overview of optical fiber communication:

Historial Development:

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 system used most extentively 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 data transmission. The greater the carrier frequency, larger the available bandwidth and information carrying capacity.

First Generation:

The first generation system uses GaAs Semiconductor laser and operating region was near 0.8 um other specifications of this generation are:

i) Bit rate : 45 Mb/s

(ii) Repeater Spacing :- 10Km

Second Generation:

i) Bit rate : 100 Mb/s

(ii) Repeater spacing : 50km

(iii) wavelength : 1.3 um

THird Generation:

(i) Bit rate : 10 Gb/s

(ii) Repeater Spacing : 100 Km

(iii) wavelength : 1.55 um

Fourth Generation:

Fourth Generation uses WDM techniques

(i) Bit rate : 100 Gb/s (ii) Repeater Spacing : 10,000 km

(iii) $\lambda = 1.55\ \mu m$

Fifth Generation:

Fifth Generation uses

(i) Bit rate : 10^6 Gb/s (ii) Repeater spacing : upto 35,000k

Need of fiber optic Communication:

(i) In long haul transmission system, there is need of low loss transmission medium.

(ii) There is need of compact and least weight transmitters and receivers

(iii) There is need of increased span of transmission

(iv) There is need of increased bit rate - distance product

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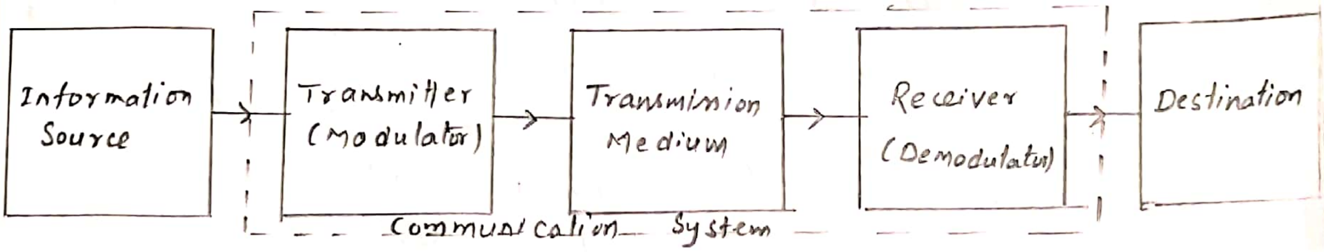
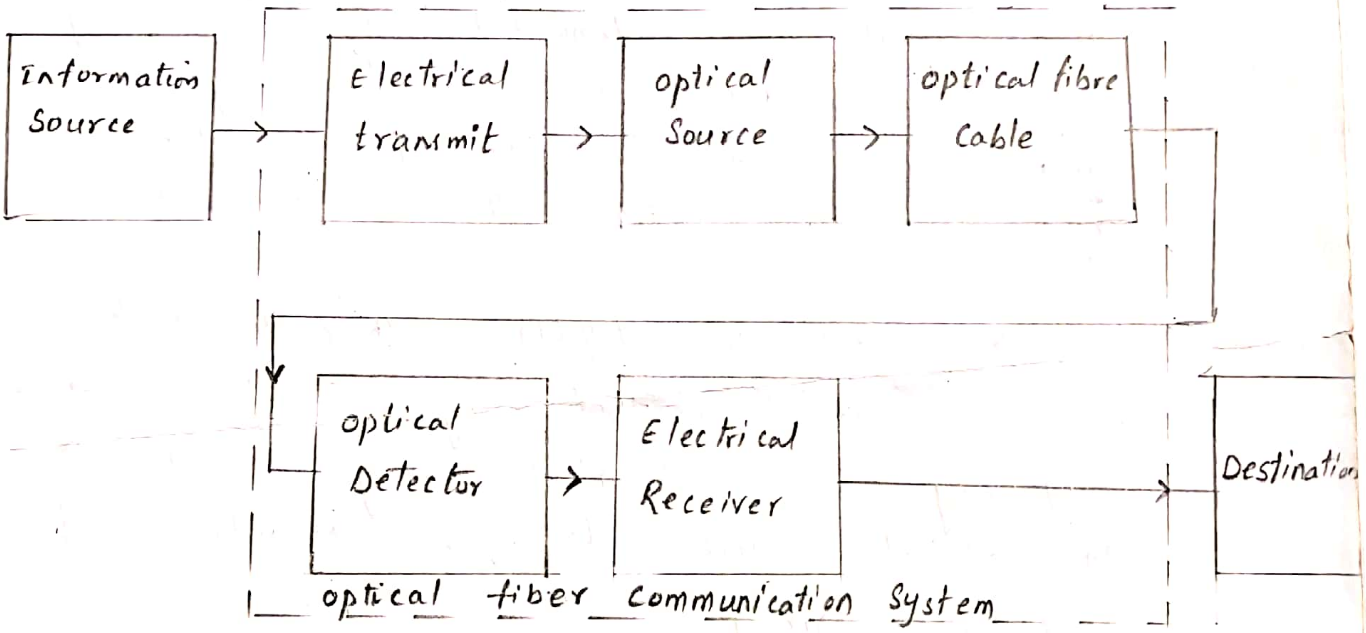
THE GENERAL SYSTEM



(a) The general communication system



(b) The optical fiber communication system

The communication system consist of transmitter linked to information source, the transmision medium and a receiver at the destination point.

* In electrical communications the information source provides an electrical signal, usually derived from a message signal which is not electrical (Eg: sound), to a transmitter comprising electrical and electronic components which converts the signal into a suitable form for propagation over the transmission medium. This is often achieved

by modulating a carrier.

* The transmission medium can consists of pair of wires co-axial cable (or) radio link through free space down which the signal is transmitted to the receiver, where it is transformed into the original electrical information signal before being passed to the destination.

* It must be noted that in any transmission medium the signal is attenuated and is subjected to degradation due to contamination by random signals and noise, as well as possible distortion imposed by mechanism within the medium itself.

* In the case of fig (b), the information source provides an electrical signal to a transmitter comprising an electrical stage which drives an optical source to give modulation of the lightwave carrier

* The optical source which provides the electrical-optical conversion may be either a semiconductor Laser (or) LED.

