Optical Fiber Communication

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Author's Note: This document was prepared under time constraints and may contain unintentional, calculation errors or inconsistencies. Readers are advised to proceed with understanding and caution.

Contents

1 Optical Fiber

Optical fibers are circular dielectric wave-guides that can transport optical energy and information.

1.1 Need of Fiber

Fiber is preferred over electrical cabling

- high bandwidth
- long distance
- immunity to electromagnetic interference

1.2 Optical Fiber used

- Transmit telephone signal
- Internet communication
- Television signals
- Medical, Defense, Govt.

1.3 Satellite vs OF Communication

- Terrain : Satellite for rough terrains, poorly connected areas. OF for urban areas
- Bandwidth : OF > Satellite
- Data Rate and Delay : OF high data rate with minimal delay
- Broadcasting : Satellite are for broadcasting.
- Mobility : Fiber for fixed but satellite not.
- Reliability
- Cost

(Have some similarities with the advantages of OF.)

1.4 SEA ME WE-4

South East Asia-Middle East-Western Europe 4 (SEA-ME-WE 4) is an optical fiber submarine communication cable system

- carries telecommunication between Signapore, Malaysia, Bangladesh, Egypt, India .. **(14 countries)**
- approx. 18,800 km long
- cost US $500 million
- initial design capacity 1.28 Tbps
- 17 cable landing stations

- Write four features of SEA-ME-WE-4

1.5 Optical fiber and Its Structure

Optical fibers are **circular dielectric wave-guides** that can transport **energy and information**.
Consists Of

- Core
  - center of the OF
  - provides a pathway for light to travel
  - made from silica
    - transparent in visible and near-IR
  - refractive index is greater than cladding (0.3% higher)
    - doping with germanium dioxide (GeO_2)
  - mode types

    * multi-mode : diameter 62.5, 50, 100 μm
    * single-mode : 8-9 μm

- Cladding
  - holds the light inside the core, prevents leaking outside
  - control the direction in which light spread
  - mode types
    * multi-mode : diameter 125 μm
    * single-mode : 125 μm
- Buffer Coating/Polymer Jacket
  - acts as the primary buffer
  - diameter 250 μm
  - cushions and protects the fiber from humidity and hostile environment
  - two layers of urethance Arcylate/plastic make up
    * Soft layer : Cushions the fiber
    * Hard layer : provides abrasion resistance
  - higher refractive index than core, cladding

Applications : Transmit telephone signals, Internet communication, cable television signals, Medical, Defense etc.

- What is optical fiber? Write down the cross-sectional view of a typical optical fiber and explain it.
- Write down the necessity of cladding layer.
- Write down the applications of optical fiber in different communication systems.
- Write the wavelength range for optical fiber communication. (1260 nm to 1625 nm)

2 Basics of Light

2.1 Substances show the various properties of light

- Transparent : Substances that allow light to pass through completely, enabling clear vision. Transmits light without scattering it.
  - Air, pure water and clear glass
  - transmits almost all of the light waves
- Translucent : Substances that allow some light to pass through but scatter it, causing blur. Transmits light but scatters.
  - the fronzed part of the soap bubble
- Opaque : Opaque matter is matter that does not let any light pass through it.
  - Wood
- A substance that transmits almost all of the light waves falling upon it is known as what type of substance? (Transparent)

2.2 Properties of Light

- Reflection of Light
- REfraction of Light
- Diffusion of Light
- Absorption of Light

- When light waves encounter any substance, what four things can happen? A substance that transmits almost all of the light waves falling upon it is known as what type of substance?

2.3 Propagation of Light

Propagation of Light refers to the transmission or movement of light waves through different mediums.

2.3.1 Theory describing the propagation of light through optical fiber

Ray Theory	**Mode Theory**
Light is described as simple ray	electromagnetic wave
Geometrical Optics Approach	EM wave representation
Describe light acceptance and guiding properties (reflection and refaction)	absorption, attenuation, dispersion
Used to understand light propagate along a fiber and approximate optical properties	calculated quantities such bandwidth
Simplified approach used to analyze how light wave propagate and transmit through fiber	Plays a vital role in fiber optics

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- Discuss the concept of light propagation along an optical fiber with respect to ray theory and mode theory.
- Which acceptance angle is larger: The skew ray angle or The meridional ray angle? (Skew)
- Two theories describing the propagation of light through optical fiber. Mention their name and functions.

