Fiber Optics Communications

Week 3 Optical Signal Loss in Optical Fiber

Lecturer: Zelalem Hailu (Assistant Prof.)

Addis Ababa Science and Technology University
Addis Ababa, Ethiopia

Topics of Previous Lecture

- Theories of Light
- Theories of Optics
- Polarization of Light
- Wave Fronts
- Light Intensity and Power Flow
- Optical Fiber structure and Light Propagation
- Optical modes in optical fiber

Lecture Learning Outcomes

1. Define the fiber attenuation coefficient
2. Interpret attenuation values and their impact on signal transmissions.
3. Identify the major sources of signal loss in optical fibers.
4. Differentiate optical windows and transmission bands used in fiber optic systems.
5. Describe the physical mechanisms behind absorption loss
6. Explain Rayleigh and Mie scattering and their role in fiber loss
7. Differentiate and explain macro-bending and micro-bending losses.

Optical Signal Loss in Optical Fiber

Outline

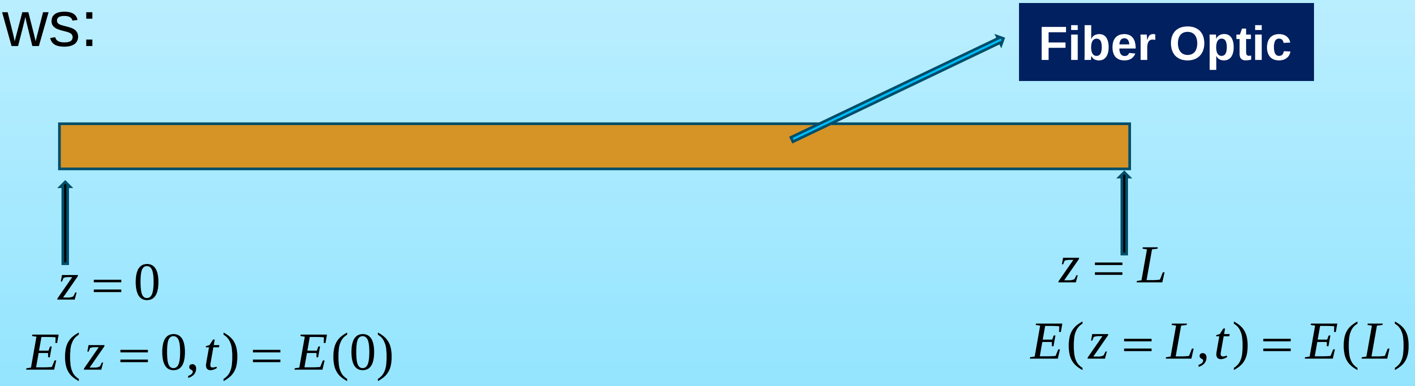
- Introduction to Optical Fiber Loss
- Fiber Attenuation Coefficient
- Origins of Fiber Optics Loss
- Absorption Loss
- Scattering Loss
- Fiber Bending Loss

Introduction to Optical Fiber Loss

- Optical signals encounters various types of Optical power losses while propagating in the optical wave guide
- Optical Fiber introduces an **attenuation** of a light signal optical power as it propagates along a fiber
- Attenuation is a critical design parameter in optical Fiber communication system design
- The maximum transmission distance between a transmitter and a receiver is mainly determining by an attenuation of the fiber
- It also largely determines the maximum unamplified or repeaterless separation between a transmitter and a receiver.

Attenuation Coefficient

- The attenuation Coefficient of optical fiber is related to the complex propagation constant of the fiber.
- Assuming a light wave propagating along the fiber axis in z direction as follows:



$z = 0$

$E(z = 0, t) = E(0)$

$z = L$

$E(z = L, t) = E(L)$

- The electric field at a given point z is given by:

$$E(z,t) = E_0 e^{j(\omega t - k'z)} \qquad \textbf{(1)}$$

Attenuation Coefficient

- The complex propagation constant k' can be written in terms of the real and imaginary part as:

$$k' = \beta - j\alpha \qquad \textbf{(2)}$$

- Substituting eq(2) in eq(1) for k' ,We will have:

$$E(z,t) = E_0 e^{j(\omega t - z(\beta - j\alpha))}$$

$$= E_0 e^{-\alpha z} e^{j(\omega t - \beta z)} = E_0 e^{-\alpha z} e^{-j\beta z} e^{j\omega t} \qquad \textbf{(3)}$$

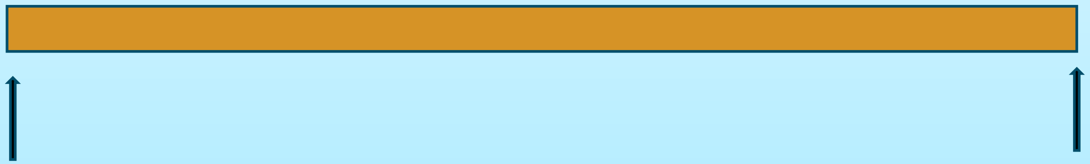
- From Eq(3), the term:

$e^{-\alpha z}$ Is related to the field amplitude exponential decay

$e^{-j\beta z}$ Is related to the phase change

Attenuation Coefficient

- Ignoring the time harmonic and the phase component since we are interested in the reduction of the field amplitude as it propagates along the fiber axis



$z = 0$

$E(z=0) = E(0) = E_0$

$z = L$

$E(z=L) = E(L) = E_0 e^{-\alpha L}$

- The optical power at z=0 and z=L can be calculated as:

at z = 0

$$P(0) = \frac{E(0)^2}{2\eta} = \frac{E_0^2}{2\eta} \qquad \textbf{(4)}$$

at z = L

$$P(L) = \frac{E(L)^2}{2\eta} = \frac{(E_0 e^{-\alpha L})^2}{2\eta} = \frac{E_0^2 e^{-2\alpha L}}{2\eta} \qquad \textbf{(5)}$$

