UNIT-I:

Introduction to Optical Fibers: -
Evolution of fiber optic system
Elements of an Optical Fiber transmission link
Ray Optics
Optical Fiber Modes and Configurations
Mode theory of Circular Wave guides
Overview of Modes-Key Modal concepts
Linearly Polarized Modes
Single Mode Fibers
Graded Index fiber structure.

INTRODUCTION:

- Optical Fiber communication is a method of transmitting information from one place to another by sending light through an optical fiber.
- The light forms an electromagnetic carrier wave that is modulated to carry information

EVOLUTION OF FIBER OPTIC SYSTEM:

- The use of light for communications has been common for many years. Ex: signal fires, reflecting mirrors & signaling lamps for limited information transfer.
- In 1880's Alexander Graham Bell reported the transmission of speech using a light beam over a distance of 200 meters.
- Due to lack of suitable light sources, light transmission in atmosphere is restricted to line of sight and effected by rain, snow, fog & dust.
- In theory, the greater the carrier frequency, the larger the available transmission bandwidth and thus the information-carrying capacity of the communication system. Communication at optical frequencies offers an increase in the potential usable bandwidth by a factor of around 10^4 over high frequency microwave transmission.
- With the invention of lasers in 1960's, Optical Communication was stimulated. This device provides powerful light source with possible modulation at high freq. The low beam divergence of laser made possible to free space optical transmission.
- But previously mentioned constraints of light transmission restricted these systems to short distance applications.
- Although use of laser for free space optical communications proved somewhat limited.
- In 1966-reserchers [Kao, Hockham & Werts] found that Optical Communication via dielectric wave guides or optical fibers from glass is possible to avoid degradation of optical signal in atmosphere
- Such systems were viewed as replacement for co-axial cables, carrier transmission systems. Initially Optical Fibers exhibits high attenuation [1000db/km]. There are also serious problems involved with joining the fiber cables.
- Within the space of ten years optical fiber losses were reduced to below 5db/km & suitable low loss jointing techniques were perfected.
- In 1973-77, semiconductor optical sources [i.e. injection lasers, LED's & detectors such as photo diodes & photo transistors] were designed & fabricated from alloys of Gallium Arsenide [Al Ga As] which emits the near infrared between of 0.8-0.9 μm region.
- More recently this wavelength range has been extended to 1.0-1.11 μm by using other semiconductor alloys.

