Satellite and Optical Communication

BEC515D

MODULE 4

Optical Fiber Structures

Introduction

- The basic function of an optical fiber link is to transport a signal from communication equipment (e.g., a computer, telephone, or video device) at one location to corresponding equipment at another location with a high degree of reliability and accuracy.
- Key Sections:
  - Transmitter
  - Optical Fiber Cable
  - Receiver

Introduction

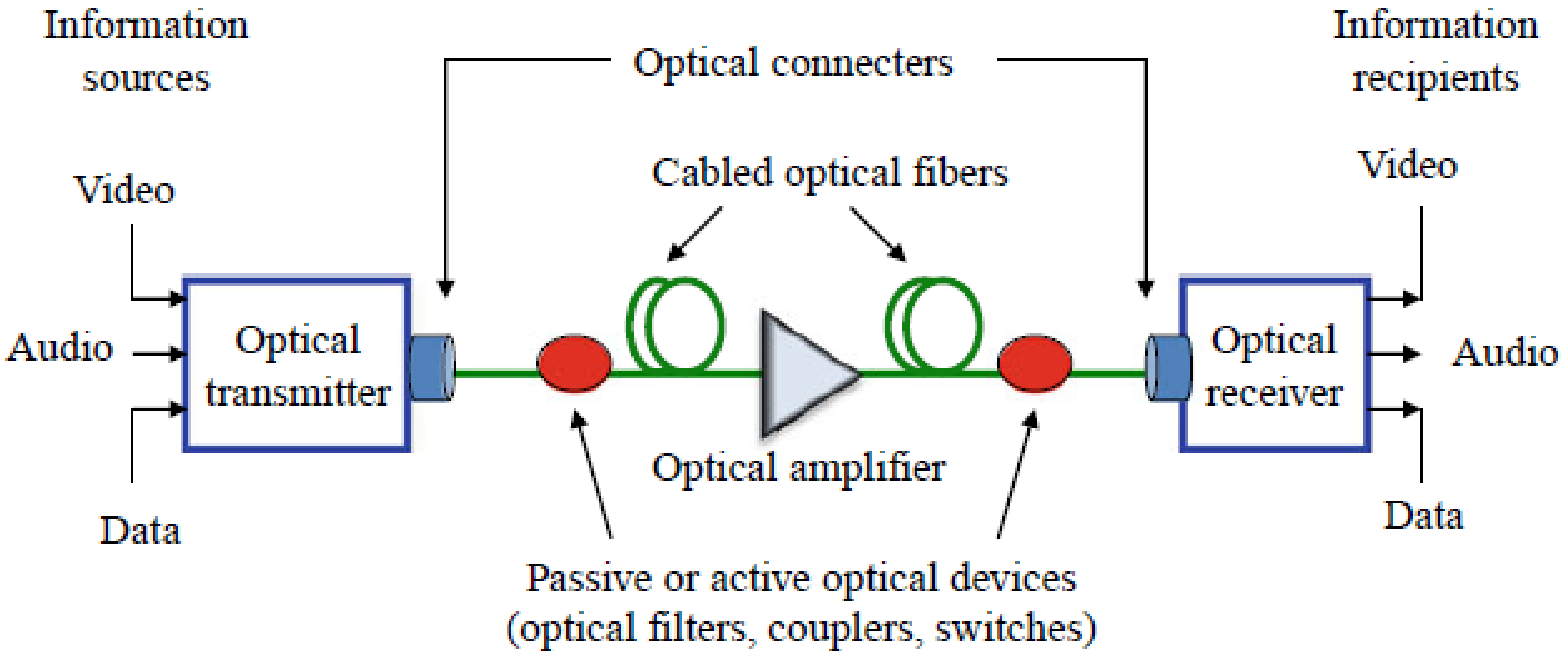


Fig. 1.10 Main constituents of an optical fiber communications link

Introduction

- Core Components of the System
  1. Transmitter:
     - Converts electrical signals into light signals.
     - Contains a light source (LED or Laser Diode) and drive circuitry.
  2. Optical Fiber Cable:
     - The transmission medium that guides the light.
     - Protects the glass fibers from mechanical stress and environmental factors.
  3. Receiver:
     - Detects the light signal and converts it back into an electrical signal.
     - Contains a photodetector, amplification, and signal-restoring circuits.

Introduction

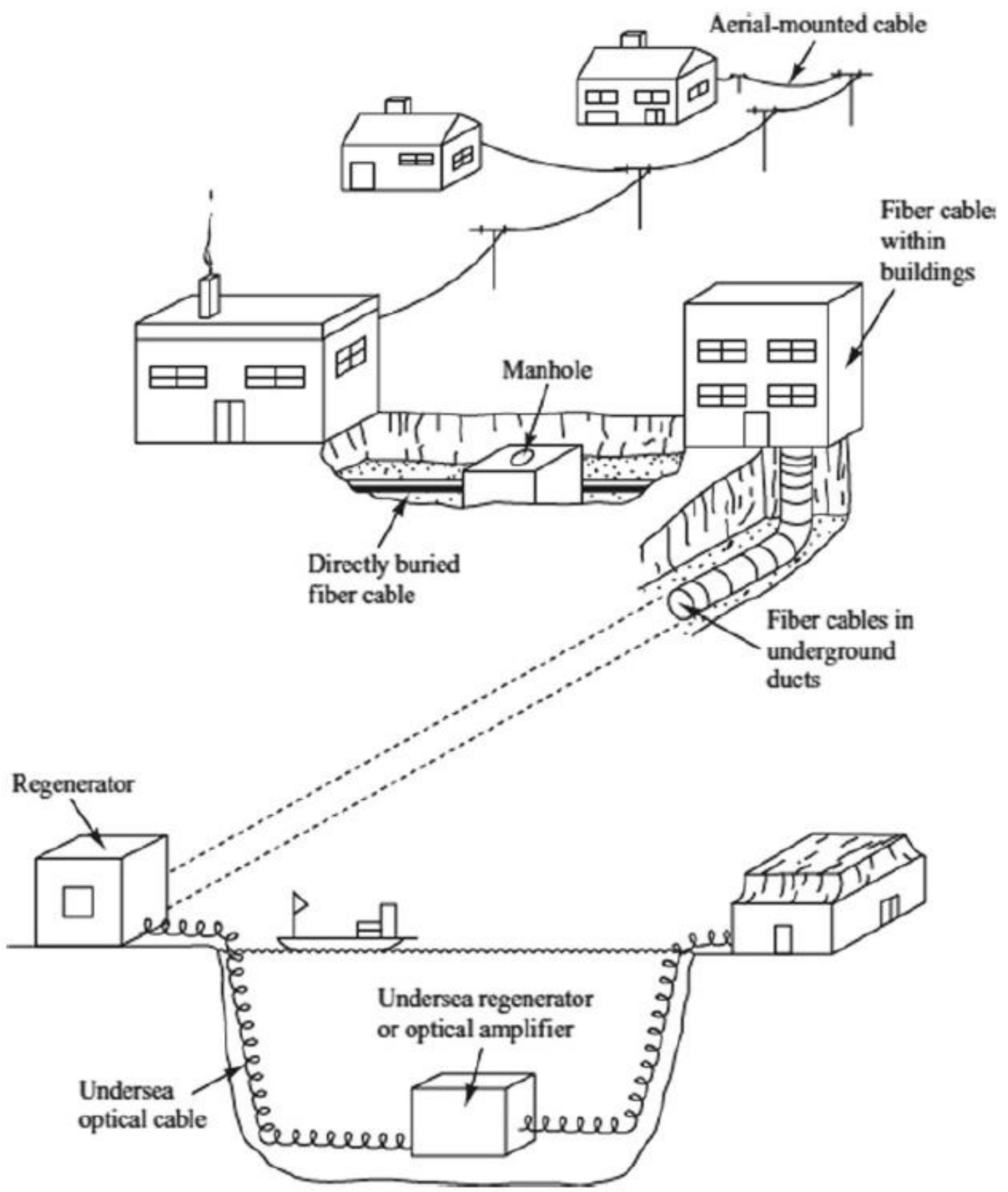
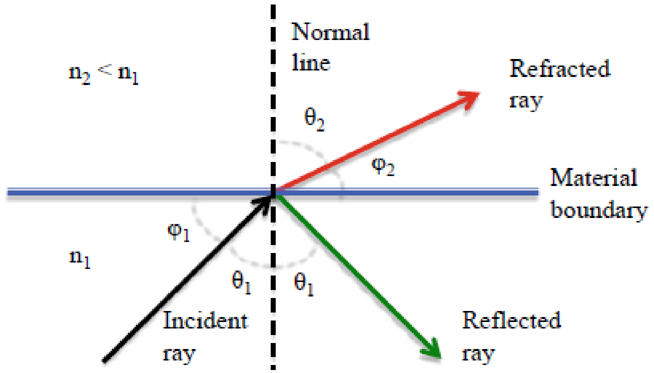


Fig. 1.11 Optical fiber cables can be installed on poles, in ducts, and underwater, or they can be buried directly in the ground

Introduction

Fig. 2.6 Refraction and reflection of a light ray at a material boundary



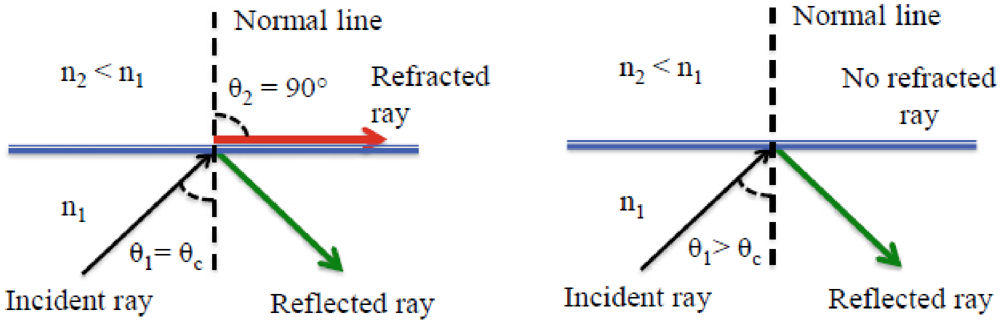


Fig. 2.7 Representation of the critical angle and total internal reflection at a glass-air interface, where n_1 is the refractive index of glass

- When a light ray encounters a boundary separating two different dielectric media, part of the ray is reflected back into the first medium and the remainder is bent (or refracted) as it enters the second material.
- The relationship at the interface is known as *Snell's law* and is given by

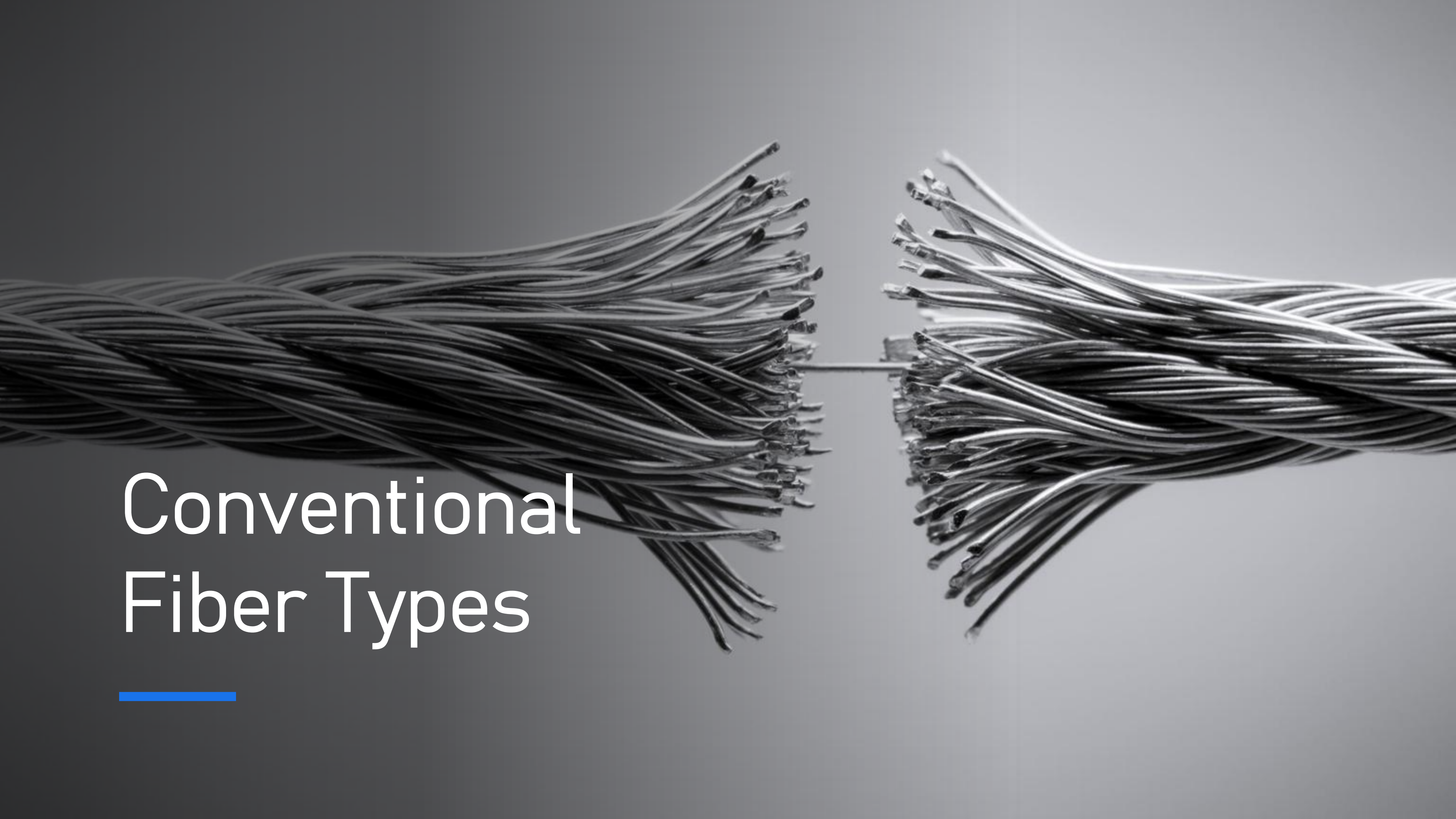
$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

- Total Internal Reflection occurs when light travels from a denser to a less dense medium and the angle of incidence is greater than the critical angle.
- The critical angle is determined from the condition

$$\sin \theta_c = \frac{n_2}{n_1}$$

Optical Fiber Configurations and Modes

Conventional Fiber Types



Optical Fiber Basics

- An optical fiber is a dielectric waveguide that operates at optical frequencies.
- It confines and guides electromagnetic energy (light) along its axis.
- The propagation of light along a waveguide can be described in terms of a set of guided electromagnetic waves called the *modes* of the waveguide.
- The fiber's structure determines its information-carrying capacity.