Attenuation Coefficient

- Let $\alpha_p = 2\alpha$ and substituting in Eq(5), We have:

$$P(L) == \frac{E_0^2 e^{-\alpha_p L}}{2\eta}$$ **(6)**

- The optical power at z=0 and z=L becomes

$z = 0$

$$P(0) = \frac{E_0^2}{2\eta}$$

$z = L$

$$P(L) = \frac{E_0^2}{2\eta} e^{-\alpha_p L} = P(0)e^{-\alpha_p L}$$

- α_p is the fiber ***attenuation coefficient***

Attenuation Coefficient

- The optical power at any arbitrary point z along the optical fiber is :

$$P(z) = P(0)e^{-\alpha_p z} \qquad \textbf{(7)}$$

- α_p can be written in the form:

$$\alpha_p = \frac{1}{z}\ln\left[\frac{P(0)}{P(z)}\right] \qquad \textbf{(8)}$$

- Decibels per kilometer, denoted by dB/km commonly used to express the attenuation coefficient [1]
- The total optical power loss in linear scale, L_T, along the length of the propagation till point z is given by:

$$L_T = \frac{P(0)}{P(z)} \qquad \textbf{(9)}$$

Attenuation Coefficient

- In Logarithm scale or Decibels (dB), the total loss can be given by :

$$L_T(dB) = 10\log\left[\frac{P(0)}{P(z)}\right] \qquad \textbf{(10)}$$

- The attenuation coefficient in decibels per kilometer, $\alpha(dB/km)$, is given by:

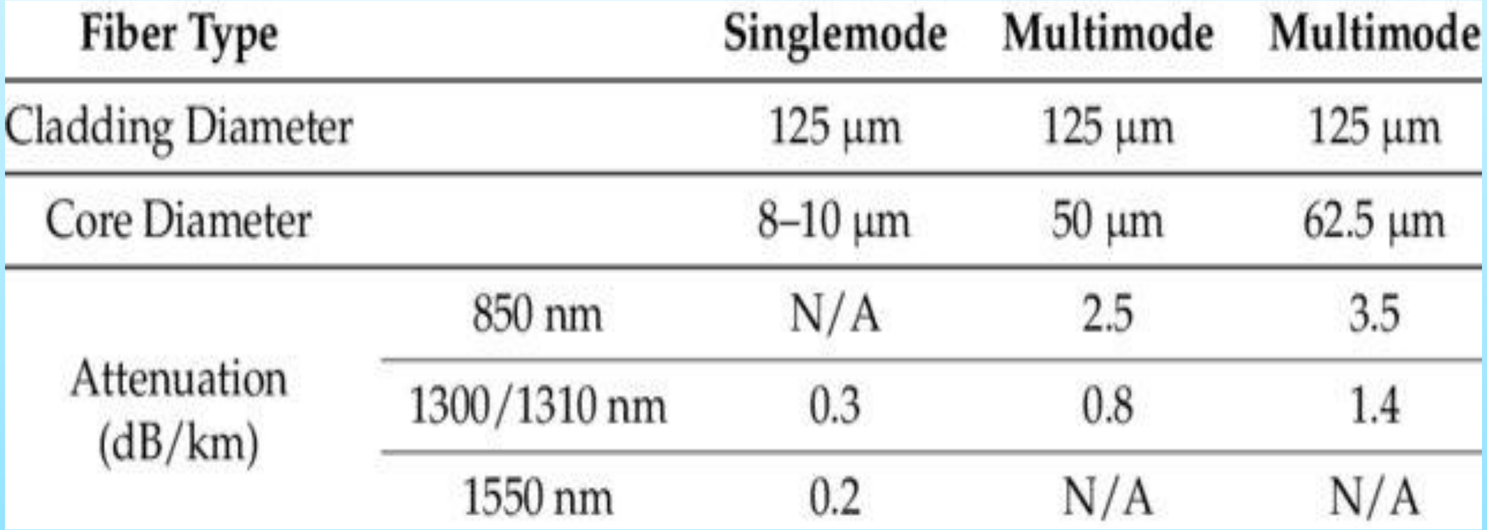
$$\alpha(dB/km) = \frac{10}{z}\log\left[\frac{P(0)}{P(z)}\right] = 4.343\alpha_p(km^{-1}) \qquad \textbf{(11)}$$

- The above term, $\alpha(dB/km)$, is generally referred to as the ***fiber loss*** or

  the ***fiber attenuation***

Fiber Loss at Different Wavelength

- The loss of conventional Sigle and multi-mode glass fibers at different wavelength is shown below:



Fiber Type		Singlemode	Multimode	Multimode
Cladding Diameter		125 µm	125 µm	125 µm
Core Diameter		8–10 µm	50 µm	62.5 µm
Attenuation (dB/km)	850 nm	N/A	2.5	3.5
	1300/1310 nm	0.3	0.8	1.4
	1550 nm	0.2	N/A	N/A

Table 1: Glass fibers loss at different wavelength

Source: K. Miah and D. K. Potter, *“A Review of Hybrid Fiber-Optic Distributed Simultaneous Vibration and Temperature Sensing Technology and Its Geophysical Applications,”* Sensors, vol. 17, no. 11, Art. no. 2511, Nov. 2017. https://www.researchgate.net/publication/320784837/figure/tbl1/AS:668724528943112@1536447760928/Attenuation-loss-of-different-types-of-optical-fiber-Adapted-from-13_W640.jpg

