INTRODUCTION TO FIBRE OPTICS: PART-I

CONTENTS

Introduction

- 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.
- Optical fibers are widely used in Fiber-optic communications, which permits transmission over longer distances and at higher bandwidths (data rates) than other forms of communication.
- Fibers are used instead of metal wires because signals travel along them with less loss and are also immune to electromagnetic interference.

Evolution of fiber Optic system

First generation

- The first generation of light wave systems uses GaAs semiconductor laser and operating region was near 0.8 μm. Other specifications of this generation are as under:
- i) Bit rate : 45 Mb/s
- ii) Repeater spacing : 10 km

Second generation

i) Bit rate: 100 Mb/s to 1.7 Gb/s ii) Repeater spacing: 50 km

iii) Operation wavelength: 1.3 μm iv) Semiconductor: In GaAsP

Third generation

i) Bit rate : 10 Gb/s

ii) Repeater spacing: 100 km

iii) Operating wavelength: 1.55 μm

Evolution of fiber Optic system

Fourth generation

- Fourth generation uses WDM technique. i) Bit rate: 10 Tb/s
- ii) Repeater spacing: > 10,000 km
- Iii) Operating wavelength: 1.45 to 1.62 μm

Fifth generation

- Fifth generation uses Roman amplification technique and optical solitiors. i) Bit rate: 40 - 160 Gb/s
- ii) Repeater spacing: 24000 km - 35000 km iii) Operating wavelength: 1.53 to 1.57 μm

Element of an Optical Fiber Transmission link

Basic block diagram of optical fiber communication system consists of following important blocks.

