Signal Attenuation & Distortion in Optical Fibers
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• What are the loss or signal attenuation mechanism in a fiber?

• Why & to what degree do optical signals get distorted as they propagate down a fiber?

• Signal attenuation (fiber loss) largely determines the maximum repeater less separation between optical transmitter & receiver.

• Signal distortion cause that optical pulses to broaden as they travel along a fiber, resulting in the limitation of information-carrying capacity of a fiber.
Attenuation

- Signal attenuation within optical fibers is usually expressed in the logarithmic unit of the decibel.
- The decibel, which is used for comparing two power levels, may be defined for a particular optical wavelength as the ratio of the output optical power $P_o$ from the fiber to the input optical power $P_i$. 

$\text{decibel} = 10 \log_{10} \left( \frac{P_o}{P_i} \right)$
Attenuation (fiber loss)

- Power loss along a fiber:

\[ P(l) = P(0)e^{-\alpha_p l} \text{ mw} \]

- The parameter \( \alpha_p \) is called fiber attenuation coefficient in units of for example \([1/\text{km}]\) or \([\text{nepers/km}]\). A more common unit is \([\text{dB/km}]\) that is defined by:

\[ \alpha[\text{dB/km}] = \frac{10}{l} \log \left[ \frac{P(0)}{P(l)} \right] \]
The signal on the optical fiber attenuates due to following mechanisms:

1. **Material absorption in the fiber.**
   - **Intrinsic absorption**
     - Infrared
   - **Extrinsic absorption**
     - UV
   - Absorption due to atomic defects
     - Impurities
     - OH molecules

2. **Scattering due to micro irregularities inside the fiber.**
   - Rayleigh and Mie

3. **Bending or radiation losses on the fiber.**
   - Macrobending and microbending

The first two losses are intrinsically present in any fiber and the last loss depend on the environment in which the fiber is laid.
Intrinsic absorption

- Intrinsic absorption is associated with basic fiber material (e.g. pure SiO2)
- Intrinsic absorption set fundamental lower limit on absorption for any particular material
- **Results from**
  - *Electronic absorption band in UV region*
  - *Atomic vibration bands in near IR region*
(1) a fundamental UV absorption

- This is due to the electron transitions within the glass molecules. The tail of this peak may extend into the shorter wavelengths of the fiber transmission spectral window.

- Absorption occurs when a photon interacts with electron in valence band and excites it to a higher energy level.

(2) A fundamental infrared and far-infrared absorption

- due to molecular vibrations (such as Si-O).

- An interaction between the vibrating bond and the electromagnetic field of the optical signal results in transfer of energy from the field to the bond, giving rise to absorption.
Fundamental fiber attenuation characteristics
Extrinsic Absorption

- Impurity absorption results from presence of minute quantities of impurities in the fiber material.
- These impurities include OH (water) ions that are dissolved in the glass and transition metal ions such as iron, chromium, cobalt, copper.
- Transition metal impurities present in the starting material used for direct melt fiber range from 1 and 10 ppb causes loss from 1 to 10 dB/km.
- Water impurity concentrations of less than few parts per billion are required if attenuation is to be less than 20 dB/km.
- Early optical fibers had high levels of OH ions which resulted in large absorption peaks occurring at 1400, 950 and 725 nm.
Major extrinsic loss mechanism is caused by absorption due to water (as the hydroxyl or OH- ions) introduced in the glass fiber during fiber pulling by means of oxyhydrogen flame.

These OH- ions are bonded into the glass structure and have absorption peaks (due to molecular vibrations) at 1.38 μm.

Since these OH- absorption peaks are sharply peaked, narrow spectral windows exist around 1.3 μm and 1.55 μm which are essentially unaffected by OH- absorption.

