Fiber Optic Communication Systems

Introduction

- **Title: Optical Communication**
- **Credit Hours: 03**
- **Semester: 7th**
- **Course Instructor: Dr. Rashmi A. Pandhare**

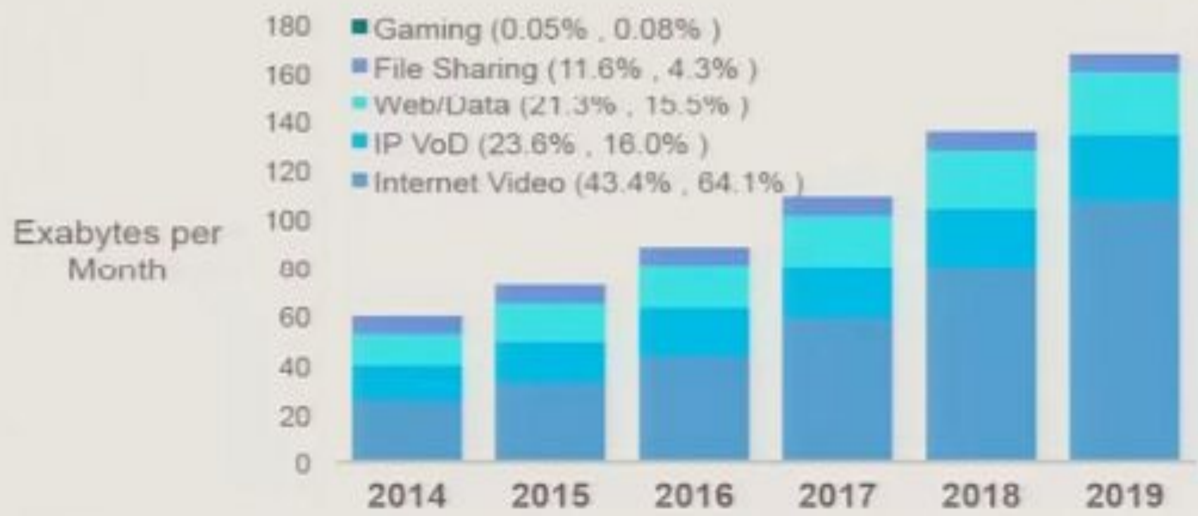
Objective

To understand the concept of optical fiber communication and its components for the implementation of High Speed Networks.

GROWING TRAFFIC TREND
Cisco global IP traffic forecsat

APPLICATION WISE IP TRAFFIC

Application wise IP traffic

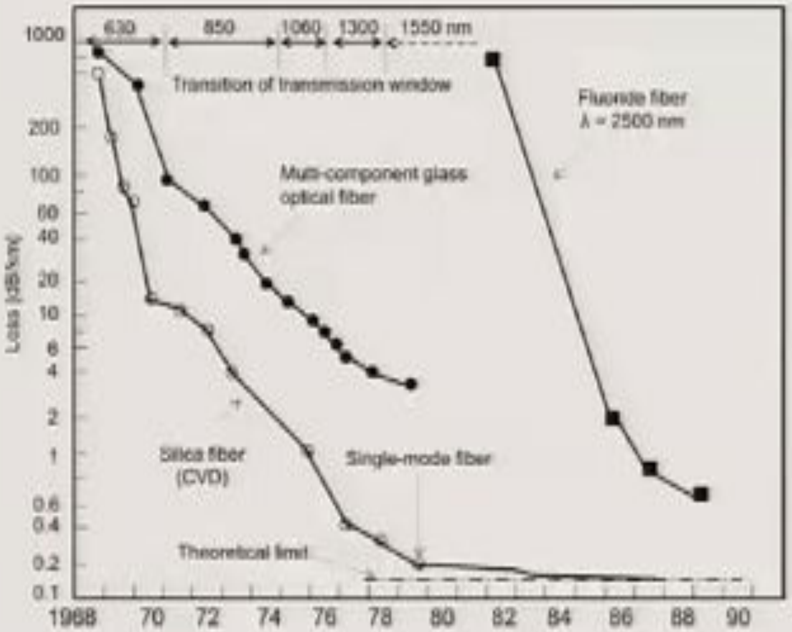


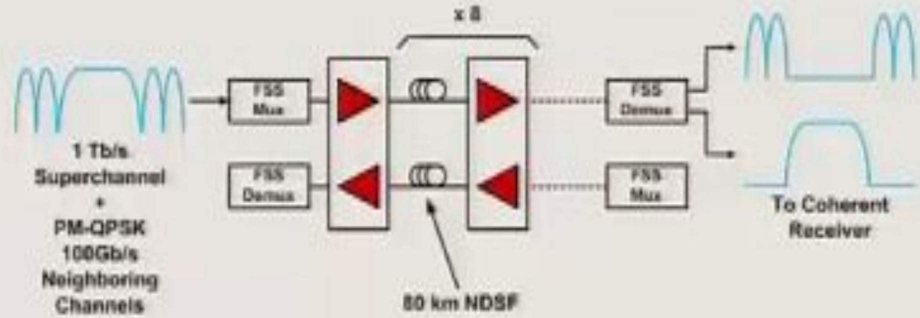
- Sadly, most video traffic is downstream
- Video-calling/P2P services expected to make traffic symmetric

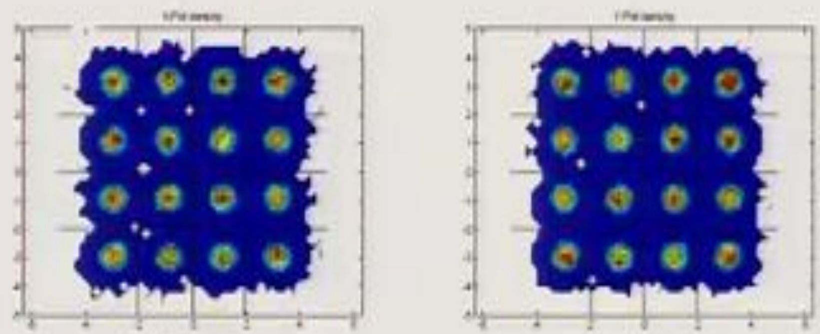
What does it take to communicate?

- Long distance communications
  - Users are **connected across continents**
  - Communication channel must have **low-loss**
  - Send DVDs by post? Significant delay!
- High-data rates
  - Users want data without delay
  - Communication channel must have **large bandwidth**
  - Copper cables cannot support data rate in Gbps
- Mobile communication
  - Users also want data on the go!
  - Mobile communication requires high-speed wired backbone network to connect stations/towers

What technology addresses these issues?





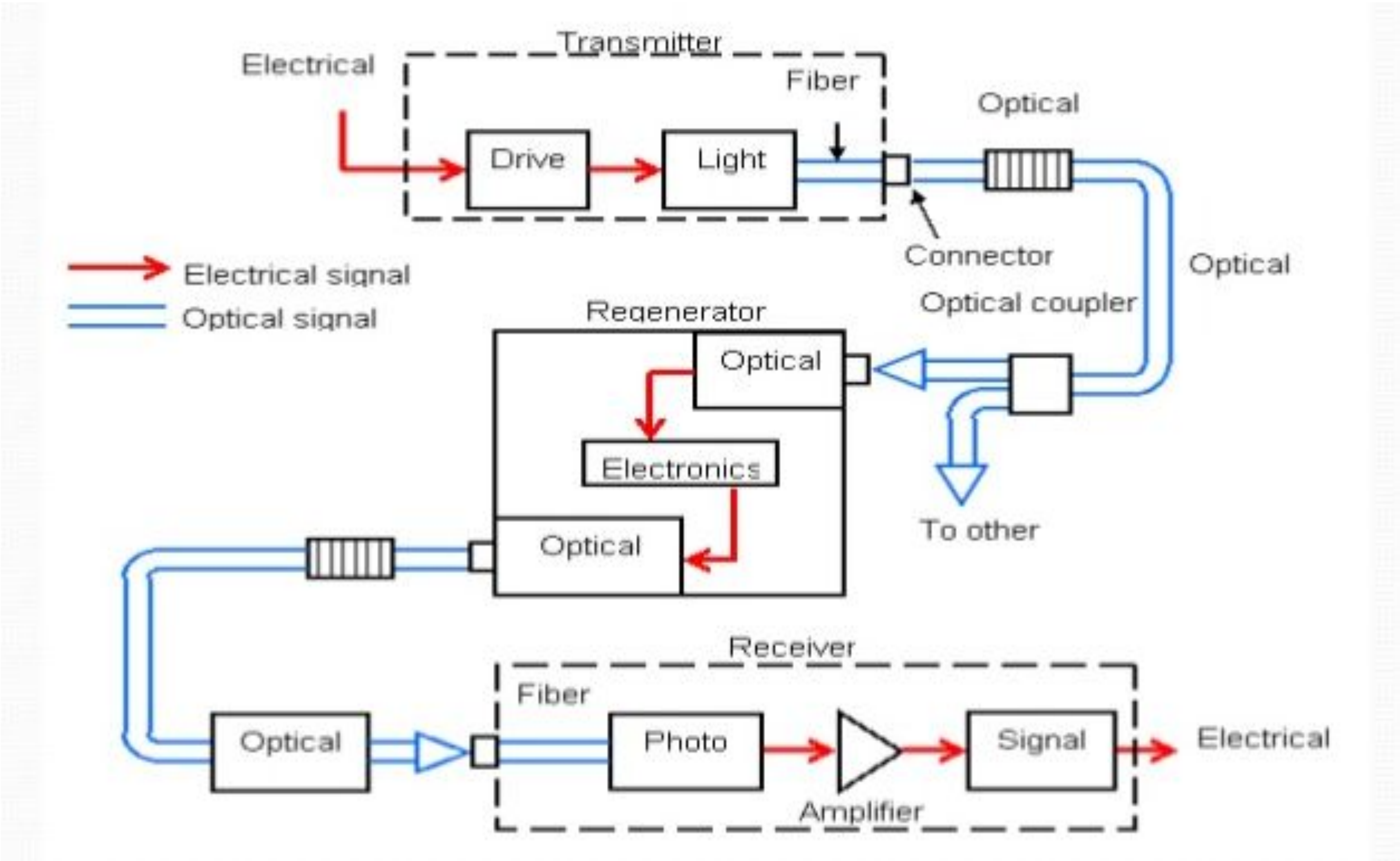


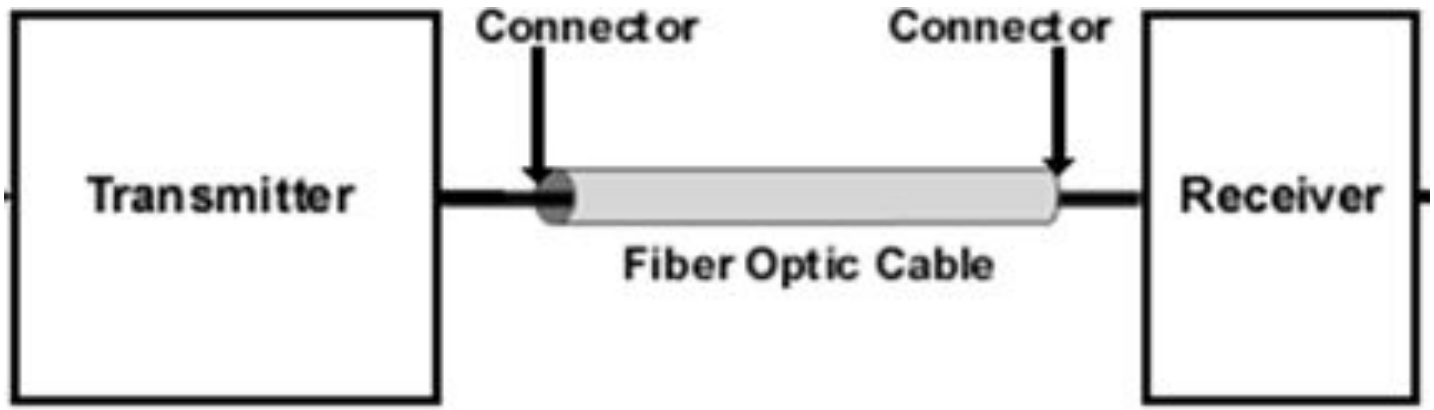
X-polarization

Y-polarization

- Optical fiber communications
- No other communication technology (satellite, wireless, copper cables) can sustain such high data rates at such low losses