Origins of Fiber Optics Loss or Attenuation

Sources of Fiber Loss/Attenuation

- Quantum Optics is more suitable to describe the Loss mechanisms in optical fiber
- optical field is viewed as a flux of particle-like quantized units of electromagnetic energy, or photons in Quantum optics theory
- Photons can be scattered and absorbed in optical fiber, thus reducing the total optical power transmitted.
- There different loss mechanisms in optical fiber:

Loss Mechanisms

- Light Absorption
- Light Scattering
- Bending of Optical Fiber

Light Absorption

- Light absorption is an optical phenomenon explained exclusively by Quantum Optics theory.
- **Photon absorption:** photons vanish, transferring their energy to atoms or electrons of the absorbing material.
- Absorption of optical power (Photon absorption) is caused by three different mechanisms:

Reasons of Light Absorption

- Absorption due to atomic defects in the glass composition
- Extrinsic absorption: due to impurity atoms in the glass material
- Intrinsic absorption: due to the basic constituent atoms of the fiber material

Atomic defects in the glass composition

- **Atomic defects:** Imperfections in the atomic structure of the fiber material

Example of Atomic Defects

- Missing molecules
- High-density clusters of atom groups
- Oxygen defects in the glass structure

- Absorption from these defects are negligible compared with intrinsic and Extrinsic absorption by impurity atoms in glass material

Extrinsic Absorption

- The dominant absorption factor in silica fibers comes from the presence of minute quantities of impurities in the fiber material (**Extrinsic absorption)**

Major Impurities

- OH (water) ions dissolved in the glass
- Transition metal ions (iron, copper, chromium, and vanadium).

- The presence of 1 part per million (ppm) transition metal ions in glass material will introduce 1-4dB/km loss in the fiber.
- Water impurity concentrations of less than a few parts per billion (ppm) are required to achieve low atteunation.

Extrinsic Absorption

Impurity	Loss due to 1 ppm of impurity (dB/km)	Absorption peak (nm)
Iron: Fe^{2+}	0.68	1100
Iron: Fe^{3+}	0.15	400
Copper: Cu^{2+}	1.1	850
Chromium: Cr^{2+}	1.6	625
Vanadium: V^{4+}	2.7	725
Water: OH^{-}	1.0	950
Water: OH^{-}	2.0	1240
Water: OH^{-}	4.0	1380

Table 2: Absorption loss in silica glass at different wavelengths due to 1 ppm of water-ions and various transition-metal Impurities [2]

Extrinsic Absorption

- The peaks and valleys in the attenuation curves resulted in the designation of the various transmission windows (1st, 2nd, and 3rd windows)
- Reducing the residual OH content of fibers to below 1 ppb in standard single mode fiber will make the attenuation:
    - Below 0.4dB/km at 1310 nm (O-band)
    - Below 0.25 dB/km at 1550 nm (C-band)
- Further elimination of water ions diminishes the absorption peak around 1440 nm and will create extra band called E-band
- Optical fibers that can be used in the E-band are known by names such as ***low-water-peak*** or ***full-spectrum fibers***.