The lowest attenuation for typical silica-based fibers occur at wavelength 1.55 μm at about 0.2 dB/km, approaching the minimum possible attenuation at this wavelength.
• Peaks and valleys in the attenuation curve resulted in “transmission windows” to optical fibers.
Three major spectral windows where fiber attenuation is low

The 1\textsuperscript{st} window: 850 nm, attenuation 2 dB/km
The 2\textsuperscript{nd} window: 1300 nm, attenuation 0.5 dB/km
The 3\textsuperscript{rd} window: 1550 nm, attenuation 0.3 dB/km

1550 nm window is today’s standard long-haul communication wavelengths.
Absorption due to material defects

• Atomic defects are imperfections in atomic structure of fiber material.

• Examples
  – Missing molecules
  – High density clusters of atom groups
  – Oxygen defects in the glass structure

• Atomic defects are small compared to instincts and extrinsic absorption unless fiber is exposed to ionizing radiation as nuclear reactor environment
Scattering Loss

• Scattering results in attenuation (*in the form of radiation*) as the scattered light may not continue to satisfy the total internal reflection in the fiber core.

• Scattering loss in glass arise from microscopic variations in material density, compositional fluctuations, and from structural in homogeneities or defect occurring during fiber manufacture.
Scattering Loss

• This gives rise to refractive index variations which occur within the glass over distances that are small compared with wavelength.

• Index variations cause Rayleigh type scattering of light.
• The scattered ray can escape by refraction according to Snell’s Law.

• Rayleigh scattering results from random inhomogeneities that are small in size compared with the wavelength.

\[ \phi \ll \lambda \]

• These inhomogeneities exist in the form of refractive index fluctuations which are frozen into the amorphous glass fiber upon fiber pulling. Such fluctuations always exist and cannot be avoided!

• Rayleigh scattering loss is inversely proportional to quadratic wavelength
Bending Losses

- Radiative losses occur when fiber undergoes a bend of finite radius of curvature.

- Two types of bends:
  - *Macroscopic*
  - *Microscopic*
• **Macrobending losses**
  
  – As radius of curvature decreases, loss increases exponentially until at certain critical radius the loss becomes observable
• Another radiation loss is caused by random **microbends of optical fiber**.

• Microbends are repetitive small scale fluctuations in radius of curvature of fiber axis. They are caused by
  
  – Non uniformities in manufacturing
  – Non uniform lateral pressure during cabling (this is referred to as cabling or packaging losses)
Microbends

Power loss from higher-order modes

Power coupling to higher-order modes

External force

Fiber

Compressible jacket
Signal Distortion
Pulse broadening limits fiber bandwidth (data rate)

An increasing number of errors may be encountered on the digital optical channel as the ISI becomes more pronounced.
Fiber Dispersion

• Fiber dispersion results in optical pulse broadening and hence digital signal degradation.

• Dispersion mechanisms:

1. Modal (or intermodal) dispersion

2. Intermodal Dispersion or Chromatic dispersion (CD)

3. Polarization mode dispersion (PMD)
• **Intramodal or chromatic dispersion:**
  - Material dispersion (the refractive indices of the core and the cladding change with wavelength)
  - Waveguide dispersion

• **Intermodal dispersion:** describes the pulse broadening due to the propagation delay differences between the propagation modes in multimode fibers.

• **Polarization-mode dispersion:** results from the fact that light signal energy at a given wavelength in single mode fiber actually occupies two orthogonal polarization mode or states.
Chromatic dispersion

- Chromatic dispersion (CD) may occur in all types of optical fiber. The optical pulse broadening results from the finite spectral line width of the optical source and the modulated carrier.

*In the case of the semiconductor laser, $\Delta \lambda$ corresponds to only a fraction of % of the center wavelength $\lambda_0$. For LEDs, $\Delta \lambda$ is likely to be a significant percentage of $\lambda_0$. 
Spectral Line width

- **Real sources emit over a range of wavelengths.** This range is the *source line width* or *spectral width*.

- The smaller is the line width, the smaller is the spread in wavelengths or frequencies, the more **coherent** is the source.

- An *ideal* perfectly coherent source emits light at a *single* wavelength. It has **zero** line width and is **perfectly** monochromatic.

