Al-Mustaqbal University

Department (Biomedical Engineering)

Class (Third Stage)

Subject (Medical Optics)

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1st term – Lect. (Fundamental Optical Fibers1)

Losses Fiber Optics

A number of mechanisms are responsible for the signal attenuation within optical fibers. These mechanisms are influenced by the material composition, the preparation and purification technique, and the waveguide structure. They may be categorized within several major areas which include material absorption, material scattering (linear and nonlinear scattering), curve and microbending losses, mode coupling radiation losses and losses due to leaky modes.

1. Material Absorption

Material absorption is a loss mechanism related to the material composition and the fabrication process for the fiber, which results in the dissipation of some of the transmitted optical power as heat in the waveguide. The absorption of the light may be intrinsic or extrinsic.

a. Intrinsic absorption Intrinsic absorption caused by the interaction with one or more of the major components of the glass. An absolutely pure silicate glass has little intrinsic absorption due to its basic material structure in the near-infrared region. However, it does have two major intrinsic absorption mechanisms at optical wavelengths which leave a low intrinsic absorption window over the 0.8 to 1.7 μm wavelength range.

b. Extrinsic absorption Extrinsic absorption is caused by impurities within the glass such as iron, nickel, and chromium during the fabrication of the fiber. These metals impurities amounts should be reduced below 1 part per billion to obtain loss level < 1 dB/km. The main source for extrinsic absorption in silica fibers is the presence of water vapors. Water in silica glass forms a silicon-hydroxyl (Si-OH) bond which has a fundamental absorption at 2.7 μm.

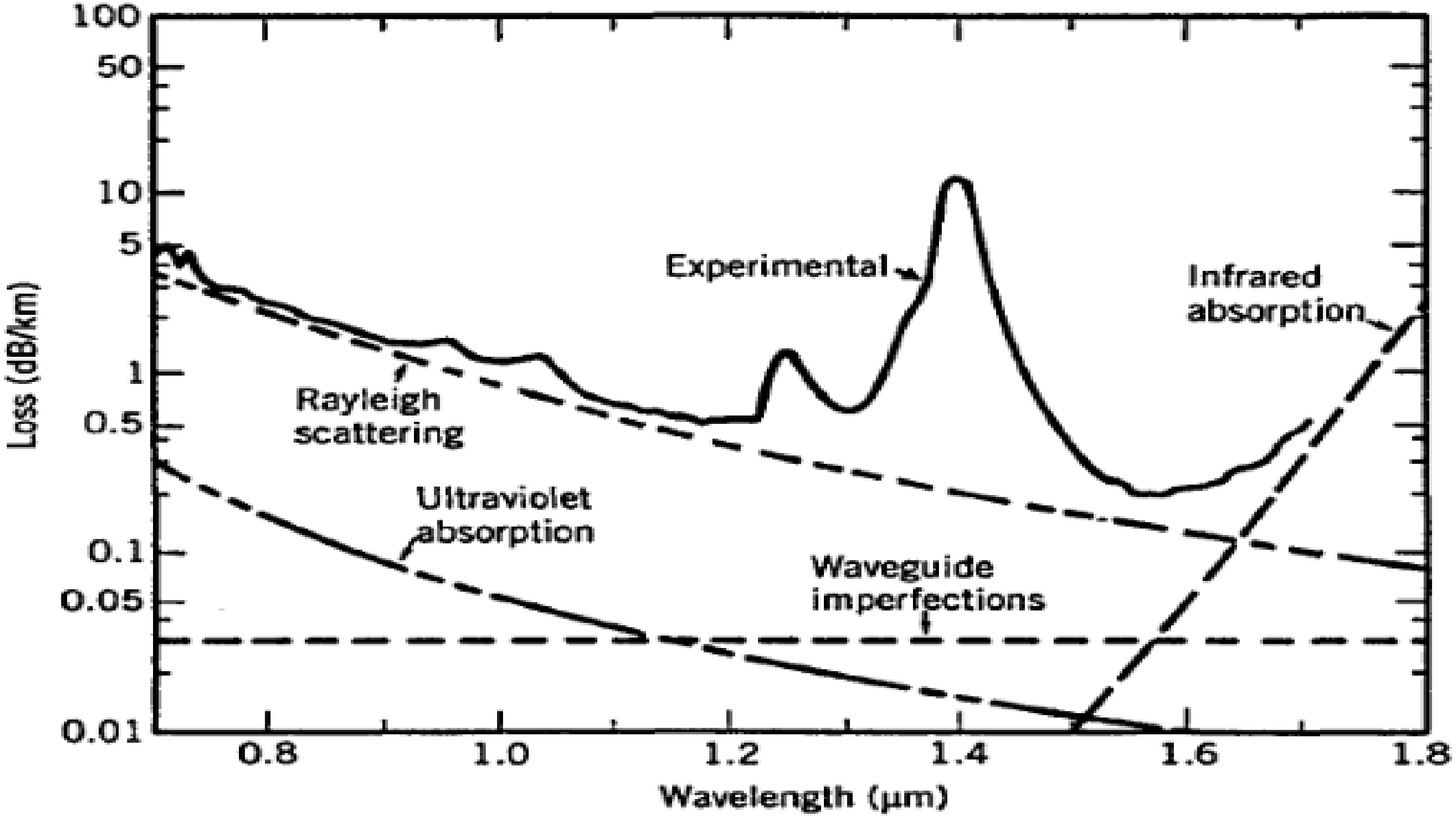


Figure 2.14: Loss spectrum of a single-mode fiber produced in 1979. Wavelength dependence of several fundamental loss mechanisms is also shown. (After Ref. [11]; ©1979 IEE; reprinted with permission.)