The tr

* The transmission medium consists of an optical fiber cable and the receiver consists of an optical detector which drives further electrical stage and hence provides demodulation of the optical carrier. photodiodes (p-n, p-i-n or avalanche) and in some instances, phototransistors and photoconductors are utilised for the ~~utilized~~ detection of the optical signal and optical electrical conversion

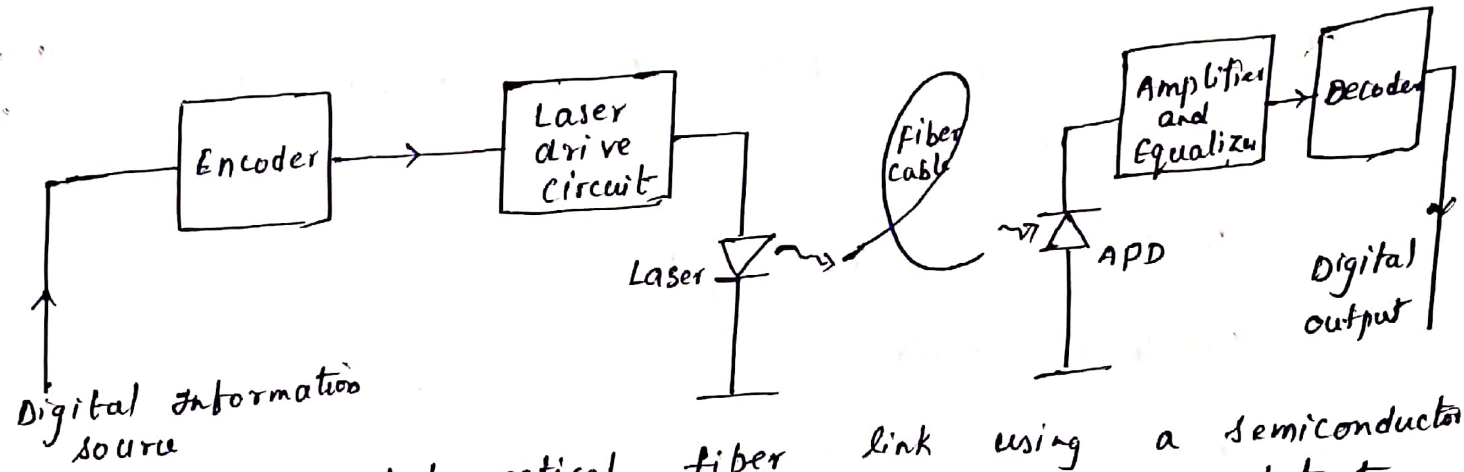


Fig. c A digital optical fiber link using a semiconductor laser source and avalanche photodiode detector

* Initially, the input digital signal from the information source is suitably encoded for optical transmission.

* The Laser drive circuit directly modulates the intensity of the semiconductor laser with the encoded digital signal. Hence, a digital optical signal is launched into the optical fiber cable.

* The APD detector is followed by a front-end amplifier and equalizer (or) filter to provide gain as well as linear signal processing and noise bandwidth reduction. Finally signal obtained to give the original digital information.

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Advantages of optical fiber communication:

(a) Large b.w

(b) Small size and weight

(c) Electrical isolation

(d) Immunity to interface and crosstalk

(e) Signal security

(f) Low transmission loss

(g) Ruggedness and flexibility

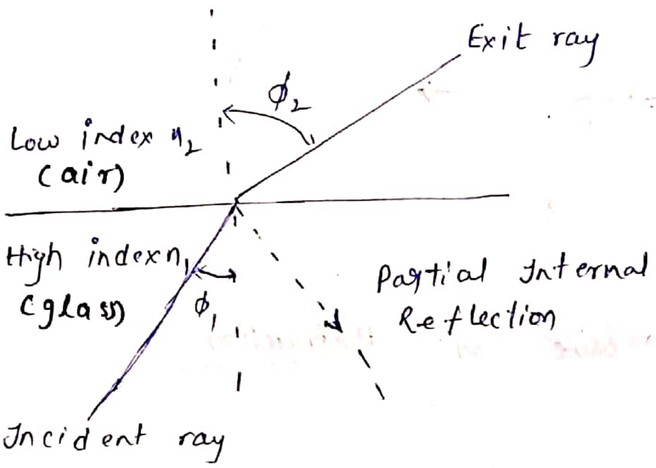
(h) System reliability and ease of maintenance

(i) Low cost

Ray Theory Transmission:

The propagation of light in optical fiber uses the ray theory model. A ray of light travels more slowly in an optically dense medium than in one that is less dense.

When a ray is incident one the interface between two dielectric of different refractive indices, refraction occurs is shown in below fig.



(a) Refraction

Ray approaching the interface is propagating in a dielectric of refractive index n_1 and at angle ϕ_1. at the dielectric on the other side of a interface has refractive index n_2 and angle ϕ_2.

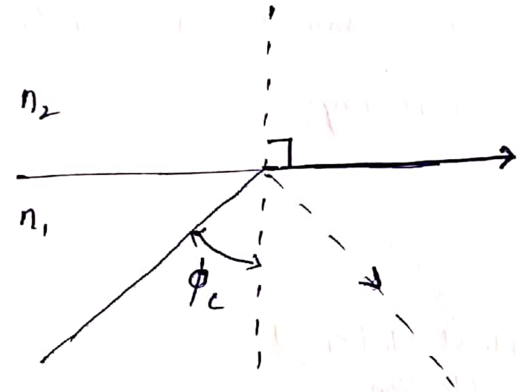
The angle of Incidence ϕ_1 and refraction ϕ_2 are related to each other and refractive Indices of the dielectrics by Snell's law of refraction

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

$$\frac{\sin\phi_1}{\sin\phi_2} = \frac{n_2}{n_1}$$

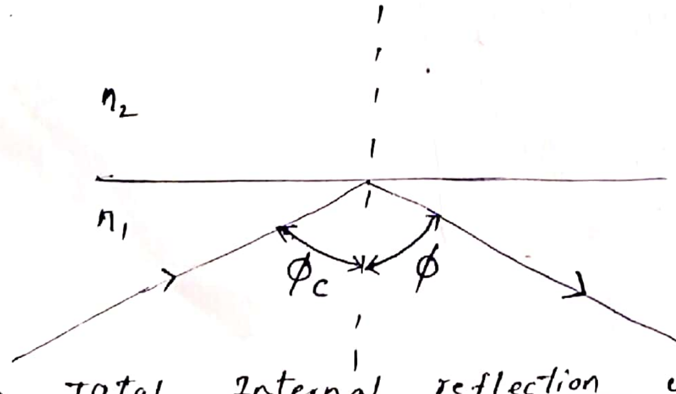
As n_1 is greater than n_2, the angle of refraction is always greater than the angle of incidence. Thus when the angle of refraction is 90° and the refracted ray emerges parallel to the interface between the dielectrics, the angle of incidence must be less than 90°. This is the limiting case of refraction and angle of incidence is known as critical angle.

