UNIT-I (INTRODUCTION)

VOLUTION OF FIBER OPTIC SYSTEMS

FIRST GENERATION

Operated at around 850nm
Low loss transmission window of early silica fiber
GaAs-based optical sources, silicon photo detectors & MM fibers were used.
Repeater spacing around 10 km
Intermodal dispersion & fiber loss limited the capacity of systems.
Bit rate of 45 Mb/s

Second Generation

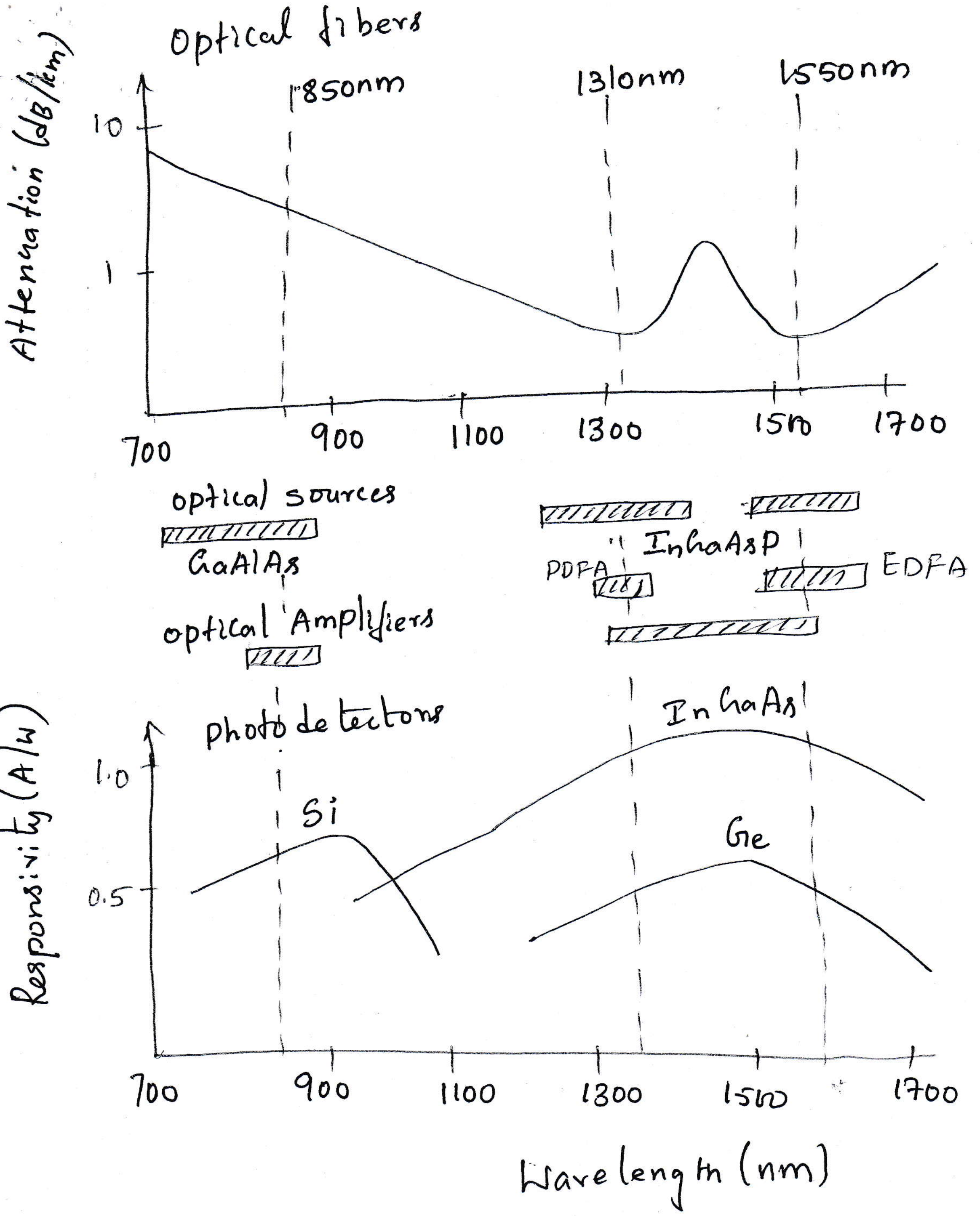
Operated at 1300nm.
Substantial increase in the repeaterless transmission distance for long-haul telephone link
Exhibit lower power loss & less signal dispersion at 1300nm.
Bit rate, limited to below 100Mb/s because of dispersion in MM fibers, this causes overcomed by SM fiber.
Bit rate of up to 1.7 Gb/s with a repeater spacing of about 20 km

Third Generation

operated at 1550 nm.
provide lowest attenuation, but std silica fibers have much larger signal dispersion at 1550 nm than at 1300 nm.
Dispersion problem was overcomed by dispersion shifted fibers.
Bit rate of 2.5 Gb/s over 90 km repeaterless distances.
In 1996, advances in high quality lasers & Rx. allowed single-λ transmission rates of around 10 Gb/s.

Fourth Generation

Make use of optical amplification for increasing repeater spacing and of WDM for increasing bit rate
WDM technique doubling the system capacity & led to operating at a bit rate of 10 Tb/s (2001)
Fiber losses are compensated periodically using (EDFA) Erbium doped fiber amplifier spaced 60-80 km apart.



EDFA - Erbium doped fiber amplifier operated at 1550nm

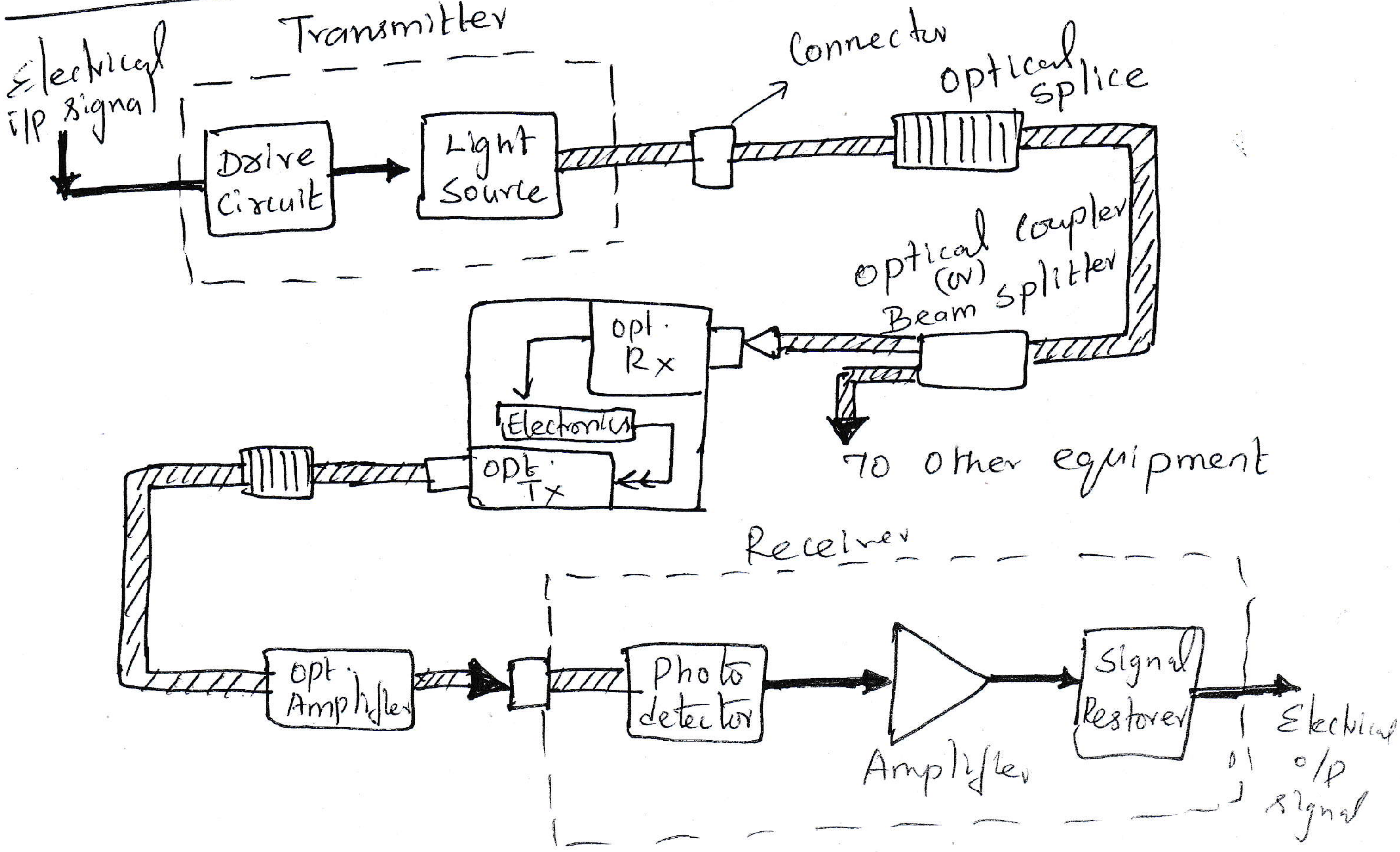
PDFA - praseodymium - doped fiber amplifiers operated at 1300 nm.

