Fiber Optics Communications

Week 1 Introduction to Fiber Optics Communications

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Course Description

- This course offers an in-depth introduction to the principles, components, and operation of optical fiber communication systems
- address both component-level and system-level perspectives.
- physical properties of optical fibers and the mechanisms of Lightwave propagation
- Basic Components of Fiber optics communications such as optical sources, modulators, optical amplifiers, and photodetectors .
- Optical fiber transmission system design, performance analysis
- Further topics including the architecture of fiber optic communication networks, optical switching, multiplexing techniques, and passive optical networks (PON)
- Emerging technologies such as Optical wireless communication will also be discussed

Lecture Learning Outcomes

1. Understand the fundamental principles of Fiber Optics communication
2. Understand the role of Fiber Optics communication in modern telecommunication systems.
3. Outline the historical development of fiber optic communication technologies.
4. Understand light propagation in optical fibers in terms of reflection, refraction, and modes of transmission.
5. Differentiate optical windows and transmission bands used in fiber optic systems.
6. Describe the structure, types, and characteristics of optical fibers
7. Identify the main components of a fiber optic communication system

Introduction

Outline

- Overview of Optical Fiber Communication
- Historical Perspectives of Fiber Optics Communications
- Optical Fiber Communication Main System components
- Overview of WDM System
- Major Applications Fiber Optic Communication

Overview: Fiber Optic Communication

- Is a method of transmitting information from one place to another by sending light wave through an optical fiber.
- The Lightwave is used as an electromagnetic carrier wave and modulated by different attributes (frequency, phase, amplitude) of the information signal.
- The carrier frequency **(193 THz)** in Optical fiber communication is much lager than the conventional Microwave communication Systems.
- The operating wavelength of optical fiber communication lies in the visible and infrared regions of the spectrum, determined by the use of plastic or glass optical fibers

Optical Band

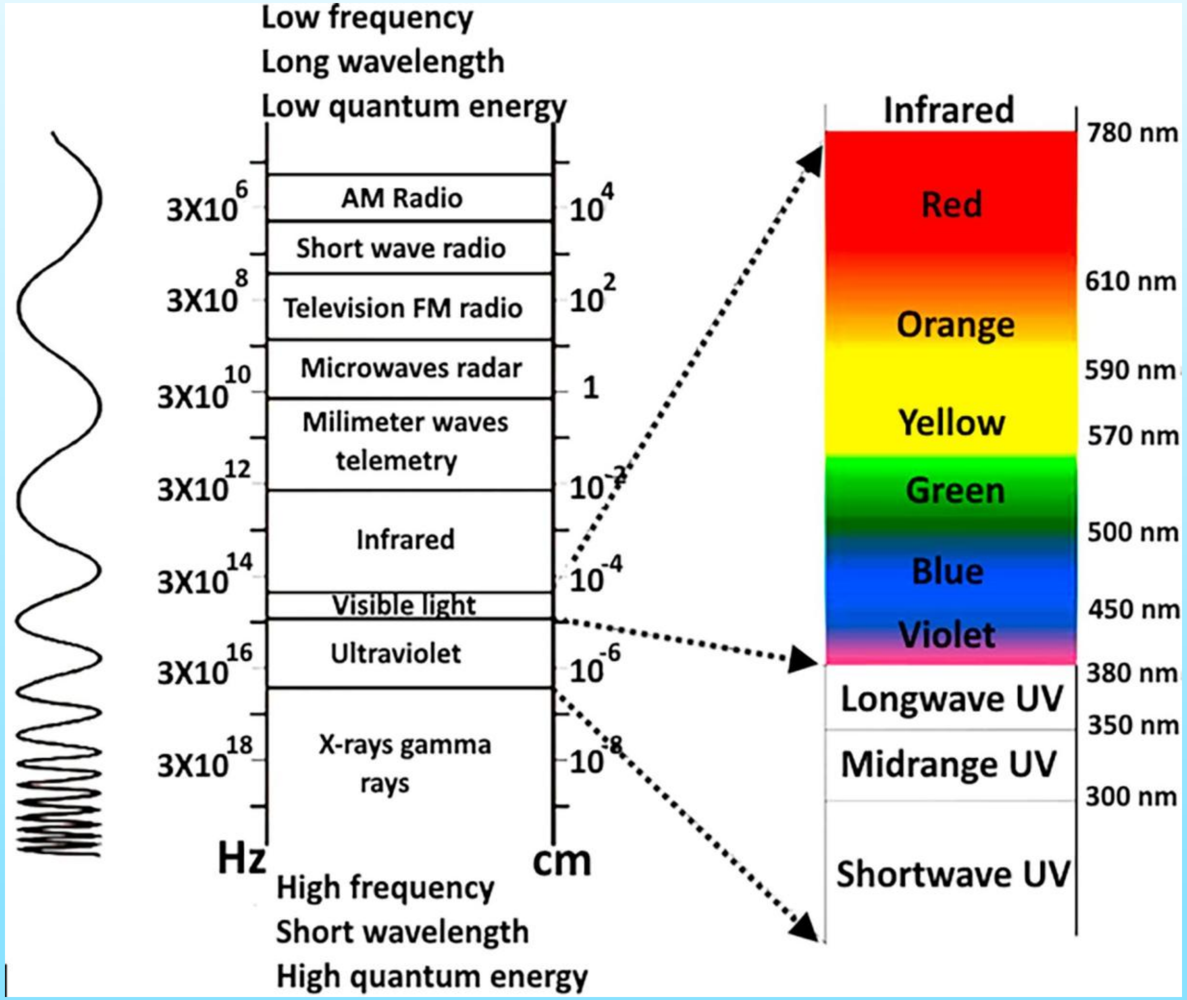


Figure 1: Electromagnetic Spectrum

Source: Satish Addanki, I.S. Amiri, and P. Yupapin, *"Review of optical fibers-introduction and applications in fiber lasers,"* Elsevier, 2018, Url: https://ars.els-cdn.com/content/image/1-s2.0-S2211379718314268-gr1_lrg.jpg

Glass Optical Fiber Communication

- Operates in near-Infrared spectrum
- **Wavelength:** 850 nm, 1310 nm, and 1550 nm.

Plastic Optical Fiber Communication

- Operates in Visible light spectrum
- **Wavelength:** 480 nm, 520 nm, and 650 nm.

Historical Perspectives

- Smoke Signal and Fire beacons were used for communication purpose in ancient times
- The History of modern communication systems can be categorized as Electrical and Optical Era
- The major inventions on those eras are as follows.

Electrical Era

- Telegraph; 1836
- Telephone; 1876
- Coaxial Cables; 1840
- Microwaves; 1948

Optical Era

- Optical Fibers; 1978
- Optical Amplifiers; 1990
- WDM Technology; 1996
- Multiple bands;; 2002

- The Communication Speed of Microwave and coaxial cable is limited to 100Mb/s
- Optical fiber communication system can operate at a speed greater Than 10Tb/s

Generations of Optical Fiber Communication

First Generation, 1980

- Optical source: GaAs Laser
- Wavelength; 800nm
- Communication Speed; 45Mb/s
- Electrical Repeaters spacing, 10km

Second Generation, 1985

- Optical source: InGaAsP Laser
- Wavelength; 1300nm
- Electrical Repeaters spacing, 50km
- Communication Speed; 2Gb/s using Sigle-mode fibers

Third Generation, 1990

- Communication Speed; 10Gb/s
- Wavelength; 1500nm
- Electrical Repeaters were used with Dispersion shifted Fibers
- Repeaters spacing, 100km

Fourth Generation, 1996

- Optical amplification, Wavelength; 1450nm-1620NM
- Wavelength Division Multiplexing, Speed; 10Tb/s

Fifth Generation, 2000

- Wavelength; 1530nm-1570NM
- Raman Amplification
- Multi Tb/s system

Motivation: Why Optical Fiber Communication?

