Institute of Applied Physics
Friedrich-Schiller-Universität Jena

Metrology and Sensing

Lecture 12-3: Optical Coherence Tomography

2021-02-02

Herbert Gross

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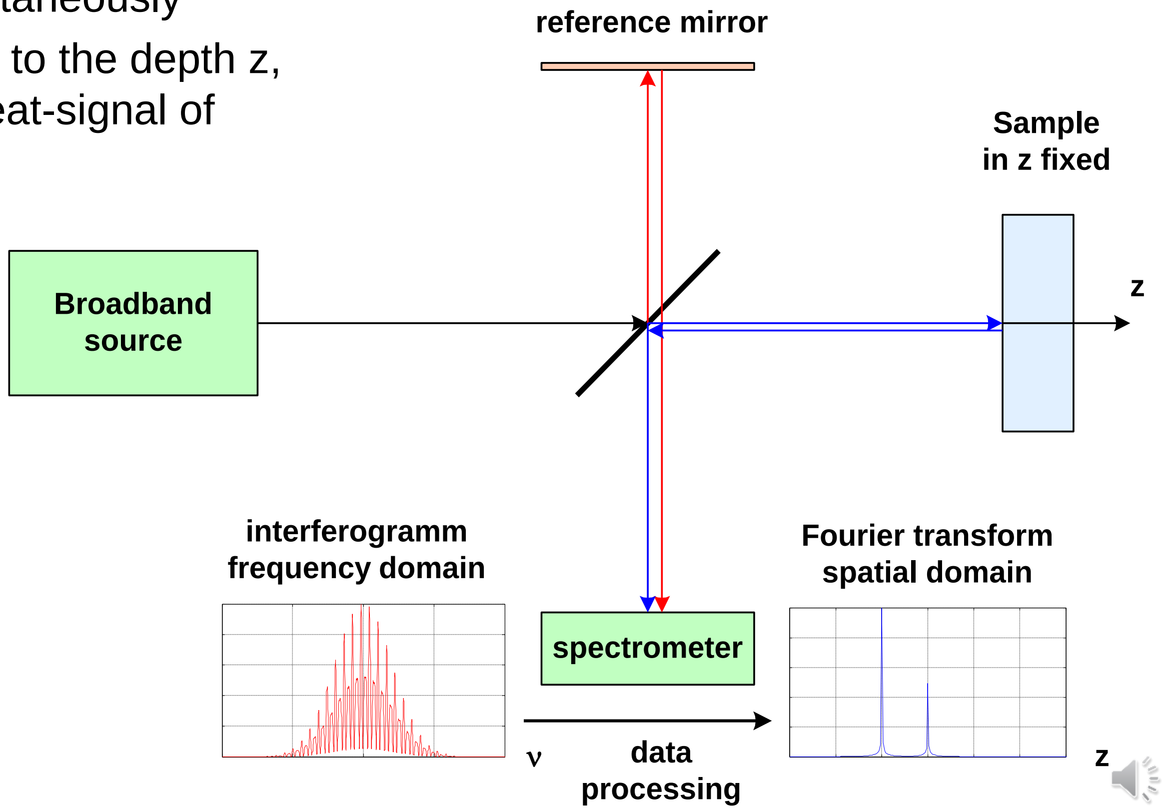
- Fourier domain OCT
- Swept source OCT
- Examples

Fourier Domain OCT

- Spectral Domain-OCT:
  - broad band source
  - reference mirror fixed in position, no A-scan necessary
  - signal splitted by spectrometer
- The high-frequency content of the signal is analyzed: full spectral resolution, no coarse envelope
- All depth are measured simultaneously
- The frequency is proportional to the depth z, measured is the overlayed beat-signal of all scatterers



