Transmission Characteristics of Optical Fiber - II
OPTICAL FIBER

- An optical fiber is a long cylindrical dielectric waveguide, usually of circular cross-section, transparent to light over the operating wavelength.

Fiber Structure

- A single solid dielectric of two concentric layers. The inner layer known as **Core** is of radius ‘a’ and refractive index ‘$n_1$’. The outer layer called **Cladding** has refractive index ‘$n_2$’. 

\[ n_2 < n_1 \rightarrow \text{condition necessary for TIR} \]
Step Index / Graded Index

Index Profile

Fiber Cross Section and Ray Paths

Monomode step-index fiber

Typical Dimensions

- 125 \( \mu \text{m} \) (cladding)
- 8–12 \( \mu \text{m} \) (core)

Multimode step-index fiber

- 125–400 \( \mu \text{m} \) (cladding)
- 50–200 \( \mu \text{m} \) (core)

Multimode graded-index fiber

- 125–140 \( \mu \text{m} \) (cladding)
- 50–100 \( \mu \text{m} \) (core)
DESIGNER’S PARAMETERS

Numerical Aperture (NA):

\[ NA = \sin \theta_a = \left[ (n_1)^2 - (n_2)^2 \right]^{1/2} \]

0.10-0.25 for SMF, 0.20-0.50 for MMF

Relative Refractive Index Difference (\( \Delta \)):

\[ \Delta = \frac{(n_1 - n_2)}{n}; \text{ n - the average refractive index} \]

<0.4% for SMF, >1% for MMF

Normalized Frequency or V-Number:

\[ V = \left[ \frac{(2\pi a)}{\lambda} \right] NA \]

\[ V \leq 2.405 \text{ for SMF;} \quad \geq 10 \text{ for MMF} \]
Transmission Characteristics

- Factors which affect the performance of optical fibers as a transmission medium
  - Important, when the suitability of optical fibers for communication purposes is investigated.

- Characteristics of Primary Importance:
  - **Attenuation** (or Transmission loss): determines the maximum *repeater less separation* between a transmitter and receiver.
  - **Dispersion**: limit the information – carrying capacity of a fiber i.e. *Bandwidth*
Fibre Performance

Attenuation

Dispersion
Typical Long-haul Telecom System

- **Amplifier spans:** 30 to 120 km
- **Regenerator spans:** 50 to 600 km
- **Terminal spans:**
  - 600 km (without regenerators)
  - 9000 km (with regenerators)

Two pairs of single-mode fiber

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Terminal Equipment

Amplifier Unit

Amplifier Unit

Regenerator Unit

Amplifier Unit

Terminal Equipment
Pulse Broadening

- In the ray model there are a continuum of ray directions between the axial ray and the critical angle $a_c$.

- The axial ray takes the shortest route and arrives at the far end first, whereas the ray at the critical angle takes the longest route and arrives last.

- A short input pulse will be broadened by the range of paths travelled.
Dispersion

- Dispersion effects broaden the pulse as it propagates along the fibre.
- The broadening is measured in nsec/km.
- After large distance the pulses overlap (intersymbol interference-ISI) and become indistinguishable.
  - Electrical dispersion.
- The broadening, $\tau$, limits the maximum data rate:

$$B_T \leq \frac{1}{2\tau}$$
Dispersion - Spreading of light pulses in a fiber
  - limits Bandwidth

Most important types

1. Intramodal (Chromatic) dispersion
   i) Material dispersion
   ii) Waveguide dispersion
2. Intermodal (Modal) dispersion
Intermodal Dispersion

Fiber Dispersion: C. Modal Dispersion

- Only in multimode fibers
- Cause:
  - Each mode has slightly different path to receiver

- Time delay between fastest and slowest is modal pulse delay distortion and in SI fiber is...

\[
\Delta \tau_{\text{SI modal}} = \frac{L(n_1 - n_2)}{c} \left(1 - \frac{\pi}{V}\right) = \frac{L(n_1 - n_2)}{c} = \frac{L \Delta n_1}{c}
\]

