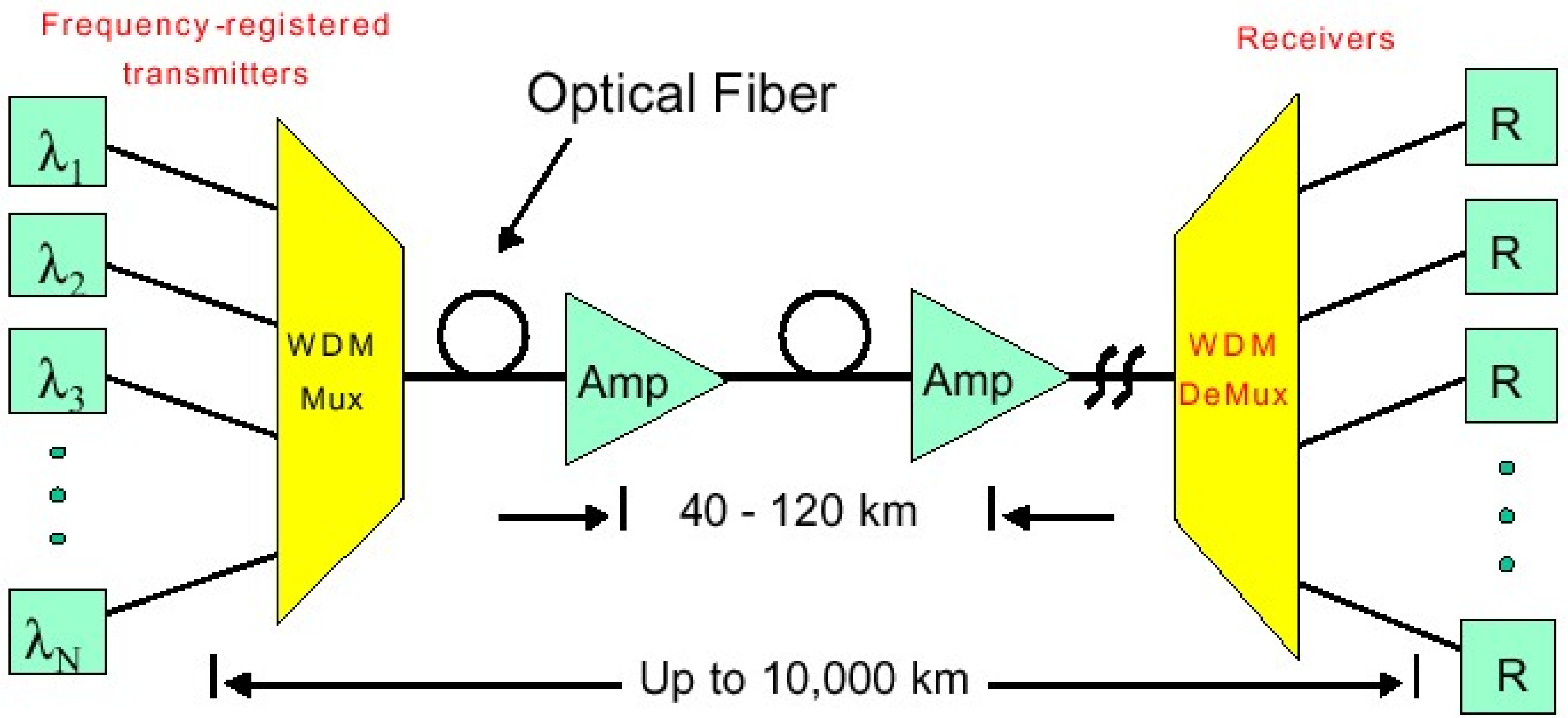
OPTICAL FIBER COMMUNICATIONS

- Evolution of fiber Optic system
- Element of an Optical Fiber Transmission link
- Ray Optics
- Optical Fiber Modes and Configurations
- Mode theory of Circular Wave guides
- Overview of Modes
- Key Modal concepts
- Linearly Polarized Modes
- Single Mode Fibers
- Graded Index fiber structure

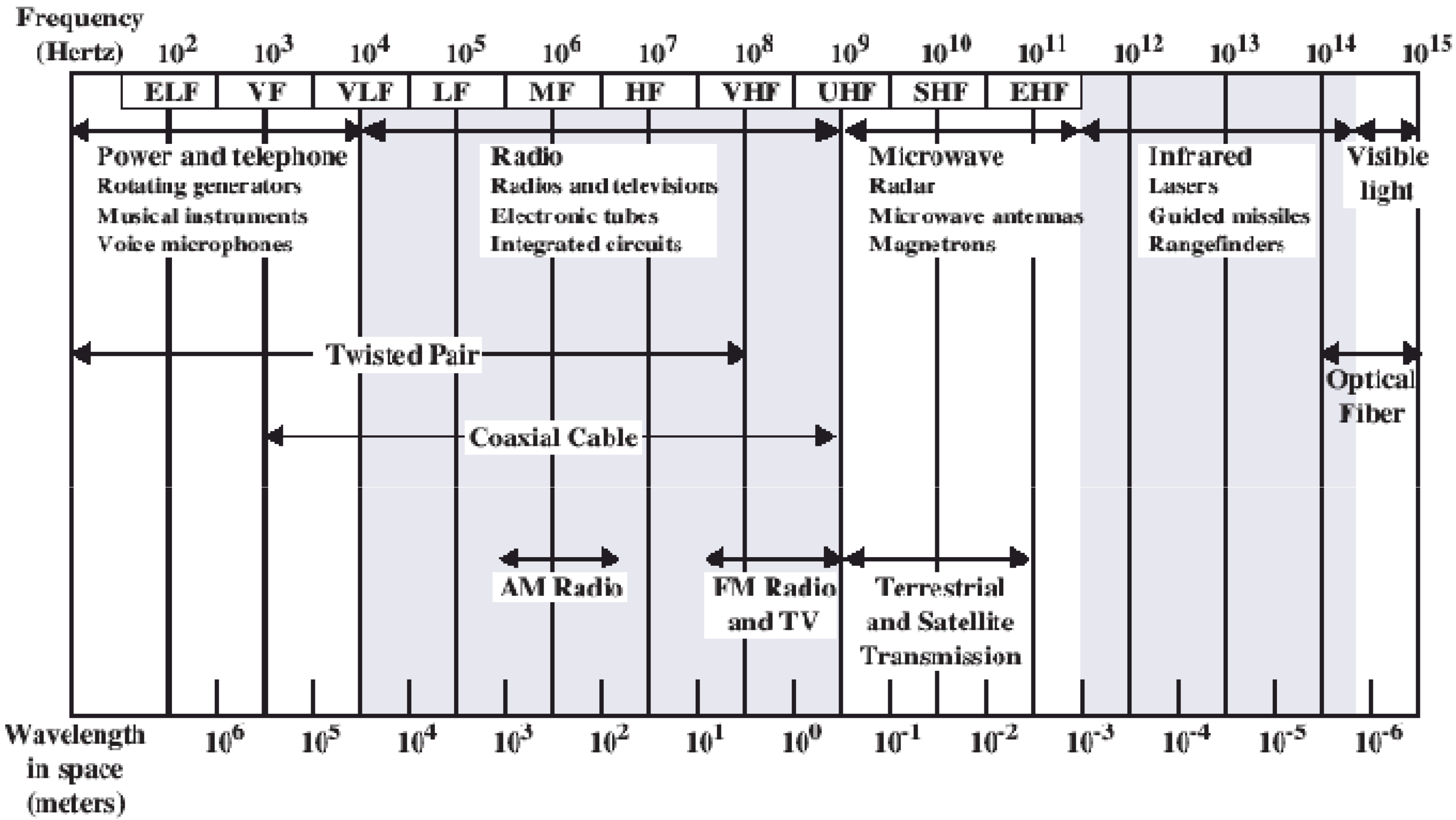
- Fiber optics deals with study of propagation of light through transparent dielectric waveguides.
- The fiber optics are used for transmission of data from point to point location.
- Fiber optic systems currently used most extensively as the transmission line between terrestrial hardwired systems.
- The carrier frequencies used in conventional systems had the limitations in handling the volume and rate of the data transmission.
- The greater the carrier frequency larger the available bandwidth and information carrying capacity.

- An optical Fiber is a thin, flexible, transparent Fiber that acts as a waveguide, or "light pipe", to transmit light between the two ends of the Fiber.
- Fibers are used instead of metal wires because signals travel along them with less loss and are also immune to electromagnetic interference.

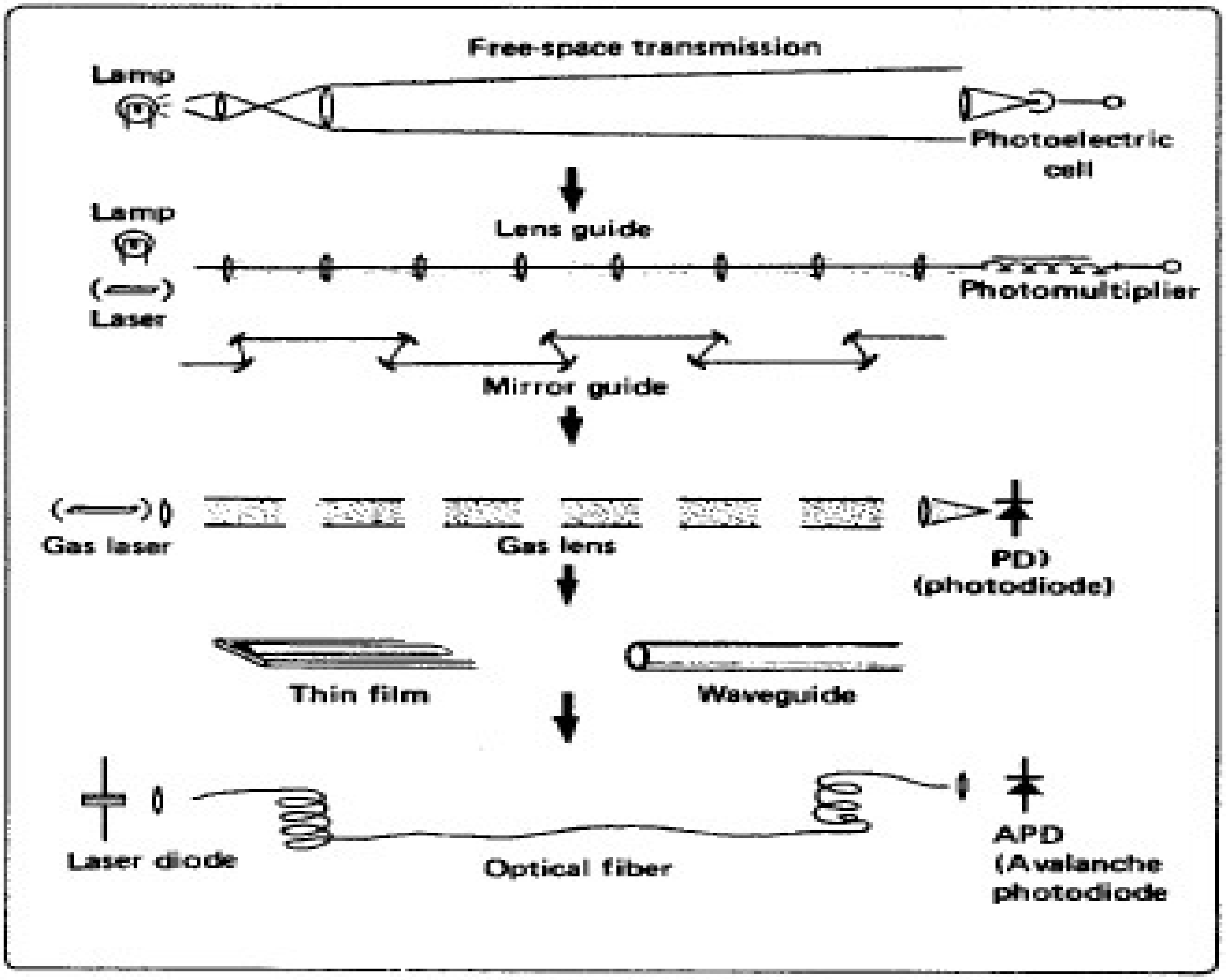


$\Delta\lambda$ = 25 - 100 GHz
(0.4 or 0.8 nm @ 1500 nm)

Introduction to Optical Communication

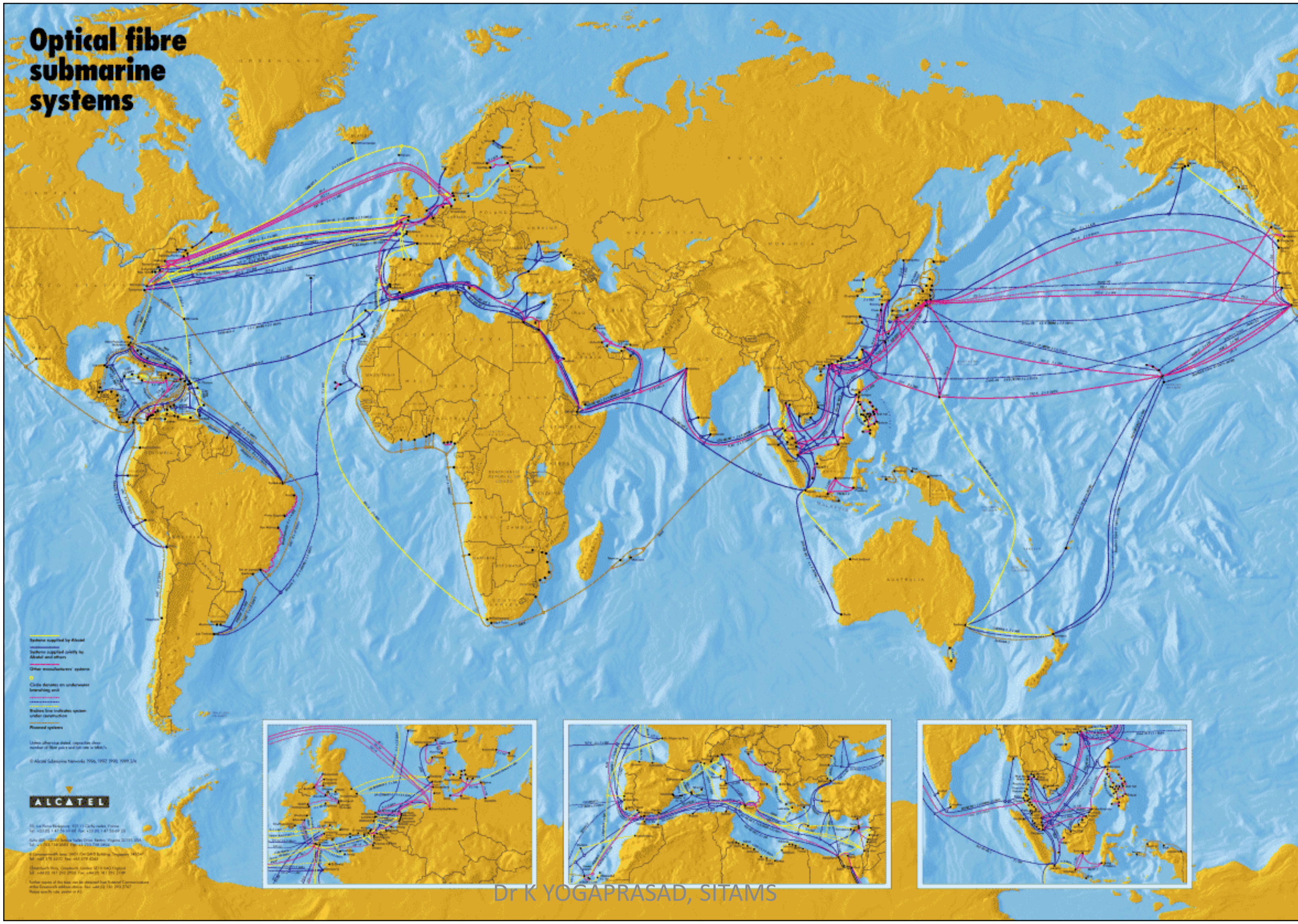


ELF – Extremely low frequency
VF – Voice frequency
VLF = Very low frequency
LF = Low frequency
MF – Medium frequency
HF – High frequency
VHF = Very high frequency
UHF – Ultrahigh frequency
SHF – Superhigh frequency
EHF = Extremely high frequency