Fourier Domain OCT

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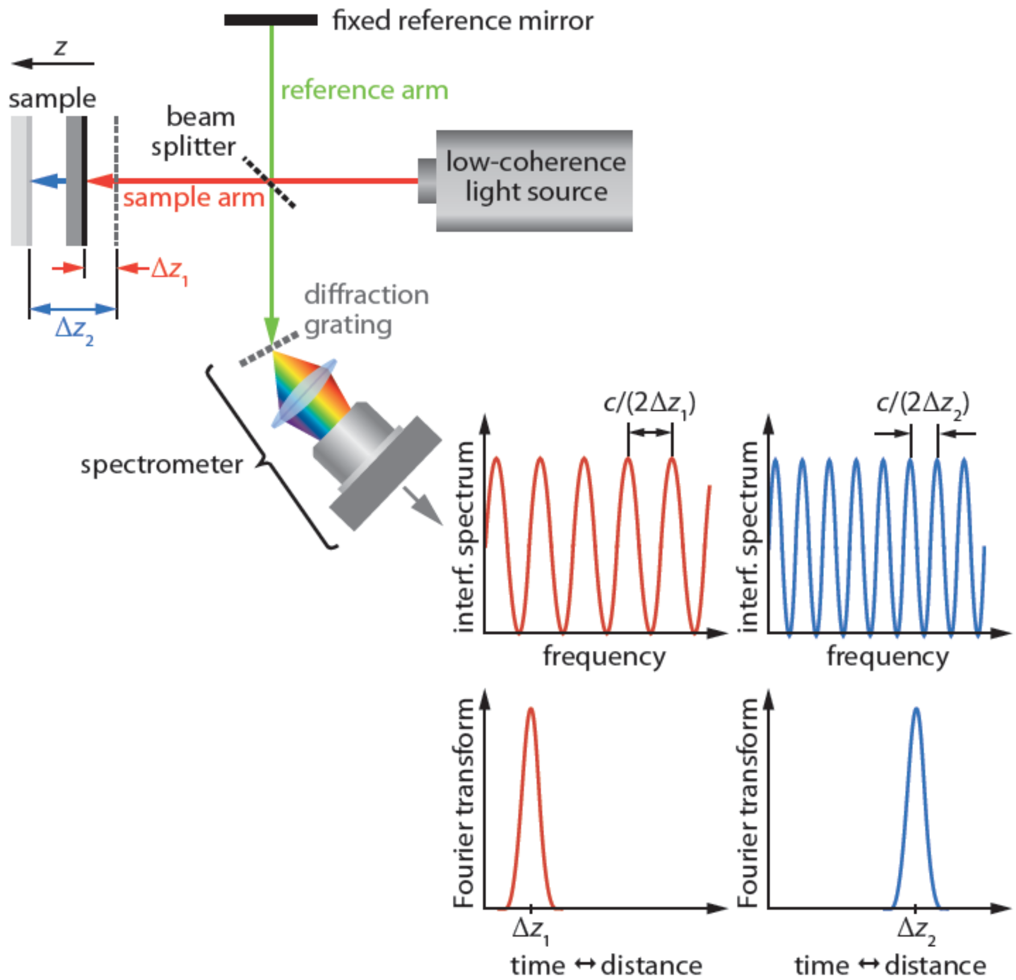
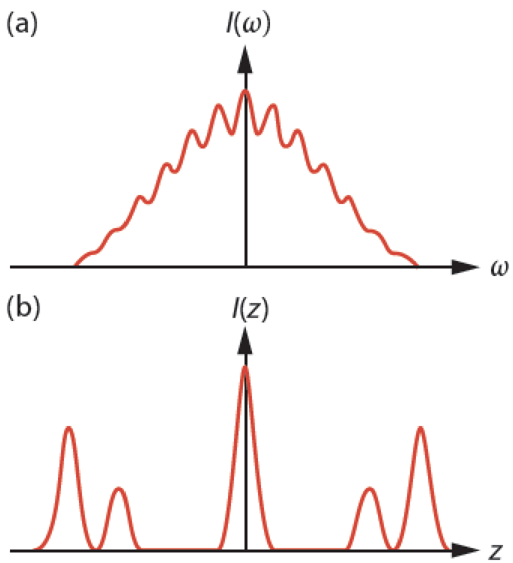
- Fourier Domain-OCT:
  setup



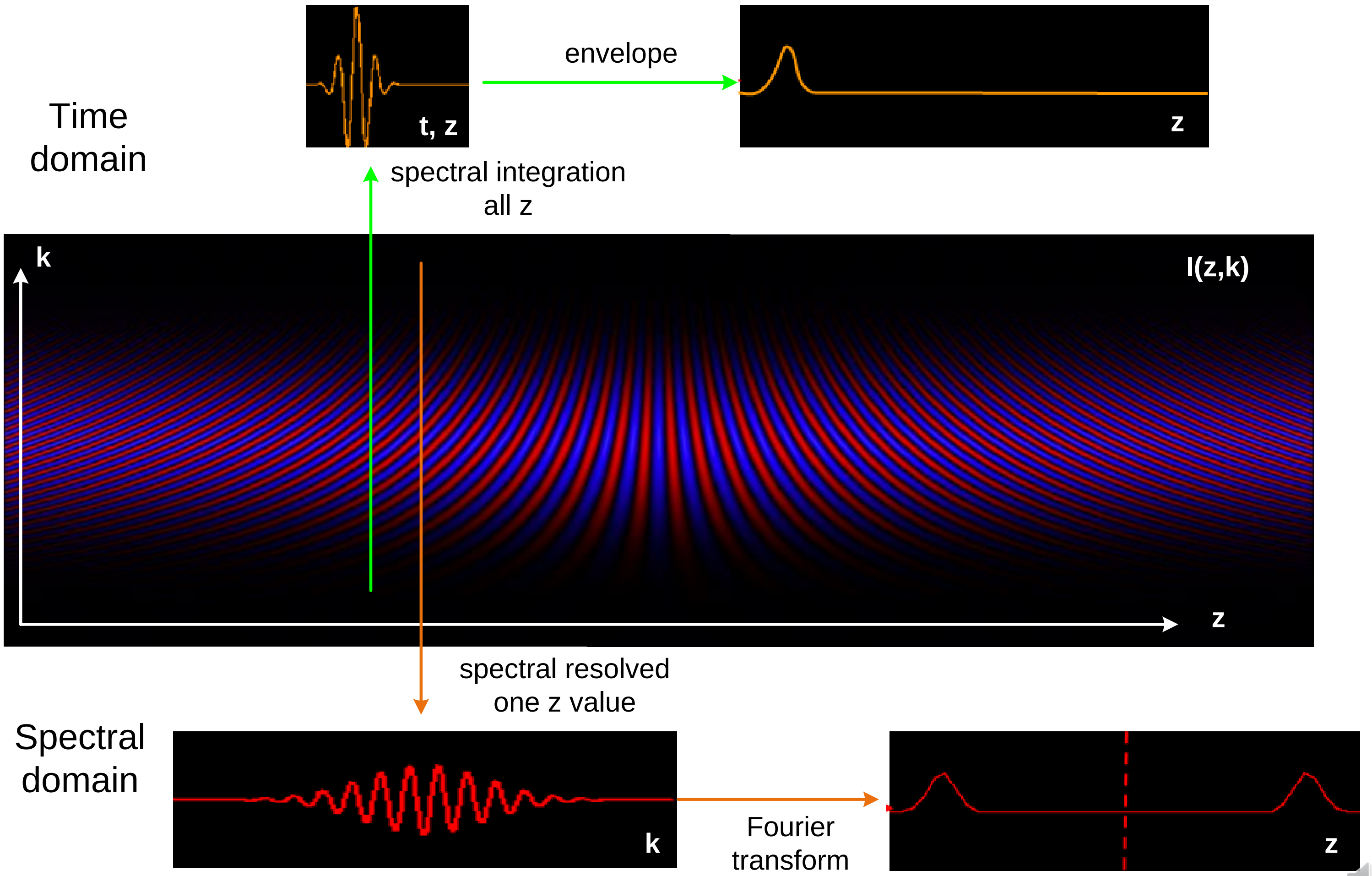
- Signals:
  a) intensity spectrum
  b) spatial intensity distribution