2.3.2 The types of rays propagate along an optical fiber

Meridional Ray	**Skew Ray**
rays pass through the axis of the optical fiber	without passing through the center axis of the OF
Acceptance angle smaller, limited by the critical angle for total internal reflection.	larger
Lower Loss (propagate closer to the core's center)	Higher loss (propagate near the core edge, leading the leaky rays)
Less numerous due to stricter entry angle requirement (within the acceptance angle, which defines the acceptance cone)	More numerous due larger acceptance angle
Classification and behavior • Bound : • remain confined within the fiber core • propagating by total internal reflection when they strike the core-cladding interface at an angle greater than the cricical angle • Unbound : • strike the interface at an angle less than critical angle • get refracted into cladding and lost	Many are leaky rays, partially reflected

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- Light transmission along an optical fiber is described by two theories. Which theory is used to approximate the light acceptance and guiding properties of an optical fiber? (Ray Theory)

2.3.3 Phase and Group Velocity

Phase Velocity	**Group Velocity**
The phase velocity of a wave is the rate at which teh phase of the wave propagate in space.	the overall shape of the waves amplitudes (modulator/envelop) of the wave propagates
$v_p = \frac{\omega}{k} = \frac{2\pi f}{\frac{2\pi}{\lambda}} = \lambda f = \frac{\lambda}{T}$	$v_g = \frac{\delta\lambda}{\lambda k}$
The constant phase wave front travels at the phase velocity	The group velocity is the velocity at which energy and information travels
Smaller by η factor (medium)	$v_p = v_g$ (vacuum)

- Differentiate between the phase and group velocity of light.
- Is phase velocity faster than group velocity?
  $\longrightarrow$ The relationship between, $v_g = \frac{d\omega}{dk} = \frac{d(kv_p)}{dk} = v_p + k\frac{dv_p}{dk}$.
  - Non-dispersive medium/vacuum : $v_p = \text{constant}, v_p = v_g$
  - Normal dispersion : $\frac{dv_p}{dk} < 0 \Longrightarrow v_p > v_g$
  - Anomalous dispersion : $\frac{dv_p}{dk} > 0 \Longrightarrow v_p < v_g$

2.3.4 Refractive Index

When light transfers from one medium to another light changes by constant number call refractive index (n).

$$n_v = \frac{c}{v}$$

2.3.5 Snell's Law

The ratio of the sine of the angle of incidence to the sine of the angle of refraction is a constant for the light of a given color and for the parir of medium.

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

- What determines the angle of refraction?
  $\longrightarrow \theta_r = \sin^{-1}(\frac{n_i}{n_r}\sin i)$, determined by refractive index of mediums and the incidence angle

2.3.6 Critical Angle

Angle of incidence for which transmitted light is parallel to the boundary. $\theta_t = 90 \longrightarrow \theta_i = \theta_c$

$$n_1 \sin\theta_c = n_2 \sin 90\deg \Longrightarrow \theta_c = \sin^{-1}\frac{n_2}{n_1}$$

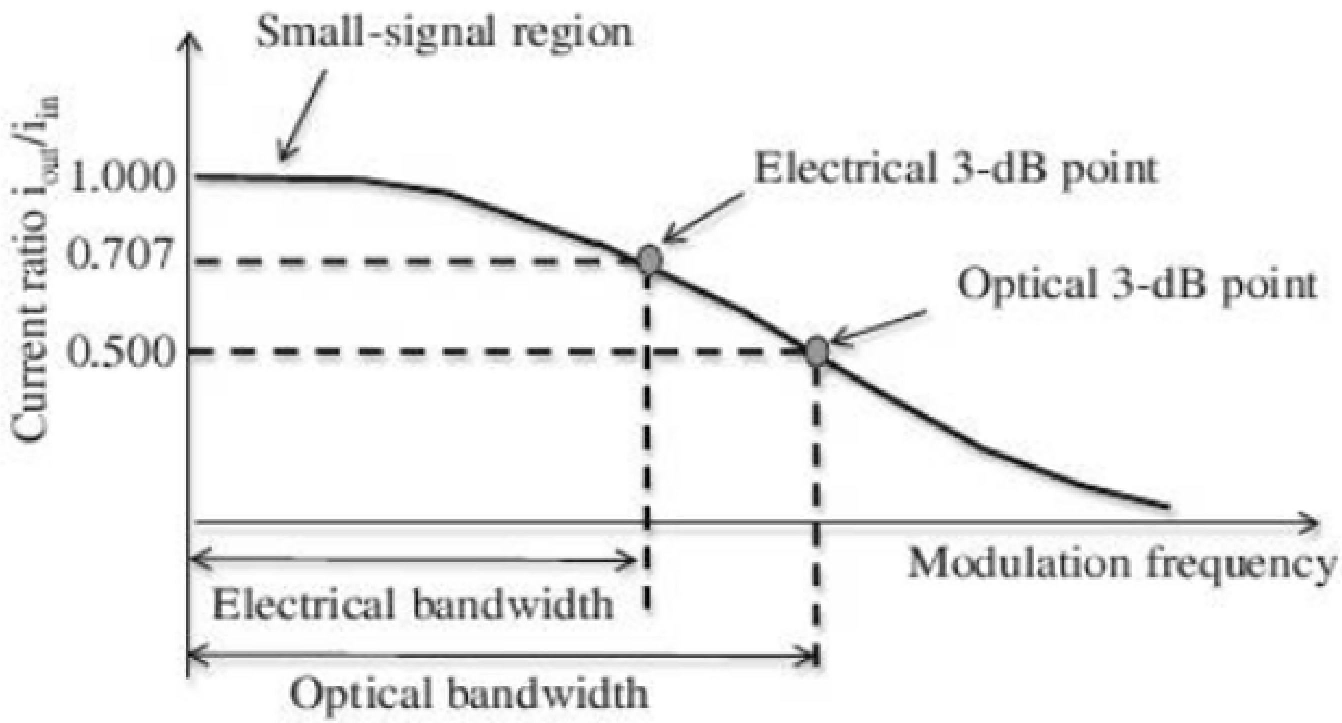
- What is meant by critical angle of an optical fiber? Obtain an expression for the critical angle.