Block diagram of Optical Communication

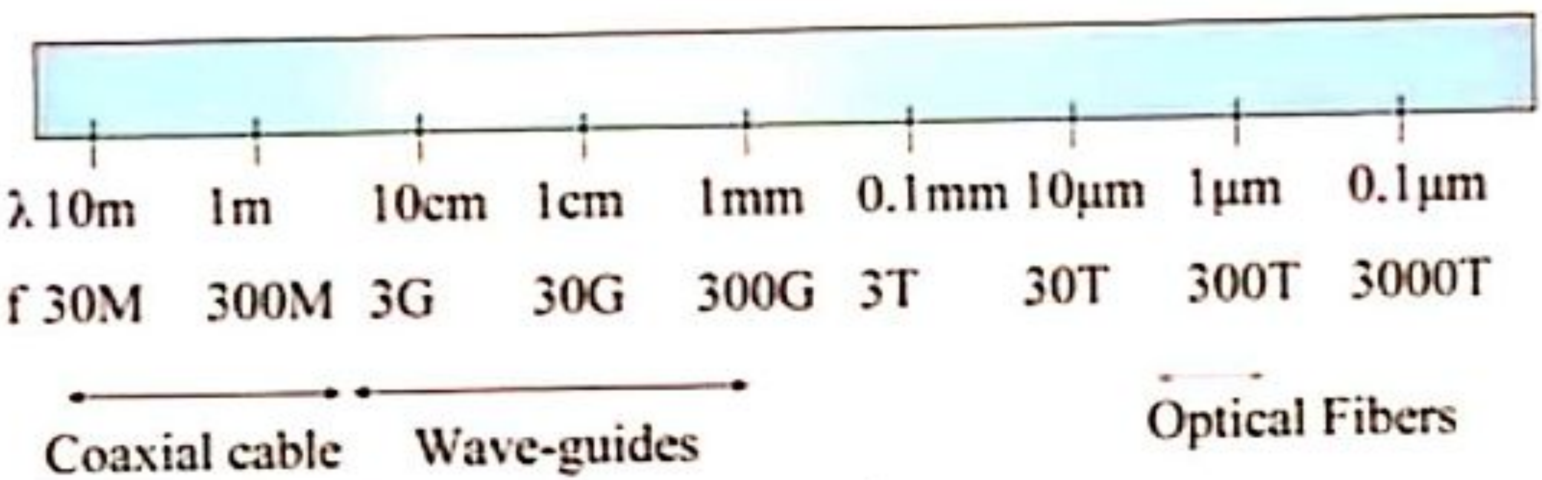




Connector
Connector
Transmitter
Receiver
Fiber Optic Cable

Electromagnetic Spectrum

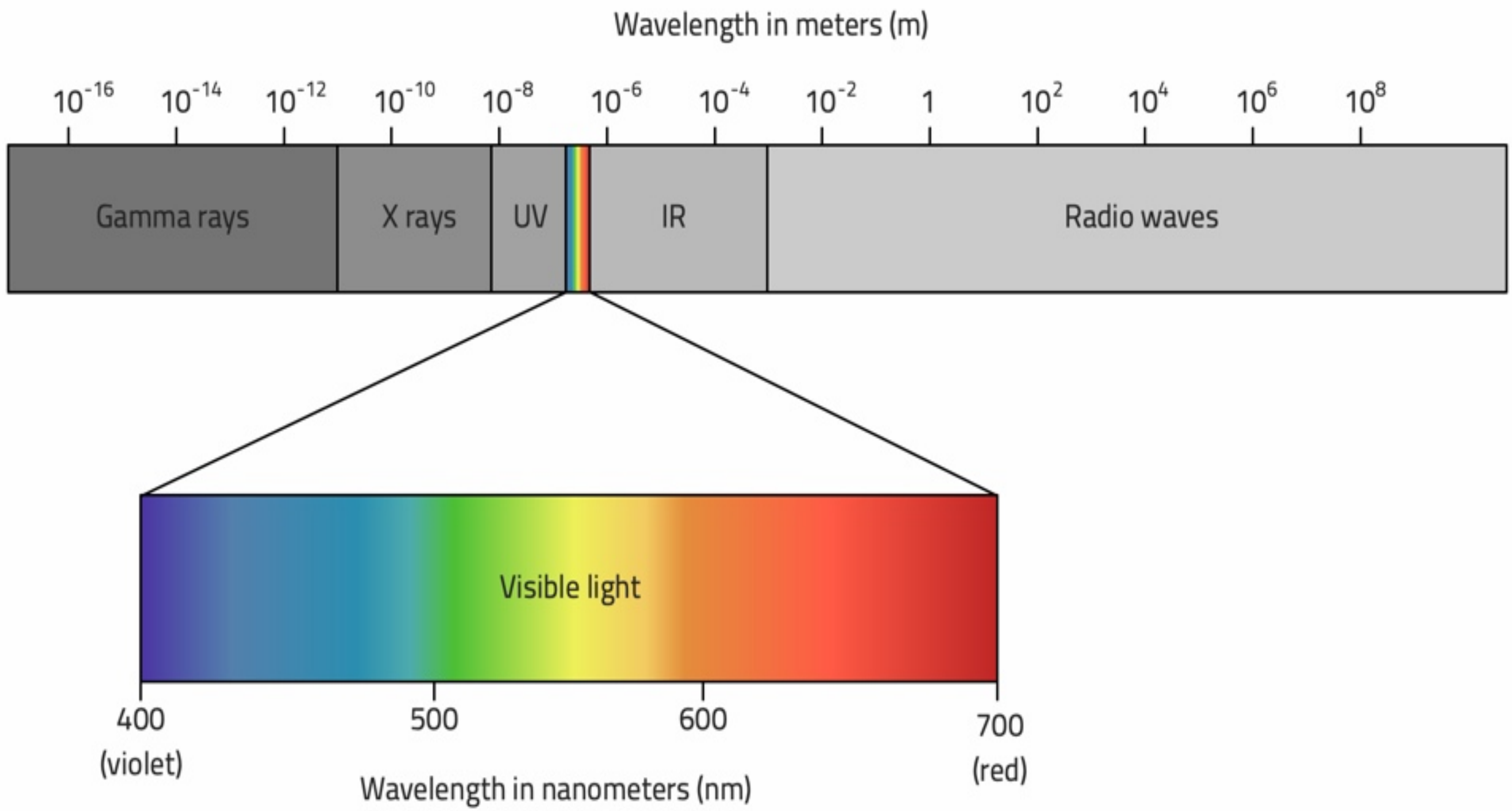
Electromagnetic Spectrum



$$BW = \frac{f_0}{Q}$$

$$BW \propto f_0$$

Electromagnetic Spectrum



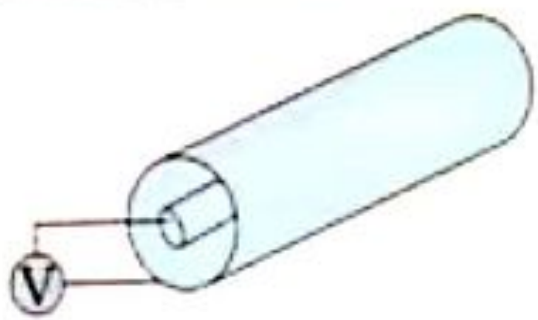
Transmission Media

Transmission Media

Twisted Pair: (point-to-point)

Telephone Lines
Low data rate
High EMI
Lossy at RF

Co-axial Cable (point-to-point)



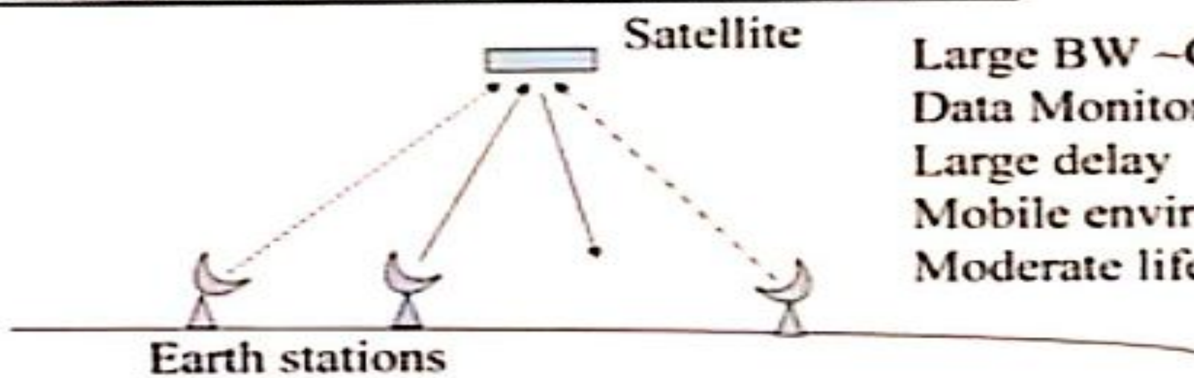
LAN
Data rates few Mbps
Low EMI
Moderate loss

Transmission Media

Microwave Link (point-to-point)

Long distance
Large BW
Line-of-sight
High free-space loss

Satellite Communication (point-to-multi-point



Large BW ~GHz
Data Monitoring
Large delay
Mobile environment
Moderate life

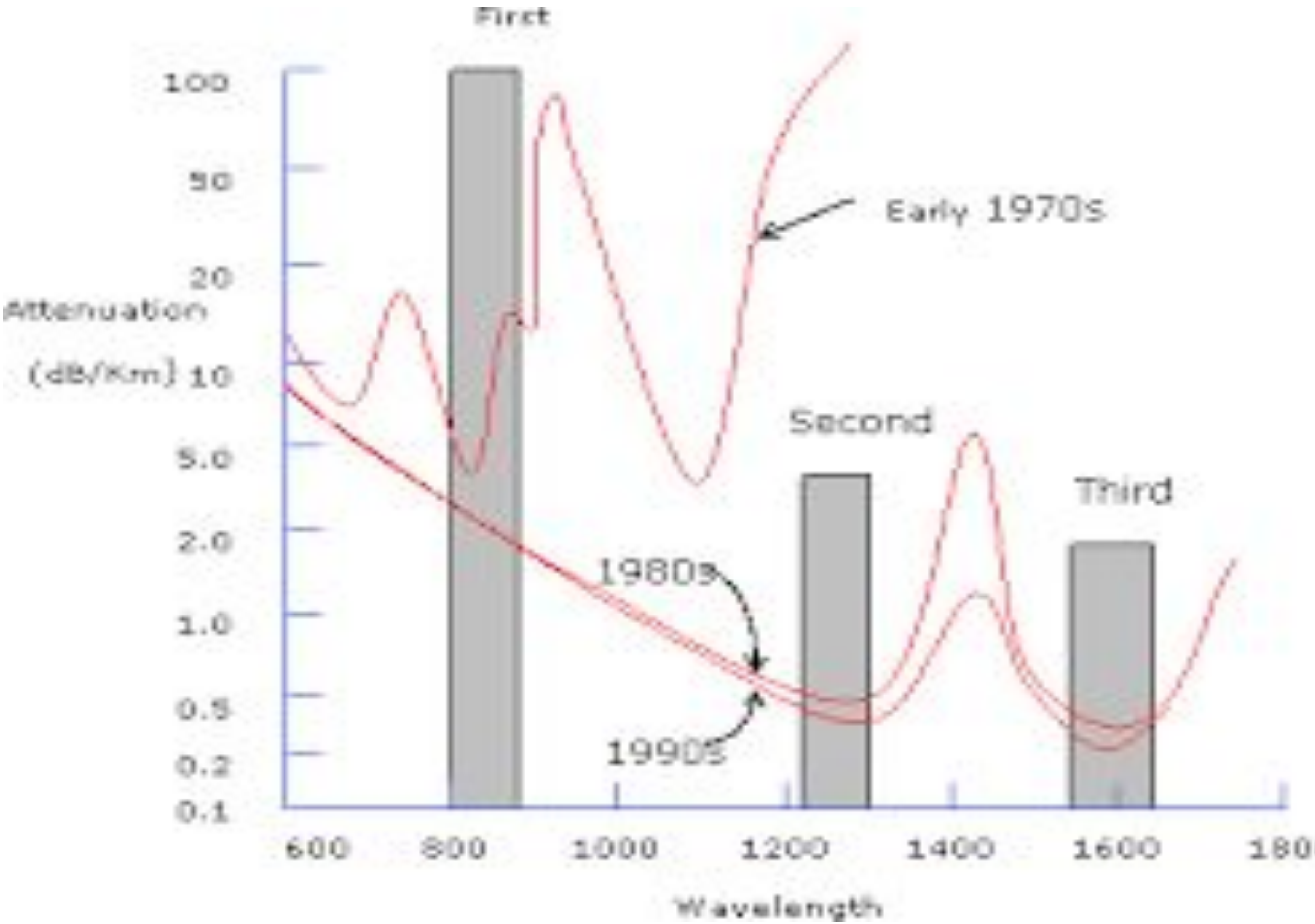
Complimentary Technology

Satellite vs Fiber Optics

- **Satellite**
  - Point to Multi-point
  - BW ~ GHz
  - Maintenance free
  - Short life ~7-8 Yr
  - No upgradeability
  - Mobile, air, sea
- **Fiber Optics**
  - Point to point
  - BW ~ THz
  - Needs Maintenance
  - Long life
  - Upgradeable
  - On ground only

Two will co-exist due their complementary nature

History of Attenuation



Advantages of Optical Communication

1. Ultra high bandwidth(THz)
2. Low loss (0.2 dB/Km)
3. Low EMI
4. Security of transmission
5. Low manufacturing cost
6. Low weight, low volume
7. Point to point communication

Characteristics of Light

- Intensity
- Wavelength
- Spectral width
- Polarization

i. Linear
ii. Circular
iii. Elliptical
iv. Random

Characteristic of Light

- **Intensity:** Intensity of light is power per unit solid angle.

- **Wavelength :(λ)** wavelength is color of light.

  The visible range of light = 400 to 700nm

- **Spectral Width : (Purity of color = Δλ)**

  It is the wavelength range over which emission takes place.

If wavelength representing color then spectral width represents purity of color

Propagation of Light

- A light wave is an **electromagnetic** wave.
- It has an **electric** and a **magnetic** component.
- Electric field , magnetic field and direction of light are perpendicular to each other.

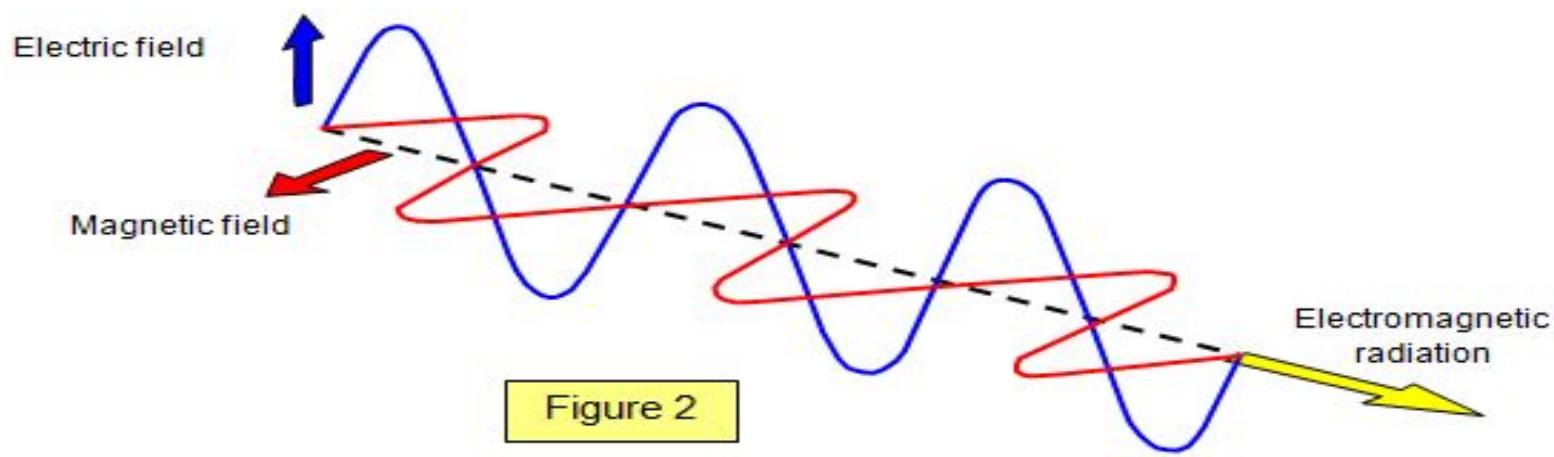


Figure 2

Whether Light is Transverse wave?

A **transverse wave** is a wave that oscillates perpendicular to its direction of propagation.

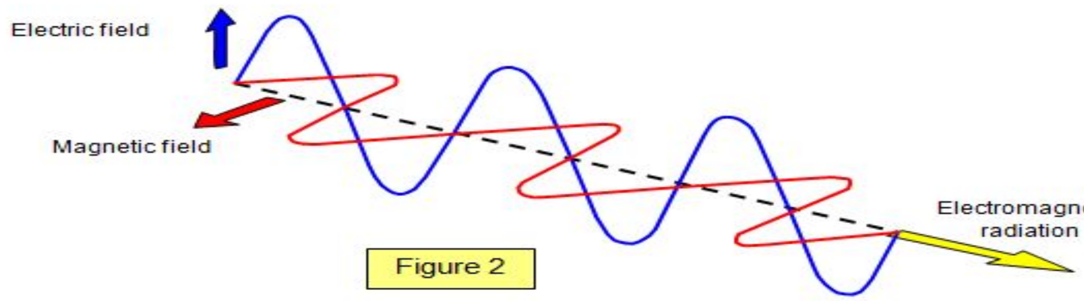


Figure 2

As the wave propagates in the z direction, the electric field is oscillating in the y direction and the magnetic field is oscillating in the x direction

Since the x and y axes are perpendicular to the z axis, light is a transverse wave

Light is a transverse wave because its components vibrate perpendicular to the direction of propagation.

Whether the light is transverse Electromagnetic wave ?

In a medium which is having the size much larger compare to the wavelength of light , the light can be treated as **transverse Electromagnetic wave**

Then E and H also related to medium parameter

$$\frac{|E|}{|H|} = \eta = \text{Intrinsic Impedance of medium}$$

$$= \sqrt{\frac{\mu}{\varepsilon}} = \frac{\text{Permability of medium}}{\text{permitivity of medium}}$$

What is Polarization of Light

- As H is completely depend on E.

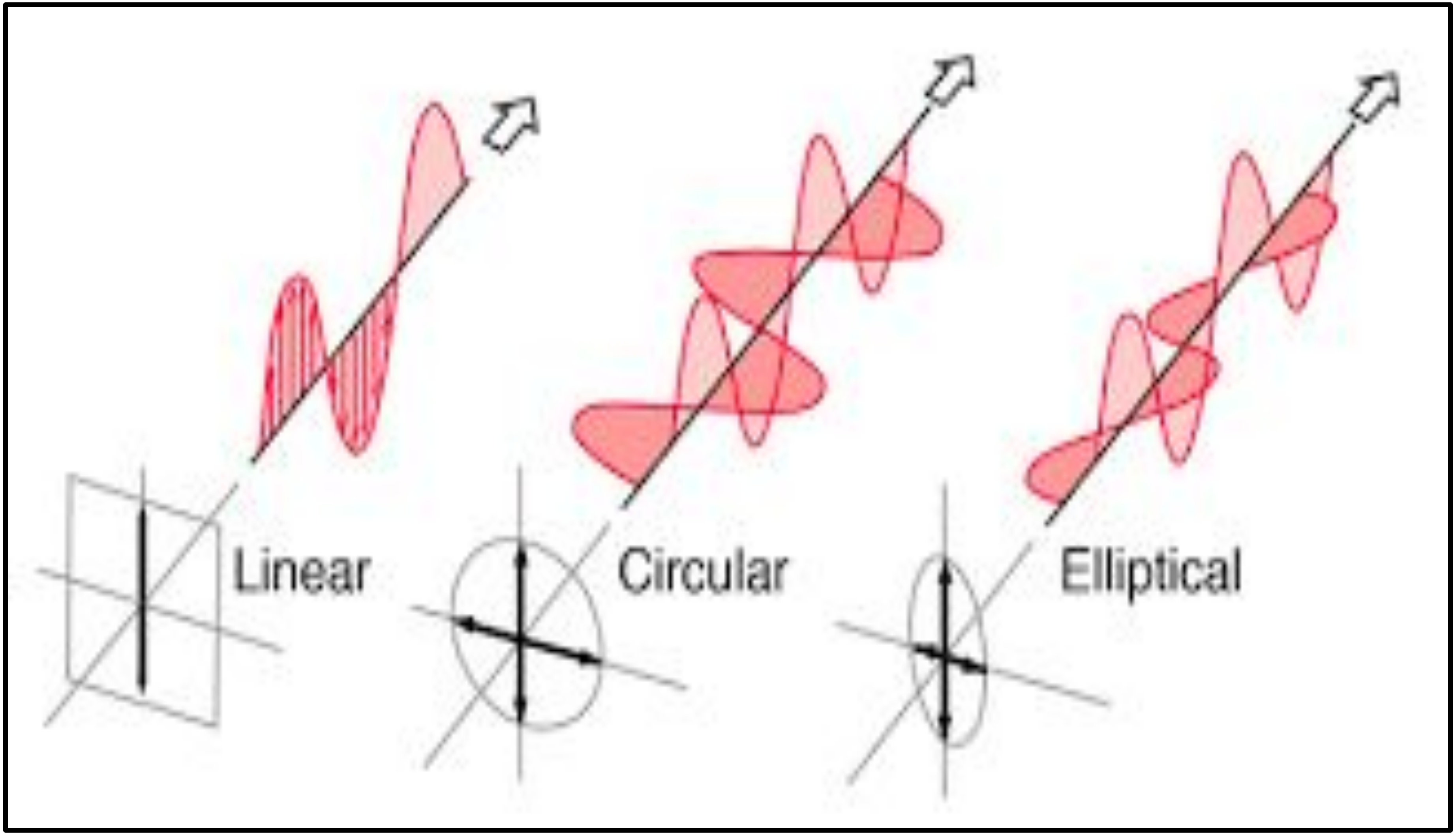
- Therefore we should observe behavior of E as a function of time