1. Transmitter
2. Information channel
3. Receiver.

Block diagram of OFC system

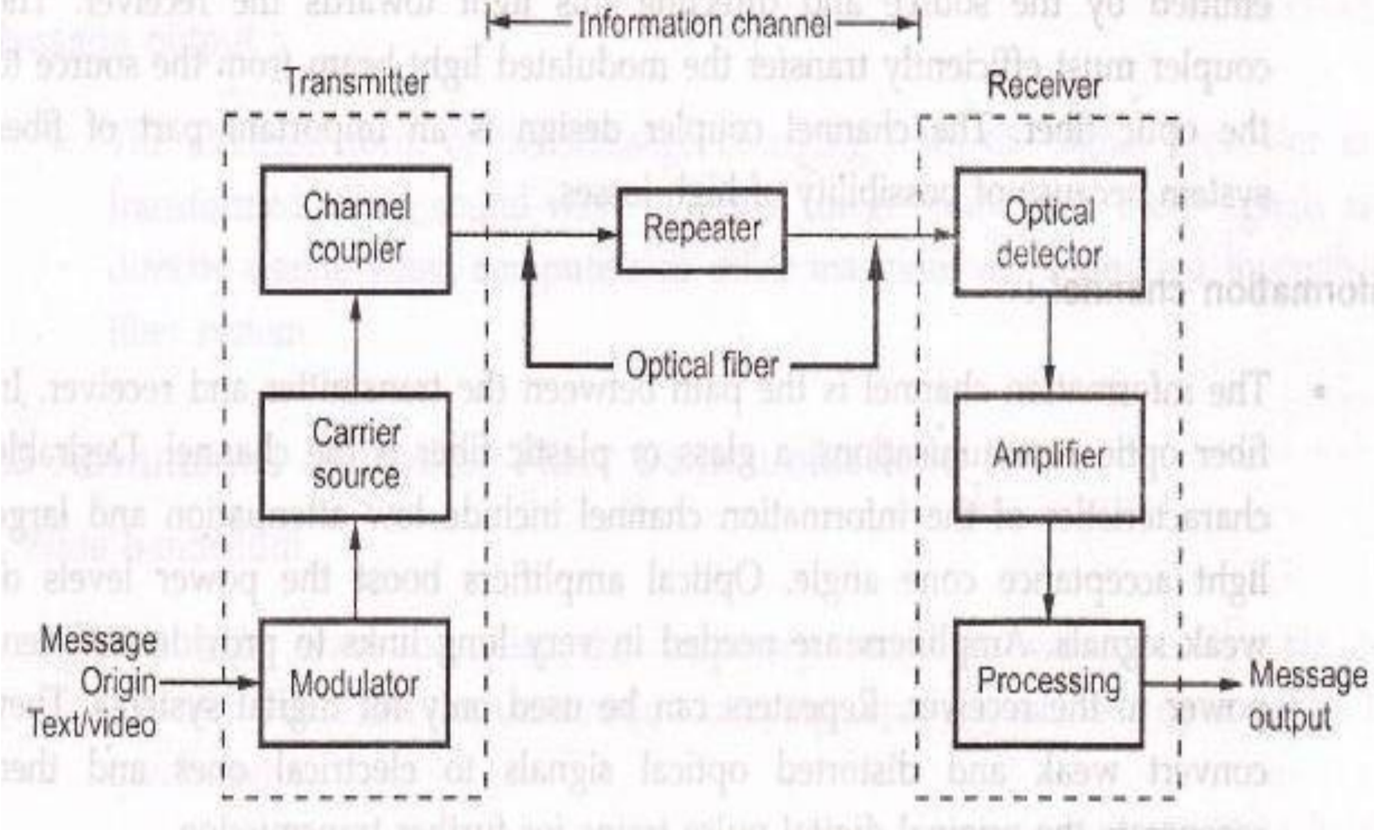


Fig. 1.2.1 Block diagram of OFC systems

- The light beam pulses are then fed into a fiber – optic cable where they are transmitted over long distances.
- At the receiving end, a light sensitive device known as a photocell or light detector is used to detect the light pulses.
- This photocell or photo detector converts the light pulses into an electrical signal.
- The electrical pulses are amplified and reshaped back into digital form.

Fiber optic Cable

Fiber Optic Cable consists of four parts.

- Core
- Cladding
- Buffer
- Jacket

Core. The core of a fiber cable is a cylinder of plastic that runs all along the fiber cable's length, and offers protection by cladding. The diameter of the core depends on the application used. Due to internal reflection, the light travelling within the core reflects from the core, the cladding boundary. The core cross section needs to be a circular one for most of the applications.

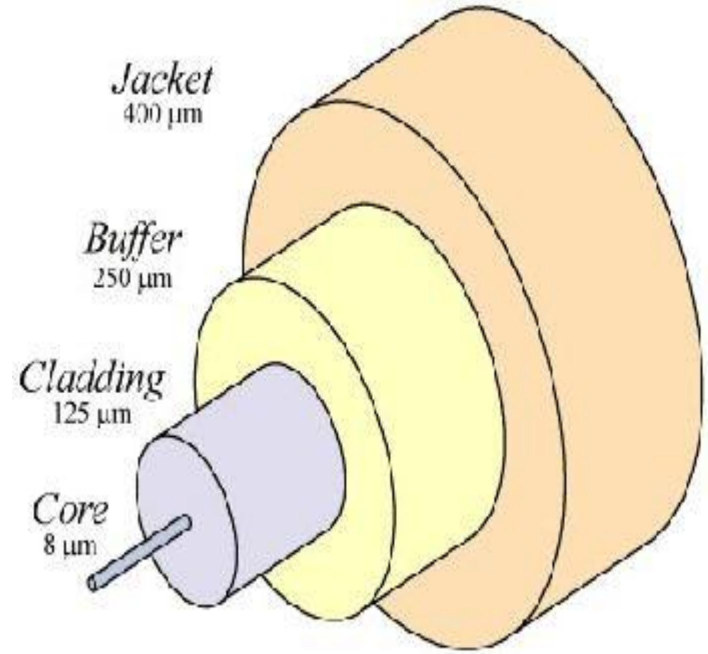
Cladding

Cladding is an outer optical material that 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.

Fiber optic Cable

Buffer

- The main function of the buffer is 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.

- Both the light sources at the sending end and the light detectors on the receiving end must be capable of operating at the same data rate.
- The circuitry that drives the light source and the circuitry that amplifies and processes the detected light must both have suitable high-frequency response.
- The fiber itself must not distort the high-speed light pulses used in the data transmission.
- They are fed to a decoder, such as a Digital – to – Analog converter (D/A), where the original voice or video is recovered.