- **Much Higher Bandwidth:** Compared to Microwave and coaxial cable systems
- **Immune to Electromagnetic Interference**
- **High Security:** Impossible to tap into
- **Low Loss/Attenuation:** fibers can be made to have only 0.2 dB/km of attenuation
- **Reliability:** More resilient than copper based systems in extreme environmental conditions

Fiber Optic Communication System Components

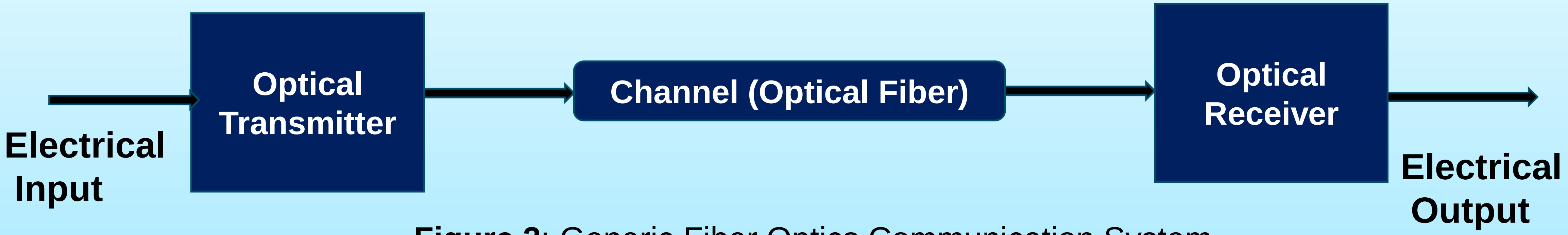


Figure 2: Generic Fiber Optics Communication System

- **Optical Transmitter:** Converts the signal from Electrical to Optical domain
- **Channel:** Optical fiber is used to transmit the optical signal from the Transmitter to Receiver
- **Optical Receiver:** Convert the optical signal to the electrical domain

System Components Cont…

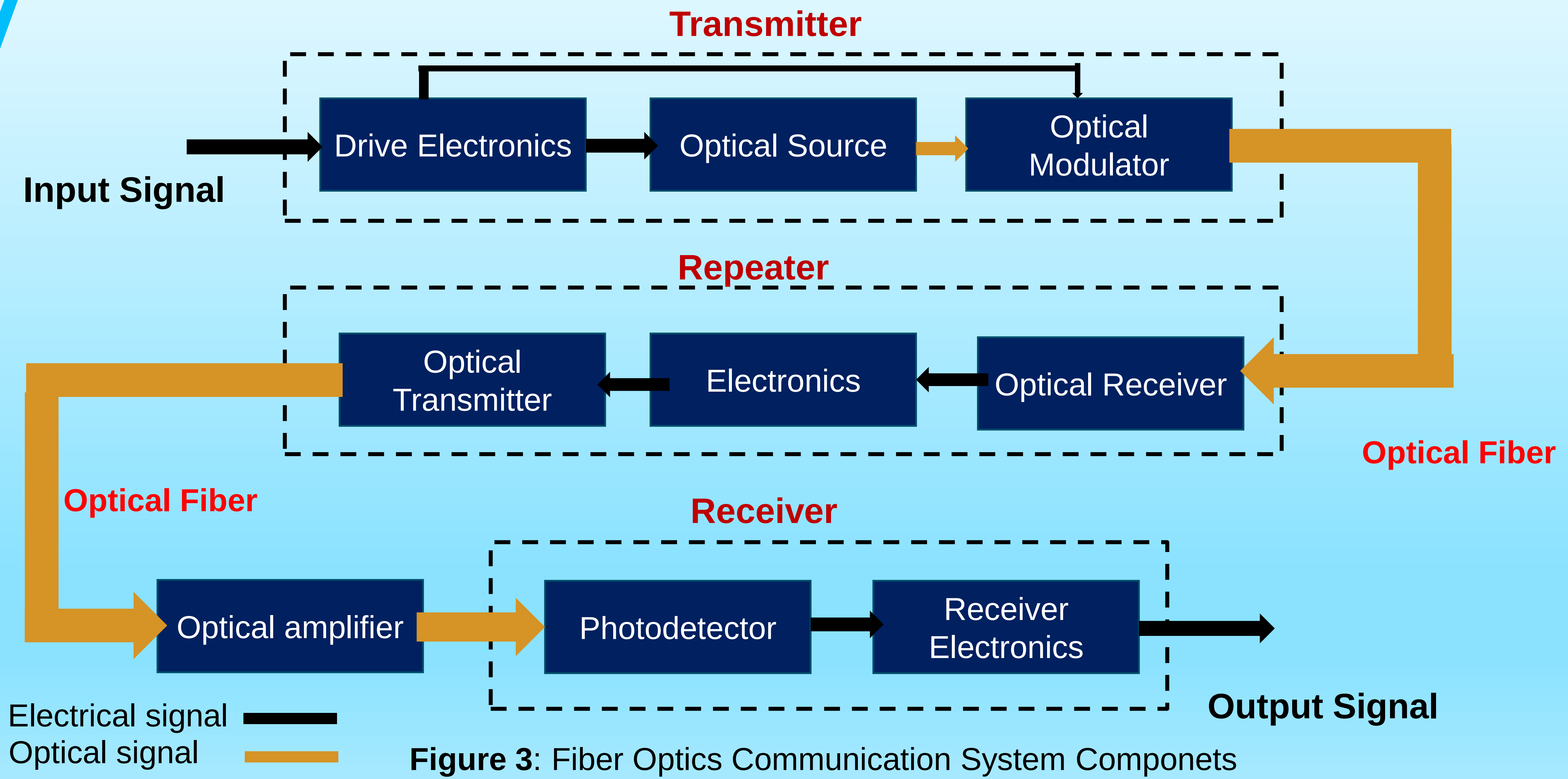


Figure 3: Fiber Optics Communication System Componets

Basic Elements In Fiber Optic Communication

Optical Transmitter

- Drive Electronics
- Optical Source
- Optical Modulators

Communication Channel

- Fiber Optics
- Passive optical elements such as
  Optical couplers and splitters

Optical Receiver

- Photodetectors
- Receiver Electronics

Optical Amplifiers

- Optical Boosters
- Inline Optical Amplifiers
- Optical Pre-Amplifers

Optical Transmitter

Optical Sources

- Optical source is used to emit optical carrier wave
- Two Types of Optical source, LED and LASER are used in fiber optic communication

LED

- Emit Incoherent Light
- Relatively Wide spectral width 30-60 nm
- Wide beam
- **Applications:** 10-100Mb/s
- **Transmission Distance:** Few Kilometers

LASER

- Emit Coherent Light
- Narrow spectral width in order of nm
- Narrow and concentrated beam
- **Applications:** High Speed
- **Transmission Distance:** Long

Optical Modulators

- Optical Modulator creates the optical bit stream
- Two Types of Optical Modulations
  - ✓ **Direct/Internal Modulation:** laser current modulated to produce the bit stream
  - ✓ **External Modulation:** Requires External Device

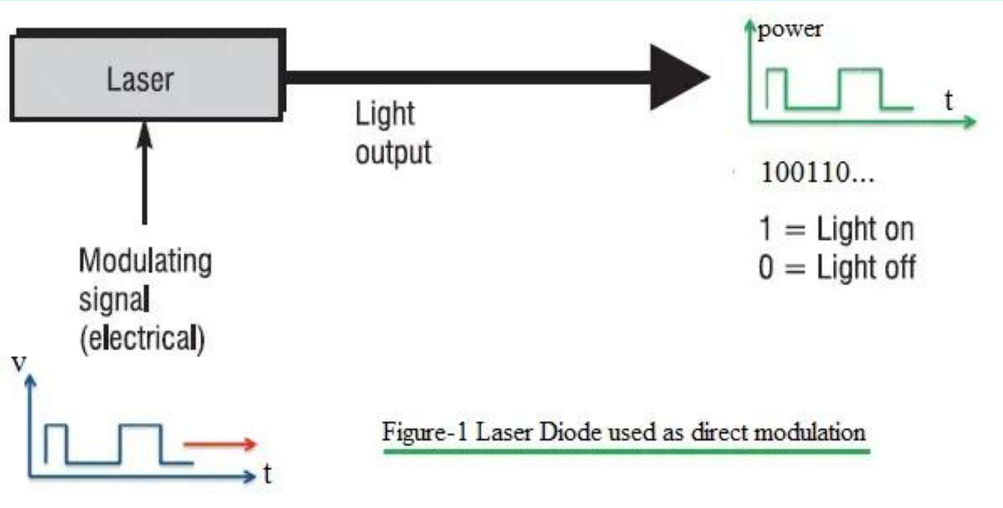


Figure 4: Direct or Internal Modulation

Source: *"Direct Modulation vs. External Modulation: Optical Techniques Compared,"* RF Wireless-World. https://www.rfwireless-world.com/.netlify/images?url=_astro%2Foptical-direct-modulation.C-ADmdEt.jpg&w=598&h=297