Ref: M. Kaschke

OCT Signal Processing

- Signal evaluation
  - time domain OCT
  - spectral domain OCT

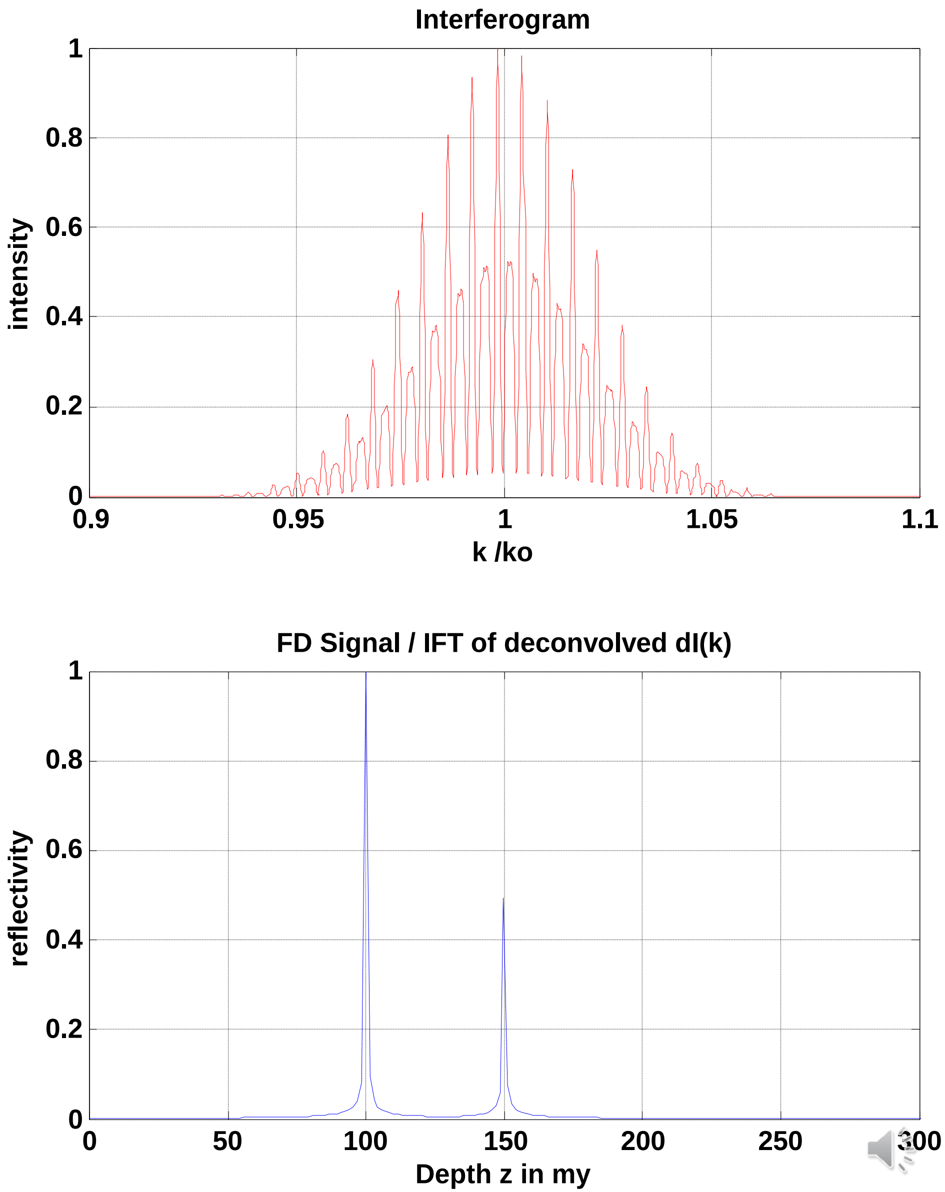


Properties of Fourier Domain OCT

- the modulation frequency depends on the path length difference
- simultaneous measurement of all backscattering contributions: larger sensitivity
  - Fourier transform adds signals coherent
  - noise is added incoherent
- faster image processing due to missing A scan
- signal drop-off with increasing depth
  spectrometer resolution changes over depth
- positive and negative Δz cannot be distinguished