Extrinsic Absorption

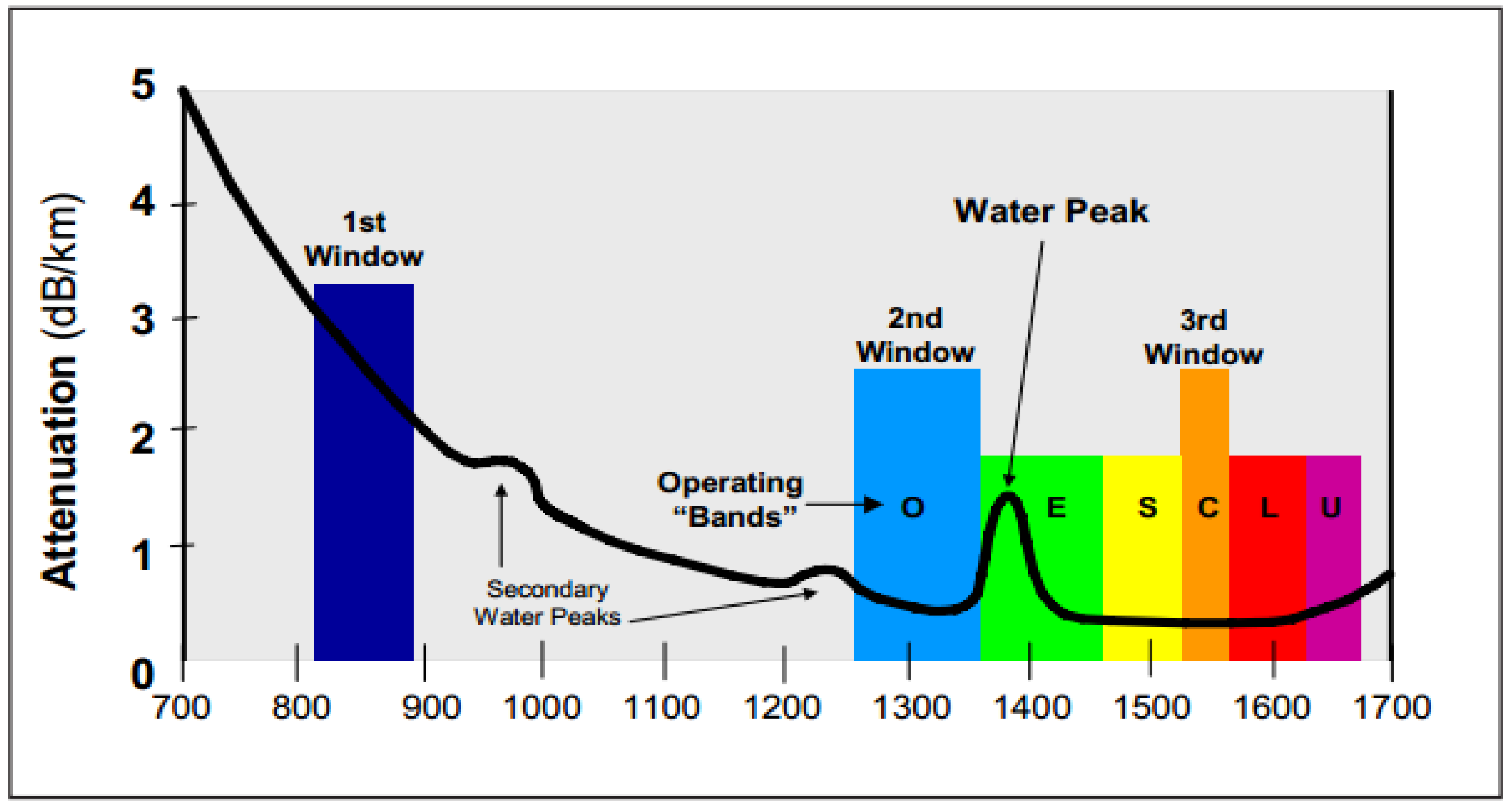


Figure 1: Water Peak loss at E-band

Source: *"Understand Fiber Attenuation,"* Fiber Optic Wiki, 2-Jun-2015. http://fowiki.com/wp-content/uploads/2015/06/fiber-attenuation.png

Low-Water-Peak or Full-Spectrum fiber

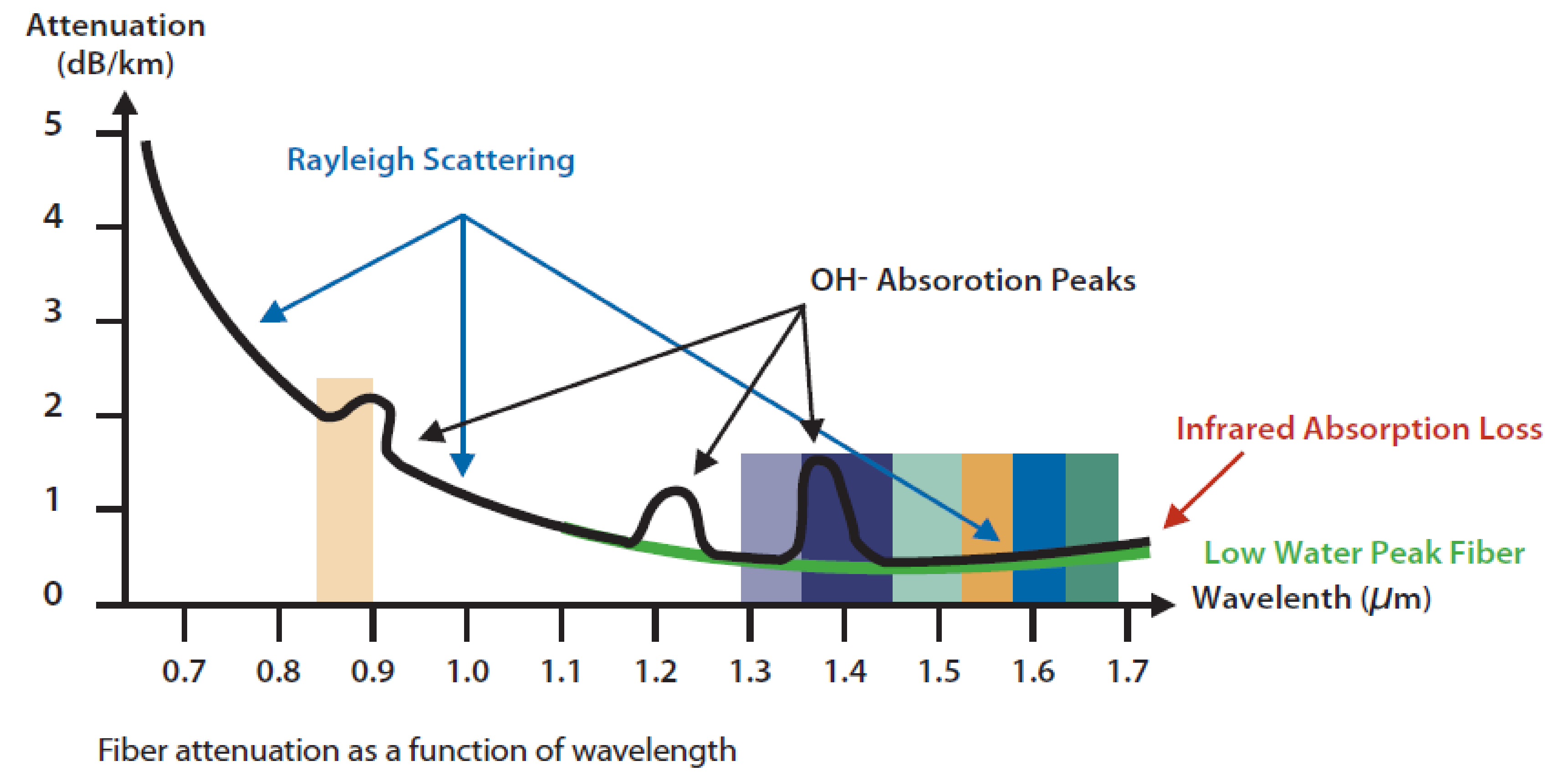


Figure 2: Low water peak fiber

Source: *"Fiber Attenuation,"* Fiber Optic Basics, 20-Jul-201. https://blogger.googleusercontent.com/img/b/R29vZ2xl/AVvXsEjLQ8TLMR7x9Umn5pYpIZTJlDM8yYikrJyytAOxKzbJTJfF1OtNEXM-qHgqOdZwOZldGBm4OonExQifhTlDedJsi89eH9m5S7Iyop-Zmr-z6fALWQJxWytx-isAGX3fadLRs1Tbd_SkHHw/s1600/spectral+attenuation.png