2.3.7 Total Internal Reflection

When the angle of incidence is greater than critical angle incident light reflects back to the same medium.

2.3.8 Bandwidth

optical bandwidth	**electrical bandwidth**
The frequency at which the optical power gain ($\frac{P_{out}}{P_{in}}$) drops to 0.5 of its midband value	voltage or current gain drops to 0.707
Defined directly at a power gain 0.5 which corresponds to -3 dB ($10\log_1 0(0.5) = -3dB$)	also -3dB, ($0.707^2 = 0.5$)
measured in terms of optical power	voltage/current
Relationship, Electrical BW = $\frac{1}{\sqrt{2}}$Optical BW	Electrical bandwidth is approx. 0.707 times the Optical BW.
greater than electrical BW, due to in system like optical receiver$P_{electrical} \propto I^2, P_{optical} \propto I$	less



- Differentiate between electrical bandwidth and optical bandwidth
- Contrast electrical BW and optical BW.
- Draw a graph showing electrical BW and optical BW and also write their equations.
- Define (ii) bandwidth length product $\Longrightarrow$ The bandwidth-distance product, often expressed in units of MHz-km, represents the information carrying capacity of an optical fiber. It emphasizes that the bandwidth achievable over a given fiber is not constant but decreases with increasing distance. This relationship is due to various factors like signal attenuation, dispersion, and noise accumulation.

3 Light Ray Guiding Condition through Optical Fiber

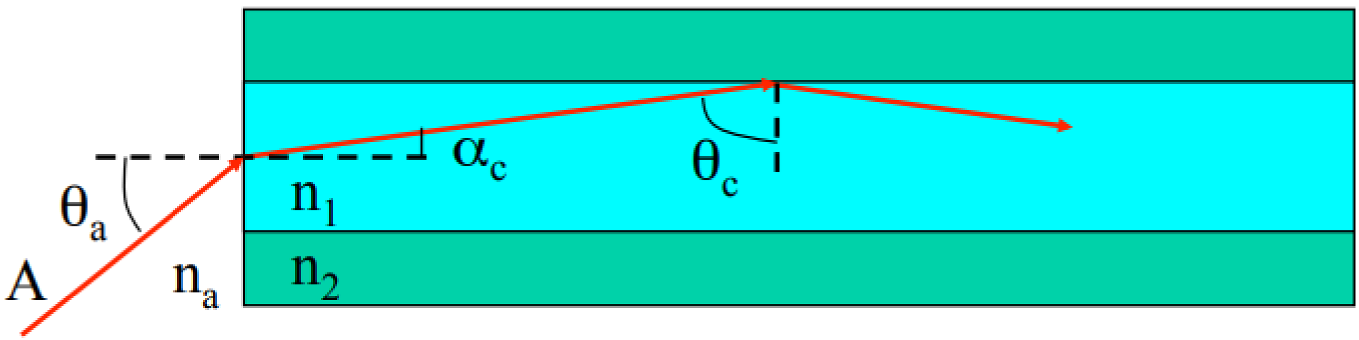
- Denser medium and light medium
- Refractive Index

- Critical angle
- Total Internal Reflection

- Write light ray guiding conditions through optical fiber

3.1 Acceptance Cone and Angle

θ_a is maximum angle at which if the light incident on optical fiber will propagate down to the optical in the core, θ_a is known as Acceptance angle.
Only rays with a sufficiently shallow grazing angle at the core-cladding interface are transmitted by total internal reflection.



$n_a \sin\theta_a = n_1 \sin\alpha_c \Longrightarrow n_a \sin\theta_a = n_1 \sin(90^\circ - \theta_c) = n_1 \cos\theta_c = n_1\sqrt{1-\sin^2\theta_c} = n_1\sqrt{1-(\frac{n_2}{n_1)}^2} = \sqrt{n_1^2 - n_2^2}$

$\Longrightarrow \theta_a = \frac{\sqrt{n_1^2-n_2^2}}{n_a}$

Acceptance Cone $= 2\theta_a$

- A fiber optic cable whose cladding and core have indices of refraction 1.40 and 1.62 respectively. Light enters the fiber from a balloon of saline solution $n = 1.35$ which is used in endoscopic procedures at the end of the fiber to increase visibility. What is the maximum entrance angle for transmission of light through the fiber?

