**Coherence & Light**

- Two waves coherent if fixed phase relationship between them for some period of time.

![Diagram](image)

**Fig. 3.8** An illustration of coherence. In (a) we show a perfectly coherent beam. All the constituent waves are in phase at all times. In (b) we have a beam which is spatially coherent, but which exhibits only partial temporal coherence. This is because the waves simultaneously change their phases by an identical amount every few oscillations. In (c) we show an almost completely incoherent beam where the phases of each wave change randomly at random times. Note however that even in this case some small degree of temporal coherence remains, since over very short time intervals the phases are to some extent predictable.
Coherence

- Coherence appear in two ways

**Spatial Coherence**
- Waves in phase in time, but at different points in space
- Required for interference and diffraction
- Before lasers need to place slits far from source or pass light through slit so only part of source seen

**Temporal Coherence**
- Correlation of phase at the same point but at different times
- Regular sources rapidly change phase relationships
- Single atom on $10^{-8}$ sec coherent lifetime of atom in an excited state
- Much shorter for groups of atoms
- For lasers in single mode much longer time

![Graph showing interference and no interference with distance](image)
Coherence Length and Time

- Time of coherence given by $\tau_{coh}$
- Coherence time about time taken for photon to pass a given distance (Coherence length) in space
- Coherence length is

$$L_{coh} = c\tau_{coh}$$

- Best seen in Michelson-Morley experiment
- Beam is split into two beam paths, reflected and combine
- If get interference pattern then within Coherence lengths
- Before lasers paths needed to be nearly equal
- With lasers only require

$$2(L_1 - L_2) < L_{coh}$$

- Coherence last 50 - 100 m with lasers

![Figure 1-24 Michelson interferometer.](image)
Coherence Length and Lasers

- As the coherence length is
  \[ L_{coh} = c \tau_{coh} \]

- If want interference distances < coherence length
- Lasers have high coherence
- It can be shown Coherence time related to laser frequency width \( \Delta \nu \) (linewidth)
  \[ \tau_{coh} = \frac{1}{\Delta \nu} \]

![Diagram](image)

**Fig. 3.10** When two identical wavetrains of length \( L_c \) which have traveled different distances \((L_1 \text{ and } L_2)\) are recombined they can only interfere over a length \( L_c - |L_1 - L_2| \).
Example of Coherence Length

Sodium vapour lamp yellow "D" line

• $\lambda = 589$ nm and linewidth $5.1 \times 10^{11}$ Hz

Thus coherence time and length is

$$\tau_{coh} = \frac{1}{\Delta v} = \frac{1}{5.1 \times 10^{11}} = 1.96 \times 10^{-12} \text{ sec}$$

$$L_{coh} = c \tau_{coh} = 2.98 \times 10^8 \left(1.96 \times 10^{-12}\right) = 5.88 \times 10^{-4} \text{ m} = 0.59 \text{ mm}$$

• Coherence small hence hard to create holograms

• HeNe laser in multimode operation

• $\lambda = 632.8$ nm and linewidth 1500 MHz

Thus coherence time and length is

$$\tau_{coh} = \frac{1}{\Delta v} = \frac{1}{1.5 \times 10^9} = 6.67 \times 10^{-10} \text{ sec}$$

$$L_{coh} = c \tau_{coh} = 2.98 \times 10^8 \left(6.67 \times 10^{-10}\right) = 0.2 \text{ m}$$

• If single mode HeNe operation linewidth goes to 1 Mz and coherence time is 1 microsec, coherence length 300 m
Fourier Domain
Optical Coherence Tomography
(FD OCT)

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Modified from J.A. Izatt, OCT Short Course
Optical Coherence Tomography

- In tissue shortest path photons are least scattered
- Consider starting with a coherent source (laser)
- 2 paths: one to tissue, other to reference
- Use Michelson interferometer methods
- By adjusting reference delay scan return in phase
- Hence can separate scattered from unscattered
- Called Time Domain OCT
Optical Coherence Tomography

Longitudinal Resolution:
\[ l_c = \frac{2 \ln 2 \lambda^2}{n \pi \Delta \lambda} \]
\[ \sim 1.5 \text{ – } 15 \mu m \]