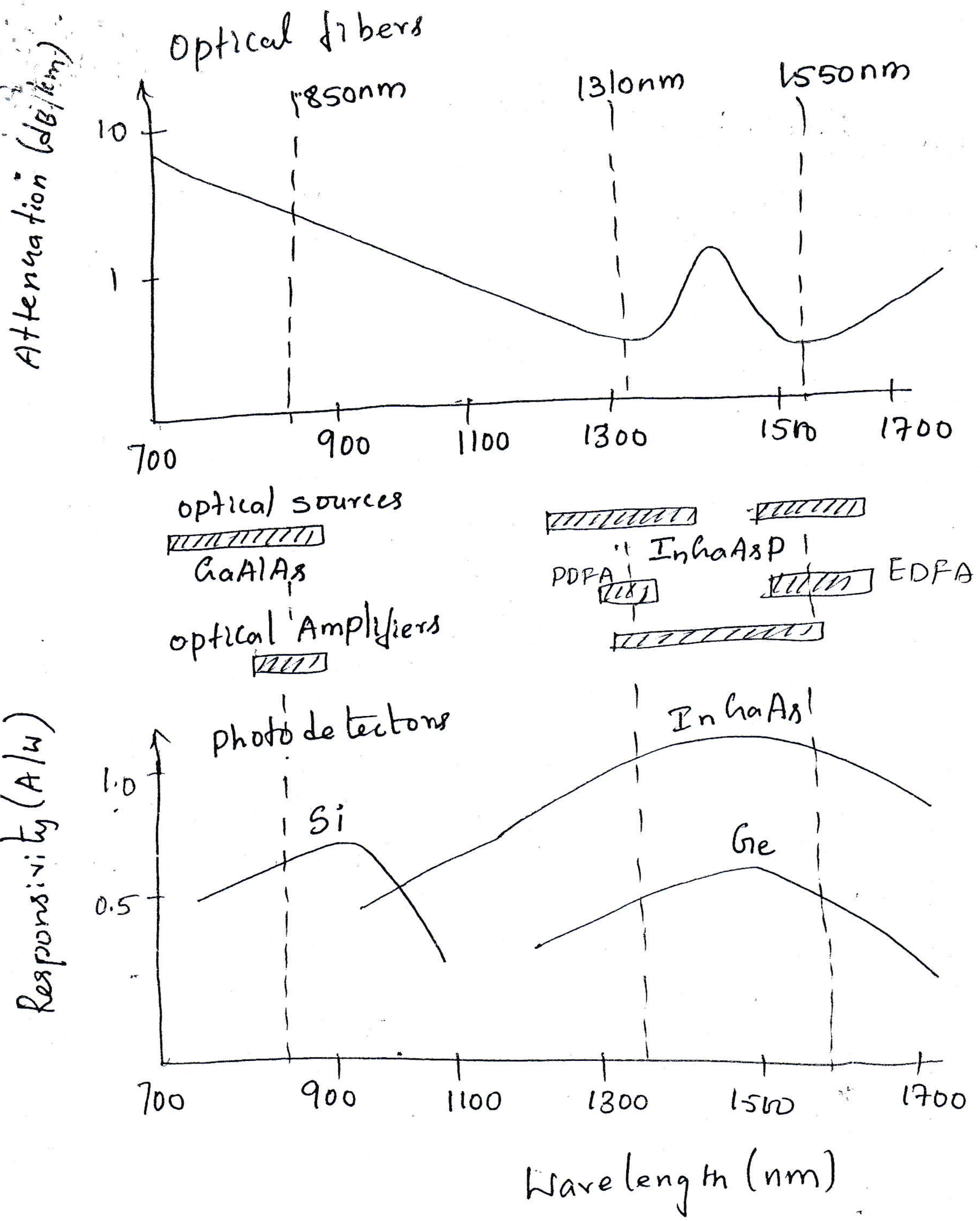
Fig: Operating range of optical fiber systems & the characteristics of 4-key link components (optical fiber, light sources, photodetectors & amplifier)

BASIC N/W INFORMATION RATES

Type of service	Data rate
1. video on demand / interactive TV	1.5 - 6 Mb/s
2. Video games	1 - 2 Mb/s
3. Remote education	1.5 - 3 Mb/s
4. Electronic shopping	1.5 - 6 Mb/s
5. Data transfer for telecommuting	1 - 3 Mb/s
6. Video conferencing	0.384 - 2 Mb/s
7. Voice (single channel)	64 kb/s .

Element of an optical fiber transmission link





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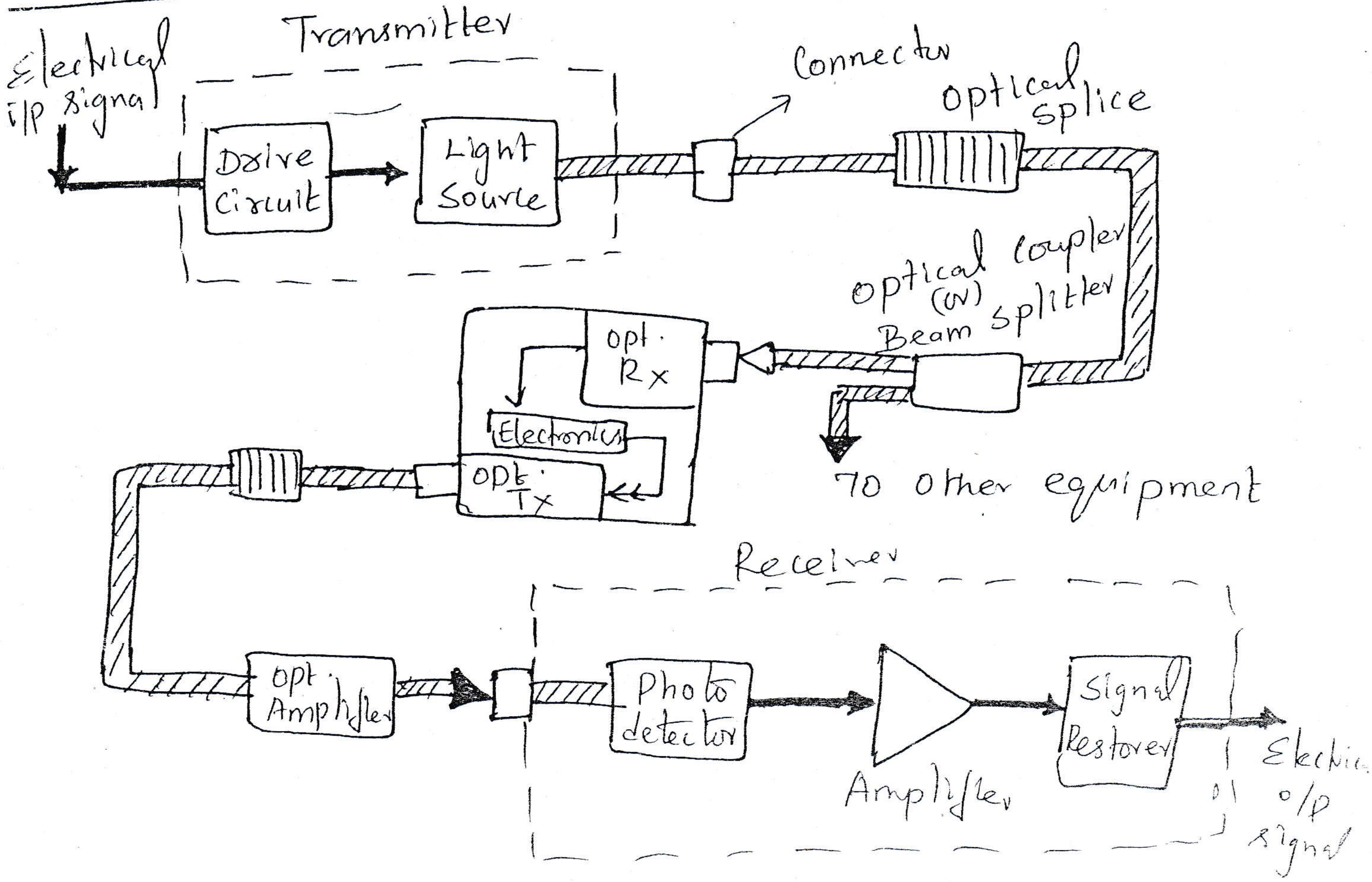
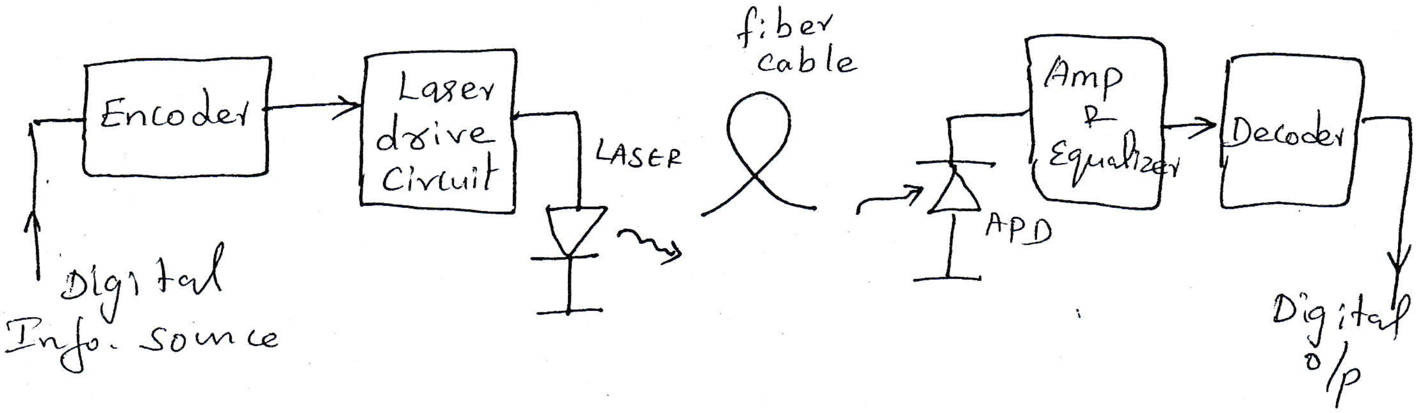
Elements of an optical fiber transmission link