Free-space transmission
Lamp
Photoelectric cell
Lens guide
Lamp
Laser
Photomultiplier
Mirror guide
Gas laser
Gas lens
PD)
(photodiode)
Thin film
Waveguide
Laser diode
Optical fiber
APD
(Avalanche
photodiode

Global Undersea Fiber systems



Evolution of fiber Optic system

- **First generation**
- uses GaAs semiconductor laser and operating region was near **0.8 µm**.
  - Bit rate : 45 Mb/s
  - Repeater spacing : 10 km
- **Second generation**
  - Bit rate: 100 Mb/s to 1.7 Gb/s
  - Repeater spacing: 50 km
  - Operation wavelength: 1.3 µm
  - Semiconductor: In GaAsP
- **Third generation**
  - Bit rate : 10 Gb/s
  - Repeater spacing: 100 km
  - Operating wavelength: 1.55 µm

- **Fourth generation**
  - uses WDM technique.
  - Bit rate: 10 Tb/s
  - Repeater spacing: > 10,000 km
  - Operating wavelength: 1.45 to 1.62 μm
- **Fifth generation**
  - Roman amplification technique and optical solitiors.
  - Bit rate: 40 - 160 Gb/s
  - Repeater spacing: 24000 km - 35000 km
  - Operating wavelength: 1.53 to 1.57 μm

Need of fiber optic communication

- It is emerged as most important communication system.
- Compared to traditional system because of following requirements:
  - In long haul transmission system there is need of low loss transmission medium
  - There is need of compact and least weight transmitters and receivers.
  - There is need of increase the span of transmission.
  - There is need of increased bit rate-distance product.

Advantages of OFC

- **Wide bandwidth**
  - The light wave occupies the frequency range between 2 x 1012 Hz to 3.7 x 1012 Hz.
  - Thus the information carrying capability of fiber optic cables is much higher.
- **Low losses**
  - Fiber optic cables offers very less signal attenuation over long distances.
  - Typically it is less than 1 dB/km. This enables longer distance between repeaters.

- **Immune to cross talk**
  - Fiber optic cables have very high immunity to electrical and magnetic field. Since fiber
  - optic cables are non-conductors of electricity hence they do not produce magnetic field.
  - Thus fiber optic cables are immune to cross talk between cables caused by magnetic induction.
- **Interference immune**
  - Fiber optic cable immune to conductive and radiative interferences caused by electrical noise sources such as lighting, electric motors, fluorescent lights.
- **Light weight**
  - As fiber cables are made of silica glass or plastic which is much lighter than copper or aluminum cables. Light weight fiber cables are cheaper to transport.
- **Small size**
  - The diameter of fiber is much smaller compared to other cables, therefore fiber cable is small in size, requires less storage space.

- **More strength**
  - Fiber cables are stronger and rugged hence can support more weight.
- **Security**
  - Fiber cables are more secure than other cables. It is almost impossible to tap into a fiber cable as they do not radiate signals.
  - No ground loops exist between optical fibers hence they are more secure.
- **Long distance transmission**
  - Because of less attenuation transmission at a longer distance is possible.
- **Environment immune**
  - Fiber cables are more immune to environmental extremes.
  - They can operate over large temperature variations. Also they are not affected by corrosive liquids and gases.
- **Sage and easy installation**
  - Fiber cables are safer and easier to install and maintain.
  - They are non-conductors hence there is no shock hazards as no current or voltage is associated with them.
  - Their small size and light weight feature makes installation easier.
- **Low cost**
  - Cost of fiber optic system is less compared to any other system.

Disadvantages of OFC

- **High initial cost**
  - The initial cost of installation or setting up cost is very high compared to all other system.
- **Maintenance and repairing cost**
  - The maintenance and repairing of fiber optic systems is not only difficult but expensive also.
- **Jointing and test procedures**
  - Since optical fibers are of very small size. The fiber joining process is very costly and requires skilled manpower.
- **Tensile stress**
  - Optical fibers are more susceptible to buckling, bending and tensile stress than copper cables.
  - This leads to restricted practice to use optical fiber technology to premises and floor backbones with a few interfaces to the copper cables.
- **Short links**
  - Even though optical fiber cables are inexpensive, it is still not cost effective to replace every small conventional connector (e.g. between computers and peripherals), as the price of optoelectronic transducers are very high.
- **Fiber losses**
  - The amount of optical fiber available to the photo detector at the end of fiber length depends on various fiber losses such as scattering, dispersion, attenuation and reflection.

- High investment cost
- Need for more expensive optical transmitters and Receivers
- More difficult and expensive to splice than wires
- Price
- Fragility
- Affected by chemicals
- Opaqueness
- Requires special skills

Applications of OFC

- include telecommunications, data communications, video control and protection switching, sensors and power applications.
- **1. Telephone networks**
  - Optical waveguide has low attenuation, high transmission bandwidth compared to copper lines; therefore numbers of long haul co-axial trunks links between telephone exchanges are being replaced by optical fiber links.
- **2. Urban broadband service networks**
  - Optical waveguide provides much larger bandwidth than co-axial cable, also the number of repeaters required is reduced considerably.

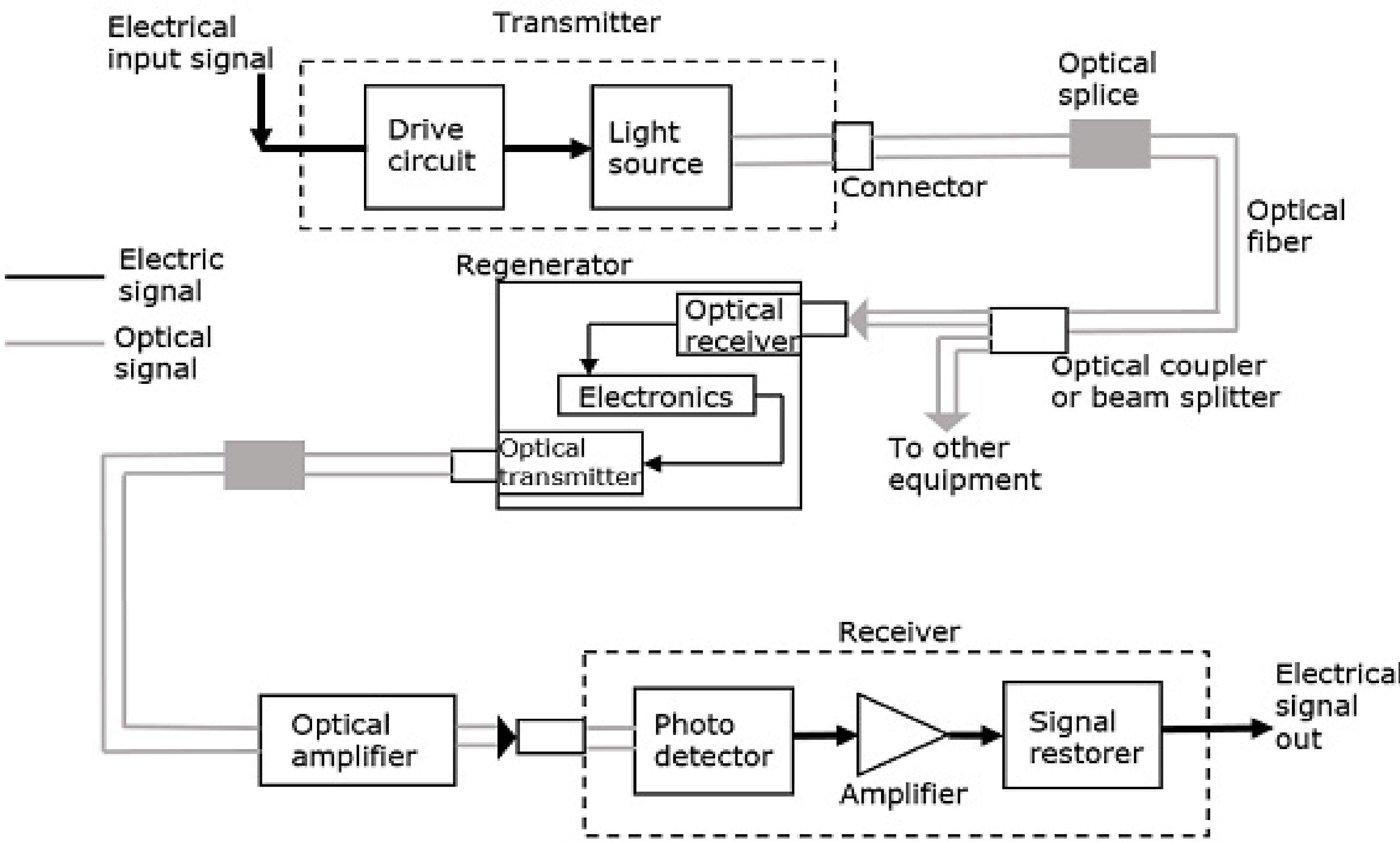
- Modern suburban communications involves videotext, videoconferencing Video telephony Switched broadband communication network.
- All these can be supplied over a single fiber optic link.
- Fiber optic cables is the solution to many of today‘s high speed, high bandwidth data communication problems and will continue to play a large role in future telecom and data-com networks.

OPTICAL FIBER COMMUNICATION SYSTEM

- **2-types of communication links**:
  - Analog link
  - Digital link
- **2-types of fiber:**
  - Plastic
  - Glass
- **2-types of optical sources:** converts E-signal into optical signal.
  - LED
  - LASER (Light Amplification by Stimulated Emission of Radiation)

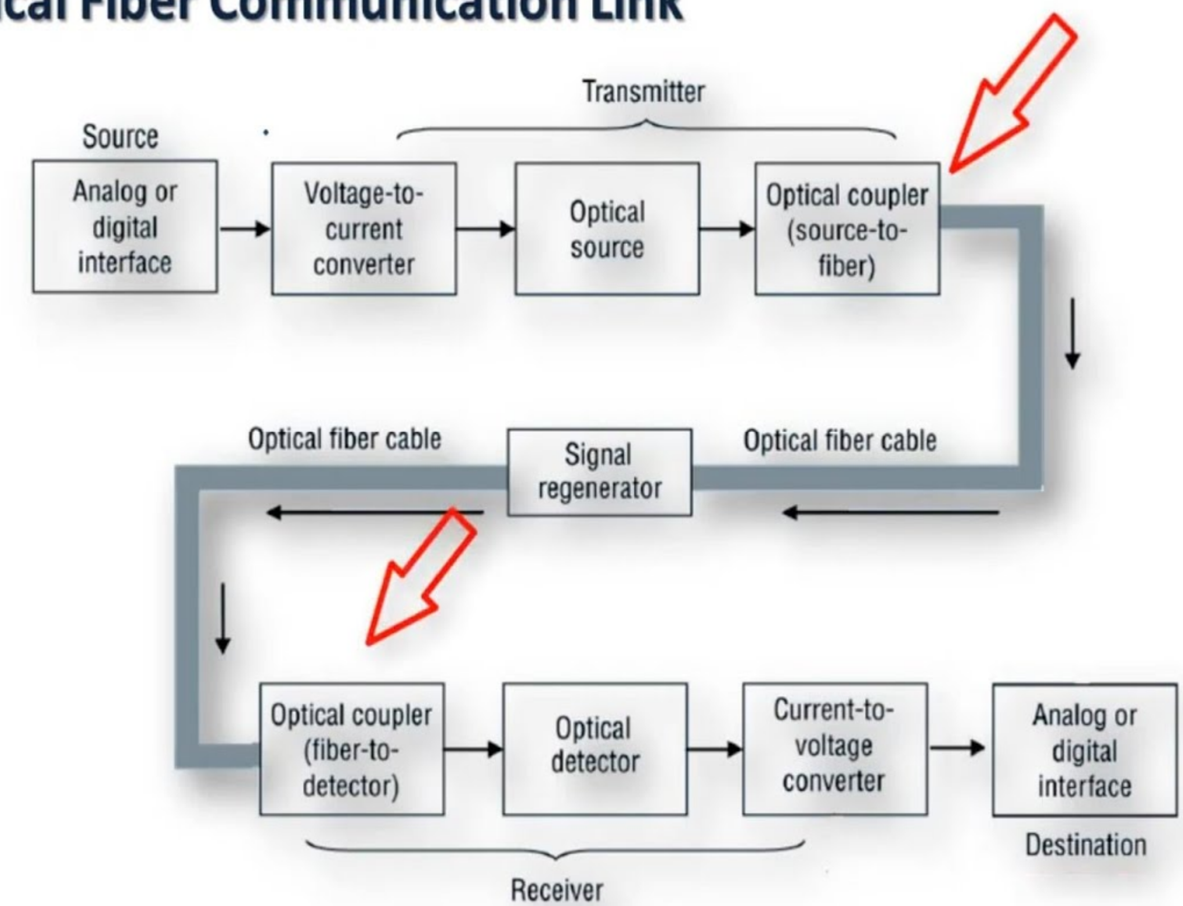
- **Optical detectors**: converts optical signal into E-signal.
  - Photo diode
  - Photo transistors
  - PIN diode
  - APD
- **Optical windows:**
  - 800-900 nm - (Typically Multimode Fiber)
  - 1300 nm (Lowest dispersion)-1310nm
  - 1550 nm (Lowest Attenuation)

Analog link



Electrical
input signal
Transmitter
Drive
circuit
Light
source
Optical
splice
Connector
Optical
fiber
Electric
signal
Optical
signal
Regenerator
Optical
receiver
Electronics
Optical
transmitter
Optical coupler
or beam splitter
To other
equipment
Receiver
Optical
amplifier
Photo
detector
Amplifier
Signal
restorer
Electrical
signal
out

Optical Fiber Communication Link

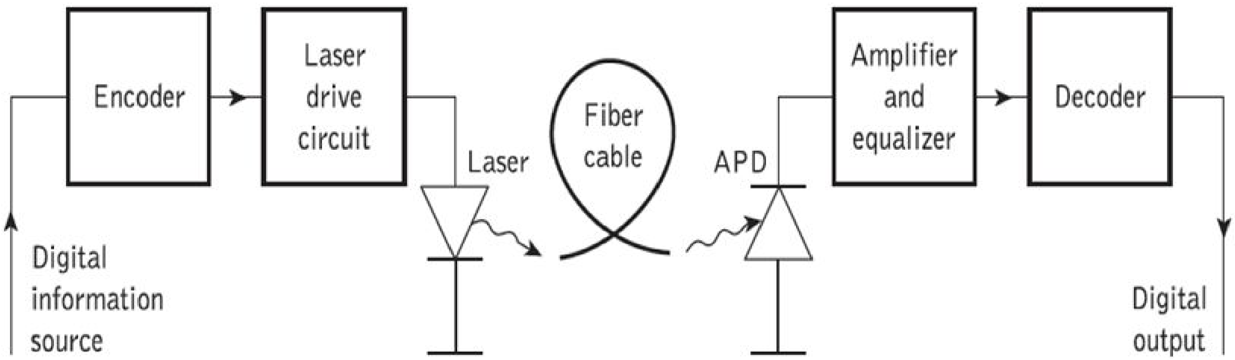


Optical components

- Optical connector: temporary bond-possible to attach or detach the fiber.
- Optical splice: permanent bond-not possible to attach or detach the fiber.
- Optical coupler: to split & combine the optical pulse.
- Regenerator: to regenerate an optical signal. Such repeaters are used to extend the reach of optical communications links by overcoming loss due to attenuation of the optical fiber.
  - Reamplification of the data pulse alone is carried out.

