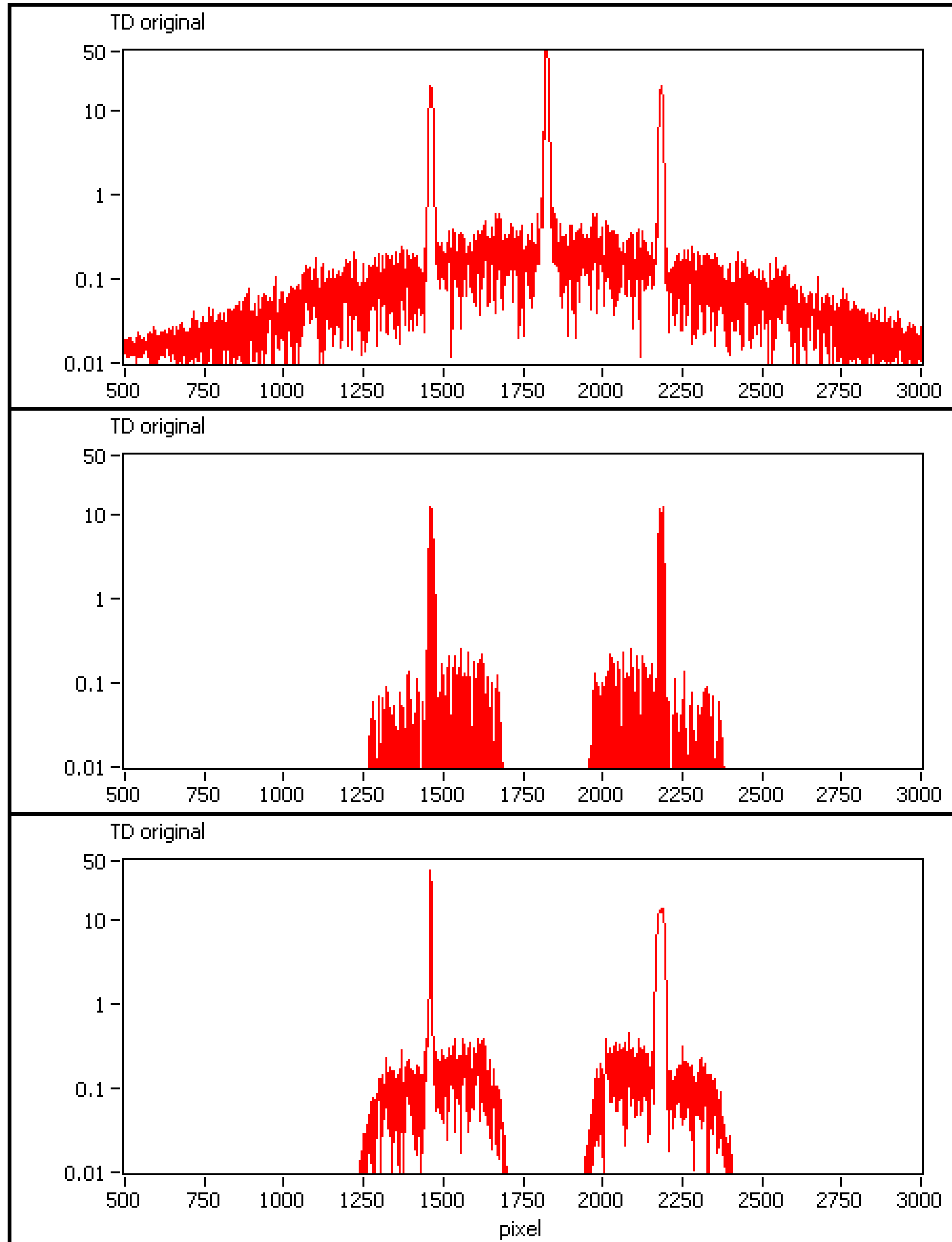


Dispersion encoded Full Range

Original

ROI Filter

$$e^{-j\psi}$$



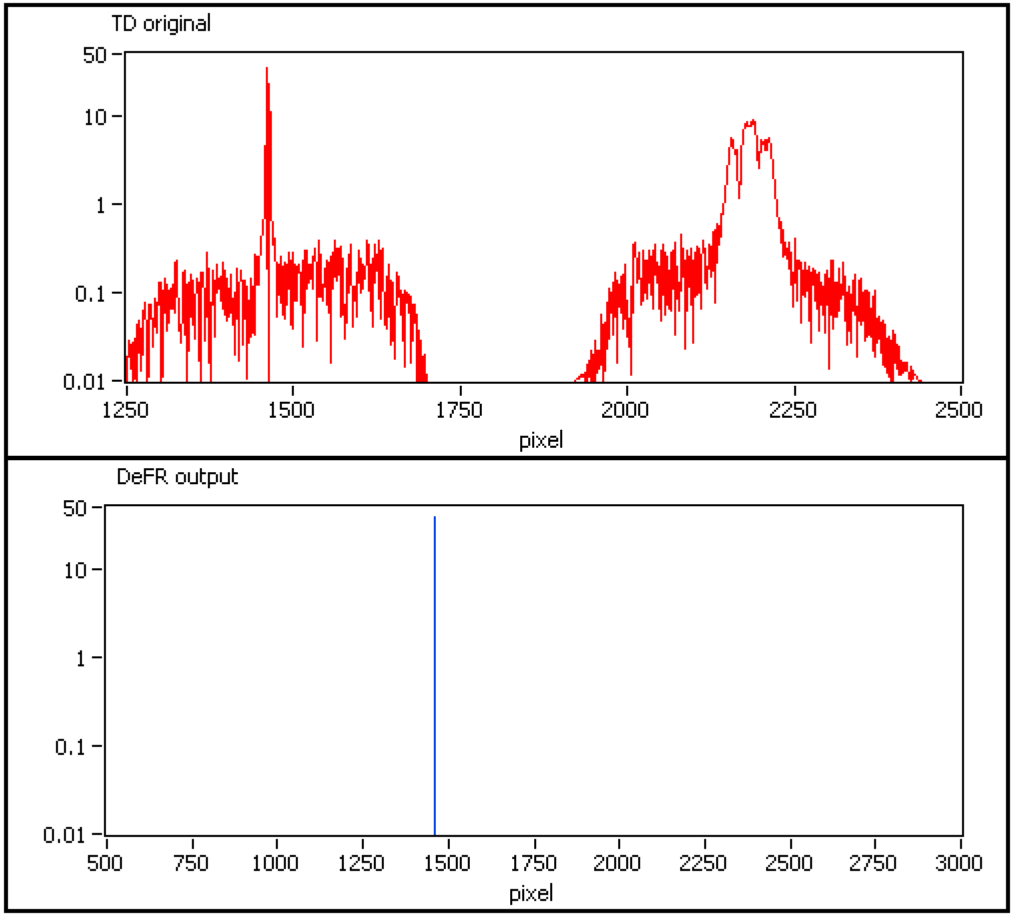
FD → TD

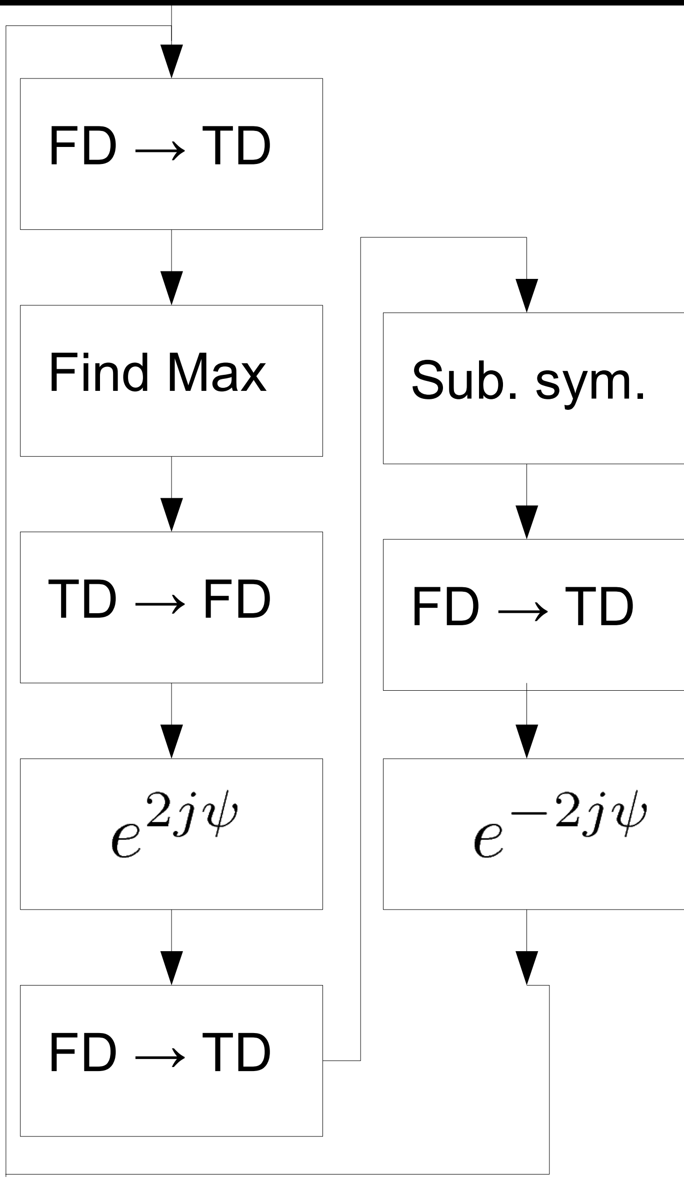
Find Max

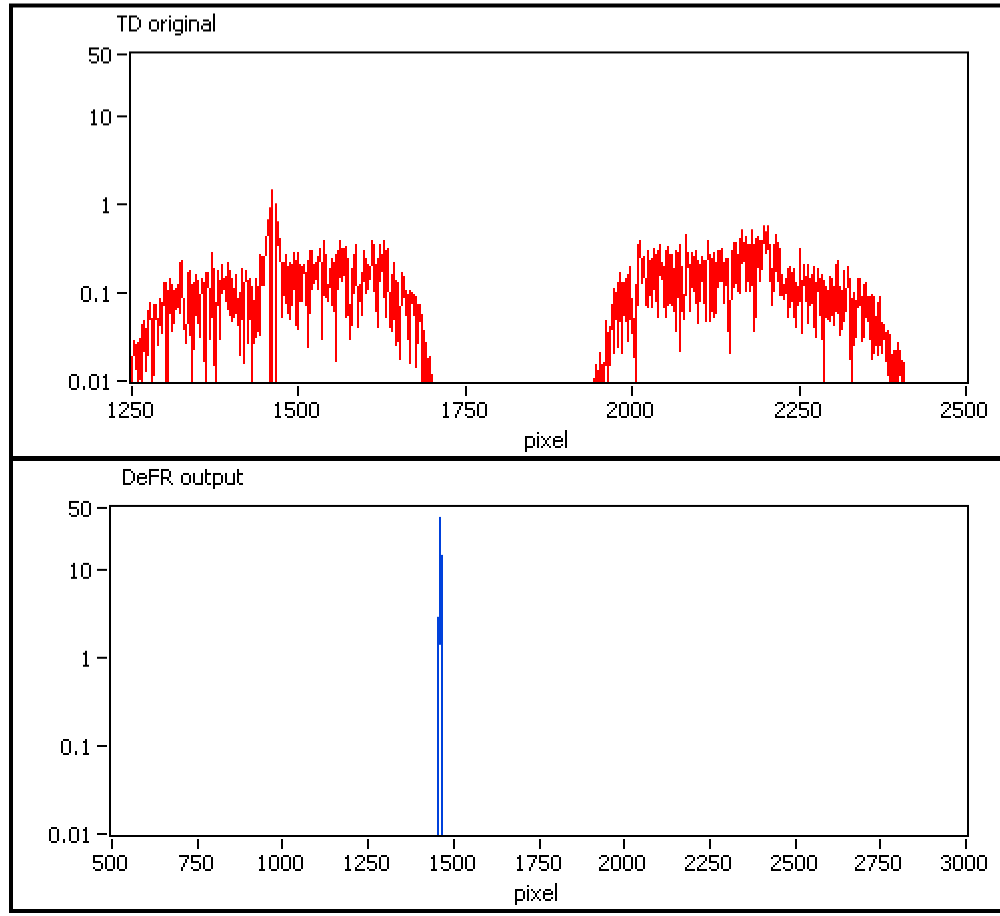