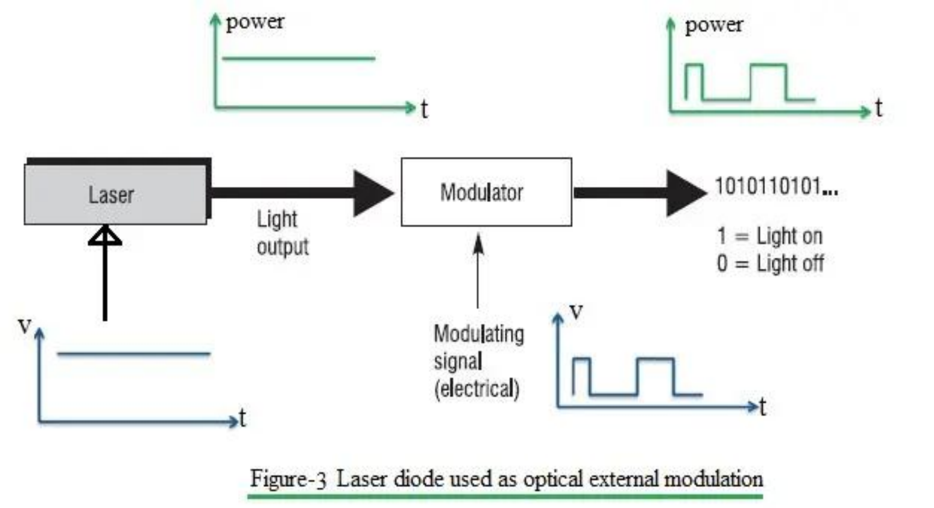


Figure 5: External Modulation

Source: *"Direct Modulation vs. External Modulation: Optical Techniques Compared,"* RF Wireless-World. https://www.rfwireless-world.com/.netlify/images?url=_astro%2Foptical-external-modulation.8dVH_jfp.jpg&w=627&h=323

Optical Modulators Cont..

Internal Modulation

- Does not require External Device
- Simple and Low Cost
- More Compact
- Slow Response
- **Applications:** Limited to 2.5 to 10Gb/s

External Modulation

- require External Device
- Complex and Expensive
- Less Compact
- Faster Response
- **Applications:** up to 40 Gbps and beyond

Fiber-Optic Communication Channel

Optical Fiber

- The Communication Channel in Lightwave System is Optical Fiber
- Optical Fiber is a cylindrical waveguide with core and cladding made of appropriate materials.

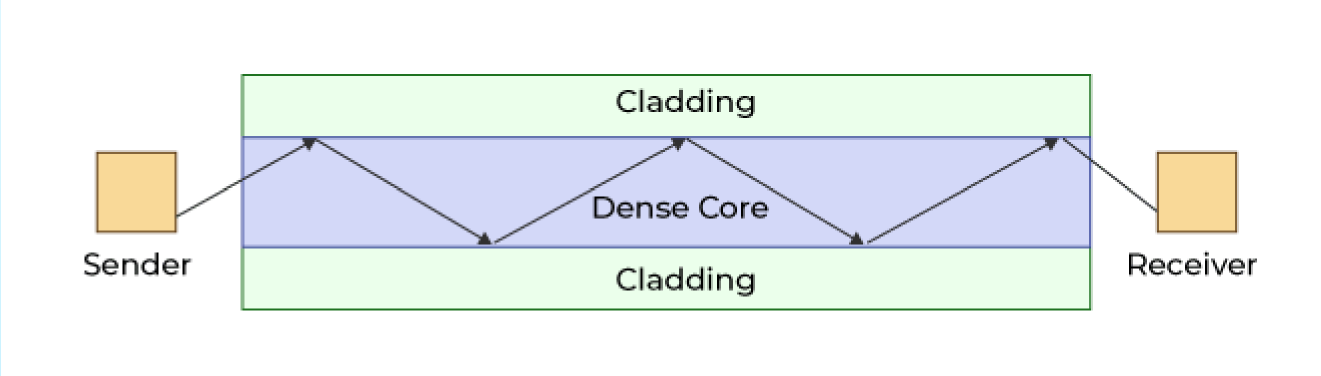


Figure 6: Light Transmission in Optical Fiber

Source: “Optical fiber light transmission,” GeeksforGeeks, Jul. 23, 2025. https://media.geeksforgeeks.org/wp-content/uploads/20231004144301/Computer-Network.png

- The Refractive index of the core is greater than the refractive Index of the cladding

Geometrical Optics

- The Propagation of Light ray through optical fiber can be explained by **Geometrical optics Theory**
- Light represented by a tiny bundle of energy traveling in straight line called **Light particles or Photons**
- The Energy of a photon, E_p is given by:

$$E_p = hf \qquad (2)$$

Where:

h is Planck's constant = 6.625 x 10 -34 J.s

f is frequency of light (photon)

Index of Refraction

- The refractive index defines how much a light ray bends when passing from one medium to another
- When Light travels with speed v in material having refractive index of n:

$$V = \frac{C}{n} \qquad (3)$$

Where:

C is the speed of light in the vacuum

- **Snell's Law:** describes how light bends when it passes from one medium to another.

Snell's Law

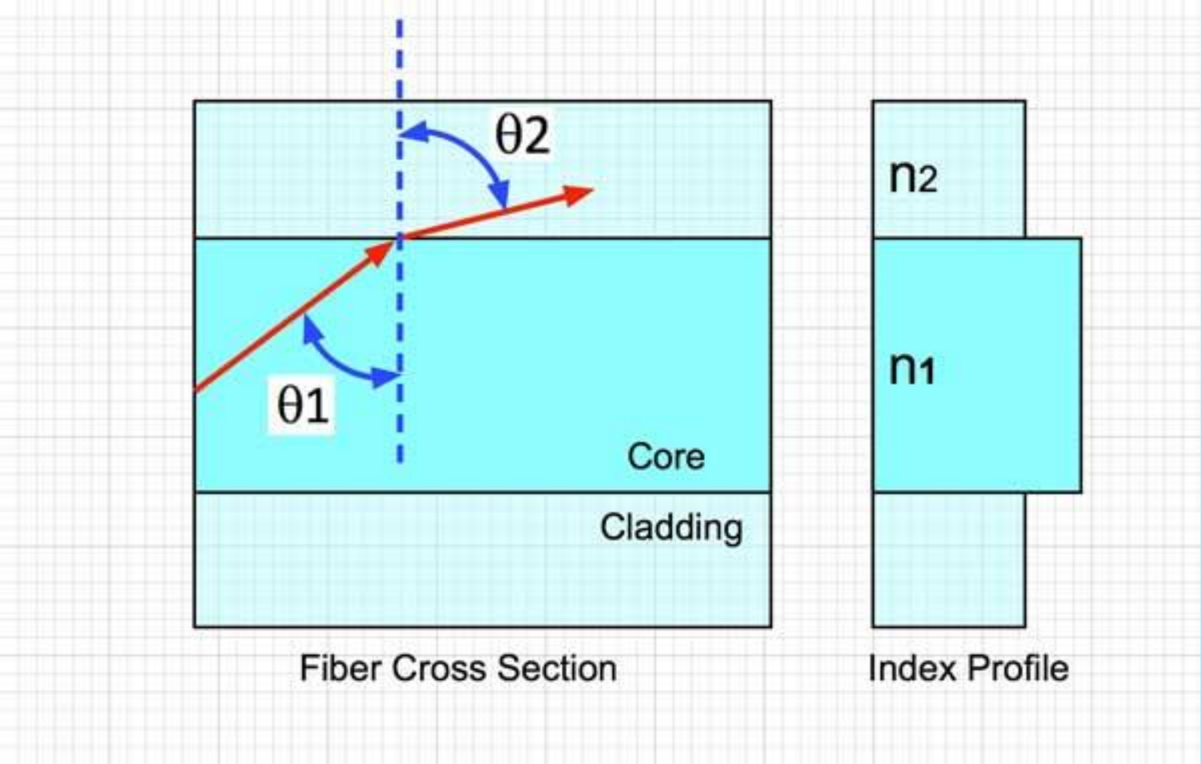


Figure 7: Light Refraction

Source: *"Total internal reflection – basic principle of optical fiber,"* The FOA Reference Guide to Fiber Optics, The Fiber Optic Association. https://www.thefoa.org/tech/ref/basic/Snells_Law_diageram.jpg