  $\Longrightarrow \sin\theta_a = \frac{\sqrt{n_1^2-n_2^2}}{n_a} = \frac{\sqrt{1.62^2-1.40^2}}{1.35}$

  $\theta_a = 39.70^\circ$

- An optical fiber is submerged in glycerine solution $n = 1.46{-}1.47$. Find the core radius for single-mode operation at 850 nm of step index fiber with $n_1 = 1.48$ and $n_2 = 1.472$. What is the numerical aperture and acceptance angle of this fiber?

  $\Longrightarrow \text{NA} = \frac{\sqrt{n_1^2-n_2^2}}{n_a} = \frac{\sqrt{1.48^2-1.472^2}}{1.465} = 0.1048$

  $\theta_a = \sin^{-1}(0.1048) = 6.02^\circ$

- Calculate fiber acceptance cone when core refractive index is 1.46 and cladding refractive index is 1.44.

  $\Longrightarrow \theta_a = \sin^{-1}(\sqrt{1.46^2 - 1.44^2}) = 13.93^\circ$

  Acceptance cone $= 2 \times 13.93^\circ = 27.86^\circ$

3.2 Relative refractive index

$\Delta = \frac{n_1^2-n_2^2}{2n_1^2}$

3.3 Numerical Aperture

- sine of the acceptance angle
- higher core index w.r.t cladding means larger NA
- measure of the the light gathering ability of a fiber
- Silica fibers : 0.1 - 0.3
- Short haul communication plastic fiber : 0.4 - 0.5

NA $= n_a \sin\theta_a = n_1\sqrt{2\Delta}$

- What fiber property does measure numerical aperture (NA)? Represent NA with the help of Snell's law.

  $\Longrightarrow$ Light Collection Ability/measure for its angular acceptance for incoming light.

  $n_a \sin\theta_a = n_1 \sin\alpha_c \Longrightarrow n_a \sin\theta_a = n_1 \sin(90^\circ - \theta_c) = n_1 \cos\theta_c = n_1\sqrt{1-\sin^2\theta_c} = n_1\sqrt{1-(\frac{n_2}{n_1})^2} = \sqrt{n_1^2 - n_2^2}$

  $NA = n_a \sin\theta_a = \sqrt{n_1^2 - n_2^2}$

- How the core diameter influence numerical aperture - justify your answer.

  $\Longrightarrow$ Not at all. Because, $NA = n_a \sin\theta_a = \sqrt{n_1^2 - n_2^2}$. It depend on the refractive index but not the diameter of core and cladding.

4 Fiber Classification

Two methods

- Index of refraction variation
- Various paths light rays

4.1 Various paths light rays

Single mode	**Multi mode**
Light Propagates only one mode (fundamental mode) through fiber core	multiple modes (over 100)
Core size small, 8 to 10 micrometer	50-100 micrometer
Index of refraction $\longrightarrow$ Step index : constant index of refraction	Graded index : varies smoothly across core diameter, maximum at center and constant in cladding
Normalized frequency V $\leq$ 2.405	V $\geq$ 2.405
Lower signal loss	Higher due to modal dispersion
Low fiber dispersion	Higher modal dispersion
Higher bandwidth due to low dispersion, suitable for higher data transfer	Lower bandwidth
Requires leaser diodes for precise light inejction	cheper, less complex LED
Lower NA	Higher (0.20 to 0.29)
Requires precise core-to-core alignment during splicing	Less critical alignment due to larger core size and higher NA
Preferred for long distance, long BW due to low loss and dispersion	Suitable for shorter distances

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- Distinguish single fibre and multifibre cable.
- Distinguish between single mode step index and multimode step index fiber.

4.2 Step Index and Graded Index

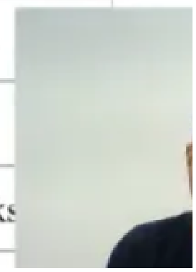
Step Index Fiber	Graded Index Fiber
Sharp step in the index of refraction between core (N1) and cladding (N2), both constant.	Index of refraction varies smoothly across the core diameter, maximum at the center, decreasing toward the edges; cladding has a constant index.
Constant throughout the core (N1).	Varies parabolically, highest at the core center, decreasing toward the core-cladding interface.
Constant (N2), lower than the core.	Constant, matches the core's index at the outer edge of the core.
Supports single mode in single mode fibers; multiple modes in multimode fibers.	Primarily used in multimode fibers, supporting multiple modes with reduced dispersion.
Used in both single mode (small core, V $\leq$ 2.405) and multimode fibers.	Typically used in multimode fibers to minimize modal dispersion.
Core size Single mode: 8–10 µm; Multimode: 50–100 µm.	Typically 50–100 µm for multimode fibers.
Lower bandwidth in multimode due to higher modal dispersion.	Higher bandwidth in multimode due to reduced modal dispersion.
Lower NA in single mode	Higher NA in multimode