Digital optical link using semiconductor laser source & an avalanche photodiode (APD)



* i/p digital signal from the information source is encoded for optical transmission.
* Laser drive circuit directly modulates the intensity of the semiconductor laser with the encoded digital signal.
* Digital optical signal is launched into the optical fiber cable.
* APD detector is followed by a front-end amplifier & equalizer or filter to provide gain as well as linear signal processing and noise bandwidth reduction.
* Finally, signal is decoded to give original digital information.

Advantages of optical fiber Communication

1) Enormous potential Bandwidth:

The optical carrier freq in the range 10^{13} to 10^{16} Hz yields a far greater potential transmission BW than metallic cable systems.

(2) Small size & weight:

Optical fibers have very small diameters ~~which~~ Hence, even when such fibers are covered with protective coatings, they are far smaller & much lighter than corresponding copper cables.

(3) Electrical Isolation

optical fibers, fabricated from glass or plastic polymer, are electrical insulators & ∴ they don't exhibit earth loop & interface problems.

(4) Immunity to Interference & Crosstalk

Optical fibers form a dielectric waveguide and ∴ free from electromagnetic interference (EMI), Radio frequency interference (RFI)

* Unlike electrical conductors, crosstalk is negligible, even when many fibers are cabled together.

(5) Signal security :

Light from optical fibers does not radiate significantly & ∴ they provide a high degree of signal security.

This feature is attractive for military, banking and general data transmission applications

(6) Low transmission loss

Optical fiber cables exhibit very low attenuation (or) transmission loss in comparison with copper conductors. They are fabricated with losses as low as 0.2 dB/km.

(7) Ruggedness & flexibility

Although protective coatings are essential, optical fibers may be manufactured with very high tensile strengths.

Cable structures, have proved flexible, compact & extremely rugged.

(8) System Reliability & ease of maintenance

These features which reduces the requirement for intermediate repeaters or line amplifiers to boost the txed signal strength.

9) Low cost : The glass, provides optical fiber tx. medium is made from sand — not a scarce resource. So in comparison with copper conductors

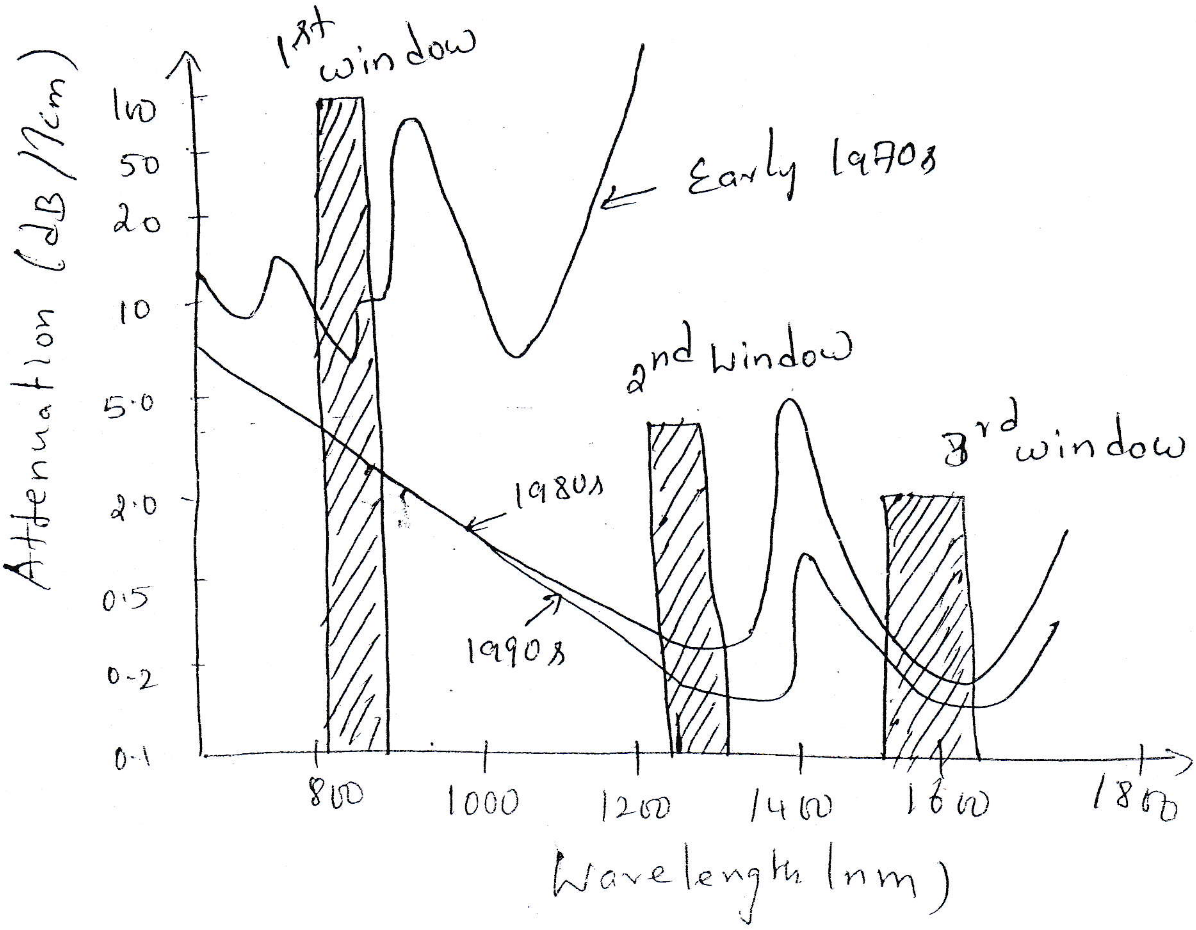
Principal Characteristics of an optical fiber is its attenuation as a function of λ. This is shown in figure.

First window: operated at 800 - 900 nm λ band

Second window - operated at 1100 - 1600 nm region. (1310 nm),

Third window - , centred around 1550 nm

→ long - Wavelength region (1100 - 1600 nm)



Optical fiber attenuation as a function of λ.