Snell's Law

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{n_1}{n_2} \qquad (4)$$

Where:

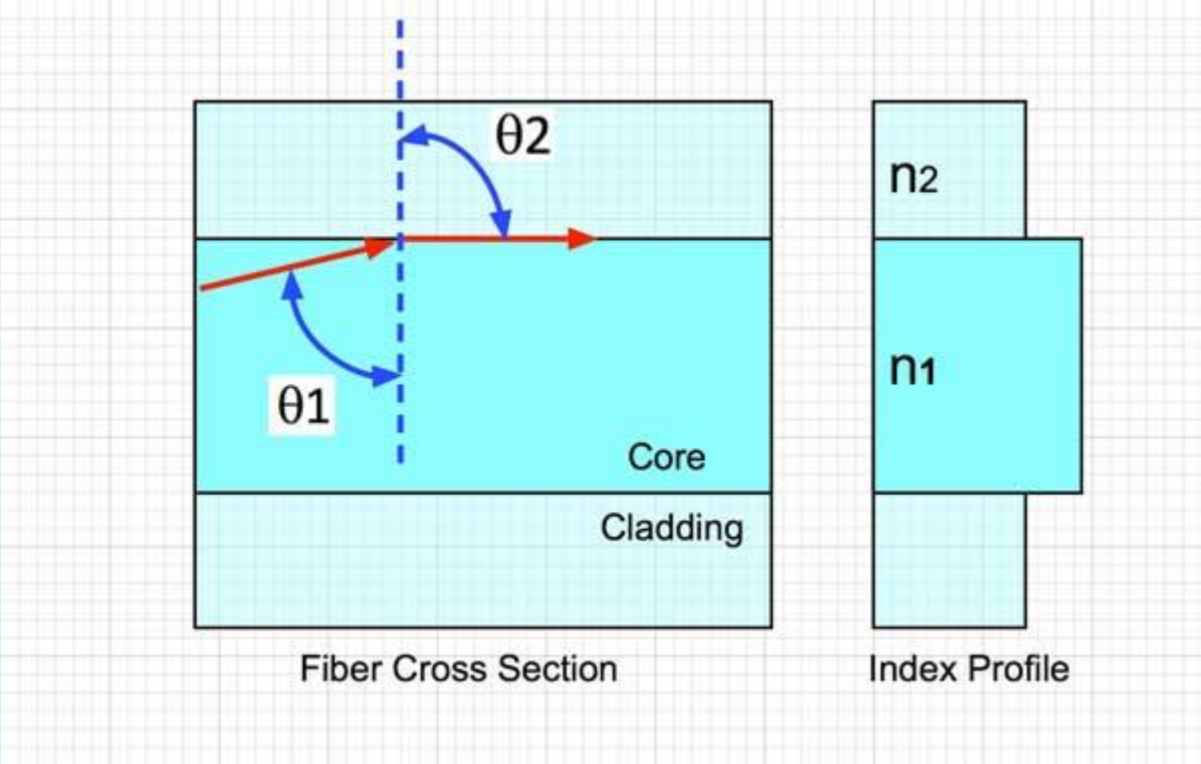
θ_1 is angle of incident

θ_2 is angle of refraction

$n_1 > n_2$

Critical Angle

- the incident angle, θ_1, which makes the angle of refraction $\theta_2 = 90^0$ is called Critical angle, θ_c



From Snell's Law, Critical angle can be obtained as [1]

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{\sin 90^0}{\sin\theta_c} = \frac{n_1}{n_2} \quad (5)$$

$$\sin\theta_c = \frac{n_2}{n_1} \quad (6)$$

Figure 8: Critical Angle

Source: *"Total internal reflection – basic principle of optical fiber,"* The FOA Reference Guide to Fiber Optics, The Fiber Optic Association. https://www.thefoa.org/tech/ref/basic/Snells_Law_critical-angle.jpg

Total Internal Reflection

- The complete reflection of light ray within a medium
- Total internal reflection occurs when the incident angle is greater than critical

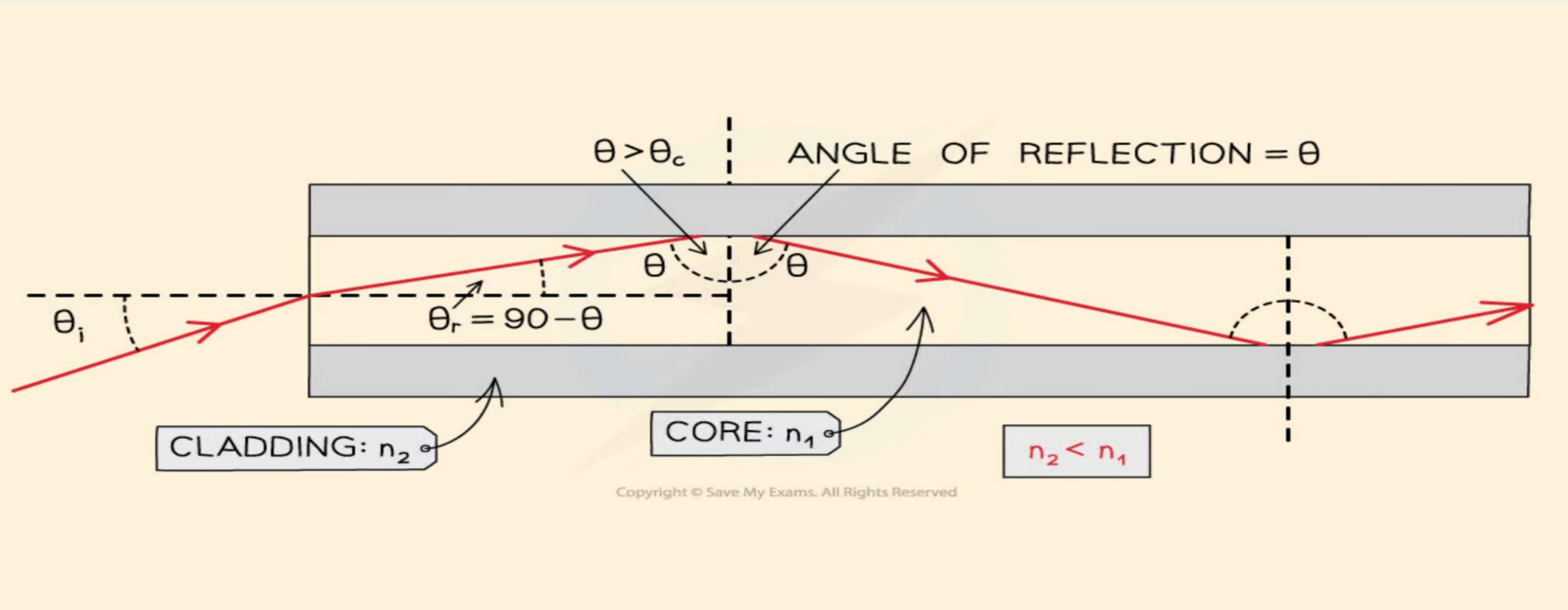


Figure 9: Total Internal Reflection

Source: A. Shijan, "TIR - Optical Fibres," A-Level Notes. https://alexgs.co.uk/lib/media/image-1.png