The Structure of a Fiber

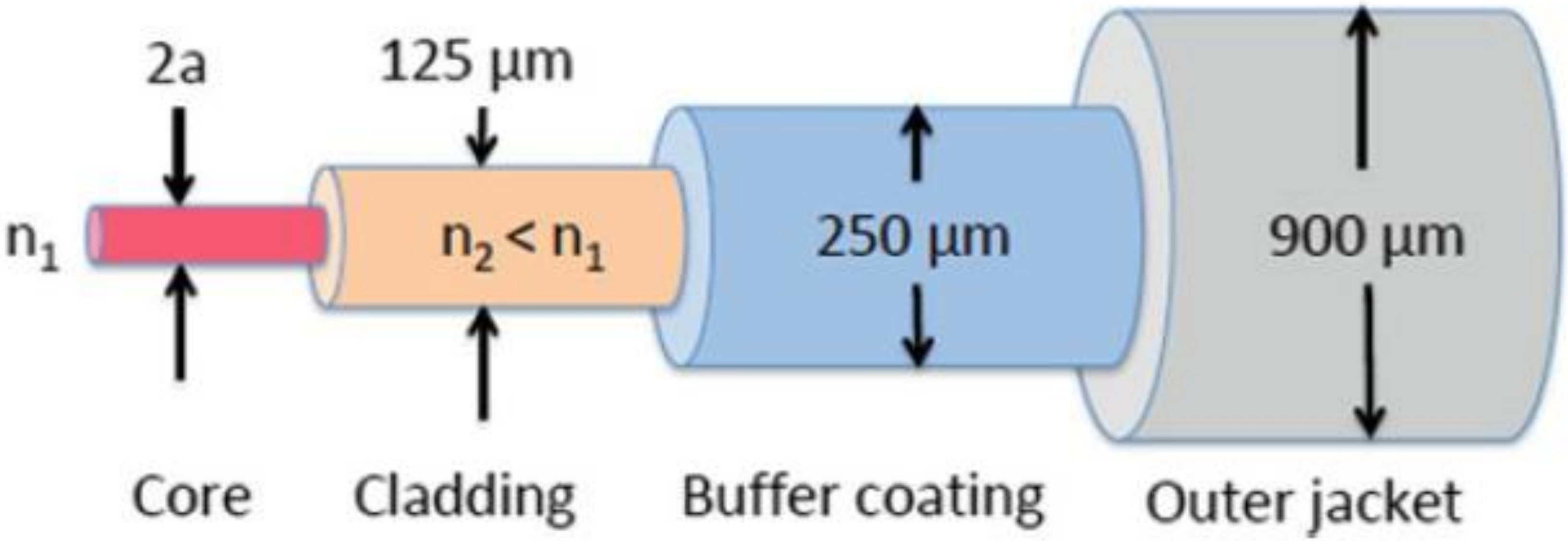


Fig. 2.14 A conventional silica fiber has a circular solid core of refractive index n_1 surrounded by a cladding with a refractive index $n_2 < n_1$; an elastic plastic buffer encapsulates the fiber

The Structure of a Fiber

- A standard optical fiber has three concentric layers:
  - **Core**:
    - The central part where light travels.
    - Made of highly pure silica glass (SiO_2).
    - Refractive Index n_1 and radius a.
  - **Cladding**:
    - Surrounds the core to enable light propagation.
    - Refractive Index: n_2 (where $n_2 < n_1$)
  - **Coating/Jacket**:
    - Outer plastic layers for protection and mechanical strength.

Conventional Fiber Types

- Based on Refractive Index Profile
  - Step-Index Fiber
  - Graded-Index Fiber
- Based on Propagation Modes
  - Single-Mode Fiber
  - Multimode Fiber

Fiber Types by Refractive Index Profile

The composition of the core creates two primary types:

- Step-Index Fiber
  - The core has a uniform refractive index.
  - Features an abrupt change (a "step") in refractive index at the core-cladding boundary.
- Graded-Index Fiber
  - The core's refractive index is not uniform.
  - It decreases gradually from the center of the core towards the cladding.

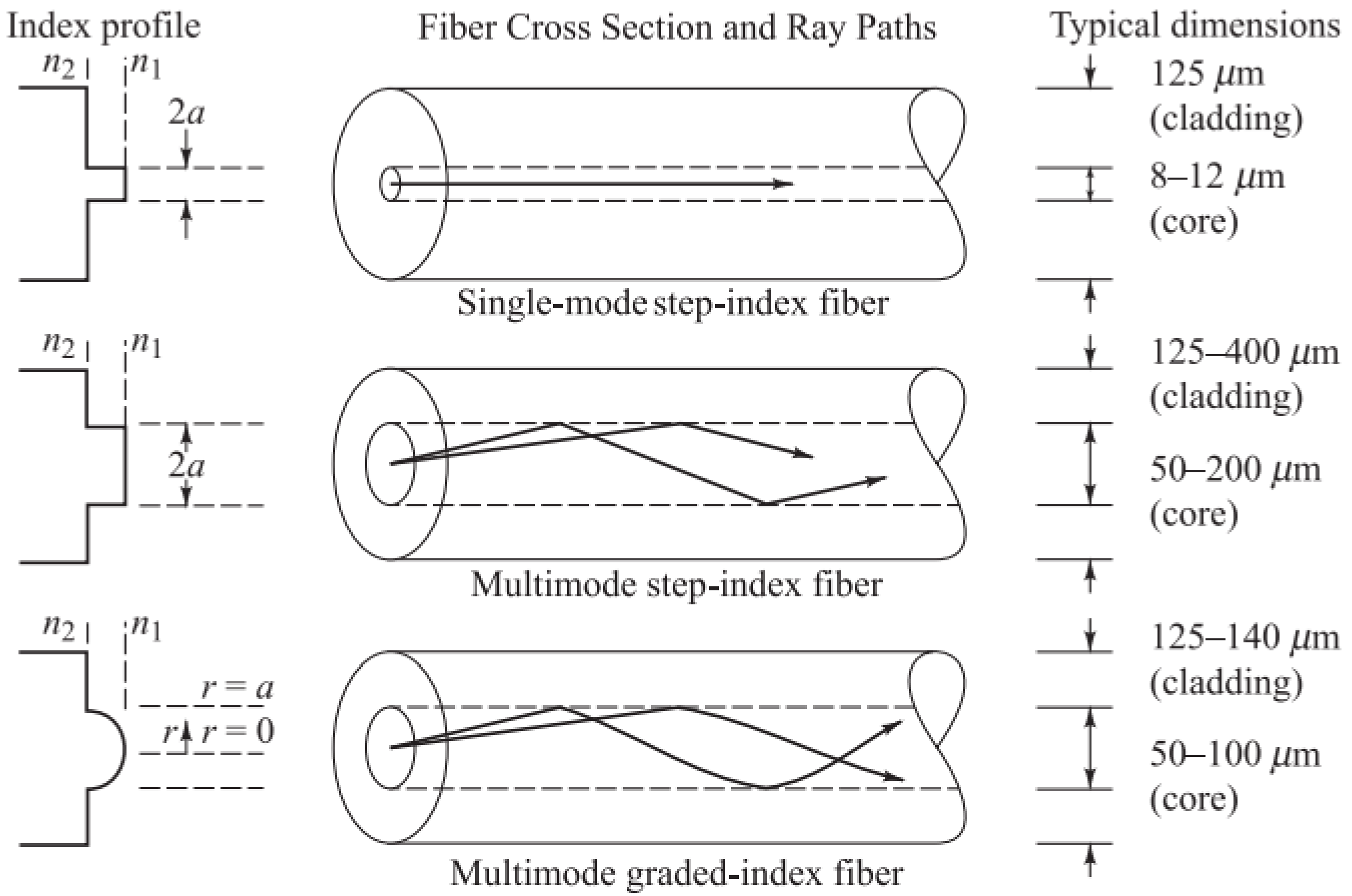
Fiber Types by Propagation Modes

Fibers can also be classified by how many modes they carry:

- Single-Mode Fiber
  - Sustains only one mode of propagation.
  - Has a very small core radius (e.g., 9 µm).
- Multimode Fiber
  - Supports hundreds of modes.
  - Has a larger core radius (e.g., 50 µm).
  - Can be either step-index or graded-index.

Conventional Fiber Types

Fig. 2.15 Comparison of conventional single-mode and multimode step-index and graded-index optical fibers



Multimode Fiber

- Advantages
  - The larger core radii makes it easier to launch light into the fiber.
  - Connecting similar fibers is simpler.
  - Can be used with cheaper, more reliable LED light sources.
    - Single-mode fibers must generally be excited with laser diodes.
    - Although LEDs have less optical output power than laser diodes, they are easier to make, are less expensive, require less complex circuitry, and have longer lifetimes than laser diodes.
- Disadvantage
  - Performance is limited by Intermodal Dispersion.

Intermodal Dispersion

- This effect occurs only in multimode fibers.
- When a pulse of light enters the fiber, it spreads across many modes.
  - Each mode travels at a slightly different velocity.
- The modes arrive at the destination at different times, causing the signal pulse to spread out and lose its integrity.
  - This limits the fiber's bandwidth (data rate).

Intermodal Dispersion

- Solutions to Dispersion
  - Graded-Index Fibers:
    - The graded profile helps to equalize the travel times of the different modes, significantly reducing intermodal dispersion compared to step-index fibers.
    - This allows for higher bandwidth.
  - Single-Mode Fibers:
    - By allowing only one mode to propagate, intermodal dispersion is completely eliminated.
    - This is the best solution for achieving maximum bandwidth and distance.

Concepts of Rays and Modes

Concepts of Rays and Modes

- Light guidance in an optical fiber can be understood through two different models:
  - Electromagnetic Modal Analysis (The "Wave" View)
    - An exact, rigorous approach based on wave theory.
    - Views light as a set of discrete "guided modes."
  - Geometrical Optics (The "Ray" View)
    - A simplified, intuitive approximation.
    - Views light as rays undergoing total internal reflection.

Modal Analysis: The Wave View

- A mode is a specific, stable electromagnetic field pattern that propagates along the fiber.
- It's described mathematically by its time and position dependence:

$$e^{j(\omega t - \beta z)}$$

- The factor β is the z component of the wave propagation constant $k = 2\pi/\lambda$ and is the main parameter of interest in describing fiber modes.
- Only a discrete, finite number of modes are allowed in any given fiber.
- These are the solutions that satisfy Maxwell's Equations and the core-cladding boundary conditions.

Geometrical Optics: Ray-Tracing Approach

- This approach provides a good approximation when the fiber core is much larger than the light's wavelength.
  - This is known as the *small-wavelength limit.*
- Best suited for multimode fibers.
- Main Advantage:
  - It offers a direct and intuitive physical picture of light guidance.
  - It simplifies the analysis by treating light as simple rays of light.

Concepts of Rays and Modes

- The two concepts are fundamentally linked.
- A single guided mode can be thought of as a superposition of many plane waves.
- These waves interfere to create a stable, standing-wave pattern across the fiber's cross-section.
- This group of waves corresponds to a set of rays (a "ray congruence") that all travel at the exact same angle relative to the fiber axis.

Concepts of Rays and Modes

- Simple ray theory suggests any angle greater than the critical angle can propagate.
- However, the wave nature of light imposes a condition: a standing wave must be formed.
- This condition ***quantizes*** the possible propagation angles.
- Since there is a finite number of modes (M), there is also a finite number (M) of allowed ray angles.

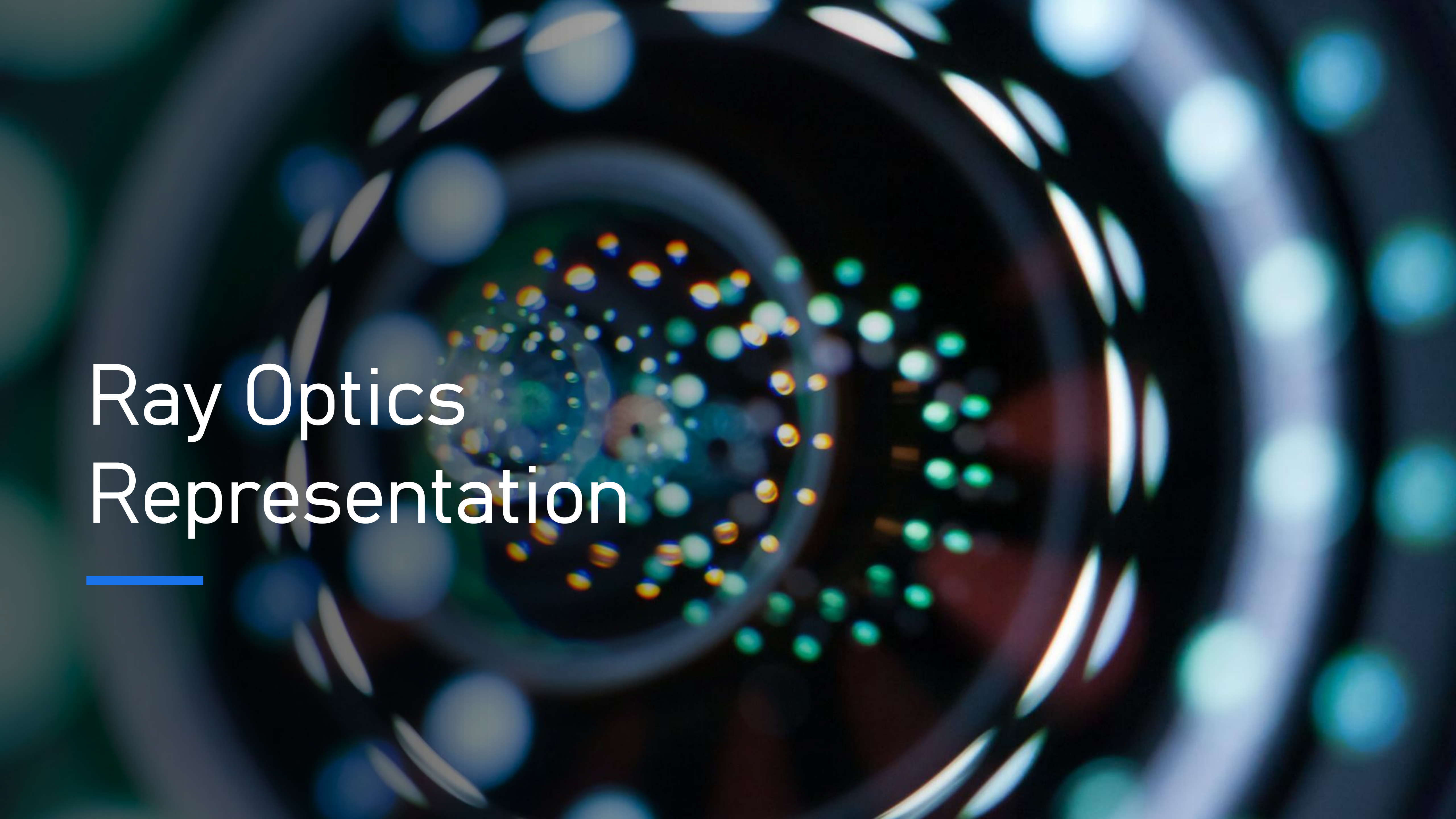
Discrepancies & Limitations of the Ray Approach

- While intuitive, the ray model is an approximation and breaks down in several key areas.
  - **Single-Mode Fibers:** It is inaccurate for single-mode or few-mode fibers where the wave nature of light is dominant.
  - **Wave Phenomena:** It cannot explain wave-based effects like **coherence** and **interference**.
  - **Field Distribution:** It provides no information on the actual shape (intensity profile) of the light propagating in the core.
  - **Bending Loss:** A major failure of the ray model is its prediction for bent fibers.
    - **Ray Optics (Incorrect):** Erroneously predicts that some rays can remain perfectly guided without any loss through a bend.
    - **Modal Analysis (Correct):** Correctly shows that **every** guided mode will experience some degree of radiation loss due to the bend.

Structure of Step-Index Fibers

Structure of Step-Index Fibers

- A step-index fiber consists of a central **core** surrounded by an outer layer called the **cladding**.
- **Core:**
  - Has a radius *a* and a uniform refractive index n_1 (typically ~1.48).
- **Cladding:**
  - Has a slightly lower uniform refractive index n_2.
- The relationship is defined by: $n_2 = n_1(1 - \Delta)$.
  - The parameter Δ is called the *core-cladding index difference* or simply the *index difference.*
    - **Typical Δ Values:**
      - **Multimode Fibers:** 1% to 3%
      - **Single-Mode Fibers:** 0.2% to 1.0%
- **Guiding Principle:**
  - Light is trapped and guided along the fiber because the core's refractive index is higher than the cladding's ($n_1 > n_2$), causing **total internal reflection** at the core-cladding interface.