- In very long transmission systems, repeater units must be used along the way.
- Since the light is greatly attenuated when it travels over long distances, at some point it may be too weak to be received reliably.
- To overcome this problem, special relay stations are used to pick up light beam, convert it back into electrical pulses that are amplified and then retransmit the pulses on another beam.
- Several stages of repeaters may be needed over very long distances.
- But despite the attenuation problem, the loss is less than the loss that occurs with the electric cables.

Characteristics of fiber

1)Wider bandwidth: The optical carrier frequency is in the range 10^13 Hz to 10^15Hz.

2)Low transmission loss: The fibers having a transmission loss of 0.002dB/km.

3)Dielectric waveguide: Optical fibers are made from silica which is an electrical insulator. Therefore they do not pickup any electromagnetic wave or any high current lightning.

4)Signal security: The transmitted signal through the fibers does not radiate. Further the signal cannot be tapped from a Fiber in an easy manner.

5)Small size and weight: Fiber optic cables are developed with small radii, and they are flexible, compact and lightweight. The fiber cables can be bent or twisted without damage.

Operation of fiber

- A hair-thin Fiber consist of two concentric layers of high-purity silica glass the core and the cladding, which are enclosed by a protective sheath.
- Core and cladding have different refractive indices, with the core having a refractive index, n1, which is slightly higher than that of the cladding, n2.
- It is this difference in refractive indices that enables the Fiber to guide the light. Because of this guiding property, the Fiber is also referred to as an “optical waveguide.”

Advatages of optical fiber

1)WAVELENGTH : It is a characteristic of light that is emitted from the light source and is measures in nanometres (nm).

2)FREQUENCY : It is number of pulse per second emitted from a light source. Frequency is measured in units of hertz (Hz). In terms of optical pulse 1Hz = 1 pulse/ sec.

3)WINDOWS :A narrow window is defined as the range of wavelengths at which a fibre best operates.

4)ATTENUATION: Attenuation in optical fiber is caused by intrinsic factors, primarily scattering and absorption, and by extrinsic factors, including stress from the manufacturing process, the environment, and physical bending.

5)DISPERSION : Dispersion is the spreading of light pulse as its travels down the length of an optical fibre . Dispersion limits the bandwidth or information carrying capacity of a fibre.

Disadvantages of optical fiber

- 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

Ray Optics

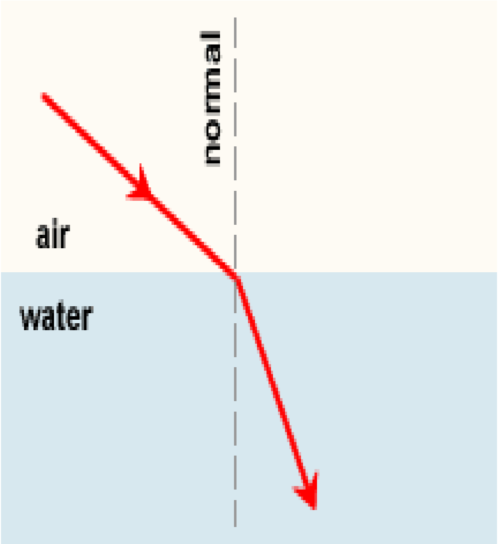
Basic laws of ray theory/geometric optics

- The basic laws of ray theory are quite self-explanatory
- In a homogeneous medium, light rays are straight lines.Light may be absorbed or reflected.
- Reflected ray lies in the plane of incidence and angle of incidence will be equal to the angle of reflection.
- At the boundary between two media of different refractive indices, the refracted ray will lie in the plane of incidence. Snell’s Law will give the relationship between the angles of incidence and refraction.

Ray Optics

Refraction of light

- As a light ray passes from one transparent medium to another, it changes direction; this phenomenon is called refraction of light. How much that light ray changes its direction depends on the refractive index of the mediums.



