2 Effects

- **Pulse Spreading – Dispersion (Distortion)**
  - Causes the optical pulses to broaden as they travel along a fiber
  - Overlap between neighboring pulses creates errors
  - Resulting in the limitation of information-carrying capacity of a fiber

- **Signal Attenuation – Losses**
  - Determines the maximum repeaterless separation between optical transmitter & receiver
Pulse Spreading

- Successive pulses overlap as they spread
- Spreading increases with distance
- Degree of dispersion depends on fiber type

Multipath/Modal Dispersion

- Modes are oscillation/propagation paths
- Mode velocities differ in step-index multimode fiber
- Visualize as difference in ray paths
  - Red ray goes shorter distance than blue
Time Delay & Bandwidth Length product

- Time delay between the two rays taking longest and shortest paths is a measure of pulse broadening; given by
  \[ dT = \frac{n_i}{c} \left[ \frac{L}{\sin \phi_i} - L \right] = \frac{L}{c} \frac{n_i}{n_2} \Delta \]
  Derive?

- Time delay can be related to the information carrying capacity of the fiber through bit rate B
  \[ B.dT < 1 \quad \Rightarrow \quad BL < \frac{n_2 c}{n_1^2 \Delta} \]
  Derive?

- This condition provides a rough estimate of fundamental limitation of SI fibers.

Wave Velocities

1– Plane wave velocity:
   For a plane wave, represented by \( \exp (j\omega t - jk_1 z) \), propagating along z-axis in an unbounded homogeneous region of refractive index, \( n_1 \), the velocity of constant phase plane is:
   \[ v = \frac{\omega}{k_1} = \frac{c}{n_1} \]

2– Modal wave phase velocity:
   For a modal wave, represented by \( \exp (j\omega t - j\beta z) \), propagating along z-axis in the fiber, the velocity of constant phase plane is:
   \[ v_p = \frac{\omega}{\beta} \]
   \[ k_1 = \text{Propagation constant} = 2 \pi / \lambda \]
   \[ \beta = \text{Propagation constant along the fiber axis} \]
Group Velocity, $V_g$

- The actual velocity at which the signal information & energy is traveling down the fiber. It is always less than the speed of light
- The observable delay experienced by the optical signal waveform & energy, is commonly referred to as group delay
- The group velocity depends on frequency and is given by:

$$V_g = \frac{d\omega}{d\beta}$$

Basics about Plane Waves

\[ \vec{E} = \vec{E}_0 e^{i(\omega t - k \cdot r)} \]

\[ = E_x e^{i(\omega t - kz)} \hat{i} + E_y e^{i(\omega t - kz)} \hat{j} \]

\[ = E_x \cos(\omega t - kz) \hat{i} + E_y \cos(\omega t - kz) \hat{j} \]

for plane waves propagating in the positive z-direction

\[ k = \frac{2\pi}{\lambda} \quad \text{[m]} \quad \text{wavenumber} \]

\[ \omega = 2\pi v = \frac{2\pi c}{\lambda} \quad \text{[rad/m]} \quad \text{frequency} \]

$E_x, E_y$ - amplitude of the waves in the x and y directions
Phase Velocity

$P$ is a point of constant phase

$$\Rightarrow \omega t - kz = \text{constant}$$

$$\Rightarrow \frac{dz}{dt} = \frac{\omega}{k}$$

$$v_p = \frac{\omega}{k} = c_0 \quad \text{phase velocity}$$

$$c_0 = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 2.998 \times 10^8 \text{ m/s}$$

speed of light

Group of Waves

Consider two plane waves $E_{x1}$ and $E_{x2}$ propagating in the +ve $z$-direction

$$E_{x1} = E_0 \cos \left[ (\omega_0 + \Delta \omega) t - (k_0 + \Delta k) z \right]$$

$$E_{x2} = E_0 \cos \left[ (\omega_0 - \Delta \omega) t - (k_0 - \Delta k) z \right]$$