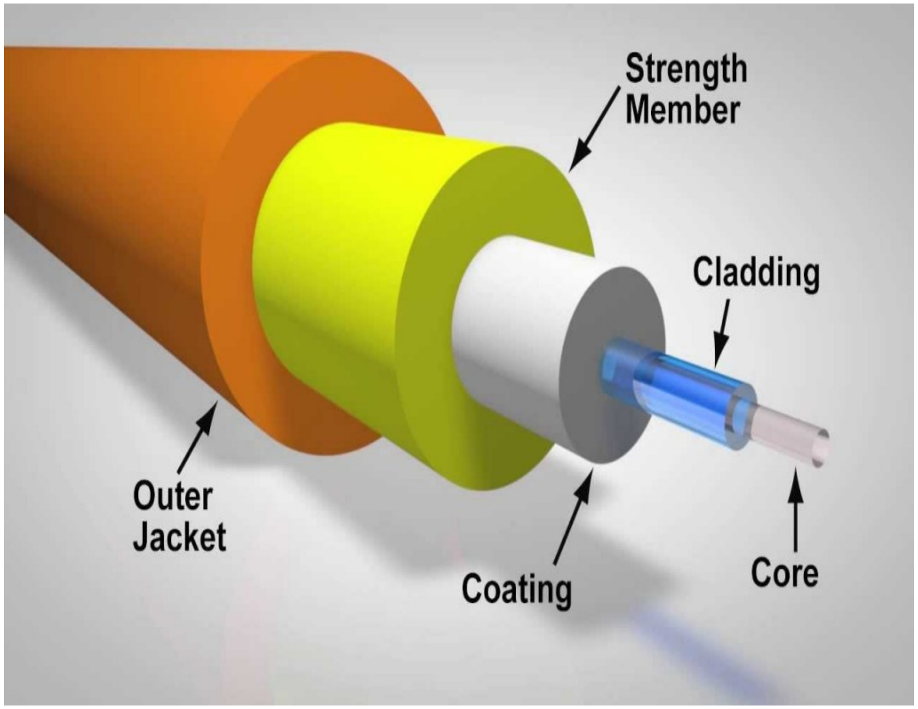
Digital Link

Digital Optical Fiber link



Fiber optic Cable

- Optic Cable consists of four parts.
  - Core
  - Cladding
  - Buffer
  - Jacket

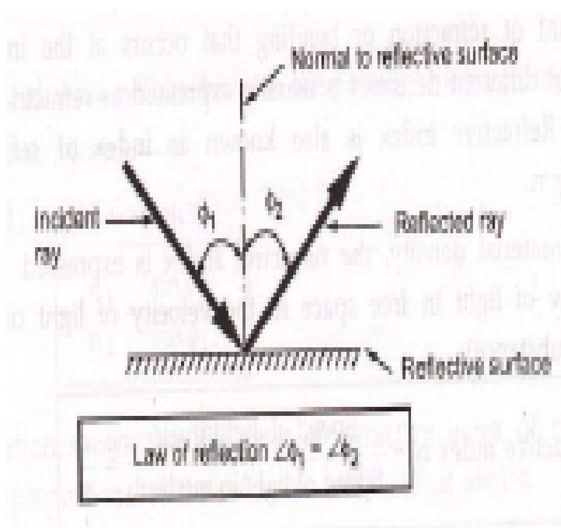


- **Core:**
  - Offers protection by cladding.
  - Due to internal reflection, the light travelling within the core reflects from the core, the cladding boundary.
- **Cladding:**
  - protects the core. The main function of the cladding is that it reflects the light back into the core.
  - When light enters through the core (dense material) into the cladding(less dense material), it changes its angle, and then reflects back to the core.
- **Buffer:**
  - Used to protect the fiber from damage and thousands of optical fibers arranged in hundreds of optical cables.
  - These bundles are protected by the cable's outer covering that is called jacket.
- **JACKET**
  - Fiber optic cable's jackets are available in different colors that can easily make us recognize the exact color of the cable we are dealing with.
  - The color yellow clearly signifies a single mode cable, and orange color indicates multimode.

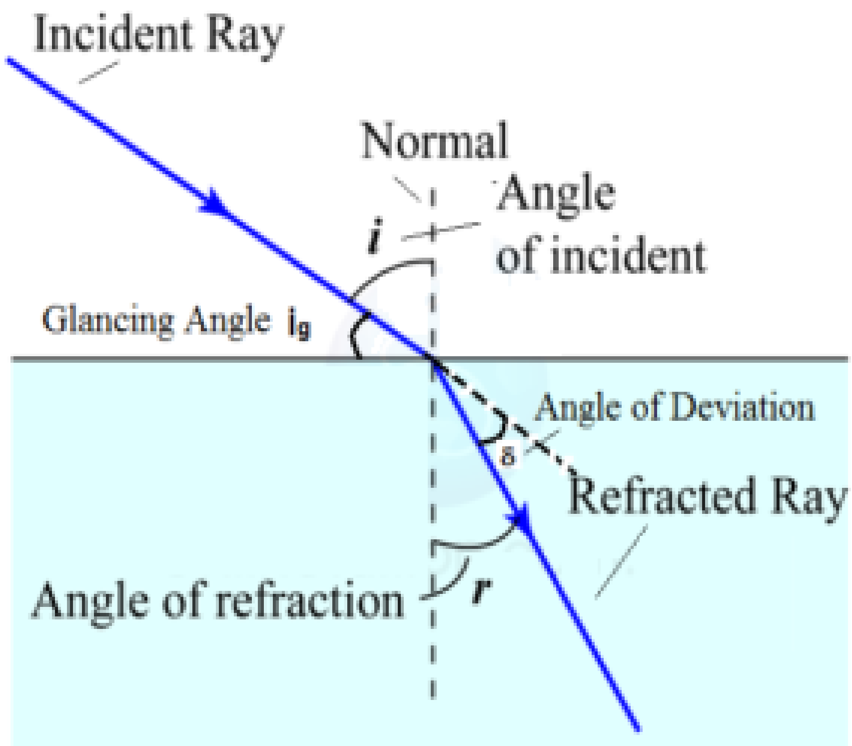
Ray Optics or Ray Transmission Theory

- called as laws of optics.
- light always travels at the same speed.
- The speed of light depends upon the material or medium through which it is moving.
- In free space light travels at its maximum possible speed i.e. 3×10^8 m/s or 186×10^3 miles/sec.
- When light travels through a material it exhibits certain behavior explained by laws of reflection, refraction.

- **Reflection:**
  - The law of reflection states that, when a light ray is incident upon a reflective surface at some incident angle ϕ_1 from imaginary perpendicular normal, the ray will be reflected from the surface at some angle ϕ_2 from normal which is equal to the angle of incidence.



- **Refraction:**
  - when light ray passes from one medium to another i.e. the light ray changes its direction at interface.
  - Refraction occurs whenever density of medium changes.
  - E.g. refraction occurs at air and water interface, the straw in a glass of water will appear as it is bent.
  - The refraction can also observed at air and glass interface.
    - When wave passes through less dense medium to denser medium, the wave is refracted (bent) towards the normal.
    - The refraction (bending) takes place because light travels at different speed in different mediums.
    - The speed of light in free space is higher than in water or glass.

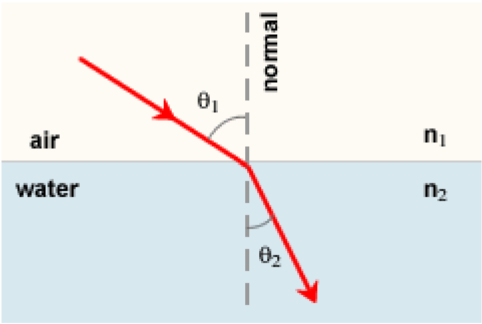

Incident Ray
Normal
Angle
of incident
i
Glancing Angle i_g
Angle of Deviation
δ
Refracted Ray
Angle of refraction
r

- **Refractive Index**
  - The amount of refraction or bending that occurs at the interface of two materials of different densities is usually expressed as refractive index of two materials.
  - Refractive index is also known as index of refraction and is denoted by "n".
  - Based on material density, the refractive index is expressed as
    - the ratio of the velocity of light in free space to the velocity of light of the dielectric material (substance).

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

index of refraction (n); velocity of light in vacuum (c); velocity of light in the medium (v)

- **Snells Law**:
  - When light passes from one transparent material to another, it bends according to Snell's law which is defined as:
    - $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$



- Critical angle:
  - The critical angle can be calculated from Snell's law, putting in an angle of 90° for the angle of the refracted ray θ2.
  - This gives θ1:
    - θ2 = 90°,
    - sin(θ2) = 1
  - **θc = θ1 = arc sin(*n2/n1*)**
  - ***Always Minimum***

- **Numerical Aperture (NA):**
  - It shows the intensity of light Wave.
  - Larger the numerical aperture,
  - the greater the amount of light
  - accepted by fiber.
  - The acceptance angle also determines
  - how much light is able to be enter
  - the fiber and hence there is relation
  - between the numerical aperture and
  - the cone of acceptance.

Acceptance Angle:

Always Maximum.
the maximum incidence angle
of a light ray which can be used
for injecting light into a
fiber core or waveguide

Applying shells law of reflection at point A,

$$\frac{sin\varphi_1}{sin\varphi_2} = \frac{n_1}{n_0} = 1 \qquad \text{as } n_0 = 1$$

In right angled Δabc

$$\theta_2 = \frac{\pi}{2} - \varphi_c$$

$$sin\varphi_1 = n_1 \sin\left(\frac{\pi}{2} - \varphi_c\right) = n_1 cos\varphi_c$$

$$cos\varphi_c = (1 - sin\varphi_c^2)^{0.5}$$

From the above equation,

$$sin\theta_1 = n_1(1 - sin\varphi_c^2)^{0.5}$$

When the TIR takes place , $\varphi_c = \theta_c$ and $\theta_1 = \theta_a$

$$sin\theta_a = n_1(1 - sin\theta_c^2)^{0.5}$$

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

$$sin\theta_a = n_1[1 - (\frac{n_2}{n_1})^2]^{0.5}$$

$$N.A = sin\theta_a$$

$$N.A = sin\theta_a = \sqrt{n_1^2 - n_2^2}$$

Total Internal Reflection (TIR)

- When the incident angle is increase beyond the critical angle, the light ray does not pass through the interface into the other medium.
- This gives the effect of mirror exist at the interface with no possibility of light escaping outside the medium.
- In this condition angle of reflection ($ø_2$) is equal to angle of incidence ($ø_1$).
- This action is called as Total Internal Reflection (TIR) of the beam.
- It is TIR that leads to the propagation of waves within fiber-cable medium.
- TIR can be observed only in materials in which the velocity of light is less than in air.

- The two conditions necessary for TIR to occur are:
  - 1. The refractive index of first medium must be greater than the refractive index of second one.
  - 2. The angle of incidence must be greater than (or equal to) the critical angle.

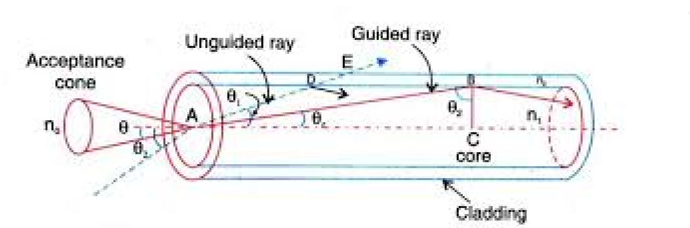
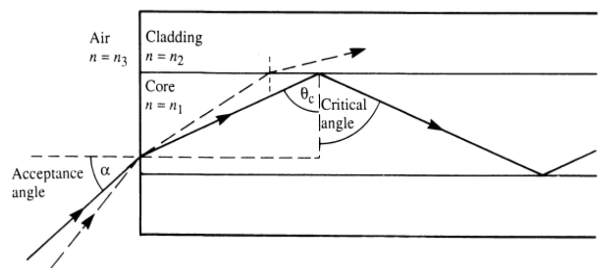
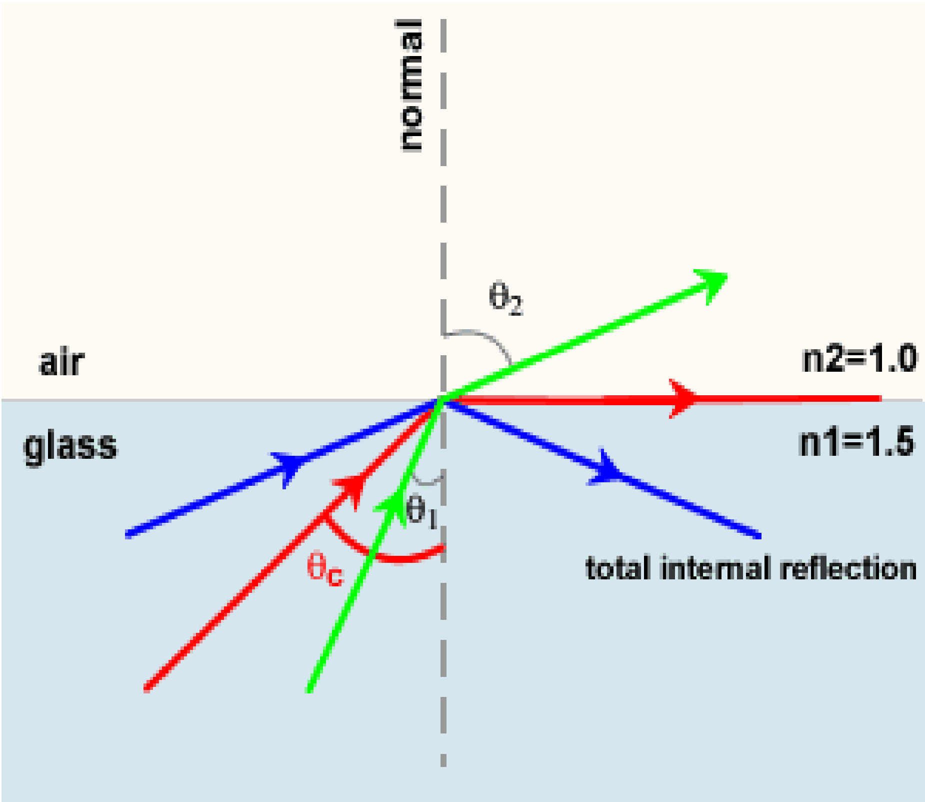