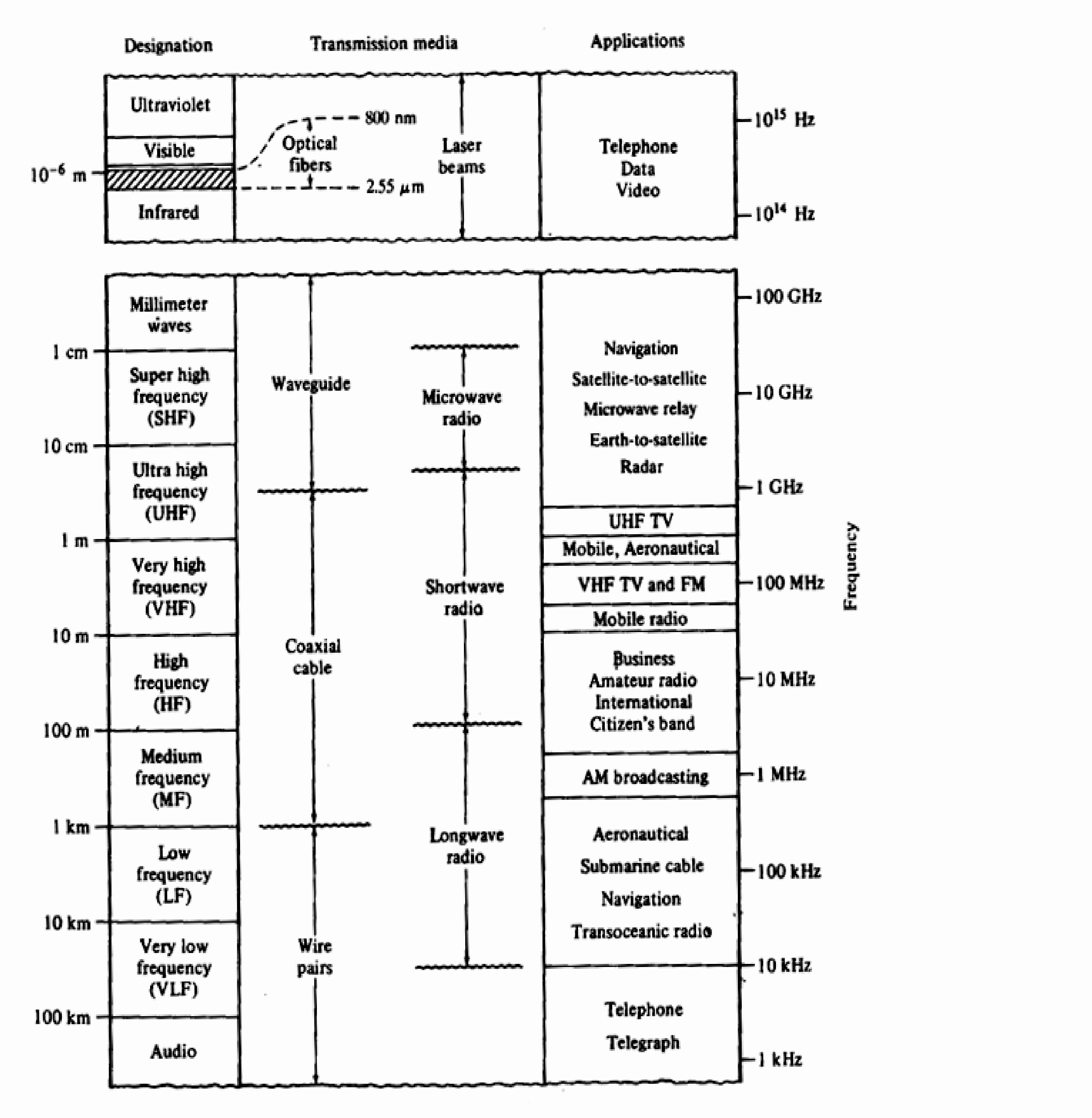


Fig1.1: The regions of electromagnetic spectrum used for radio and optical fiber communications.

ELEMENTS OF AN OPTICAL FIBER TRANSMISSION LINK:

The process of communicating using fiber-optics involves the following basic steps:

- Creating the optical signal using a transmitter,
- Relaying the signal along the fiber, ensuring that the signal does not become too distorted or weak, and receiving the optical signal and converting it into an electrical signal.

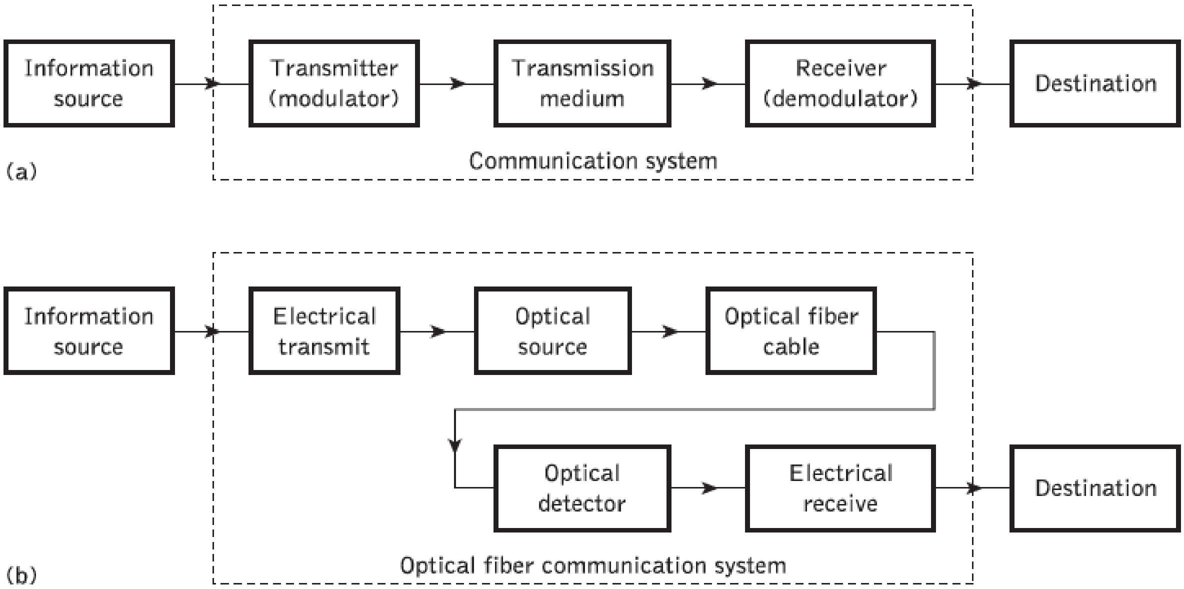


Fig 1.2: [a] Block diagram of general communication system [b] block diagram of OFC system.