The superposition of the waves (wavepacket) is given by

$$E = E_{x1} + E_{x2}$$

$$= 2E_0 \cos(\Delta \omega t - \Delta kz) \cos(\omega_0 t - k_0 z)$$

slowly varying envelope

rapid oscillation (carrier frequency)
Carrier and Envelope

Group Velocity

For a point of “constant phase” on the envelope

\[ \Rightarrow \Delta \omega t - \Delta kz = \text{constant} \]

\[ \Rightarrow \frac{dz}{dt} = \frac{\Delta \omega}{\Delta k} \]

\[ v_g = \frac{d\omega}{dk} = \frac{c_0}{n} \]

\( n \): refractive index

Physical meaning of group velocity: speed at which energy (or information) in a wavepacket travels (no information carried by phase velocity)
Dispersion can be described as:

- Any phenomenon in which the velocity of propagation of any electromagnetic wave is wavelength dependent.
- Any process by which any electromagnetic signal propagating in a physical medium is degraded because the various wavelength signals have different propagation velocities within the physical medium.

Types of Dispersion

- Intermodal/Modal Dispersion
  
  *(already discussed)*

- Intramodal Dispersion
  1. Material Dispersion
  2. Waveguide Dispersion

- Polarization-Mode Dispersion
Intramodal Dispersion/GVD

- The propagation constant, $\beta(\omega)$, is frequency dependent over band width $\Delta \omega$, with the center frequency $\omega_0$.
- Each frequency component has a specific delay time.
- As the output signal is collectively represented by group velocity & group delay this phenomenon is called **intramodal dispersion or Group Velocity Dispersion (GVD)**
- In the case of optical pulse propagation down the fiber, GVD causes pulse broadening, leading to Inter Symbol Interference (ISI)

How to characterize dispersion?

- If the spectral width of the optical source is not too wide, For spectral components which are $\delta \lambda$ apart, symmetrical around center wavelength, the total delay difference $\delta \tau$ over a distance $L$ is:

$$\Delta T = \left| \frac{d \tau_g}{d \omega} \right| \Delta \omega = \frac{d}{d \omega} \left( \frac{L}{V_g} \right) \Delta \omega = L \left( \frac{d^2 \beta}{d \omega^2} \right) \Delta \omega = \beta_2 L \Delta \omega$$

where, the group delay, $\tau_g = \frac{L}{V_g}$ and $\frac{1}{V_g} = \frac{d \beta}{d \omega}$

$\beta_2$ is called **GVD parameter**, and shows how much a light pulse broadens as it travels along an optical fiber.
The more common parameter is called **Dispersion**, and can be defined as the delay difference per unit length per unit wavelength as follows:

\[
D = \frac{d}{d\lambda} \left( \frac{1}{V_g} \right) = -\frac{2\pi c}{\lambda^2} \beta_2
\]

In the case of optical pulse, if the spectral width of the optical source is characterized by its *rms* value of the Gaussian pulse \(\Delta\lambda\), the pulse spreading \(\Delta T\), over the length of \(L\), can be well approximated by:

\[
\Delta T = DL \Delta\lambda
\]

\(D\) has a typical unit of \([\text{ps}/(\text{nm–km})]\)

---

**Material Dispersion**

- All excitation sources are inherently non-monochromatic and emit within a spectrum, \(\Delta\lambda\), of wavelengths.
- Waves in the guide with different free space wavelengths travel at different group velocities due to the wavelength dependence of \(n_1\).
- The waves arrive at the end of the fiber at different times and hence result in a broadened output pulse.
Material Dispersion

- The refractive index of the material varies as a function of wavelength, \( n(\lambda) \)
- Material-induced dispersion for a plane wave propagation in homogeneous medium of refractive index \( n \):

\[
D_M = -\frac{2\pi}{\lambda^2} \frac{dn_2}{d\omega} = \frac{1}{c} \frac{dn_2}{d\lambda}
\]