- This behavior of light as a function of time , i.e. how the electric field behaves as a function of time is **known as a polarization of light**

- The tip of the vector E will draw as a function of time is having different shape and that shape is known as **shape of polarization**

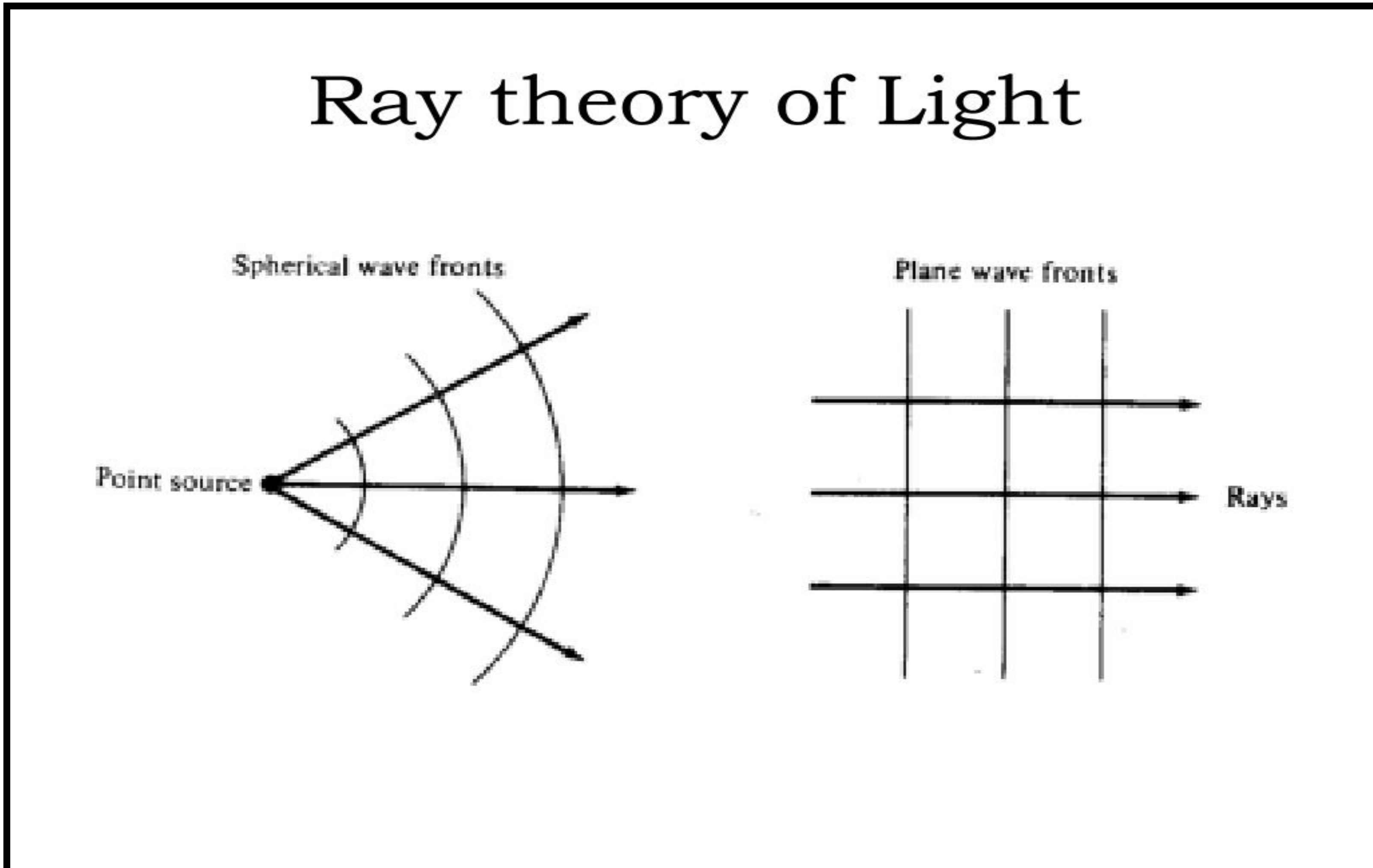
So polarization is a parameter which capture vector nature of light

Types of Polarization of Light



Light as Ray

The simplest possible description of light is as “RAY”



Light as Electromagnetic Wave

Wave Function

□ $\Psi(x, t) = A \exp(\omega t - \beta x)j$

- A: Amplitude of the wave

□ ω: Angular frequency of the wave (rad/s)

□ β: Phase constant (rad/m)

VELOCITY OF LIGHT

- Velocity of light is a medium dependant property.

- Velocity of light changes if light goes from vacuum to any other material.

- Whether the velocity of light is structure dependant ?

- If light goes through a same medium and if the medium is bound then the velocity of light also changes

Refractive Index of the medium

- **Refractive Index of the medium is**

index of refraction

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

velocity of light in vacuum

velocity of light in the medium

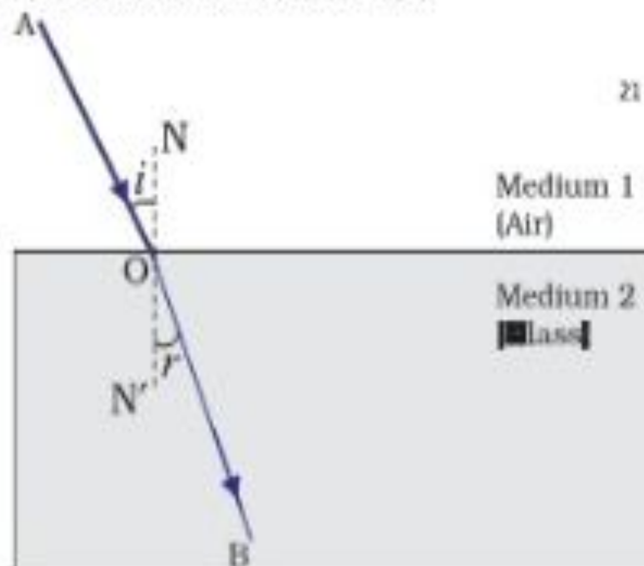
- Refractive index shows at what factor speed of light reduces when it enters from vacuum to other media

- For most of the directive media refractive index is greater than 1

- Refractive index of glass = 1.5
- Refractive index of water= 1.33

THE REFRACTIVE INDEX

- Consider a ray of light travelling from medium 1 into medium 2, as shown in Fig. Let v1 be the speed of light in medium 1 and v2 be the speed of light in medium 2. The refractive index of medium 2 with respect to medium 1 is given by the ratio of the speed of light in medium 1 and the speed of light in medium 2. This is usually represented by the symbol n_{21}. This can be expressed in an equation form as
- $$n_{21} = \frac{\text{Speed of light in medium 1}}{\text{Speed of light in medium 2}} = \frac{v1}{v2}$$



Effective Refractive Index of the medium

$$\overset{\text{index of refraction}}{n} = \frac{\overset{\text{velocity of light in vacuum}}{c}}{\underset{\text{velocity of light in the medium}}{v}}$$

- But this velocity of light need not to be in medium which could be one bound nature

- This velocity will be a structure velocity which could be an optical fiber structure or bound structure

- As velocity is structure dependant then as the size of medium changes velocity also changes

Effective Refractive Index of the medium

- **The change in velocity of light by**

1. **Keeping the medium same**

2. **Changing the size of medium**

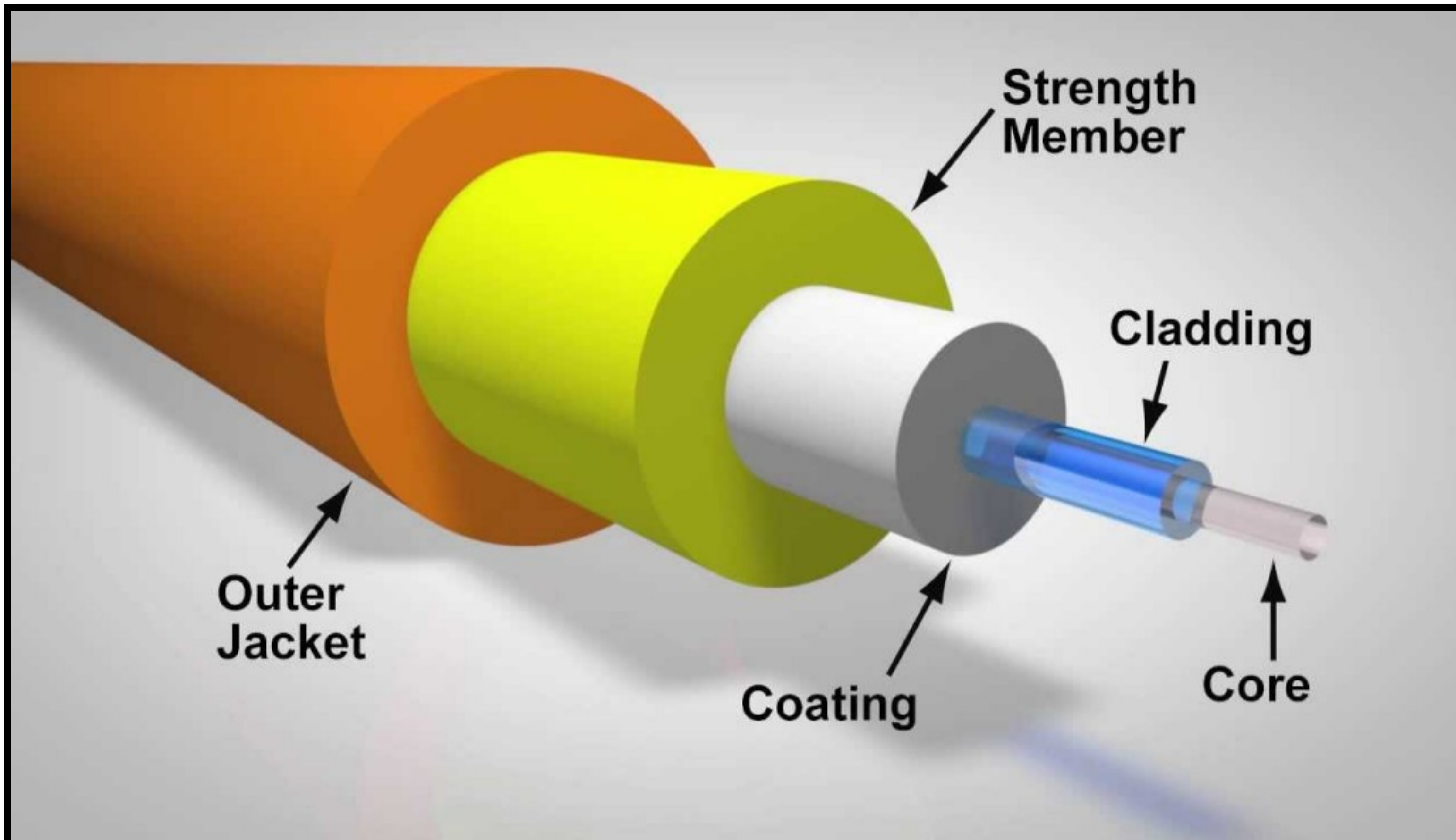
Result

This will changes the effective refractive index of guiding structure

This concept is useful in determining the propagation of light in optical fiber

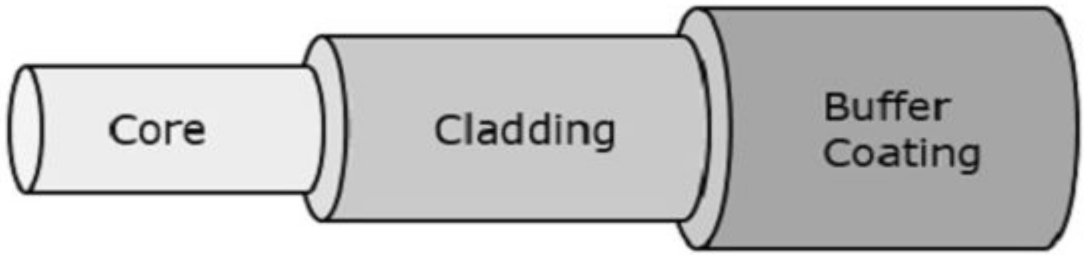
Optical Fiber

- **Propagation of light in an optical fiber in term of ray**



Optical Fiber

- optical fiber is basically a solid glass rod consist of an inner structure which is called as a core and outer structure which is cladding.



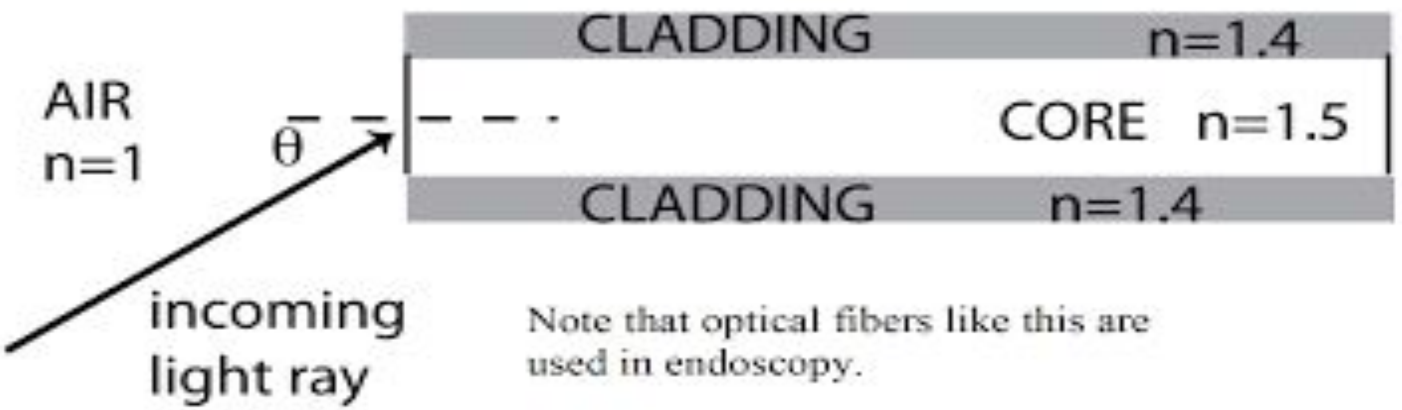
Parts of an Optical fiber

- For propagation of light core and cladding structure is important

- To support the structure mechanically the other layer like buffering layer is used.