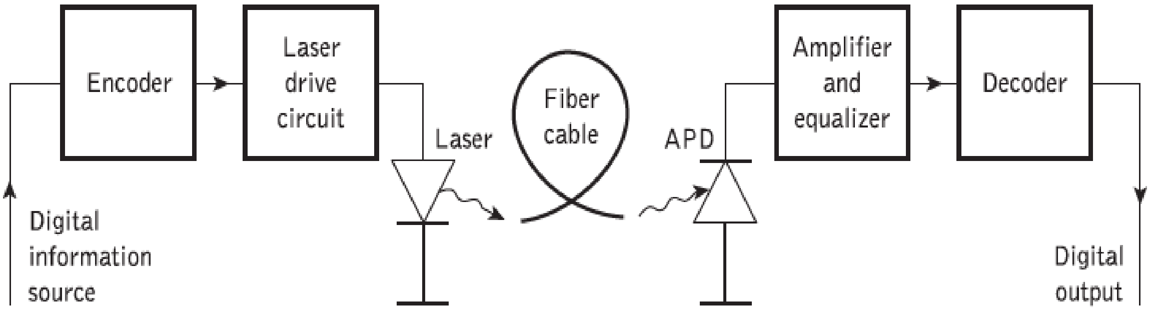


Fig 1.3: A digital optical fiber link using a semiconductor laser source and an avalanche photodiode (APD) detector

- INFORMATION SOURCE: Provides an electrical signal [Analog/Digital] to a transmitter comprising an electrical stage which drives an optical source to give modulation of light wave carrier.
- The optical source which provides the electrical-optical conversion may be either a semiconductor laser or LED.
- The transmission medium consists of an optical fiber cable which is made with glass, contains core & cladding structure. There are different types of Optical Fiber cables such as indoor, outdoor & under water cables.
- ENCODER: The digital signal from information source is encoded for optical transmission.
- LASER DRIVE CKT: Modulates the intensity of LASER with encoded digital data.

- OPTICAL SOURCE: Provides electrical to optical conversion by either a LASER or LED.
- TRANSMISSION MEDIUM: Optical Fiber CABLE
- OPTICAL DETECTOR: Provides optical to electrical conversion by photo diodes/photo transistors demodulates the optical carrier.
- AMPLIFIER & EQUALIZER: To provide gain & noise reduction.
- Decoder: Decoded in to original digital information.

Major elements in a transmission fiber optical link:

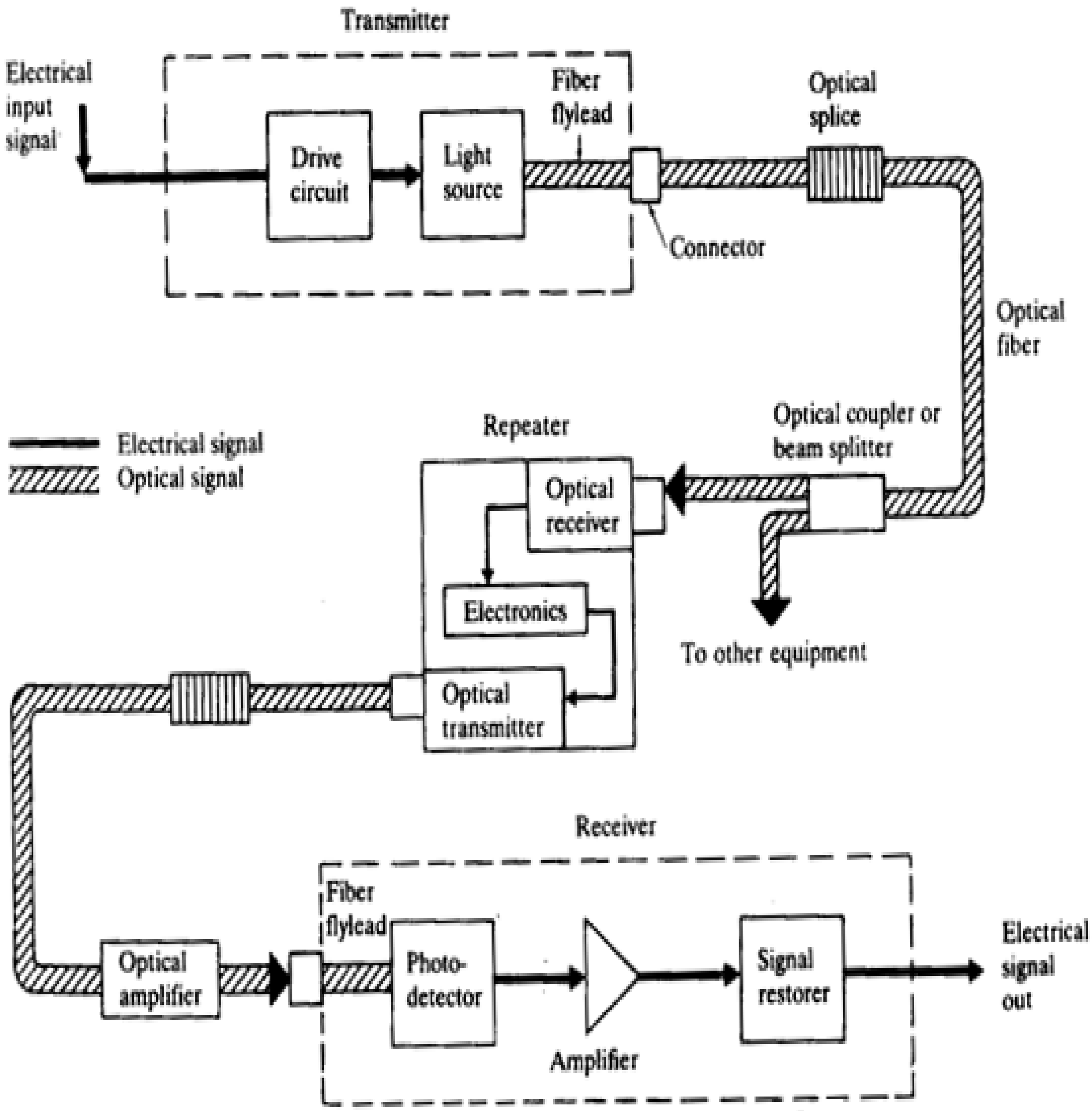


Fig 1.2: (c) Major elements in a transmission fiber optical link

The key sections in OF transmission link are a transmitter consisting of a light source and its associated drive circuitry, a cable offering mechanical & environmental protection to the optical fibers contained inside, & a receiver consisting of a photo detector plus amplification and signal restoring circuitry. Additional components include optical connectors, splices, couplers & repeaters.

THE CABLED OPTICAL FIBER is one of the most important elements in an optical fiber link.

In addition to protecting the glass fibers during installation and service, the cable may contain copper wires for powering repeaters which are needed for periodically amplifying and reshaping the signal when the link spans long distances. The cable generally contains several cylindrical hair-thin glass fibers, each of which is an independent communication channel.

The installation of Optical Fiber cables can be either aerial, buried directly the ground or undersea. Individual cable lengths will range from several hundred meters to several KMs. The complete long distance transmission line is formed by splicing or connecting together these individual cable sections.

TRANSMITTER: The electric input signals to the transmitter can be either of an analog or of a digital form. The transmitter circuitry converts these electric signals to an optical signal by varying the current flow through the light source. LED and laser diodes are suitable transmitter sources for this purpose since their light output can be modulated rapidly by simply varying the bias current.

RECEIVER: After an optical signal has been launched into the fiber, it will become attenuated and distorted with increasing distance. At the receiver the optical power emerging from the fiber end will be detected by a photodiode. The photo detector converts the received optical power directly into an electric current output. PIN and APDs are 2 photo detectors used in fiber optic link.

REPEATER: An optical repeater consists of a receiver and a transmitter placed back to back. The receiver section detects the optical signal and converts it to an electric signal, which is amplified, reshaped and sent to the electric input of the transmitter section. The transmitter section converts this electric signal back to an optical signal and sends it on down the optical fiber waveguide.

ADVANTAGES:

- Enormous Potential BW
- Small size & Light Weight
- Electrical Isolation
- Immunity to interference and crosstalk
- Signal Security
- Low Transmission loss
- Ruggedness & Flexibility
- Low cost
- ENORMOUS POTENTIAL BW: The optical carrier frequency in the range of 10^{13} to 10^{16} Hz gives greater potential Transmission Bandwidth. At present BW available to fiber system is not fully utilized but modulation at several GHz over hundreds KMs without repeaters is possible. Therefore information carrying capacity of Optical Fiber system is superior to cable system.
- SMALL SIZE AND WEIGHT: Optical Fibers have very small diameters, not greater than the diameters of human hair. They are much lighter than metallic cables.
- ELECTRICAL ISOLATION: Optical Fiber is fabricated from Glass & plastic polymers which are electrical insulators. They don't exhibit earth loop & interface problems. Fibers do not create sparks or short circuits.
- IMMUNITY TO INTERFERENCE AND CROSSTALK: Optical Fiber form a dielectric wave guide, they are free from electromagnetic interference, radio frequency interference. No optical interference between fibers hence crosstalk is negligible.
- SIGNAL SECURITY: A transmitted Optical signal cannot be obtained from a fiber in a non-invasive manner. Any attempt to acquire a message signal transmitted optically may be detected. Impossible to "tap into." This feature is attractive for MILITARY applications.
- LOW TRANSMISSION LOSS: Exhibits loss as low as 0.2db/Km. it facilitates the implementation of communication links with extremely wide repeater spacing.
- RUGGEDNESS & FLEXIBILITY: Optical Fibers may be manufactured with very high tensile strengths. Fibers may also bend to small radius or twisted without damage. Easy to storage, transportation & handling.
- POTENTIAL LOW COST: The glass which generally provides Optical Fiber transmission medium is made from sand. Sand is not a scare resource when compare with copper.