Intrinsic Absorption

- Intrinsic absorption is associated with the basic fiber material (e.g., pure SiO2)
- It is the major physical factor that defines the transparency window of a material over a specified spectral region
- It is also the fundamental lower limit on absorption for any particular material
- It determines the absorption that occurs when the material is in a perfect state
- Intrinsic absorption results from two major causes:
    - Electronic absorption bands in the ultraviolet
    - Atomic vibration bands in the near-infrared region

Intrinsic Absorption

Ultraviolet (UV) Absorption:

- Electronic absorption bands in UV region arise from the energy band gaps of amorphous glass materials
- This kind of Absorption happens when a photon excites a valence band electron to a higher energy level.
- The Ultraviolet (UV) edge of electron absorption bands in amorphous and crystalline materials follows an empirical relationship:

$$\alpha_{uv} = Ce^{E/E_0} \qquad \textbf{(12)}$$

Where: C and E_0 are empirical constants

E is photon energy

Intrinsic Absorption

Ultraviolet (UV) Absorption Cont.

- Since $E \propto \frac{1}{\lambda}$, UV absorption decreases exponentially as wavelength increases
- Ultraviolet loss (dB/km) at a given wavelength (µm) is empirically expressed as a function of GeO_2 mole fraction:

$$\alpha_{uv} = 10^{-2}\left(\frac{154.2x}{46.6x+60}\right)e^{\frac{4.63}{\lambda}} \qquad \textbf{(13)}$$

Where:

x The mole fraction of GeO_2

Intrinsic Absorption

Infrared (IR) Absorption:

- Intrinsic IR absorption arises from the vibrational frequencies of chemical bonds in the fiber material.
- Energy transfer from the optical field to the bond arises due to the interaction of Vibrating bond and the electromagnetic field of the optical signal
- IR absorption is strong due to the availability of many bonds in the fiber
- IR absorption for GeO_2–SiO_2 glass material in dB/km at a given wavelength λ (μm) is expressed by an empirical formula:

$$\alpha_{IR} = (7.81 \times 10^{11}) e^{\left(\frac{-48.48}{\lambda}\right)} \qquad \textbf{(14)}$$