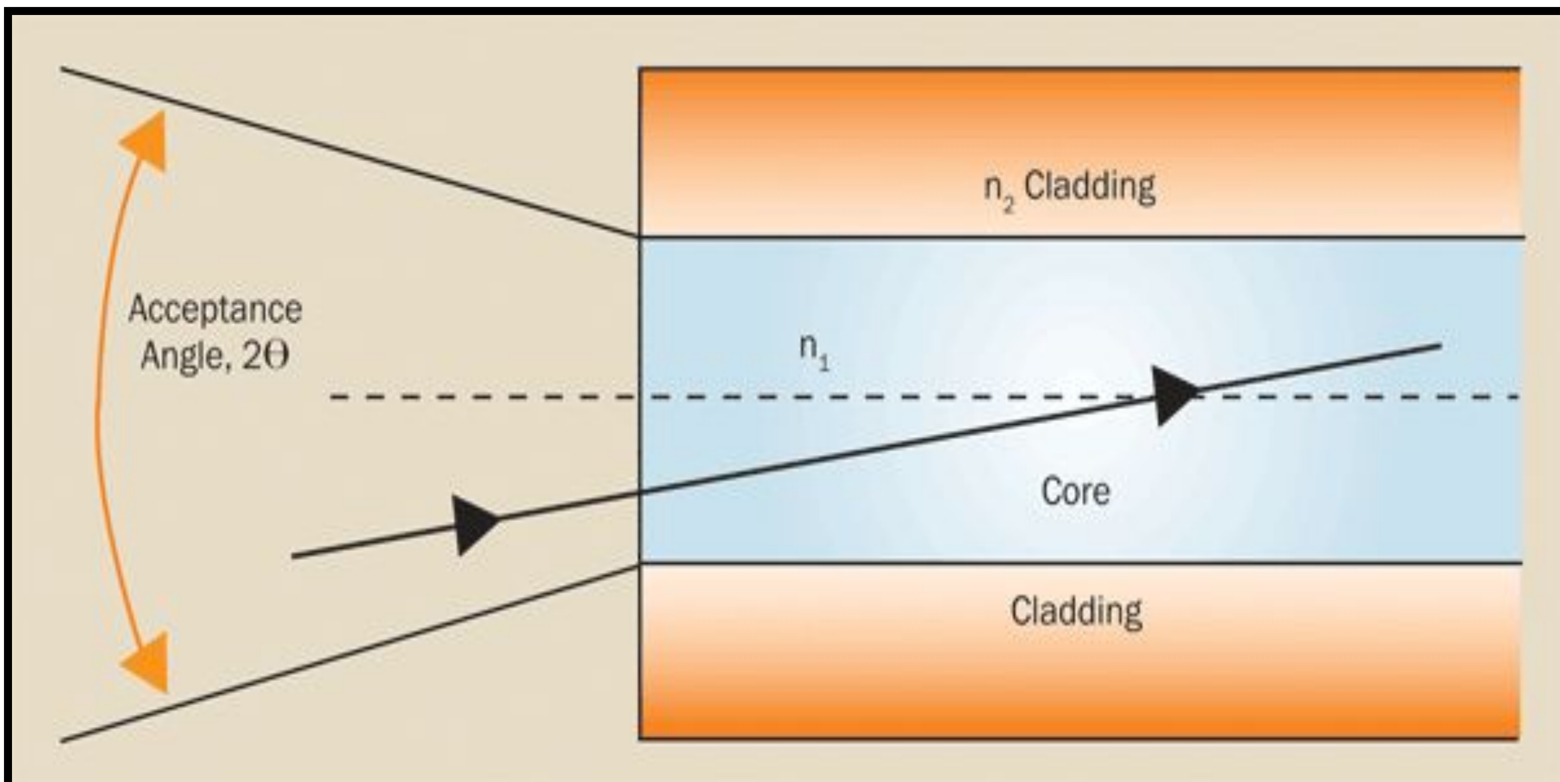
Optical Fiber

- Optical fiber is made from thin strands of either glass or plastic
- It has little mechanical strength, so it must be enclosed in a protective jacket
- Often, two or more fibers are enclosed in the same cable for increased bandwidth and redundancy in case one of the fibers breaks
- It is also easier to build a full-duplex system using two fibers, one for transmission in each direction

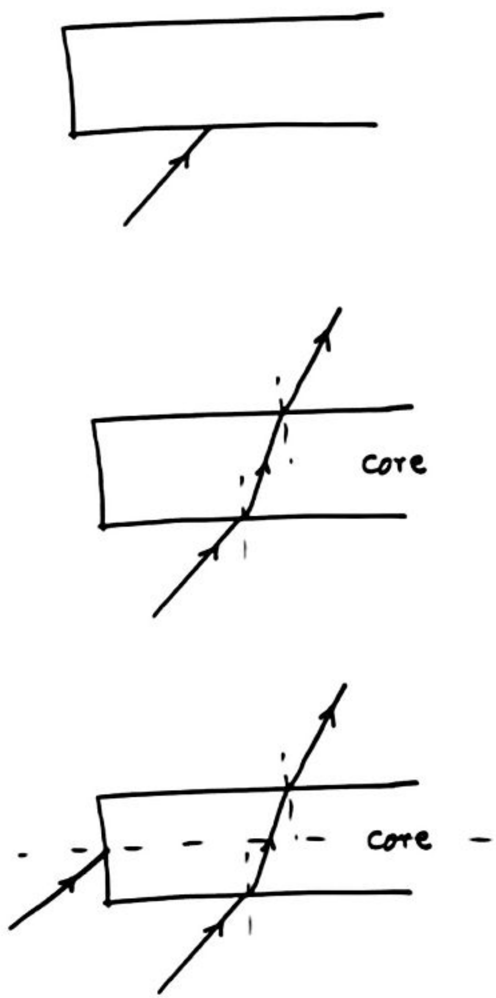


Launching of light

- Launching condition of light inside the core under which light propagates inside the core for long distance

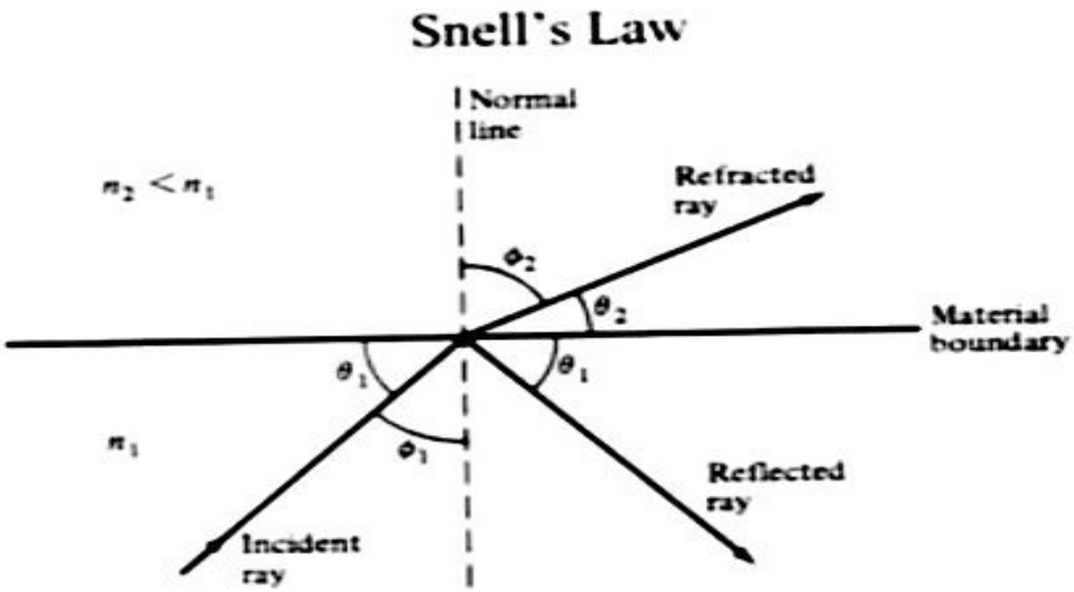


Launching of light

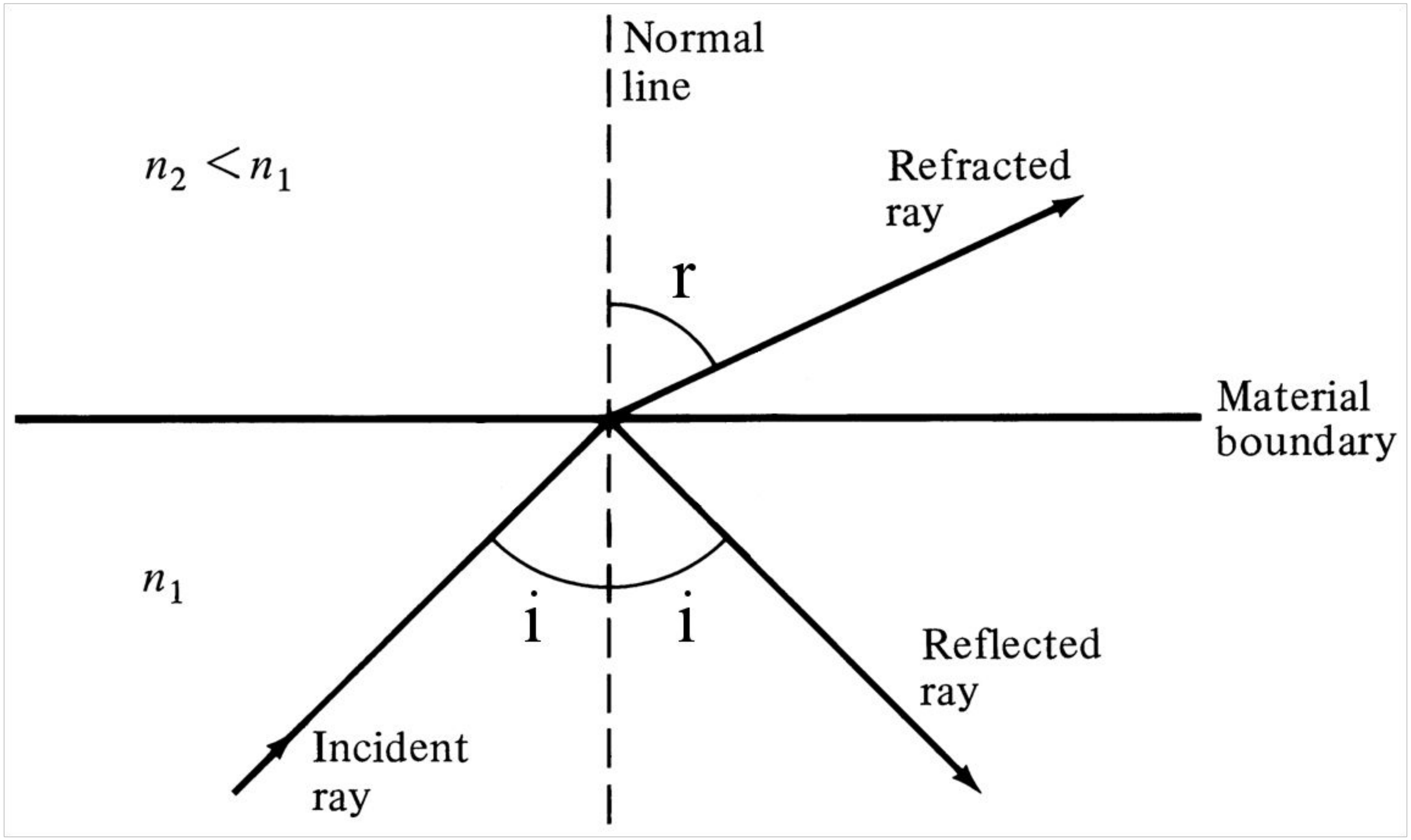


Snell's law

- **Ray model of light obeys the Snell's law**



$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$


Normal
line
$n_2 < n_1$
Refracted
ray
r
Material
boundary
n_1
i
i
Reflected
ray
Incident
ray

Launching the light in to an optical fiber

- There are two possibility of launching the light in to an optical fiber

- In the form of **Meridional ray**

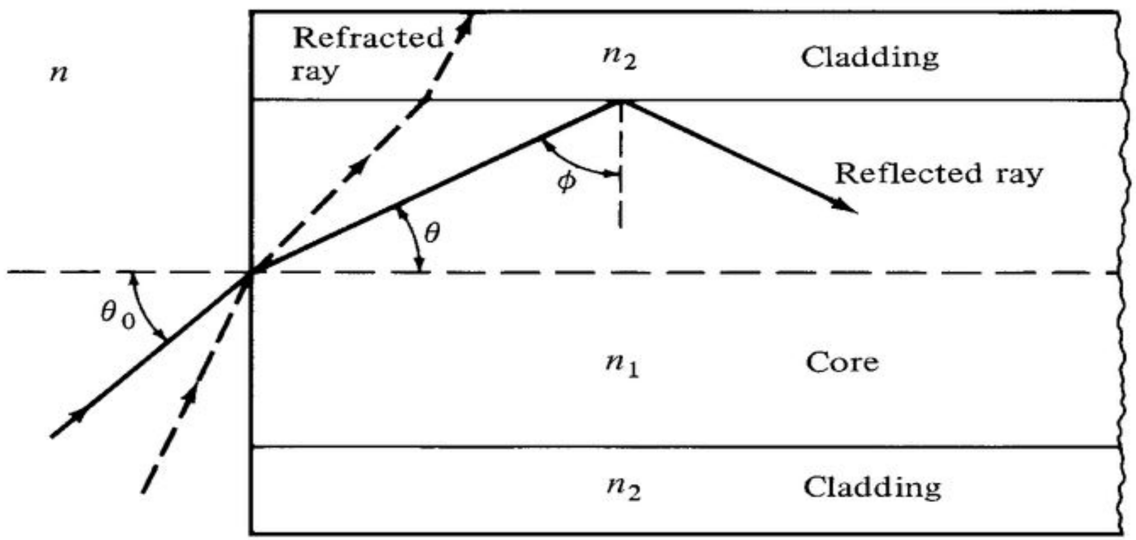
- In the form of **Skew rays**

Meridional rays

- A light ray is launched in a plane containing the axis of the fiber. We can then see the light ray after total internal reflection travels in the same plane i.e., the ray is confined to the plane in which it was launched and never leave the plane. In this situation the rays will always cross the axis of the fiber. These are called the **Meridional rays**

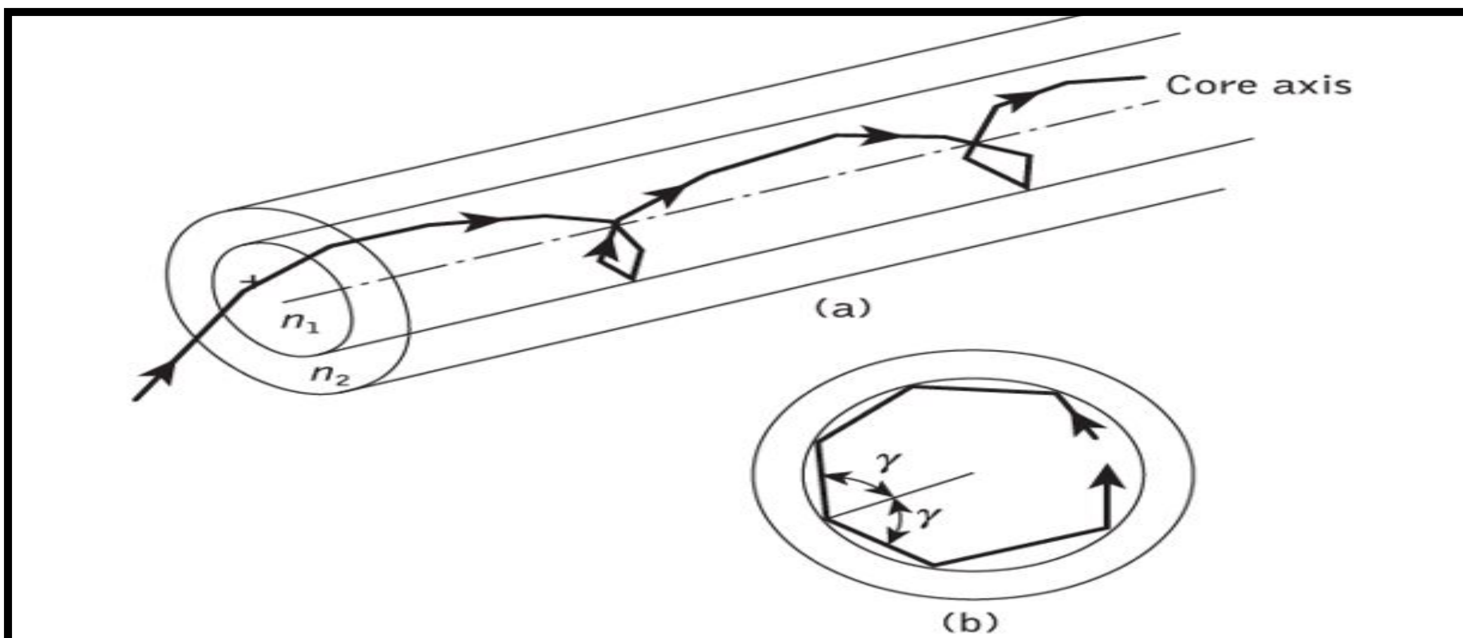
Meridional ray representation

Fig. 2-12: Meridional ray representation

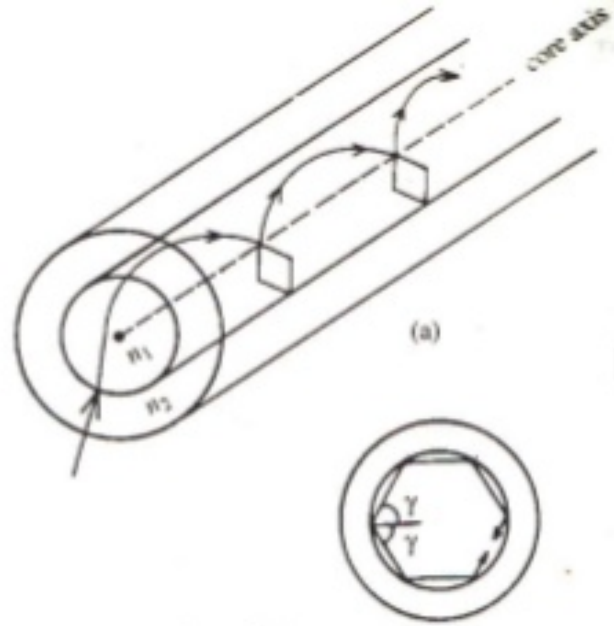


Skew rays

The ray is not launched in a plane containing the axis of the fiber. For example if the ray is launched at some angle such that it does not intersect the axis of the fiber, then after total internal reflection it will go to some other plane. We can see that in this situation the ray will never intersect the axis of the fiber. The ray essentially will spiral around the axis of fiber. These rays are called the **Skew rays.**



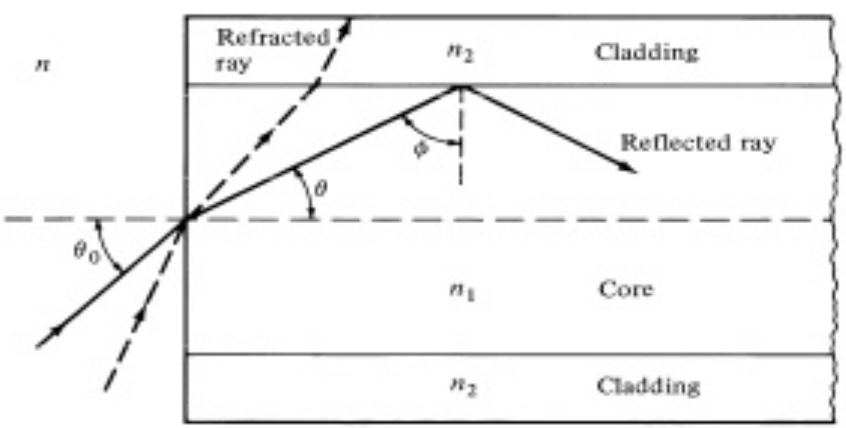
SKEW RAYS.