Fourier Domain OCT Example Calculation

- Only z-dependence
- 2 discrete scatterers

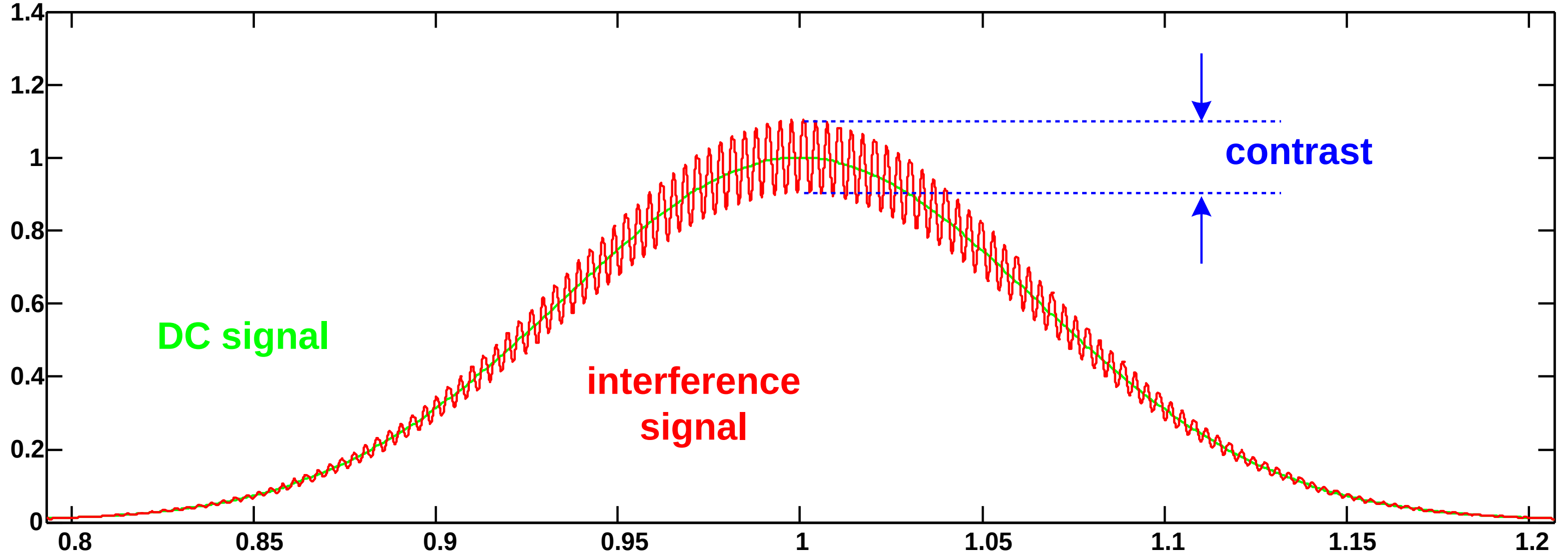


Fourier Domain OCT Signal

- Typical Fourier Domain OCT signal only z-part

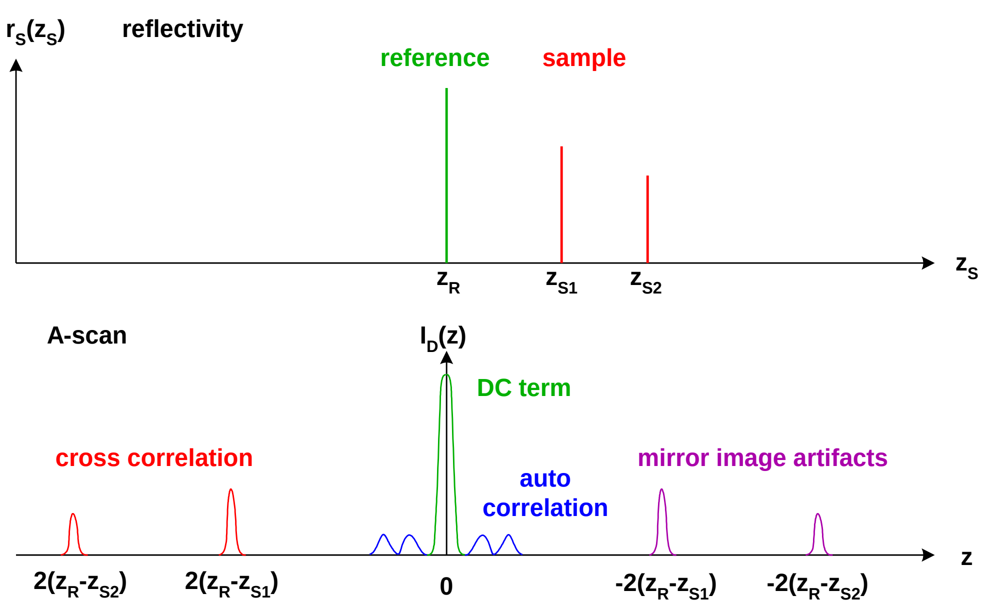
$$I_{FD}(k,\omega) = \boxed{\frac{\rho}{4}\cdot S(k)\cdot\left(r_R^2 + \sum_j \left|r_{Sj}\right|^2\right)} + \boxed{\frac{\rho}{2}\cdot S(k)\cdot r_R\cdot\sum_j r_{Sj}\cdot\cos\left(2k(z_R - z_{Sj})\right)}$$
$$\boxed{+\frac{\rho}{4}\cdot S(k)\cdot\sum_{j\neq m} r_{Sj}\cdot r_{Sm}\cdot\cos\left(2k(z_{Sj} - z_{Sm})\right)}$$