Figure : (7)



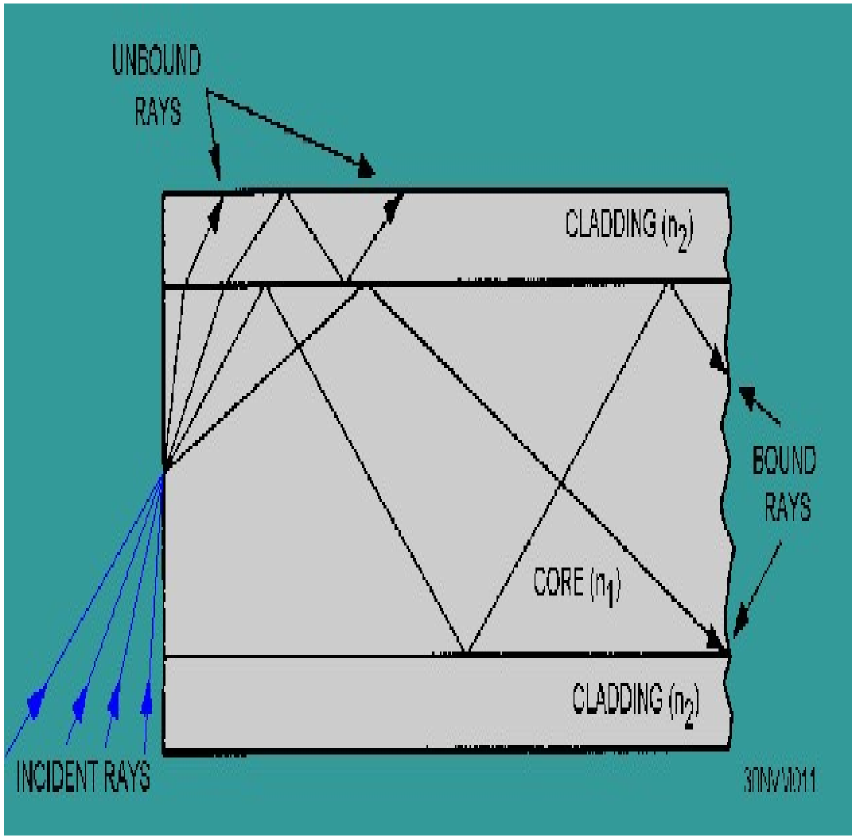
$\sin \alpha = (n_1^2 - n_2^2)^{1/2}\, 1/n_3$

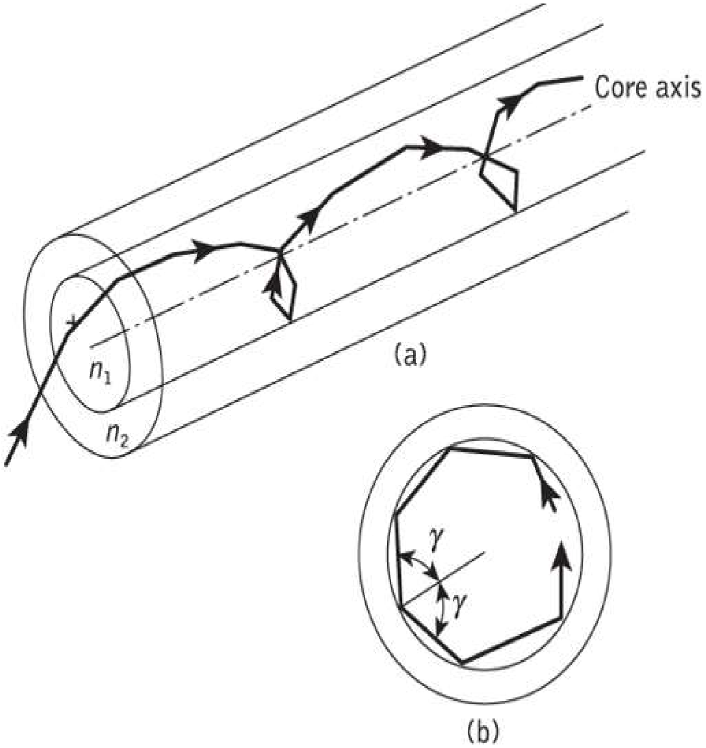
Numerical aperture (N.A.) = $\sin \alpha$


normal
θ2
air
n2=1.0
glass
n1=1.5
θ1
θc
total internal reflection

Optical rays

- 2-types
  - MERIDIONAL RAYS
  - SKEW RAYS
- Meridional rays are **rays that pass through the axis of the optical fiber**.
- Meridional rays are used to illustrate the basic transmission properties of optical fibers.
- Skew rays are rays that travel through an optical fiber without passing through its axis.
- Represented as "**Helical Path**".


UNBOUND
RAYS
CLADDING (n_2)
BOUND
RAYS
CORE (n_1)
CLADDING (n_2)
INCIDENT RAYS


Core axis
n_1
n_2
(a)
γ
γ
(b)

Fiber Optic Modes

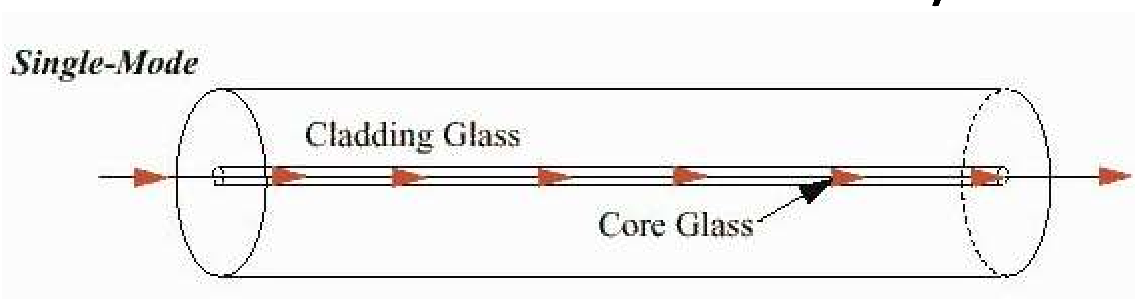
- Mode is the one which describes the nature of propagation of electromagnetic waves in a wave guide.
- i.e. it is the allowed direction whose associated angles
- satisfy the conditions for total internal reflection and constructive interference.
- The two components, the electric field and the magnetic field form patterns across the fiber.
- These patterns are called modes of transmission.
- The mode of a fiber refers to the number of paths for the light rays within the cable.

- Based on the number of modes that propagates through the optical fiber, they are classified as:
  - Single mode fibers
  - Multi mode fibers

Single mode fibers

- Single mode fiber allows propagation to light ray by only one path.
- Only one mode is transmitted through it, then it is said to be a single mode fiber.
- A typical single mode fiber may have a core radius of 3 μm and a numerical aperture of 0.1 at a wavelength of 0.8 μm.
- The condition for the single mode operation is given by the V number of the fiber which is defined as such that $V \leq 2.405$.

- Properties:
  - Only one path is available.
  - V-number is less than 2.405
  - Core diameter is small
  - No dispersion
  - Higher band width (1000 MHz)
  - Used for long haul communication
  - Fabrication is difficult and costly



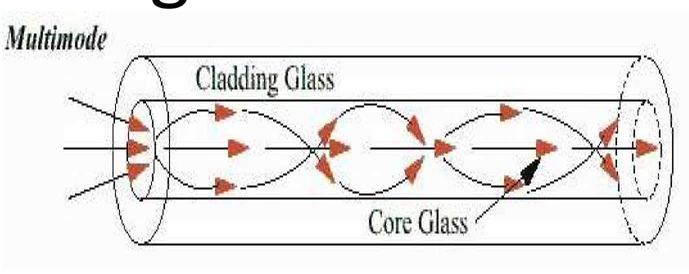
Disadvantages of SMF

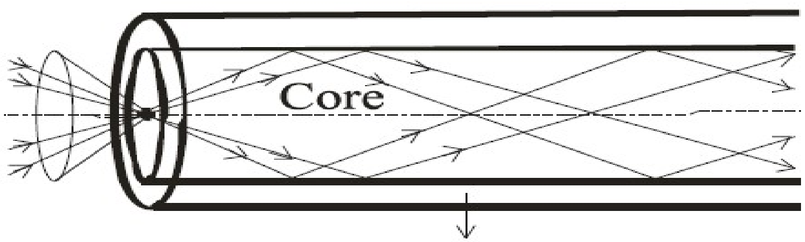
- Are smaller core diameter makes coupling light into the core more difficult.
- Precision required for single mode connectors and splices are more demanding.

Multimode fibers

- Multimode fiber was the first fiber type to be manufactured and commercialized.
- If more than one mode is transmitted through optical fiber, then it is said to be a multimode fiber.
- The larger core radii of multimode fibers make it easier to launch optical power into the fiber and facilitate the end to end connection of similar powers.
- V-number is greater than 2.405.

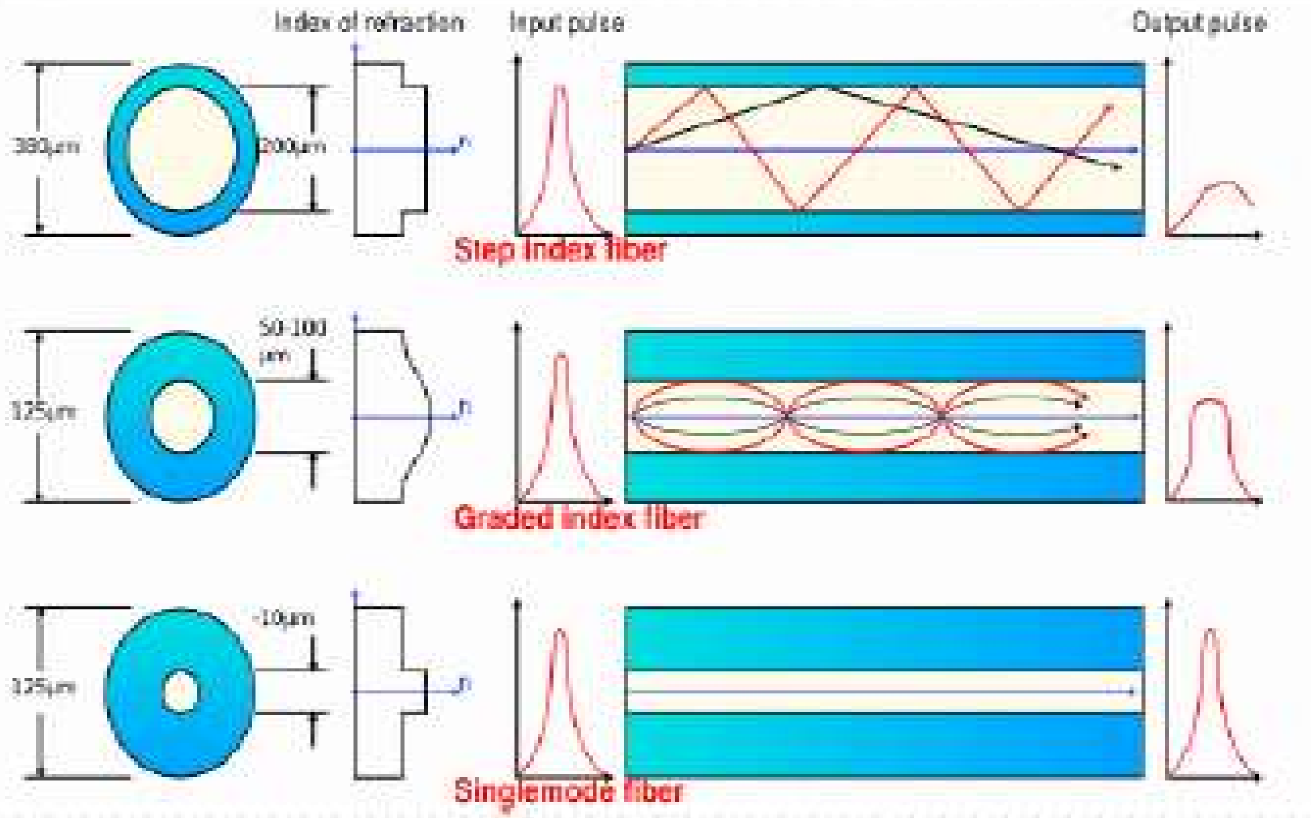
- The term multimode simply refers to the fact that numerous modes (light rays) are carried simultaneously through the waveguide.
- Multimode fiber has a much larger diameter, compared to single mode fiber, this allows large number of modes.





Types of fibers based on Refractive Index Profile

- Based on the refractive index profile of the core and cladding diameters, the optical fibers are classified into two types:
  - Step index fiber
  - Graded index fiber

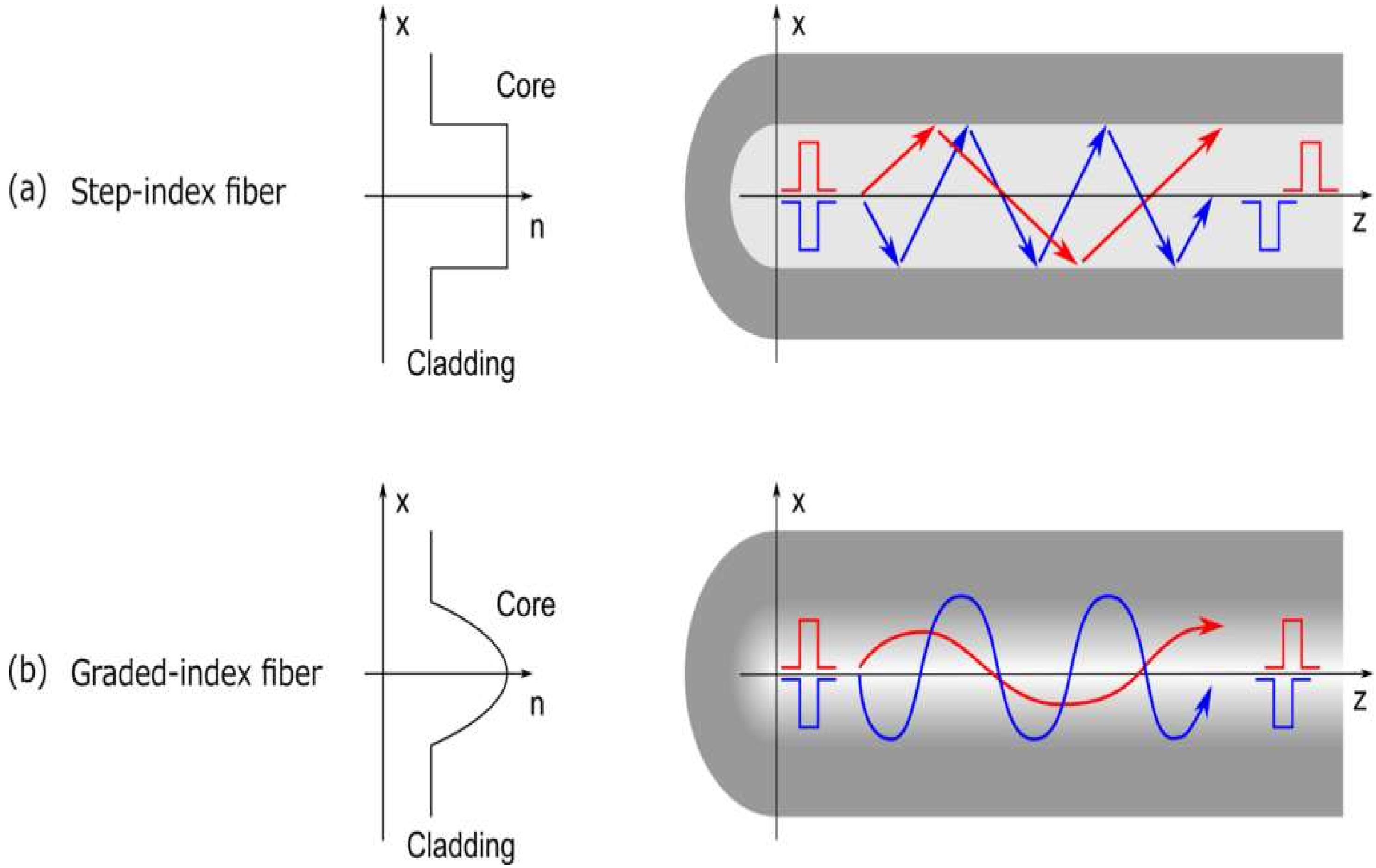


Different Modes of Optical Fibers

Step Index (SI) Fiber

- The step index (SI) fiber is a cylindrical waveguide core with central or inner core has a uniform refractive index of n_1 and the core is surrounded by outer cladding with uniform refractive index of n_2.
- The cladding refractive index (n_2) is less than the core refractive index (n_1).
- But there is an abrupt change in the refractive index at the core cladding interface.
- Index is plotted on horizontal axis and radial distance from the core is plotted on vertical axis.