Intrinsic Absorption

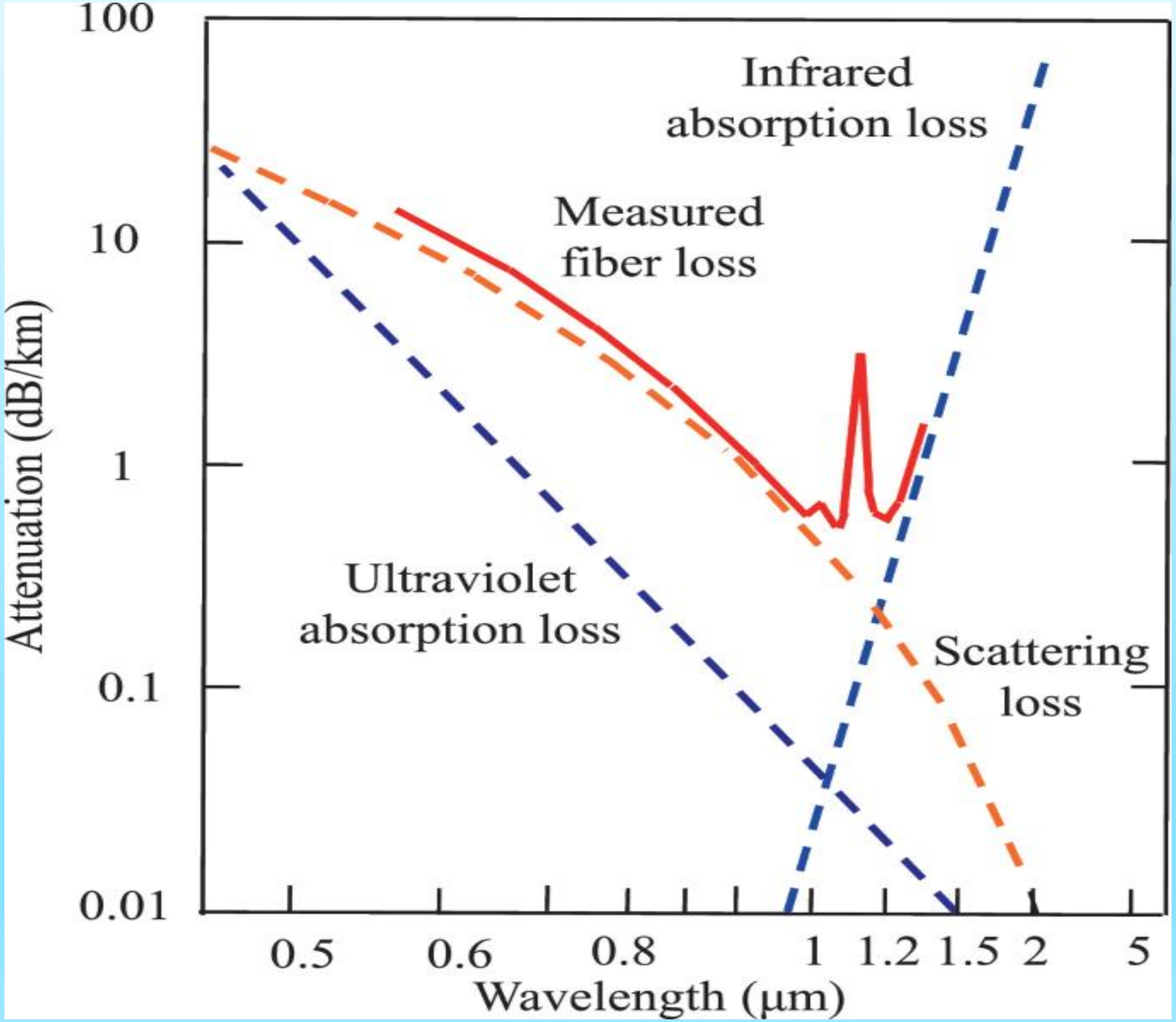


Figure 3: Intrinsic absorption and scattering loss

Source: G. Keiser, *“Optical Signal Attenuation and Dispersion,”* In Fiber Optic Communications, Springe, 2021. https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-981-33-4665-9_3/MediaObjects/495048_1_En_3_Fig3_HTML.png

Scattering Losses

- Scattering loss arises due to the microscopic inhomogeneities of the glass material.
- Those inhomogeneities or variations may come from:
  - Material density Variations
  - Compositional fluctuations
  - structural inhomogeneity or defects during manufacturing
- Two types of scattering may occur in Fiber Optics:
  - Rayleigh Scattering
  - Mie Scattering

Rayleigh Scattering

- Rayleigh Scattering arises due to Material density and Compositional fluctuations.
- Refractive index variation at microscopic level (over a dimension less than the wave length of light) arises due to Material density and Compositional Variations.
- The portion of light propagating through the optical fiber will be scattered due to the refractive index variation.
- Approximated scattering loss at a give wavelength λ due to **density variation** for **single component** glass is given by:

$$\alpha_{scat} = \frac{8\pi^3}{3\lambda^4}(n^2 - 1)^2 k_B T_f \beta_T \qquad \textbf{(15)}$$

Where:

n	Refractive index	β_T	Isothermal Compressibility
k_B	Boltzmann's constant		
T_f	The temperature at which the density fluctuations are frozen		

Rayleigh Scattering

- An alternative formula for Eq(15):

$$\alpha_{scat} = \frac{8\pi^3}{3\lambda^4} n^8 p^2 k_B T_f \beta_T \qquad \textbf{(16)}$$

Where:

n	Refractive index
k_B	Boltzmann's constant
β_T	Isothermal Compressibility
T_f	The temperature at which the density fluctuations are frozen
p	The photoelastic coefficient

Mie Scattering

- Mie scattering is caused by fiber structural inhomogeneity or imperfect structure during manufacturing such as:
  - Core-cladding interface irregularities
  - Irregularities in Core-cladding refractive index difference along the fiber length
  - Fiber diameter fluctuation
  - Fiber shape fluctuation
- Mie scattering arises when the above fluctuations are occurred in dimension comparable to the wavelength of the light

Fiber Bending Losses

- Bending loss is a losses caused by changes in the external or internal geometry of an optical fiber.
- Optical power losses occur when an optical fiber bends with a finite radius of curvature:
- In a bent fiber, outer-radius light cannot maintain its mode profile and excess energy escapes as **radiation loss**
- There are two types of bending loss based on the size of bending curvature:
  - Macro-bending loss
  - Micro-bending Loss

Macro-Bending Losses Cont.

- **Macro-Bending loss** occurs when the curvature of the bend is much larger than the fiber diameter.
- The light wave suffers power loss due to radiation of optical field in the cladding region.