The pulse spread due to material dispersion is therefore:

\[
\Delta T_g = L \Delta_{\lambda} |D_{mat}(\lambda)|
\]
Waveguide Dispersion

- Waveguide dispersion is due to the dependency of the group velocity of the fundamental mode as well as other modes on the ‘V’ number (Normalized Frequency).
- In order to calculate waveguide dispersion, we consider that \( n \) is independent of wavelength.
- Waveguide dispersion is given by:

\[
D_W = -\frac{2\pi \Delta}{\lambda^2} \left[ \frac{n_{2g}^2}{n_2} \frac{V d^2(Vb)}{dV^2} + \frac{dn_{2g}}{d\omega} \frac{d(Vb)}{dV} \right]
\]

where, group delay is expressed in terms of the normalized propagation constant, ‘\( b \)’, also called waveguide parameter.

Total Dispersion, Zero Dispersion

Minimum loss here
Dispersion Shifted Fiber Profiles

Polarization Mode Dispersion

- Effect of fiber birefringence on polarization (electric field orientation) states of an optical signal
- Due to geometric irregularities, internal stresses, deviations in circularity, external factors like bending, twisting & pinching
- Resulting difference in propagation times between the two orthogonal modes causes pulse spreading, hence leading to PMD
- PMD varies randomly along the fiber, ps/√km
Suppose that the core refractive index has different values along two orthogonal directions corresponding to electric field oscillation direction (polarizations). We can take $x$ and $y$ axes along these directions. An input light will travel along the fiber with $E_x$ and $E_y$ polarizations having different group velocities and hence arrive at the output at different times.
Polarization Mode Dispersion

- **Polarization mode dispersion** (PMD) is due to slightly different velocity for each polarization mode because of the lack of perfectly symmetric & anisotropicity of the fiber.
- If the group velocities of two orthogonal polarization modes are $v_{gx}$ and $v_{gy}$, then the differential time delay $\Delta T_{pol}$ between these two polarization over a distance $L$ is

$$\Delta T_{pol} = \left| \frac{L}{v_{gx}} - \frac{L}{v_{gy}} \right|$$

- The rms value of the differential group delay can be approximated as: $$\langle \Delta T_{pol} \rangle \approx D_{PMD} \sqrt{L}$$

Losses in Optical Fibers

Coaxial cable Vs. Optical Fiber Attenuation

![Graph showing attenuation vs frequency for different cables and fiber types](attachment:image.png)
Attenuation (fiber loss)

- Power loss along a fiber:

\[ P(z) = P(0)e^{-\alpha_p z} \]

- The parameter \( \alpha_p \) is called fiber attenuation coefficient having the unit of for example \([1/\text{km}]\) or \([\text{nepers/km}]\).

- A more common unit is \([\text{dB/km}]\) that is defined by:

\[
\alpha[\text{dB/km}] = \frac{10}{l} \log \left( \frac{P(0)}{P(l)} \right) = 4.343 \alpha_p [1/\text{km}]
\]

Fiber loss in dB/km

\[ P(l)[\text{dBm}] = P(0)[\text{dBm}] - \alpha[\text{dB/km}] \times l[\text{km}] \]

\[ P = 10 \text{ mW} = 10 \log_{10} \left( \frac{10 \text{ mW}}{1 \text{ mW}} \right) = 10 \text{ dBm} \]

\[ P = 27 \text{ dBm} = 1 \text{ mW} \left( \frac{27}{10} \right) = 501 \text{ mW} \]
**Fiber loss**

- **Example**: 10mW of power is launched into an optical fiber that has an attenuation of $a=0.6$ dB/km. What is the received power after traveling a distance of 100 km?
  - Initial power is: $P_{in} = 10$ dBm
  - Received power is: $P_{out} = P_{in} - aL = 10$ dBm $- (0.6)(100)$
    $$= -50$$ dBm

- **Example**: 8mW of power is launched into an optical fiber that has an attenuation of $a=0.6$ dB/km. The received power needs to be $-22$ dBm. What is the maximum transmission distance?
  - Initial power is: $P_{in} = 10\log_{10}(8) = 9$ dBm
  - Received power is: $P_{out} = 1$ mW $10^{-2.2} = 6.3$ mW
  - $P_{out} - P_{in} = 9$ dBm $- (-22$ dBm$) = 31$ dB $= 0.6$ L
  - $L = 51.7$ km