4.3 Three types of fiber optic cable

- Single Mode Step Index
- Multimode Step Index
- Multimode Graded index

Comparison of step index and graded index

Sr.	Parameter	Step index fiber	Graded index fiber
1.	Data rate	Slow	Higher
2.	Coupling efficiency	Coupling efficiency with fiber is higher	Lower coupling efficiency
3.	Ray path	By total internal reflection	Light travels in oscillatory fashion
4.	Index variation	$\Delta = \frac{n_1 - n_2}{n_1}$	$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$
5.	Numerical aperture	NA remains same	Changes continuously with distance from fiber axis
6.	Material used	Normally plastic or glass is preferred	Only glass is preferred
7.	Pulse spreading	Pulse spreading by fiber length is more	Pulse spreading is less
8.	Attenuation of light	Less typically 0.34 dB/km at 1.3 .	More 0.6 to 1 dB/km at 1.3 .
9.	Typical light source	LED	LED, Lasers
10.	Applications	Subscriber local network communication	Local and wide area networks



4.4 Normalized Frequency V Number

V-number that determines which modes propagate in a fiber. These factors include: indices of refraction of core and cladding, core diameter, and wavelength.

$V = \frac{2\pi a}{\lambda}\text{NA}$

- a : core radius
- λ : operating wavelength
- Number of modes M, for step indexed Multimode, $M = \frac{V^2}{2}$
- Step Index single mode when V $<$ 2.405

- A fiber optic cable with a core diameter of 50 μm has cladding and core indices of refraction 1.46 and 1.466 respectively. If the operating wavelength of the rays is 0.85 μm, calculate the normalized frequency and the number of modes which the fiber will support. How can you determine the type of fiber from the above problem?

  $\implies V = \frac{2\times\pi\times 25}{0.85}\sqrt{1.46^2 - 1.466^2} = 24.48 \ M = \frac{V^2}{2} = 300$

  $V \geq 2.405$ So, it is multi mode. The core and cladding refractive index are constant. So, It is Step-index fiber. It is a Step-Index Multi mode fiber.

- A multimode step index fiber with a core diameter of 80 μm and a refractive index difference of 1.5% is operating at a wavelength of 0.85 μm. If the core refractive index is 1.48, estimate the normalized frequency for the fiber and the number of guided modes.

  $\implies V = \frac{2\times\pi\times 40}{0.85} 1.48\sqrt{2\times 0.015} = ... \ M = \frac{V^2}{2} = ...$

- In a multimode step index fiber the number of modes passing at an operating wavelength of 1300 nm are 1000. The refractive index of the core is 1.50 and cladding is 1.48. The value of core diameter is what?

  $\implies M = \frac{V^2}{2} \implies V = \sqrt{2M} \implies a = \frac{\sqrt{2m}\lambda}{2\pi\times NA} = 37,905.84$ nm, diameter $= 2\times a$

- A step index fiber is made with a core of refractive index 1.52, a diameter of 29 μm and a fractional difference index of 0.0007. It is operated at wavelength of 1.3 μm. Find the V-number and the number of modes that the fiber will support.

- How normalized frequency declares the fiber is either single mode or multimode - justify your answer.

  $\implies$V $\geq$ 2.405 $\longrightarrow$ Multimode else single mode.

4.4.1 Cutoff Wavelength

The cutoff wavelength is the minimum wavelength in which a particular fiber still acts as a single mode fiber. $\lambda_c = \frac{2\pi a}{V_c}$ NA
$V_c = 2.405$

- Above the cutoff wavelength
  - LP_{01} mode to propagate
- Below the cutoff wavelength
  - higher order modes ($LP_{11}, LP21, LP_{02}$) will able to propagate (fiber becomes multimode)

- Solve the cut off wavelength for a step index fiber to exhibit single mode operation when the core refractive index is 1.46 and the core radius is 4.5μm, with the relative index difference is of 0.25%.
  $\implies \lambda = \frac{2\pi a}{V} n_1 \sqrt{2\Delta} = \frac{2\pi \times 4.5}{2.405} \times 1.46 \times \sqrt{2 \times 0.0025} = ...$

5 Properties of Optical Fiber Transmission

Optical fiber transmission performance is primarily determined by signal loss (attenuation) and bandwidth (limited by dispersion).