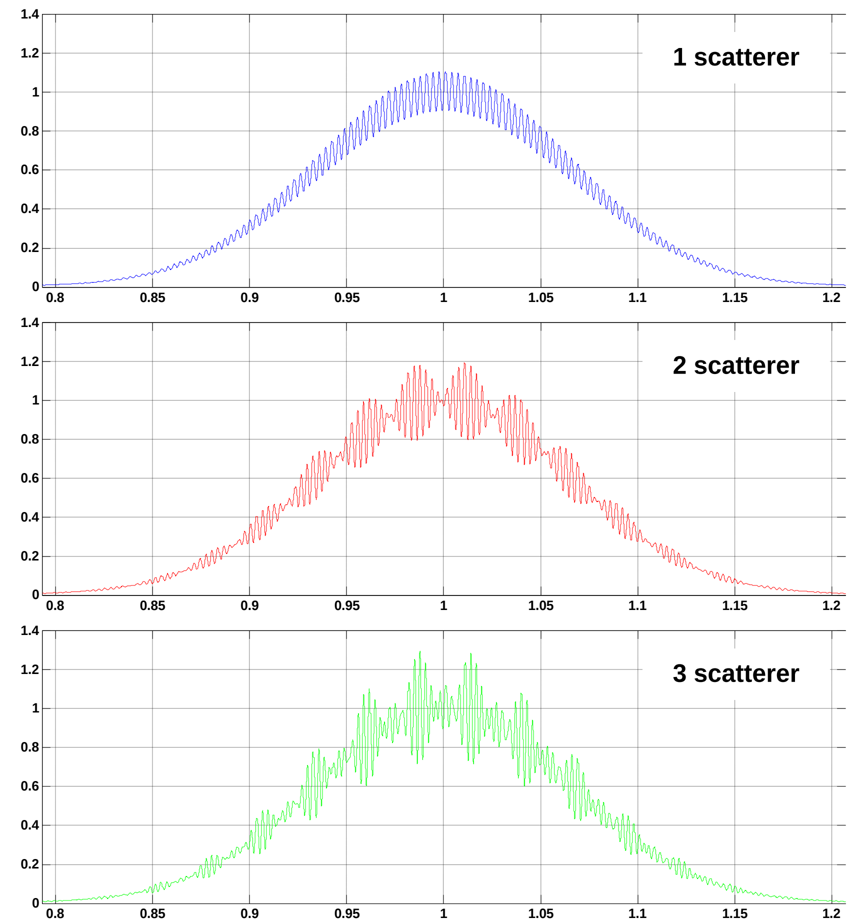
- First term: DC
  Second term: interference, cross-correlation, contains information
  Third term: autocorrelation between scatterers