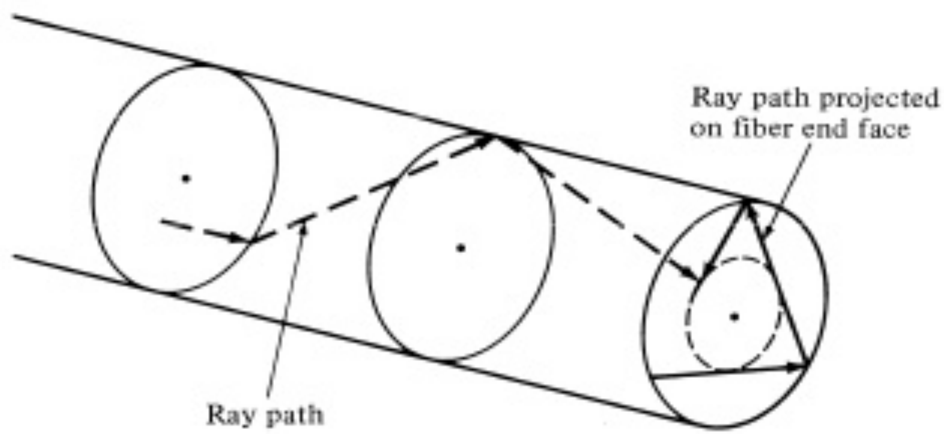


•Direction of ray changes by angle 2γ at each reflection where γ is angle between projection of ray in two dimensions and radius of fiber core.
•Skew rays show smoothening effect on distribution of light transmitted even if light launched in fiber is not uniform.
• Numerical aperture of skew rays is greater than meridional rays.

Meridional and skew rays

- A *meridional* ray is one that has no ϕ component – it passes through the z axis, and is thus in direct analogy to a slab guide ray.
- Ray propagation in a fiber is complicated by the possibility of a path component in the ϕ direction, from which arises a *skew* ray.
- Such a ray exhibits a spiral-like path down the core, never crossing the z axis.





Intensity Distribution

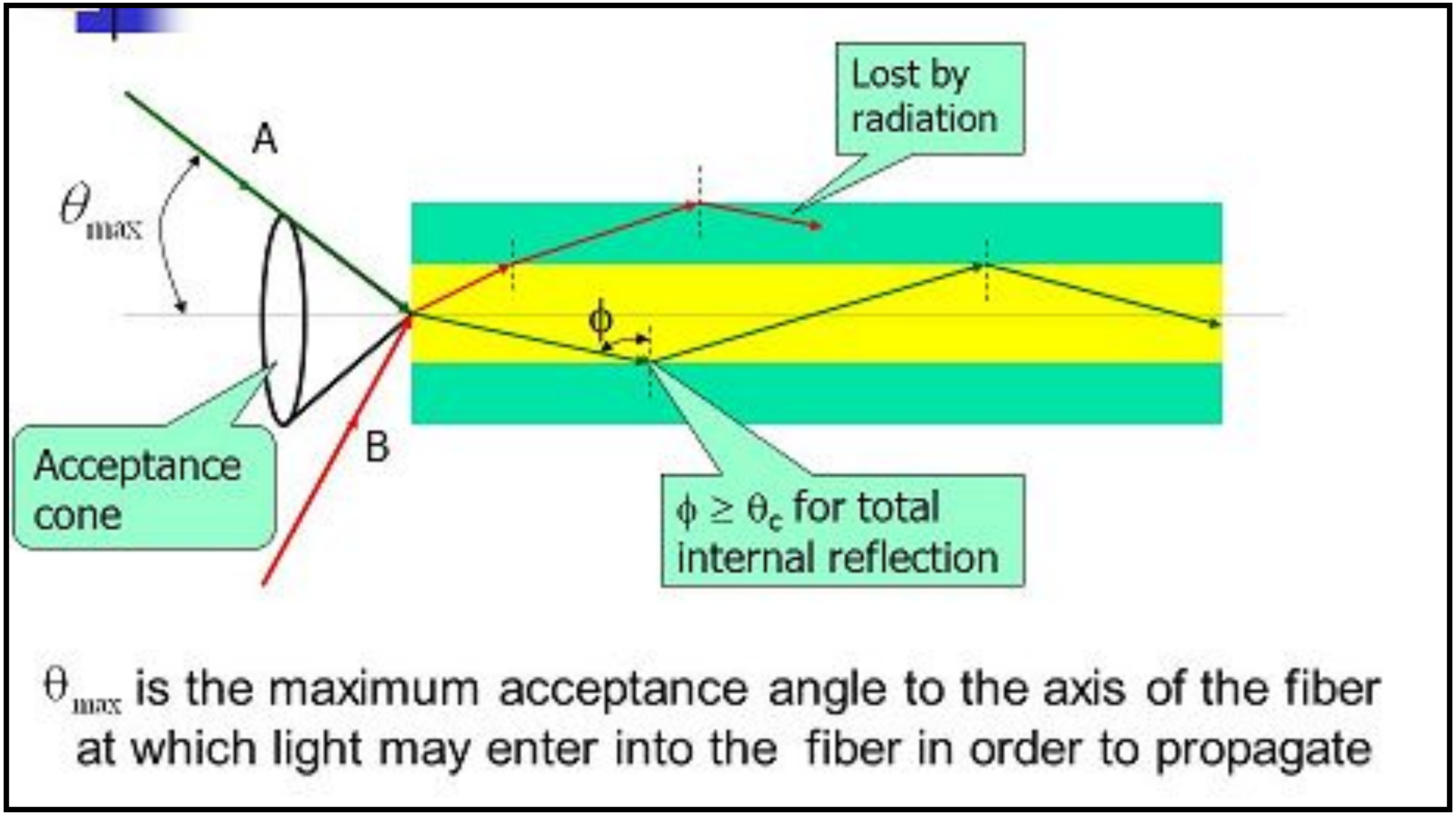
- The way light is launched inside the optical fiber there are two possibilities of intensity distribution

- **a) Meridional rays:** The rays which always pass through the axis of fiber giving high optical intensity at the center of the core of the fiber.

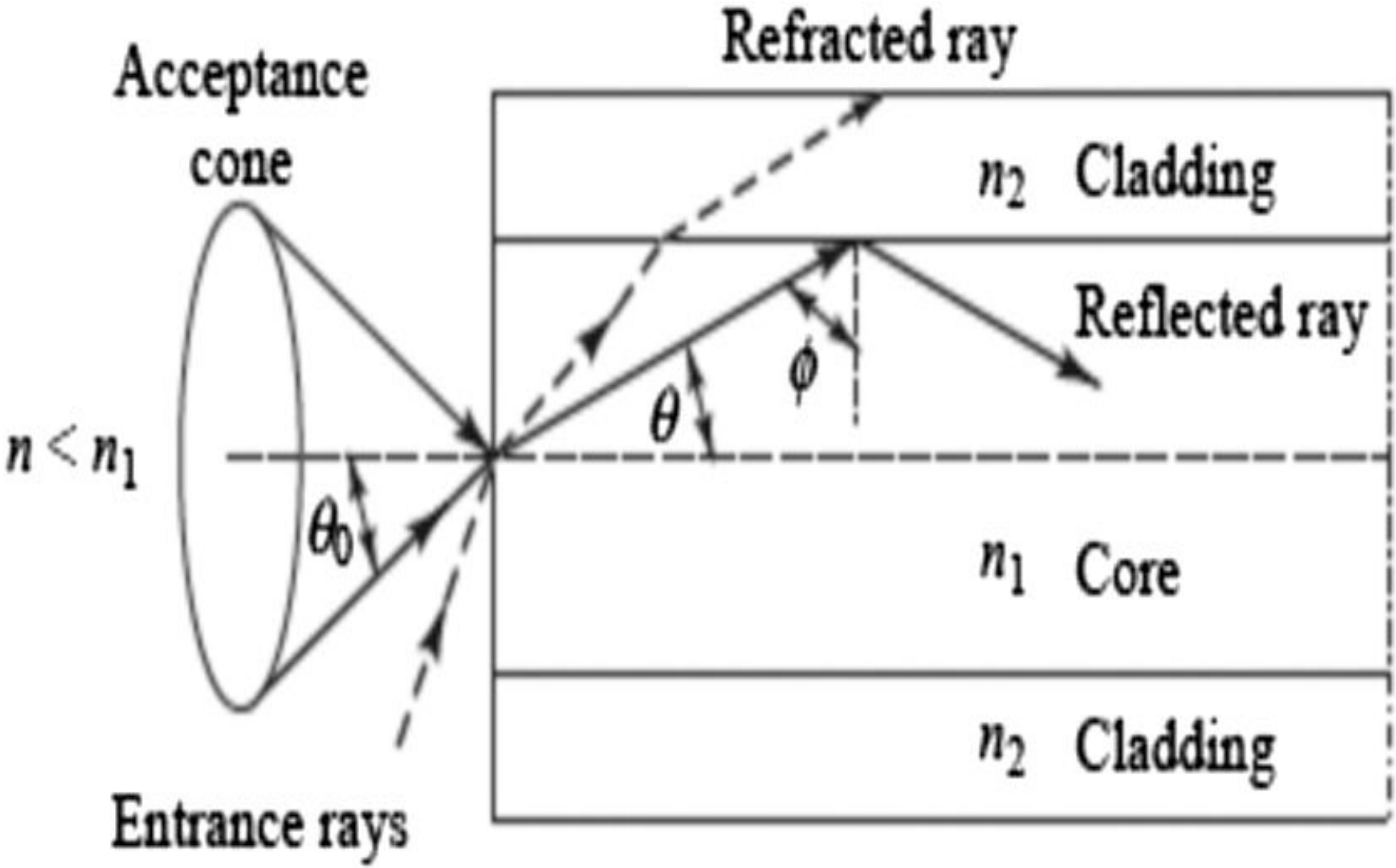
- **b) Skew Rays**: The rays which never intersect the axis of the fiber, giving low optical intensity at the center and high intensity towards the rim of the fiber.

Acceptance angle

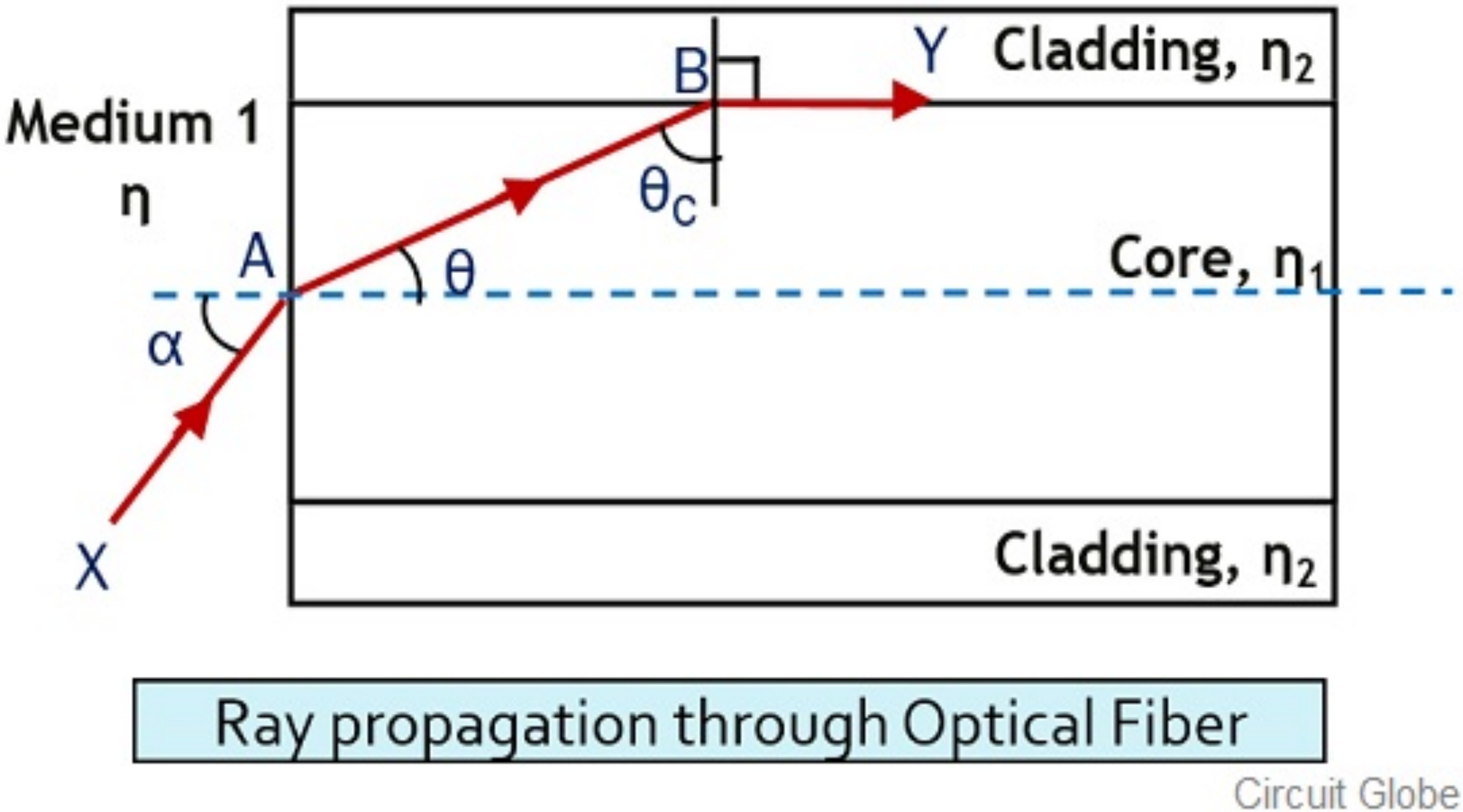
- It is a maximum angle to the fiber axis at which light ray may enter the fiber axis in order to get propagated.