5.1 Attenuation

- Attenuation is the loss of optical power as light travels along the fiber.
- ratio of optical input power and optical output power
- Unit db/km
- attenuation $= \frac{10}{L} \log_{10} \frac{P_i}{P_o}$
- three primary mechanism : absorption, scattering, bending losses

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- What is attenuation in an optical fiber? List three major causes of attenuation in an optical fiber.
  $\implies$ loss of optical power, three major causes : absorption, scattering, bending loss

5.1.1 Absorption

Absorption is the portion of attenuation where optical power is converted into another energy form, typically heat, due to interactions with the fiber material. It is caused by:

- Imperfections in the atomic structure (e.g., missing molecules, oxygen defects).
- Intrinsic material properties (basic properties of the fiber material).
- Extrinsic material properties (impurities introduced during manufacturing).

Types of absorption

- Intrinsic Absorption
  - Caused by the basic material properties of the fiber (e.g., silica glass).
  - Occurs even in pure fibers with no impurities, setting the minimum absorption level.
  - Regions of Intrinsic Absorption
    * Ultraviolet Region: Below 400 nm, caused by electronic absorption bands (photon-electron interactions excite electrons to higher energy levels).
    * Infrared Region: Above 2000 nm, caused by the vibration of silicon-oxygen (Si-O) bonds interacting with the electromagnetic field of light.
  - Operating Wavelengths: Silica fibers operate between 700 nm and 1600 nm, avoiding high intrinsic absorption in ultraviolet and infrared regions (see Figure 2-21).
- Extrinsic Absorption:
  - Caused by impurities introduced during fiber fabrication.
  - Trace Metal Impurities: Metals like iron, nickel, and chromium cause absorption through electronic transitions between energy levels.
  - Hydroxyl Ions (OH): Water impurities form silicon-hydroxyl (Si-OH) bonds, leading to absorption peaks at:

    * 2700 nm (fundamental absorption).
    * Harmonics at 1383 nm, 1250 nm, and 950 nm (Q41).
  - These peaks define three preferred operating windows:
    * First Window: Centered at 850 nm.
    * Second Window: Centered at 1300 nm.
    * Third Window: Centered at 1550 nm.
  - Minimizing Extrinsic Absorption: Reducing impurities (e.g., OH to a few parts per billion) lowers absorption and overall attenuation.

- Optical power launched into fiber at transmitter end is 150 μW. The power at the end of 10 km length of the link working in first window is – 38.2 dBm. Another system of same length working in second window is 47.5 μW. Same length system working in third window has 50 % of launched power. Calculate fiber attenuation for each case and mention wavelength of operation. **(dbm = decibel-milliwatts.)**

  $\Longrightarrow$ Length, $L = 10km\ P_{in} = 150\mu W$

  $P_{\text{out in dbm}} = -38.2dbm = 10\log(P_{out}) \Longrightarrow P_{out} = 10^{\frac{38.2}{10}}mW(\text{milliwatts}) = 1.513 \times 10^{-4}mW = 1.513 \times 10^{-4} \times 1000\mu W = 0.153\mu W$

  First Window $\lambda = 850$ nm,

  $\alpha = \frac{10}{L}\log_{10}\frac{P_{in}}{P_{out}} = \frac{10}{10}\log_{10}\frac{150}{0.153} = 2.99\text{db/km}$

  Second Window $\lambda = 1300$ nm $P_{out} = 47.5\mu m$,

  $\alpha = \frac{10}{L}\log_{10}\frac{P_{in}}{P_{out}} = \frac{10}{10}\log_{10}\frac{150}{47.5} = 0.5\text{db/km}$

  Third Window $\lambda = 1550$ nm $P_{out} = 150 \times 50\% = 75\mu m$,

  $\alpha = \frac{10}{L}\log_{10}\frac{P_{in}}{P_{out}} = \frac{10}{10}\log_{10}\frac{150}{75} = 0.3\text{db/km}$

- A continuous 12 km long optical fiber link has a loss of 4.5 dB/km. What is the minimum optical power level that must be launched into the fiber to maintain an optical power level of 0.3 μW at the receiving end?

  $\Longrightarrow$ Length,$L = 12$km, $\alpha = 4.5$ db/km, $P_o = 0.3\mu$W

  $P_i = 10^{\frac{\alpha \times L}{10}} \times P_o = 75356.59\mu$W

5.1.2 Scattering

Scattering losses occur due to the interaction of light with density fluctuations in the fiber, caused by manufacturing variations in molecular density.Light is scattered in all directions, reducing optical power (see Figure 2-22).
Types of Scattering:

- Rayleigh Scattering (Q42):
  - The main loss mechanism between ultraviolet (400 nm) and infrared (2000 nm) regions.
  - Occurs when density fluctuations (defects) are less than one-tenth of the operating wavelength.
  - Loss is proportional to the fourth power of the wavelength ($1/\lambda^4$), meaning shorter wavelengths experience higher scattering losses.
  - Decreases as wavelength increases (e.g., less loss at 1550 nm than at 850 nm).
- Mie Scattering (Q43):
  - Occurs when density fluctuations (defects) are greater than one-tenth of the operating wavelength.
  - Causes light to scatter out of the fiber core but is insignificant in commercial fibers due to minimal large defects.