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



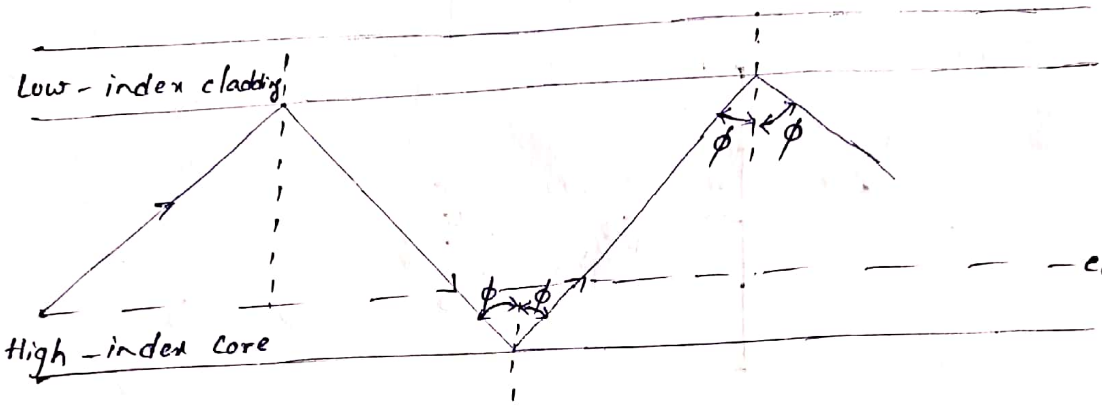
(b) Limiting case of Refraction

At angles of incidence greater than the critical angle the light is reflected back into the originating dielectric medium with high efficiency. From below fig. c the total internal reflection occurs at the interface between two dielectrics of different refractive indices when light is incident on the dielectric of lower index from the dielectric of higher index, and the angle of incidence of the ray exceeds the critical angle.



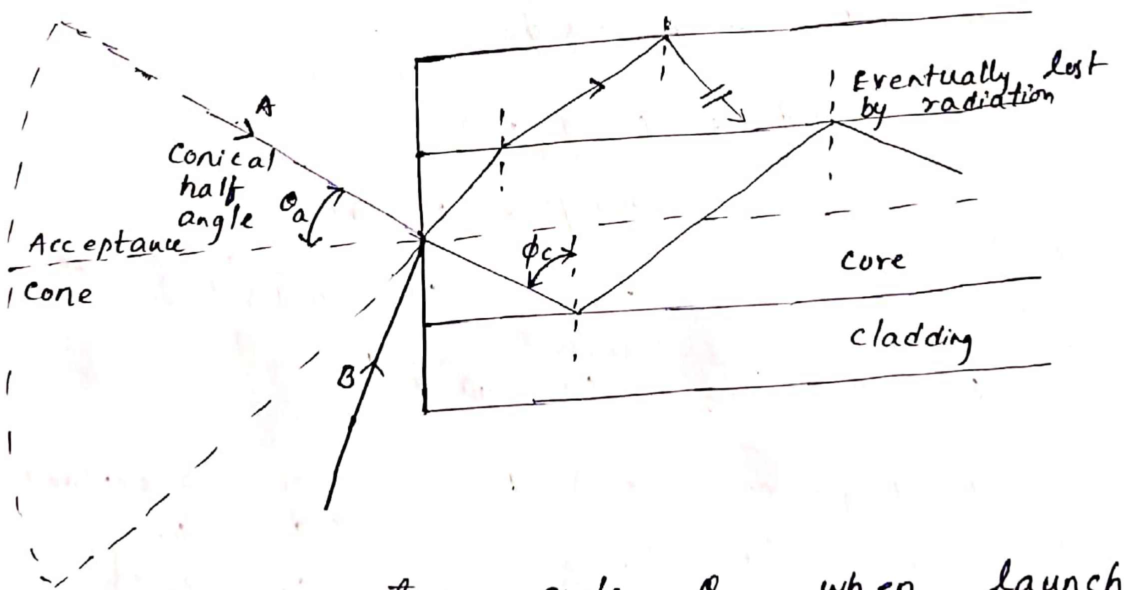
(C) Total Internal reflection where $\phi > \phi_c$

The transmission of a light ray in an optical fiber via a series of total internal reflections at the interface of silica core and the slightly refractive index silica cladding.



Acceptance angle :

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



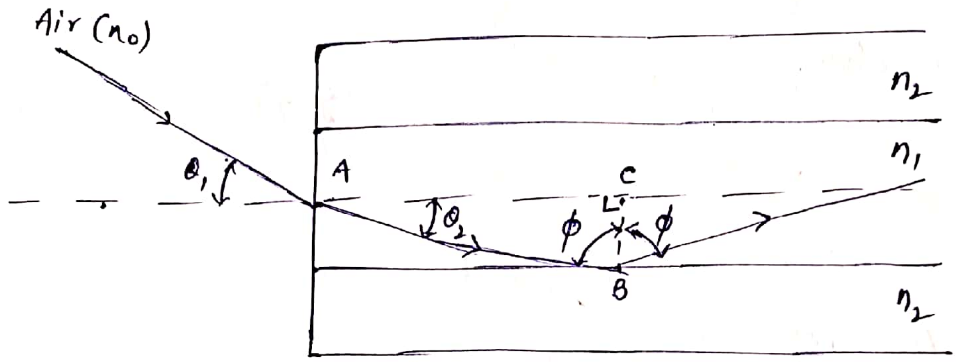
The acceptance angle θ_a when launching light into an optical fiber.