Ray Optics Representation

Ray Optics Representation

- Two Types of Propagating Rays:
  - Meridional Rays
  - Skew Rays

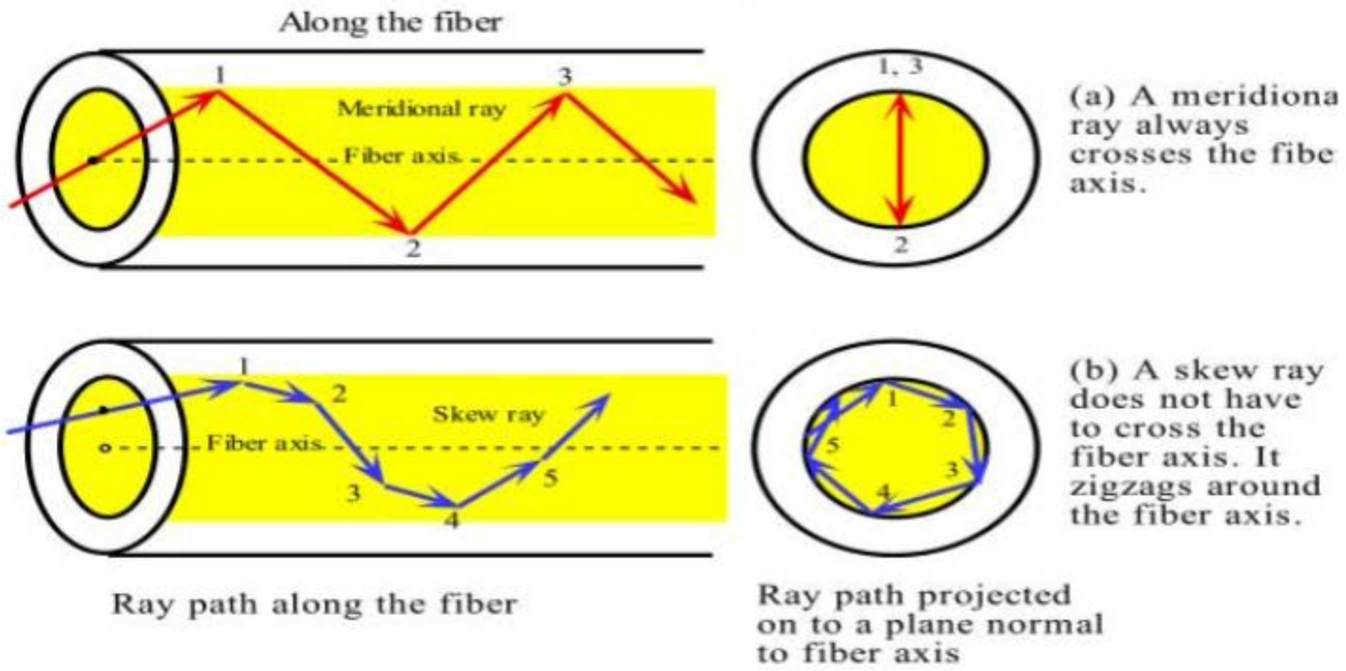


Illustration of the difference between a meridional ray and a skew ray. Numbers represent reflections of the ray.

Meridional Rays: The Zigzag Path

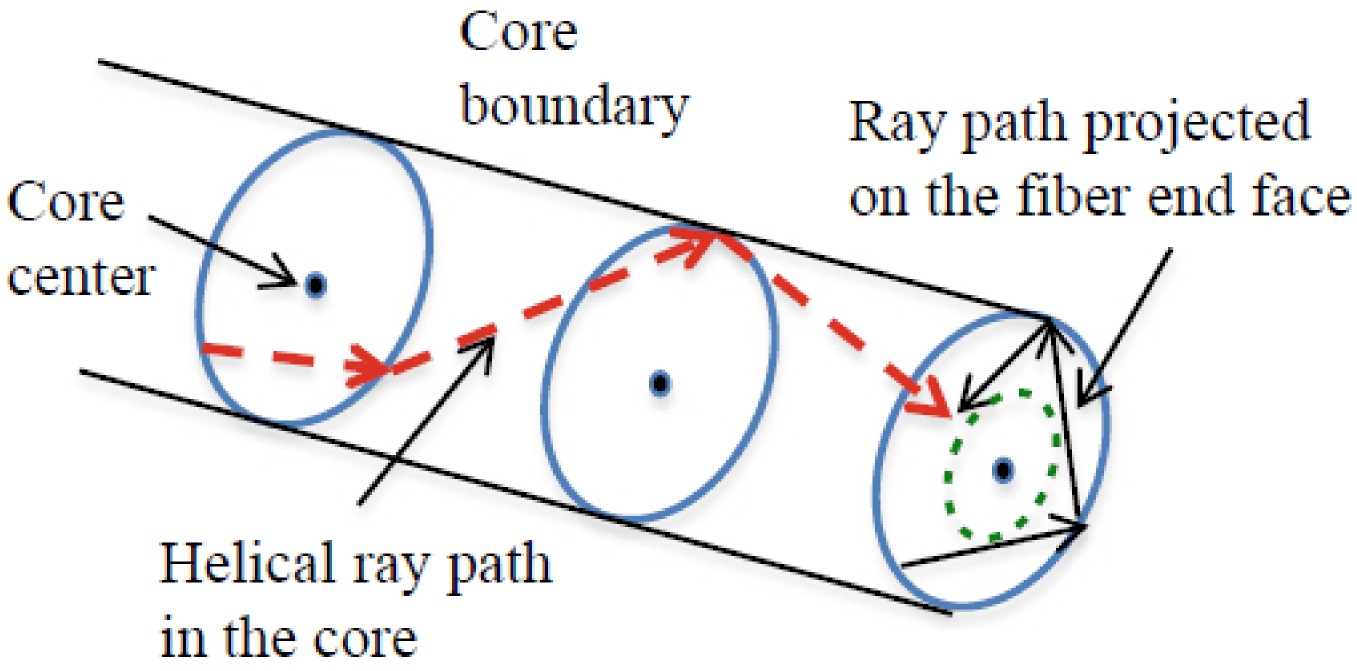
- Confined to a single plane that contains the central axis of the fiber.
- Travels in a simple **zigzag pattern**, crossing the fiber axis after each reflection.
- Relatively easy to track and analyze.
- **Types:**
  - **Bound Rays:** Trapped in the core by total internal reflection.
  - **Unbound Rays:** Refracted out of the core and lost.

Skew Rays: The Helical Path

- **Not** confined to a single plane.
- Follows a spiral or **helical-type path** along the fiber, never crossing the central axis.
- **Significance:**
  - Skew rays constitute a **major portion** of the total guided light.
  - They must be included in analyses for accurate calculations of light-gathering ability and power loss.

Skew Rays: The Helical Path

Fig. 2.16 Ray optics representation of skew rays traveling in a step-index optical fiber core



Skew Rays: The Helical Path

- Many rays that ray optics predicts are trapped (especially skew rays) are actually "leaky rays”.
- These rays are only **partially confined** to the core and **attenuate** (lose power) as they travel along the fiber.
- This attenuation from leaky rays **cannot be explained by pure ray theory**.
  - A full analysis of this radiation loss requires the more advanced **mode theory**.

Critical Angle

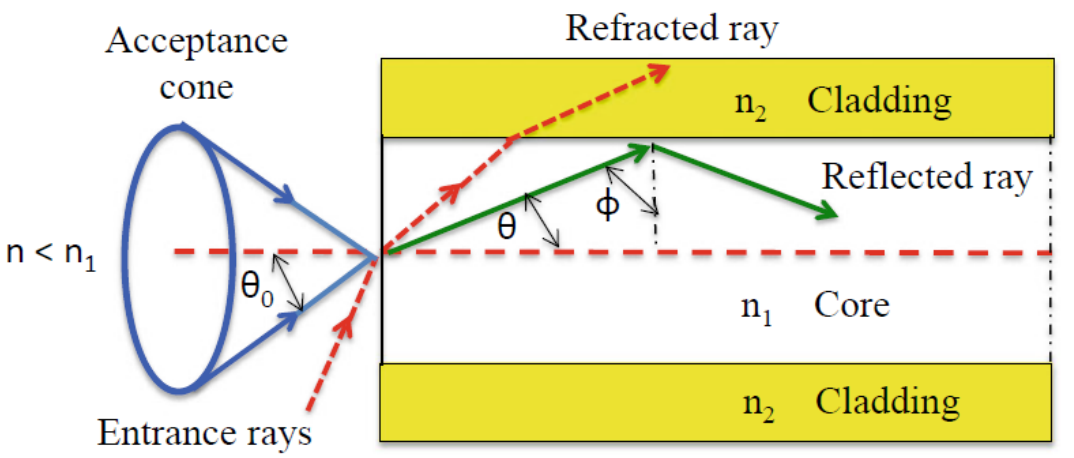


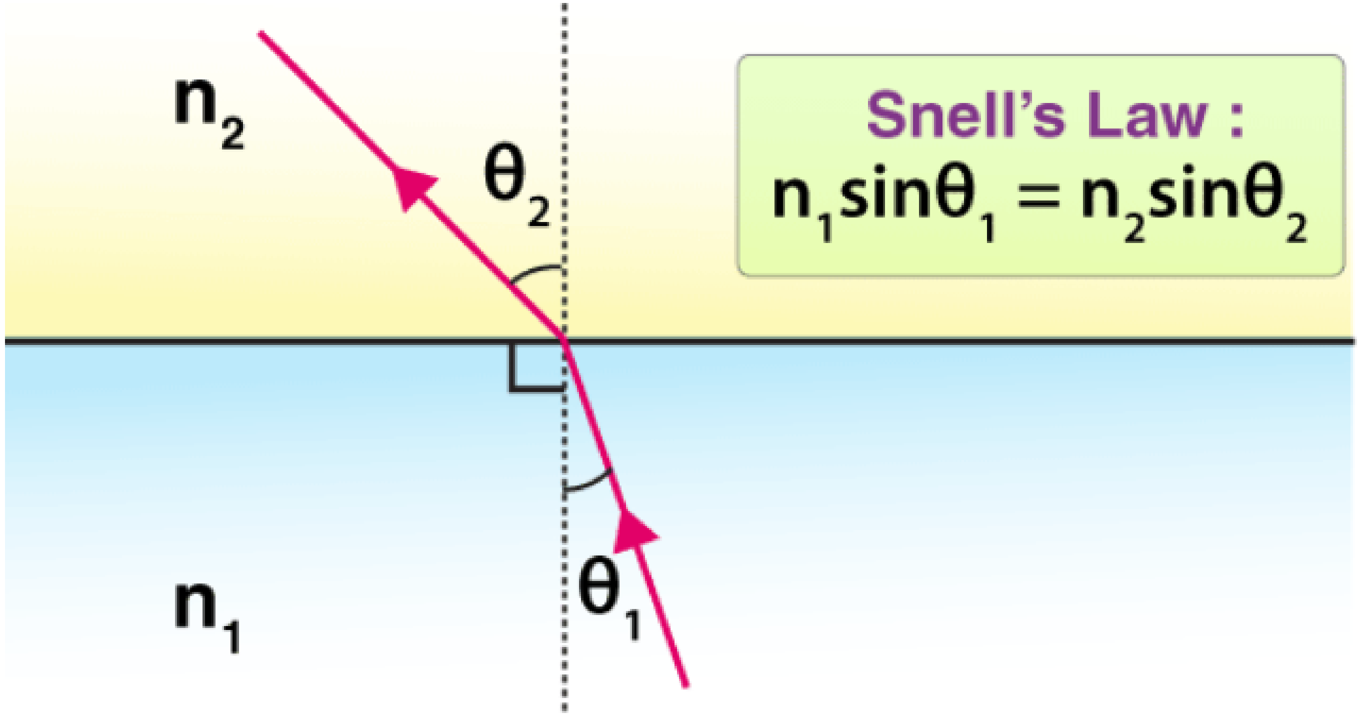
Fig. 2.17 Meridional ray optics representation of the propagation mechanism in an ideal step-index optical waveguide

- Light is guided via **Total Internal Reflection (TIR)** at the core-cladding interface.
- The light ray enters the fiber core from a medium of refractive index n at an angle θ_0 with respect to the fiber axis and strikes the core-cladding interface at a normal angle ϕ.
- **Critical Angle (ϕ_c)**: The minimum angle at the interface for TIR to occur.

$$sin\ \phi_c = \frac{n_2}{n_1}$$

  - Rays striking at an angle $< \phi_c$ are refracted out and lost.

Snell's Law



Acceptance Angle and Acceptance Cone

- **Acceptance Angle ($\boldsymbol{\theta_A}$):** The **maximum** angle at which a ray can enter the fiber and still be guided.

$$n\ sin\ \theta_{0,max} = n\ sin\ \theta_A = n_1 sin\ \theta_c = \left(n_1^2 - n_2^2\right)^{1/2}$$

  where $\theta_c = \pi/2 - \phi_c$.

- Those rays having entrance angles θ_0 less than θ_A will be totally internally reflected at the core–cladding interface.
- Thus θ_A defines an **acceptance cone**, which represents the fiber's field of view for capturing light.

Numerical Aperture

- The Numerical Aperture (NA) is the key parameter that measures a fiber's light-gathering capability.
- It's directly related to the acceptance angle.
- For a ray entering from air (where n ≈ 1): $NA = \sin\theta_A$
- It can be calculated directly from the core (n_1) and cladding (n_2) refractive indices:

$$NA = n\sin\theta_A = \sqrt{n_1^2 - n_2^2} \approx n_1\sqrt{2\Delta}$$

Numerical Aperture

- A higher NA means a wider acceptance cone and better light collection.
- It is a dimensionless quantity.
- Typical values range from 0.14 to 0.50.

Example 2.5 Consider a multimode silica fiber that has a core refractive index $n_1 = 1.480$ and a cladding index $n_2 = 1.460$. Find (a) the critical angle, (b) the numerical aperture, and (c) the acceptance angle.

Solution:

(a) The critical angle is given by

$$\varphi_c = sin^{-1}\frac{n_2}{n_1} = sin^{-1}\frac{1.460}{1.480} = 80.5°$$

(b) The numerical aperture is

$$NA = \sqrt{n_1^2 - n_2^2} = 0.242$$

(c) The acceptance angle in air ($n = 1.00$) is

$$\theta_A = \sin^{-1} NA = \sin^{-1} 0.242 = 14^{\circ}$$

Example 2.6 Consider a multimode fiber that has a core refractive index of 1.480 and a core-cladding index difference of 2.0% ($\Delta = 0.020$). Find (a) the numerical aperture, (b) the acceptance angle, and (c) the critical angle.

Solution:

The cladding index is

$$n_2 = n_1(1 - \Delta) = 1.480(0.980) = 1.450$$

(a) The numerical aperture is

$$NA = n_1\sqrt{2\Delta} = 1.480\sqrt{0.04} = 0.296$$

(b) The acceptance angle in air ($n = 1.00$) is

$$\theta_A = \sin^{-1}\mathrm{NA} = \sin^{-1}0.296 = 17.2°$$

(c) The critical angle at the core–cladding interface is

$$\varphi_c = sin^{-1}\frac{n_2}{n_1} = sin^{-1}0.980 = 78.5°$$

Drill Problem 2.3 Consider the interface between fiber core and cladding materials that have refractive indices of n_1 and n_2, respectively. If n_2 is smaller than n_1 by 1% and $n_1 = 1.450$, show that $n_2 = 1.435$. Show that the critical angle is $\varphi_c = 81.9°$.