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**Optical fiber attenuation vs. wavelength**

![Optical fiber attenuation vs. wavelength](chart.png)
Attenuation in Optical Fibers

Three causes of Losses

■ Absorption
■ Scattering
■ Radiative Losses

Absorption-I (Extrinsic)

■ Absorption is caused by three different mechanisms:
  1- (a) Impurities in fiber material: from transition metal [iron, chromium, cobalt and copper] ions (must be in order of 1~10 ppb)
     (b) OH ions with absorption peaks at wavelengths 1400 nm, 950 nm & 725nm (overtones of the fundamental absorption peak of water around 2700nm).

Reduction of residual OH contents to around 1 ppb, commercially available fibers have attenuation around 0.3 dB/km in 1550 nm window.

An effectively complete elimination of water molecule results in the Allwave fiber
Absorption-II

2- Intrinsic absorption (fundamental lower limit): electronic absorption band (UV region) & atomic bond vibration band (IR region) in basic SiO₂.

3- Radiation defects
2 Scattering losses

- Linear scattering losses: transfer of optical power from one mode (proportionally to the mode power) into some other mode
  - Rayleigh scattering
  - Mie scattering
- Nonlinear scattering losses: Disproportionate attenuation, usually at high optical power levels in long SM fibers
  - Stimulated Brillouin scattering
  - Stimulated Raman scattering

Linear Scattering

- Rayleigh scattering: - Refractive index variations over small distances compared with wavelength due to:
  - Microscopic variations in the material density
  - Defects during fiber manufacture
  - Compositional fluctuations due to oxides

\[ \alpha_R = c_R \frac{1}{\lambda^4} \ (dB/km) \]

where \( c_R \) is the Rayleigh scattering coefficient and is the range from 0.8 to 1.0 (dB/km)·(mm)^4
Mie scattering: ---- inhomogeneities comparable in size to the guided wavelength due to non perfect cylindrical structure: e.g
- Imperfections at core-cladding interface
- Diameter fluctuations
- Core-cladding refractive index differences along the fiber length
- Mie scattering is typically very small in optical fibers

Nonlinear Scattering
Insignificant unless the power is greater than 100 mW
- Stimulated Brillouin scattering: modulation of light through thermal molecular vibrations within the fiber: incident photon produces a phonon of acoustic frequency as well as a scattered photon
- Stimulated Raman scattering: high frequency optical phonon is generated instead of acoustic phonon

Phonon is a quantum of elastic wave in lattice structure
Absorption & Scattering Losses in Fibers

Radiative Losses (Bending Loss)

Macrobending Loss:
- Lightwave suffers severe loss due to radiation of the evanescent field in the cladding region. As the radius of the curvature decreases, the loss increases exponentially until it reaches a certain critical radius.
- For any radius a bit smaller than this point, the losses suddenly become extremely large.
- Higher order modes radiate away faster than lower order modes.
**Microbending Loss:**

- Microscopic bends of the fiber axis that can arise when the fibers are incorporated into cables.
- The power is dissipated through the microbended fiber, because of the repetitive coupling of energy between guided modes & the leaky or radiation modes in the fiber.

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### Losses in standard SM fiber

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>SMF28</th>
<th>62.5/125</th>
</tr>
</thead>
<tbody>
<tr>
<td>850 nm</td>
<td>1.8 dB/km</td>
<td>2.72 dB/km</td>
</tr>
<tr>
<td>1300 nm</td>
<td>0.35 dB/km</td>
<td>0.52 dB/km</td>
</tr>
<tr>
<td>1380 nm</td>
<td>0.50 dB/km</td>
<td>0.92 dB/km</td>
</tr>
<tr>
<td>1550 nm</td>
<td>0.19 dB/km</td>
<td>0.29 dB/km</td>
</tr>
</tbody>
</table>