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

ii. $P_2O_3 - SiO_2$ Core; SiO_2 cladding

Numerical Aperture:

It is used to describe the light gathering & light collecting ability of optical fiber



The ray path for a meridional ray launched into an optical fiber in air at an input angle less than the acceplance angle for the fiber

$$n_0 \sin\theta_1 = n_1 \sin\theta_2$$

from right angle ΔABC

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

$$n_0 \sin\theta_1 = n_1 \cos\phi$$

$$\sin^2\phi + \cos^2\phi = 1$$

$$\cos^2\phi = 1 - \sin^2\phi$$

$$\cos\phi = (1 - \sin^2\phi)^{1/2}$$

$$n_0 \sin\theta_1 = n_1 (1 - \sin^2\phi)^{1/2}$$

Limiting case θ_1 becomes the acceptance angle for the fiber θ_a

$$\begin{bmatrix} \phi = \phi_c \\ \theta_1 = \theta_a \end{bmatrix}$$

$$NA = n_0 \sin\theta_a = \sqrt{n_1^2 - n_2^2}$$

$$NA = n_0 \sin\theta_a = \sqrt{(n_1^2 - n_2^2)} = \sqrt{(n_1 - n_2)(n_1 + n_2)}$$

$$= \sqrt{n_1 \left(1 - \frac{n_2}{n_1}\right)(2n_1)}$$

$$= n_1 \sqrt{2\Delta}$$

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$$

$$\simeq \frac{n_1 - n_2}{n_1} \quad \text{for } \Delta << 1$$

$$N.A = n_1 \sqrt{2\Delta}$$ where $\Delta \rightarrow$ relative refractive index difference.

→ A silica optical fiber with a core diameter large enough to be considered by ray theory analysis has a core refractive index of 1.5 and a cladding refractive index of 1.47. Determine (a) the critical angle at the core - cladding interface

(b) The NA for the fiber

(c) The acceptance angle in air for the fiber

Sol: (a)

$$\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) = \sin^{-1}\left(\frac{1.47}{1.5}\right) = 78.5^\circ$$

(b)

$$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{(1.5)^2 - (1.47)^2}$$

$$= 0.3$$

(c) The acceptance angle in air θ_a is given by

$$\theta_a = \sin^{-1}(NA)$$

$$= \sin^{-1}(0.3)$$

$$= 17.4^\circ$$

→ A typical relative refractive index difference for an optical fiber designed for long - distance transmission is 1%. Estimate the NA and the solid acceptance angle in air for the fiber when the core index is 1.46. cal the critical angle at the core - cladding interface within the fiber

$$NA = n_1 \sqrt{2\Delta} = 1.46 \sqrt{0.02}$$

$$= 0.21$$

$$\zeta = \pi \theta_a^2 = \pi \sin^2 \theta_a$$

$$\zeta = \pi (NA)^2 = \pi \times 0.044$$

$$= 0.13 \text{ rad.}$$

$$\Delta = \frac{n_1 - n_2}{n_1} = 1 - \frac{n_2}{n_1}$$

$$\frac{n_2}{n_1} = 1 - \Delta = 1 - 0.01$$

$$= 0.99$$

$$\phi_c = \sin^{-1} \frac{n_2}{n_1} = \sin^{-1}(0.99)$$

$$= 81.9°.$$

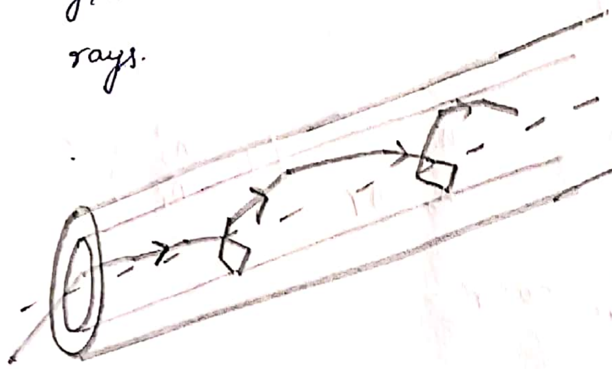
~~Skew Rays~~ :

→ A multimode graded index fiber has an acceptance angle in air of 8°. Estimate the relative refractive index difference between the core axis and cladding when the refractive index at the core axis is 1.52

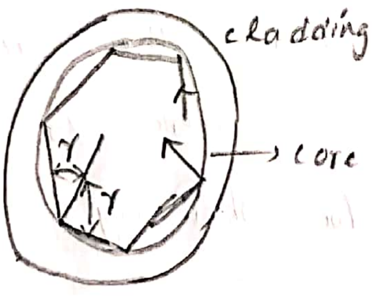
$$\sin \theta_a = n_1 \sqrt{2\Delta}$$

Skew Rays:

: These Rays transmitted without passing through fiber axis. These Rays follow a helical path through the fiber and are called skew Rays.
Skew Ray have larger acceptance angle which is greater than the acceptance angle for Meridional rays.



Helical path taken by skew ray in an optical Fiber



Cross sectional view of the fiber

For every reflection, the helical path traced through the fiber gives a change in direction of 2r where r is the angle b/w the projection of the ray on to a plane normal to core axis and the radius of fiber core

Let 'θ' be the angle of incident at a point in the core - cladding boundary and is greater than the critical angle of fiber.

Let θ_i be the incident angle at the entrance end of the fiber. The angle γ is the half of the angular change in every reflection

$$\cos\gamma \sin\theta_i = \cos\theta$$

when $\theta_i = \phi_{as}$ then $\theta = \theta_c$

$$\sin\phi_{as} = \frac{n_1}{n_0}\frac{\cos\theta_c}{\cos\gamma} = \frac{n_1}{n_0 \cos\gamma}\left(1-\frac{n_2^2}{n_1^2}\right)^{1/2}$$

$$(NA)_{skew} = n_0 \sin\phi_{as} \cos\gamma$$

when $n_0 = 1$ (air)

$$\boxed{(N.A)_{skew} = \sin\phi_{as} \cos\gamma}$$

Since ϕ_{as} is more than the acceptance angle 'ϕ_a' for meridional rays, there is an increased light gathering ability for skew rays.

when $\gamma = 0$, $\phi_{as} = \phi_a$

→ An optical fiber in air has an NA of 0.4 compare the acceptance angle for meridional rays with that for skew rays which change direction by 100° at each reflection.

$$NA = \sin\theta_a$$

$$\theta_a = \sin^{-1}(NA)$$

$$= \sin^{-1}(0.4) = 23.6^\circ$$

The skew rays change direction by 100° at each reflection therefore $\gamma = 50^\circ$