Acceptance angle



Acceptance angle



Snell's Law at point 'A'

$$n \sin \theta_a = n_1 \sin \theta$$

In right angled Δabc

$$\theta = 90^\circ - \theta_c$$

$$\therefore \quad n \sin \theta_a = n_1 \sin (90^\circ - \theta_c) \quad \text{—— (A)}$$

as $n = 1$; equ^n (A) becomes

$$\sin \theta_a = n_1 \cos \theta_c \quad \text{—— (B)}$$

as $\cos \theta_c = \sqrt{1 - \sin^2 \theta_c}$; equ^n (B) becomes

$$\sin \theta_a = n_1 \sqrt{1 - \sin^2 \theta_c} \quad \text{—— (C)}$$

Now at point 'B' as per the snell's Law

$$n_1 \sin \theta_c = n_2 \sin 90^\circ$$

$$\sin \theta_c = \frac{n_2}{n_1} \quad \text{—— (D)}$$

$$\boxed{\theta_c = \sin^{-1} \frac{n_2}{n_1} = \text{critical angle}}$$

Now $\sin \theta_a = n_1 \sqrt{1 - \frac{n_2^2}{n_1^2}}$ —— by puting equ^n (D) into (C)

$$\boxed{\sin \theta_a = \sqrt{n_1^2 - n_2^2} = \text{Numerical Aperture}}$$

$$\boxed{\theta_a = \sin^{-1} \sqrt{n_1^2 - n_2^2} = \text{Acceptance Angle}}$$

Acceptance Angle

Acceptance angle of the fiber is the maximum angle of incidence up to which a light ray can enter into the fiber and still be totally internally reflected

$$\sin \phi_{\max} = \left(n_1^2 - n_2^2\right)^{1/2}$$

$$\phi_{\max} = \sin^{-1}\left(n_1^2 - n_2^2\right)^{1/2}$$

$$\phi_{\max} = \sin^{-1}\sqrt{\left(n_1^2 - n_2^2\right)}$$

Numerical Aperture (NA)

- Used to describe the light-gathering or light-collecting ability of an optical fiber.
- In optics, the **numerical aperture** (**NA**) of an optical system is a dimensionless number that characterizes the range of angles over which the system can accept or emit light

Numerical Aperture

Sine of the maximum angle accepted by the fiber.

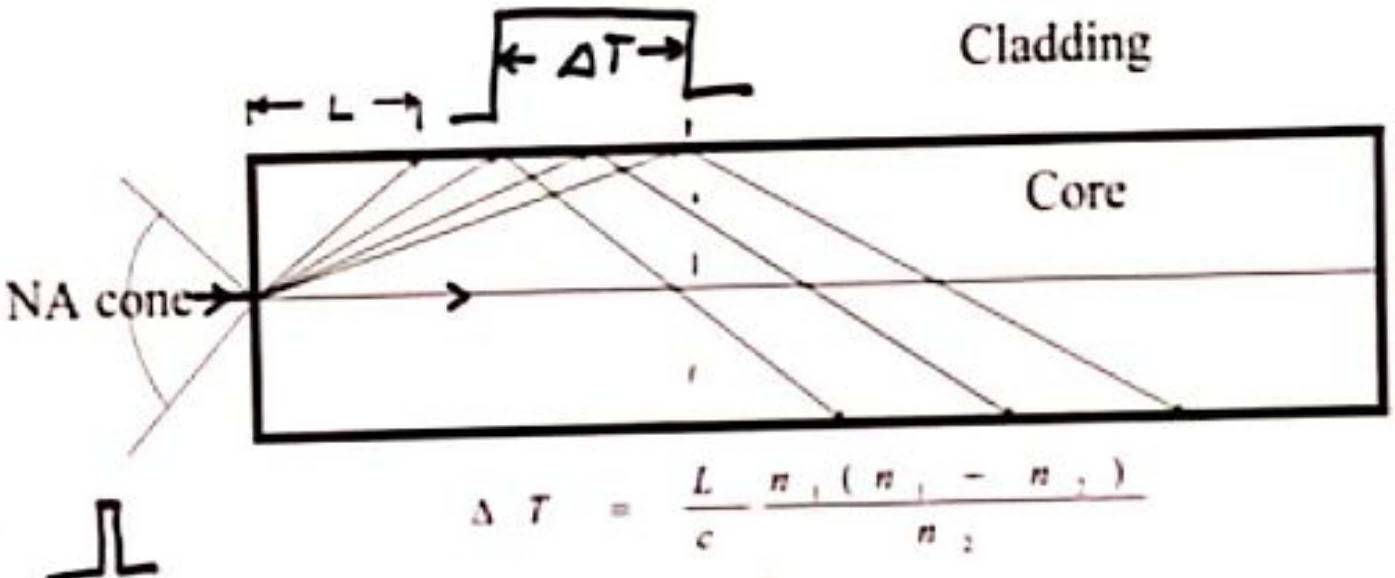
It defines the light launching efficiency

$$NA = \sin\theta_{0\max} = (n_1^2 - n_2^2)^{1/2}$$

For high launching efficiency NA should be as large as possible.

Group delay

- A pulsed signal travels by multiple paths within the NA cone.



$$\Delta T = \frac{L}{c}\frac{n_1(n_1 - n_2)}{n_2}$$

$$BW = \frac{1}{\Delta T}$$

DISPERSION

- The time difference essentially is the measure of pulse broadening on the optical fiber.

- This phenomenon is called **DISPERSION** of an optical fiber. The dispersion (pulse broadening) has to be small since the data rate is inversely proportional to the pulse broadening. For high speed communication the pulse broadening and hence the dispersion should be minimal.

Problem

A light ray enters from air to a fibre. The refractive Index of air is 1.0. The fibre has refractive index of core is equal to 1.5 and that of cladding is 1.48. Find the critical Angle, the fractional refractive index, the acceptance angle and Numerical aperture.

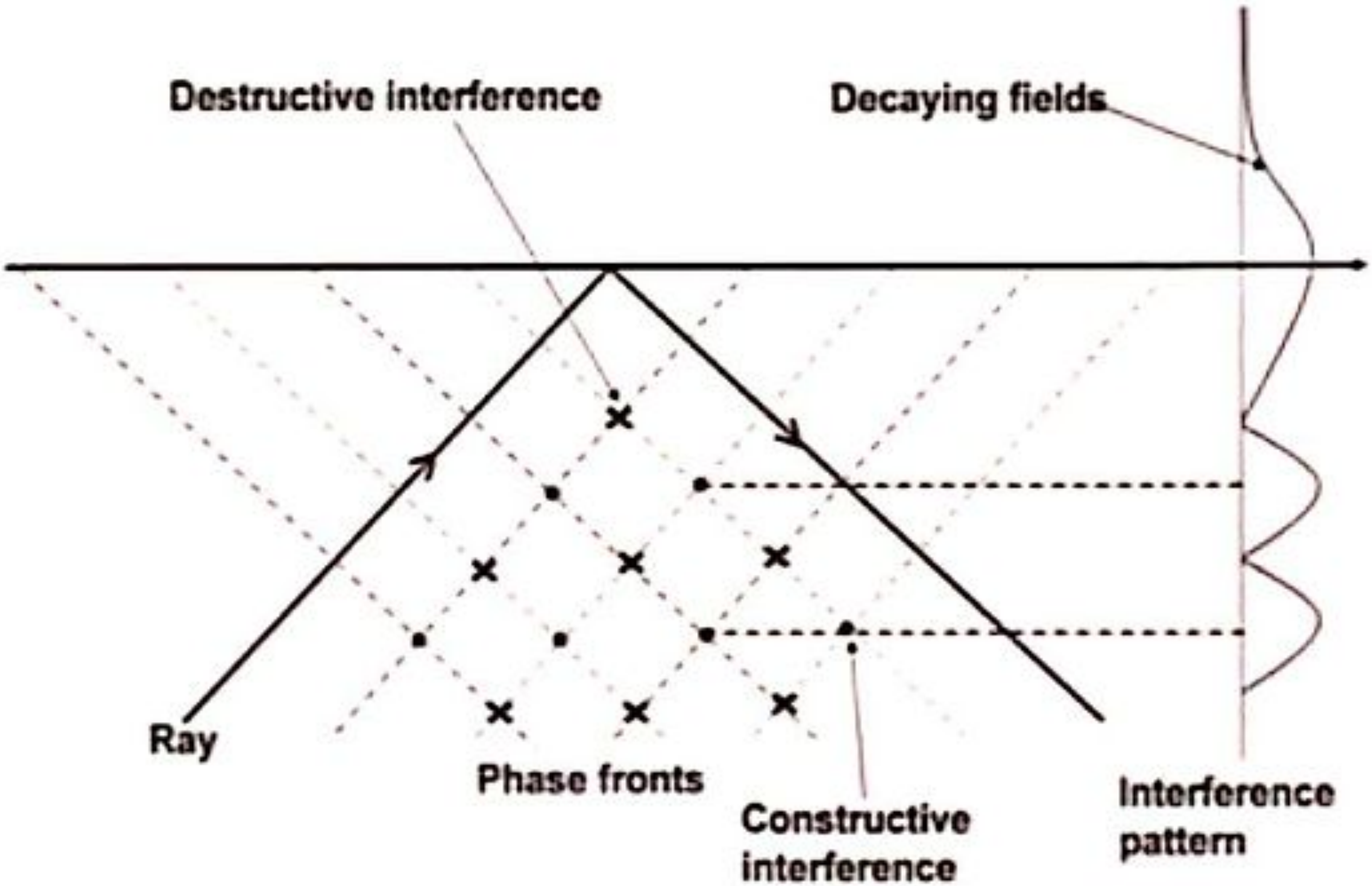
Ans: θ_c **= 80.63^0**

Fractional Refractive index **= 1.33% of light**

Numerical Aperture **Ans = 0.568**

Acceptance angle (θ_0) **Ans θ_o = 14.13^o**

Total Internal Reflection

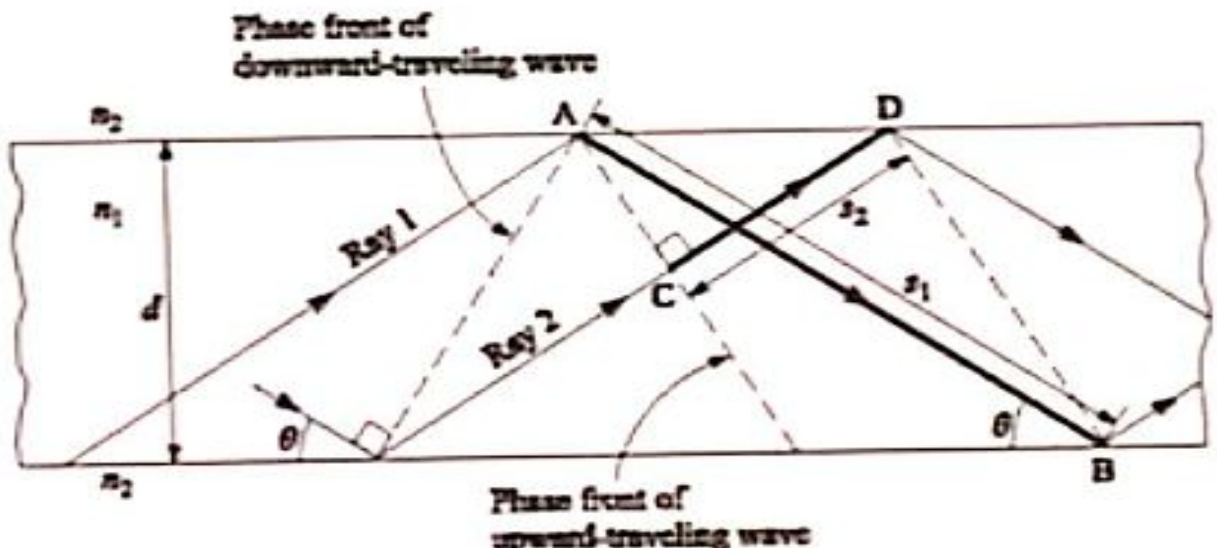


At total internal reflection we have

- Standing wave type of fields in the core
- Decaying fields in cladding
- The ray undergo the phase change at the reflecting boundary

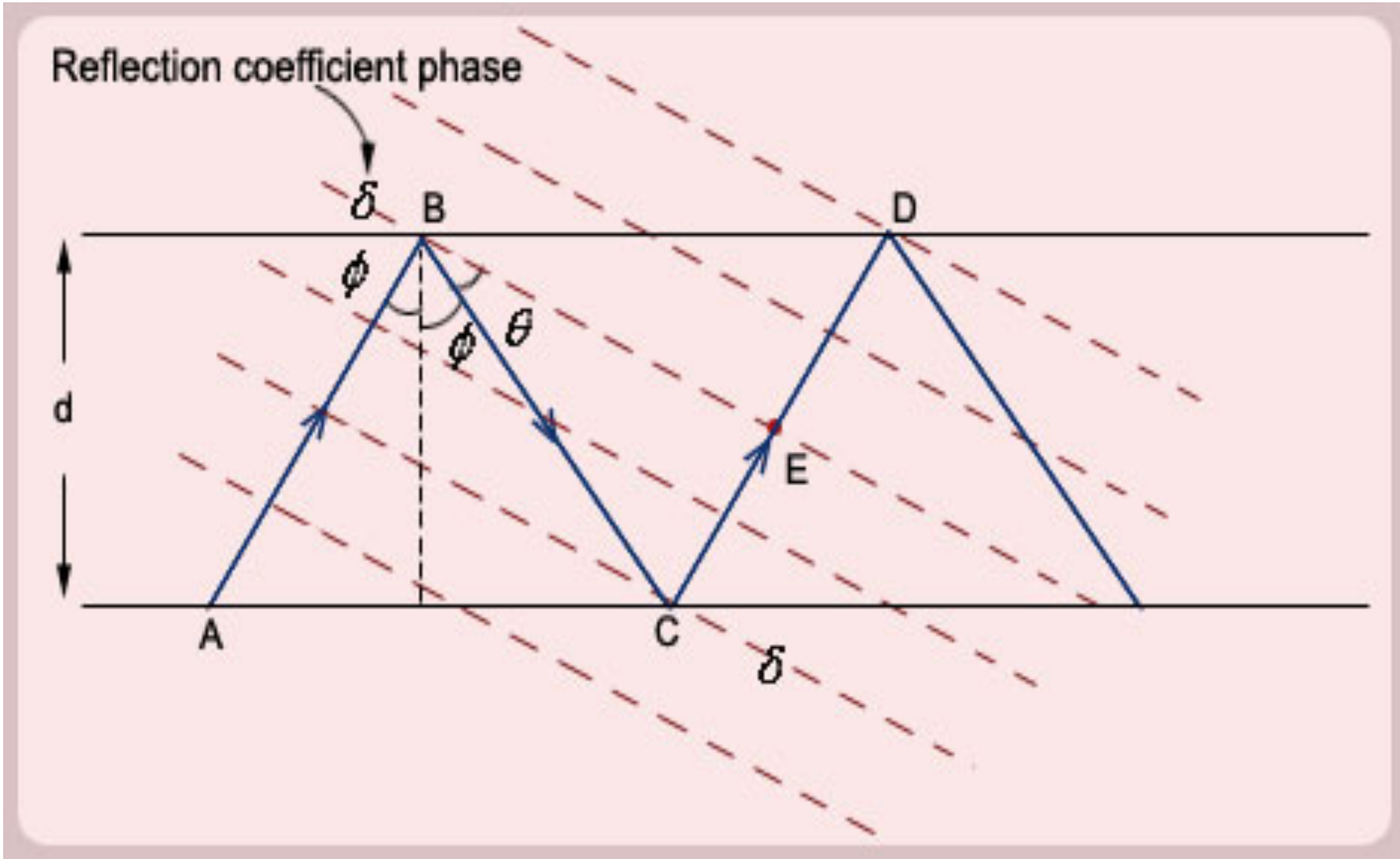
Light Propagation

Light propagation



1. Rays can survive at discrete angles
2. There are finite number of rays

Prof. R.K. Shevgaonkar, IIT Bombay


Reflection coefficient phase
δ
B
D
φ
φ
θ
d
E
A
C
δ

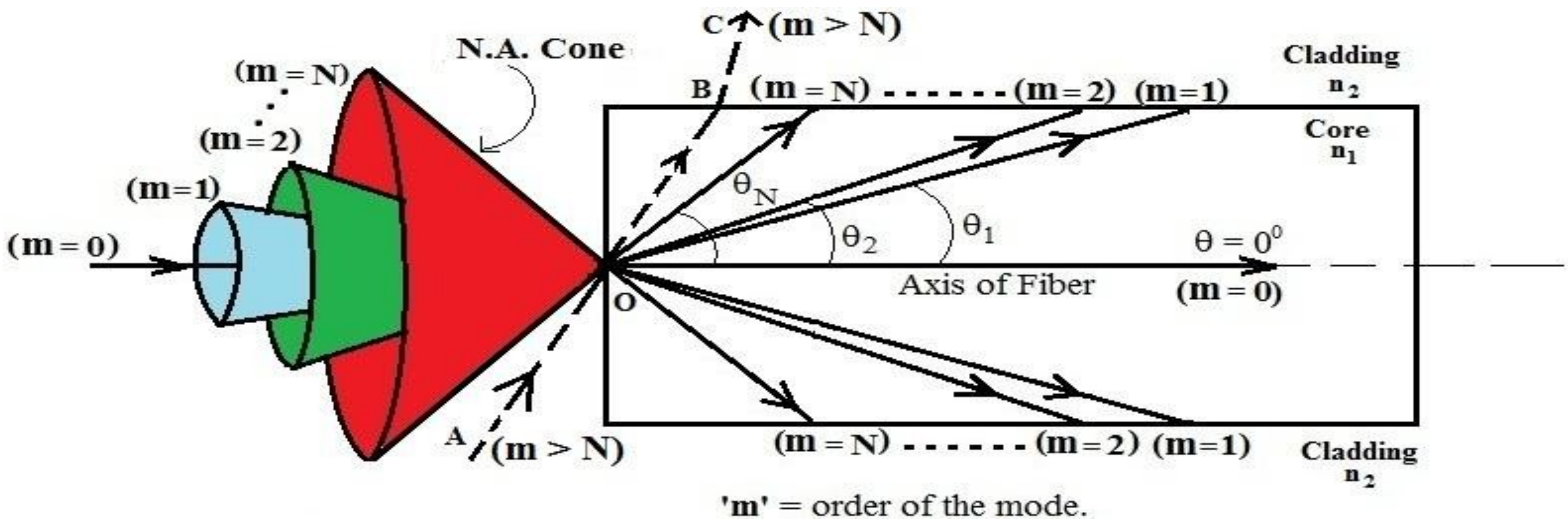
$$s_1 = d / \sin\theta$$

$$s_2 = AD\cos\theta = (\cos^2\theta - \sin^2\theta) d / \sin\theta$$

$$\frac{2\pi n_1}{\lambda}(s_1 - s_2) + 2\delta = 2\pi m$$

$$\frac{2\pi n_1 d \sin\theta}{\lambda} + \delta = \pi m$$

Annular rings of different modes



- The number of different values of 'm' signifies the number of different possible launching angles which can successfully propagate in the optical fiber core.