<table>
<thead>
<tr>
<th>Light sources</th>
<th>Linewidth (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light-emitting diodes</td>
<td>20 nm – 100 nm</td>
</tr>
<tr>
<td>Semiconductor laser diodes</td>
<td>1 nm – 5 nm</td>
</tr>
<tr>
<td>Nd:YAG solid-state lasers</td>
<td>0.1 nm</td>
</tr>
<tr>
<td>HeNe gas lasers</td>
<td>0.002 nm</td>
</tr>
</tbody>
</table>
- Pulse broadening occurs because there may be *propagation delay differences among the spectral components of the transmitted signal*.

- **Chromatic dispersion (CD):** Different spectral components of a *pulse* travel at different *group velocities*. *This is known as group velocity dispersion (GVD).*
• **Waveguide dispersion:** causes the pulse spreading because only part of the optical power propagation is confined to the core.

• Dispersion arises because only fraction of light power propagating in the cladding travels faster than the light confined to the core, since the index is lower in the cladding.

• Usually can be ignored in multimode fibers, but its effect is significant in single mode fibers.
• **Polarization-mode Dispersion**

• At the start of the fiber the two polarization states are aligned.

• Since fiber material is not perfect uniform throughout its length, each polarization mode will encounter a slightly different refractive index, each mode will travel at a slightly different velocity.

• The resulting difference in propagation times between the two orthogonal polarization modes will cause the pulse spreading.
BL = 20 MHz.km

BL = 1 GHz.km

BL = 100 GHz.km
Intermodal Dispersion

Modal dispersion results in pulse broadening

Optical pulse

multimode fiber

fastest mode

slowest mode

modal dispersion: different modes arrive at the receiver with different delays => pulse broadening
Estimated modal dispersion pulse broadening using phase velocity

- A zero-order mode traveling near the waveguide axis needs time:
  \[ t_0 = \frac{L}{v_{m=0}} \approx \frac{L n_1}{c} \quad (v_{m=0} \approx \frac{c}{n_1}) \]

- The highest-order mode traveling near the critical angle needs time:
  \[ t_m = \frac{L}{v_m} \approx \frac{L n_2}{c} \quad (v_m \approx \frac{c}{n_2}) \]

\[ \Rightarrow \text{the pulse broadening due to modal dispersion:} \]
\[ \Delta T \approx t_0 - t_m \approx (L/c) (n_1 - n_2) \]
\[ \approx (L/2cn_1) \ NA^2 \quad (n_1 \sim n_2) \]
Bit-rate distance product

• We can relate the pulse broadening $\Delta T$ to the information-carrying capacity of the fiber measured through the bit rate $B$.

• Although a precise relation between $B$ and $\Delta T$ depends on many details, such as the pulse shape, it is intuitively clear that $\Delta T$ should be less than the allocated bit time slot given by $1/B$.

$\Rightarrow$ An order-of-magnitude estimate of the supported bit rate is obtained from the condition $B\Delta T < 1$.

$\Rightarrow$ Bit-rate distance product (limited by modal dispersion)

$$BL < 2c n_{core} / NA^2$$

This condition provides a rough estimate of a fundamental limitation of step-index multimode fibers.

(the smaller is the $NA$, the larger is the bit-rate distance product)
Because the energy of a harmonic wave is proportional to the square of its field amplitude, the energy carried by a wave packet that is composed of many frequency components is concentrated in regions where the amplitude of the envelope is large.

Therefore, the energy in a wave packet is transported at group velocity \( v_g \).

The constant-phase wavefront travels at the phase velocity, but the group velocity is the velocity at which energy (and information) travels.

Any information signal is a wave packet, and thus travels at the group velocity, not at the phase velocity.
Due to the dispersion, there is pulse broadening

- B is the bit rate and T the bit duration.
- To get an order of magnitude of the dispersion effect, one uses the following criteria: the pulse broadening $\delta T$ must be less than the pulse width $T$.

\[ \delta T < T = \frac{1}{B} \]

$BL < a certain value$
The chromatic dispersion parameter \( D \) is fundamental for single mode fibres

\[
D = \frac{d\tau_g}{d\lambda} = -\frac{\lambda}{c} \frac{d^2 n_{\text{eff}}}{d\lambda^2}
\]

