



Al-Mustaqbal University / College of Engineering & Technology
Department of Medical Instrumentation Techniques Engineering

Class: 4th

Subject: Medical Laser Systems

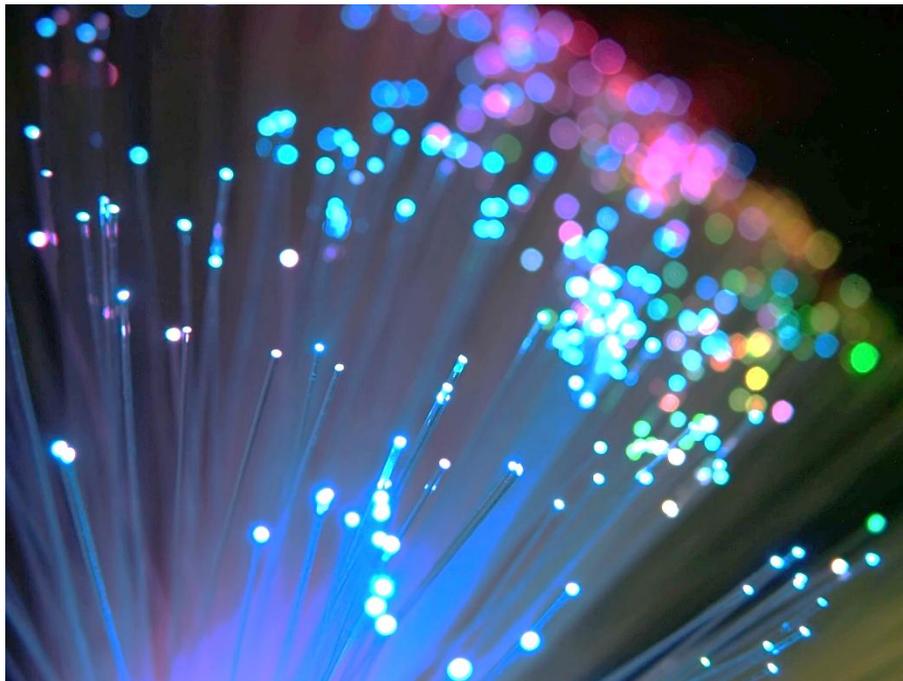
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2nd term – Lecture No. 9 & Lecture Name: Transmission Characteristics of Optical Fiber



Lecture 9

Transmission Characteristics of Optical Fiber



Lecturer:
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Transmission Characteristics of Optical Fiber Cables

The transmission characteristics of optical fiber cables play a crucial role in determining the overall performance and efficiency of optical fiber-based communication systems. These characteristics are essential for assessing the suitability of optical fibers for various applications. Among the different transmission parameters, **attenuation** and **bandwidth** are considered the most significant factors affecting system performance.

1- Attenuation in Optical Fibers:

Attenuation is one of the primary transmission characteristics of optical fibers and is defined as the gradual reduction of optical signal power as it propagates along the length of the fiber. Optical fibers with lower attenuation enable a higher proportion of the transmitted optical power to reach the receiver, resulting in improved signal quality and allowing for longer transmission distances compared to fibers with higher attenuation.

In optical fiber systems, attenuation is commonly expressed in terms of **decibels per unit length**, typically measured in **decibels per kilometer (dB/km)**. This standardized unit provides a convenient and consistent method for quantifying optical power loss along the fiber.

The optical power loss in decibels is calculated using the following relationship:

$$\text{Loss (dB)} = 10 \log_{10} \left(\frac{P_i}{P_o} \right)$$

where P_i represents the input (transmitted) optical power, and P_o represents the output (received) optical power.