Solution:

The cladding index is

$$n_2 = n_1(1 - \Delta) = 1.450(0.99) = 1.435$$

The numerical aperture is

$$\varphi_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1}\frac{1.435}{1.450} = 81.9°$$

Modes in Circular Waveguides

Basic Modal Concepts

- To understand complex optical fibers, we use a simpler model – **the planar dielectric slab waveguide.**
- Structure:
  - Core: A central slab with a high refractive index (n_1).
  - Cladding: Two surrounding layers with a lower refractive index (n_2).
- The fundamental condition for guiding light is $n_1 > n_2$.
- Modes are the specific, stable patterns of the electromagnetic field that can propagate through a waveguide.
- **Mode Order:** A key characteristic of a mode.
  - Defined by the **number of field zeros** (points where the field is zero) across the core.
  - Related to the propagation angle: **steeper angle = higher-order mode**.

Basic Modal Concepts

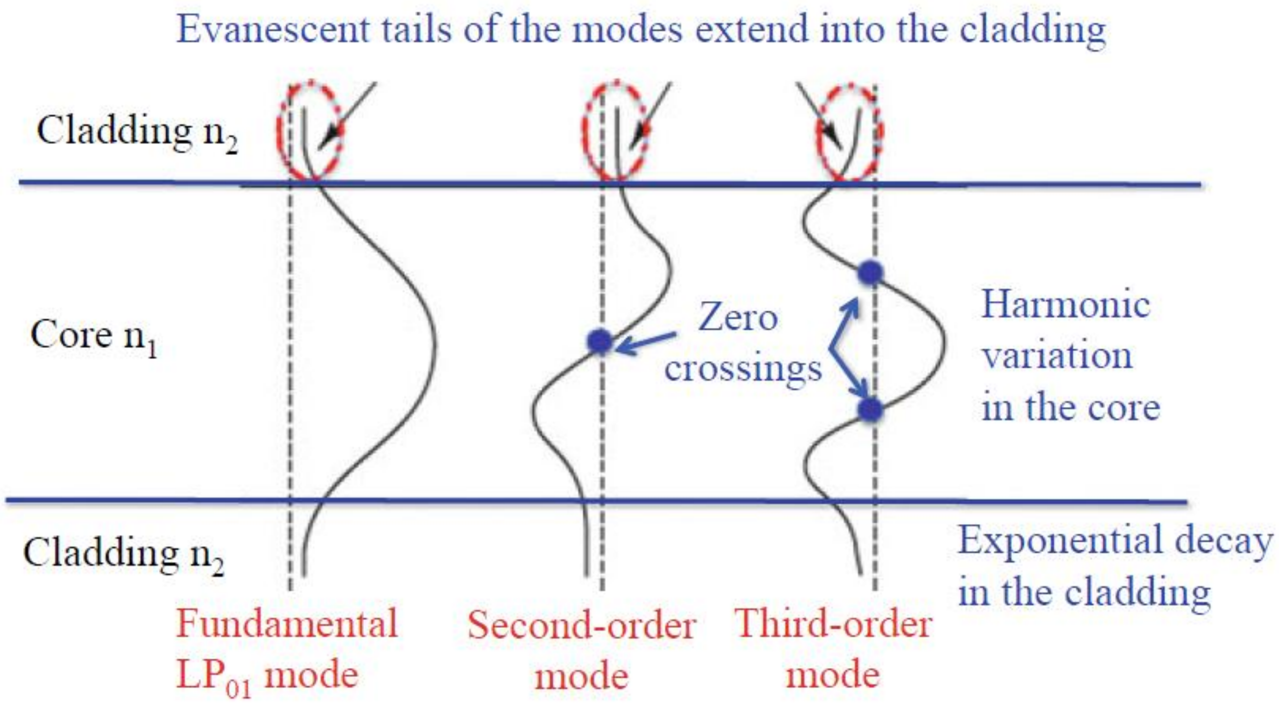


Fig. 2.19 Electric field distributions for several of the lower-order guided modes in a symmetrical-slab waveguide

Field Distribution of Guided Modes

- The electric field of a guided mode is not entirely trapped in the core.
  - Inside the Core ($\boldsymbol{n_1}$): The field has a harmonic (sine-wave-like) shape.
  - Inside the Cladding ($\boldsymbol{n_2}$): The field decays exponentially but does not go to zero at the interface.
- All guided modes extend partially into the cladding.
- Lower vs. Higher-Order Modes
  - Low-Order Modes:
    - Tightly concentrated near the center of the core.
    - Penetrate very little into the cladding.
    - Represent light traveling nearly parallel to the fiber axis.
  - Higher-Order Modes:
    - More spread out towards the edges of the core.
    - Penetrate much farther into the cladding.

The Different Types of Modes

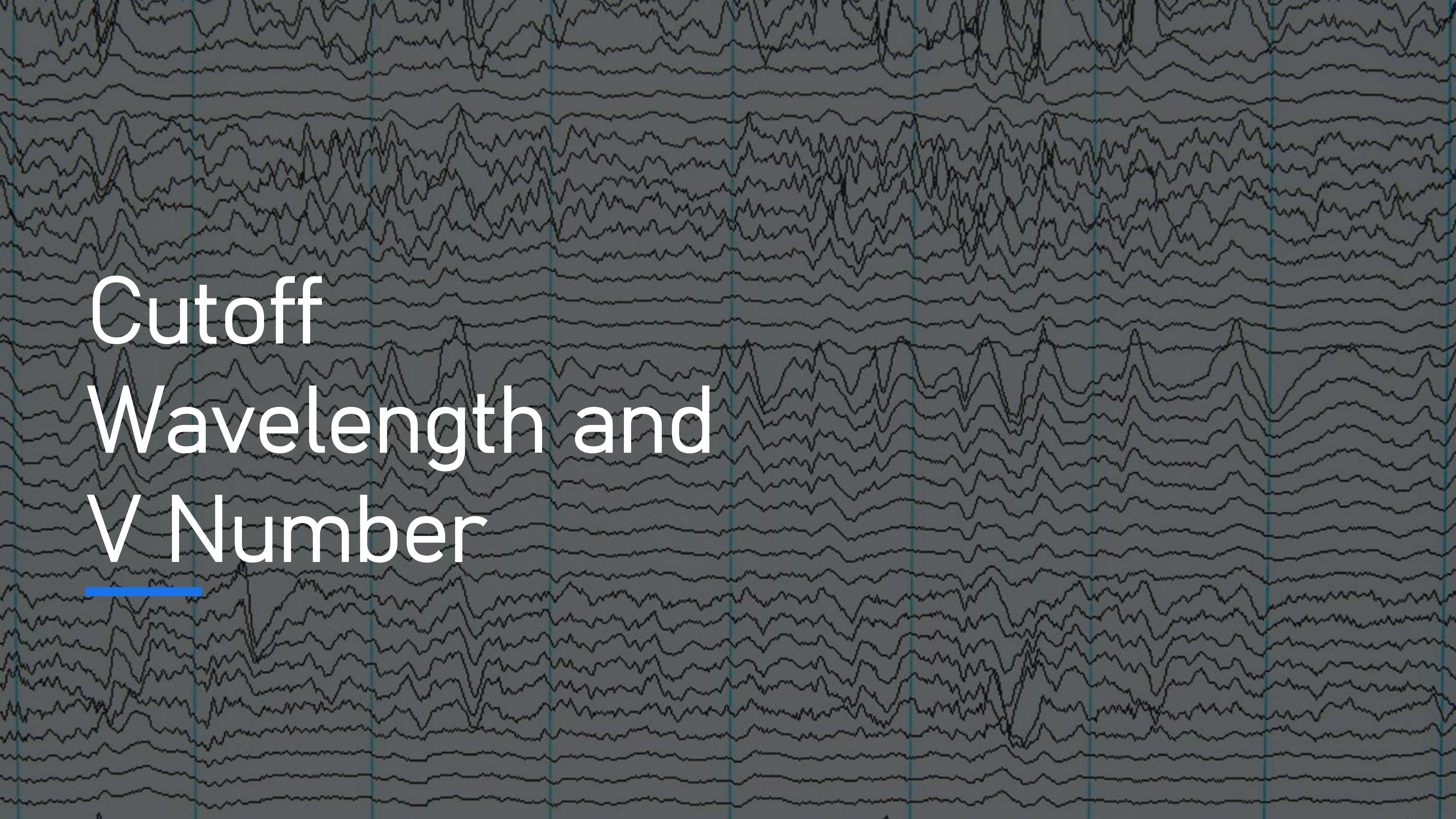
- Guided Modes:
  - Trapped in the core and propagate along the fiber.
  - Condition: $n_{2k} < \beta < n_{1k}$ (where β is the propagation constant).
- Radiation Modes:
  - Unguided light that refracts out of the core.
- Cladding Modes:
  - Radiation modes that become trapped and propagate within the cladding layer.

Mode Coupling & Power Loss

- The fields of guided core modes extend into the cladding, where they can overlap and interact with cladding modes.
- This overlap causes **mode coupling**, a process where power diffuses back and forth between the core and cladding.
- A net loss of signal power from the guided core modes as they travel down the fiber.

Mode Cutoff & Leaky Modes

- **Mode Cutoff:** The point at which a mode is no longer effectively guided.
  - This occurs when the propagation condition is at its limit: $\beta = n_{2k}$.
  - Below cutoff ($\beta < n_{2k}$), modes become radiation modes.
- **Leaky Modes:** A special case below cutoff.
  - They are partially confined and can travel a considerable distance.
  - They continuously "leak" power into the cladding, causing signal attenuation.



Cutoff Wavelength and V Number

The V Number (Normalized Frequency)

- V Number is a dimensionless parameter, also called normalized frequency or V *parameter*), that determines the number of modes an optical fiber can support.
- It connects the fiber's physical properties to the wavelength of light being transmitted.
- The V number is defined as:

$$V = \frac{2\pi a}{\lambda_c} NA = \frac{2\pi a}{\lambda_c} \sqrt{n_1^2 - n_2^2} \approx \frac{2\pi a}{\lambda_c} n_1 \sqrt{2\Delta}$$

- V number decides how many modes will travel through the fiber.
- The number of modes that can exist in a waveguide as a function of *V* may be represented in terms of a *normalized propagation constant b* defined by

$$b = \frac{(\beta/k)^2 - n_2^2}{n_1^2 - n_2^2}$$

The V Number (Normalized Frequency)

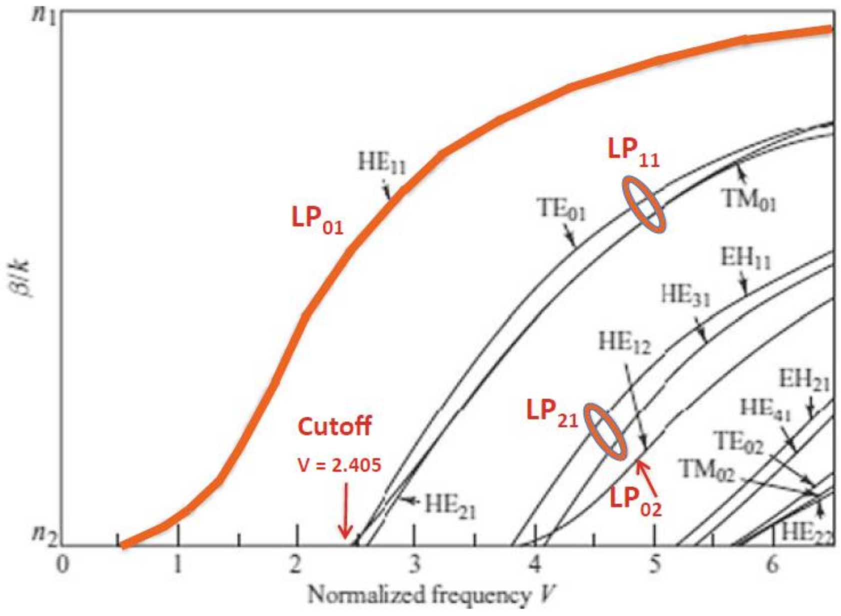


Fig. 2.20 Plots of the propagation constant (in terms of β/k) as a function of V for a few of the lowest-order modes

- Figure 2.20 gives a plot of *b* (in terms of *β/k)* as a function of *V* for a few of the low-order modes.
- This figure shows that except for the lowest-order HE_{11} mode, each mode can exist only for values of *V* that exceed a certain limiting value (with each mode having a different *V* limit).

Modes and the Cutoff Condition

- Each light mode (e.g., HE_{11}, TE_{01}, TM_{01}) has a minimum V number required for it to propagate through the fiber.
  - If the fiber's V number is below this minimum value for a specific mode, that mode is **"cut off"** and cannot exist.
- **The Cutoff Wavelength (λ_c)**
  - This is the specific wavelength at which a mode is cut off.
  - For any given fiber, operating it at a wavelength longer than λ_c will cut off higher-order modes.
- The fundamental mode, **HE_{11}**, is unique because it has **no cutoff**.
  - It can always propagate, as long as the fiber core exists. This is the foundation for single-mode fiber.

Modes and the Cutoff Condition

- The condition for single-mode operation is:

$$V = \frac{2\pi a}{\lambda} NA = \frac{2\pi a}{\lambda} \sqrt{n_1^2 - n_2^2} \leq 2.405$$

- This is achieved by appropriately choosing a, n_1, and n_2 so that all modes except the HE_{11} mode are cut off.

Practical Standards

- Industry standards ensure reliable performance.
- The **ITU-T G.652** recommendation states the effective cutoff wavelength (λ_c) should be **1260 nm or less**.
- This guarantees the fiber operates in single-mode for the crucial 1310 nm and 1550 nm communication windows.

V Number and Mode Count

- In a multimode step-index fiber, the V number can be used to estimate the total number of modes (M) it can support, especially when V is large.
- For the multimode step-index case, an estimate of the total number of modes supported in such a fiber is:

$$M = \frac{1}{2}\left(\frac{2\pi a}{\lambda}\right)^2 (n_1^2 - n_2^2) = \frac{V^2}{2}$$

Example 2.7 A step-index fiber has a normalized frequency $V = 26.6$ at a 1300 nm wavelength. If the core radius is 25 μm, what is the numerical aperture?

Solution:

- The Numerical Aperture is

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

$$NA = 26.6 \times \frac{1300\times10^{-9}}{2\pi\times25\times10^{-6}}$$

$$NA = 0.22$$

Example 2.8 Consider a multimode step-index fiber with a 62.5 μm core diameter and a core-cladding index difference of 1.5%. If the core refractive index is 1.480, estimate the normalized frequency of the fiber and the total number of modes supported in the fiber at a wavelength of 850 nm.

Solution:

- The normalized frequency is

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

$$= \frac{2\pi a}{\lambda} n_1 \sqrt{2\Delta}$$

$$= \frac{2\pi \times 31.25\mu m}{0.85\mu m} \times 1.480 \times \sqrt{2 \times 0.015}$$

$$= 59.2$$

Example 2.8 Consider a multimode step-index fiber with a 62.5 μm core diameter and a core-cladding index difference of 1.5%. If the core refractive index is 1.480, estimate the normalized frequency of the fiber and the total number of modes supported in the fiber at a wavelength of 850 nm.

- The total number of modes is

$$M = \frac{V^2}{2}$$

$$M = \frac{59.2^2}{2}$$

$$M = 1752$$

Example 2.9 Consider a multimode step-index optical fiber that has a core radius of 25 μm, a core index of 1.48, and an index difference $\Delta = 0.01$. How many modes are in the fiber at wavelengths 860, 1310, and 1550 nm?

Solution:

(a) At $\lambda = 860\ nm,$ the value of V is $V = \frac{2\pi a}{\lambda} n_1 \sqrt{2\Delta}$

$$= \frac{2\pi \times 25\mu m}{0.86\mu m} \times 1.480 \times \sqrt{2 \times 0.01}$$

$$= 38.2$$

The total number of modes is $M = \frac{V^2}{2}$

$$M = \frac{38.2^2}{2} = 729$$

Example 2.9 Consider a multimode step-index optical fiber that has a core radius of 25 μm, a core index of 1.48, and an index difference $\Delta = 0.01$. How many modes are in the fiber at wavelengths 860, 1310, and 1550 nm?