1st window

→ Short λ region operated at 850nm

→ Absorption by water molecule - low attenuation spike

→ optical source - GaAlAs

→ optical detector → Si

→ Loss - 3 dB/km

2nd window | 3rd window

Long λ region

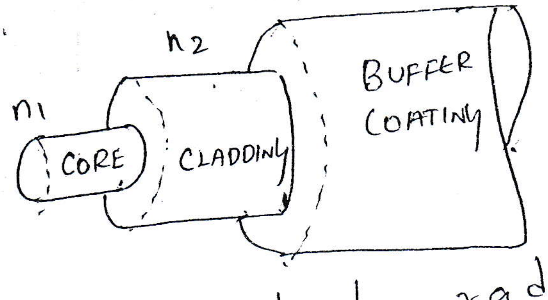
→ Reducing the concentrations of OH⁻ ions & metallic impurities

2nd window	3rd window
→ O band	→ c band
→ 1310nm	→ 1550nm
→ loss: 0.5dB/km	→ 0.2 dB/km
→ zero dispersion for Si fiber	→ Non-zero dispersion
→ opt. amplifier PDFA	→ EDFA

→ Light source - InGaAsP

→ photodetector - InGaAs

Basic Structure of optical fiber - It consists of 3 layers, Core (inner), cladding (outer) & buffer coating layer



Core:

* Dielectric cylinder radius 'a'
* Innermost layer, having ref. index n_1
* light travels thro' axis of the core
* Core material - glass
* $n_1 > n_2$

Cladding:

→ Thickness must be 2 times > λ of light to be guided.
→ provides strength to fiber
→ Reduces scattering loss
→ $n_2 < n_1$
→ Cladding material - pure Si or plastic

Buffer Coating:

→ Last layer, - protective layer
→ provides strength to fibers
→ It isolates or buffers the fiber from distortion & geometric irregularity, drastic environmental protects the fiber from changes.

RAY THEORY TRANSMISSION

~~Critical~~ Angle: A fundamental optical parameter of a material is the refractive index (index of refraction). In free space light wave travels at a speed $c = 3 \times 10^8$ m/s. The speed of light is related to frequency ν & wavelength λ by $\boxed{c = \nu\lambda}$

Refractive index: The ratio of speed of light in a vaccum to that in matter

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

$n = 1$ for air
$= 1.33$ for water
$= 1.5$ for glass
$= 2.42$ for diamond.

Note:

Condition for TIR to be statisfied

(1) Light ray must pass thro' denser to rarer medium
(11) Incident angle in denser medium must be greater than 90' (ie)
Critical angle of that medium

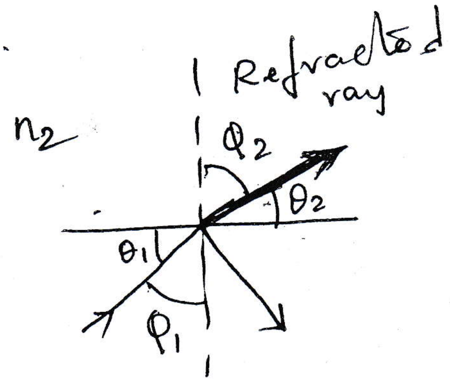
* Angle of incidence ϕ_1 & angle of refraction ϕ_2 are related to each other & ref. indices of dielectric by Snell's law of refraction

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

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

Three Cases:

(1) $\phi_1 < \phi_c$, refracted into rarer medium
(11) $\phi_i = \phi_c$, It traverse along the interface so that $\phi_2 = 90°$
(111) $\phi_i > \phi_c$, Totally reflected back into denser medium.

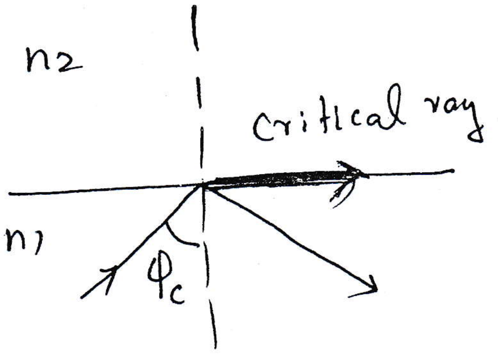


$n_1 > n_2$

Where
φ_1 - Angle of incidence
φ_2 - angle of refraction

$n_1 > n_2$
$\varphi_i < \varphi_c$

⇒ When $\varphi_i < \varphi_c$, it is refracted into the rarer medium.



$n_1 > n_2$

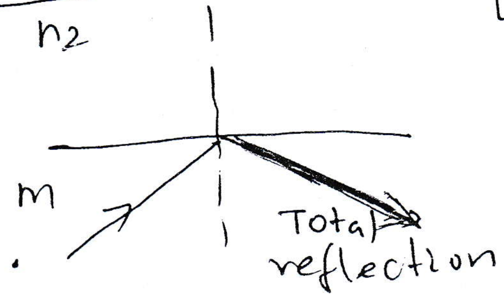
$\varphi_1 = \varphi_c$

⇒ When $\varphi_1 = \varphi_c$, it traverses along the interface so that angle of refraction is 90°

$\therefore$ $n_1 \sin\varphi_1 = n_2 \sin\varphi_2$

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

$$\boxed{\sin\varphi_c = \frac{n_2}{n_1}}$$



$n_1 > n_2$

$\varphi_1 > \varphi_c$

⇒ When $\varphi_1 > \varphi_c$, it is totally reflected back into the denser medium itself with high η (99.9%) → This is called TIR

Angle of incidence > Critical angle

Critical Angle: The value of the incident angle at which the angle of refraction is 90°

Angle of incidence: The angle φ_1 between the incident ray & the normal to the surface.

Acceptance Angle :

Maximum value of the angle of incidence at the entrance end of the fiber, at which angle of incidence at core-cladding interface is equal to critical angle of core medium

(or)

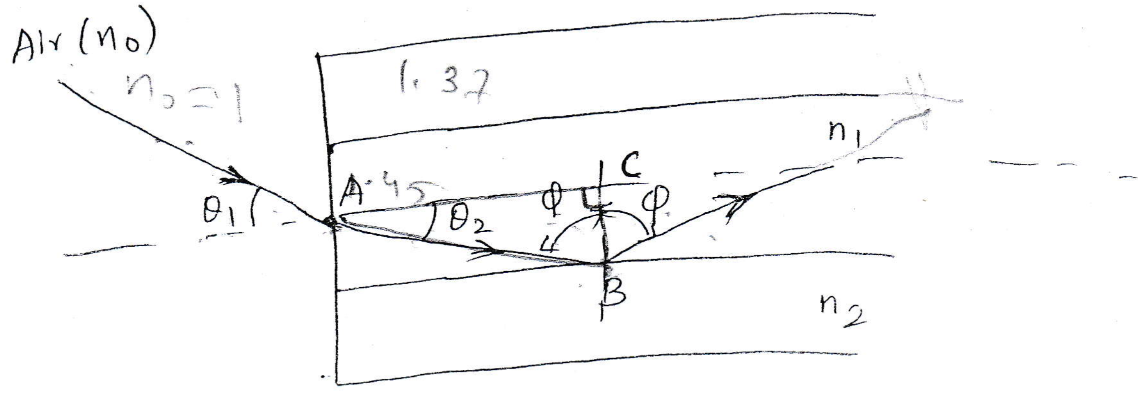
Angle at which the ray enters the fiber core.

$$\sin \phi_{max} = \sqrt{n_1^2 - n_2^2} = NA$$

$$\boxed{\phi_{max} = \phi_A = \sin^{-1} NA}$$

Numerical Aperture :

It is the light collecting of the fiber. It is the measure of amount of light accepted by the fiber.



Ray path for meridional ray launched into an optical fiber in air at an input angle less than acceptance angle for the fiber.

Relationship between NA & Acceptance angle

(8)

According to Snell's law, $n_0 \sin\theta_1 = n_1 \sin\theta_2$ (Meridional ray) —— (1)

$$\therefore \frac{\sin\theta_1}{\sin\theta_2} = \frac{n_1}{n_0}.$$

From the figure, Consider right angled triangle ABC.

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

$$\theta_2 = \frac{\pi}{2} - \phi \quad \text{—— (2)}$$

substitute θ_2 value in equ (1) $\{\because \sin(90-\theta) = \cos\theta\}$

$$n_0 \sin\theta_1 = n_1 \sin\left(\frac{\pi}{2} - \phi\right) \quad \text{—— (3)}$$

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

Using the trignometrical relationship
$\sin^2\phi + \cos^2\phi = 1$, we get $\cos^2\phi = 1 - \sin^2\phi$

$$n_0 \sin\theta_1 = n_1 (1 - \sin^2\phi)^{1/2} \quad \text{—— (4)}$$

By considering the limiting case of TIR, (ie)

$\theta_1 = \phi_a$ (Acceptance angle)

$\phi = \phi_c$ (critical angle)

& $n_0 = 1$

$\therefore$ Equ (4). becomes

$$n_0 \sin\phi_a = n_1 (1 - \sin^2\phi_c)^{1/2}$$

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

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

$$\boxed{\therefore \sin\phi_a = \sqrt{n_1^2 - n_2^2} = NA}$$

$$\boxed{\phi_a = \sin^{-1}\sqrt{n_1^2 - n_2^2}}$$

Skew Rays

The rays that follows helical path around the fiber axis when they travel thro' the fiber & & is transmitted without passing through the fiber axis.