- \( D_{\text{modal}} = \frac{\Delta \tau_{\text{modal}}}{L} \) [ps·km\(^{-1}\)]
Intermodal Dispersion

\[ D = \frac{\Delta T}{L} = \frac{n_1}{n_2} \cdot \frac{\Delta n}{c} \approx \frac{\Delta n}{c} \approx \frac{NA^2}{2nc} \quad \text{[ns / km]} \]

\[ B \cdot L = \frac{L}{\Delta T} = \frac{2nc}{NA^2} \quad \text{[(Mb / s)km]} \]

\[ T_{\text{min}} = L \cdot \frac{n_1}{c} \quad T_{\text{max}} = L \cdot \frac{n_1}{c \cdot \cos \theta_c} \]

\[ \cos \theta_c = \frac{n_2}{n_1} \]
Intermodal Dispersion (also Modal Dispersion)

- can be minimized by:
  - using a smaller core diameter
  - using graded-index fiber (less by a factor of 100)
  - use single-mode fiber - single-mode fiber is only single-mode at wavelengths greater than the cutoff wavelength

- When multimode dispersion is present, it usually dominates to the point that other types of dispersion can be ignored.
Modal Dispersion in Graded Index Fibers

- Graded Index Fibers: Solution to modal dispersion

A multimode graded index fiber: (a) Parabolic refractive index profile; (b) Meridional ray paths within the fiber core.

- Core is designed with different refractive index layers so that the beam traveling the **farthest distance** does so at the **highest velocity** and the beam traveling the **shortest distance** propagates at the **slowest velocity**.
Intramodal Dispersion

- **Intramodal dispersion** occurs due to the differing propagation delays of different wavelengths of light *within a single mode* (intra-modal)

  - Caused by *material dispersion* and *waveguide dispersion*

  - Light sources have a finite spectral width ($\pm \Delta \lambda$)
    - a fraction of a per cent of the centre frequency for a laser
    - several per cent for a LED

- Each spectral component of a pulse travels at a different rate leading to pulse broadening
Light sources are NOT monochromatic (linewidth of source, chirp effects, modulation sidebands)

Different wavelengths travel at slightly different speeds (this effect is called “Chromatic Dispersion”)

Chromatic dispersion causes pulse broadening (problem at high bit rates over long distances)

Standard single-mode fiber:
- 1300 nm window has lowest CD
- 1550 nm lowest loss
Fiber Dispersion: A. Material Dispersion

- Velocity of light in SiO$_2$ is weak function of wavelength, $n(\lambda)$
- All light sources have spectral width $\Delta\lambda$
  - Lasers narrower spectrum than LEDs
- Longer $\lambda$s arrive at RCVR before shorter $\lambda$s
Material Dispersion (cont.)

- Pulse spread due to material dispersion

\[
\Delta \tau_{\text{mat}} = -\frac{L}{c} \frac{\Delta \lambda}{\lambda} \left( \lambda^2 \frac{d^2 n_1}{d \lambda^2} \right)
\]

Figure 3.8, p. 47

- Frequently normalized: \( D_{\text{mat}} = \frac{\Delta \tau_{\text{mat}}}{(L \Delta \lambda)} \) [ps·km\(^{-1}\)·nm\(^{-1}\)]
Material dispersion Parameter (M)

\[ M = \frac{1}{L} \frac{d\tau_m}{d\lambda} \]

is expressed in ps.nm\(^{-1}\).km\(^{-1}\)

- Material dispersion may be minimized by control of system parameters.

The material dispersion parameter for silica as a function of wavelength
Waveguide Dispersion

• Light travels at different speeds in core and cladding.

• Results from the variation in group velocity with wavelength which leads to a variation in transmission time for the modes.