OPTICAL FIBER WAVE GUIDES: INTRODUCTION

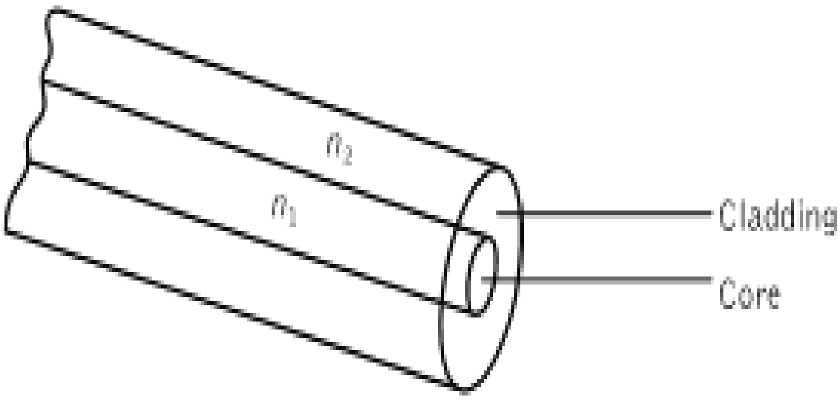


Figure: Optical fiber waveguide showing the core of refractive index n_1, surrounded by the cladding of slightly lower refractive index n_2

- RAY THEORY TRANSMISSION:
- Refractive Index of a medium = $\dfrac{\text{Velocity of light in vacuum}}{\text{Velocity of light in medium}}$
- A ray of light travels slowly in an dense medium

Refraction:

When a ray is incident on interface between 2 dielectrics of different RI's [air-glass] refraction occurs. If a ray incident with an angle θ_1 to the normal at the surface of interface where $n_1 > n_2$ then the ray will have refraction with θ_2 to the normal when $\theta_2 > \theta_1$. According to Snell's law $n_1 \mathrm{Sin}\theta_1 = n_2 \mathrm{Sin}\theta_2$ then.

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1} \rightarrow \begin{array}{ll} \text{if } n_2 > n_1 & \theta_2 < \theta_1 \\ \text{if } n_1 > n_2 & \theta_2 > \theta_1 \end{array}$$

Critical angle: When the angle of refraction is 90^0 , the refracted ray emerges parallel to interface between dielectrics, then the angle of incident is known as critical angle [θ_C].

$$n_1 \ \mathrm{Sin}\theta_C = n_2 \ \mathrm{Sin}90^0$$

$$\mathrm{Sin}\theta_C = [n_2 / n_1]$$

- **TOTAL INTERNAL REFLECTION:** If the angle of incident is > critical angle then the light is reflected back into originating dielectric medium which is known as total internal reflection.