It is not easy to visualize the skew ray paths in two dimensions, but it may be observed from figure (b) that the helical path traced thro' the fiber gives a change in direction of 2γ at each reflection where γ is the angle b/w projection of the ray in 2 dimension & radius of the fiber core at the pt. of reflection

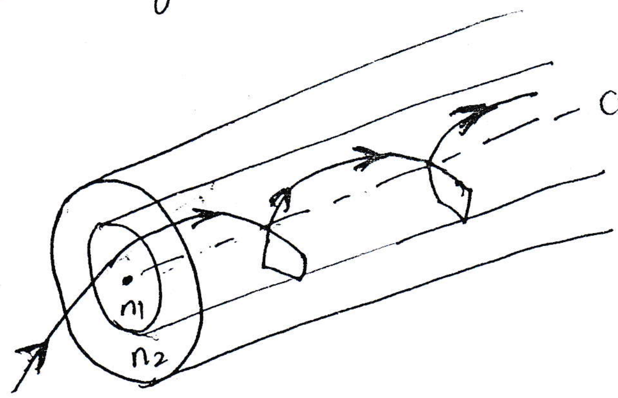
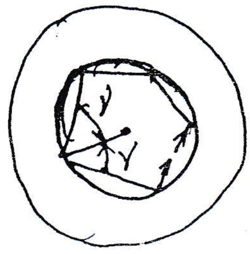


Figure (a). Helical Path taken by skew ray in an opt. fiber



Cross-sectional view of fiber
(b)

Analysis of skew rays

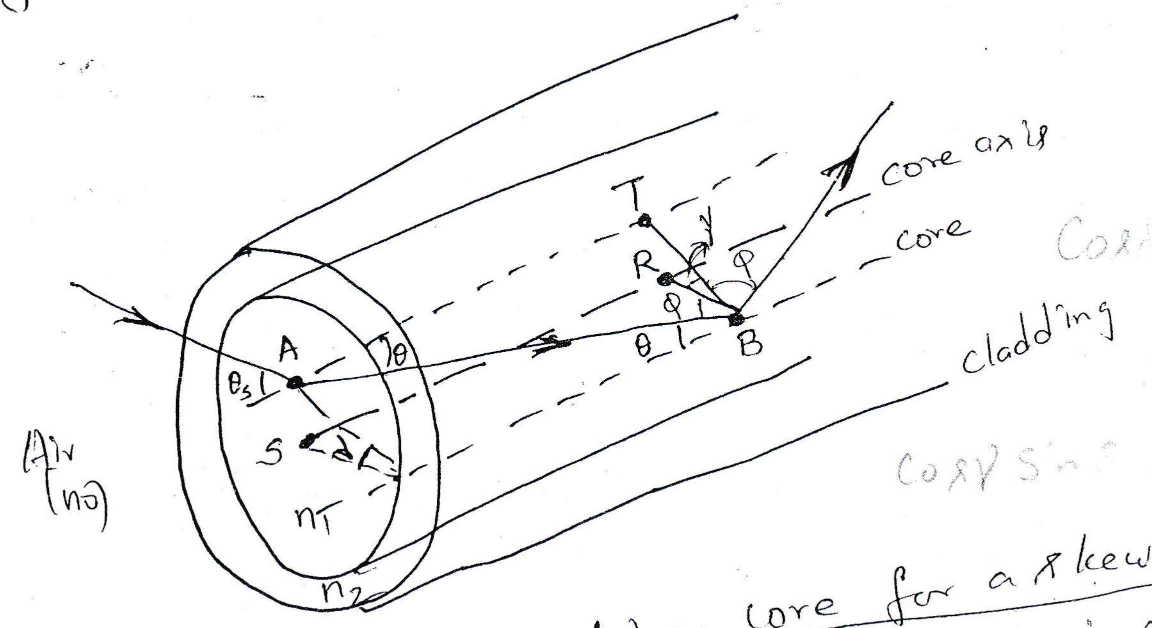
Relationship b/w NA & acceptance angle for

Skew rays

* Skew ray is incident on the fiber Core at the point A, at an angle θ_s to the normal at fiber end face.

* The ray is refracted at air-core interface before travelling to point B in the same plane.

* The angle of incidence & reflection at the point B are ϕ, > ~~than~~ critical angle for core - cladding interface.



Ray path within fiber core for a skew ray incident at an angle θ_s to the normal at air-core interface.

* As incident & reflected rays at the point B are in the same plane, this is simply $\cos\phi$.
* However, if two $\perp$r plane thro' which ray path AB traverses are considered, then γ is the angle b/w core radius & projection of ray on to a plane BRS normal to core axis. θ is the angle b/w ray & a line AT $\parallel$'l to core axis.
* $\therefore$ To resolve ray path AB relative to radius BR in these 2 $\perp$r plane requires multiplication by $\cos\gamma$ & $\sin\theta$.
* Hence, reflection at point B at an angle ϕ is given by

$$\cos\gamma \sin\theta = \cos\phi \quad \text{——— (1)}$$

* Using trignometric relation, $\sin^2\phi + \cos^2\phi = 1$, Eqn (1) becomes

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

* By considering the limiting case of TIR, $\{\phi = \phi_c,\ \theta_a = \theta_{as}\}$

$$\therefore \cos\gamma \sin\theta = \cos\phi_c = (1 - \sin^2\phi_c)^{1/2}$$

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

* Using Snell's law at point A, $n_0 \sin\theta_a = n_1 \sin\theta$.

where θ_a - max i/p axial angle for meridional rays

$$\sin\theta_{as} = \frac{n_1}{n_0}\frac{\cos\phi_c}{\cos\gamma}$$

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

Where θ_{as} - max i/p angle (or) acceptance angle for skew rays.

* Thus acceptance conditions for skew rays are

$$n_0 \sin\theta_{as}\cos\gamma = \sqrt{n_1^2-n_2^2} = NA$$

for air, $n_0 = 1$ ∴

$$\boxed{\therefore \sin\theta_{as}\cos\gamma = NA}$$

Problem:
An OF 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.

solution: For meridional rays,

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

Skew rays change direction by 100° at each reflection
∴ $\gamma = 50^\circ$ ∴ acceptance angle for skew rays is

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

Note: θ_{as} is about $15^\circ > \theta_a$

Mode Theory for optical propagation

(Refer OHP sheets) Refer book

Modes in a planar guide

* planar guide is the simplest form of optical waveguide
* Assume that It consists of a slab of dielectric with ref. index n_1 sandwitched b/w two regions of lower ref. index n_2.
* To obtain an improved model for optical propagation, it is necessary to consider the interference of plane wave components within this dielectric.
* As the ref. index within the guide is n_1, the optical λ is reduced to λ/n_1, while the Vaccum propagation constant is ↑ed to $n_1 k$.
* When θ is the angle b/w propagation vector & guide axis, plane wave is resolved into two Component plane wave propagating in z & x dir. β_z & β_x (ie) $\beta_z = n_1 k \cos\theta$

$\beta_x = n_1 k \sin\theta$

UNIT - I

Electromagnetic Mode Theory for Optical Propagation

Electromagnetic Waves:

In order to obtain an improved model for propagation of light in an optical fiber, EM wave theory must be considered.

The basis for the study of electromagnetic wave propagation is provided by Maxwell's equation. For a medium with zero conductivity these vector relationships may be written in terms of E, H, D & B as curl equations.

$$\nabla \times E = \frac{-\partial B}{\partial t} \quad \text{——— (1)}$$

$$\nabla \times H = \frac{\partial D}{\partial t} \quad \text{——— (2)}$$

Divergence conditions: $\nabla \cdot D = 0$ (no free charges) — (3)

$\nabla \cdot B = 0$ (no free poles) — (4)

Where ∇ is a vector operator

The four field vectors are related by the relations;

$$\left.\begin{array}{l} D = \epsilon E \\ B = \mu H \end{array}\right\} \quad \text{——— (5)}$$

Where ϵ is the dielectric permittivity

μ is the magnetic permeability of the medium

Substituting for D & B & taking curl of (1) & (2) eqn

$$\nabla \times (\nabla \times E) = -\mu \epsilon \frac{\partial^2 E}{\partial t^2} \quad \text{——— (6)}$$

$$\nabla \times (\nabla \times H) = -\mu \epsilon \frac{\partial^2 H}{\partial t^2} \quad \text{——— (7)}$$

Then using the divergence condition of eqn (3) & (4)
with the vector identity:

$$\nabla \times (\nabla \times y) = \nabla(\nabla \cdot y) - \nabla^2(y)$$

& we obtain the nondispersive wave eqn.

