Transmission Characteristics of Optical Fibers

Dr. BC Choudhary
Professor
NITTTR, Sector-26, Chandigarh-160019.
Optical fiber- A long cylindrical dielectric waveguide, usually of circular cross-section, transparent to light over the operating wavelength.

- A single solid dielectric of two concentric layers. The inner layer known as **Core** is of radius ‘a’ and refractive index ‘n₁’. The outer layer called **Cladding** has refractive index ‘n₂’

  \[ n_2 < n_1 \rightarrow \text{condition necessary for TIR} \]
Classification of Optical Fibers

Classified on basis of:

- Core and Cladding materials
- Refractive index profile
- Modes of propagation
Fiber Materials: Three Varieties

a. Glass core and cladding (SCS: silca-clad silica)
   • Low attenuation & best propagation characteristics
   • Least rugged – delicate to handle

b. Glass core with plastic cladding (PCS: plastic clad silica)
   • More rugged than glass; attractive to military applications
   • Medium attenuation and propagation characteristics

c. Plastic core and cladding
   • More flexible and more rugged
   • Easy to install, better withstand stress, less expensive, weigh 60% less than glass
   • High attenuation- limited to short runs.
Refractive Index Profile: Two types

- **Step Index**: Refractive index makes abrupt change
- **Graded Index**: Refractive index is made to vary as a function of the radial distance from the centre of the fiber

Mode of propagations: Two types

- **Single mode**: Single path of light
- **Multimode**: Multiple paths
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** (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/Data rate*
Fibre Performance

Attenuation

Dispersion
Optical Fiber Attenuation

- Measure of the decay of signal strength or light power

\[ P(z) = P_0 e^{-\alpha z} \]

where,
- \( P(z) \): Optical power at distance \( z \) from the input
- \( P_0 \): Input optical power
- \( \alpha \): Fiber attenuation coefficient, [dB/km]

- Logarithmic relationship between optical output power and input power

\[ \text{Power ratio (dB)} = 10 \log \frac{P_0}{P_I} \]

- Convenient method to establish, measure and interrelate signal levels is to reference the signal level either to some absolute value or to a noise level.
Examples of decibel measures of power ratios

<table>
<thead>
<tr>
<th>Power ratio</th>
<th>$10^N$</th>
<th>10</th>
<th>2</th>
<th>1</th>
<th>0.5</th>
<th>0.1</th>
<th>$10^{-N}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>dB</td>
<td>$+10N$</td>
<td>+10</td>
<td>+3</td>
<td>0</td>
<td>-3</td>
<td>-10</td>
<td>-$10N$</td>
</tr>
</tbody>
</table>

Power levels in dBm: Decibel power level referred to 1mW.

$$\text{Power level} = 10 \log \frac{P}{1\text{mW}}$$

Examples of dBm units

<table>
<thead>
<tr>
<th>Power (mW)</th>
<th>100</th>
<th>10</th>
<th>2</th>
<th>1</th>
<th>0.5</th>
<th>0.1</th>
<th>0.01</th>
<th>0.001</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value (dBm)</td>
<td>+20</td>
<td>+10</td>
<td>+3</td>
<td>0</td>
<td>-3</td>
<td>-10</td>
<td>-20</td>
<td>-30</td>
</tr>
</tbody>
</table>
Fiber Attenuation (Loss)

- Usually, attenuation is expressed in terms of decibels (dB) or mostly dB/km – *attenuation coefficient*

\[
\alpha = \frac{1}{z} \log_{10} \left( \frac{P_{\text{out}}}{P_{\text{in}}} \right)
\]

\[
\alpha_{\text{Total}} = \alpha_{\text{absorption}} + \alpha_{\text{scattering}} + \alpha_{\text{bending}}
\]
Basic Attenuation Mechanisms

- **Material Absorption (Intrinsic and Extrinsic)**
- **Scattering (Linear and Non-linear)**
- **Bending loss (Macrobends and Microbends)**
Material Absorption

- A loss mechanism related to the *material composition and fabrication process* for the fiber
  - Results in the dissipation of some of the transmitted optical power in the waveguide

- **Absorption of light** (Optical Energy)
  a. *Intrinsic*: caused by the interaction with one of the major components of the glass
    - Absorption in the IR-wavelength region (Molecular absorption)
    - Absorption in UV wavelength region (Electronic absorption)
b. **Extrinsic**: caused by impurities within the glass

- Mainly absorption by *transition metal* impurities (Cr, Cu, Fe, Mn, Ni, V etc.)
  
  ➢ Reduced to acceptable levels (i.e. one part in $10^{10}$) by glass refining techniques.