Ray Optics

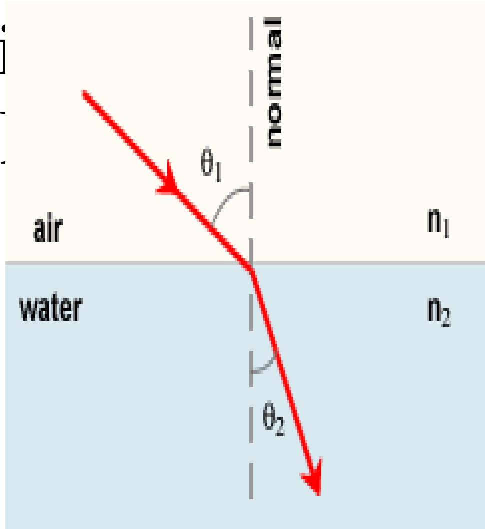
Refractive Index

- Refractive index is the speed of light in a vacuum (abbreviated **c**, **c**=299,792.458km/second) divided by the speed of light in a material (abbreviated **v**). Refractive index measures how much a material refracts light. Refractive index of a material, abbreviated as **n**, is defined as
- **n=c/v**

Ray Optics
Snells Law

- When light passes from one transparent material to another, i bends according to Snell's law whicl is defined as:

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



where:

n_1 is the refractive index of the medium the light is leaving

$\boldsymbol{\theta_1}$ is the incident angle between the light beam and the normal (normal is 90° to the interface between two materials)

$\boldsymbol{n_2}$ is the refractive index of the material the light is entering

$\boldsymbol{\theta_2}$ is the refractive angle between the light ray and the normal

Ray Optics
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 $\boldsymbol{\theta_2}$. This gives $\boldsymbol{\theta_1}$:

Since

$$\boldsymbol{\theta_2} = 90°$$

So

$$\mathbf{sin(\boldsymbol{\theta_2})} = 1$$

Then

$$\boldsymbol{\theta_c = \theta_1 = \mathrm{arcsin}(n_2/n_1)}$$

Numerical Aperture (NA) For step-index multimode fiber, the acceptance angle is determined only by the indices of refraction:

$$NA = n \sin\theta_{max} = \sqrt{n_f^{\,2} - n_c^{\,2}}$$

Where

n is the refractive index of the medium light is traveling before entering the fiber

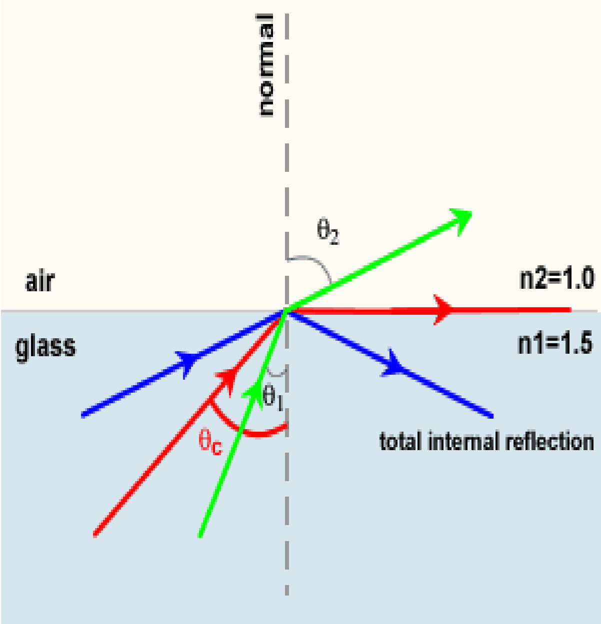
$\boldsymbol{n_f}$ is the refractive index of the fiber core

$\boldsymbol{n_c}$ is the refractive index of the cladding

Ray Optics

Total internal reflection

- If the light hits the interface at any angle larger than this critical angle, it will not pass through to the second medium at all. Instead, all of it will be reflected back into the first medium, a process known as **total internal reflection**.



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.