Numerical Aperture (NA)

- Describes the light collecting ability of optical fiber
- Dimensionless number which shows the range of angles the optical fiber can accept light ray with out creating leaky mode in the cladding

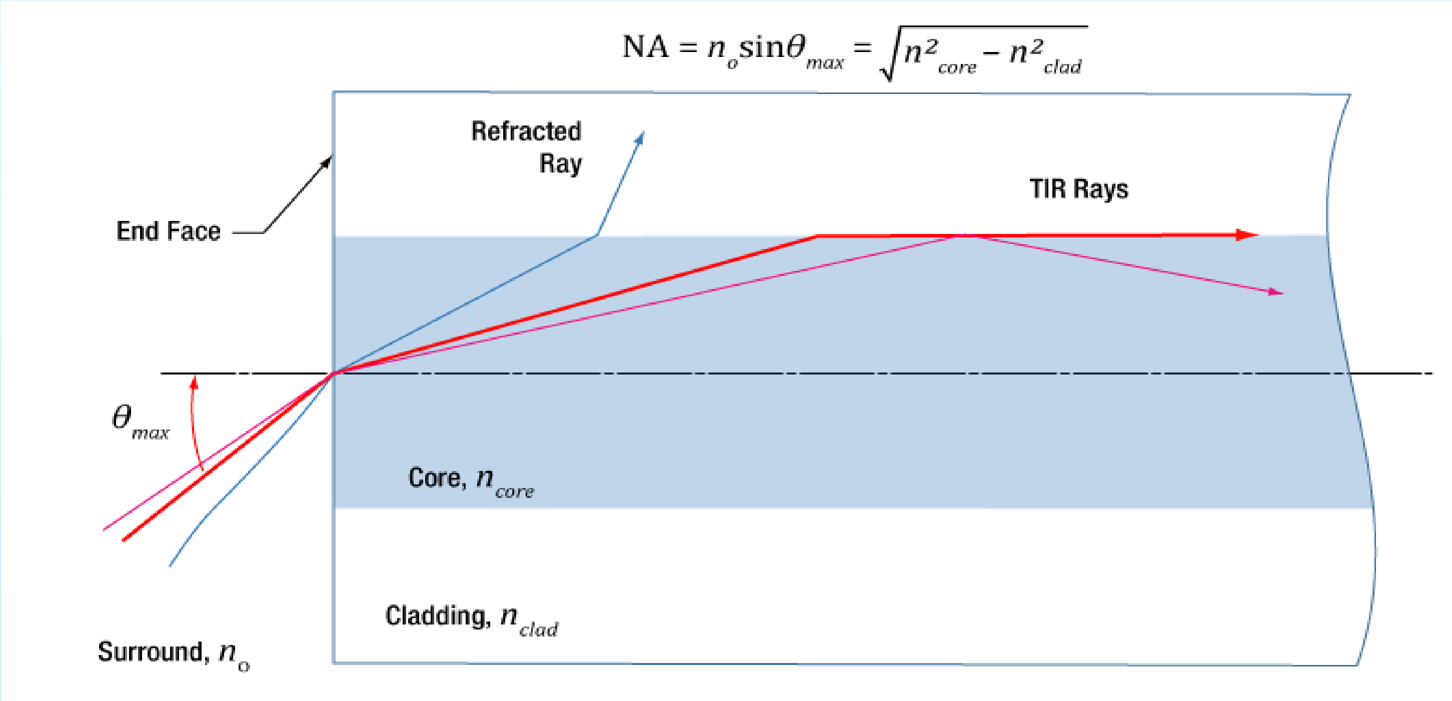


Figure 10: Numerical Aperture

Source: *"Numerical aperture and multimode fiber acceptance angle,"* Thorlabs. https://www.thorlabs.com/images/tabimages/Fiber_TIR_Refracted_Rays_A1-780.gif

- NA is Given by:

$$NA = n_o \sin\theta_{\max} \quad (7)$$

$$= \sqrt{n_{core}^2 - n_{clad}^2}$$

Glass and Plastic Optical Fibers

Glass Optical Fiber

- The Core and Cladding are Glass
- SiO_2 is the main material for the core and cladding
- Has Low attenuation: 0.2dB/km at 1550nm for Sigle-Mode Fiber
- Operate in Near Infrared band
- **Applications:** Low to High speed communication
- **Transmission Distance:** Short to Long Distance

Plastic Optical Fiber

- The Core and Cladding are Plastic
- Has High attenuation: more than 100dB/km
- Operate in Visible light band
- **Applications:** Low speed communication
- **Transmission Distance:** Short Distance (LAN and Automotive Applications)

Optical Fiber Attenuation Profile

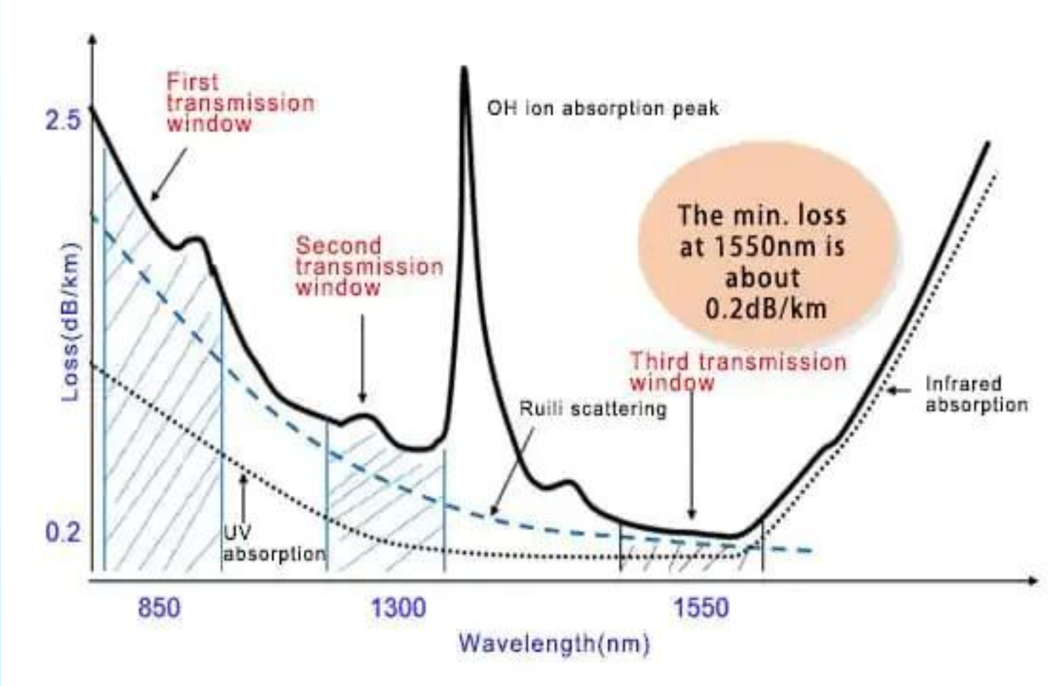


Figure 11: Glass Optical Fiber Attenuation Profile

Source: *"Loss at different wavelengths in optical fibers,"* Introduction of optical fiber, Yingda Photonic Co. Ltd. https://yingdapc.com/wp-content/uploads/2025/04/figure-4-loss-at-different-wavelengths.jpg