Attenuation in optical fibers arises from several physical mechanisms. These include **material absorption**, where a portion of the optical energy is converted into heat



within the fiber material; **scattering losses**, particularly **Rayleigh scattering**, which result from microscopic variations in the fiber's refractive index; and **bending losses**, which occur when the fiber is subjected to excessive curvature. Bending losses are further classified into **macro bending** and **microlending** losses. Collectively, these mechanisms contribute to the overall reduction of optical signal power during transmission

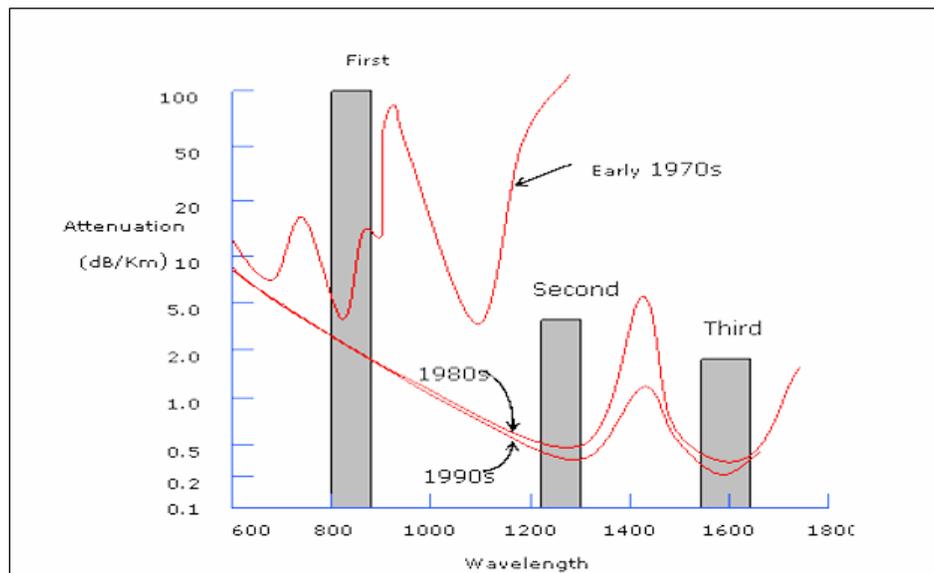


Figure 1: Attenuation to wavelength diagram of optical fiber.

The figure shows the variation of **optical fiber attenuation (dB/km)** with **wavelength**. Attenuation decreases as fiber technology improves from the early 1970s to the 1980s and 1990s.

Three main transmission windows are highlighted:

- **First window (~850 nm):** High attenuation, used in early systems.
- **Second window (~1310 nm):** Lower attenuation and low dispersion.



- **Third window (~1550 nm):** Lowest attenuation, used in modern long-distance optical communication.

The figure demonstrates the importance of wavelength selection and technological advances in reducing optical fiber losses.

2- Linear Scattering Losses

Linear scattering losses occur when a portion of the optical power traveling in one propagation mode is transferred to another mode. If this transferred power moves into a leaky or radiation mode, it escapes from the fiber, resulting in attenuation. Linear scattering losses are mainly classified into two types: **Mie scattering** and **Rayleigh scattering**.

2.1 Mie Scattering

Mie scattering is caused by imperfections in the optical fiber structure. These imperfections include deviations from a perfect cylindrical shape, irregularities at the core-cladding interface, diameter variations, mechanical strains, and the presence of air bubbles or defects within the fiber. Such non-uniformities scatter light and contribute to signal loss in the fiber.

2.2 Rayleigh Scattering

Rayleigh scattering is primarily caused by microscopic fluctuations in the refractive index of the fiber core. These fluctuations result from variations in material density and composition during the fiber manufacturing process. Rayleigh scattering is the dominant intrinsic loss mechanism, especially in the low-attenuation



wavelength region. Its effect can be significantly reduced by operating the fiber at longer wavelengths.