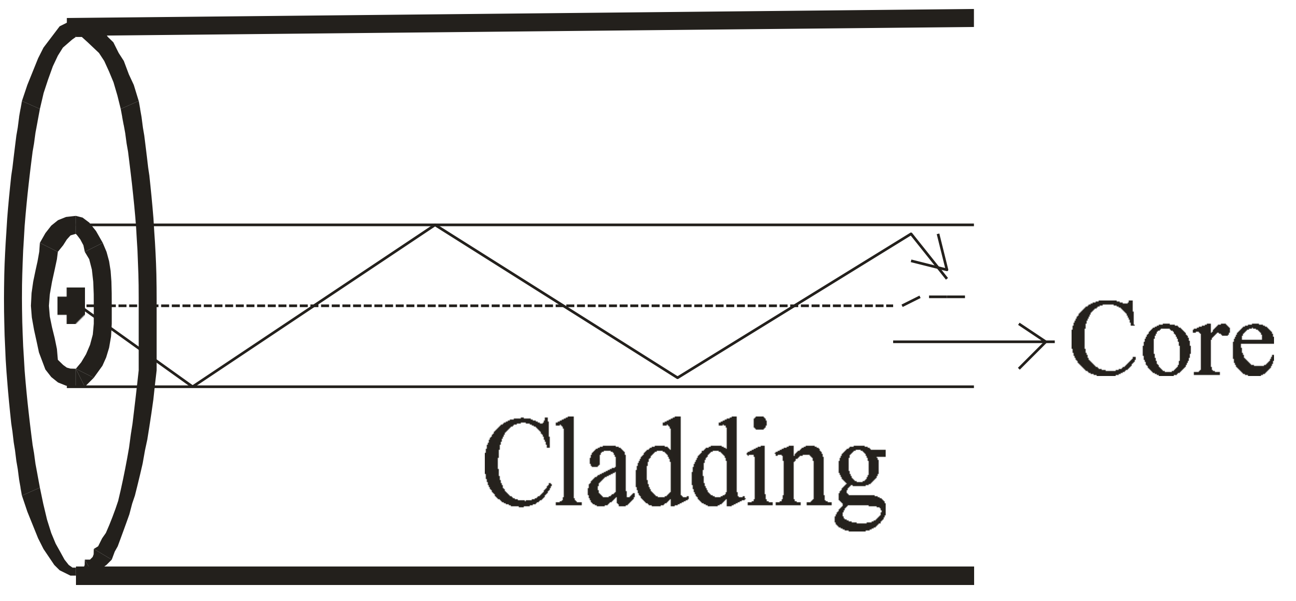
Based on the number of modes that propagates through the optical fiber, they are classified as:

- Single mode fibers
- Multi mode fibers

Single mode fibers

- In a fiber, if 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 $V \leq 2.405$.
- Here, n_1 = refractive index of the core; a = radius of the core; λ = wavelength of the light propagating through the fiber; Δ = relative refractive indices difference.