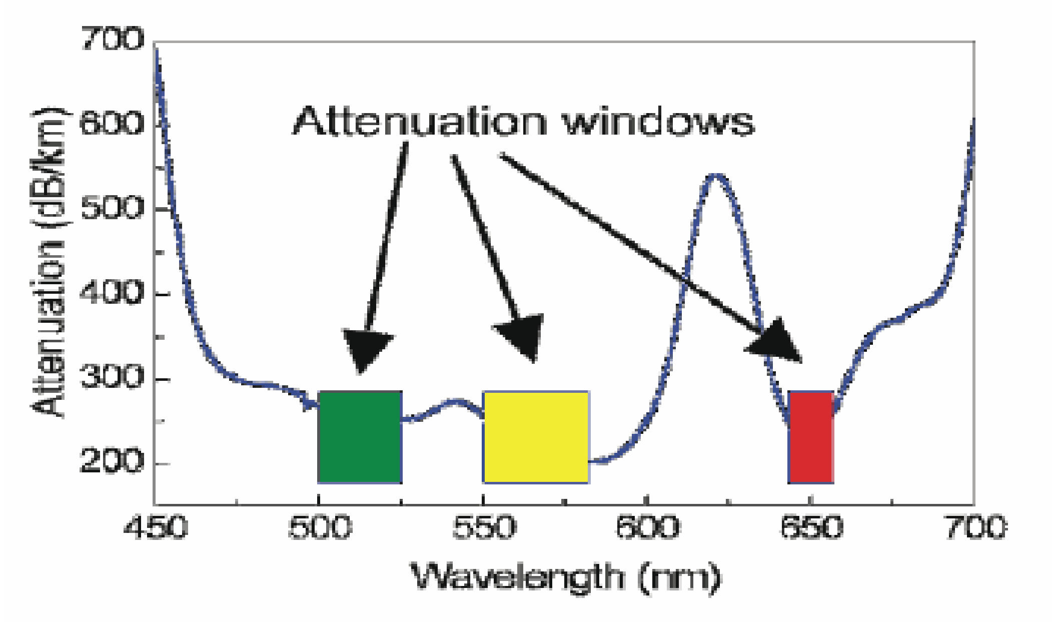


Figure 12: Plastic Optical Fiber Attenuation Profile

Source: Ana Charas et al., *"Plastic Optical Fibers with Gain and Switching," 2009.* https://www.researchgate.net/profile/Guglielmo-Lanzani/publication/237807556/figure/fig1/AS:298756814721036@1448240583289/Attenuation-of-PMMA-and-selected-transmission-windows.png

Single-Mode and Multi-Mode Optical Fibers

- In optical fibers, light propagates in the form of guided modes
- Optical Fiber can be classified as single-mode and multi-mode optical fibers based on the number of guided modes propagating through the fiber

Single-Mode Optical Fiber

- Transmit one Mode or signal per fiber
- Small Core, Diameter: 9 micrometer
- Suitable to use with LASER source
- Suitable for Long distance and High Speed Communication

Multi-Mode Optical Fiber

- Transmit Multi Modes or signals per fiber
- Large Core, Diameter: 62.5 micrometer
- Suitable to use with LED source
- Suitable for Short distance and Low Speed Communication

Number of Modes

- The number of modes supported by optical fiber determined by the parameter called **V number** or **Normalized Frequency**

$$V = \frac{2\pi a\sqrt{n_1^2 - n_2^2}}{\lambda} \qquad (1)$$

- For single mode propagation, $V \leq 2.4$

Where:

a is the radius of the fiber core
λ is the Wavelength of light
n_1 is the refractive index of the core
n_2 is the refractive index of the cladding

Single-Mode and Multi-Mode Cont..

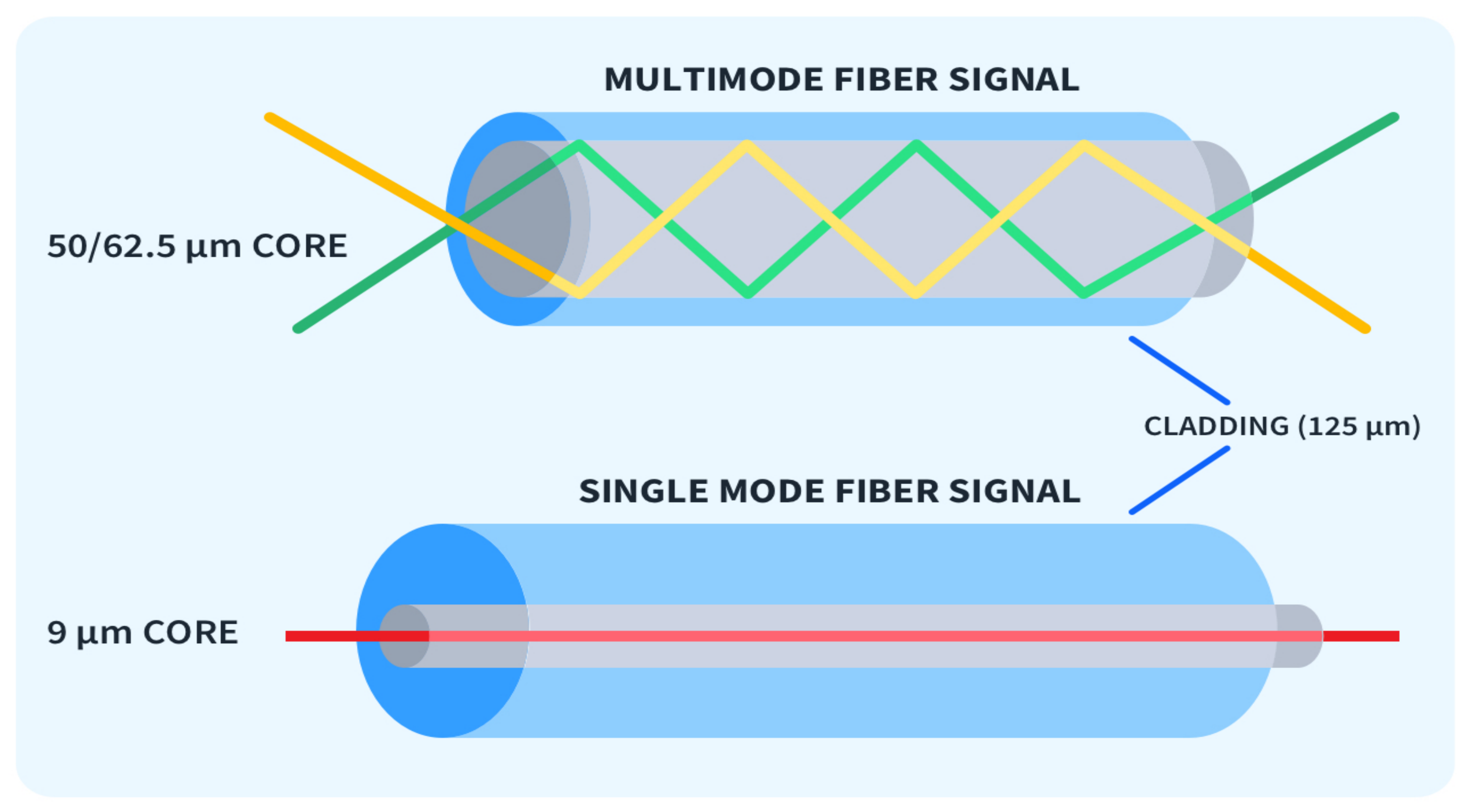


Figure 13: Multi-mode and Single-mode Fiber Signal

Source: *"Single mode vs. multimode fiber: A complete comparison,"* DEKAM. https://images.ctfassets.net/aoyx73g9h2pg/2akZ34C0SwKh3lRZg3u0M5/bbdbf30bbe3d7f6939a78d50df925a28/Single-Mode-vs-Multimode-Fiber-Diagram.jpg

Step Index and Graded Index Multimode Fiber

- Based on the profile of the core refractive index, Multimode Fiber classified as:
  - ✓ Step Index Multimode Fiber: Abrupt change of refractive index at Core-Cladding boundary
  - ✓ Graded Index Multimode Fiber: the index of refraction of the core decreases continuously till Core-Cladding boundary