Fourier Domain OCT Signal

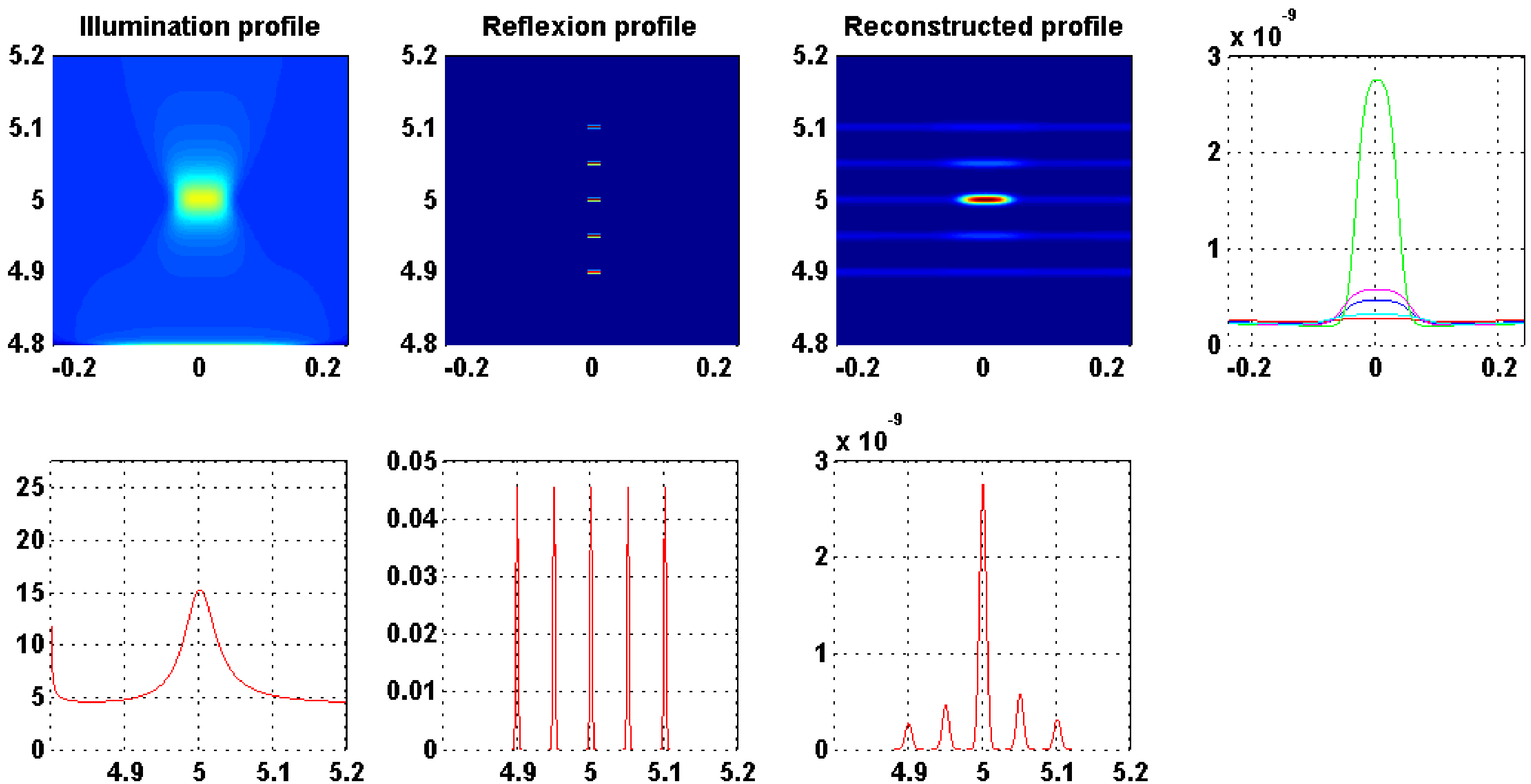
- Signal complexity depends on scatter-distribution





FD OCT in 3D Gaussian Beams Example

- 5 discrete scatter planes with finite extend
- Without EDF-caustic



Fourier Domain OCT with Swept Source

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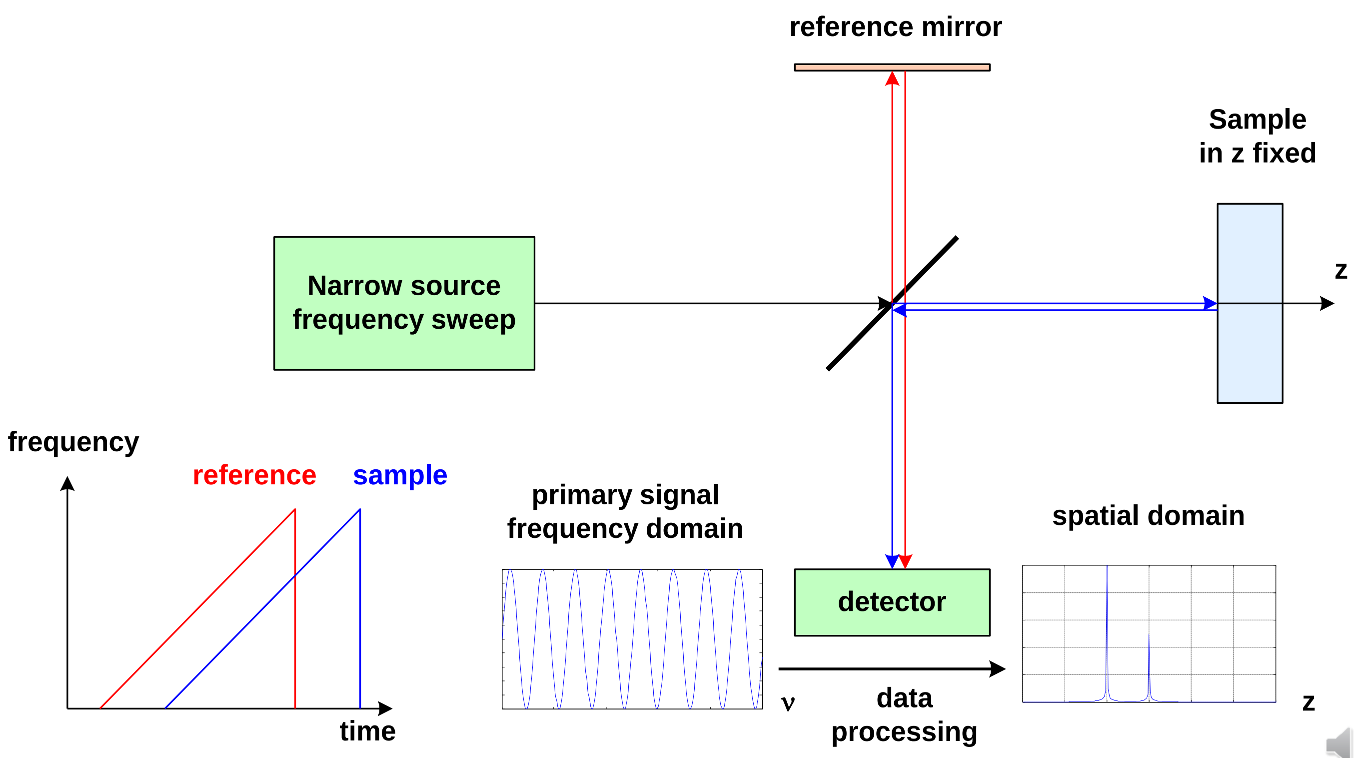
- Special setup for Fourier domain OCT:
  - SS-OCT: swept source instead of broad spectral source
  - source has tunable wavelength
  - advantage: no spectrometer necessary
  - usually faster than classical Fourier domain OCT
  - tunable laser expensive