(b) At $\lambda = 1310\ nm$, the value of V is $V = \frac{2\pi a}{\lambda} n_1 \sqrt{2\Delta}$

$$= \frac{2\pi \times 25\mu m}{1.31\mu m} \times 1.480 \times \sqrt{2 \times 0.01}$$

$$= 25.1$$

The total number of modes is $M = \frac{V^2}{2}$

$$M = \frac{25.1^2}{2} = 315$$

Example 2.9 Consider a multimode step-index optical fiber that has a core radius of 25 μm, a core index of 1.48, and an index difference $\Delta = 0.01$. How many modes are in the fiber at wavelengths 860, 1310, and 1550 nm?

(c) At $\lambda = 1550\ nm$, the value of V is $V = \frac{2\pi a}{\lambda} n_1 \sqrt{2\Delta}$

$$= \frac{2\pi \times 25\mu m}{1.55\mu m} \times 1.480 \times \sqrt{2 \times 0.01}$$

$$= 21.2$$

The total number of modes is $M = \frac{V^2}{2}$

$$M = \frac{21.2^2}{2} = 224$$

Example 2.10 Consider three multimode step-index optical fibers each of which has a core index of 1.48 and an index difference $\Delta = 0.01$. Assume the three fibers have core diameters of 50, 62.5, and 100 μm. How many modes are in these fibers at a wavelength of 1550 nm?

Solution:

(a) At a core diameter of $50\ \mu m, a = 25\ \mu m,$

the value of *V* is $V = \frac{2\pi a}{\lambda} n_1 \sqrt{2\Delta}$

$$= \frac{2\pi \times 25\mu m}{1.55\mu m} \times 1.480 \times \sqrt{2 \times 0.01}$$

$$= 21.2$$

The total number of modes is $M = \frac{V^2}{2}$

$$M = \frac{21.2^2}{2} = 224$$

Example 2.10 Consider three multimode step-index optical fibers each of which has a core index of 1.48 and an index difference $\Delta = 0.01$. Assume the three fibers have core diameters of 50, 62.5, and 100 µm. How many modes are in these fibers at a wavelength of 1550 nm?

(b) At a core diameter of $62.5\ \mu m, a = 31.25\ \mu m,$

the value of V is $V = \frac{2\pi a}{\lambda} n_1 \sqrt{2\Delta}$

$$= \frac{2\pi \times 31.25 \mu m}{1.55 \mu m} \times 1.480 \times \sqrt{2 \times 0.01}$$

$$= 26.5$$

The total number of modes is $M = \frac{V^2}{2}$

$$M = \frac{26.5^2}{2} = 351$$

Example 2.10 Consider three multimode step-index optical fibers each of which has a core index of 1.48 and an index difference $\Delta = 0.01$. Assume the three fibers have core diameters of 50, 62.5, and 100 µm. How many modes are in these fibers at a wavelength of 1550 nm?

(c) At a core diameter of $100\ \mu m, a = 50\ \mu m,$

the value of V is $V = \frac{2\pi a}{\lambda} n_1 \sqrt{2\Delta}$

$$= \frac{2\pi \times 50 \mu m}{1.55 \mu m} \times 1.480 \times \sqrt{2 \times 0.01}$$

$$= 42.4$$

The total number of modes is $M = \frac{V^2}{2}$

$$M = \frac{42.4^2}{2} = 898$$

Single-Mode Fibers

Single-Mode Fibers

- In **multimode fibers**, different modes of light travel at different speeds, causing varied propagation delays.
- This leads to a phenomenon called **intermodal dispersion**, where the signal spreads out and gets distorted.
  - This dispersion effect ultimately limits the fiber's maximum data transmission speed (bandwidth).
- The solution is to use a **Single-Mode Fiber (SMF)**, which is designed to allow only one mode of light to propagate.
  - By guiding just a single mode, SMFs completely eliminate intermodal dispersion.

SMF Construction

- Single-mode fibers are created with two key features:
  - A very **small core diameter**, typically only 8 to 12 micrometers wide.
  - A **small refractive index difference** between the core and cladding, usually between 0.2% and 1.0%.
- For a fiber to be single-mode, its **V-number** (a value combining core size, wavelength, and index difference) must be less than **2.405**.
- In real-world designs, the core diameter and index difference are carefully chosen to make the V-number **just below 2.4**.
  - This ensures only the fundamental mode propagates while optimizing the fiber's performance.

Example 2.12 A manufacturing engineer wants to make an optical fiber that has a core index of 1.480 and a cladding index of 1.478. What should the core size be for single-mode operation at 1550 nm?

Solution:

- The condition for single-mode operation is $V \leq 2.405$

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} \leq 2.405$$

$$a \leq \frac{2.405 \times \lambda}{2\pi\sqrt{n_1^2 - n_2^2}}$$

$$a \leq \frac{2.405 \times 1.55\mu m}{2\pi\sqrt{1.480^2 - 1.478^2}}$$

$$a \leq 7.7\mu m$$

Example 2.13 An applications engineer has an optical fiber that has a 3.0 μm core radius and a numerical aperture of 0.1. Will this fiber exhibit single-mode operation at 800 nm?

Solution:

- The condition for single-mode operation is $V \leq 2.405$

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

$$V = \frac{2\pi \times 3\mu m}{0.8\mu m} \times 0.1$$

$$V = 2.356$$

Since $V < 2.405$, this fiber will exhibit single-mode operation at $800\ nm$.

Mode-Field Diameter (MFD)

- In single-mode fibers, the **Mode-Field Diameter (MFD)** is the fundamental parameter describing the size of the light distribution propagating through the fiber.
  - It's the equivalent of the "core diameter" for multimode fibers.
- Unlike in multimode fibers, the light in a single-mode fiber is **not entirely confined to the core**.
  - The MFD gives the effective diameter of this light field.
  - For example, at a V-number of 2.0, only about 75% of the optical power is actually inside the core; the rest travels in the cladding.

Mode-Field Diameter (MFD)

- MFD is a critical parameter, essential for predicting the performance and behavior of a single-mode fiber.
- Understanding the MFD allows engineers to calculate and predict several crucial properties:
  - Splice Loss (loss when joining two fibers)
  - Bending Loss (loss when the fiber is bent)
  - Cutoff Wavelength
  - Waveguide Dispersion

Mode-Field Diameter (MFD)

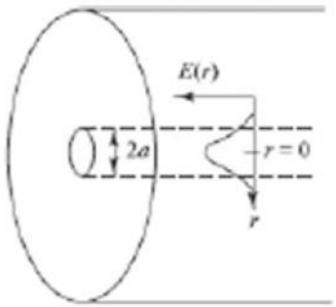
- The MFD is calculated from the mode-field distribution of the light.
- For practical purposes, the distribution of the electric field $E(r)$ is often modeled as a **Gaussian function**, especially for V-numbers between 1.8 and 2.4.

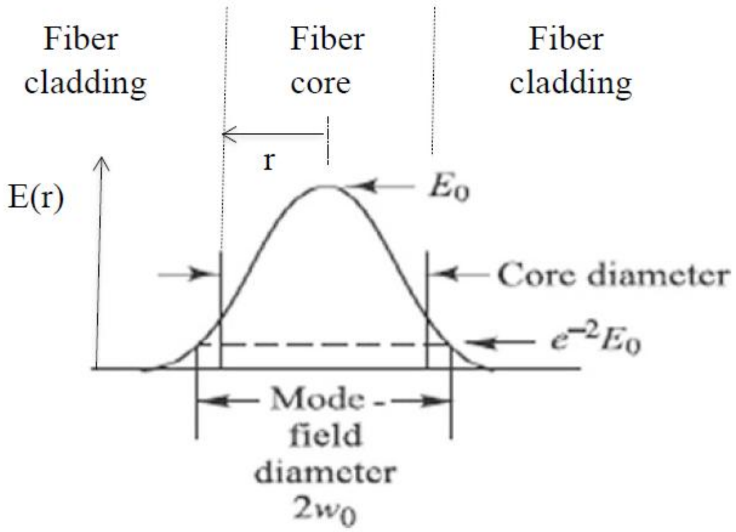
$$E(r) = E_0 exp\left(-r^2/w_0^2\right)$$

  - Here, ω_0 is the **spot size** (or mode-field radius).
- The MFD is simply twice the spot size ($MFD = 2\omega_0$).
  - It represents the width of the beam where the optical power drops to $1/e^2$ (about 13.5%) of its maximum value.

Mode-Field Diameter (MFD)

Fig. 2.21 Distribution of light in a single-mode fiber above its cutoff wavelength





Mode-Field Diameter (MFD)

- The MFD is directly related to the fiber's V-number.
- An approximate formula for the spot size (ω_0) is:

$$\frac{w_0}{a} = 0.65 + 1.619V^{-3/2} + 2.879V^{-6}$$

- As the V-number **decreases**, the spot size (ω_0) **increases**.
  - This means the light field spreads further out into the cladding.

Mode-Field Diameter (MFD)

- **The Design Trade-off:**
  - Too Low V-Number: The light is loosely bound, making it highly susceptible to bending losses.
  - Too High V-Number (> 2.405): The fiber starts carrying more than one mode.
- **Optimal Design Window:** Manufacturers typically design single-mode fibers with a V-number between **2.0 and 2.4** to balance tight light confinement and pure single-mode operation.

Origin of Birefringence

- Every standard single-mode fiber actually supports **two independent degenerate polarization modes** at the same time.
- These two modes are identical except that their electric field polarization planes are perpendicular (orthogonal) to each other, like horizontal (H) and vertical (V).
- Either one of these two polarization modes constitutes the fundamental HE_{11} mode.
- In general, the electric field of the light propagating along the fiber is a linear superposition of these two polarization modes and depends on the polarization of the light at the launching point into the fiber.

Origin of Birefringence

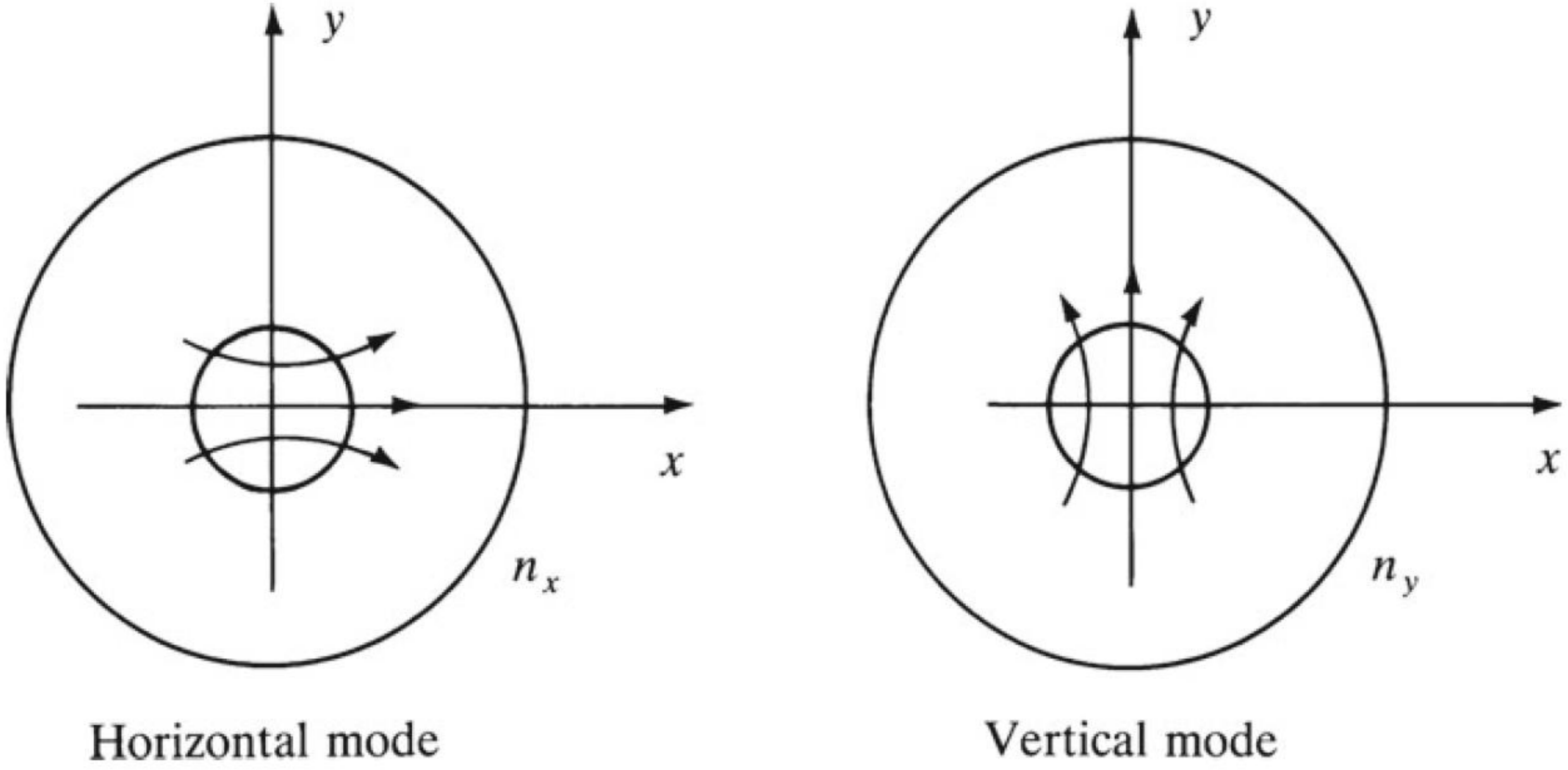


Fig. 2.22 Two polarizations of the fundamental HE_{11} mode in a single-mode fiber

Origin of Birefringence

- Real-world fibers are never geometrically perfect.
  - Causes of Imperfection:
    - Asymmetrical stresses from manufacturing or handling.
    - Non-circular cores (slightly elliptical).
    - Variations in the refractive index profile.
- These imperfections break the fiber's symmetry, causing the two polarization modes to travel at slightly different speeds.
- Birefringence: This phenomenon, where the two modes have different effective refractive indices, is called fiber *birefringence*.

Birefringence and Beat Length

- Birefringence ($\boldsymbol{B_f}$):
  - **Definition: Birefringence** is a measure of the difference in effective refractive index between the two orthogonal polarization modes.

$$B_f = \frac{\lambda}{2\pi}(\beta_x - \beta_y)$$

    where β_x and β_y are the propagation constants of the two modes.

- Beat Length ($\boldsymbol{L_B}$):
  - **Definition:** The **beat length** is the distance the light must travel for the initial polarization state to be repeated.
    - As the modes travel at different speeds, their relative phase shifts.

$$L_B = \frac{\lambda}{B_f} = \frac{2\pi}{(\beta_x - \beta_y)}$$

  - A shorter beat length implies a higher, more significant birefringence.

Example 2.15 A single-mode optical fiber has a beat length of 8 cm at 1310 nm. What is the birefringence?

Solution:

- The modal birefringence is

$$B_f = \frac{\lambda}{L_B}$$

$$= \frac{1310 \times 10^{-9} m}{8 \times 10^{-2} m}$$

$$= 1.64 \times 10^{-5}$$

- This is characteristic of an intermediate type fiber, because birefringence can vary from $B_f = 1 \times 10^{-3}$ (for a typical high birefringence fiber) to $B_f = 1 \times 10^{-8}$ (for a typical low birefringence fiber).