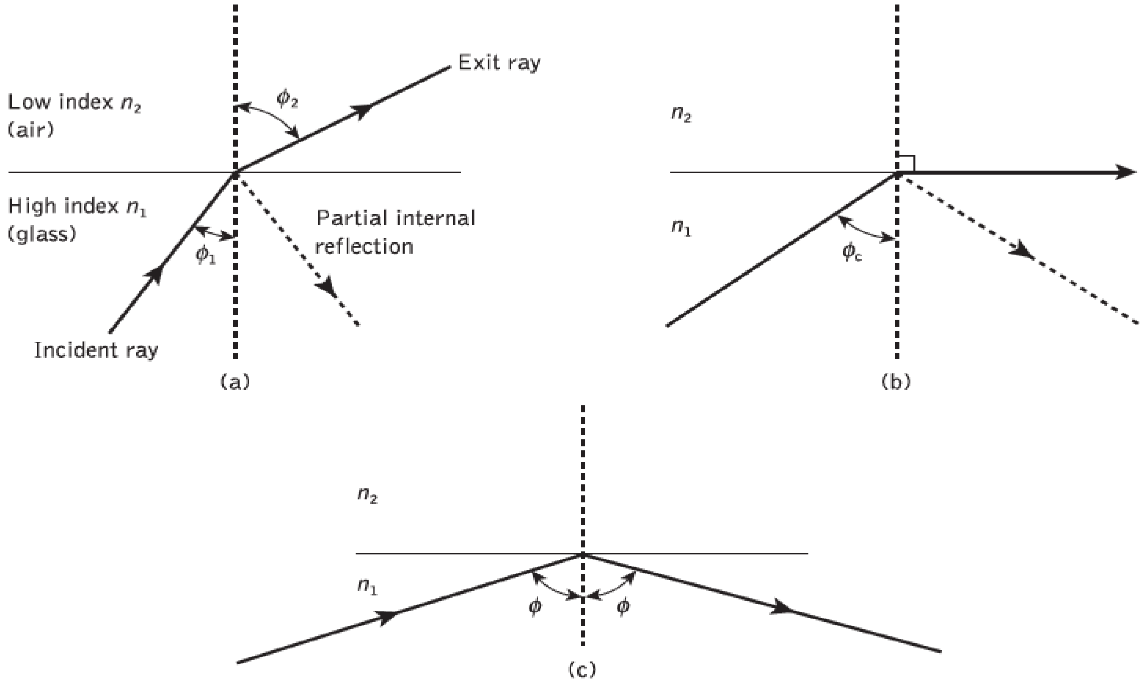


Figure : Light rays incident on a high to low refractive index interface (e.g. glass–air): (a) refraction; (b) the limiting case of refraction showing the critical ray at an angle φc; (c) total internal reflection where φ > φc

TYPES OF RAYS:

- If the transmitted rays are passing through fiber axis, then they are known as MERIDIONAL rays.
- If the transmitted rays are not passing through fiber axis, then they are known as SKEW rays which follow a helical path through the fiber.

Acceptance angle /cone half-angle:

- The maximum angle to axis at which external light rays may strike the air/glass interface and may enter in to fiber in order to propagate is referred as acceptance angle.

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.

THE RAY ANALYSIS to obtain a relationship between Acceptance Angle, Refractive Index & Numerical Aperture:

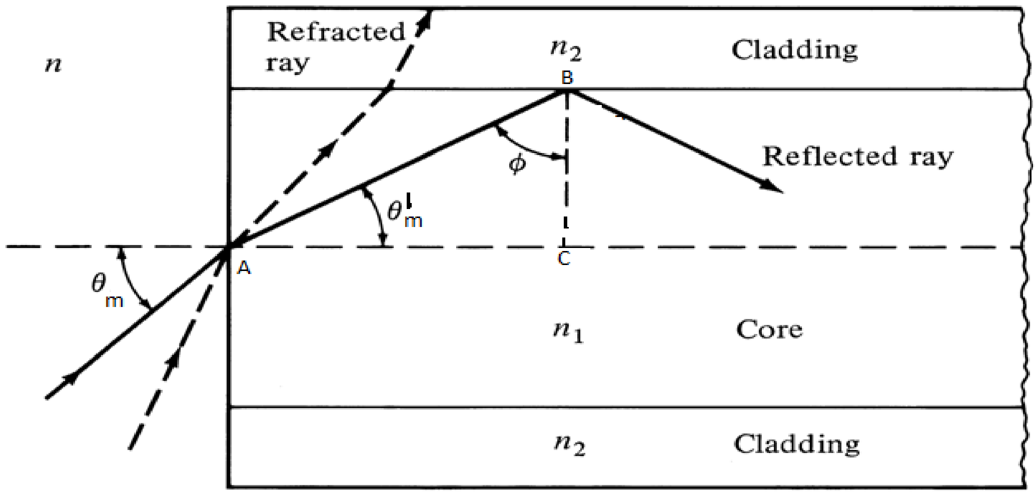


Figure : Meridional ray optics representation of the propagation mechanism in an ideal step-index optical waveguide.