If \( \Delta\omega \) is the spectral width of the source, the broadening \( \Delta T \) can be written as

\[
\Delta T = \frac{dT}{d\omega} \Delta\omega = L \frac{d\tau_g}{d\omega} \Delta\omega = L \beta_2 \Delta\omega
\]

with

\[
\beta_2 = \frac{d^2\beta}{d\omega^2}
\]

If \( \Delta T_0 \) is the initial pulse duration, the non-deformation condition is:

\[
DL\Delta\lambda \ll \Delta T_0
\]
The intramodal dispersion is composed by two main contributions:

\[ D = \frac{d\tau_g}{d\lambda} = -\frac{\lambda}{c} \frac{d^2 n_{\text{eff}}}{d\lambda^2} \]

\[ b = \frac{a^2 w^2}{V^2} = \frac{(\beta/k)^2 - n_2^2}{n_1^2 - n_2^2} \simeq \frac{n_{\text{eff}} - n_2}{n_2 \Delta} \]

→ If \( \Delta \) is independent on \( \lambda \)

\[ D = -\frac{\lambda}{c} \frac{d^2 n}{d\lambda^2} - \frac{\Delta n}{c\lambda} V \frac{d^2 V}{dV^2} \]

- The **first term** only depends on the material \((n)\) and is therefore the dispersion of silica \( \Rightarrow \text{material dispersion } D_M \).
- The **second term** depends of the fibre structure \((b, \Delta n)\) and corresponds to the contribution of the waveguiding structure \( \Rightarrow \text{waveguide dispersion } D_W \).

→ If \( \Delta \) is not dependent on \( \lambda \) \( \Rightarrow \) additional term called the **profil dispersion** \( D_p \) (negligible in practice).

\[ D_p \propto \frac{d\Delta}{d\lambda} \]
The waveguide dispersion can be computed from the $b=f(V)$ curve

$b$ depends on the waveguiding structure and therefore depends on the refractive index profile ⇒ it can be modified.

The waveguide dispersion can be negative on a large spectral range and compensate the positive material dispersion for wavelength larger than $\lambda_{m0}$.

⇒ manufacture of fibre with different dispersion profile since waveguide dispersion can be modified.
The waveguide dispersion is negative and shifts the total dispersion towards higher wavelengths. The main effect of waveguide dispersion is to shift the zero dispersion wavelength by an amount of 30-40 nm to higher wavelengths.

Figure 3.15 The material dispersion parameter ($D_M$), the waveguide dispersion parameter ($D_W$) and the total dispersion parameter ($D_T$) as functions of wavelength for a conventional single-mode fiber.

from Senior, "Optical Fiber Communications", Prentice Hall, 1992
By adjusting the waveguide dispersion, it is possible to shift the dispersion curve from Senior, "Optical Fiber Communications", Prentice Hall, 1992

Decreasing the core diameter shifts the total chromatic dispersion curve to higher wavelength.

Figure 3.16 The total first order intramodal dispersion as a function of wavelength for single mode fibers with core diameters of 4, 5, and 6 μm. Reproduced with permission from W. A. Gambling, A. H. Hartog, and C. M. Kogdaile, The Radio and Electron. Eng., 51, p. 313, 1981.
By adjusting the waveguide dispersion, it is possible to realize dispersion shifted fibers from Senior, "Optical Fiber Communications", Prentice Hall, 1992.

- Since $D_W$ depends on the fibre parameters such as core diameter and index profile, it is possible to shift the zero dispersion wavelength to 1.55 $\mu$m $\Rightarrow$ Dispersion Shifted Fibres (DSF).
- It is also possible to tailor the waveguide contribution such that the total dispersion is relatively small over a wide wavelength range $\Rightarrow$ Dispersion Flattened Fibres.
A new type of fiber has recently been proposed: NZDSF fibres

- **Non Zero Dispersion Shifted Fibres** presents a shifted dispersion curve in the 1550 nm region but the dispersion at 1550 nm is non zero ($\approx 2$ ps).