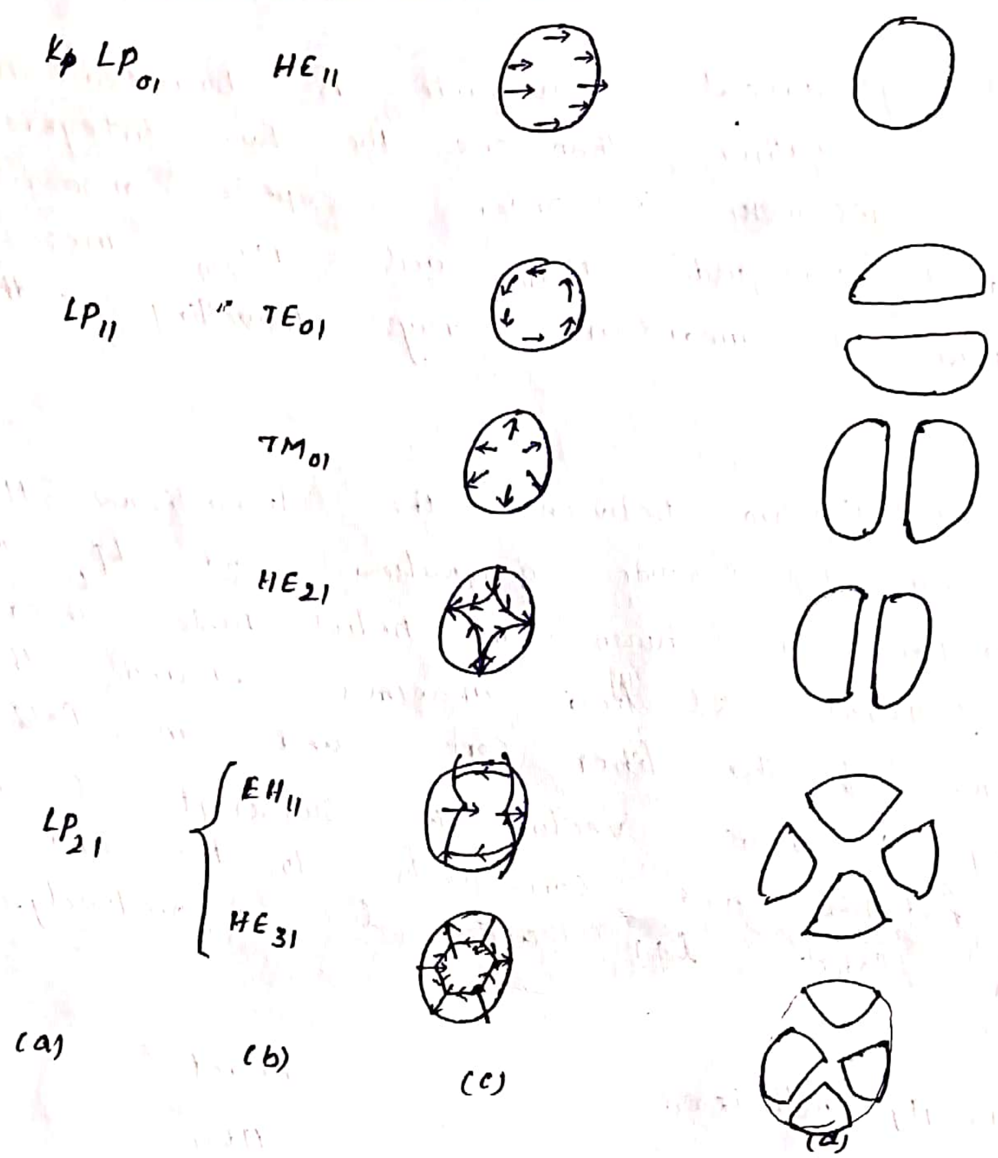
$$\therefore \theta_{as} = \sin^{-1}\left(\frac{NA}{\cos\gamma}\right) = \sin^{-1}\left(\frac{0.4}{\cos 50^\circ}\right) = 38.5^\circ$$

Modes:

The cylindrical waveguide is bounded in two dimensions rather than one. The two integers l and m are necessary in order to specify modes. For cylindrical waveguide TE_{lm} and TM_{lm}. These modes correspond to meridional rays travelling within the fibre.

The relationship between the traditional HE, EH, TE and TM mode designations and LP_{lm} mode designations is shown in below Table. There are in general $2l$ field maxima around the circumference of the fiber core and m field maxima along a radius vector. The subscript l in the LP notation now corresponds to HE and EH modes with labels $l+1$ and $l-1$ respectively.

Linearly polarized	Exact
LP_{01}	HE_{11}
LP_{11}	HE_{21}, TE_{01}, TM_{01}
LP_{21}	HE_{31}, EH_{11}
LP_{02}	HE_{12}
LP_{31}	HE_{41}, EH_{21}
LP_{12}	HE_{22}, TE_{02}, TM_{02}
LP_{lm}	HE_{2m}, TE_{0m}, TM_{0m}
LP_{lm} ($l \neq 0$ or 1)	$HE_{l+1\,m}$, $EH_{l-1,m}$



The Electrified configurations for the three lowest Lp modes

(a) Lp mode designation

(b) Exact mode designation

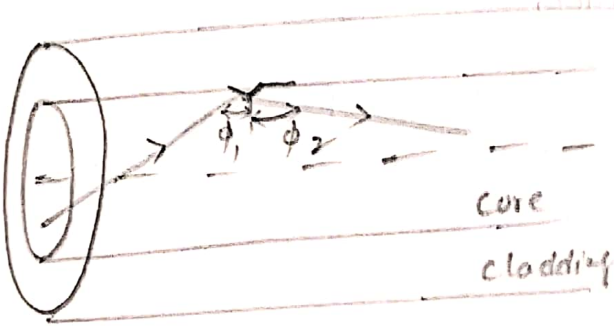
(c) Electrifield distribution of the Exact Mode

(d) Intensity distribution of E_x for the Exact modes indicating the Electrifield Intensity for Corresponding Lp modes.