- The ray that is launched along the axis of the fiber propagates without any phase condition requirement to be satisfied and corresponds to the first mode of propagation, also called as the zero order mode of propagation. This is shown by m=0

- Only those modes would propagate along the fiber whose launching angles lie within the N.A. cone of the fiber.

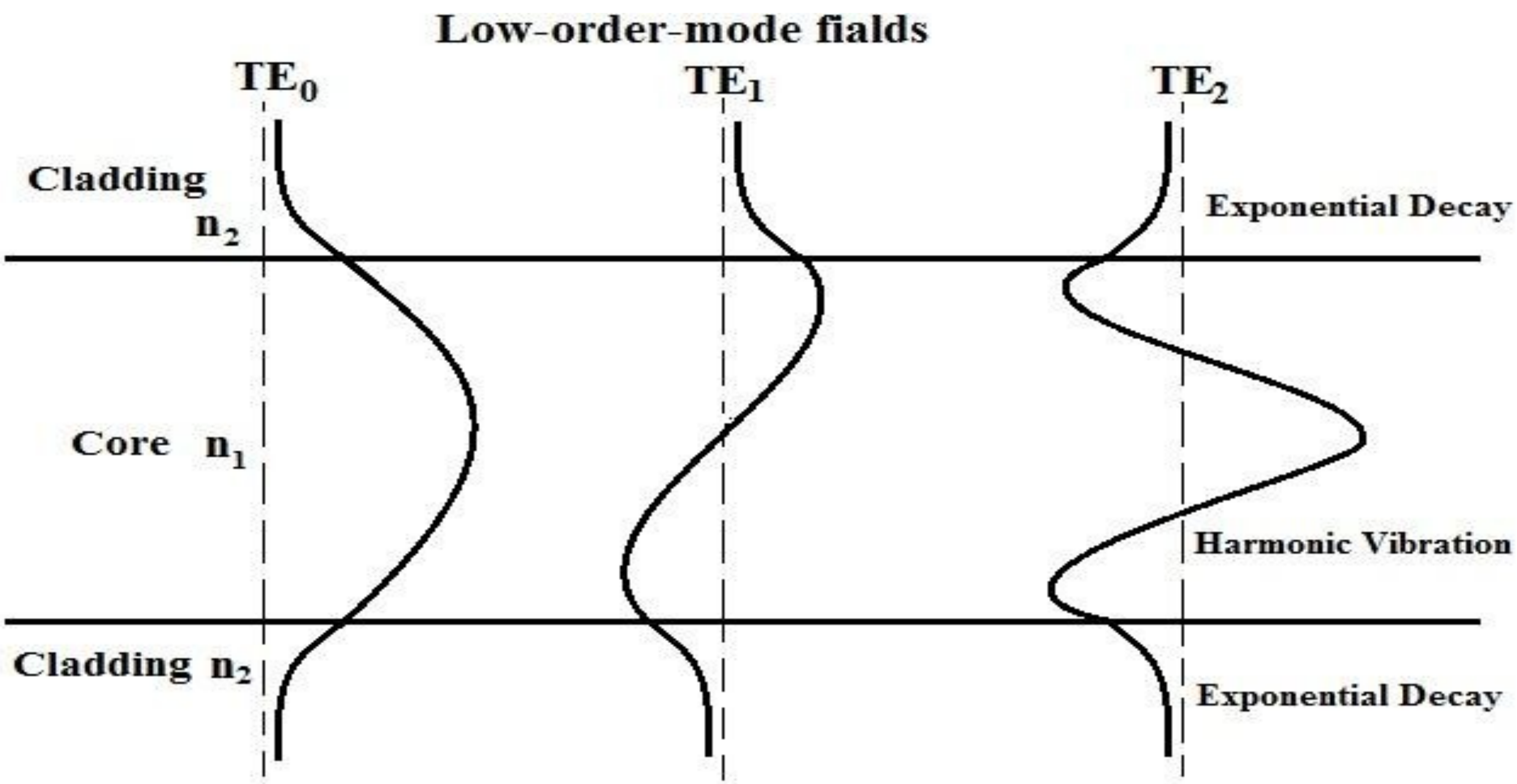
propagation of the rays in the optical fiber in relevance to wave theory of light.

- Treating light a transverse electromagnetic wave.

- when Meridional rays propagate along the fiber, their electric and magnetic fields of all the rays superimpose to result in electric and magnetic field distribution which may be either transverse electric (TE_x) or transverse magnetic (TM_x) in nature.

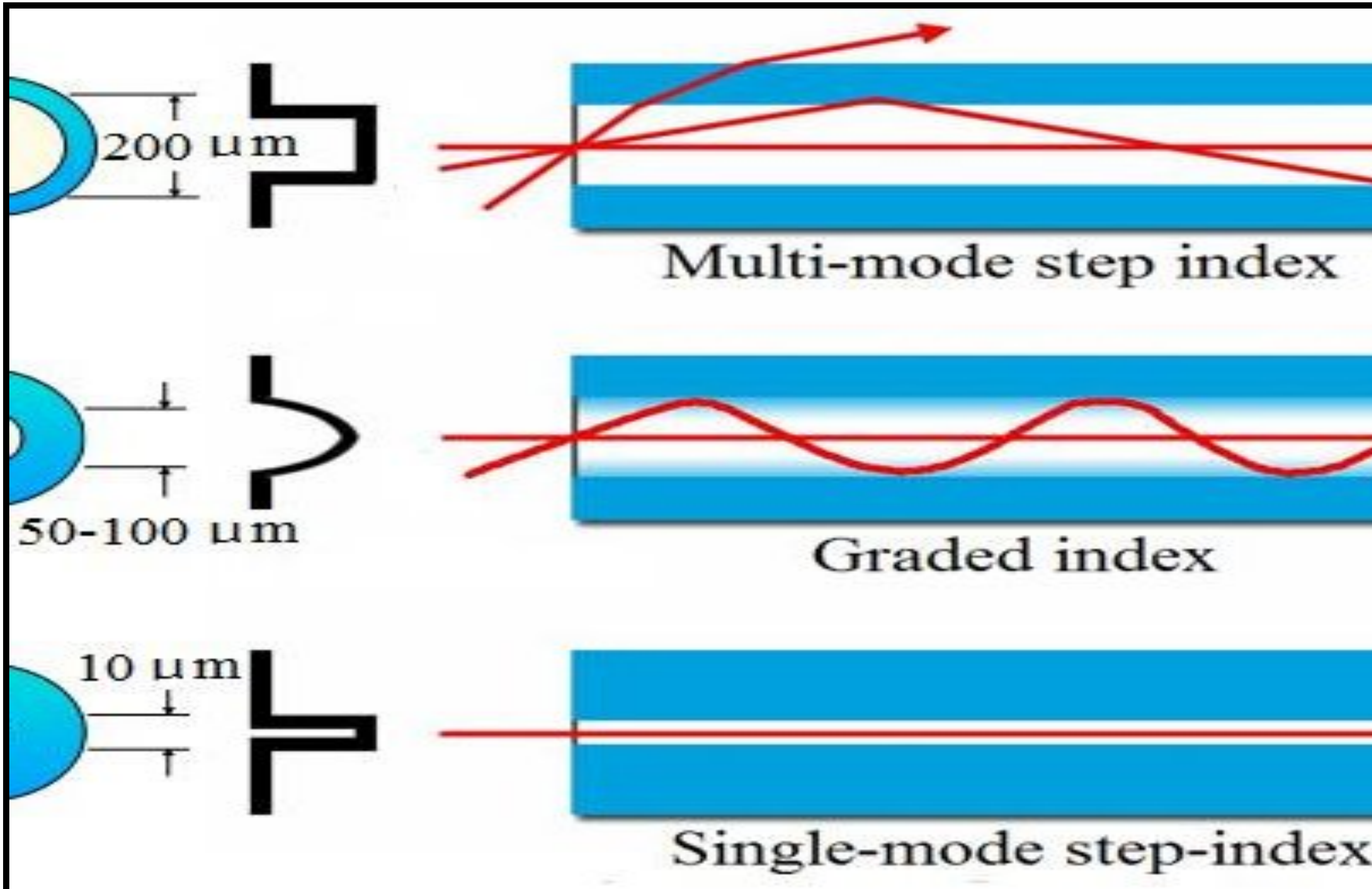
- The subscript ‘x’ denotes the definite number of maxima and minima in the resultant light intensity pattern.

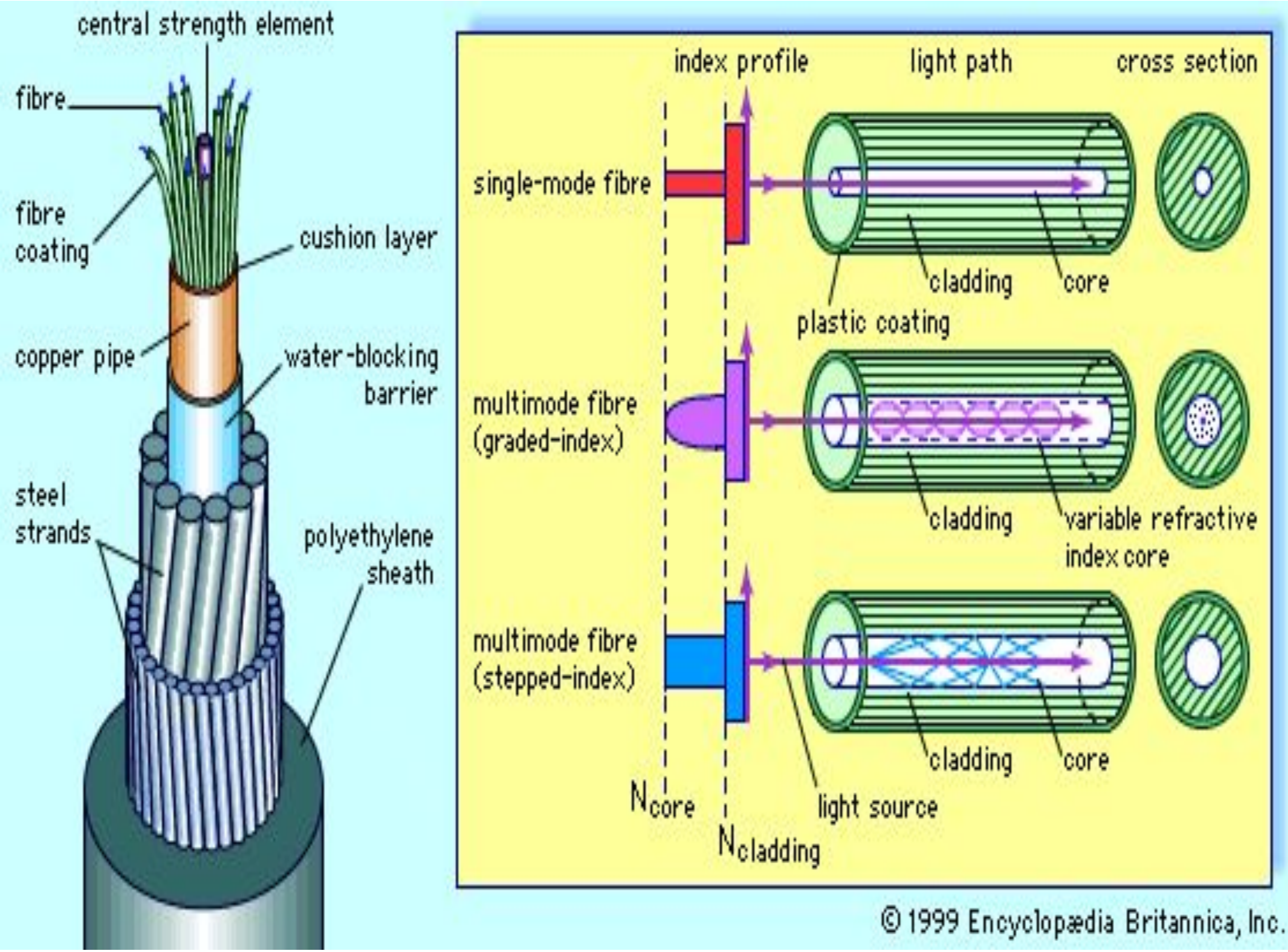
Different intensity patterns created by superposition of the wave-fronts of all the light rays for Transverse Electric modes that propagate in an optical fiber



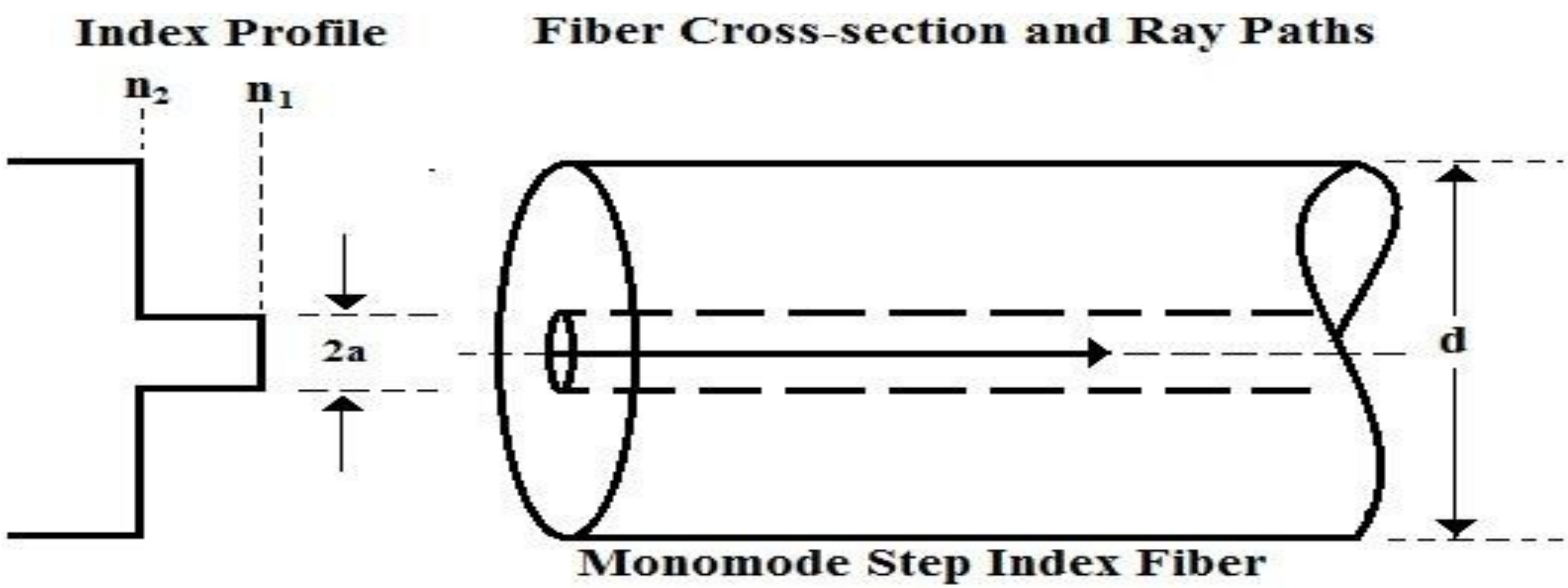
- The subscript ‘x’ denotes the definite number of maxima and minima in the resultant light intensity pattern.