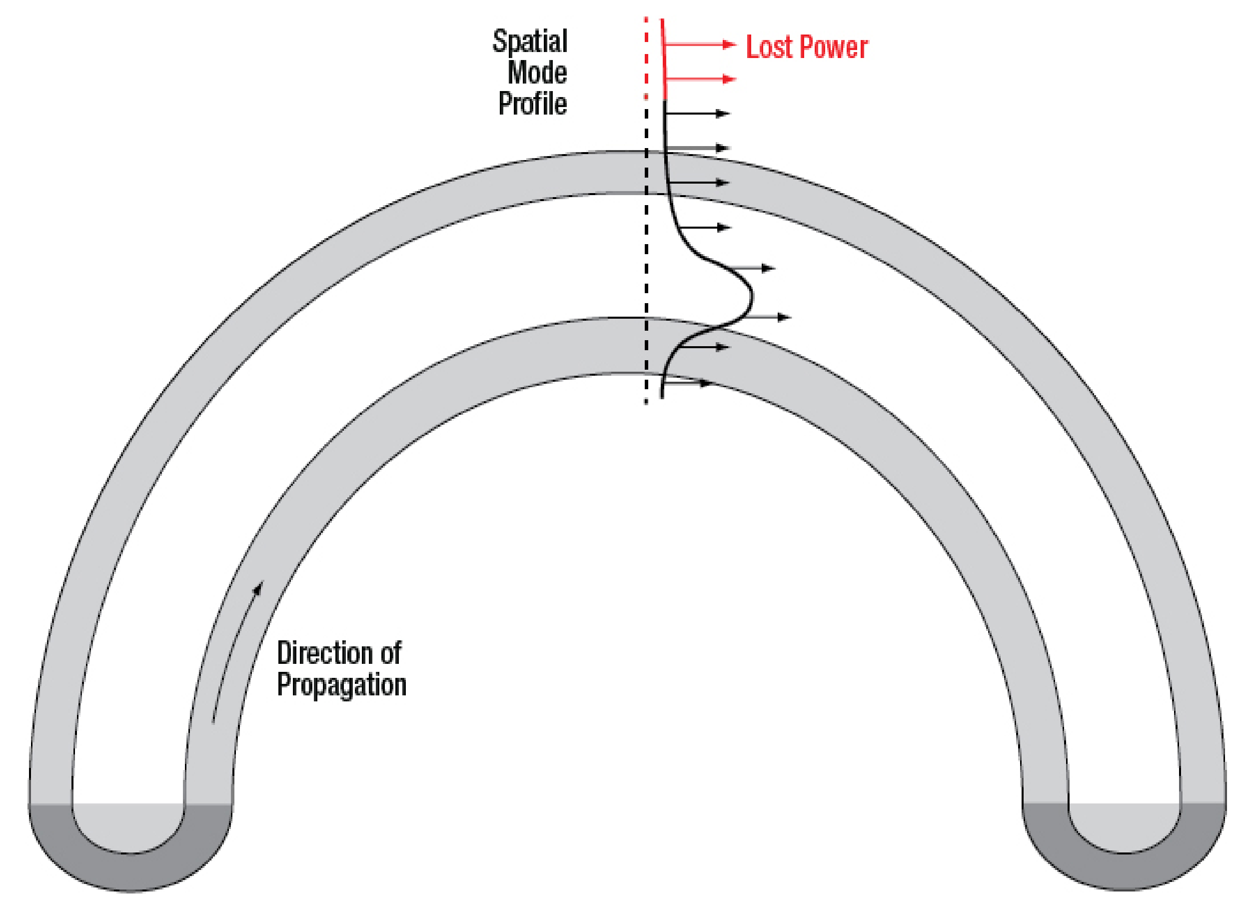


Figure 4: Macro-bending loss

Source: *“Multimode Fiber Tutorial,”* Thorlabs. https://www.thorlabs.com/images/tabimages/Multimode_Fiber_Tutorial_Bending_A1-780.jpg

Macro-Bending Losses

- **For Slight bends** the power loss is negligible
- Decreasing bend radius results in exponential grows of the radiative loss until the bend radius reaches a critical/threshold bend radius.
- The bending loss rises dramatically for bending radius a bit below the threshold/critical radius of curvature
- The approximate critical radius of curvature, R_c , for multimode fiber is given by:

$$R_c = \frac{3n_1^2\lambda}{4\pi(n_1^2 - n_2^2)^{\frac{3}{2}}} \qquad \textbf{(17)}$$

Where:

n_1	Refractive index of core
n_2	Refractive index of cladding

Macro-Bending Losses

- Higher-order modes in a multimode fiber are more affected by the bending loss since they bound less tightly to the fiber core.
- The total number of modes that can be supported by a curved fiber is less than in a straight fiber.
- Effective number of guided modes a curved multimode fiber can support is given by [3]:

$$M_{eff} = M_{\infty}\left[1 - \frac{\alpha+2}{2\alpha\Delta}\left[\frac{2a}{R} + \left(\frac{3}{2n_2 kR}\right)^{2/3}\right]\right] \qquad \textbf{(18)}$$

Where:

a Core radius

n_2 Refractive index of the cladding

Δ Core-cladding index refractive index difference

R Radius of curvature

$k = \frac{2\pi}{\lambda}$

Macro-Bending Losses

- M_{∞} in Eq (18) is given by :

$$M_{\infty} = \frac{\alpha}{\alpha+2}(n_1 ka)^2 \Delta \qquad \textbf{(19)}$$

Where:

n_1	Refractive index of the core
α	Graded index profile of the fiber

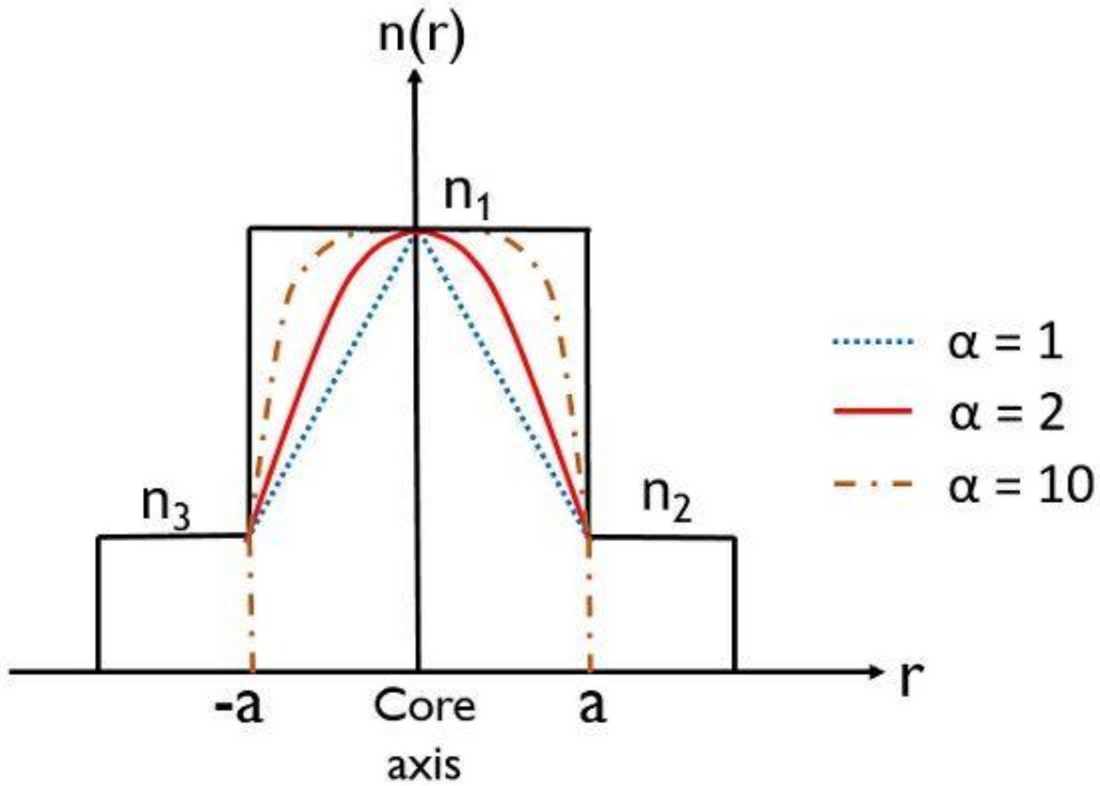


Figure 5: Different graded index profile

Source: *"Graded Index Fiber,"* Circuit Globe. https://circuitglobe.com/wp-content/uploads/2019/04/graph-for-graded-index-fiber.jpg

Micro-Bending Losses

- Micro-bending loss occurs due to repetitive small-scale fluctuations in the radius of curvature of the fiber axis:
- In micro bending the bending radius is comparable to the diameter of the fiber [4]
- Power loss arises due to power coupling to higher order modes and power loss from higher order modes as a result of micro bending
- It can be reduced by using compressible outer jacket

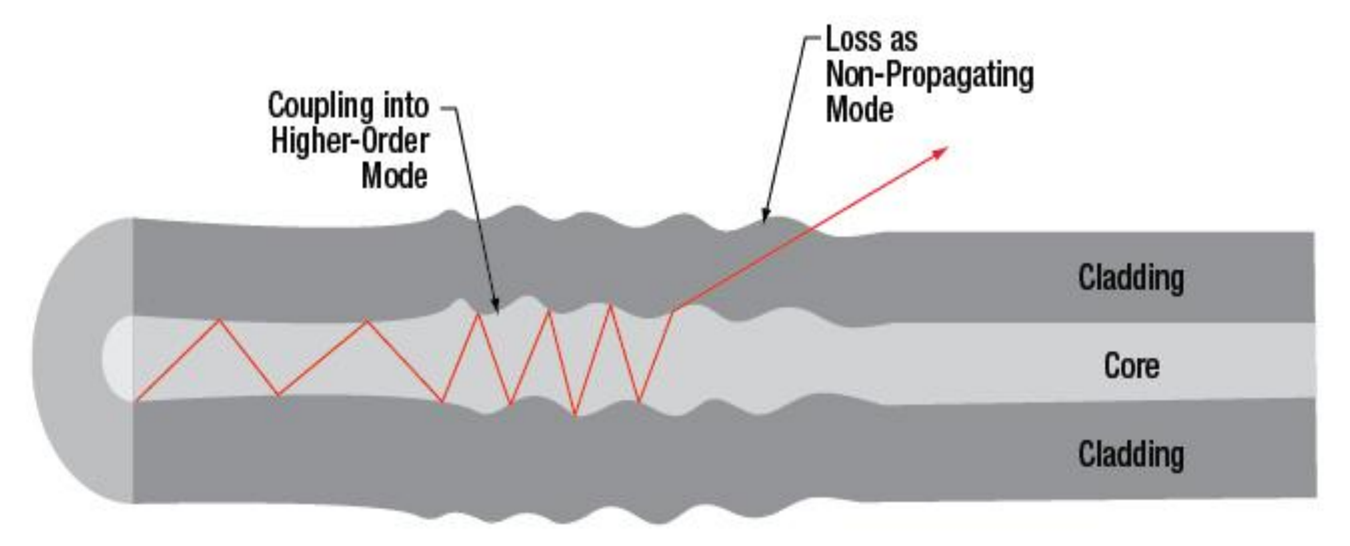


Figure 5: Micro-bending loss

Source: “Multimode Fiber Tutorial,” Thorlabs. https://www.thorlabs.com/images/tabimages/Multimode_Fiber_Tutorial_Bending_A2-780.jpg

Summary

- **Fiber Attenuation Coefficient:**
  - ✓ Measures the reduction in light power per unit length of fiber.
  - ✓ Expressed in dB/km.
  - ✓ Determines maximum transmission distance without amplification.
- **Origins of Fiber Optics Loss:**
  - ✓ Absorption, scattering, and fiber bending,
- **Absorption Loss:**
  - ✓ Extrinsic and Intrinsic Absorption
- **Scattering Loss:**
  - ✓ Rayleigh and Mie scattering
- **Fiber Bending Loss:**
  - ✓ Macro and Micro-bending

References

[1] Govind P. Agrawal,*‘’ Fiber-Optic Communication Systems”,* John Wiley & Sons, 5th ed., Pp.46, 2021.

[2] Gerd Keiser, *“Fiber Optic Communications”,* Springer, Pp.97, 2021.

[3] D. Sabrina, A. Budi Pantjawati, and B. Mulyanti, *“Macrobending Loss Analysis of Singlemode-Multimode-Singlemode (SMS) Optical Fiber Structures on Variation of Macro Bend and Multimode,”* 2021 3rd International Symposium on Material and Electrical Engineering Conference (ISMEE), Bandung, Indonesia, 2021, pp. 337-342, doi: 10.1109/ISMEE54273.2021.9774243.

[4] S.O. Kasap*,‘’ Optoelectronics and Photonics Principles and Practices”, PEARSON*, 2nd ed., Pp.164, 2013.

Thank You !