5.1.3 Bending Losses

Bending losses occur when the fiber is bent, causing light to radiate out of the core, increasing attenuation. There are two types: microbend and macrobend losses.
Types of Bending Losses

- Microbend Losses (Q44):
  - Caused by small, microscopic bends in the fiber axis, often due to:
    * Uneven coating applications during manufacturing.
    * Improper cabling procedures.
    * External forces deforming the cable jacket.
  - Microbends alter the path of propagating modes, coupling low-order modes with lossy high-order modes, increasing attenuation (see Figure 2-23).
- Macrobend Losses:

- Occur when the fiber is bent with a large radius of curvature (relative to fiber diameter, typically less than several centimeters).
- Light on the inner side of the bend travels a shorter distance, requiring the mode phase velocity to increase. If the bend is too sharp (below the critical radius), the velocity exceeds the speed of light, converting light to lossy high-order modes that radiate out of the fiber.

Reducing Bending Losses (Q45):

- Increase the refractive index of the core: Reduces sensitivity to bending by better confining light.
- Increase overall fiber diameter: Decreases bending sensitivity, though larger core sizes may increase mode propagation and lossiness.

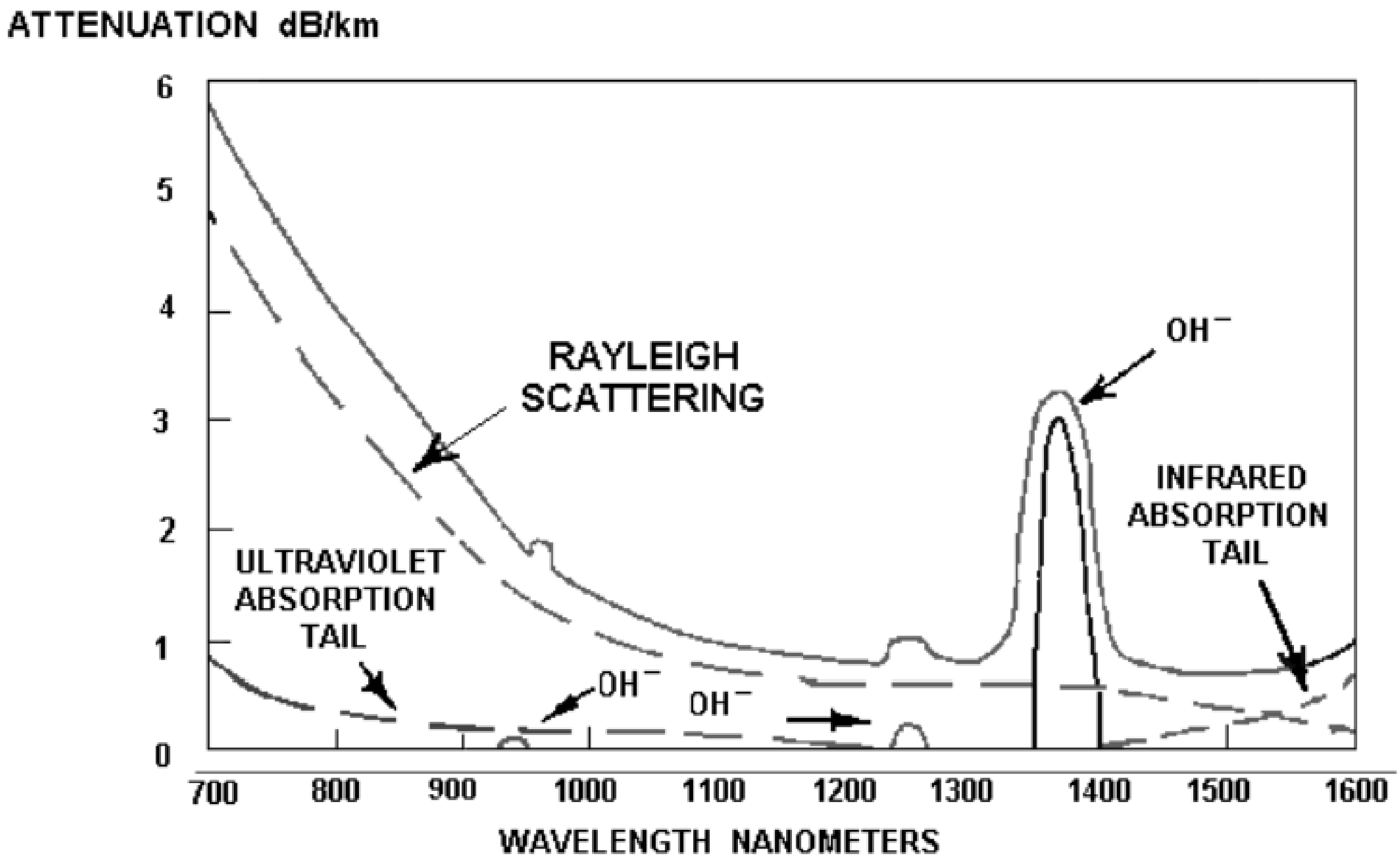

Figure 2-21.—Fiber losses.