2. Scattering

- **Linear Scattering**

Linear scattering mechanisms cause the transfer of some or all of the optical power contained within one propagating mode to be transferred linearly (proportionally to the mode power) into a different mode. This process tends to result in attenuation of the transmitted light as the transfer may be to a leaky or radiation mode which does not continue to propagate within the fiber core, but is radiated from the fiber. It must be noted that as with all linear processes, there is no change of frequency on scattering. Linear scattering may be categorized into two major types: Rayleigh and Mie scattering.

a. Rayleigh Scattering

- It results from inhomogeneities of a random nature occurring on a small scale compared with the wavelength of the light. These inhomogeneities manifest themselves as refractive index fluctuations and arise from density and compositional variations which are frozen into the glass lattice on cooling. The compositional variations may be reduced by improved fabrication, but the index fluctuations caused by the freezing-in of density inhomogeneities are fundamental and cannot be avoided. The subsequent scattering due to the density fluctuations which is in almost all directions, produces an attenuation α_R;

$$\alpha_R = \frac{A_r}{\lambda^4} \qquad dB/Km$$

- The Rayleigh scattering coefficient A_r is is a constant for a given material depending on the constituents of the fiber core in the range 0.7- 0.9 (dB/km).μm^4.
- α_R between 0.12 – 0.16 dB/km at wavelength 1.55μm

The Rayleigh scattering coefficient A_r depends:

-The fiber refractive index profile

-The doping used to achieve a given core refractive index

The Rayleigh scattering coefficient is related to the transmission loss factor (transmissivity) of the fiber τ;

$$\tau = \exp(\alpha_R L)$$

where L is the length of the fiber.

The Rayleigh scattering is strongly reduced by operating at longer wavelength since the losses caused by Rayleigh scattering is inversely proportional to fourth power of the wavelength ($1/\lambda^4$).

b. Mie Scattering

Occur at inhomogeneities which are comparable in size with the guided wavelength. These result from the nonperfect cylindrical structure of the waveguide and may be caused by fiber imperfections such as irregularities in the core–cladding interface, core–cladding refractive index differences along the fiber length, diameter fluctuations, strains and bubbles. When the scattering inhomogeneity size is greater than $\lambda/10$, the scattered intensity which has an angular dependence can be very large. Depending upon the fiber material, design and manufacture, Mie scattering can cause significant losses. The inhomogeneities may be reduced by:

(a) removing imperfections due to the glass manufacturing process

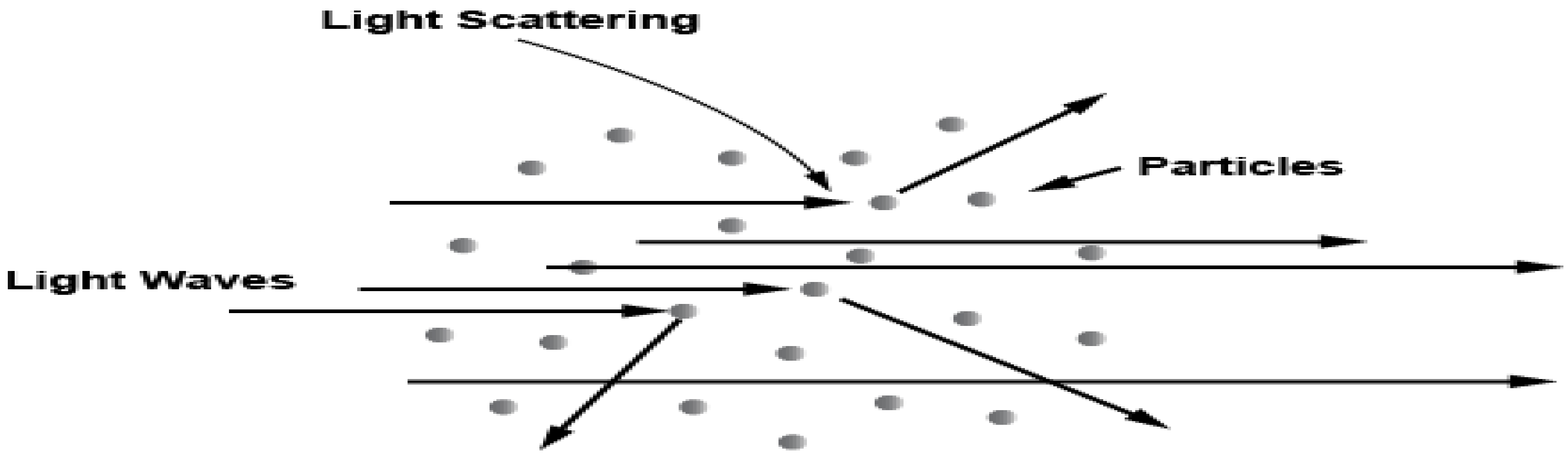
(b) carefully controlled extrusion and coating of the fiber

(c) increasing the fiber guidance by increasing the relative refractive index difference.