• Variation of propagation constant (β) with wavelength (λ),

\[ \frac{d^2 \beta}{d\lambda^2} \neq 0 \]
Fiber Dispersion:

B. Waveguide Dispersion

- In low material-dispersion region of 1000 to 1600 nm in SM fibers...
  - *Waveguide dispersion* becomes important
  - Negligible in MM fibers and in SM fibers operated below 1,000 nm and above 1600 nm
- Cause: velocity of mode is function of $a/\lambda$
- Waveguide dispersion

$$\Delta \tau_{\text{wg}} \approx -\left( \frac{n_2 L \Delta}{c} \right) \left( \frac{\Delta \lambda}{\lambda} \right) \left( V \frac{d^2 (Vb)}{dV^2} \right)$$

$$D_{\text{WG}} = \Delta \tau_{\text{WG}} / L \Delta \lambda \quad [\text{ps} \cdot \text{km}^{-1} \cdot \text{nm}^{-1}]$$

![Figure 3.10, p. 51](image)
• Dispersion is sum of material and waveguide components

• Minimum dispersion occurs at $\lambda = 1.3 \ \mu m$
  – dispersion negligible
  – attenuation $\sim 0.3 \ \text{dB km}^{-1}$

• Minimum attenuation occurs at $\lambda = 1.5 \ \mu m$
  – dispersion $15 \ \text{ps nm}^{-1} \ \text{km}^{-1}$
  – attenuation $0.2 \ \text{dB km}^{-1}$

• Dispersion flattening enables $2 \ \text{ps nm}^{-1} \ \text{km}^{-1}$ over $1.3-1.6 \ \mu m$ range
  – enables low-loss AND low dispersion at $1.5 \ \mu m$
**Overall Fiber Dispersion**

**Total Dispersion**

\[ D_T = D_M + D_W + D_P \ (\text{ps nm}^{-1} \text{ km}^{-1}) \]

- **In MMFs**, the overall dispersion comprises both
  - Intermodal
  - Intramodal (Material & Waveguide)

**Note**: In MMFs, waveguide dispersion is negligible compared to material dispersion

- **In SMFs**, dispersion is entirely from Intramodal or Chromatic dispersion
  - BW is limited by finite spectral width of the source (\(\Delta\lambda\))
  - Dominated by material dispersion of fused silica
  - Zero Material Dispersion by control of dopants
Schematic diagram showing a multimode step index fiber, multimode graded index fiber and single-mode step index fiber, and illustrating the pulse broadening due to intermodal dispersion in each fiber type.
Dispersion Modified SMFs

Total Dispersion:

\[ D_T = D_M + D_W = \frac{\lambda}{c} \left| \frac{d^2 n_1}{d\lambda^2} \right| - \left[ \frac{n_1 - n_2}{\lambda c} \right] \frac{Vd^2(Vb)}{dV^2} \]

- At wavelengths longer than the **ZMD point** in most common fiber designs, the \( D_M \) and \( D_W \) are of opposite sign and can therefore be made to cancel at some longer wavelengths.

- Hence, \( \lambda_{ZMD} \) can be shifted to the lowest loss wavelength for silicate glass fibers at 1550 nm to provide both low dispersion and low loss fiber.

- **Dispersion Modified SM Fibers**
  - Dispersion Shifted
  - Dispersion flattened
Dispersion Shifted & Dispersion Flattened SMFs

Total dispersion characteristics for various types of SMFs

• Achieved by mechanisms such as; Reduction in fiber core diameters, Increase in relative or fractional index difference and Variation in fiber material composition
TRANSMISSION RATE

Bit-Rate and Dispersion

- Maximum bit rate

\[ B_{R_{\text{max}}} \approx \frac{1}{4 \Delta \tau_{\text{total}}} \]

where

\[ \Delta \tau_{\text{total}} = \sqrt{\Delta \tau_{\text{modal}}^2 + \Delta \tau_{\text{GVD}}^2} \quad \text{and} \quad \Delta \tau_{\text{GVD}} = \Delta \tau_{\text{material}} + \Delta \tau_{\text{waveguide}} \]

- Note that \( B_{R_{\text{max}}} \sim 1/L \)
- (bit-rate)-distance product is constant for a given fiber
SMFs For Telecom

- **SMF**: Standard, 1310 nm Optimized, unshifted
  - Most widely deployed by far distances

- **SMF DS**: Dispersion shifted
  - For single channel operation at 1550 nm

- **SMF DF**: Dispersion flattened
  - For WDM/DWDM operation in the 1550 nm region
THANK YOU