TD → FD

$e^{2j\psi}$

FD → TD







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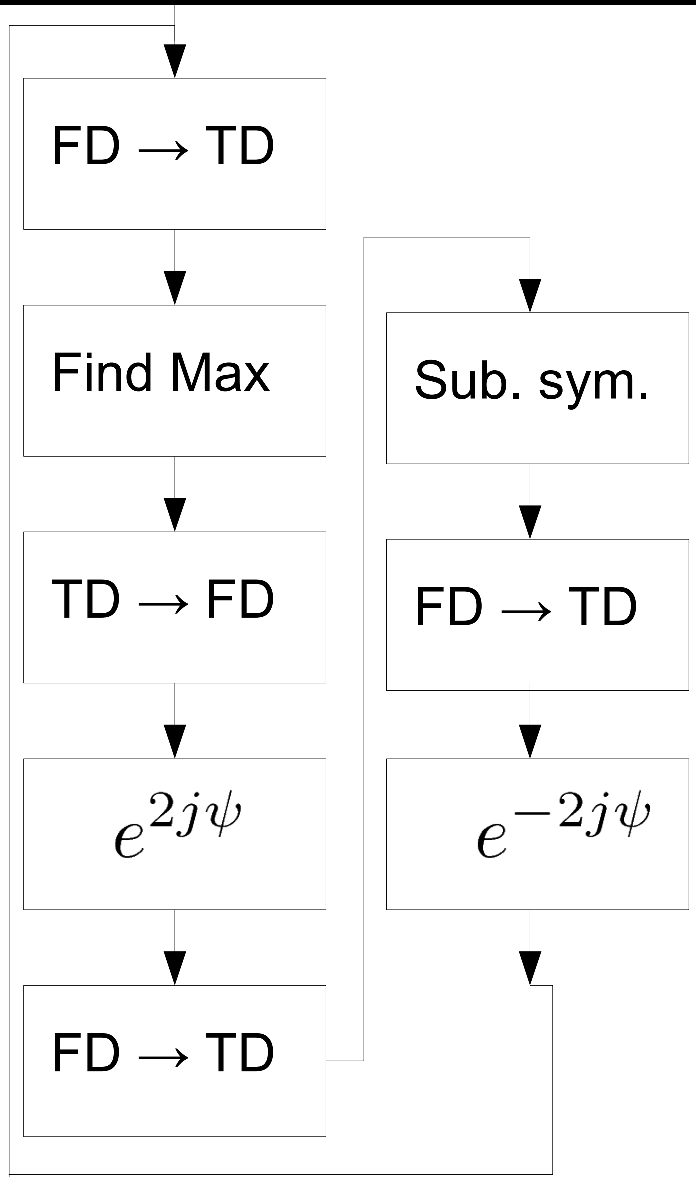
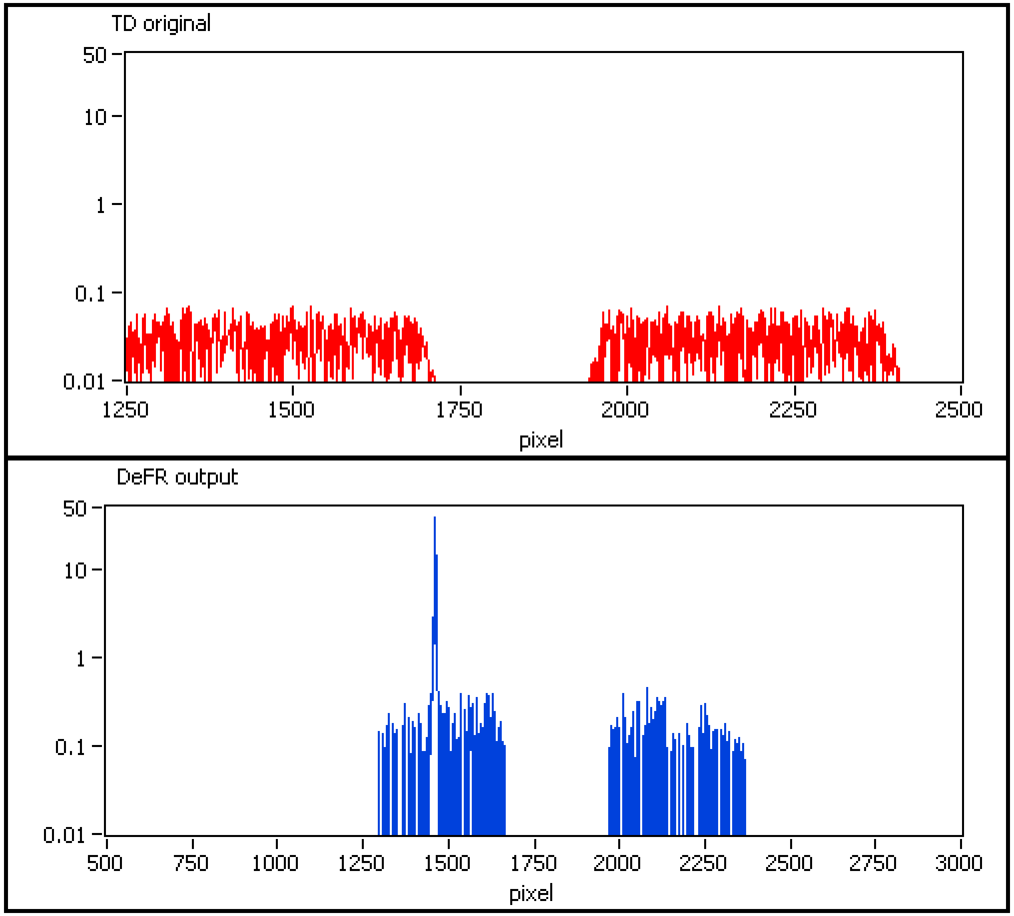
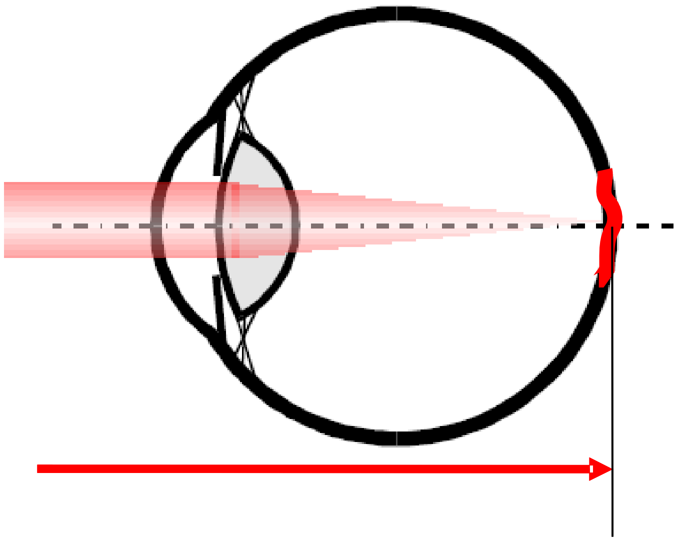

FD → TD
Find Max
TD → FD
$e^{2j\psi}$
FD → TD
Sub. sym.
FD → TD
$e^{-2j\psi}$


TD original
50
10
1
0.1
0.01
1250
1500
1750
2000
2250
2500
pixel
DeFR output
50
10
1
0.1
0.01
500
750
1000
1250
1500
1750
2000
2250
2500
2750
3000
pixel

Application of DeFR in actual project

- High measurement range z_{range} > 6 mm
- Resolution dz = 10 um
- A-scan rate > 100 Hz



The challenges are:

- Compact module
- Large measuring range
- Low manufacturing cost
-

Conclusion

- Removal of the mirror ambiguity in FD-OCT is a issue
- Dispersion handling enables
  signal enhancement and full range FD-OCT
- Dispersion handling is software based,
  don't need expensive and time consuming hardware
- FD-OCT with low-cost elements is feasible

Thank you for your attention