- **Nonlinear Scattering in Optical Waveguides**
- Optical waveguides, such as optical fibers, are not always purely linear systems. In a linear system, the output optical power increases proportionally with the input optical power. However, at **high optical power levels**, nonlinear effects begin to dominate, leading to phenomena such as **nonlinear scattering**.
- **Key Features of Nonlinear Scattering:**

1. **Disproportionate Attenuation**:
   1. Nonlinear scattering causes losses that are not proportional to the input power. This means the higher the optical power, the more significant the scattering becomes.
2. this threshold, the fiber operates primarily in a linear regime.

2. **Energy Redistribution**:
   - The optical power in one mode can be redistributed to other modes (forward or backward) or even within the same mode but at a **different frequency**.
   - This energy transfer depends heavily on the **optical power density** within the fiber.
3. **Threshold Power Levels**:
   - Nonlinear scattering effects only become prominent when the **power density** exceeds certain **threshold levels**. Below this threshold, the fiber operates primarily in a linear regime.

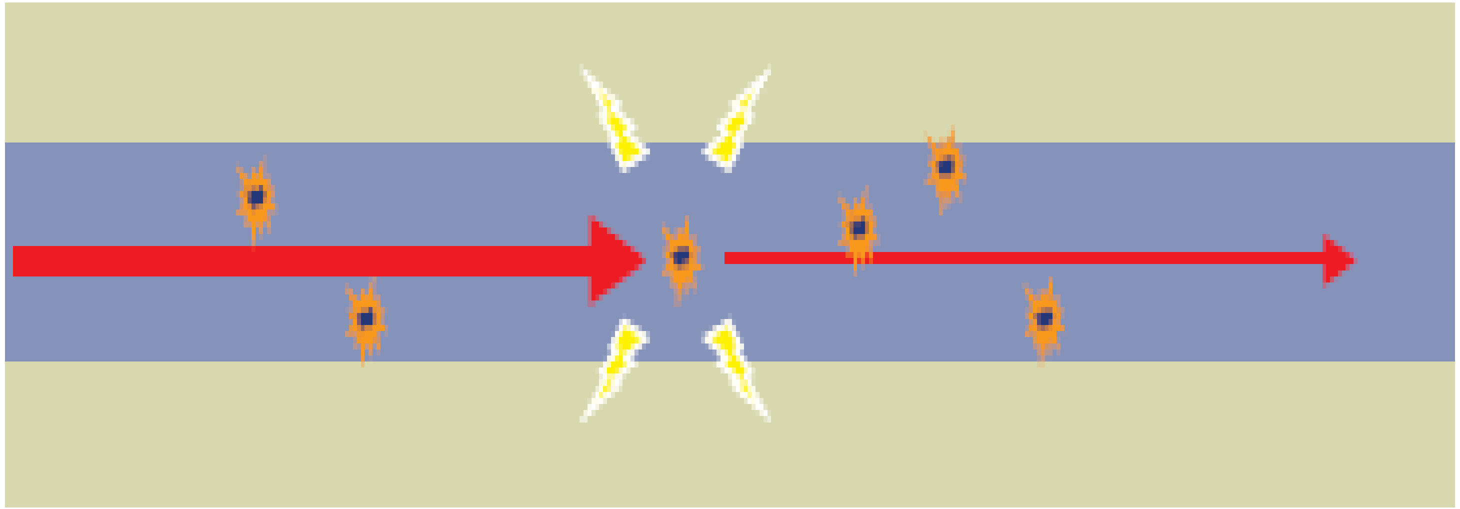


Types of Nonlinear Scattering:

- The two most important types of nonlinear scattering in optical fibers are:

1. **Stimulated Brillouin Scattering (SBS)**:
    - Occurs when incident light interacts with acoustic vibrations (phonons) in the fiber material.
    - SBS generates a **backward-scattered light** at a slightly lower frequency (shifted due to interaction with phonons).
    - Significant in long fibers with narrow linewidth lasers.
2. **Stimulated Raman Scattering (SRS)**:
    - Involves interaction between incident light and molecular vibrations (optical phonons) in the fiber.
    - SRS generates scattered light that can propagate in both forward and backward directions, with a frequency shift proportional to the molecular vibration energy.
    - More power is required to observe SRS compared to SBS.

Absorption



Scattering