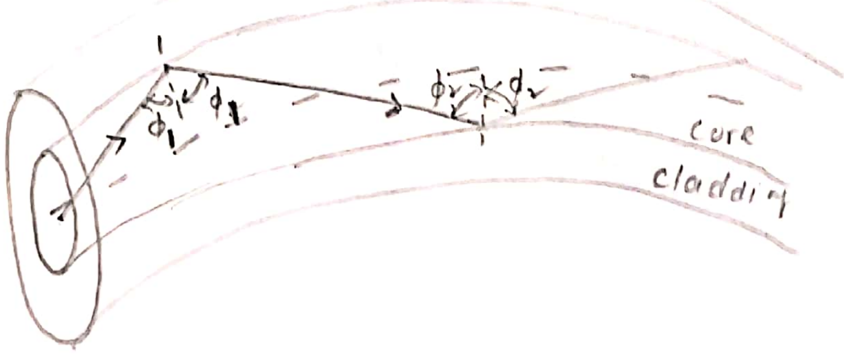
Mode coupling :

Deviations of fiber axis from straightnes variations in the core diameter, irregularitis at the core-cladding interface and refractive index variations may change the propagation characteristics of the fiber. These will have the effect of coupling energy travelling in one mode to another depending on specific variation.

Ray theory helps the understanding of this phenomenon, as shown in below dig, which illustrate two types of interruption.



(a) irregularity at the core-cladding interface



(b) fiber bend

It may be observed that in both cases ray no longer maintains the same angle with the axis. In EM wave theory this corresponds to a change in the propagating mode for the light. The individual modes do not propagate throughout the length of the fiber without large energy transfer to adjacent modes, even when the fiber is good quality and is bent by its surroundings. This mode conversion is known as mode coupling.

Mode coupling affects the transmission properties of fibers in several ways, a major one in relating to the dispersive properties of fibers over long distances.

axially Symmetric modes TE_{0l} and TM_{0l} we have hybrid hybrid modes EH_{nl} and HE_{nl} E_z & $H_z \neq 0$

Mixture of TE and TM modes.

Exact analysis for the modes of an optical fiber is Mathematically very Complex. $HE_{n+1\,l}$ $EH_{n-1\,l}$

$\{HE_{n+1\,l}\}$ & $\{EH_{n-1\,l}\}$ EM Field pattern & Propagation constants

HE_{11} TE_{0l}, TM_{0l}, HE_{2l} $\longrightarrow$ $HE_{n+1\,l}$ & $EH_{n-1\,l}$

HE_{31} & EH_{11} HE_{31} & EH_{11}

LP_{0l} mode HE_{1l} mode

LP_{1l} mode TE_{0l}, TM_{0l} & HE_{2l} modes

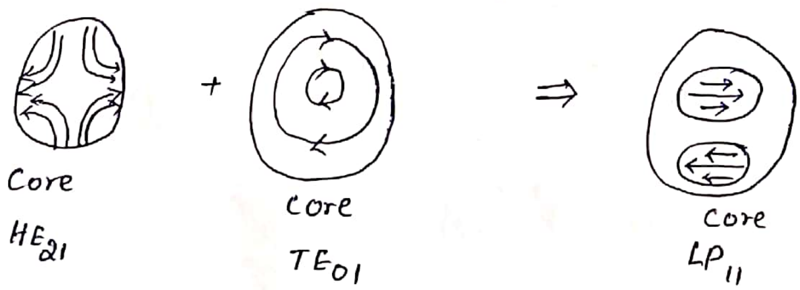
LP_{nl} modes $(n \geq 2)$ Comes

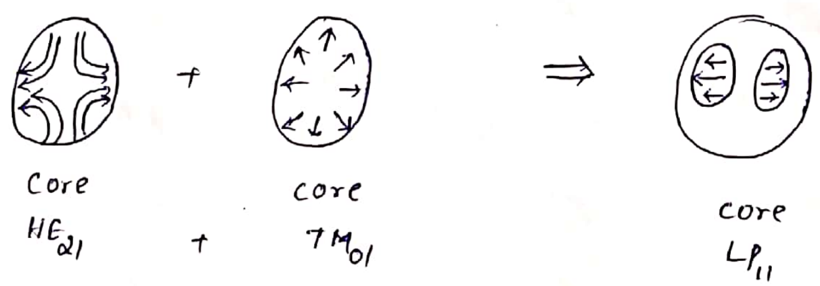
Merits of LP mode designation:

mode quickly & easily

the transmission chart of optical Fibers.

In a complete Set of modes only one electric field Comp and one Magnetic field component are significant





LP Mode concept is valid only under the weakly guiding approx. ($\Delta << 1$).

LP_{ml} (m) → no of variations of Transverse Electric field

$\theta_{as} = \sin^{-1}\left(\overline{\cos\gamma}\right) = \sin^{-1}\left(\overline{\cos 50^\circ}\right)$

Step index fibers:

The optical fiber with a core of constant refractive index n_1 and cladding of lower refractive index n_2 is known as step index fiber

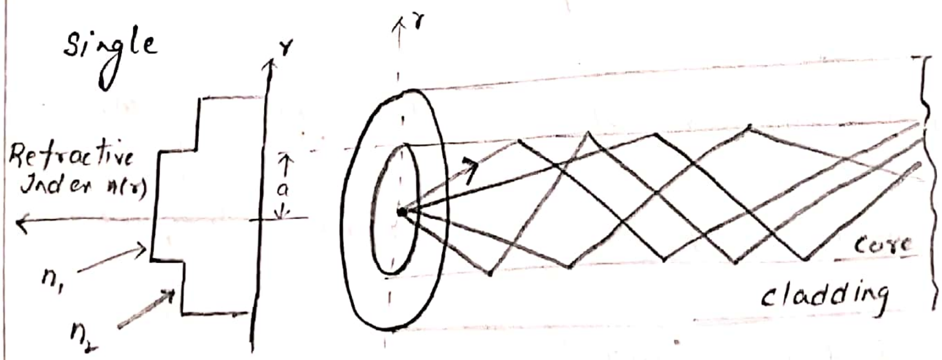
Step index fibers are divided into '2' Types

1. Singlemode step index fiber
2. multi mode step index fiber

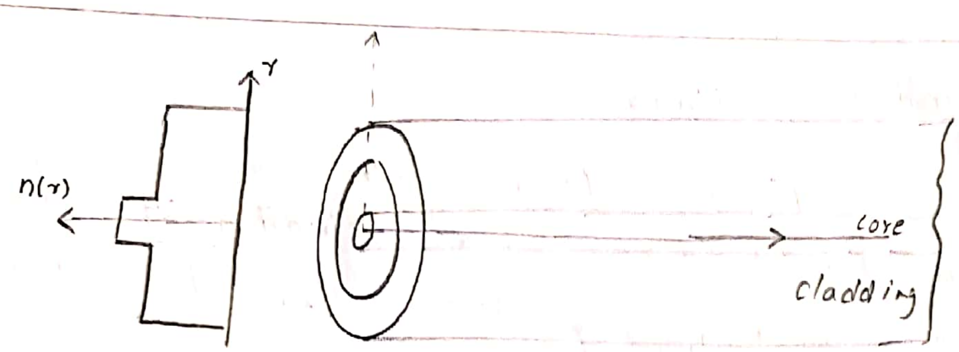
The refractive index profile for both cases is

$$n(r) = \begin{cases} n_1 & r < a \quad \text{(core)} \\ n_2 & r \geq a \quad \text{(cladding)} \end{cases}$$

Multimode step index fiber with a core diameter of around 50 μm (or) greater which is large to allow the propagation of many modes within the fiber core.