Effective Refractive Index

- The **effective refractive index ($\boldsymbol{n_{eff}}$)** is a crucial parameter that defines the propagation characteristics for a *specific mode* of light in a fiber.
  - It represents the "average" refractive index that a particular mode experiences as it travels through both the core and the cladding.
- It's defined as the ratio of the mode's **propagation constant ($\boldsymbol{\beta}$)** to the **vacuum wave number ($\boldsymbol{k_0}$)**:

$$n_{eff} = \frac{\beta}{k_0}$$

- Where vacuum wave number $k_0 = 2\pi/\lambda$

Effective Refractive Index

- Since guided modes travel in both the core and cladding, the value of $\boldsymbol{n_{eff}}$ is always **between the refractive index of the core ($\boldsymbol{n_1}$) and the cladding ($\boldsymbol{n_2}$)**.
  - $n_2 < n_{eff} < n_1$
- The effective refractive index is related to the **phase change per unit length** (i.e., the phase velocity) of a mode, not its intensity or power distribution.

Optical Fiber Materials

Optical Fiber Materials

- In selecting materials for optical fibers, a number of requirements must be satisfied.
- For example:
  1. It must be possible to make long, thin, flexible fibers from the material;
  2. The material must have a low loss at a particular optical wavelength in order for the fiber to guide light efficiently;
  3. Physically compatible materials that have slightly different refractive indices for the core and cladding must be available.

Optical Fiber Materials

- Materials that satisfy these requirements are glasses and plastics.

Feature	**Glass Fibers (e.g., Silica, SiO_2)**	**Plastic Optical Fibers (POF)**
Primary Use	**Long-haul telecommunications**	**Short-distance links** (< several hundred meters) & harsh environments
Optical Loss	**Extremely Low**	**Substantially Higher** than glass
Key Advantage	Unmatched transparency for long-distance data transmission	**Greater mechanical strength** and durability

Glass Optical Fibers

- Glass is made by fusing mixtures of metal oxides, sulfides, or selenides.
- The resulting material is a randomly connected molecular network rather than an ordered structure as found in crystalline materials.
- A consequence of this random order is that glasses do not have well-defined melting points.
- When glass is heated up from room temperature, it remains a hard solid up to several hundred degrees centigrade.
- As the temperature increases further, the glass gradually begins to soften until, at very high temperatures, it becomes a viscous liquid.
- In glass manufacturing, the term "melting temperature" refers to the temperature range where the glass becomes fluid enough to be processed and freed of gas bubbles, not a specific point.

Glass Optical Fibers

- The most common materials for optical fibers are **oxide glasses**, with silica (SiO_2) being the foundational choice for most telecommunication applications.
- Silica is derived from high-purity sand and is also known as fused silica or vitreous silica.
- Silica has a refractive index ranging from 1.458 at 850 nm to 1.444 at 1550 nm.
- The entire fiber, both core and cladding, is typically built upon a base of silica.

Glass Optical Fibers

- To guide light, the core's refractive index must be slightly higher than the cladding's.
  - This is achieved by adding materials called **dopants** to the pure silica.
- To INCREASE Refractive Index (for the Core):
  - Germanium Dioxide (GeO_2) or Phosphorus Pentoxide (P_2O_5)
- To DECREASE Refractive Index (for the Cladding):
  - Boron Trioxide (B_2O_3) or Fluorine

Glass Optical Fibers

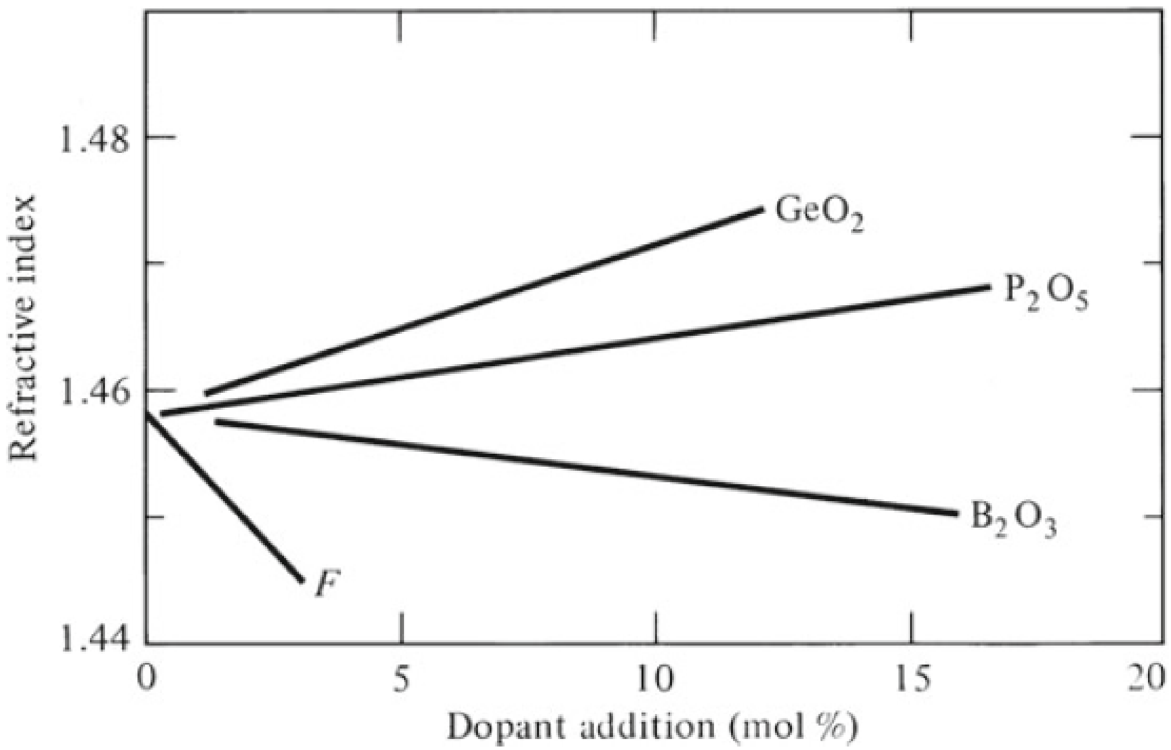


Fig. 2.24 Variation in refractive index as a function of doping concentration in silica glass

Glass Optical Fibers

- Because the cladding must have a lower index than the core, examples of fiber compositions are
  - GeO_2–SiO_2 core; SiO_2 cladding
  - P_2O_5–SiO_2 core; SiO_2 cladding
  - SiO_2 core; B_2O_3–SiO_2 cladding
  - GeO_2–B_2O_3–SiO_2 core; B_2O_3–SiO_2 cladding.
- Here, the notation GeO_2–SiO_2, for example, denotes a GeO_2-doped silica glass.

Glass Optical Fibers

- Glass made from pure silica is referred to as *silica glass*, *fused silica*, or *vitreous silica*
  - It is the principal material for optical fibers due to its exceptional properties.
- Derived from high-purity sand, silica glass offers:
  - **High-temperature resistance** (up to 1000 °C)
  - **Low thermal expansion**, making it highly resistant to breakage from thermal shock
  - **Good chemical durability**
  - **High transparency** in the visible and infrared regions essential for communication

Standard Fiber Fabrication

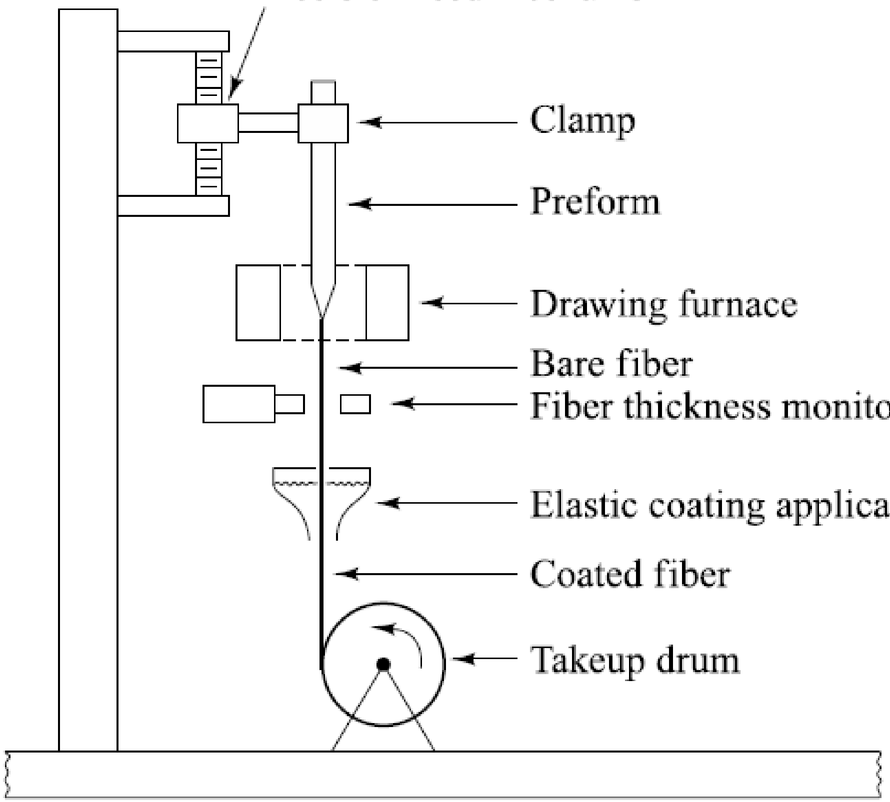
- Two Primary Methods:
  - Direct-Melt Method:
    - A traditional glass-making technique.
    - Fibers are drawn directly from a crucible of molten, purified silicate glass.
  - Vapor-Phase Oxidation (Most Common):
    - A modern, high-purity process that creates a glass "preform" first.
    - This preform is then used to draw the fiber.
    - This is the standard for high-quality telecommunication fibers.

Vapor-Phase Oxidation Process

- Step 1 – Creating the Preform
- Step 2 – Drawing the Fiber from the Preform
- Step 3 – Applying the Protective Coating

Vapor-Phase Oxidation Process

Fig. 2.25 Schematic of a fiber-drawing apparatus



Vapor-Phase Oxidation Process

Step 1 - Creating the Preform

- This process creates a large-scale version of the final fiber.

1. **Vapor Reaction:** Highly pure chemical vapors (like $SiCl_4$ and $GeCl_4$) react with oxygen.
2. **Particle Formation:** This reaction creates a fine powder of pure silica (SiO_2) particles.
3. **Sintering:** The particles are collected and **sintered –** heated to fuse them into a solid, transparent glass rod without melting.
4. **The Preform:** This solid glass rod is the **preform**.
    - **Size:** Typically 1-2.5 cm in diameter and 60-120 cm long.

Vapor-Phase Oxidation Process

Step 2 - Drawing the Fiber from the Preform

- The preform is drawn into the final, hair-thin optical fiber.

1. **The Drawing Tower:** The preform is vertically mounted in a tall structure and fed into a high-temperature **drawing furnace**.
2. **Softening:** The tip of the preform is heated until it becomes soft enough to be pulled.
3. **Drawing:** The softened glass is pulled down into a thin filament. This filament is the optical fiber.
4. **Speed Control:** A rotating "takeup drum" at the bottom pulls the fiber.
   - The speed of this drum precisely controls the final diameter of the fiber, regulated by a feedback monitor.

Vapor-Phase Oxidation Process

Step 3 – Applying the Protective Coating

- Protecting the pristine glass surface is the final critical step.
- As soon as the fiber is drawn and cooled, an **elastic polymer coating** is applied.
- The coating shields the bare glass fiber from environmental contaminants like:
  - Dust and dirt
  - Water vapor and moisture
- This protective layer is essential for preserving the fiber's incredible tensile strength and ensuring its long-term reliability and optical performance.

Active Glass Optical Fibers

- An active fiber is a standard glass fiber (like silica) whose core has been **doped** with a small amount of **rare-earth elements** (atomic numbers 57–71).
- This transforms the passive glass into an active medium that can manipulate light.
- Common dopants include **Erbium (Er)** and **Neodymium (Nd)**.

Active Glass Optical Fibers

- Primary Function: Optical Amplification
  - A "pump laser" injects energy, exciting the rare-earth ions.
  - A weak incoming signal photon stimulates these excited ions to release their energy.
  - This releases new photons that are identical to the signal photon.
  - The result is a much stronger, amplified optical signal.
- Key Design Factor:
  - Low Concentration: The doping level is kept very low (0.005–0.05 mol %) to prevent the rare-earth ions from clustering together, which would decrease the amplifier's efficiency.

Plastic Optical Fibers

- Plastic Optical Fibers are high-bandwidth, graded-index fibers developed for **high-speed, short-distance applications**, such as delivering services directly to a workstation or on customer premises.
- Commonly made from **Polymethylmethacrylate (PMMA)** or a **Perfluorinated Polymer (PF)**.

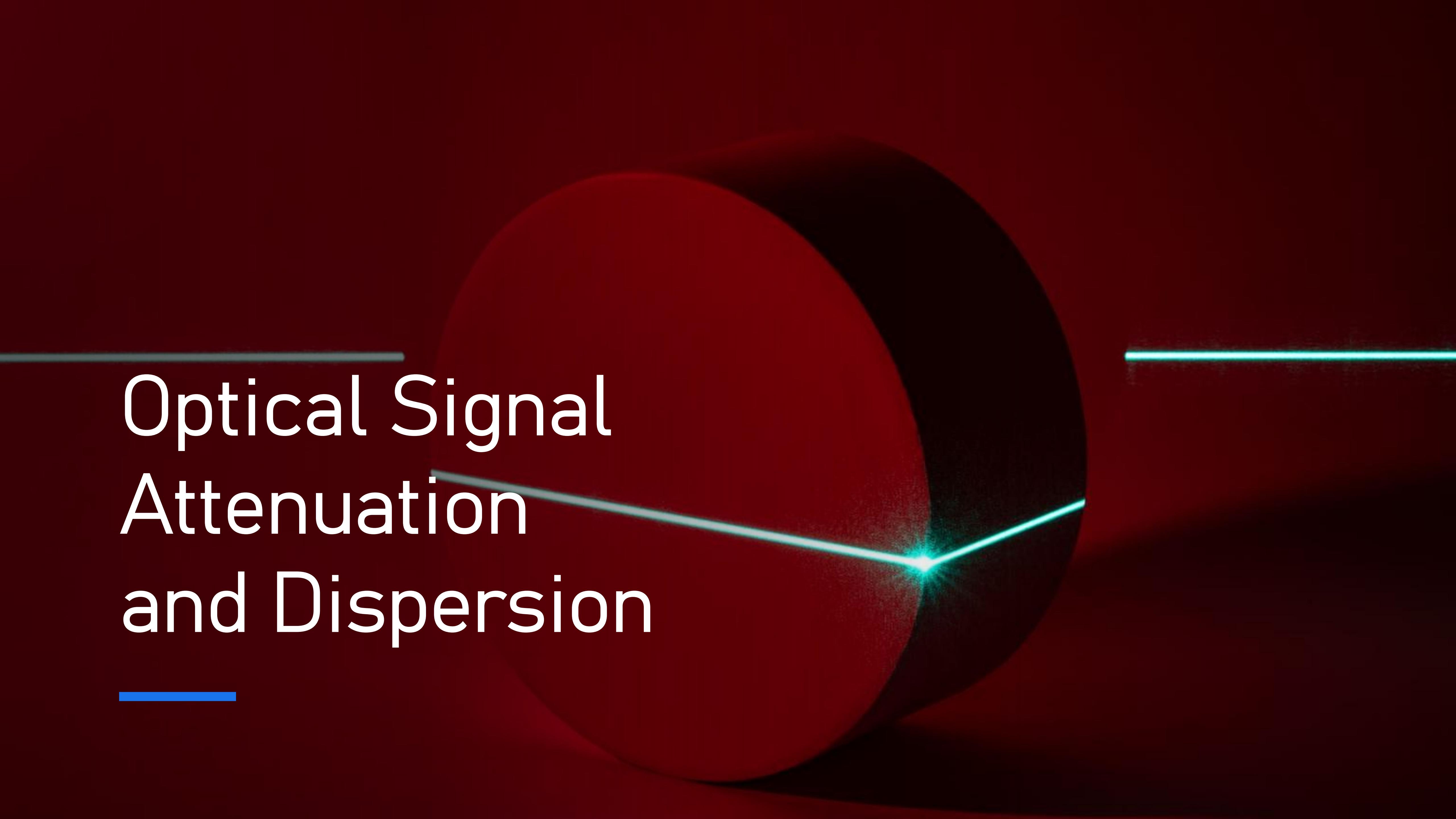
Plastic Optical Fibers

Table 2.4 Sample characteristics of PMMA and PF polymer optical fibers

Characteristic	PMMAPOF	PFPOF
Core diameter	0.4 mm	0.050–0.30 mm
Cladding diameter	1.0 mm	0.25–0.60 mm
Numerical aperture	0.25	0.20
Attenuation	150 dB/km at 650 nm	<40 dB/km at 650–1300 nm
Bandwidth	2.5 Gb/s over 200 m	2.5 Gb/s over 550 m

Plastic Optical Fibers

Advantages	Disadvantage
Tough & Durable: POF is mechanically strong and highly flexible, making it easy to install even in large diameters. **Compatibility:** Can use standard connectors compatible with multimode glass fibers, simplifying connections. **Low Cost:** Components like connectors, splices, and transceivers can be inexpensively fabricated using plastic injection-molding.	**High Attenuation:** The primary drawback is a **considerably greater signal loss** compared to glass fibers, limiting their effective range.