- n= RI of air
- n_1 = RI of core
- n_2 = RI of cladding
- Assuming the entrance face at the fiber core to be normal to the axis, then refraction at the air-core interface using Snell's law is given by
- using Snell's law $n \operatorname{Sin}\theta_m = n_1 \operatorname{Sin}\theta_m^{\,1}$ ...[1]
- Consider a right angle triangle ABC, then $\theta_m^{\,1} = 90^0 - \varphi$ where $\varphi >$ critical angle θ_C
- $n \operatorname{Sin}\theta_m = n_1 \operatorname{Sin}[90^0 - \varphi] = n_1 \operatorname{Cos}\varphi$
  $= n_1 [1 - \operatorname{Sin}^2 \varphi]^{1/2}$ .....[2]
- When the limiting case for total internal reflection is considered, φ becomes equal to critical angle for core-cladding interface $\varphi = \theta_C$
- Therefore $n \operatorname{Sin}\theta_m = n_1 [1 - \operatorname{Sin}^2 \theta_C]^{1/2}$ .....[3]
- wkt $\operatorname{Sin}\theta_C = n_2 / n_1$
- $n \operatorname{Sin}\theta_m = n_1 [1 - (n_2 / n_1)^2]^{1/2}$
- $n \operatorname{Sin}\theta_m = n_1 [n_1^2 - n_2^2]^{1/2} / n_1$
- $n \operatorname{Sin}\theta_m = [n_1^2 - n_2^2]^{1/2}$ ....[4]
- Wkt n=1 for air $\operatorname{Sin}\theta_m = [n_1^2 - n_2^2]^{1/2}$
- Numerical Aperture [NA]: Is a measure of amount of light rays can be accepted by the fiber $NA = \operatorname{Sin}\theta_m = [n_1^2 - n_2^2]^{1/2}$ ....[5]
- The maximum angle to axis at which external light rays may strike the air/glass interface and may enter in to fiber in order to propagate is referred as Acceptance Angle [AA].
- $AA = \theta_m = \operatorname{Sin}^{-1} [n_1^2 - n_2^2]^{1/2}$ ....[6]
- $AA = \operatorname{Sin}^{-1} [NA]$ ....[7]

A relationship between Numerical Aperture & Relative Refractive Index Difference:

- Refractive Index difference = $[n_1 - n_2]$
- Relative Refractive Index difference or Fraction Index difference = $\Delta = [n_1 - n_2]/n_1$
- Wkt $NA = [n_1^2 - n_2^2]^{1/2}$ ..

$$= [(n_1 + n_2)(n_1 - n_2)]^{1/2}$$
$$= [(2n_1)(n_1 - n_2)]^{1/2} \qquad \text{for } n_1 > n_2$$
$$= [(2n_1)(n_1 \Delta)]^{1/2}$$
$$= [2 n_1^2 \Delta]^{1/2} \qquad NA = n_1 [2\Delta]^{1/2}$$

PROBLEM NO:1

Silica OF with a core diameter large enough to be considered by ray theory analysis has a core RI of 1.50 and a cladding RI of 1.47. Determine [a] critical angle at the core-cladding interface [b] the NA for the fiber [c] the AA in air for the fiber.

SOLUTION:

- Wkt $\theta_C = \text{Sin}^{-1}[n_2 / n_1]$
- $= \text{Sin}^{-1}[1.47/1.50]$
- $= 78.5^0$
- Wkt $NA = [n_1^2 - n_2^2]^{1/2}$
- $= [(1.50)^2 - (1.47)^2]^{1/2}$
- $= 0.30$
- Wkt $AA = \text{Sin}^{-1}[NA]$
- $= \text{Sin}^{-1}[0.30]$

$= 17.4^0$

PROBLEM NO:2

A typical RRID for an OF designed for long distance Transmitter is 1%. Estimate NA for fiber when the core index is 1.46. Calculate the critical angle at core-cladding interface with in the fiber.

SOLUTION:

- $\Delta = 0.01$
- $NA = n_1[2\Delta]^{1/2}$
- $= 1.46[2 \times 0.01]^{1/2}$
- $= 0.21$
- $\Delta = [n_1 - n_2]/n_1$
- $= 1 - n_2/n_1 = 0.01$
- $= n_2/n_1 = 1 - 0.01 = 0.99$
- Wkt $\theta_C = \text{Sin}^{-1}[n_2 / n_1]$
- $= \text{Sin}^{-1}[0.99]$
- $= 81.9^0$

SKEW RAYS - NA & AA:

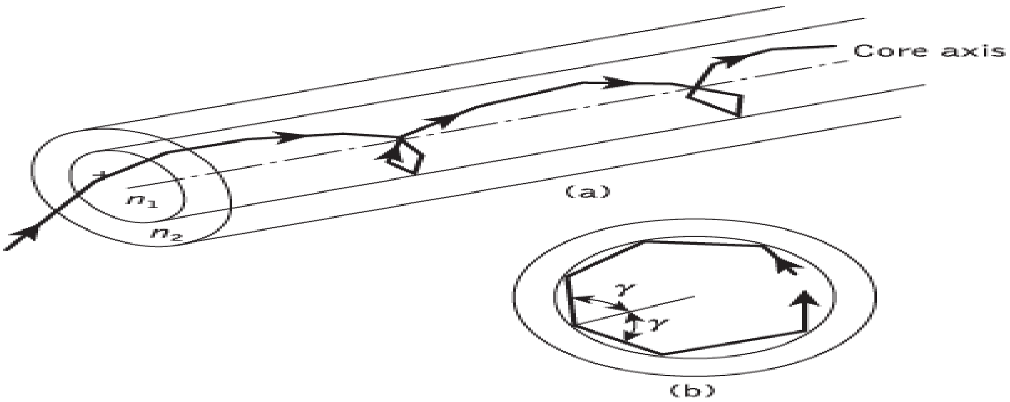


Figure: The helical path taken by a skew ray in an optical fiber: (a) skew ray path down the fiber; (b) cross-sectional view of the fiber