$$\nabla^2 E = \mu \epsilon \frac{\partial^2 E}{\partial t^2} \quad \& \qquad (8)$$

$$\nabla^2 H = \mu \epsilon \frac{\partial^2 H}{\partial t^2}. \qquad (9)$$

Where ∇^2 is the laplacian operator.
For rectangular cartesian & cylindrical polar coordinates, the above wave eqn. hold for each component of the field vector, & component satisfying the scalar wave equation:

$$\nabla^2 \psi = \frac{1}{V_p^2} \frac{\partial^2 \psi}{\partial t^2} \qquad (10)$$

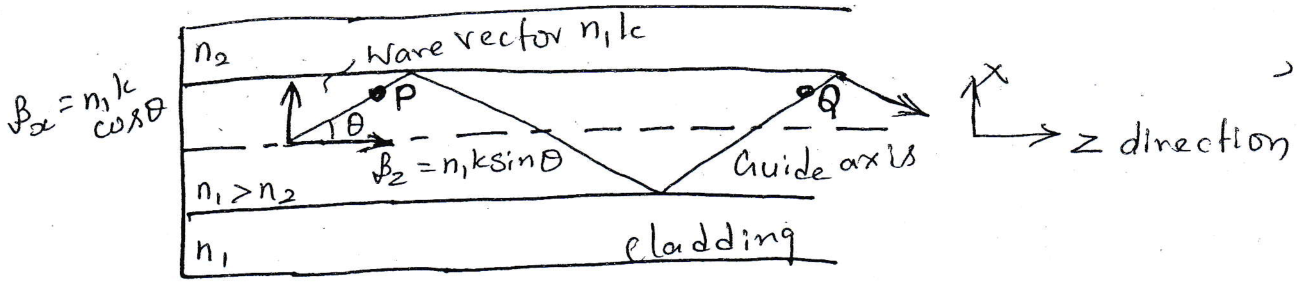
Where ψ may represent a component of E or H field & V_p is the phase velocity (i.e. velocity of propagation of a point of constant phase in the wave) in the dielectric medium.

$$\therefore \quad V_p = \frac{1}{\sqrt{\mu \epsilon}} = \frac{1}{\sqrt{\mu_r \mu_0 \epsilon_r \epsilon_0}}. \qquad (11)$$

Where μ_r & ϵ_r are the relative permeability & permittivity for the dielectric medium & μ_0 & ϵ_0 are the permeability & permittivity of free space.
The velocity of light in free space c is

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \qquad (12)$$

Formation of a mode in a planar dielectric guide



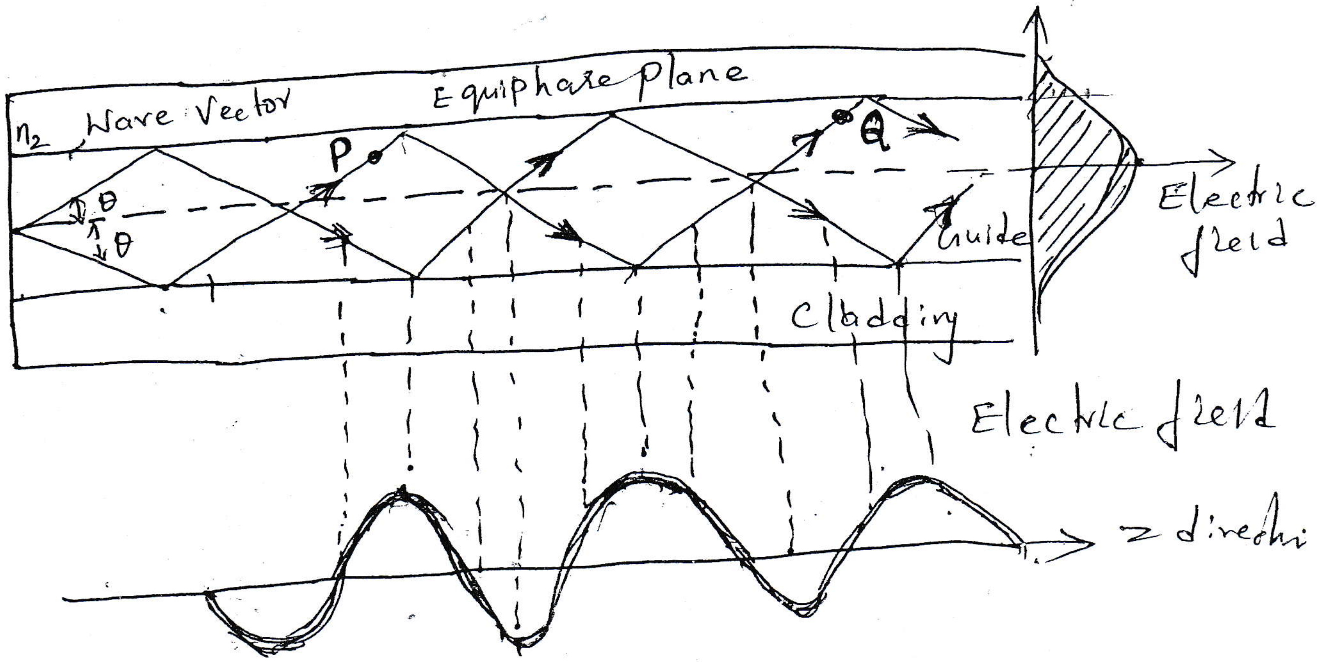


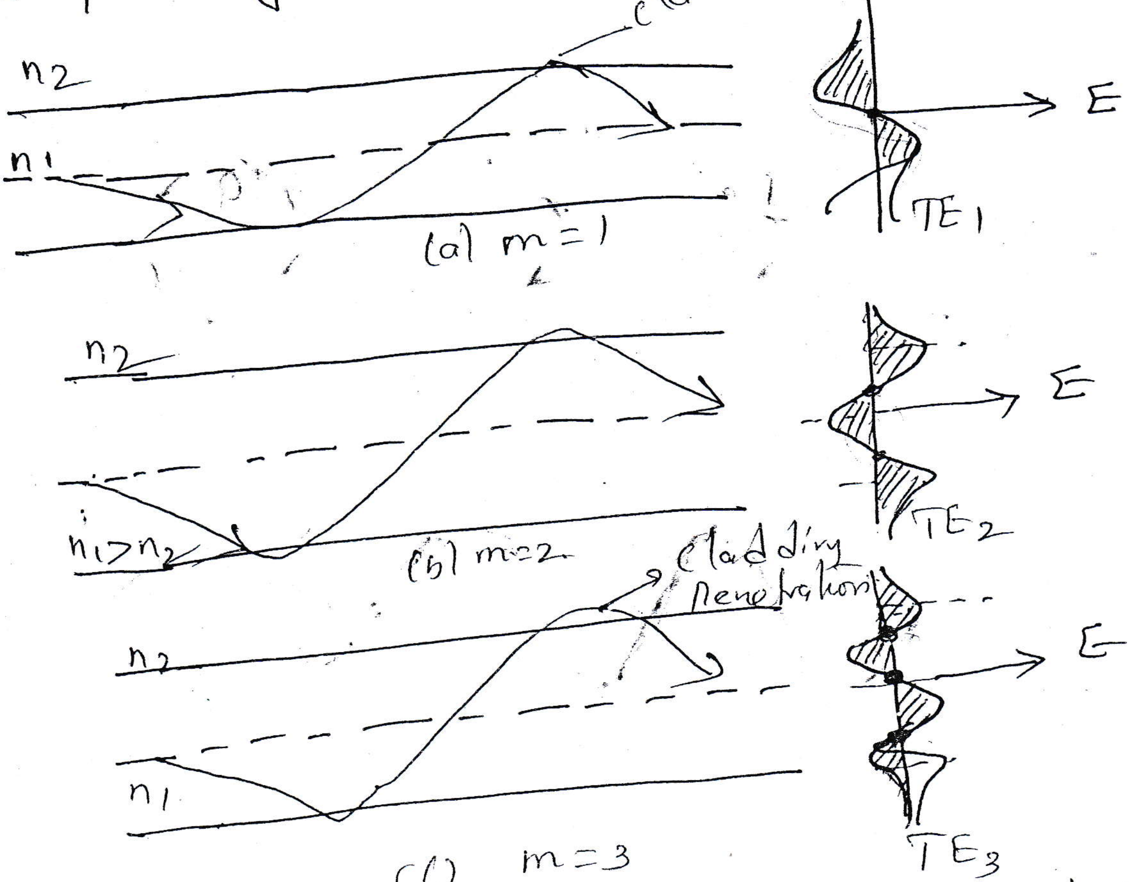
Fig (b)

* When the total phase change after two successive reflections at the upper & lower interfaces (b/w P & Q) is $2m\pi$ radians, where m is an integer, then constructive interference occurs in x direction & a standing wave is obtained (This is in fig (b))

* E is max. at the centre of guide decaying towards zero at the boundary b/w guide & cladding

* The stable field distribution in x-direction with only a periodic z dependence is known as a Mode.