Overview on OCT Setups

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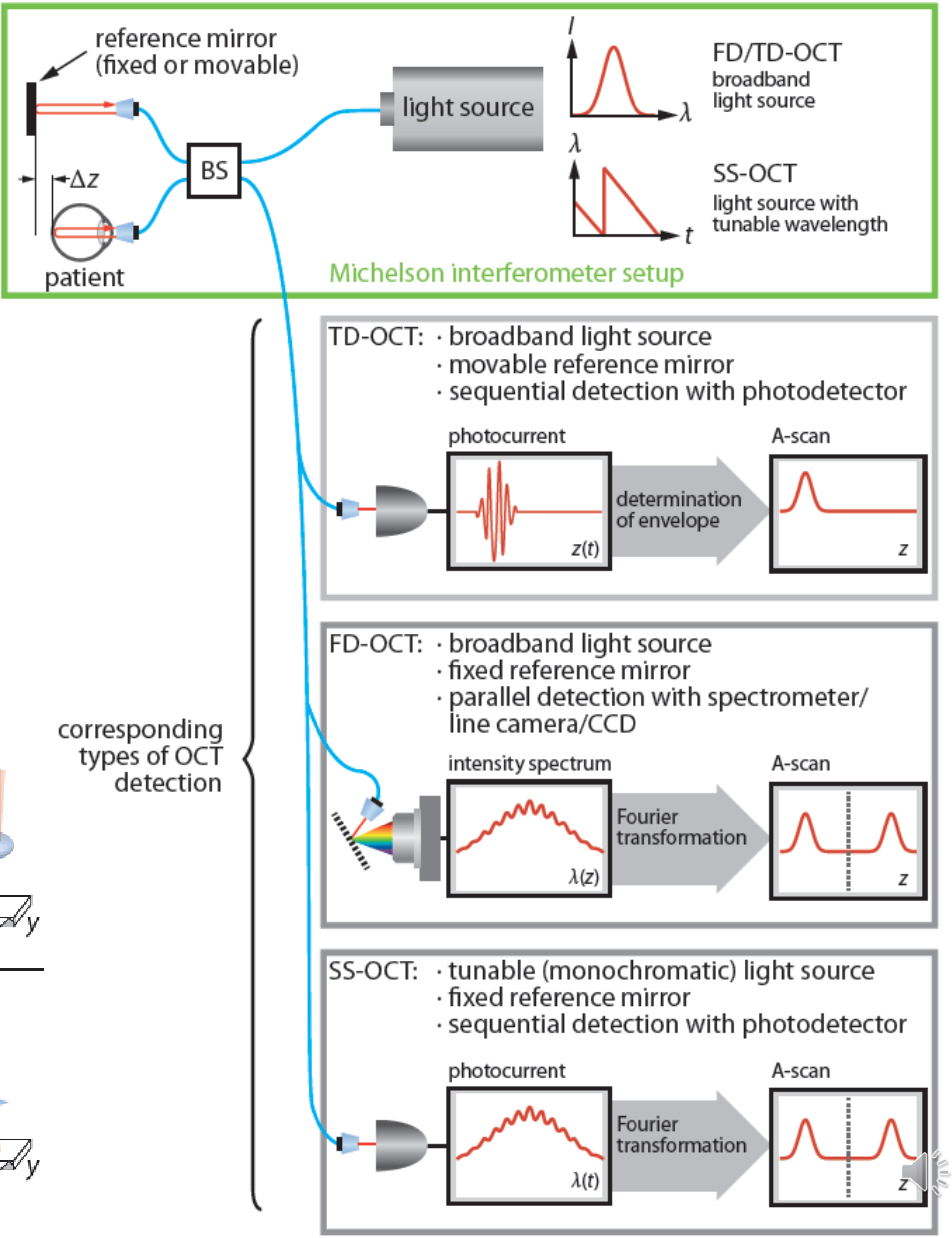