Singlemode step index fiber with a core diameter of 2 to 10 μm. which allows the propagation of only one transverse EM mode (single mode)



The single mode step index has the distinct advantag of low intermodal dispersion as only one mode is transmitted, whereas with multimode step index, the dispersion occur due to the differing group velocities of propagation modes

lower bandwidth applications multimode fibers have Saveral advantages over single-mode fibers

(a) The use of incoherent optical sources

(b) Larger numerical apertures, as well as core diamet-ers, facilitating easier coupling to optical sources

(c) Lower tolerance requirements on fiber connectors.

The total number of guided modes $(M_s) = \frac{V^2}{2}$

where 'V' is normalized frequency.

→ Graded index fibers:

Graded index fibers do not have a Constant refractive index in the core but a decreasing core index n(r) with radial distance from a maximum value of n_1 at the axis to a constant value n_2 beyond the core radius a in the cladding

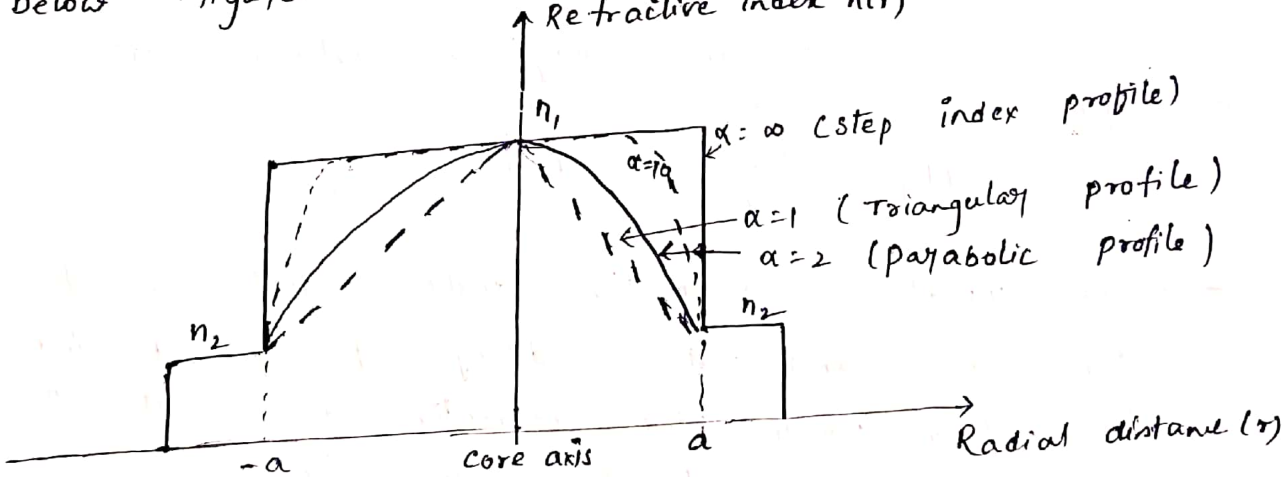
$$n(r) = \begin{cases} n_1 (1 - 2\Delta (r/a)^\alpha)^{1/2} & r < a \text{ (core)} \\ n_1 (1 - 2\Delta)^{1/2} = n_2 & r \geq a \text{ (cladding)} \end{cases}$$

where Δ is relative refractive index difference

α is profile parameter

Step index profile $\alpha = \infty$
Triangular profile $\alpha = 1$
parabolic profile $\alpha = 2$

The range of refractive index profiles is shown below figure.



$$M_g \approx \left(\frac{\alpha}{\alpha+2}\right)\left(\frac{V^2}{2}\right)$$

Hence for a parabolic core fiber ($\alpha = 2$),

$$\boxed{M_g \approx \frac{V^2}{4}}$$

multimode graded index fibers exhibit far less intermodal dispersion than multimode step index fibers due to their refractive index profile. Many different modes are excited in the graded index fiber, the different group velocities of the modes tend to be normalised by the index grading

→ A Graded index fiber has a core with a refractive index profile which has a diameter of 50 um. The fiber has numerical aperture of 0.2. Estimate the total number of guided modes propagating in the fiber when it is operating at wave length of 1 um

$$V = \frac{2\pi}{\lambda} a (NA) = \frac{2\pi (25 \times 10^{-6}) 0.2}{1 \times 10^{-6}} = 31.4$$

The mode volume may be obtained for parabolic profile

$$M_g = \frac{V^2}{4} = \frac{986}{4} = 247$$

→ The relative refractive index difference between the core axis and the cladding of graded index fiber is 0.7% when the refractive index at the core axis is 1.45. Estimate values for the Numerical aperture of the fiber when:

(a) The index profile not taken into account; and

(b) The index profile is assumed to be triangular.

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Single - mode fibers:

The advantage of the propagation of a single mode within an optical fiber is that the signal dispersion Caused by the delay differences between different modes in a multimode fiber may be avoided.

For the transmission of single - Mode the fiber must be designed to allow propagation of only one mode, while all other modes are attenuated by leakage or absorption.

Single - mode propagation of The LP_{01} mode in step index fibers over the range

$$0 \leq V < 2.405$$

1. They exhibit the greatest transmission bandwidth and the lowest losses of the fiber transmission medium
2. They have superior transmission quality
3. They are compatible with the developing integrated optic technology

Cutoff wavelength:

$$\lambda_c = \frac{2\pi a n_1}{V_c} (2\Delta)^{1/2}$$

$$\frac{\lambda_c}{\lambda} = \frac{V}{V_c}$$

$$\lambda_c = \frac{V\lambda}{2.405}$$

→ Determine the cutoff wavelength for a step index fiber to exhibit single-mode operation when the core refractive index and radius are 1.46 and 4.5 um resp., with the relative index difference being 0.25 %.