- The propagation of light wave within the core of step index fiber takes the path of meridional ray i.e. ray follows a zig-zag path of straight line segments.
- The core typically has diameter of 50-80 µm and the cladding has a diameter of 125 µm.


(a) Step-index fiber
x
Core
n
Cladding
x
z
(b) Graded-index fiber
x
Core
n
Cladding
x
z

Graded Index (GRIN) Fiber

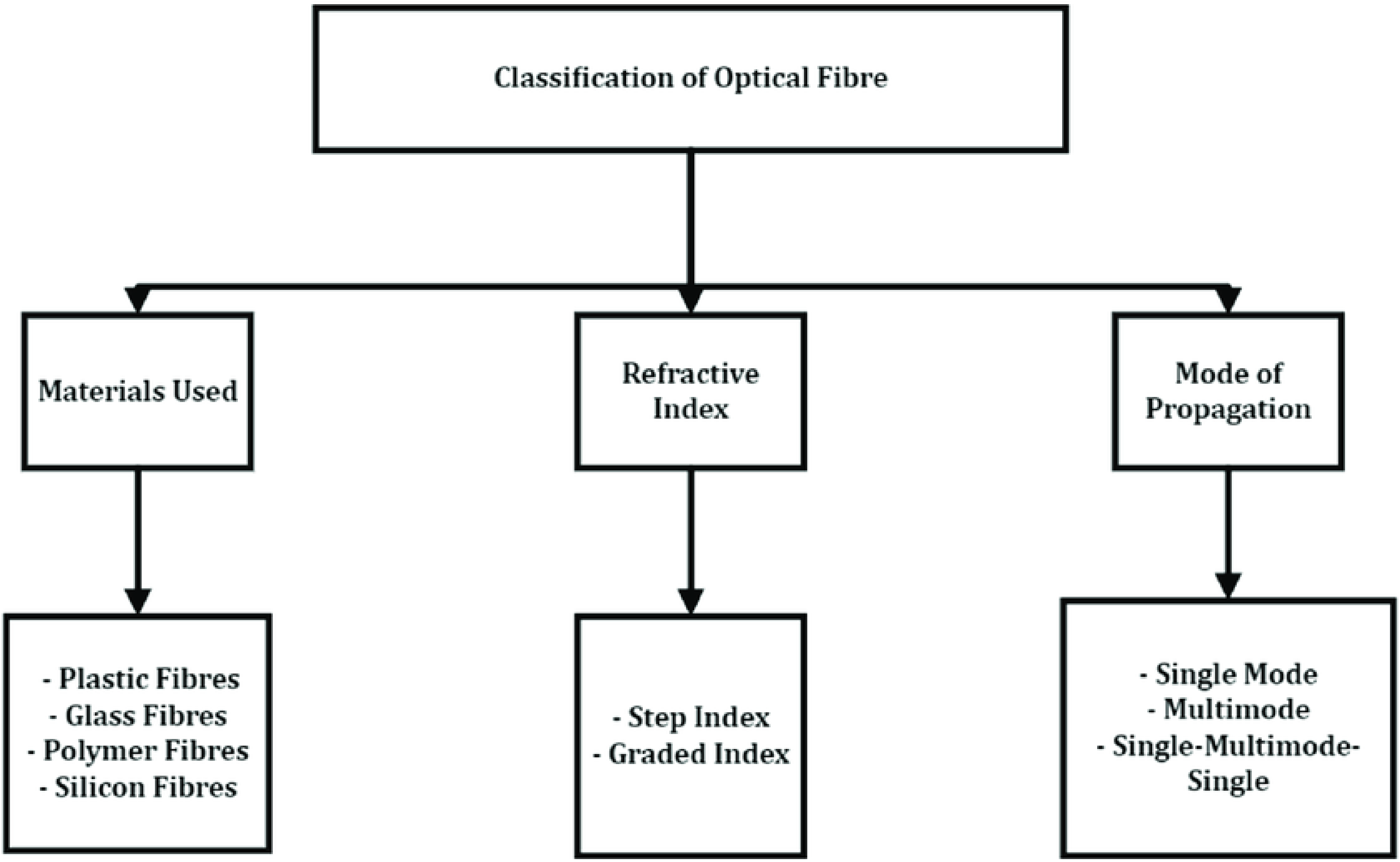
- The graded index fiber has a core made from many layers of glass.
- In the graded index (GRIN) fiber the refractive index is not uniform within the core, it is highest at the center and decreases smoothly and continuously with distance towards the cladding.
- The refractive index profile across the core takes the parabolic nature.

- In graded index fiber the light waves are bent by refraction towards the core axis and they follow the curved path down the fiber length.
- This results because of change in refractive index as moved away from the center of the core.
- A graded index fiber has lower coupling efficiency and higher bandwidth than the step index fiber.

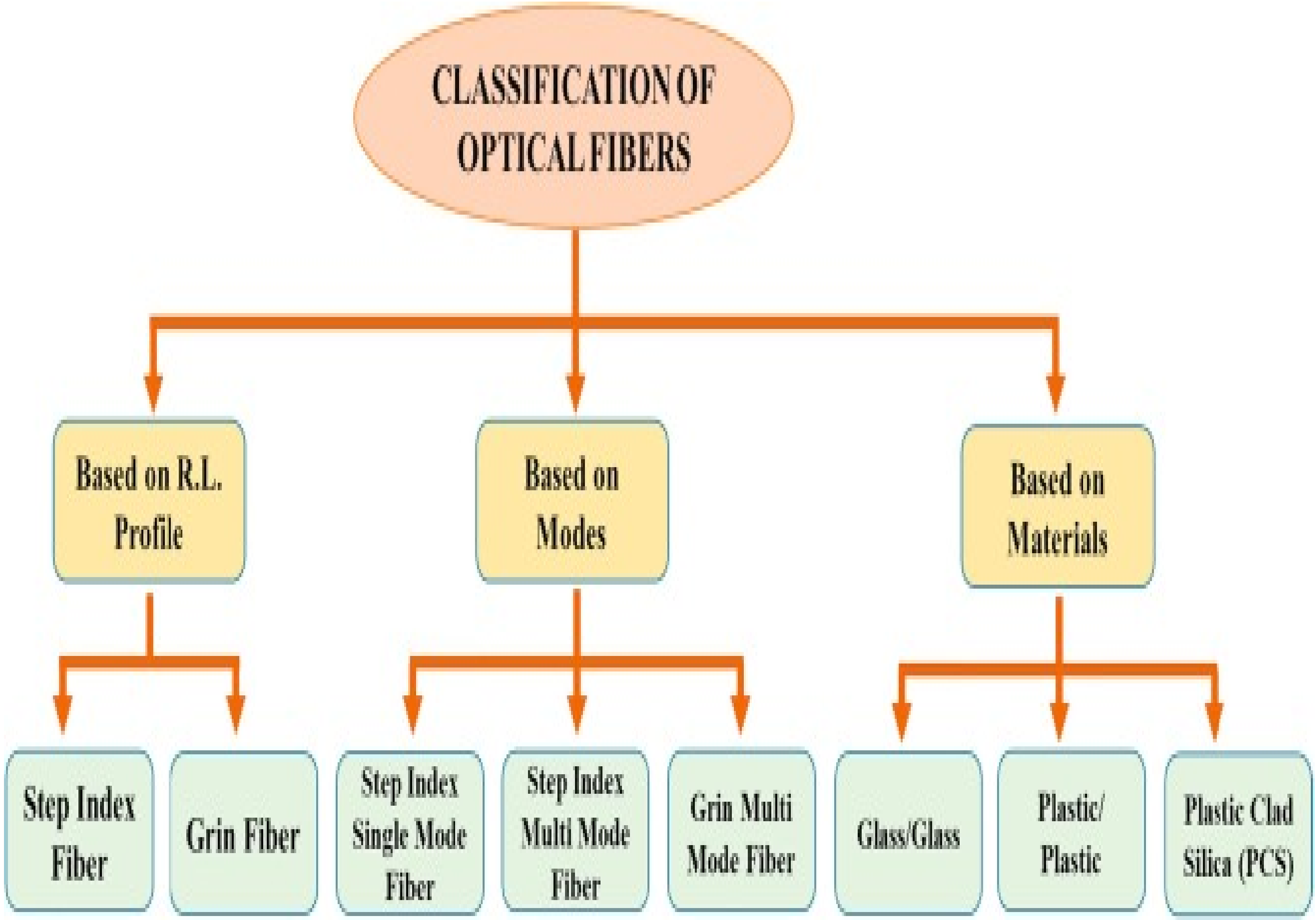
Sr. No.	Parameter	Step index fiber	Graded index fiber
1.	Data rate	Slow.	Higher
2.	Coupling efficiency	Coupling efficiency with fiber is higher.	Lower coupling efficiency.
3.	Ray path	By total internal reflection.	Light ray travels in oscillatory fashion.
4.	Index variation	$\Delta = \frac{n_1 - n_2}{n_1}$	$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$
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.	Bandwidth efficiency	10 – 20 MHz/km	1 GHz/km
8.	Pulse spreading	Pulse spreading by fiber length is more.	Pulse spreading is less
9.	Attenuation of light	Less typically 0.34 dB/km at 1.3 μm.	More 0.6 to 1 dB/km at 1.3 μm.
10.	Typical light source	LED.	LED, Lasers.
11.	Applications	Subscriber local network communication.	Local and wide area networks.

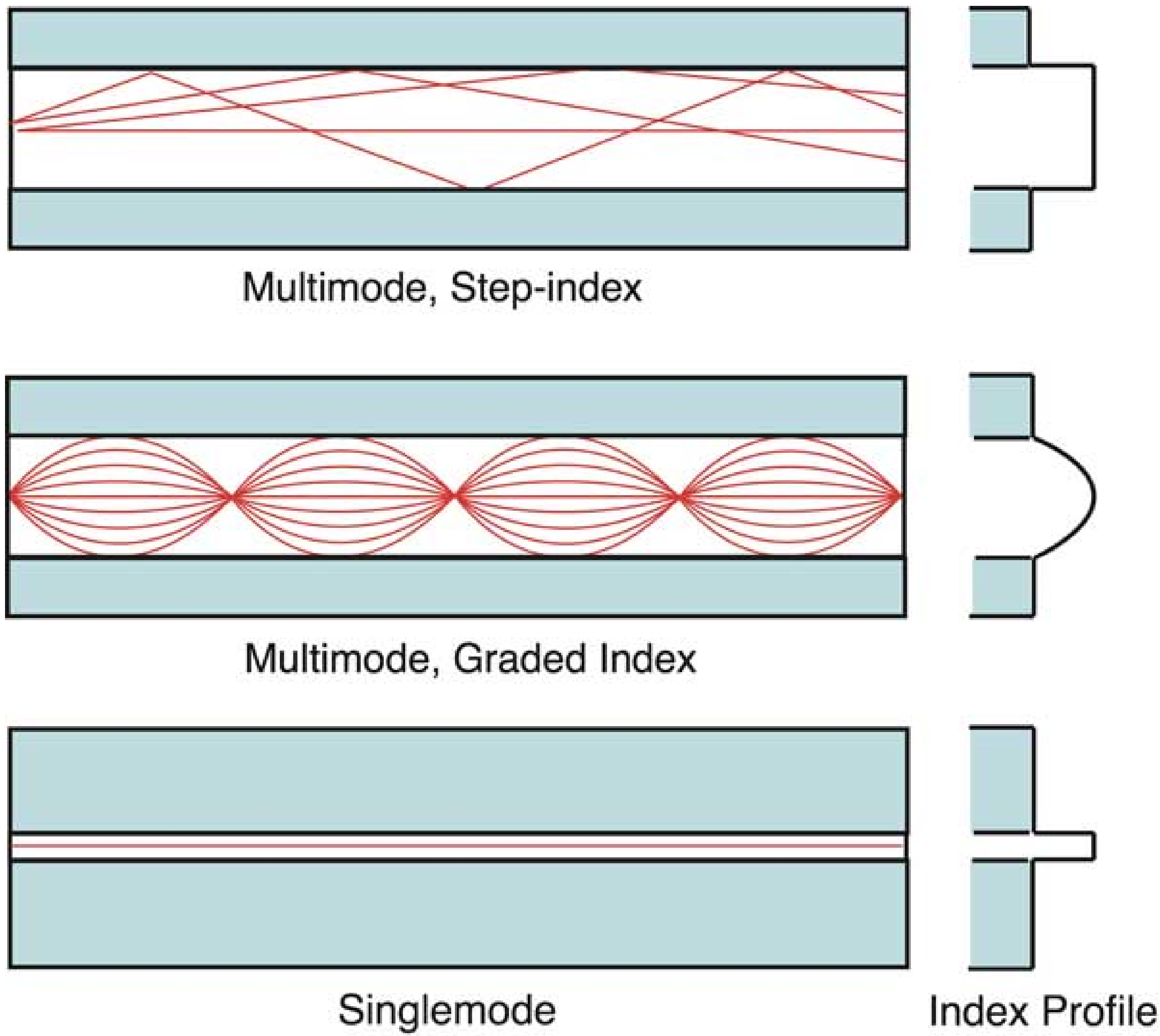
OPTICAL MODES

- Fiber cables cal also be **classified as per their mode**.
- Light rays propagate as an electromagnetic wave along the fiber.
- The **two components, the electric field and the magnetic field form patterns across the fiber**.
- **These patterns are called modes of transmission**.
- The mode of a fiber **refers to the number of paths for the light rays within the cable**.
- According to modes optic fibers can be classified into two types.