- Another major extrinsic loss mechanism is caused by absorption due to water (Hydroxyl- OH ion) dissolved in the glass
  
  ➢ Hydroxyl groups are bonded to glass structure and have fundamental stretching vibrations depending on group position.

☞ **Taken care during manufacturing of fibers ⇒ Use of ultra pure materials/Clean rooms.**
SCATTERING

- Scattering effect prevents attainment of total internal reflection at the core cladding boundary – resulting in power loss
  - Due to Obstacles or inhomogeneities

![Scattering Loss]

- Even very small changes in the value of the core’s refractive index will be seen by a traveling beam as an optical obstacle and this obstacle will change the direction of original beam.
Scattering Mechanisms

- Wave interacts with “particle” or molecules
- Transfers power to other directions

  a. Linear scattering:
    - Scattered power proportional to incident power
    - No change in frequency of scattered light

  » Rayleigh scattering:
    - Particles $<< \lambda$
      - Molecules, changes in $n$ (change in composition), changes in density
    - Scattering strength $\sim 1/\lambda^4$
    - Fundamental loss at low wavelengths
      - Minimum loss at 1550 nm in silica ($\text{SiO}_2$)
      - Theoretical minimum $\sim 0.15 \text{ dB/km}$
Rayleigh Scattering Loss

- **Rayleigh scattering coefficient** \((\gamma_R)\) is proportional to \((1/\lambda^4)\) and is related to transmission loss factor of the fiber as

\[
\Gamma = \exp(-\gamma_R L)
\]

- Rayleigh scattering component can be reduced by operating at the longest possible wavelength.

- **Attenuation due to Rayleigh scattering in silica at different wavelengths:**
  - 850nm: 4.0 dB km\(^{-1}\)
  - 1300 nm: 0.5 dB km\(^{-1}\)
  - 1550 nm: 0.2 dB km\(^{-1}\)
Attenuation spectra for intrinsic loss mechanisms in pure GeO$_2$ - SiO$_2$ glass
Material Absorption & Scattering Losses

![Graph showing material absorption and scattering losses in silica fibers.](image)

Fig. 12.2. Measured attenuation in silica fibers (solid line) and theoretical limits (dashed lines) given by Rayleigh scattering in the short-wavelength region, and by molecular vibrations (infrared absorption) in the infrared spectral region.
Mie Scattering

a. Linear scattering (cont)
  – Mie scattering
    » Particles \( \sim \lambda \)
      • Inhomogeneities
        – Core-cladding refractive index variations
        – Core-cladding interface impurities
        – Diameter fluctuations
      • Strains in fiber
      • Bubbles in fiber
    » Solution:
      • Remove imperfections
  ➢ occurs at inhomogeneities comparable in size to guided wavelength
          
  ❆ Mainly in the forward direction

  • Controlled extrusion & cabling of the fiber
  • Increasing fiber guidance by increasing ‘\( \Delta \)’
Scattering Loss: **Nonlinear**

b. **Nonlinear Scattering**: Usually at high optical power levels

- Cause: high $E$ field (V/m) (i.e., combination of power, area, and distance)
- Power scattered forward, backward, or side directions, depending on interaction

A. **Brillouin scattering**: SBS

» Photon undergoes nonlinear interaction to produce...
  - Vibrational energy ("phonons") and
  - Scattered light ("photons")

» Upward and downward frequency shifts
  - Strength of scattering varies with scattering angle
    - Maximum in backward direction; minimum of zero in forward direction

» Solution: keep power level below threshold
  - Nonlinear scattering imposes "ceiling" on source power
  - Threshold power level

$$P_B = (17.6 \times 10^{-3}) a^2 \lambda^2 \alpha \Delta \nu'$$ (typically $\leq 1$ W in SM fiber)
b. Nonlinear Scattering (cont)

B. Raman scattering: SRS

» Nonlinear interaction produces….
  • High-frequency phonon (instead low-frequency phonon of Brillouin scattering) ⇒ Optical phonon
  • Scattered photons

» Scattering predominantly in forward direction (power not lost)

» Power level threshold:

\[ P_{\text{Raman}} = \left(23.6 \times 10^{-2}\right) a^2 \lambda \alpha \] (typically few W)

» Solution: keep power level below threshold
  • Single channel fiber
    – Brillouin threshold lower than Raman and determines power “ceiling”

 vulnerably, SBS threshold occurs at 100 mW, and SRS threshold at 1W
BENDING LOSSES

- Bending an optical fiber introduces a loss in light power
  - Microbends
  - Macrobends

- **Microbending** - Result of microscopic imperfections in the geometry of the fiber
- **Macrobending** - Fiber bending with diameters on the order of centimeters (usually if the radius of the bend is larger than 10 cm)
Microbending losses