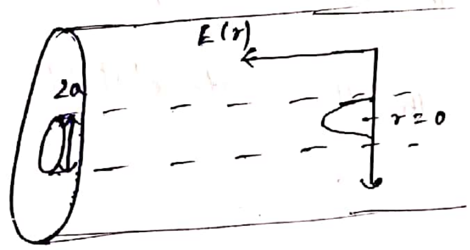
$$\lambda_c = \frac{2\pi a n_1 (2\Delta)^{1/2}}{2.405} = \frac{2\pi (4.5)\ 1.46\ (0.005)^{1/2}}{2.405}$$

$$= 1.214 \ \mu m$$

$$= 1214 \ nm$$

→ Mode - field diameter :

MFD is a primary parameter of single-mode fibers. It is obtained from the mode field distribution of the fundamental mode.



where w_0 → is the nominal width of the i/p excitation

$$\boxed{MFD = 2w_0}$$

$$= 2\sqrt{\frac{2\int_0^\infty E^2(r)\, r^3\, dr}{\int_0^\infty E^2(r)\, r\, dr}}$$

where $2w_0$ = spot size

To avoid complexity, E(r) can be taken as

$$E(r) = E(0)\ \exp(r^2/w_0^2)$$

where 'r' radius

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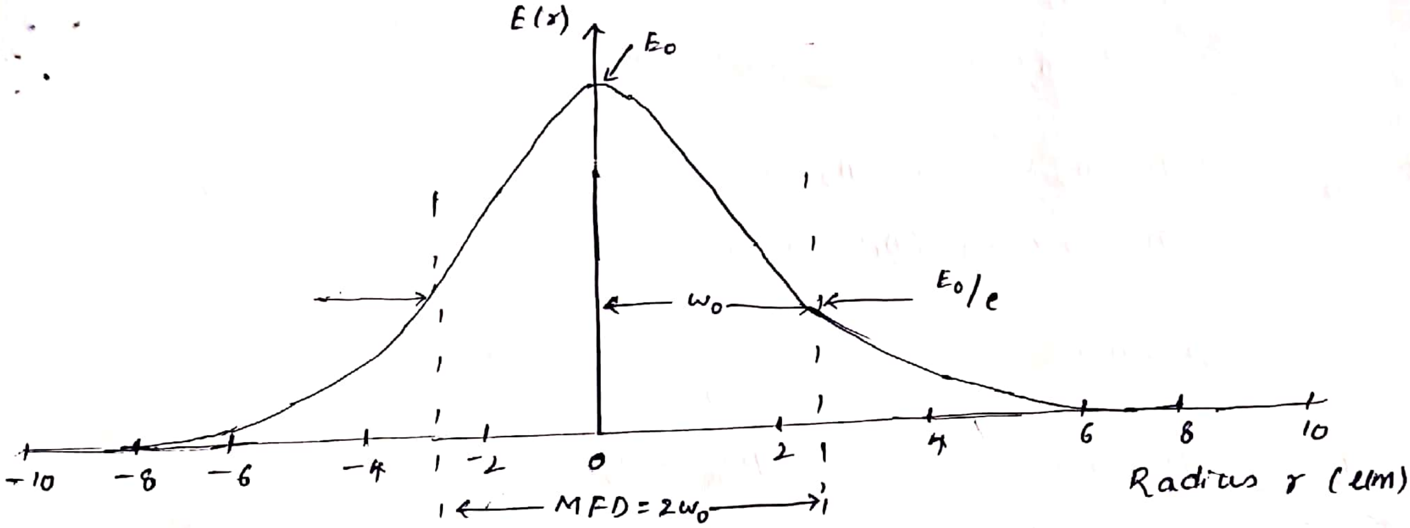

Field amplitude distribution E(r) of the fundamental mode in a single-mode fiber

→ **Effective refractive Index**

$$\beta \lambda_{01} = 2\pi$$

$$\lambda_{01} = \frac{2\pi}{\beta}$$

n_{eff} - normalized phase change coefficient

$$n_{eff} = \frac{\beta}{k} = \frac{\text{propagation constant of the fundamental mode}}{\text{vaccum propagation constant}}$$

The wavelength of fundamental mode λ_{01} is smaller the vaccum wavelength λ by the factor $1/n_{eff}$ where

$$\lambda_{01} = \frac{\lambda}{n_{eff}}$$

The relation b/w the effective refractive index and Normalized propagation constant b

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

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

$$b = \frac{(\beta + n_2 k)\ (\beta - n_2 k)}{(n_1 k + n_2 k)\ (n_1 k - n_2 k)}$$

$$\beta \approx n_1 k$$

$$b \simeq \frac{\beta - n_2 k}{n_1 k - n_2 k} = \frac{\beta/k - n_2}{n_1 - n_2}$$

$$n_{eff} = \beta/k$$

$$\boxed{b \simeq \frac{n_{eff} - n_2}{n_1 - n_2}}$$

→ calculate the V number and number of modes propagating through the fiber having $n_1 = 1.53$, $n_2 = 1.5$ and $\lambda_0 = 1 \mu m$. The radius of core = 50 um

$$V_{number} = \frac{2\pi a}{\lambda_0} (n_1^2 - n_2^2)^{1/2}$$

$$= 94.72$$

→ A step index fiber has a core diameter of 200 um and N.A = 0.3, compute the number of propagating modes at an operating wavelength of 850 nm.

$d = 2a$

Core radius(a) = 100 um

$$\text{Number of modes} = \frac{V^2}{2}$$

$$= 24589$$

→ Calculate the maximum number of guided modes through the graded index fiber having NA = 0.21 index profile = 1.85 and radius of core = 25 um at the operating wavelength of 1.3 um

$\alpha = 1.85$, $\lambda = 1.3 \times 10^{-6}$ m

$a = 25 \times 10^{-6}$ m, NA = 0.21

$$\text{No. of modes} = \left(\frac{\alpha}{\alpha + 2}\right) \frac{V^2}{2}$$

$$= 155$$

→ In the design of single mode fiber, find the value of maximum core radius of the fiber having NA = 0.05, the operating wavelength = 1.3 um, the V for the fiber is 2.405

$$a_{max} = \frac{V \lambda}{2\pi (N.A)}$$

$$= \frac{2.405 \times 1.3}{2\pi \times 0.05}$$

$$= 9.95 \ \mu m$$