* To visualize the dominant modes propagating in the z-direction, we consider plane waves corresponding to rays at diff. specific angles in the planar guide.



Ray Propogation & Corresponding TE field patterns of 3 lower order models (m=1, 2, 3) in the planar dielectric guide.

* when light is described as an EM wave it consists of a periodically varying E & H which are orientated at right angles to each other.

* When $E_z = 0$ & magnetic field H is in direction of propogation. modes are said to be transverse Electric (TE)
when a component of E field is in dir. of propagation & $H_z = 0$, modes are called transverse magnetic (TM)
... $H_z = 0$, TEM waves exist [rarely found in optical waveguides ... coaxial cables.

~~Phase vector~~

Overview of Modes:

* Order of mode is equal to the no. of field zeros across the guide
* Low-order Modes: Fields are tightly concentrated near the centre of the slab (axis of OF), with little penetration into the cladding region. - Bounded
* Higher-order modes: Fields are distributed more towards the edges of the guide & penetrate further into the cladding region. - Radiation modes
* Leaky modes: Boundary b/w bounded & radiation modes, which is defined by some cut-off condition. (ie)

$n_2 k < \beta < n_1 k$. for modes guided inside the core.

* These leaky modes are only partially confined to the core region & attenuate by continuously radiating their power out of the core as they propagate along the fiber. These radiation out of the waveguide results from a quantum mechanical phenomenon known as Tunnel Effect.

Phase velocity :

The velocity of propagation of a point of constant phase in the wave. In the case of plane waves these constant phase points form a surface called Wavefront. Hence the points of constant phase in a wave front travel at a phase velocity such that

$$\boxed{V_p = \frac{\omega}{\beta}}$$

Where, ω - angular frequency of the wave
β - phase / propagation constant

Group velocity :

velocity of wave packet which is formed by a sum of plane wave components of diff. frequencies such that

$$V_g = \frac{\partial \omega}{\partial \beta}$$

Cylindrical fiber

Modes:

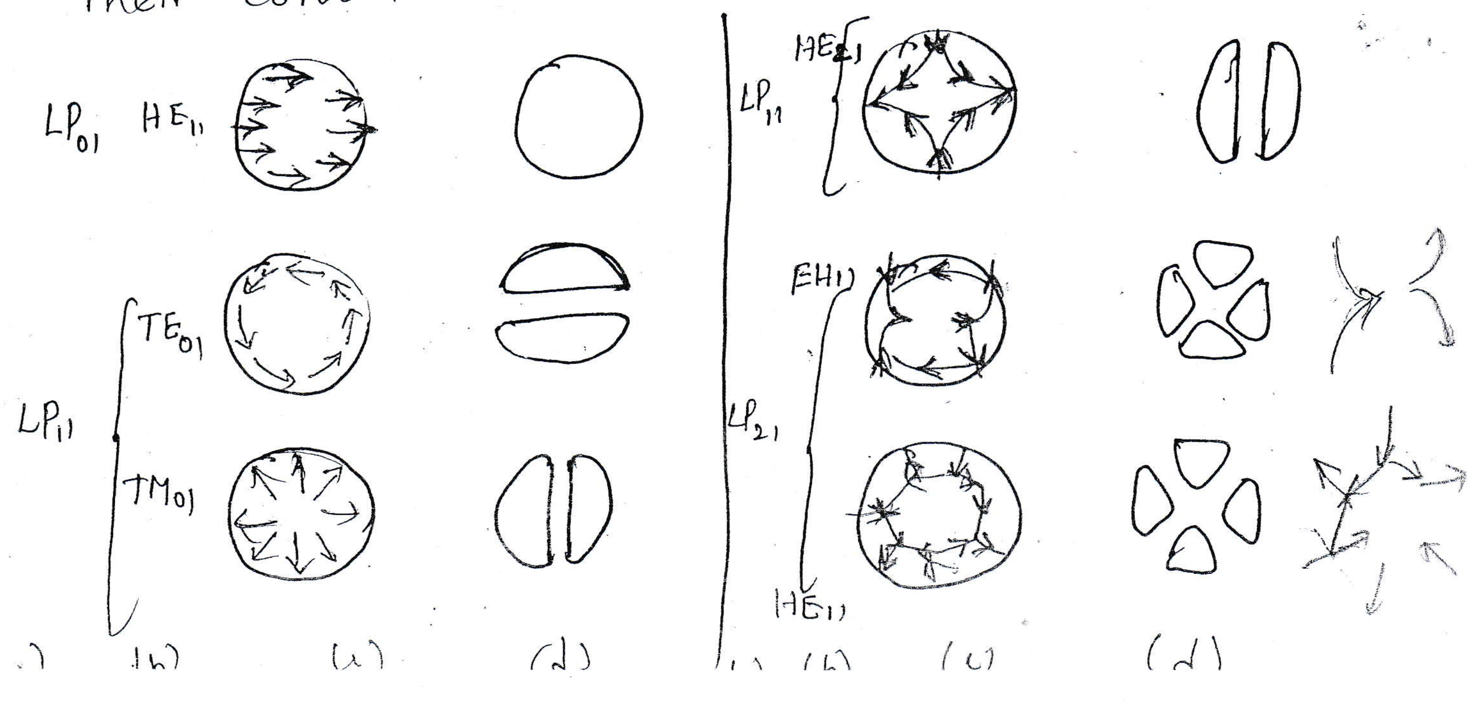
* For cylindrical waveguide, we refer to TE_{lm} & TM_{lm} modes. These modes correspond to meridional rays travelling within the fiber.
* However, hybrid modes where E_z & $H_z \neq 0$ also occur within the cylindrical waveguide. These modes result from skew ray propagation within the fiber are designated as HE_{lm} & EH_{lm} depending upon whether the components of H or E make the larger contribution to transverse field (axis)
* Thus exact description of modal fields in a step index fiber proves complicated. Therefore the analysis may be simplified when the fibers satisfy the weakly guided approximation where $\Delta \ll 1$ for optical fiber communications
* In fact $\Delta < 3\%$.
* For weakly guided structures, the approximate solutions for HE, EH, TE & TM modes may be given by two linearly polarized components (LP)
* These LP modes are not exact modes of the fiber. except for fundamental (lowest order mode)
* However, as Δ is very small in weakly guiding fiber HE-EH modes are said to be degenerate.

* Relationship b/w traditional HE, EH, TE & TM mode designations & LP_{lm} mode designation are given a

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}

Correspondence b/w lower order in LP modes & traditional exact modes from which they are formed

* The mode subscripts l & m are related to electric field intensity profile for a particular LP mode
* Electric field intensity profiles for the lowest three LP modes, together with E distribution of their constituent exact modes are shown below.



* for the cylindrical homogeneous core waveguide under the weak guidance conditions, the scalar wave equation can be written in the form:

$$\frac{d^2\psi}{dr^2} + \frac{1}{r}\frac{d\psi}{dr} + \frac{1}{r^2}\frac{d^2\psi}{d\phi^2} + (n_1^2k^2 - \beta^2)\psi = 0 \quad (1)$$

where ψ is the field (E or H),
n_1 - ref. index of the fiber core
k - propagation constant for light in a vaccum
r, ϕ - cylindrical co-ordinates.

* The propagation constant of guided modes β lie in the range: $n_2k < \beta < n_1k$ (2)

where n_2 - ref. index of fiber cladding.

* Solutions of the wave equation for cylindrical fiber are seperable, having the form:

$$\psi = E(r)\left\{\frac{\cos(l\phi)}{\sin(l\phi)}\exp(\omega t - \beta z)\right\} \quad (3)$$

where ψ - dominant transverse E component.
periodic dependence on ϕ following $\cos l\phi$ (or) $\sin l\phi$ gives a mode of radial order l. Hence the fiber supports a finite no. of guided modes of the form of above equation.

* Introducing the solution given by equ (3) into (1) results in a differential equation of the form

$$\frac{d^2E}{dr^2} + \frac{1}{r}\frac{dE}{dr} + \left[(n_1 k^2 - \beta^2) - \frac{l^2}{r^2}\right]E = 0 \quad (4)$$

* For a step index fiber with a constant refractive index core, equ (4) is a Bessel differential equation & the solutions are cylinder function.
* In the core region, the solution are Bessel functions denoted by J_l. & in cladding region, the solutions are modified Bessel functions denoted by K_l. These modified Bessel function decay exponentially with respect to r.
* ∴ Electric field may be given by

$$E(r) = G J_l(UR) \quad \text{for } R<1 \text{ (core)}$$
$$= G J_l(U) \frac{K_l(WR)}{K_l(W)} \quad R>1 \text{ (cladding)}$$

Where G is the amplitude coefficient

$R = r/a$ is the normalized radial co-ordinate

a - radius of fiber core.