3- Nonlinear Scattering Losses

Nonlinear scattering losses occur mainly at high optical power levels, where the fiber exhibits nonlinear behavior. In this case, optical power is transferred from one mode to the same or other modes, either in the forward or backward direction, and often at different frequencies. This results in excessive and uneven attenuation. The two most important types of nonlinear scattering losses are:

- **Stimulated Brillouin Scattering (SBS)**
- **Stimulated Raman Scattering (SRS)**

4- Material Absorption Losses

Material absorption losses occur when optical energy is absorbed by the fiber material and converted into heat. These losses arise due to imperfections in the material composition or during the fiber fabrication process. Absorption losses are classified into two types: **intrinsic absorption** and **extrinsic absorption**. Intrinsic absorption is caused by the interaction of light with the basic components of the glass material itself. Extrinsic absorption, on the other hand, is due to impurities present in the fiber, such as transition metal ions or water molecules.

5- Dispersion

Dispersion is defined as the spreading of optical pulses as they propagate along the fiber. As pulses spread, they may overlap with adjacent pulses, making them



difficult to distinguish at the receiver. This leads to signal distortion in both digital and analog transmission systems. Dispersion limits the maximum achievable bandwidth of an optical fiber. In digital communication systems, pulse broadening caused by dispersion restricts the data rate; therefore, the bit rate must be lower than the inverse of the broadened pulse duration.

5.1 Intermodal Dispersion

Intermodal dispersion occurs in multimode fibers due to differences in propagation delay between various modes. Each mode travels at a different group velocity, causing pulse broadening at the output. Multimode step-index fibers suffer from significant intermodal dispersion, while single-mode fibers do not experience this type of dispersion. Intermodal dispersion can be greatly reduced by using graded-index fibers with an optimized refractive index profile, typically a parabolic profile.

5.2 Intramodal Dispersion

Intramodal dispersion occurs because optical sources emit light over a range of wavelengths rather than a single frequency. Different wavelength components travel at different speeds, leading to pulse spreading. This type of dispersion occurs in almost all optical fibers. When pulse broadening is caused by the wavelength-dependent properties of the fiber material, it is called **material dispersion**. When it results from the guiding characteristics of the fiber structure, it is known as **waveguide dispersion**. In multimode fibers, waveguide dispersion is almost negligible.



6- Fiber Bending Losses

Fiber bending losses occur when light escapes from the fiber due to bending along its length. When the fiber is bent, part of the guided light radiates out of the core and is lost. There are two main types of bending losses: **macro bending** and **microlending**.

Macro bending occurs when the fiber is bent sharply, preventing the light from following the curved path and causing it to leak out. Micro bending results from small, microscopic bends caused by mechanical stresses such as pressure, contraction, or manufacturing defects. These bends are usually not visible to the naked eye but still cause significant signal loss.

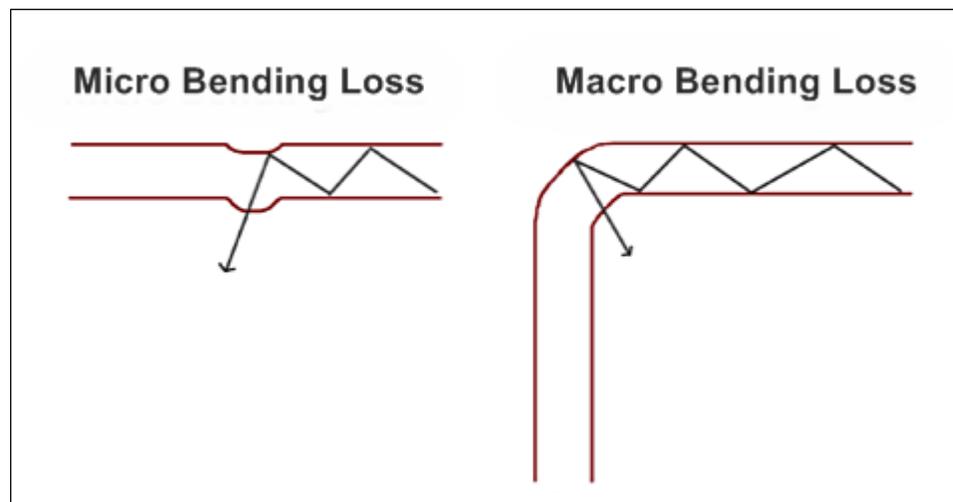


Figure 2: Fiber Bending loss.