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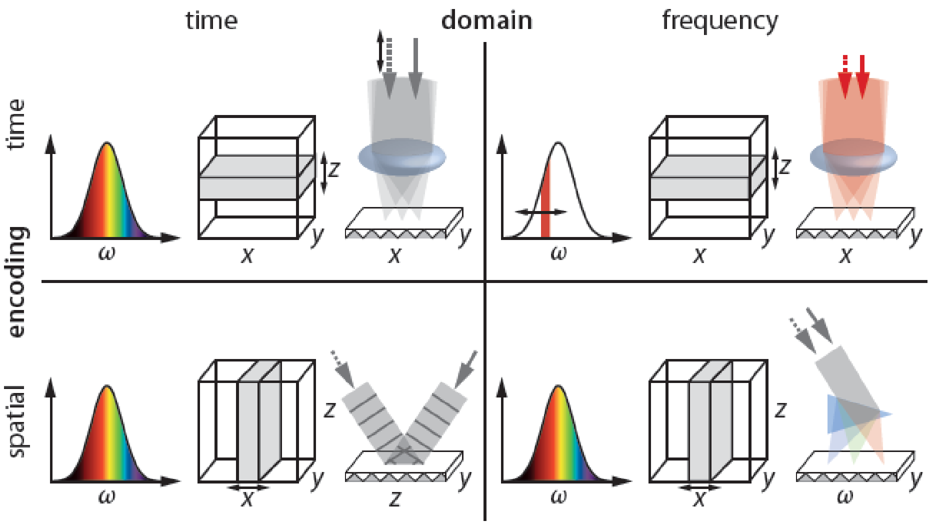

Fourier Domain OCT Signal

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- Field in the reference arm

$$E_R = \frac{E_0(k,\omega)}{\sqrt{2}} \cdot r_R \cdot e^{i2kz_R}$$

- Field in the sample arm

$$E_S = \frac{E_0(k,\omega)}{\sqrt{2}} \cdot r_S(z) \otimes e^{i2kz_S}$$

- Interference field

$$I_{FD} = \rho \cdot \left| E_R + E_S \right|^2$$

- Discrete scattering model: OCT signal

$$I_{FD}(k,\omega) = \frac{\rho}{2} \left| \frac{E_0(k,\omega)}{\sqrt{2}} \right|^2 \cdot \left| r_R \cdot e^{i\cdot(2kz_R - \omega t)} + \sum_j r_{Sj} \cdot e^{i\cdot(2kz_{Sj} - \omega t)} \right|^2$$

  with reflectivities r_j

$$r_S(z_S) = \sum_j r_{Sj} \cdot \delta\left(z_S - z_{Sj}\right)$$

- Final signal evaluation
  1st term: DC signal (underground)
  2nd term cross correlation with reference, interesting term
  3rd term autocorrelation between scatterers (small)

$$I_{FD}(k,\omega) = \frac{\rho}{4} \cdot S(k) \cdot \left(r_R^2 + \sum_j \left| r_{Sj} \right|^2 \right)$$
$$+ \frac{\rho}{2} \cdot S(k) \cdot r_R \cdot \sum_j r_{Sj} \cdot \cos\left(2k(z_R - z_{Sj})\right)$$
$$+ \frac{\rho}{4} \cdot S(k) \cdot \sum_{j \neq m} r_{Sj} \cdot r_{Sm} \cdot \cos\left(2k(z_{Sj} - z_{Sm})\right)$$

Fourier Domain OCT Signal

- Signal evaluation: inverse Fourier transform
  DC-term subtracted by difference measurement
  Auto-correlation: mostly negligible

$$I(z) = \hat{F}^{-1}[I(k)] = \hat{F}^{-1}[S(k)] \otimes \left\{ \frac{r_S^2}{2n_S} \cdot \delta(z) + \frac{r_R \cdot r_S}{2n_S} + \frac{1}{16 n_S^2} \cdot A_C(r_S(z)) \right\}$$

$$r_S(z) = \frac{n_S}{r_R} \cdot F^{-1}\left[\frac{\Delta I(k)}{S(k)} \right]$$

- Heterodyne efficiency:
  Decrease in signal strength due to scattering underground for gaussian beams

$$\left\langle I^2(z) \right\rangle_{cohgate} = \frac{\alpha^2 P_R P_S \sigma_b}{\pi\, w_{non}^2} \cdot \left[e^{-2\mu_s z} + \frac{4 w_{non}^2}{w_{non}^2 + w_S^2} \cdot e^{-2 p_b \mu_s z} \cdot e^{-\mu_s z} \cdot \left(1 - e^{-\mu_s z}\right) + \frac{w_{non}^2}{w_S^2} \cdot e^{-4 p_b \mu_s z} \cdot \left(1 - e^{-\mu_s z}\right)^2 \right]$$

$$= \left\langle I^2 \right\rangle_0 \cdot \Psi(z)$$