Optical Signal
Attenuation
and Dispersion

Fiber Attenuation

Fiber Attenuation

- **Signal attenuation** (also known as ***fiber attenuation***, ***fiber loss***, or ***power level reduction***) is the reduction in power of the light signal as it travels along a fiber.
- This is a critical factor that limits the maximum transmission distance in any optical communication system.
- Fiber attenuation is typically measured in **decibels per kilometer (dB/km),**
- There are three fundamental mechanisms responsible for signal loss:
  - **Absorption:** This loss is inherent to the fiber material itself. Impurities in the glass (like water molecules) absorb light energy at specific wavelengths, converting it into heat.
  - **Scattering:** Caused by microscopic variations in the material density and structural imperfections in the fiber. This phenomenon, primarily Rayleigh scattering, deflects light from its intended path.
  - **Radiative Losses:** These occur when the fiber is bent or curved (macrobending and microbending). The geometric perturbations cause some light to escape from the fiber core.

Absorption of Optical Power

- Absorption is a process where the optical power in a signal is converted into heat within the fiber material.
- This is one of the primary mechanisms of attenuation and limits how far a signal can travel.
- Absorption of optical power is caused by three different mechanisms:
    1. Absorption by atomic defects in the glass composition.
    2. Extrinsic absorption by impurity atoms in the glass material.
    3. Intrinsic absorption by the basic constituent atoms of the fiber material.

Absorption by Atomic Defects

- Atomic defects are imperfections in the atomic structure of the fiber material.
- Examples of these defects include missing molecules, high-density clusters of atom groups, or oxygen defects in the glass structure.
- Usually, absorption losses arising from these defects are negligible compared with intrinsic and impurity absorption effects.

Extrinsic Absorption

- **Extrinsic Absorption** is caused by he presence of minute quantities of impurities in the fiber material.
- These impurities include
  - **Transition Metal Ions (Iron, Copper, Chromium)**
    - A major issue in early fibers (1970s), causing losses of 1-4 dB/km.
    - Modern manufacturing has reduced these to insignificant levels.
  - **Hydroxyl (OH^-) Ions from Water**
    - The **single most important impurity** in modern fibers.
    - Gets trapped during manufacturing from the chemical reaction.
    - Concentrations must be kept below a few **parts per billion (ppb)** to achieve low loss (< 20 dB/km).

Extrinsic Absorption

Table 3.1 Examples of absorption loss in silica glass at different wavelengths due to 1 ppm of water-ions and various transition-metal impurities

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

Extrinsic Absorption

- The presence of OH^- ions is not uniform across the spectrum; it creates specific, high-loss spikes.
- OH^- ions cause strong absorption peaks at specific wavelengths (e.g., 1380 nm).
- The low-loss regions between these peaks are called **"transmission windows."**
- **Key Windows:**
  - **O-band** (~1310 nm): Attenuation below 0.4 dB/km.
  - **C-band** (~1550 nm): Attenuation below 0.25 dB/km.
- Fibers with ultra-low water content are called ***low-water-peak*** or ***full-spectrum fibers***, opening up the **E-band** for more capacity.

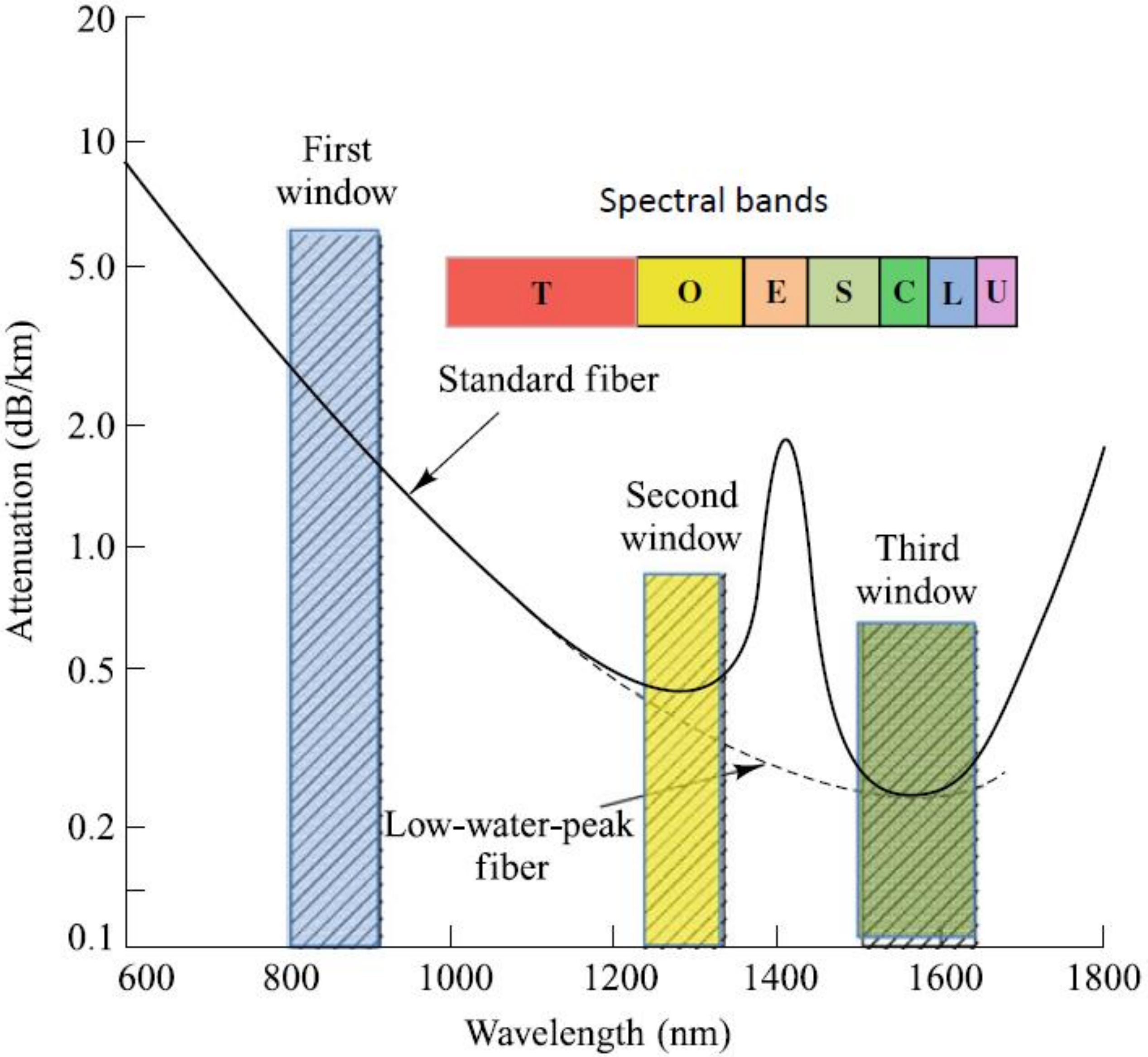


Fig. 3.2 Optical fiber attenuation as a function of wavelength yields nominal values of 0.40 dB/km at 1310 nm and 0.25 dB/km at 1550 nm for standard single-mode fiber; the dashed curve is the attenuation for low-water-peak fiber

Intrinsic Absorption

- Intrinsic absorption results from electronic absorption bands in the ultraviolet region and from atomic vibration bands in the near-infrared region.
- It is defined as the absorption that occurs when the material is in a perfect state with no density variations, impurities, or material inhomogeneity.
- The electronic absorption bands are associated with the energy band gaps of the amorphous glass materials.
- Absorption occurs when a photon interacts with an electron in the valence band and excites it to a higher energy level.

Intrinsic Absorption

- Intrinsic absorption comes from two sources:
  - Ultraviolet (UV) Absorption
    - Caused by electron excitation.
    - Dominant at very short wavelengths (< 0.5 μm) and drops off exponentially as wavelength increases.
  - Infrared (IR) Absorption
    - Caused by vibrations of the chemical bonds (Si–O) in the glass.
    - Dominant at very long wavelengths (> 1.6 μm) and increases exponentially.

Intrinsic Absorption

- Combining all effects gives us the characteristic performance curve of an optical fiber.
- The UV and IR absorption tails form a **"V-shaped" wedge**, creating a region of high transparency in the middle.
- This transparent region is where all optical communication operates.
- Extrinsic absorption from OH^- ions adds sharp loss peaks on top of this fundamental curve.
- By minimizing impurities, manufacturers can get very close to the theoretical minimum loss, with values as low as **0.148 dB/km** achieved near 1570 nm.

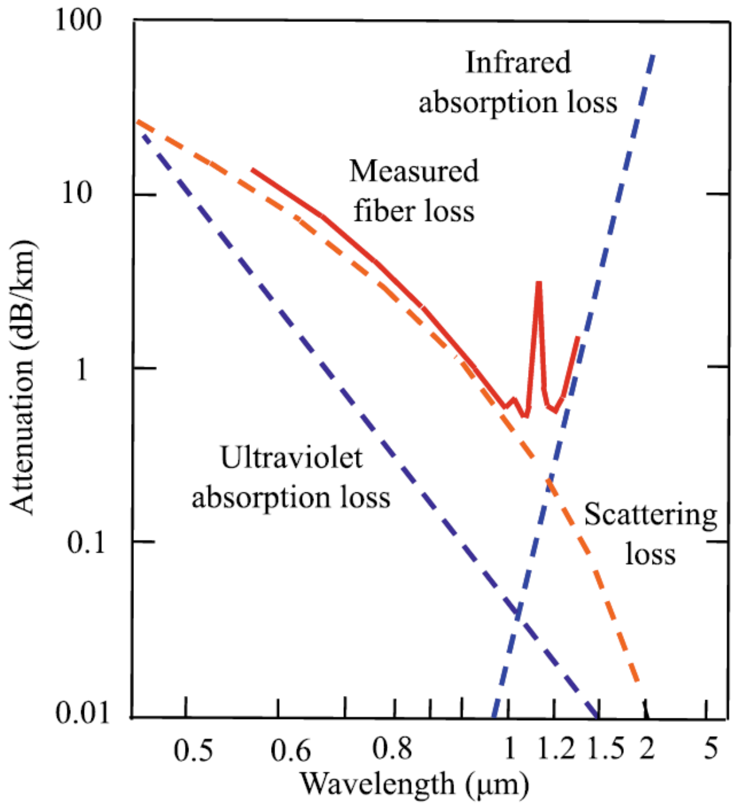


Fig. 3.3 Optical fiber attenuation characteristics and their limiting mechanisms for a GeO_2-doped low-loss low-water-content silica fiber

Scattering Losses in Optical Fibers

- Scattering is a primary cause of signal loss where light is deflected in multiple directions due to microscopic non-uniformities in the fiber.
- This redirection of light causes a portion of the signal's power to be lost.
- Scattering arises from the fundamental, random nature of the glass structure. It is caused by:
  - **Density Fluctuations:** The glass is a random network of molecules, creating tiny regions that are more or less dense than average.
  - **Compositional Fluctuations:** Optical fibers are made from a mix of oxides (e.g., SiO_2, GeO_2). The distribution of these components is not perfectly uniform.
- These variations create microscopic changes in the refractive index, which act as scattering points for the light signal.

Scattering Losses in Optical Fibers

- The scattering that occurs in optical fibers is primarily **Rayleigh Scattering**.
  - This is an **intrinsic** loss mechanism, meaning it's a fundamental property of the glass material and cannot be completely eliminated.
  - It's the very same phenomenon that scatters sunlight in the atmosphere, making the sky appear blue.
- Rayleigh scattering is extremely sensitive to the wavelength (λ) of the light. (λ^{-4} dependence)
  - **Shorter wavelengths** are scattered very strongly.
  - **Longer wavelengths** are scattered much, much less.
  - This is the primary reason why optical communication systems operate at longer, infrared wavelengths (e.g., 1310 nm and 1550 nm) where scattering loss is minimal.

Scattering Losses in Optical Fibers

- Scattering's unique wavelength dependence defines a key part of the fiber's performance graph.
  - It is the **dominant loss mechanism at shorter wavelengths** (below ~1 µm).
  - It is responsible for the steep downward slope in the attenuation curve as wavelength increases.
  - At longer wavelengths, the effect of scattering becomes very small, and **Infrared Absorption** takes over as the main cause of loss.