- Useful in the frame of **WDM technology** (Wavelength division multiplexing) to avoid nonlinear phenomena.
Dispersion compensating fibres are used to increase the capacity of existing conventional fibre links

- By tailoring the index profile, the dispersion can be made very negative at 1.55 µm ⇒ Dispersion Compensating Fibres (DCF) for SMF.

- ⇒ One can compensate the dispersion at 1.55 µm on a standard single mode fibre by adding the correct length of DCF.

- **Ex: LYCOM Fibre**
  - Dispersion at 1550 nm : < -80 ps/km.nm
  - Dispersion slope at 1550 nm : < -0.15 ps/(km.nm²)
  - Attenuation at 1550 nm : < 0.6 dB/km
  - Cut-off wavelength : < 1300 nm
Two parameters \( \lambda_0 \) and \( S_0 \) are used to characterize the dispersion

- The **zero total dispersion wavelength** is denoted by \( \lambda_0 \):
  \[
  D(\lambda_0) = 0
  \]

- Another important dispersion parameter is the **slope of the dispersion curve** \( (S_0) \) and the zero dispersion wavelength:
  \[
  S_0 = S(\lambda_0)
  \]
  
  where \( S = \frac{dD}{d\lambda} \)

- It can be shown that the **chromatic dispersion** at an arbitrary wavelength can be estimated from \( \lambda_0 \) and \( S_0 \) using:
  \[
  D(\lambda) = \frac{\lambda S_0}{4} \left[ 1 - \left(\frac{\lambda_0}{\lambda}\right)^4 \right]
  \]
Dispersion shifted fibres allow to transmit at 1.55 µm

High dopant concentration
⇒ excess losses

\[ \text{Sensitivity to bending losses because cutoff around 0.9 µm} \]

Reduced bending losses due to the depressed cladding because cutoff around 1.1 µm

from Senior, "Optical Fiber Communications", Prentice Hall, 1992
Dispersion shifted fibres can be obtained by index profile tailoring

Use of multiple index designs

from Senior, "Optical Fiber Communications", Prentice Hall, 1992
Dispersion flattened fibers are a compromise for 1.3 and 1.55 µm

Figure 3.23 Dispersion flattened fiber refractive index profiles: (a) double clad fiber (W fiber); (b) triple clad fiber; (c) quadruple clad fiber.

from Senior, "Optical Fiber Communications", Prentice Hall, 1992
NZDSF Fibres have complex refractive index profiles

« Pedestal » type

« Trapeze + ring » type

from Meunier, « Physique et Technologie des Fibres Optiques »
Dispersion compensating fibres profiles

« W » type

« Triple cladding » type

from Meunier, « Physique et Technologie des Fibres Optiques »
Polarization Mode Dispersion limits the bit rate on high speed communication systems

In practice, fibres exhibits circular asymmetries (elliptical core, stress, impurities,...) $\Rightarrow$ degeneracy between $HE_{11}^x$ and $HE_{11}^y$ is removed (birefringence). $\beta_x \neq \beta_y$

Because the $\beta$ are different, the two modes propagates at different velocities $\Rightarrow$ their arrival time at the fibre output are also different.

$\Rightarrow$ broadening of the optical pulse.

The PMD is defined as :

$$\text{PMD}_{lin} = \tau_x - \tau_y = \frac{\partial(\beta_x - \beta_y)}{\partial \omega} = -\frac{\lambda^2}{2\pi c} \frac{\partial \Delta \beta}{\partial \lambda}$$

from Derickson, « Fiber-Optics Test and Measurement »
Graded index fibres reduce the intermodal dispersion by equalizing arrival times

- Modes close to the fibre axis have the smallest optical paths but see the largest refractive indices and propagate slower.
- Modes far from the fibre axis have the largest optical paths but see the smallest refractive indices and propagate faster.

from Senior, "Optical Fiber Communications", Prentice Hall, 1992
The optimum graded index profile is nearly parabolic.

Figure 3.13 The intermodal pulse broadening δT_g for graded index fibers having Δ = 1%, versus the characteristic refractive index profile α.

from Senior, "Optical Fiber Communications", Prentice Hall, 1992