Types of optical fiber



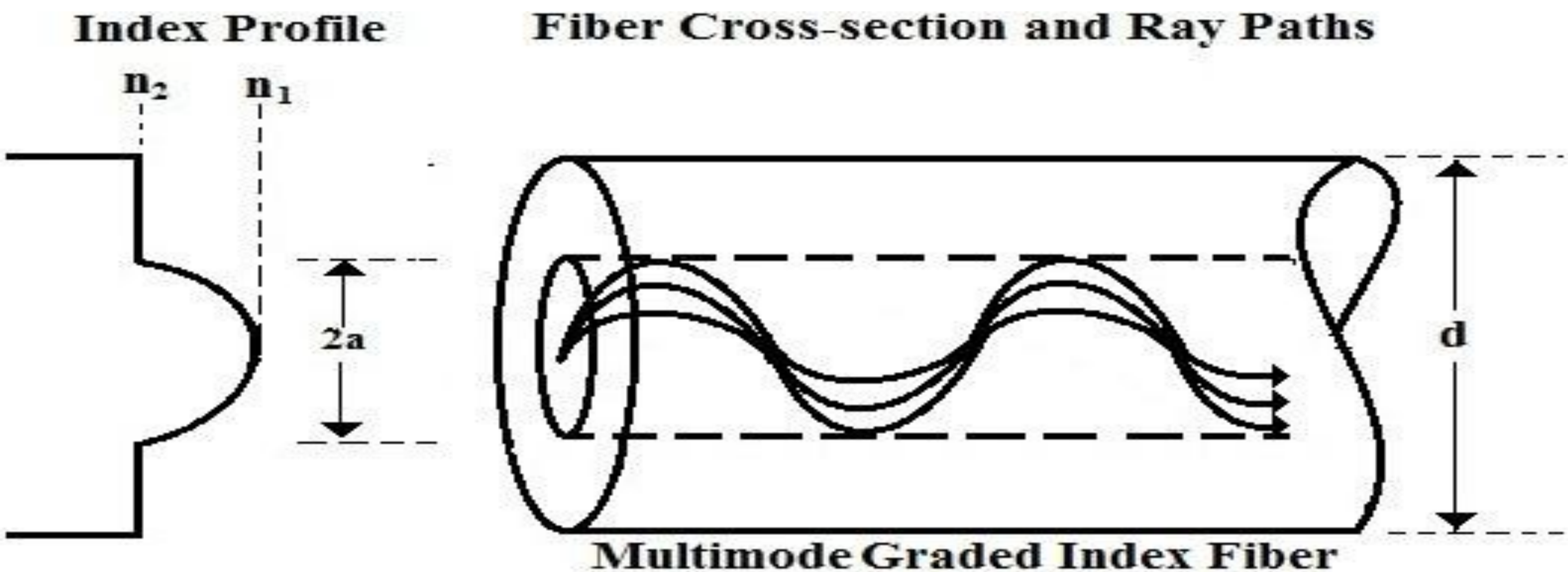

central strength element
fibre
fibre coating
cushion layer
copper pipe
water-blocking barrier
steel strands
polyethylene sheath
index profile
light path
cross section
single-mode fibre
cladding
core
plastic coating
multimode fibre (graded-index)
cladding
variable refractive index core
multimode fibre (stepped-index)
cladding
core
N_{core}
light source
$N_{cladding}$

Index Profile and Cross-sectional View of different types of fibers



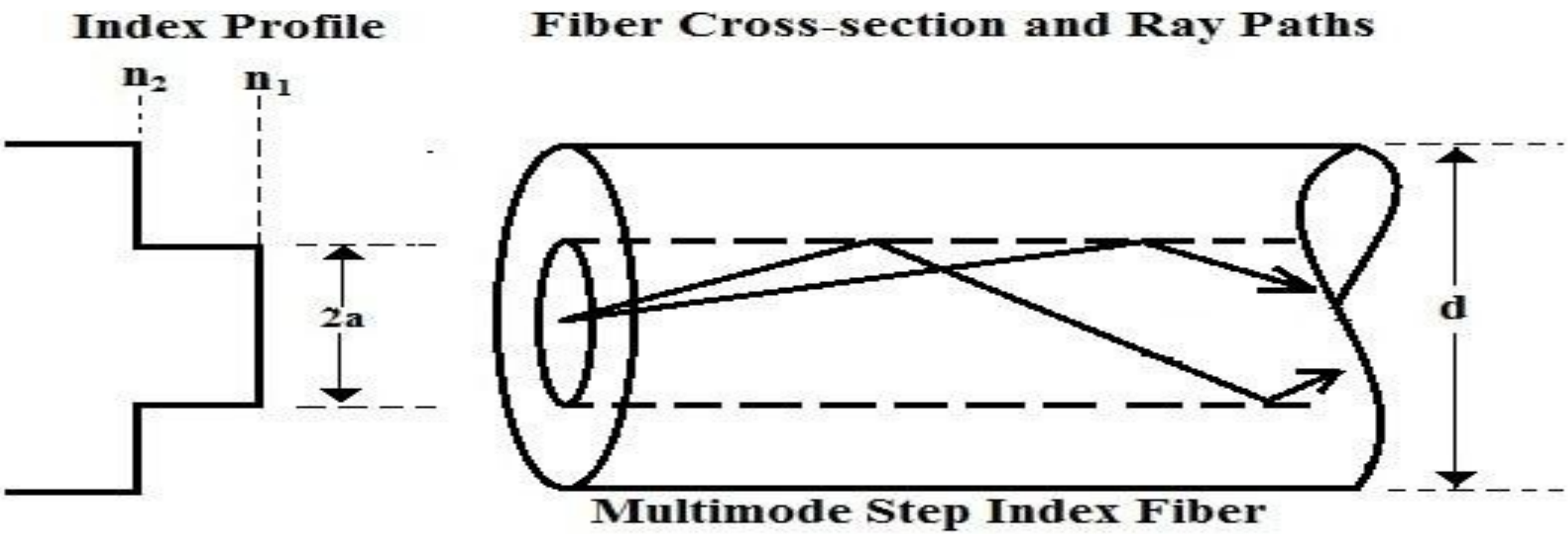
Core Diameter (2a) (µm)	Cladding Diameter (d) (µm)	Bandwidth
8-12	125	High

Index Profile and Cross-sectional View of different types of fibers



50-100	**125-140**	**Fare**

Index Profile and Cross-sectional View of different types of fibers



50-200	**125-400**	**Lowest**

Advantages of Fibers

- No electric current flows through the fiber, therefore, fibers have excellent rejection of radio-frequency interference (RFI) and of electromagnetic interference (EMI).
- We can pack numerous fibers together in a cable to transmit many channels of information along a single path without any cross talk
- Optic coupling eliminates the need for a common ground between a fiber transmitter and receiver.

Advantages of Fibers

- Fiber optic systems can easily be incorporated into systems originally designed for wire transmission.
- Fiber optic systems can even be made invisible to the user.
- Glass fibers can withstand extreme temperatures e.g. 800 Celsius leaves fiber unaffected.
- Security,Safety,no cross talk

Application of Fiber Optic Communications

Cable Television System (CATV)

- Cable television systems collect and distribute a large number of color channels.

- The distances covered range from a few tens of meters to several kilometers.

- CATV systems obtain their signals from various sources.

- These sources are satellite earth stations, microwave links, antennas picking up broadcasts from nearby transmitters, and local studios where programming originates.

- All these sources can be connected to the central distribution location (the CATV headend) by fibers.

Fiber System for Transmission of Digital Data

- Fiber system are particularly suited for transmission of digital data such as that generated by computes.
- Interconnections can be made between the central processing unit (CPU) and peripherals, between CPUs and memory, and between CPUs.
- Example: the connection of several hundred cathode ray-tube (CRT) terminals, located throughout a high-rise, to a processor located on one of the floors.

Military Applications

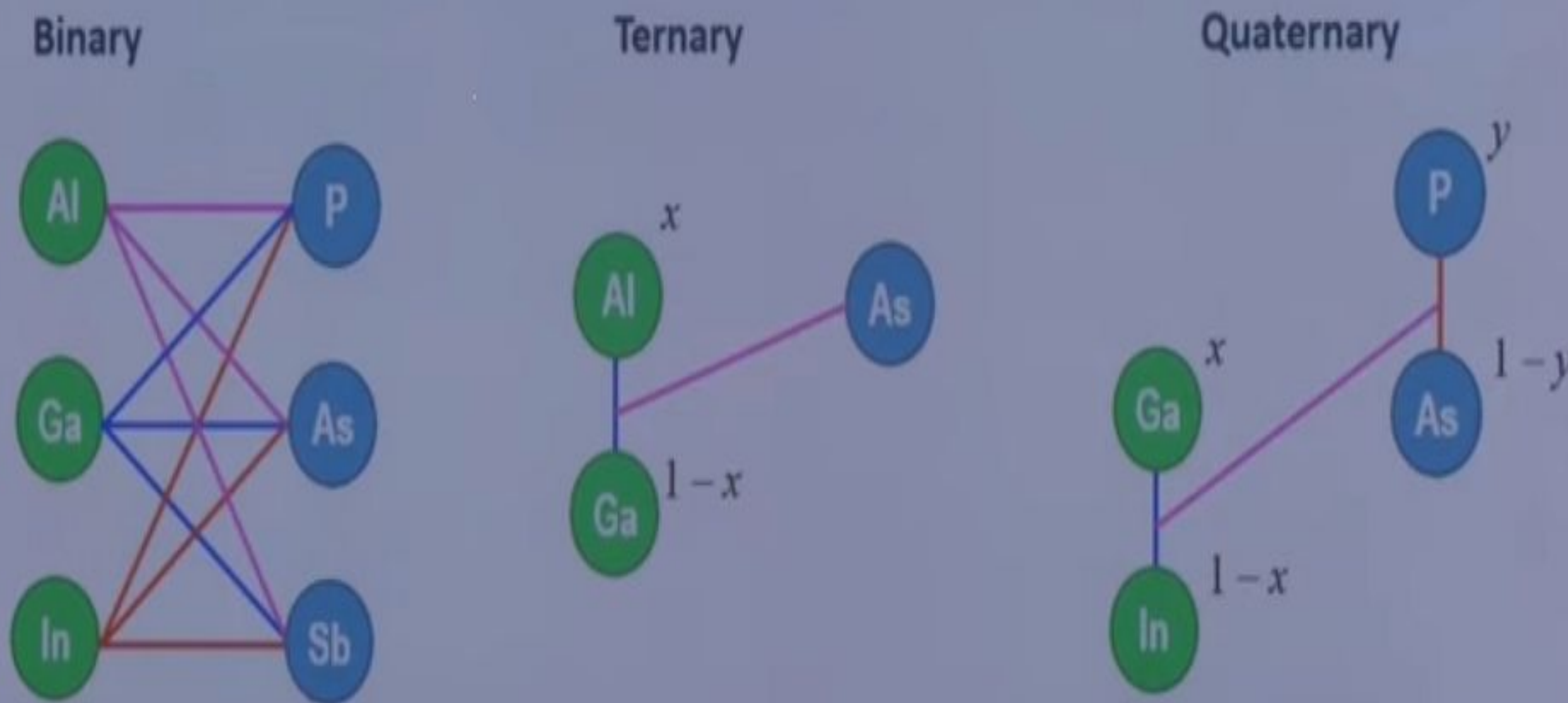
- Military applications include communications ,command and control links on ships and aircraft, data links for satellite earth stations, and transmission lines for tactical command-post communications.

- The important fiber characteristics are low weight ,small size ,EMI rejection, and no signal radiation.

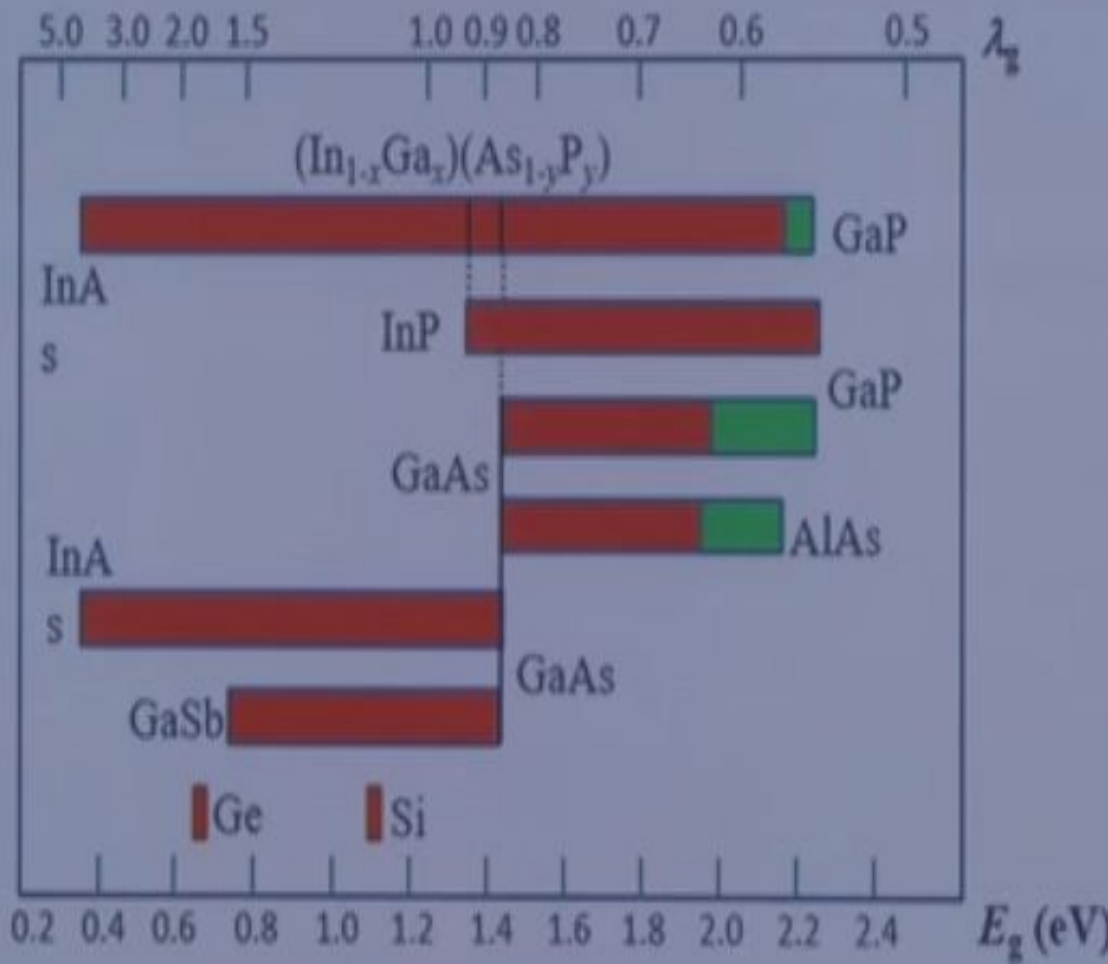
- On aircraft and ships the reduced shock, fire, and spark hazards are significant assets.

Unit- II
Optical sources

Semiconducting Materials



Bandgap wavelength $\boxed{\lambda_g(\mu m) = \frac{hc}{E_g}} = \frac{\frac{6.6\times10^{-34}}{1.6\times10^{-19}}(eVs)\times3\times10^{8}(ms^{-1})}{E_g} = \boxed{\frac{1.24}{E_g(eV)}}$



Some important semiconductors, their bandgap energies and bandgap wavelengths at room temperature

Material	E_g (eV)	λ_g (μm)	Type
Ge	0.66	1.88	Indirect
Si	1.11	1.15	Indirect
AlP	2.45	0.52	Indirect
AlAs	2.16	0.57	Indirect
AlSb	1.58	0.75	Indirect
GaP	2.26	0.55	Indirect
GaAs	1.42	0.87	Direct
GaSb	0.73	1.70	Direct
InP	1.35	0.92	Direct
InAs	0.36	3.50	Direct
InSb	0.17	7.30	Direct

Probability of occupancy of an energy state

At $T = 0$ K

- all electrons occupy the lowest possible energy state
- the valence band is completely filled
- the conduction band is completely empty

At elevated temperatures

- some electrons from valence band are thermally excited to conduction band
- some states in the conduction band are occupied
- correspondingly some empty states in the valence band are created

Probability of occupation of an energy state E is given by Fermi function

$$\boxed{f(E) = \frac{1}{1+\exp\left(\frac{E-E_f}{k_B T}\right)}}$$