Transverse Resolution:
\[ \Delta x = 1.22 \frac{\lambda}{2NA} \]
\[ \sim 2 \text{ - } 25 \mu m \]
Ophthalmic Optical Coherence Tomography

Anterior Segment

Retina
IN VIVO HUMAN ENDOSCOPIC OCT

Esophagus
Stomach
Small Intestine
Colon
Rectum

J.A. Izatt, OCT Short Course
CANCER IMAGING WITH ENDOSCOPIC OCT

Invasive Adenocarcinoma in Barrett’s Esophagus

B – Barrett’s Esophagus
A – Adenocarcinoma

J.A. Izatt, OCT Short Course
Cardiac Morphology And Development In Chick Embryos

Yelbuz, et.al., Circulation 106: 2771, 2002
Balance Sheet for OCT

- Non-Contact Measurement
- High resolution: 10 - 20 µm in 3 dimensions
- Compact, Inexpensive Diode-Fiber System
- Compatible with Existing Medical Instrumentation

- Speed limited by maximum optical exposure
  - Particularly important in ophthalmic imaging
    » MPE < 770 µW @ 830 nm
    » MPE < 15.4 mW @ 1310 nm
- High speed systems require complicated rapid scanning optical delay line (RSOD)
- Axial resolution trade-off with sensitivity
- Maximum tissue depth of ~2mm
Fourier Domain OCT

- Time domain OCT: reference moves
- Fourier Domain: reference fixed
- Now look at frequency (wavelength) changes

Spectral Domain
- Diffraction grating spreads spectrum
- Different $\lambda$ different phase
- Use array type detector

Swept Source
- Sweep Laser source (narrow line)
- Encode spectrum in time
Fourier Domain OCT

- Fixed reference arm
- Interferogram acquired as function of wavenumber

**SD OCT**

- Low coherence source
- 2x2 Fiber coupler
- Diffraction grating
- Array detector
- Wavelength swept laser
- Photodiode detector

**SS OCT**

- Fixed reference
- Sample

Mathematical expression:

\[ \hat{D}_i[k_m] \propto \hat{S}[k_m] \cdot (R_R + R_S + 2\sqrt{R_R R_S} \cos(2\Delta z k_m)) \]

\[ D_i[z_n] \propto S[z_n] \otimes \left( R_R + R_S \delta(z_n) \right) \]

\[ + 2\sqrt{R_R R_S} \left( \delta(z_n + \Delta z) + \delta(z_n - \Delta z) \right) \]

Symmetric signal peaks

DC peak

Complex conjugate artifact
High Resolution Retinal FDOCT

Compare to commercial TD OCT results

Acquisition Parameters:
• 1000 A-scans/B-scan
• 50μs A-scan int. time (20 kHz)
• 17 frames/sec display
• 11mm lateral scan
• $\lambda_o = 841$ nm, $\Delta\lambda = 49$nm

B.A. Bower, SPIE Photonics West, 2006

B.A. Bower, SPIE Photonics West, 2006
High Speed Volumetric Retinal FDOCT

Summed voxel projection from raster canned OCT Data: “OCT Fundus” Image

B.A. Bower, SPIE Photonics West, 2006
Small Animal Imaging

- Video light microscopy, SEM, confocal microscopy often inadequate for quantitative measurements.
- OCT is uniquely suited to image popular small model organisms such as fruit fly, chick embryo, zebrafish, and xenopus

**Bioptigen, Inc. OCT Microscope**

- $\lambda_0 = 1300$ nm,
- $\Delta \lambda = 70$ nm
- LPS: 6-24 kHz
- FPS: 6-24 Hz
- Volume: 4-25 s
- Flow measurement using Doppler processing

Chick embryo Cardiac Doppler flow measurement

Limited Sample Depth FD OCT: Imaging the Human Eye

- **Posterior Segment**
  - Retina, macula, optic nerve head
  - Structures < 1 mm thick
- **Anterior chamber**
  - Cornea, iris, crystalline lens
  - > 6 mm sample depth required
High Speed Complex Conjugate Resolved Ocular Anterior Segment Images

- Average all three detector signals
  - Image corrupted by complex conjugate artifact

- Quadrature projection processing
  - Complex conjugate resolved images

Labels:
- Limbus
- Sclera
- Cornea
- Epithelium
- Iris
- Ciliary body
- DC artifact
- Angle
- Crystalline lens