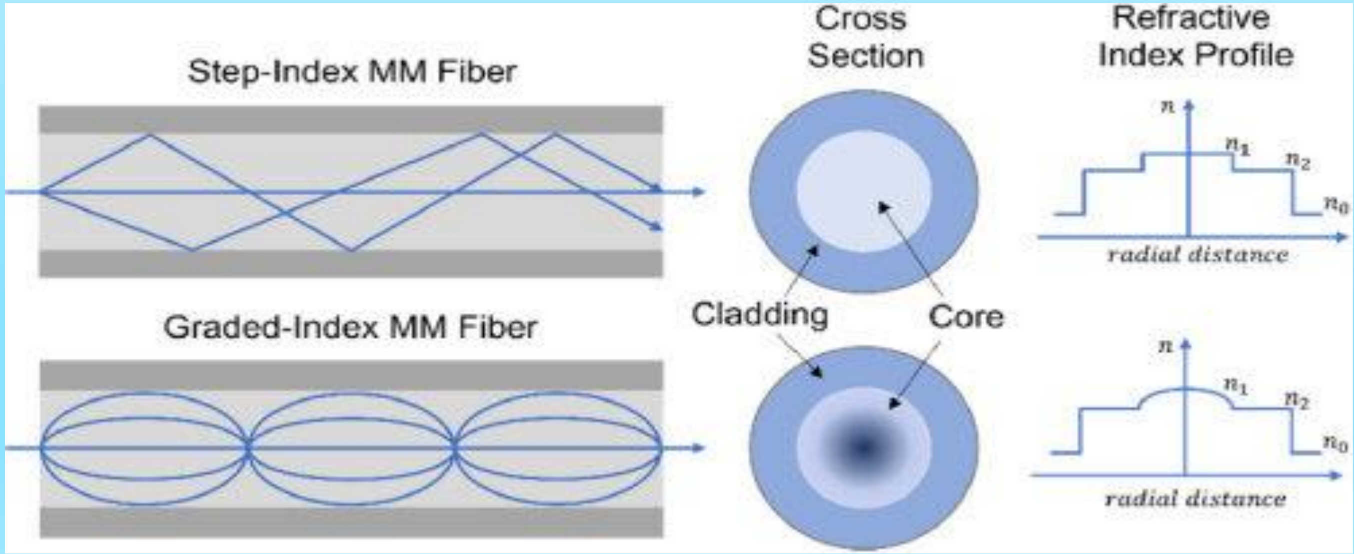


Figure 14: Step-Index and Graded-Index Multi-mode Fibers

Source: A. Lee et al., *"Quantum bit error rate timing jitter dependency on multi-mode fibers,"* Optics Express, 2023. https://www.researchgate.net/publication/367179528/figure/fig1/AS:11431281330636367@1743200424250/The-differences-between-a-step-index-fiber-and-a-graded-index-fiber-For-the-refractive.jpg

Optical Amplifiers

- Optical Amplifiers amplify the optical signal directly without requiring conversion of the optical signal to the electric domain [2].
- Three Common types of Optical amplifiers:

Semiconductor Optical Amplifier

- compact
- Relatively Lower gain
- High noise figure

Erbium-Doped Fiber Amplifier (EDFA)

- Higher gain
- Low noise figure

RAMAN Amplifier

- Distributed amplification
- Low noise figure
- Extend transmission distance

Photodetectors

- Photodetector is the main component of Optical Receiver
- Convert the received optical signal to electrical signal through Photoelectric effect
- The Most Common Types of Photodetectors in Optical fiber communication are:

PIN photodiode:

- ✓ No internal Gain
- ✓ High Bandwidth and Suitable for High speed Communication

Avalanche Photodiode:

- ✓ Internal Gain
- ✓ High Sensitivity

WDM Systems

- works by using multiple light sources at slightly different wavelengths to transmit several independent data streams simultaneously through a single optical fiber [3]
- Signals with different wavelength are multiplexed together for transmission over an optical link.

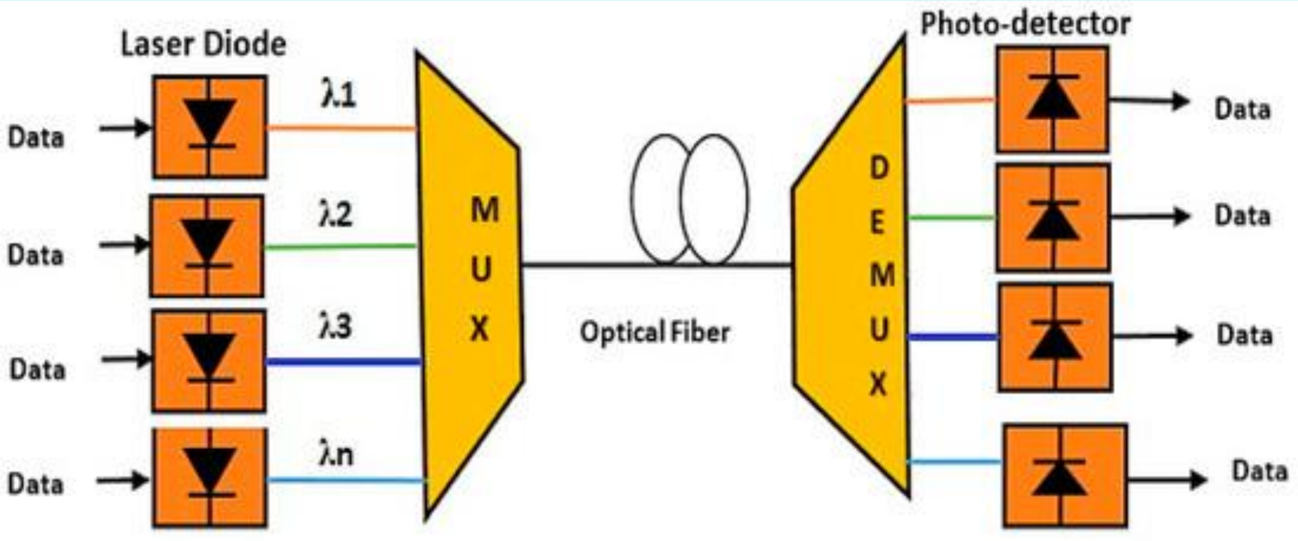


Figure 15: Wavelength Division Multiplexing

Source: Ali AH, Farhood AD., *"Design and Performance Analysis of the WDM Schemes for Radio over Fiber System With Different Fiber Propagation Losses,"* Fibers, 2019. https://www.mdpi.com/fibers/fibers-07-00019/article_deploy/html/images/fibers-07-00019-g001-550.jpg