U & W - Eigen values in core & cladding respectively

denoted as $U = a(n_1^2k^2 - \beta^2)^{1/2}$

$W = a(\beta^2 - n_2^2k^2)^{1/2}$

* $V = (U^2 + W^2)^{1/2} = ka(n_1^2 - n_2^2)^{1/2}$

1. An optical fiber in air has an numerical aperture (NA) of 0.4. Find acceptance angle → light collecting efficiency of fiber

$\theta_a = n_0 \sin^{-1} NA$

refractive index

$n_0 = 1$ for air

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

2) Let medium 1 be glass : medium 2 be water. For an angle of incidence of 30° determine angle of refraction.

n_1 (glass) $= 1.5$

n_2 (water) $= 1.33$

Angle of incidence $= \phi_1 = 30^\circ$

using Snell's law, $\boxed{n_1 \sin\phi_1 = n_2 \sin\phi_2}$

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

$= \frac{1.5}{1.33} \sin 30^\circ$

$\sin\phi_2 = 0.56 \quad = (1.128)(0.5)$

$\phi_2 = \sin^{-1}(0.56) = 34.05^\circ$

(3) A silica optical fiber with a core ref. index of 1.50 (n_1) and a cladding refractive index of 1.47 (n_2). Determine

(i) critical angle

(ii) Numerical Aperture

(iii) Acceptance angle.

(i) Critical angle: $\boxed{\phi_c = \sin^{-1}\frac{n_2}{n_1}}$

$$= \sin^{-1}\left(\frac{1.47}{1.50}\right)$$

$$= \sin^{-1}(0.98) = 78.5^\circ$$

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

$$= \sqrt{(1.50)^2 - (1.47)^2} = \sqrt{(2.25 - 2.16)}$$

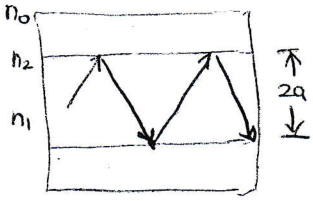
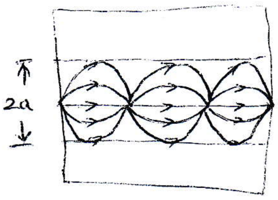
$$= \sqrt{0.09} = 0.3$$

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

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

$$\boxed{\theta_a = 17.46^\circ}$$

Comparision

Parameter ~~Step Index Fiber~~	Step Index Fiber	Graded Index Fiber
Data rate	Slow	Higher
Coupling efficiency	Coupling efficiency with fiber is higher	Lower coupling efficiency.
3. Ray path	By total internal reflection 	Light ray travels in oscillatory fashion 
Index variation	$\Delta = \frac{n_1 - n_2}{n_1}$	$\Delta = \frac{n_1^2 - n_2^2}{2 n_1^2}$
Numerical Aperture	NA remains same	Changes continuously with distance from fiber axis
Material used	Plastic or glass is prefered	Glass is prefered.
Pulse spreading	Pulse spreading by fiber length is more	Pulse spreading is less
Attenuation of light	Less typically 0.34 dB/km at 1.3 um	More 0.6 to 1 dB/km at 1.3 um
7. Typical light source	LED	LED, Laser
Applications	Subscriber local network communication	Local and wide area networks.

Step Index

ameter of core is about

50 - 200 μm → multimode fiber.

8 - 10 μm → Single mode fiber

Light rays propogating through it are in form of meridional rays which will oss the fiber axis during every eflection at the core - cladding boundary & are propogating in a zig - zag manner

2. Signal distortion → more in multimode step index fibers ince the rays reflected at high angles or the higher order modes travel a greater distance than the rays reflected at low angles or the lower order modes, to reach the exit end of the fiber. So high angle rays arrive later than the low angle rays ∴ signal pulses are broadened & distortion takes place Not distortion in single mode step index fiber

4. BW → 50 MHz - km → multimode step index fibers

> 1 GHz → single mode step index

5. Attenuation more → multimode step index fiber

less → single mode step index

more → multimode

Graded index

1. Diameter of core

- 50 μm (multimode)

2. Light rays propogating through it is in the form of skew rays (or) helical rays which will not cross the fiber axis at any time & are propogating around the fiber axis in helical or spiral manner.

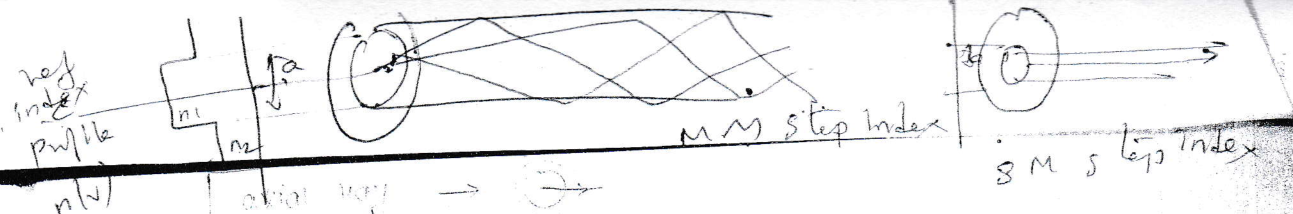
3. Signal distortion low →

self focusing effect. Light rays travel at different speeds in different paths of the fiber as the refractive index varies throughout the fiber. As a result light rays near outer edge travel faster than light rays near the centre of the core. In effect light rays are continuously refocussed as they travel down the fiber & almost all rays reach the exit end of fiber at the same time due to helical path of light propogation

4. BW → 200 MHz km - 600 MHz-k

5. Attenuation - less

6. Numerical aperture → less



axial ray →
Meridional ray →
[illegible]

MULTIMODE STEP INDEX :

- Centre core layer has large light to fiber aperture end.
- Allows more light to enter the cable.
- Light rays strike the core cladding interface and propagate down the core in zig zag fasion.
- Do not take same amount of time to travel along the length of the fiber.

MULTIMODE GRADED INDEX :

- Light propagate through refraction constantly refracted and result in continuous bending of light rays.
- Light enters at many different angle.

of core is step

index is ...nce. It is ...hat the ...the core.

DIMENSIONS 14.07.09

DIMENSIONS		
1. DIAMETER	Single mode → 8-10 μm Multimode → 50-200μm	Multimode → 50 μm
2. DATA RATE	Slow	Higher.
3. RAY PATH	CLADDING CORE Light rays propagating is in the form of meridonial ray which will cross the fiber axis during every reflection at the core cladding boundary & are propagating in a zig-zag manner.	Light rays propagating in the form of skew ray or helical rays which will not cross the fiber axis every time & are propagating around the fiber axis in helical or spiral manner.
4. COUPLING EFFICIENCY	Higher	Lower
5. SIGNAL DISTORTION	Signal dist. is more in multimode step index fiber since the rays reflected at high angles or the higher order modes travel a greater distance than the rays reflected at low ...	Signal dist. is low self focussing effect - light rays travel at different speed in different paths of the fibre as the refractive index varies ... the fiber ...

step index fiber

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

Graded index.

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

	rays arrive later than the low angle rays. ∴ single pulses are broadened & distortion takes pulse. No distortion in single mode step index fiber.	near the center of the core. In effect light rays are continuously refocussed as they travel down the fiber & almost all rays reach the exit end of the fiber at the same path of light propagation time due to helical.
Index VARIATION	$\Delta = \frac{n_1 - n_2}{n_1}$	$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$
MATERIAL USED	Plastic or glass	Glass
LIGHT SOURCE	LEDs	LED, LASER
NUMERICAL APPERTURE	Remains the same.	Changes continuously with distance from the fiber axis.
BANDWIDTH	Multimode - 50 MHz-km Single mode > 1 GHz	200 MHz·km - 600 MHz·km
PULSE SPREADING	More	Less.
APPLICATION	subscriber local n/w communication.	LAN & WAN

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GRADED INDEX FIBER STRUCTURE:

$$n(r) = \begin{cases} n_1\left[1 - 2\Delta\left(\frac{r}{a}\right)^{\alpha}\right]^{1/2} & 0 \le r \le a \quad \text{(core)} \\ n_1[1-2\Delta]^{1/2} \simeq n_1[1-\Delta] \simeq n_2 & r > a \quad \text{(cladding)} \end{cases}$$

$r \rightarrow$ radial distance

$a \rightarrow$ core radius

$n_1, n_2 \rightarrow$ refractive index of core, cladding.

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