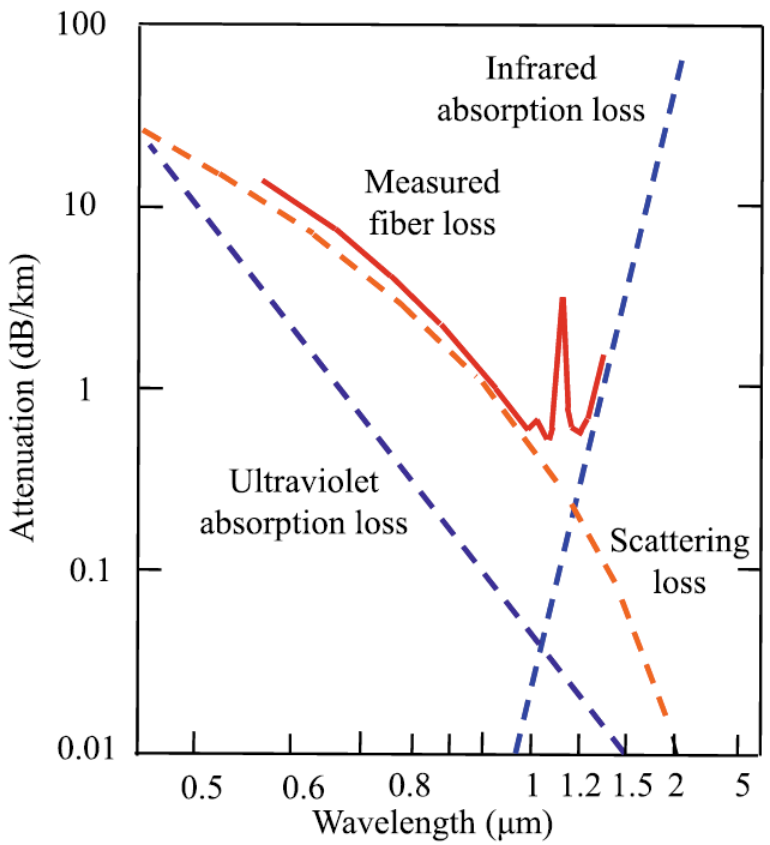
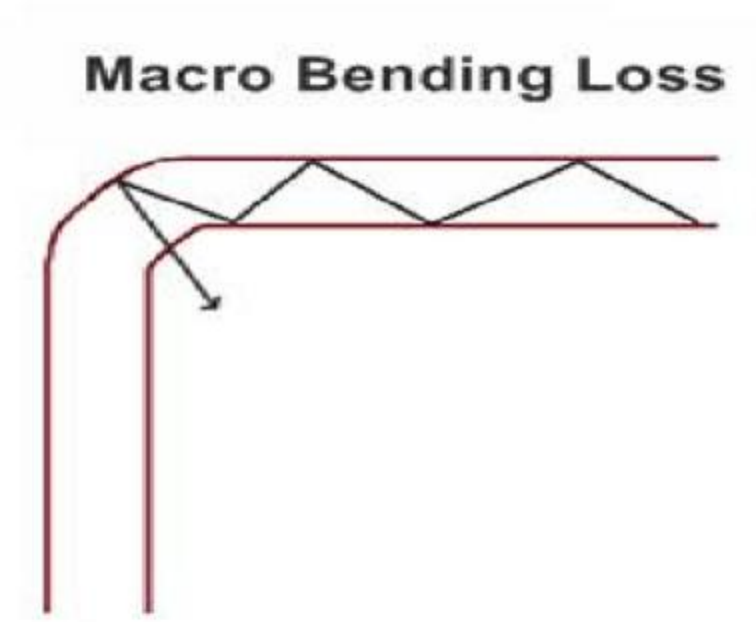


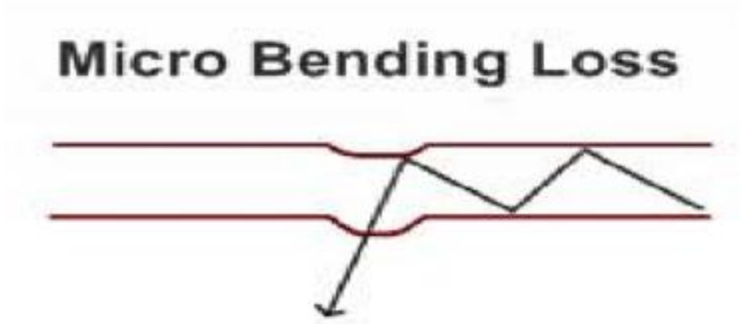
Fig. 3.3 Optical fiber attenuation characteristics and their limiting mechanisms for a GeO_2-doped low-loss low-water-content silica fiber

Fiber Bending Losses

- Radiative losses occur whenever an optical fiber undergoes a bend of finite radius of curvature.
- The bend disrupts the conditions for total internal reflection, allowing some light to escape from the core into the cladding and radiate away.
- Fibers can be subject to two types of curvatures:
  1. *Macroscopic bends* having radii that are large compared with the fiber diameter, such as those that occur when a fiber cable turns a corner
  2. *Microscopic bends* of the fiber axis that can arise when the fibers are incorporated into cables.

Fiber Bending Losses





Macrobending Loss

- When a fiber is bent, the light on the outer edge of the curve must travel a longer path.
- To stay within the core, it would need to travel faster than the speed of light in the cladding, which is impossible. As a result, this light is lost.
- For slight bends, the loss is negligible. However, as the bend radius gets smaller, the loss increases **exponentially**.
- There is a "critical bend radius" below which the loss suddenly becomes extremely large.
- **Higher-order modes**, which are less tightly bound to the core, are the first to be lost in a bend.

Microbending Loss

- Microbends are tiny, almost invisible bends that can be a significant source of loss.
- They are typically introduced by non-uniform lateral pressure when the fiber is packaged into a cable. This is often called **"cabling loss"** or **"packaging loss."**
- These repetitive, small-scale fluctuations cause energy to be coupled from the guided modes in the core to leaky or non-guided modes, which then radiate away.
- The most effective way to minimize microbending loss is through cable design.
- **Compressible Jackets:** A soft, compressible jacket is extruded over the fiber.
  - When external forces are applied to the cable, the soft jacket deforms and absorbs the pressure.
  - The much stiffer glass fiber inside is shielded and tends to remain straight, preventing the formation of microbends.

Microbending Loss

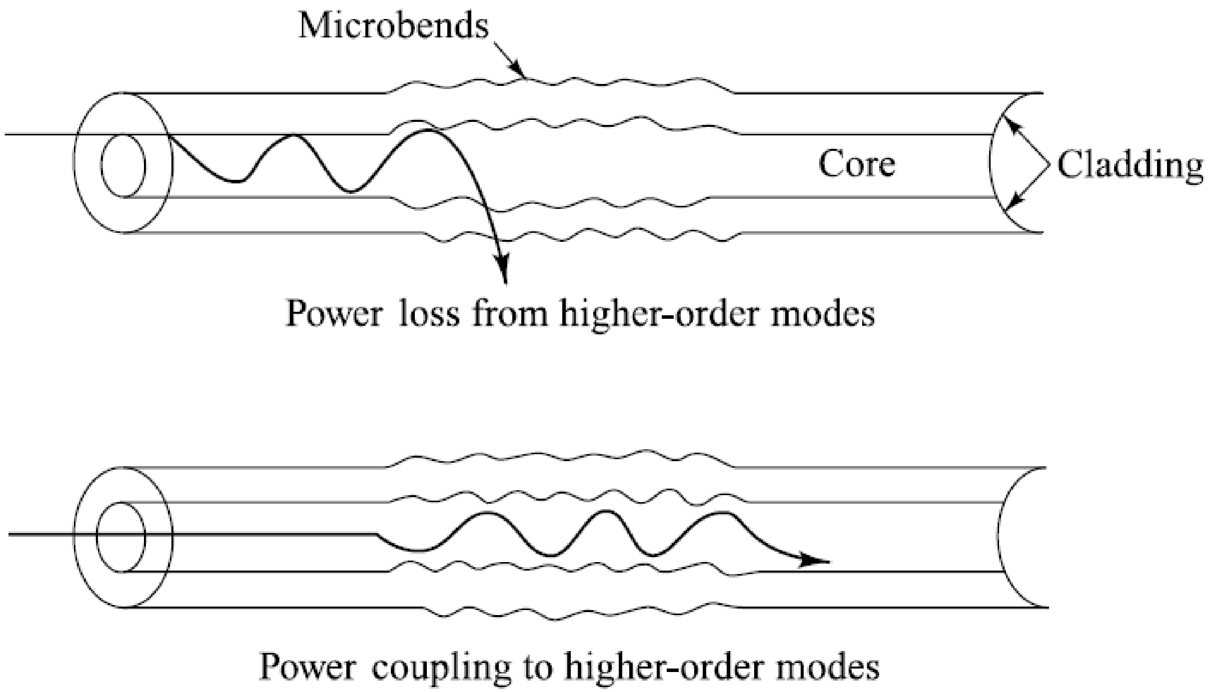


Fig. 3.4 Small-scale fluctuations in the radius of curvature of the fiber axis lead to microbending losses, which can cause power from low-order modes to couple to higher-order modes

Optical Signal Dispersion Effects

Optical Signal Dispersion Effects

- As an optical signal travels through a fiber, it experiences two main forms of degradation:
  - **Attenuation:** The signal strength weakens over distance.
  - **Dispersion:** The signal pulse broadens and spreads out in time.
- The combined effect is that adjacent pulses begin to overlap, a phenomenon known as **Intersymbol Interference (ISI)**.
  - This makes it difficult for the receiver to distinguish between individual bits, leading to errors.

Optical Signal Dispersion Effects

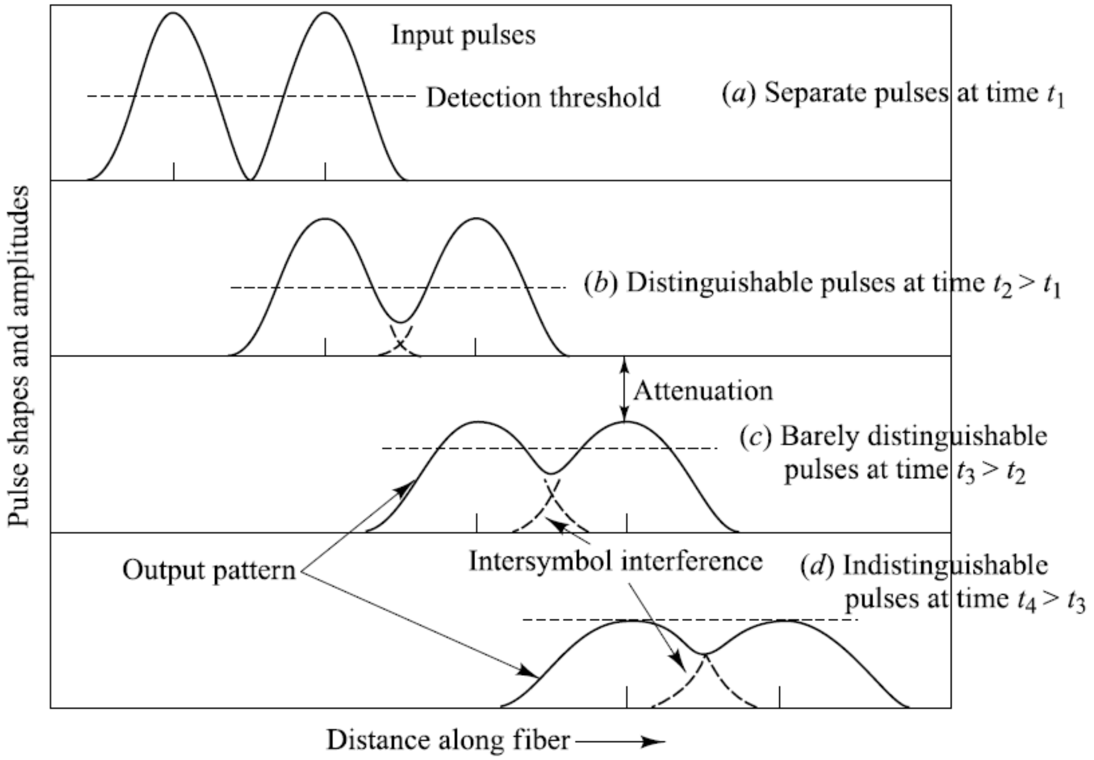


Fig. 3.6 Broadening and attenuation of two adjacent pulses as they travel along a fiber: **a** Originally the pulses are separate; **b** the pulses overlap slightly and are clearly distinguishable; **c** the pulses overlap significantly and are barely distinguishable; **d** eventually the pulses strongly overlap and are indistinguishable

Origins of Signal Dispersion

- Signal dispersion is the spreading of a light pulse as it travels along an optical fiber.
- It is caused by different components of the signal traveling at different speeds.
- These effects can be explained by examining the behavior of the group velocities of the guided modes,
  - *Group velocity* is the speed at which energy in a particular mode travels along the fiber
- The main consequence is a limitation of the fiber's bandwidth and data-carrying capacity.
- The Three Main Types of Dispersion
  - Intermodal Dispersion (also called Modal Delay)
  - Intramodal Dispersion (also called Chromatic Dispersion)
  - Polarization-Mode Dispersion (PMD)

Intermodal Delay

- Intermodal Dispersion is also called ***Intermodal delay*** (or simply ***modal delay***).
- This type of dispersion only occurs in **multimode fibers**.
- Higher-order modes travel a longer zig-zag path than the direct path of the fundamental mode, causing them to arrive later.
- As a result, modes that start at the same time arrive at different times, which smears the pulse.

Intramodal Dispersion

- *Intramodal dispersion is also called* ***chromatic dispersion***
- This occurs within a single light mode and affects **all fiber types**.
- This spreading arises from the finite spectral emission width of an optical source.
- The phenomenon also is known as ***group velocity dispersion***, because the dispersion is a result of the group velocity being a function of the wavelength (colour).
- The effect is worse with light sources that have a wider range of wavelengths, like LEDs, compared to the narrow range of lasers.

Intramodal Dispersion

- Two Causes of Intramodal Dispersion
  - **Material Dispersion:** Arises from the properties of the glass itself.
  - **Waveguide Dispersion**: Arises from the fiber's physical structure (core/cladding).

Material Dispersion

- Material Dispersion is also called ***Chromatic Dispersion***.
- The refractive index (n) of the fiber material (e.g., silica) naturally varies with the wavelength of light.
- This is the same physical principle that allows a **prism to separate white light** into a rainbow.
- Since the speed of light depends on the refractive index, different wavelengths travel at different speeds.

Waveguide Dispersion

- Waveguide Dispersion is a significant factor in single-mode fibers.
- It is related to how much light is confined to the core versus the cladding.
- **Shorter wavelengths** are more tightly confined to the core.
- **Longer wavelengths** spread further into the cladding, which has a lower refractive index and allows for faster travel.
- This difference in spatial distribution and speed causes pulse spreading.

Intramodal Dispersion

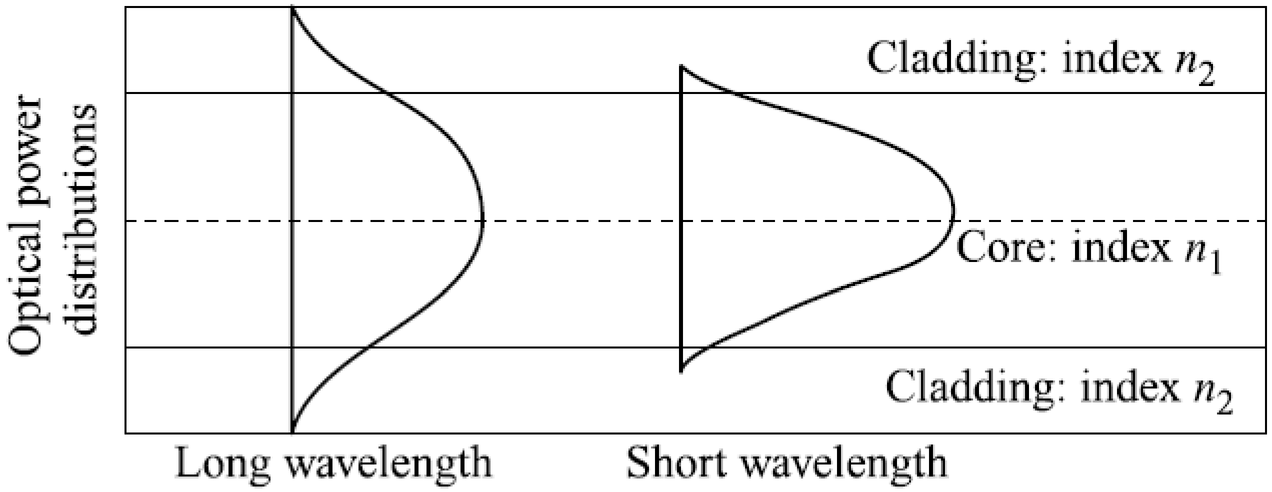


Fig. 3.8 Shorter wavelengths are confined closer to the center of a fiber core than longer wavelengths

Polarization-Mode Dispersion

- **Polarization-Mode Dispersion (PMD) o**ccurs primarily in **single-mode fibers**.
- It is caused by a light signal's two orthogonal polarization states traveling at slightly different speeds.
- Due to imperfections and stress in the fiber, the two polarization states encounter slightly different refractive indices and travel at different speeds.
- This results in a time difference between them, spreading the overall pulse.

Summary of Dispersion Types

Dispersion Type	Fiber Affected	Fundamental Cause
Intermodal	Multimode	Different light paths (modes) have different speeds.
Intramodal	All	Different wavelengths (colors) have different speeds.
PMD	Single-Mode	Different polarization states have different speeds.

Reference

- Gerd Keiser, ***Optical Fiber Communication***, 5th Edition, McGraw Hill Education (India) Private Limited, 2016. ISBN:1-25-900687-5.