- Enhance transmission capacity with adding additional fiber

Fiber Optics communication Applications

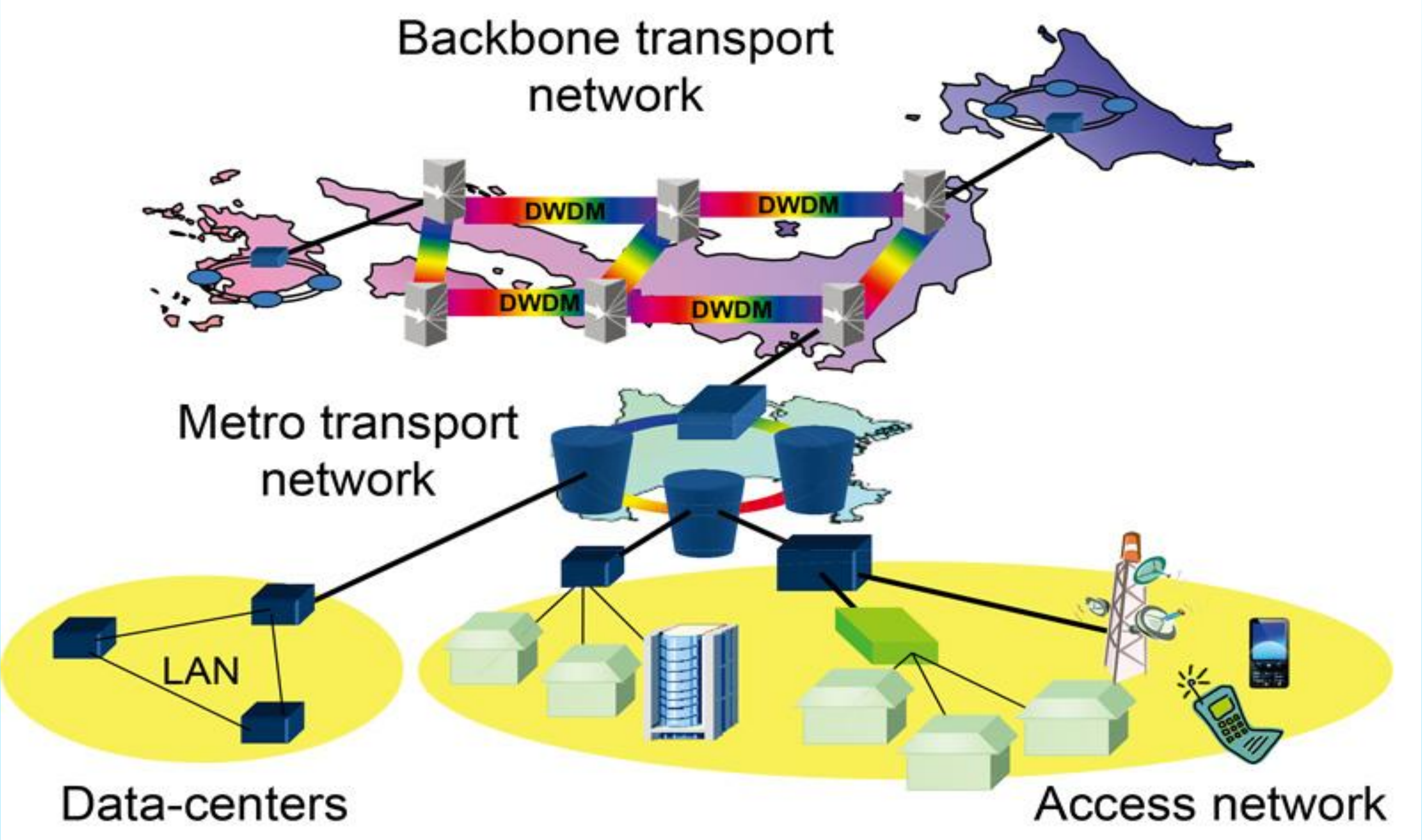


Figure 16: Fiber Optics Backbone, Metro, and Access Networks

Source: S. Akihide, *"Optical fiber communications technology and its application,"* Ritsumeikan University. https://en.ritsumei.ac.jp/image.jsp?id=554641&version=English

Backbone Network

- Long distance transmission above 50km
- Inter-city signal transmission

Metro Network

- Medium distance transmission, below 50km
- Intra-city signal transmission

Access Network

- Relatively short distance transmission, below 20km
- Last mile communication

Global Submarine Fiber Optic links

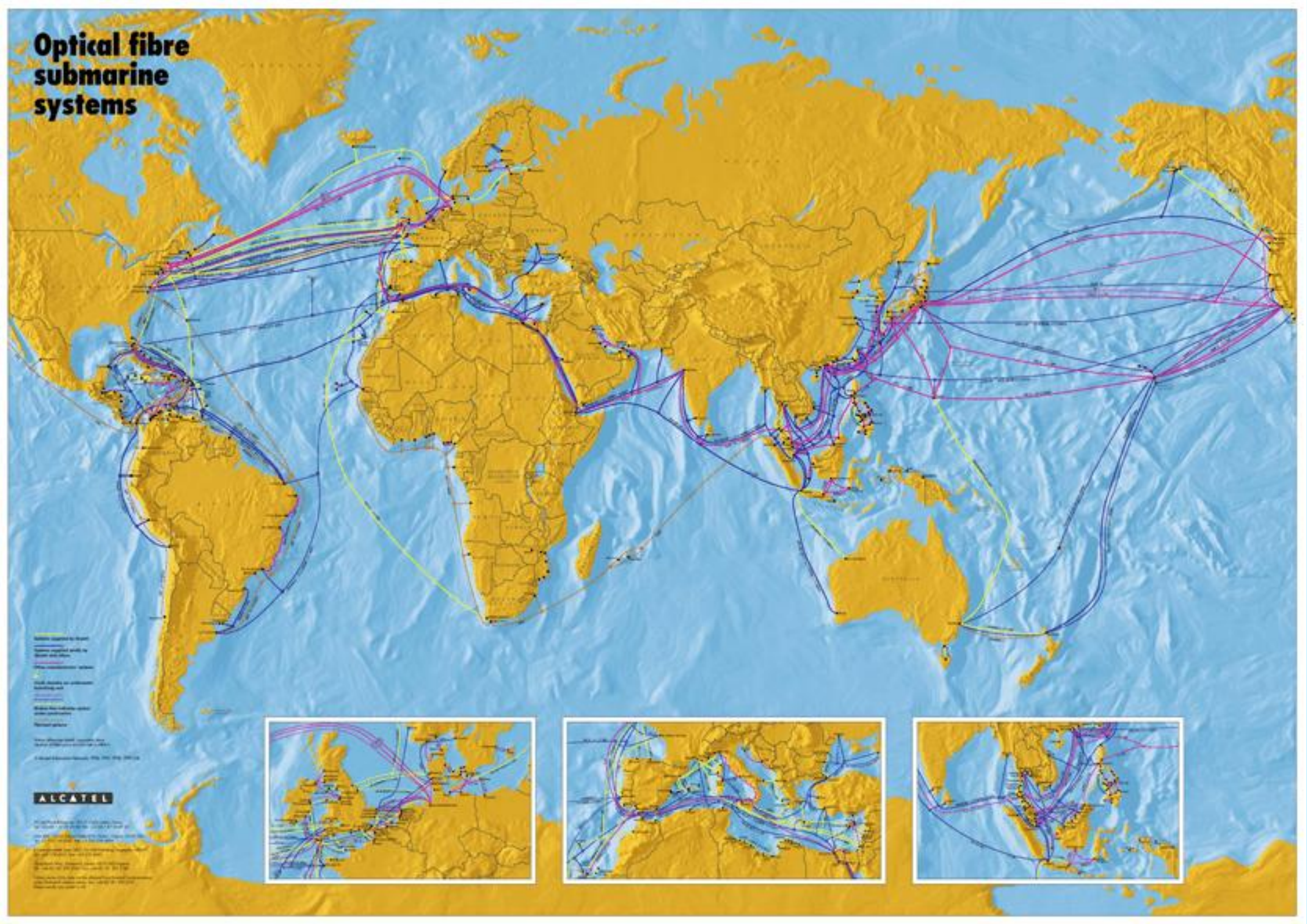


Figure 17: Global Submarine Fiber Optic links

Source: Martin Dodge, Rob Kitchin, *"Examining different approaches to mapping Internet infrastructure,"* CASA Working Paper Series No. 39, 2001. https://www.researchgate.net/profile/Rob-Kitchin/publication/262008090/figure/fig12/AS:668360480137216@1536360964055/World-map-of-submarine-fibre-optic-cables-Courtesy-of-Alcatel-http-wwwalcatelcom.ppm

Summary

- Fiber Optic Communication Uses light signals for data transmission
- Offers High bandwidth, low loss, immunity to Electromagnetic Interference
- Light ray propagate through optical fiber using total internal reflection and guided modes
- **Fiber Optics types:** Single-mode, Multimode, Glass/Plastic Optical Fibers
- **Basic System components:** Optical Transmitter , Optical Fiber , Optical Amplifier, and Optical Receiver
- **Major Applications:** backbone Network , Metro Network, Access Network, Data centers Connectivity
- **Advantages:** High speed, high capacity, long distance transmission

References

[1] Shiva Kumar and M. Jamal Deen, ‘’ Fiber Optic Communication Systems’’, Wiley, Pp.57, 2014.

[2] Govind P. Agrawal,‘’ Fiber-Optic Communication Systems’’, John Wiley & Sons, Pp.226, 2002.

[3] Gerd Keiser, ‘’ Fiber Optic Communications’’, Springer, Pp.18, 2021.

Thank You !