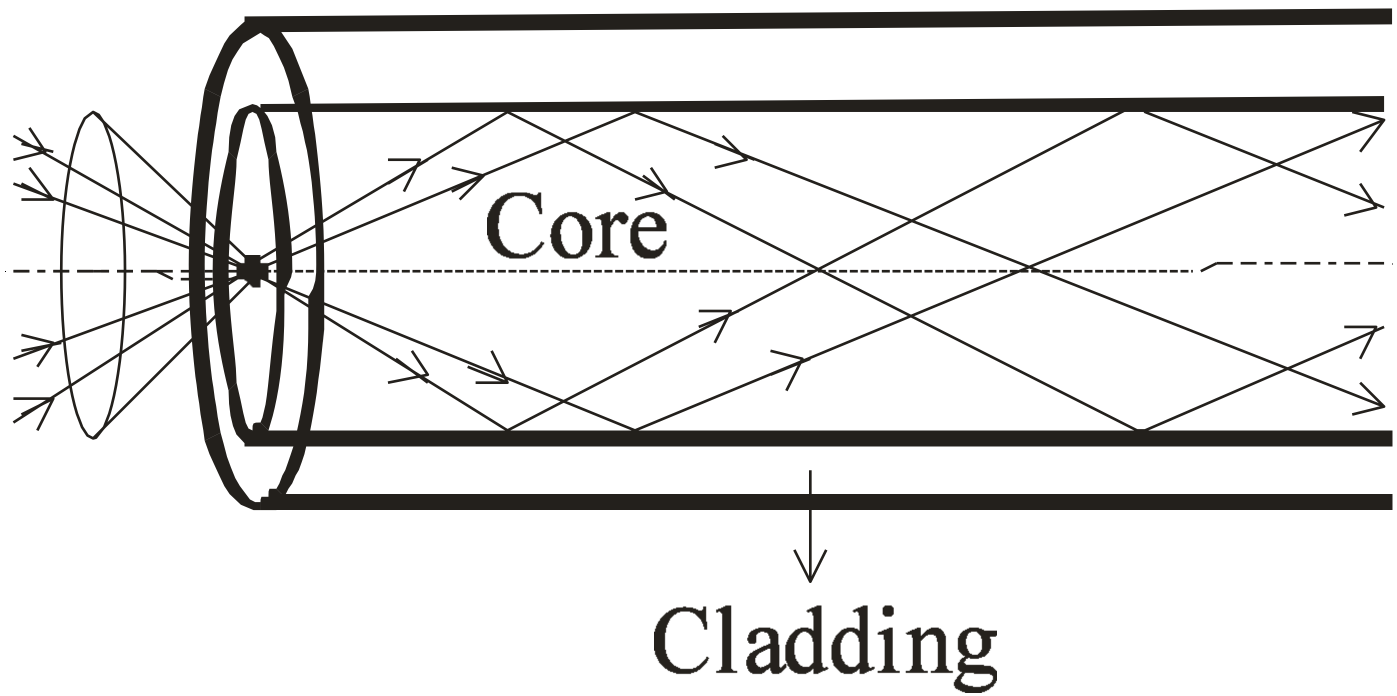
Single mode fibers



Single mode fibers

- 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

Multimode fibers



Multi mode fibers

- 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.

Some of the basic properties of multimode optical fibers are listed below :

- More than one path is available
- V-number is greater than 2.405

Types of fibers based on Refractive Index Profile

Based on the refractive index profile of the core and cladding, the optical fibers are classified into two types:

- Step index fiber
- Graded index fiber

Step index fiber

- In a step index fiber, the refractive index changes in a step fashion, from the centre of the fiber, the core, to the outer shell, the cladding.
- It is high in the core and lower in the cladding. The light in the fiber propagates by bouncing back and forth from core-cladding interface.
- The step index fibers propagate both single and multimode signals within the fiber core.
- The light rays propagating through it are in the form of meridinal rays which will cross the fiber core axis during every reflection at the core – cladding boundary and are propagating in a zig – zag manner.

Step index fiber

- With careful choice of material, dimensions and λ, the total dispersion can be made extremely small, less than 0.1 ps /(km × nm), making this fiber suitable for use with high data rates.
- In a single-mode fiber, a part of the light propagates in the cladding.
- The cladding is thick and has low loss.
- Typically, for a core diameter of 10 μm, the cladding diameter is about 120 μm.
- Handling and manufacturing of single mode step index fiber is more difficult.

Step index multimode fibers

- A multimode step index fiber is shown.
- In such fibers light propagates in many modes.
- The total number of modes *MN* increases with increase in the numerical aperture.
- For a larger number of modes, *MN* can be approximated by

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

Step index multimode fibers

where *d* = diameter of the core of the fiber and *V* = V – number or normalized frequency.
The normalized frequency *V* is a relation among the fiber size, the refractive indices and the wavelength. *V* is the normalized frequency or simply the *V* number and is given by

$$V = \left(\frac{2\pi a}{\lambda}\right) \times \mathrm{N.A} = \left(\frac{2\pi a}{\lambda}\right) \times n_1 \times (2\Delta)^{\frac{1}{2}}$$

where *a* is the fiber core radius, λ is the operating wavelength, *n1* the core refractive index and Δ the relative refractive index difference

Graded index fiber

- A graded index fiber is shown in Fig.3.27. Here, the refractive index *n* in the core varies as we move away from the centre.
- 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 refractive index (*n*) profile with reference to the radial distance (*r*) from the fiber axis is given as:

Graded index fiber

when $r = 0, n(r) = n1$

$r < a, n(r) =$

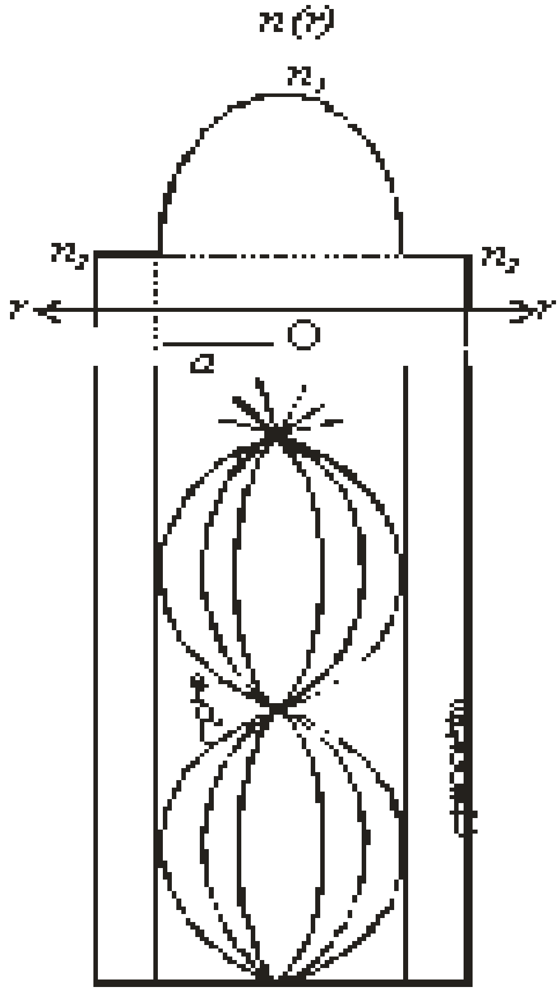
$$n_1 \left[1 - \left(2\Delta \left[\frac{r}{a} \right]^2 \right) \right]^{\frac{1}{2}}$$

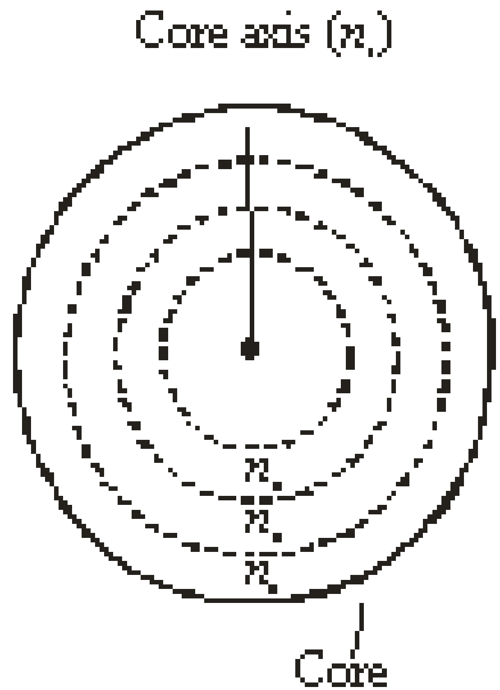
$r \geq a,\ n(r) = n2\ =$

$$n_1(1-2\Delta)^{\frac{1}{2}}$$

At the fiber centre we have *n1*; at the cladding we have *n2*; and in between we have *n(r)*, where n is the function of the particular radius as shown in Fig. simulates the change in *n* in a stepwise manner.

Graded index fiber





Graded index fiber

- Each dashed circle represents a different refractive index, decreasing as we move away from the fiber center.
- A ray incident on these boundaries between $n_a - n_b$, $n_b - n_c$ etc., is refracted.
- Eventually at n_2 the ray is turned around and totally reflected.
- This continuous refraction yields the ray tracings as shown in Fig.

Graded index fiber

- 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.

Reference book

Introduction to fiber optics, AK Ghatak & K Thyagarajan, Cambridge University Press (1998)