Classification of Optical Fibre
Materials Used
Refractive Index
Mode of Propagation
- Plastic Fibres
- Glass Fibres
- Polymer Fibres
- Silicon Fibres
- Step Index
- Graded Index
- Single Mode
- Multimode
- Single-Multimode-Single


CLASSIFICATION OF OPTICAL FIBERS
Based on R.I. Profile
Based on Modes
Based on Materials
Step Index Fiber
Grin Fiber
Step Index Single Mode Fiber
Step Index Multi Mode Fiber
Grin Multi Mode Fiber
Glass/Glass
Plastic/ Plastic
Plastic Clad Silica (PCS)


Multimode, Step-index
Multimode, Graded Index
Singlemode
Index Profile

SMF

- Single mode fiber allows propagation to **light ray by only one path**.
- Single Mode cable is a single stand of glass fiber with a diameter of 8.3 to 10 microns that has one mode of transmission.
- Single Mode Fiber with a **relatively narrow diameter**, through which **only one mode will propagate**.

Condition for S.M

$0 \leq V \leq 2.405$

SMF

- Carries higher bandwidth than multimode fiber, but requires a light source with a narrow spectral width.
- Synonyms
  - monomode optical fiber,
  - single-mode fiber,
  - single-mode optical waveguide &
  - unimode fiber.

- Single-mode fiber gives you a **higher transmission rate and up to 50 times more distance than multimode**, but it **also costs more**.
- Single-mode fiber has a **much smaller core than multimode**.
- The small core and single light wave virtually eliminate any distortion that could result from overlapping light pulses, providing the least signal attenuation and the highest transmission speeds of any fiber cable type.

- Single-mode optical fiber is an optical fiber in which only the lowest order bound mode can propagate at the wavelength of interest typically 1300 to 1320nm.
- Thus more information can be transmitted per unit of time.

DISADVANTAGES

- single mode fiber are **smaller core diameter makes coupling light into the core more difficult**.
- Precision required for single mode connectors and splices are more demanding.

Multimode Fiber

- Multimode fiber was the first fiber type to be manufactured and **commercialized**.
- The term multimode simply refers to the fact that **numerous modes** (light rays) are carried **simultaneously through the waveguide**.
- Multimode fiber has a **much larger diameter**, compared to single mode fiber, this **allows large number of modes**.

- Multimode fiber gives you **high bandwidth at high speeds over medium distances**.
- Light waves are dispersed into numerous paths, or modes, as they travel through the cable's core typically 850 or 1300nm.
- Typical multimode fiber core diameters are 50, 62.5, and 100 micrometers.

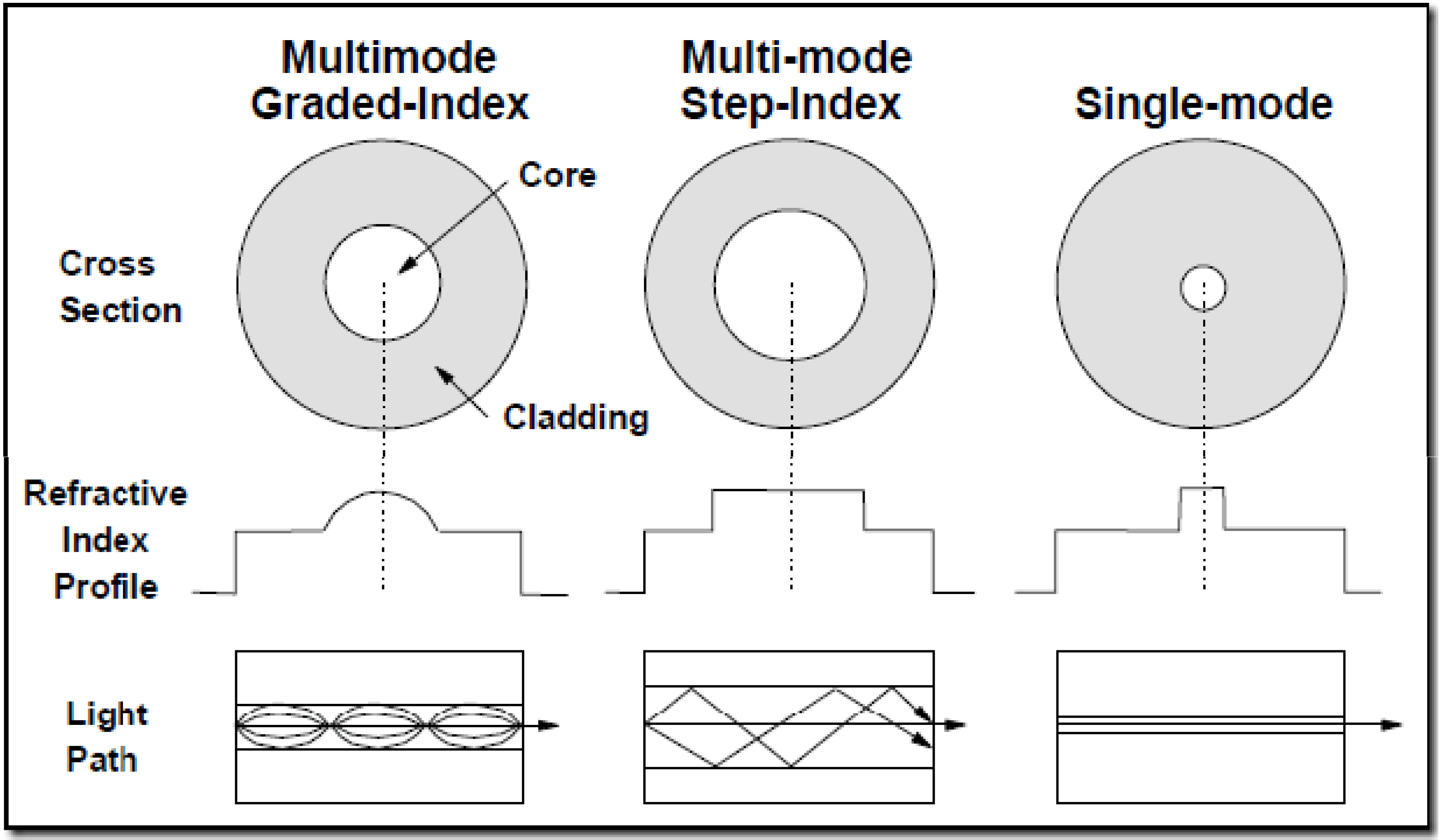
Fiber Profiles

- A **fiber is characterized by its profile and by its core and cladding diameters**.
- One way of classifying the fiber cables is **according to the index profile at fiber**.
- The index profile is a graphical representation of value of refractive index across the core diameter.
- There are **two basic types of index profiles**.
  - 1. Step index fiber.
  - 2. Graded index fiber.

Step Index (SI) Fiber

- The step index (SI) fiber is a **cylindrical waveguide core with central** or **inner core has a uniform** refractive index of n1 and the core is surrounded by outer cladding with uniform refractive index of n2.
- The cladding refractive index (n2) is less than the core refractive index (n1).
- But there is an abrupt change in the refractive index at the core cladding interface.

- The propagation of light wave within the core of **step index fiber takes the path of meridional ray** i.e. ray follows a **zig-zag path** of straight line segments.
- The core typically has diameter of 50-80 μm and the cladding has a diameter of 125 μm.


Multimode
Graded-Index
Multi-mode
Step-Index
Single-mode
Core
Cross
Section
Cladding
Refractive
Index
Profile
Light
Path

Graded Index (GRIN) Fiber

- The graded index fiber **has a core made from many layers of glass**.
- In the graded index (GRIN) fiber the **refractive index is not uniform within the core**, it is highest at the center and decreases smoothly and continuously with distance towards the cladding.
- The refractive index profile across the core takes the **parabolic nature**.

- In graded index fiber the **light waves are bent by refraction towards the core axis and they follow the curved path down the fiber length**.
- This results because of change in refractive index as moved away from the center of the core.
- A graded index fiber has **lower coupling efficiency and higher bandwidth** than the step index fiber.

2.5. FIBER PARAMETERS

	Step Index Fiber	**Graded Index Fiber**
Refractive Index Profile	$n_1\,; r \leq a$ $n_2\,; r > a$	$n_1\sqrt{1-2\Delta(r/a)^{\alpha}}\,; r \leq a$ $n_2\,; r > a$
Numerical Aperture	$\sqrt{n_1^2 - n_2^2}$	$\sqrt{n(r)^2 - n_2^2}\,; r \leq a$
Normalized Frequency (V)	$\frac{2\pi a}{\lambda}(NA)$	$\frac{2\pi a}{\lambda}(NA)$
Cut-off Value of the normalized frequency	2.405	$2.405\sqrt{1+2/\alpha}$
Number of Modes (M)	$V^2/2$	$\frac{V^2\alpha}{2(\alpha+2)}$
Modal Dispersion $\Delta T_{mod}/L$	$\frac{n_1^2\Delta}{cn_2}$	$\frac{n_1\Delta^2}{8c}$ (when $\alpha = 2(1-\Delta)$)

n_1	Core refractive index
n_2	Cladding refractive index ($n_1 > n_2$)
a	Core radius
r	Varying radius
α	Profile parameter
NA	Numerical Aperture
L	Total length of the optical fiber (typically in km)
Δ	$\frac{n_1^2 - n_2^2}{2n_1^2} \approx 1 - \frac{n_2}{n_1}$

Sr. No.	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 ray 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.	Bandwidth efficiency	10 – 20 MHz/km	1 GHz/km
8.	Pulse spreading	Pulse spreading by fiber length is more.	Pulse spreading is less
9.	Attenuation of light	Less typically 0.34 dB/km at 1.3 µm.	More 0.6 to 1 dB/km at 1.3 µm.
10.	Typical light source	LED.	LED, Lasers.
11.	Applications	Subscriber local network communication.	Local and wide area networks.

- Parabolic refractive **index profile** ($\alpha = 2$)

Normalized Frequency V number

- In optical fibers, the **normalized frequency**, also known as the **V-number** (V), is a **dimensionless parameter** that relates the core radius, wavelength, and refractive index difference between the core and cladding, determining whether a fiber supports single-mode or multi-mode operation.
- The normalized frequency (V) is calculated as: $V = (2\pi a/\lambda) * NA$, $NA = n_1(2\Delta)^{1/2}$ $V = \frac{2\pi a(n_1^2 - n_2^2)^{1/2}}{\lambda}$

- **Single-mode:** For a fiber to operate in a single-mode (meaning only one mode of light can propagate), the **V-number must be less than approximately 2.4048**.
- **Multi-mode:** If **the V-number is greater than 2.4048**, the fiber will support multiple modes of light propagation.

- For a step-index multimode fiber, the number of modes (M) can be estimated as $M \approx V^2/2$, where V is the V-number, which is a measure of the fiber's normalized frequency.
- **Single-mode vs. Multimode:**
- If $V < 2.405$, the fiber is considered single-mode (supports only one mode).
- If V is significantly larger than 2.405, the fiber is multimode, supporting many modes.

Number of Modes

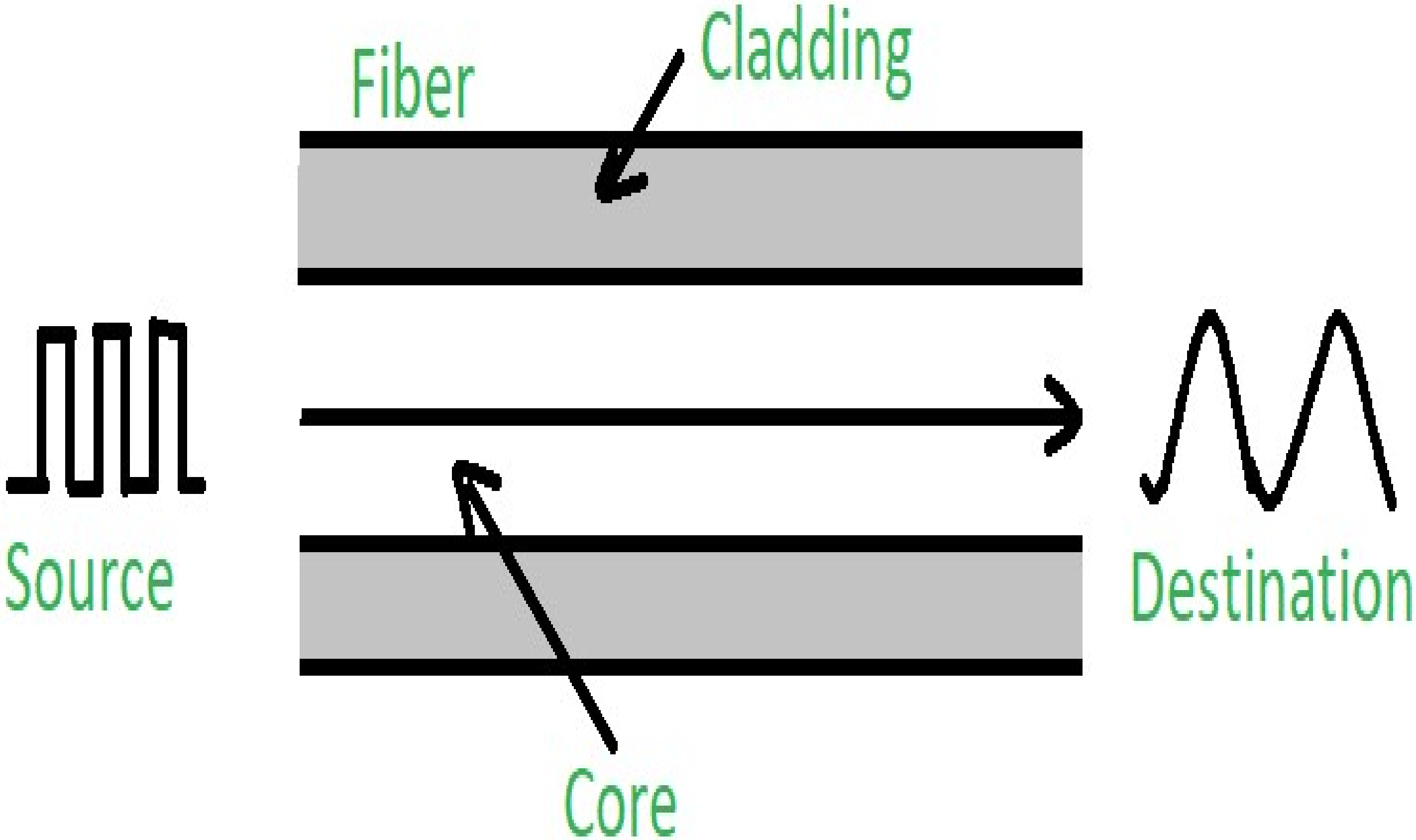
- Only for large number of modes (*V >> 2:4), the number of modes can be given by M=***V*** ^{2}***/2***.
- *Under this condition the* ratio between power travelling in the cladding and in the core is given by,

$$\frac{P_{cladding}}{P_{total}} \approx \frac{4}{3\sqrt{M}}$$

$$M = \left(\frac{\alpha}{\alpha+2}\right)\frac{V^2}{2}$$

Single-mode fiber

- has a small core diameter (5um) and high cladding diameter (70um)
- no dispersion i.e. no degradation of the signal during traveling through the fiber.
- The condition for the single mode operation is given by the V number of the fiber which is defined as such that $V \leq 2.405$.
- Higher band width (1000 MHz)
- Used for long haul communication
- Fabrication is difficult and costly