- Mention the signal transmission impairments in the optical fiber. Draw the attenuation vs wavelength graph and point out the impairments.

  $\implies$ attenuation, dispersion

5.2 Dispersion

Dispersion is the spreading of an optical pulse as it travels along the fiber, reducing system bandwidth (information-carrying capacity). Pulse spreading causes overlap, making it difficult for receivers to distinguish pulses, leading to errors (see Figure 2-24).

For non-dispersion-shifted fibers (1270 nm – 1340 nm)
Dispersion, $D(\lambda) = \frac{\lambda S_0}{4}[1 - (\frac{\lambda_0}{\lambda})^4]$
Dispersion for dispersion shifted fibers(1500 nm- 1600 nm)
Dispersion, $D(\lambda) = (\lambda - \lambda_0)S_0$

- λ_0 zero-dispersion wavelength
- S_0 the value of the dispersion slope [ps/(nm^2)·km]

- What is the chromatic dispersion for a graded-index fiber if $S_0 = 0.0097 ps/(nm^2.km)$,$\lambda_0 = 1341$ nm and $\lambda = 1300$nm ?

  $\implies$ Dispersion, $D(\lambda) = \frac{\lambda S_0}{4}[1 - (\frac{\lambda_0}{\lambda})^4]$

Types of Dispersion:

5.2.1 Intramodal (Chromatic) Dispersion

Intramodal dispersion occurs in all types of fibers (single mode and multimode) because different colors (wavelengths) of light travel at different speeds through the fiber material or waveguide structure. It consists of two subtypes:

- Material Dispersion
  - Caused by the wavelength-dependent refractive index of the fiber core.
  - Different wavelengths travel at different speeds, causing pulses to spread as they exit the fiber at different times.
  - Depends on the source spectral width (range of wavelengths emitted).
  - Effect: Less significant at longer wavelengths (e.g., 1550 nm), where material dispersion is reduced.
- Waveguide Dispersion:
  - Caused by the waveguide structure of the fiber (core and cladding design).
  - Different wavelengths interact differently with the fiber's geometry, affecting their propagation speeds.

5.2.2 Intermodal (Modal) Dispersion

Intermodal dispersion occurs only in multimode fibers because multiple modes travel different paths through the core, arriving at the fiber end at slightly different times. This causes pulse spreading and reduces bandwidth.

- The number of modes depends on core size and numerical aperture (NA). Larger cores and higher NA increase the number of modes, worsening modal dispersion.
- Graded Index Fibers: Reduce intermodal dispersion by varying the refractive index across the core, slowing light paths near the edges to align arrival times.
- Step Index Fibers: Higher modal dispersion in multimode fibers due to constant refractive index, leading to greater path length differences.
- Intermodal Dispersion $\Delta T = (\frac{L}{\sin\theta_c} - L)\frac{n_1}{c} = \frac{n_1^2 L}{n_2 c}\Delta$ (From YT)

  $\Delta T_{SI} = \frac{L}{2cn_2}(NA)^2 = \frac{L}{c}(n_1 - n_2)$ (From PDF (senior), preferred)

- A step-index fiber is with a core of refractive index 1.55 and cladding of refractive index 1.51. Compute the intermodal dispersion per kilometer of length of the fiber and the total dispersion in a 15 km length of the fiber.

  $\Longrightarrow \Delta T = \frac{n_1^2 L}{n_2 c}\Delta$ or $\Delta T_{SI} = \frac{L}{2cn_2}(NA)^2 = \frac{L}{c}(n_1 - n_2)$
- How much will a light pulse spread after travelling along 1000 meter of a step index fiber whose NA = 0.275 and core refractive index is 1.487?

  $\Longrightarrow \Delta T_{SI} = \frac{L}{2cn_2}(NA)^2$ (Class)
- Discuss intramodal and intermodal dispersion in fiber optic.
- (Extra) There are 3 dispersion types in the optical fibers, in general:
  - Material Dispersion
  - Waveguide Dispersion
  - Polarization-Mode

6 References

- Slides provided by the instructor
- Elearn (Daffodil International University)
- Optical Fiber Communications Principles and Practice by JOHN M. SENIOR
- BEC701 - FIBRE OPTIC COMMUNICATION
- Reference notes from senior batches
- Lec 52: Dispersion- Intermodal dispersion derivation by NPTEL-NOC IITM
- AI for improved summarization