- Results from non-uniform lateral pressures of fiber surface (core-cladding interface)

- Minimized by extruding a compressible jacket over the fiber.
Power loss in a curved fiber

- Velocity of evanescent field at the bend exceeds the velocity of light in the cladding
- Guidance mechanism inhibited

Critical radius of curvature:

\[ R_c \approx \frac{3n_1^2\lambda}{4\pi\left(n_1^2 - n_2^2\right)^{\frac{1}{2}}} \]

- Designing fibers with large relative refractive index differences;
- Operating at the shortest wavelength possible.
LOSS SUMMARY

- Losses in fiber are due to
  - Material Absorption
  - Scattering (Linear and Nonlinear)
  - Bending (Macrobends & Microbends)
  - Interface inhomogenenities

- Minimum loss is at 1550 nm
- Theoretical minimum loss ($\approx 0.15 \text{ dB/km}$) almost achieved in practice with Silica fibers.
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 (ISI) and become indistinguishable
  - electrical dispersion
- The broadening, ‘τ’ limits the maximum data rate.

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

Types of Dispersion

- Multimode Dispersion
- Material Dispersion
- Waveguide Dispersion

Most important types

- Intermodal (Modal) dispersion – MMFs
- Intramodal or Chromatic dispersion – SMFs
  - Material dispersion
  - Waveguide dispersion
Pulse broadens linearly with distance so that the maximum bandwidth reduces inversely with distance.

- **Bandwidth-distance** is a constant for a fibre and is a quoted parameter.

- Best bandwidth-length products:
  - For a multimode fibre ~20 MHz km
  - For a single-mode fibre ~100 GHz km
Intermodal Dispersion

Fiber Dispersion: C. Modal Dispersion

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

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

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

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

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

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

\[ T_{\text{min}} = L \cdot \frac{n_1}{c} \]

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

\[ \cos \theta_c = \frac{n_2}{n_1} \]
Intermodal Dispersion

- 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.
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

![Diagram showing broadband input pulse and spectrally dispersed output pulse](image-url)
Intramodal (Chromatic) Dispersion

- Light sources are NOT monochromatic (linewidth of source, chirp effects, modulation sidebands)

- Different wavelengths travel at slightly different speeds

  ⇒ “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: Material Dispersion

- Velocity of light in SiO₂ 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

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

Figure 3.8, p. 47

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

![Graph showing the relationship between \( \lambda \) (nm) and \( \frac{d^2 n_1}{d\lambda^2} \)]
Material dispersion Parameter (M)

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

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

Material dispersion parameter for silica as a function of wavelength

Material dispersion may be minimized by control of system parameters.
Waveguide Dispersion

- Waveguide Dispersion
  - occurs because optical energy travels in both the core and cladding at slightly different speeds.
  - A greater concern for SMFs than for MMFs

- Results from the *variation in group velocity with wavelength* which leads to a *variation in transmission time* \((\tau_g)\) for the modes.

- Variation of propagation constant \((\beta)\) with wavelength \((\lambda)\),

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

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

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

$\Rightarrow$ Waveguide dispersion parameter
• Dispersion is sum of material and waveguide components

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

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

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

Total Dispersion

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

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

  ![Note](image)
  
  **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.

- \(\lambda_{ZMD}\) can be shifted to the lowest loss wavelength for silicate glass fibers at 1550nm 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
Dispersion Shifted SMFs

- $\lambda_0$ may be selected in the range 1.3 to 2 $\mu$m by careful control of the fiber core diameter and profile.
Dispersion Shifted Fibers

Dispersion characteristics of SI SMFs showing variation with composition and spot size

- Higher concentration of dopants cause a shift to longer wavelength which when coupled with reduction in MFD (negative of $D_W$) leads to shifted fiber characteristics.
RI Profiles for GI DSFs

- Several GI profiles investigated and proposed for DSFs.

- Alternate approaches for DS-SMFs involve use of multiple index designs.
  - Doubly clad or W-fiber
  - Multiple index triangular profile
  - Segmented –core-triangular profile
  - Dual shaped core
RI Profiles for Dispersion Flattened Fibers

- **First demonstrated using W-fiber structure**
  - Require high degree of dimensional control
  - Comparatively higher overall fiber loss (0.3 dB km$^{-1}$)
  - High sensitivity to bend losses (DFFs operation is very close to cutoff to obtain flat dispersion characteristics)

- **Alternate designs to reduce sensitivity to bend losses.**
  - Light penetrating outer cladding can be retrapped by introducing region of raised index \(\text{lower attenuation } \approx 0.19 \text{ dB km}^{-1}\), less sensitive to bends
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
Variety of Optical Fiber Cables
Thank You