Fiber
Cladding
Source
Destination
Core

Multi-mode fiber

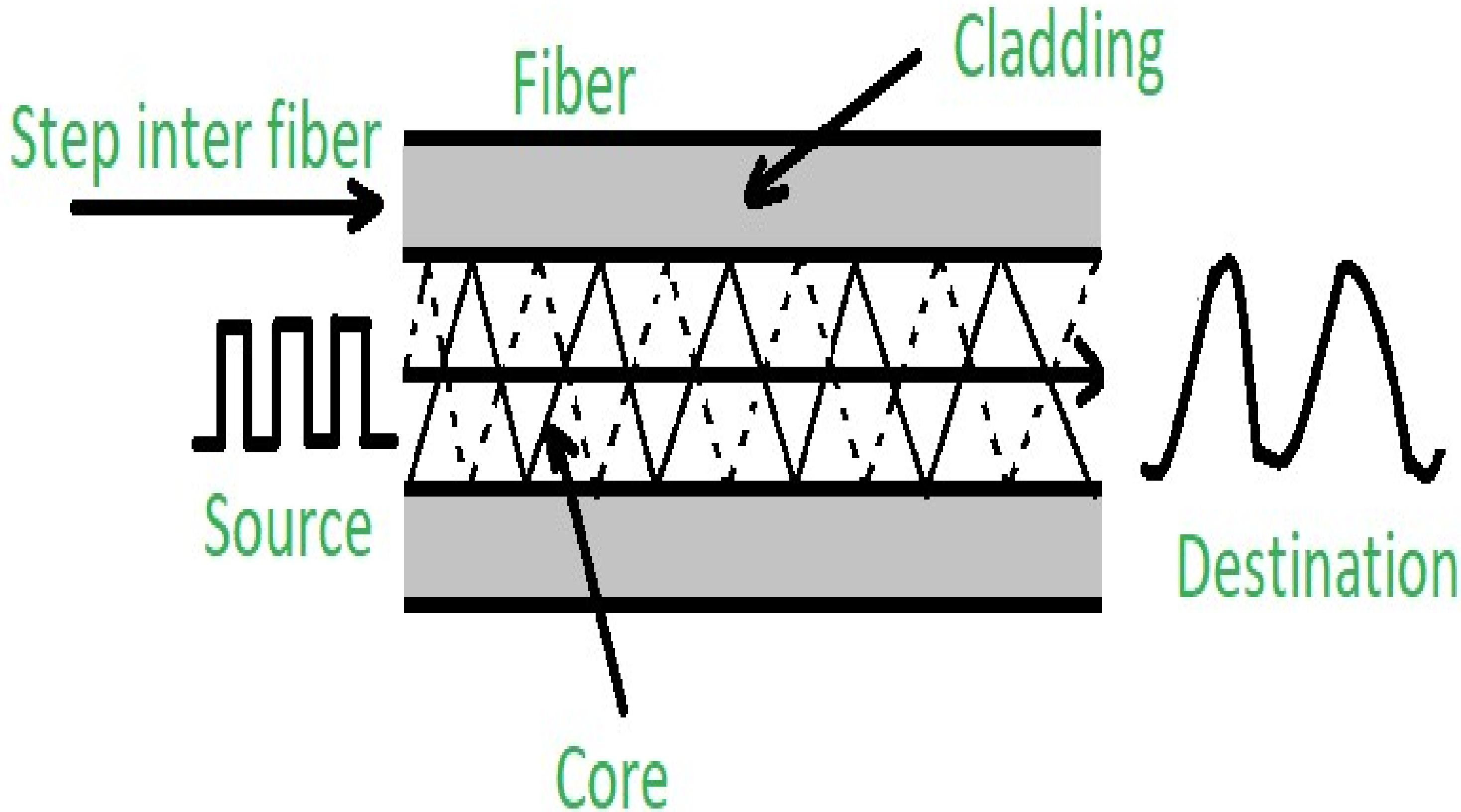
- allows a large number of modes for the light ray traveling through it.
- The core diameter is generally (40um) and that of cladding is (70um).
- The relative refractive index difference is also greater than single mode fiber.
- There is signal degradation due to multimode dispersion.
- It is not suitable for long-distance communication due to large dispersion and attenuation of the signal.

- V-number is greater than 2.405.
- The step index fibers propagate both single and multimode signals within the fiber core.
- are propagating in a zig – zag manner.
- Handling and manufacturing of single mode step index fiber is more difficult.
- fibers light propagates in many modes.
- The total number of modes M increases with increase in the numerical aperture.
- For a larger number of modes, M can be approximated by

$$M_N = \frac{V^2}{2} = 4.9\left[\frac{dn_1\sqrt{2\Delta}}{\lambda}\right]^2$$

Step-index optical fiber

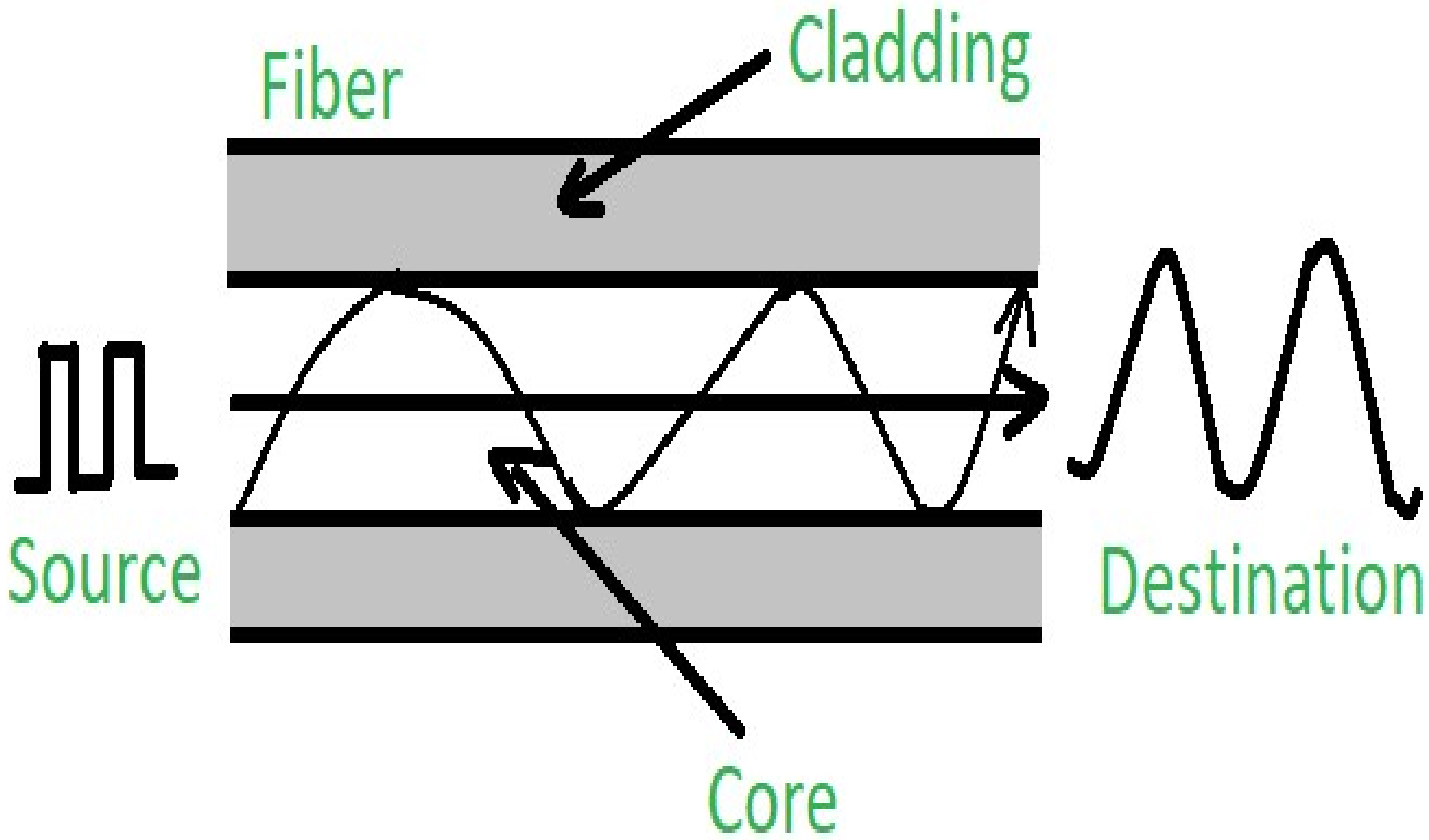
- The refractive index of core is constant.
- The refractive index of the cladding is also constant.
- The rays of light propagate through it in the form of meridional rays which cross the fiber axis during every reflection at the core-cladding boundary.

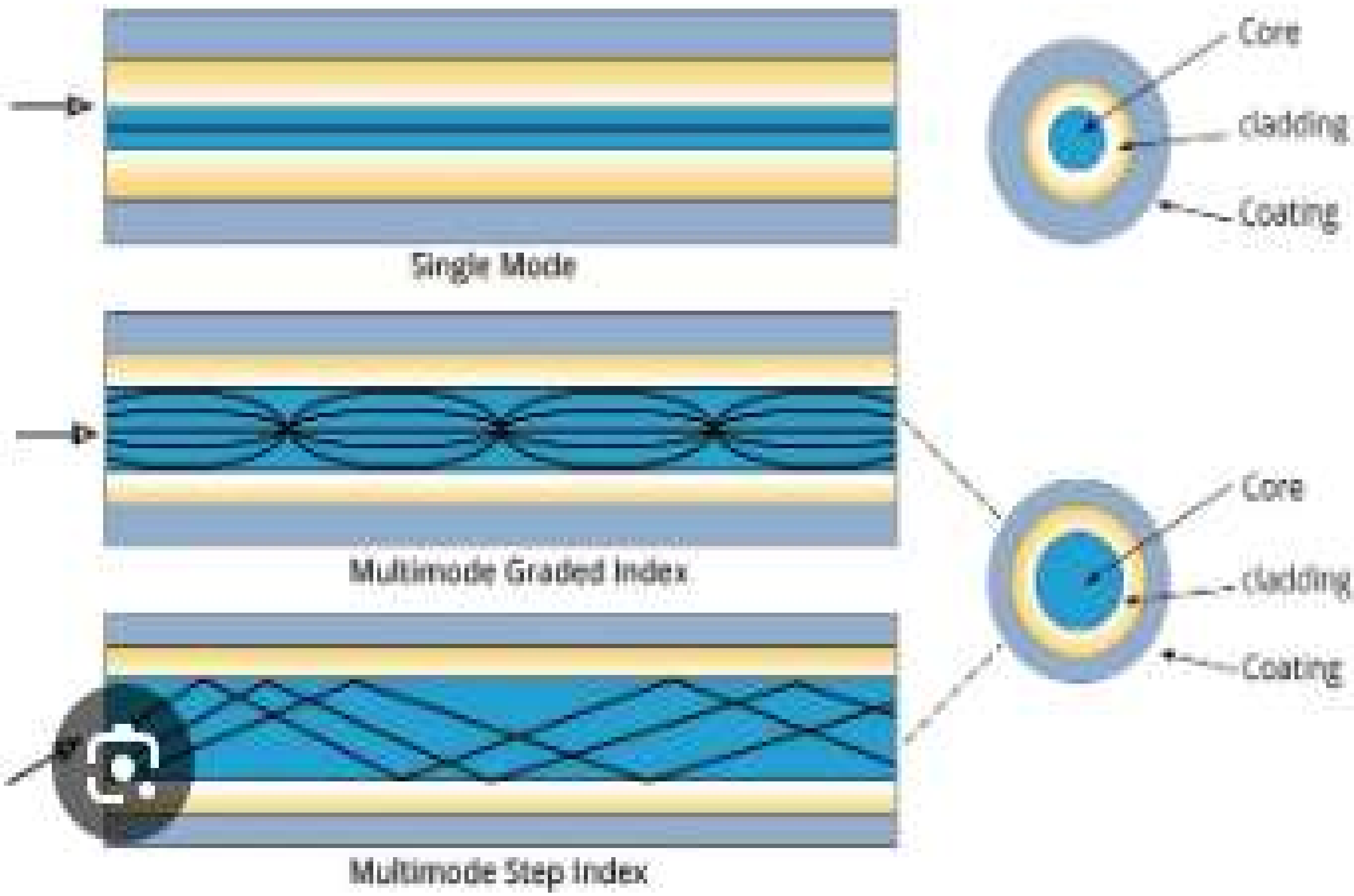

Step inter fiber
Fiber
Cladding
Source
Destination
Core

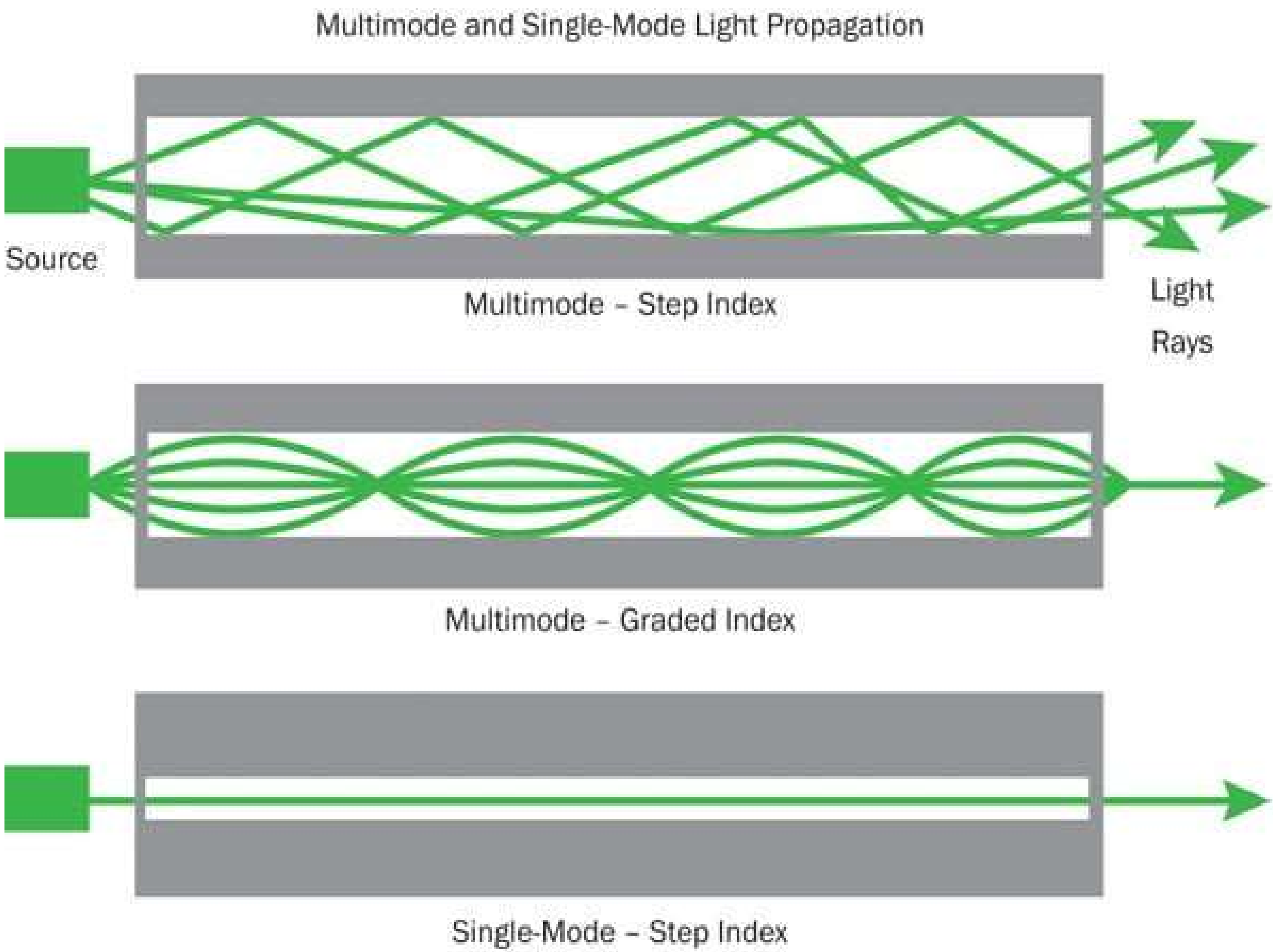
Graded index optical fiber

- In this type of fiber, the core has a non-uniform refractive index that gradually decreases from the centre towards the core-cladding interface.
- The cladding has a uniform refractive index.
- The light rays propagate through it in the form of skew rays or helical rays.
- it is not cross the fiber axis at any time.

- The refractive index of the core is made to vary in the form of parabolic manner such that the maximum refractive index is present at the centre of the core.
- The light rays will be propagated in the form skew rays (or) helical rays which will not cross the fiber axis at any time and are propagating around the fiber axis in a helical or spiral manner.
- The effective acceptance angle of the graded-index fiber is somewhat less than that of an equivalent step-index fiber.
- This makes coupling fiber to the light source more difficult.


Fiber
Cladding
Source
Destination
Core


Core
cladding
Coating
Single Mode
Multimode Graded Index
Core
cladding
Coating
Multimode Step Index


Multimode and Single-Mode Light Propagation
Source
Multimode – Step Index
Light
Rays
Multimode – Graded Index
Single-Mode – Step Index

Attenuation

- The attenuation or transmission loss of optical fibers has proved to be one of the most important factors.

$$\alpha_{dB}L = 10\log_{10}\frac{P_i}{P_o}$$

$$\text{Number of decibels (dB)} = 10\log_{10}\frac{P_i}{P_o}$$

Material absorption losses

- **Intrinsic absorption**:
- An absolutely pure silicate glass has little intrinsic absorption due to its basic material structure in the near-infrared region.
- **Extrinsic absorption**
- from transition metal element impurities.

Linear scattering losses

- cause the transfer of some or all of the optical power contained within one propagating mode to be transferred linearly (proportionally to the mode power) into a different mode.
- This process tends to result in attenuation of the transmitted light as the transfer may be to a leaky or radiation mode which does not continue to propagate within the fiber core, but is radiated from the fiber.

Linear scattering

- may be categorized into two major types: **Rayleigh** and **Mie scattering.**
- Rayleigh scattering:
  - dominant intrinsic loss mechanism in the low-absorption window between the ultraviolet and infrared absorption tails.
  - It results from inhomogeneities of a random nature occurring on a small scale compared with the wavelength of the light.
  - These inhomogeneities manifest themselves as refractive index fluctuations and arise from density and compositional variations which are frozen into the glass lattice on cooling.
  - The compositional variations may be reduced by improved fabrication.

$$\gamma_R = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F$$

$$\mathscr{L} = \exp(-\gamma_R L)$$

Mie scattering

- Linear scattering may also occur at inhomogeneities which are comparable in size with the guided wavelength.
- These result from the nonperfect cylindrical structure of the waveguide and may be caused by fiber imperfections such as irregularities in the core–cladding interface, core–cladding refractive index differences along the fiber length, diameter fluctuations, strains and bubbles.

- The inhomogeneities may be reduced by:
- (a) removing imperfections due to the glass manufacturing process;
- (b) carefully controlled extrusion and coating of the fiber;
- (c) increasing the fiber guidance by increasing the relative refractive index difference

Nonlinear scattering losses

- **Stimulated Brillouin scattering**
  - regarded as the modulation of light through thermal molecular vibrations within the fiber.
  - The scattered light appears as upper and lower sidebands which are separated from the incident light by the modulation frequency.
  - The incident photon in this scattering process produces a phonon* of acoustic frequency as well as a scattered photon.
  - This produces an optical frequency shift which varies with the scattering angle because the frequency of the sound wave varies with acoustic wavelength.
  - The frequency shift is a maximum in the backward direction, reducing to zero in the forward direction, making SBS a mainly backward process.

$$P_B = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{dB} \nu \text{ watts}$$

Stimulated Raman scattering

- SBS except that a high-frequency optical phonon rather than an acoustic phonon is generated in the scattering process.
- Also, SRS can occur in both the forward and backward directions in an optical fiber.

$$P_R = 5.9 \times 10^{-2} d^2 \lambda \alpha_{dB} \text{ watts}$$

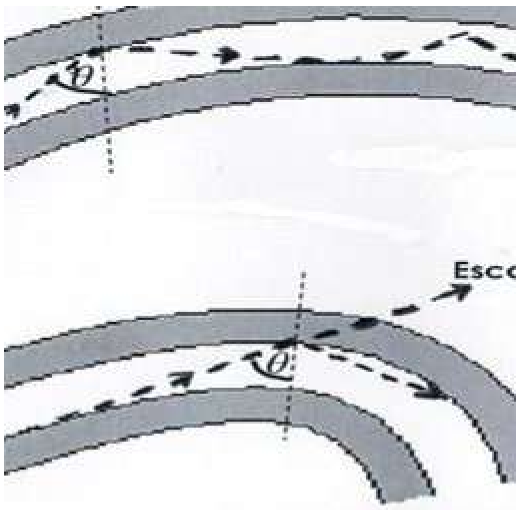
Fiber Bend Loss

- Optical fibers suffer radiation losses at bends or curves on their paths.
- This is due to the energy in the evanescent field at the bend exceeding the velocity of light in the cladding and hence the guidance mechanism is inhibited, which causes light energy to be radiated from the fiber.
- The loss can generally be represented by a radiation attenuation coefficient $R_c \simeq \frac{3n_1^2\lambda}{4\pi(n_1^2 - n_2^2)^{\frac{3}{2}}}$

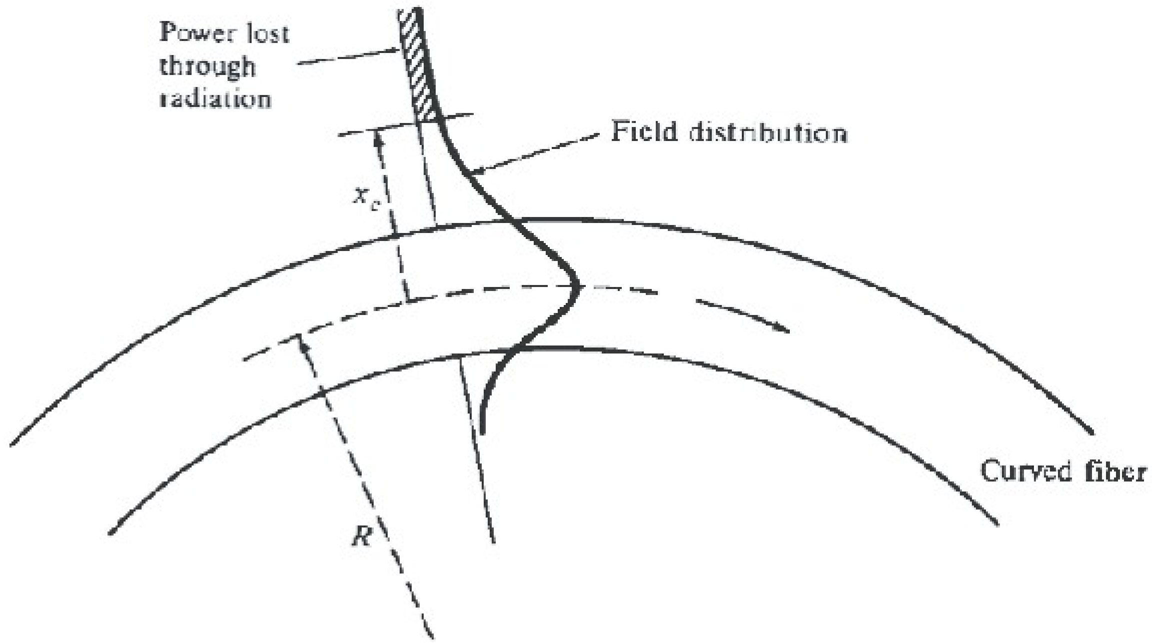
$$\alpha_r = c_1 \exp(-c_2 R)$$

- 2-types:
- Macro-bending
- Micro-bending

$$R_{cs} \simeq \frac{20\lambda}{(n_1 - n_2)^{\frac{3}{2}}}\left(2.748 - 0.996\frac{\lambda}{\lambda_c}\right)^{-3}$$



θ
Esc
θ



Power lost through radiation
Field distribution
x_c
R
Curved fiber

Bending Loss

Example bending loss

1 turn at 32 mm diameter
causes 0.5 db loss

Index profile can be adjusted to reduce loss but this degrades the fibers other characteristics

Rule of thumb on minimum bending radius:

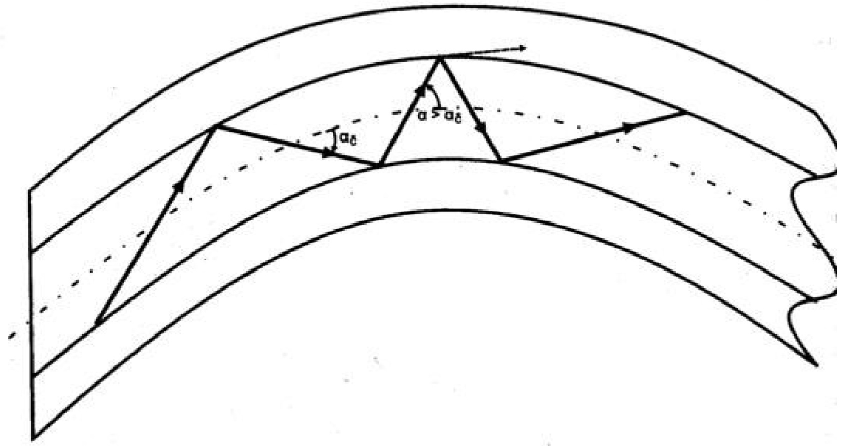
Radius>100x Cladding diameter for short times
13mm for 125μm cladding
Radius>150x Cladding diameter for long times
19mm

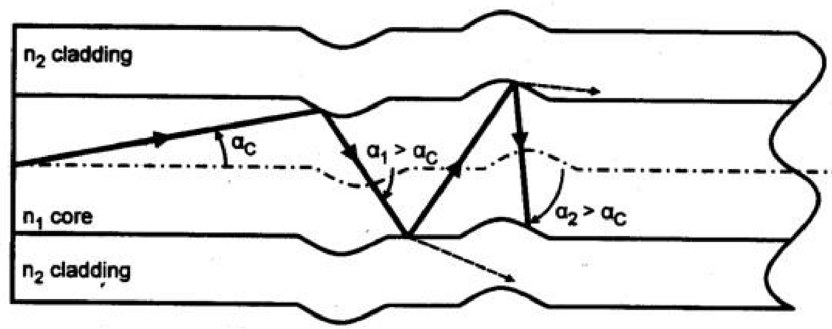
This loss is ***mode dependent***

Can be used in attenuators, mode filters fiber identifier, fiber tap, fusion splicing

Microbending loss

Property of fiber, under control of fabricator, now very small, usually included in the total attenuation numbers

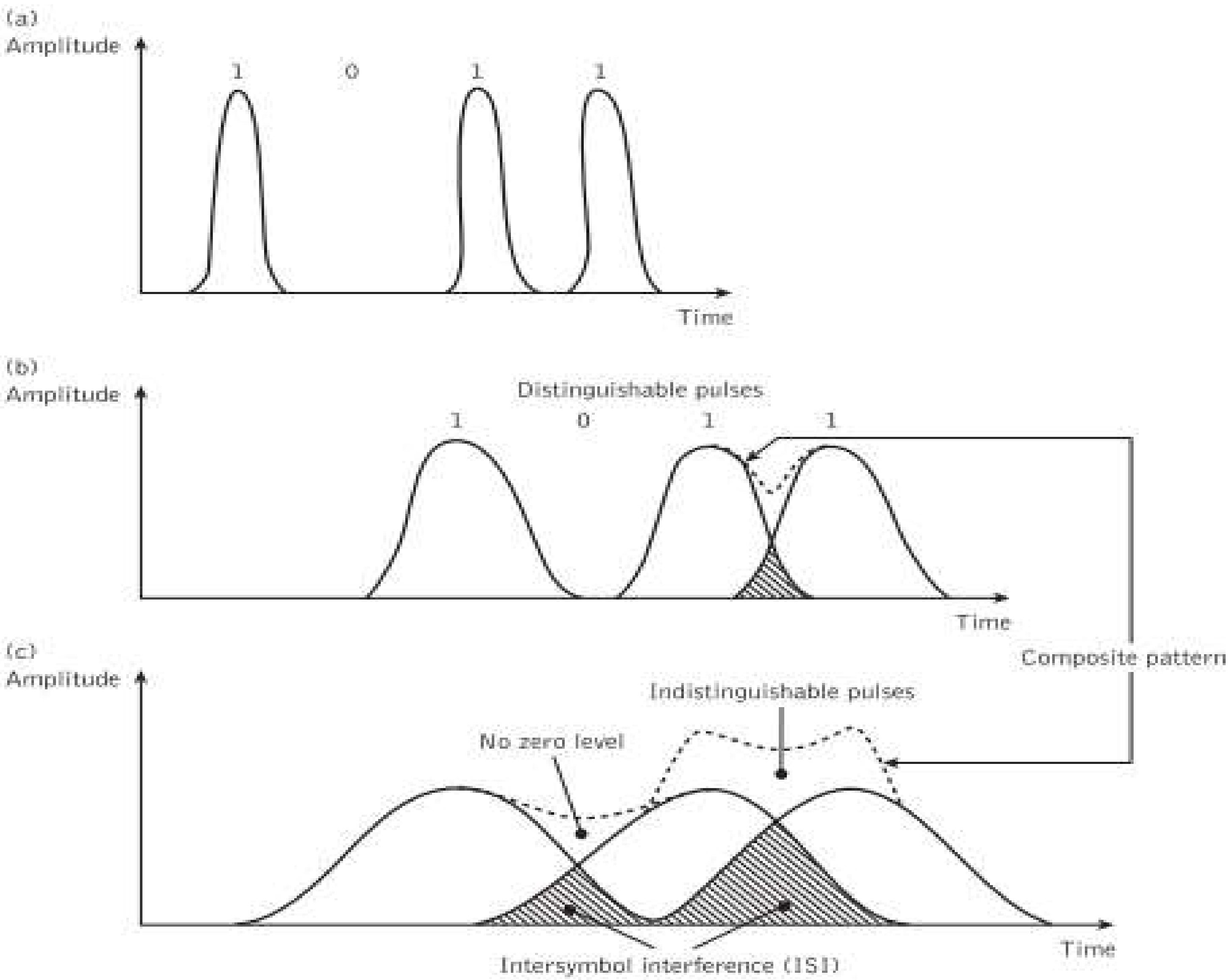




Fiber Optics Communication Technology-Mynbaev & Scheiner

Dispersion

- optical signal causes distortion for both digital and analog transmission along optical fibers.


(a)
Amplitude
1
0
1
1
Time
(b)
Amplitude
Distinguishable pulses
1
0
1
1
Time
Composite pattern
(c)
Amplitude
Indistinguishable pulses
No zero level
Time
Intersymbol interference (ISI)