- If the transmitted rays are not passing through fiber axis, then they are known as SKEW rays which follow a helical path through the fiber.
- The helical path traced through fiber gives a change in direction of 2ϒ at each reflection.
- NA $= \sin\theta_{as} = [n_1^2 - n_2^2]^{1/2} / \cos\gamma$
- NA $= \sin\theta_{as} \cos\gamma = [n_1^2 - n_2^2]^{1/2}$
- $\sin\theta_{as} = NA/\cos\gamma$

AA$= \theta_{as} = \sin^{-1} [NA/\cos\gamma]$

PROBLEM NO:3

An OF in air has NA of 0.4. Compare the AA for Meridional rays with that for skew rays which change direction by 100^0 at each reflection.

Optical Fiber Modes and Configurations:

TYPES OF FIBERS:

- Based on no. of modes propagating, fibers are classified into 2 types. 1] SINGLE MODE FIBERS 2] MULRI MODE FIBERS.
- Based on RI’s variation in core cladding region, fibers are classified into 2 types. 1] STEP INDEX FIBER 2] GRADED INDEX FIBER.

STEP INDEX FIBER [SIF]:

- An OF with a core of constant Refractive Index n_1 and cladding of slightly lower Refractive Index n_2 is known as Step Index Fiber.
- The Refractive Index profile for these types of fiber makes a step change at core- cladding interface.
- The Refractive Index profile may be defined as

$$n(r) = \begin{cases} n1, & r < a \quad (core) \\ n2, & r \geq a \; (cladding) \end{cases}$$

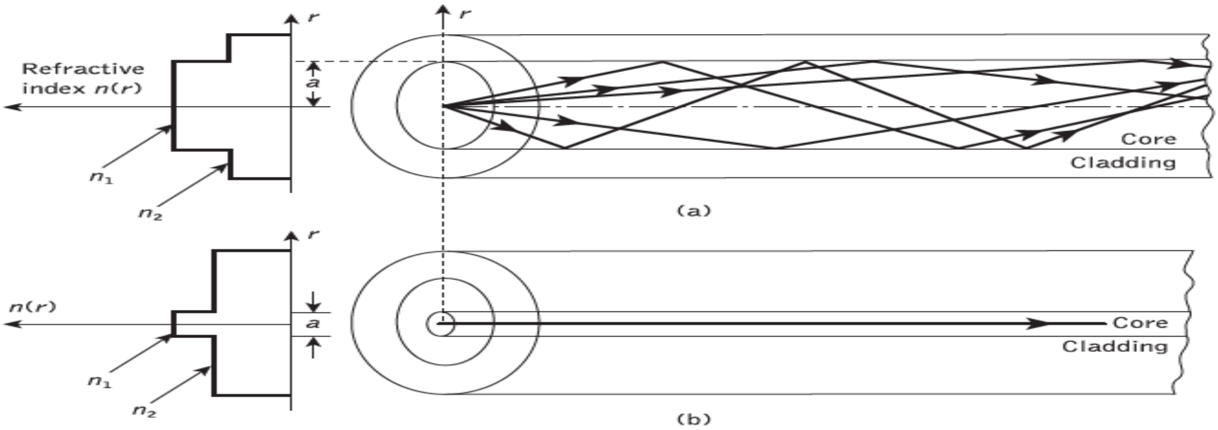


Figure: The refractive index profile and ray transmission in step index fibers: (a) multi mode step index fiber (b) single mode step index fiber

2 Major types of Step Index Fibers:

- 1] SINGLE MODE SIF [SMSIF] 2] MULTIMODE SIF [MMSIF]
- SINGLE MODE SIF [SMSIF]: Which allows the propagation of only one mode typically HE_{11} & hence the core diameter must be of the order of 1.10 μm
- MULTIMODE SIF [MMSIF]: Which allows the propagation of many modes & hence the core diameter must be of the order of 50 μm or greater. GRADED INDEX FIBER [GIF]:
- GIF do not have a constant RI 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.

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

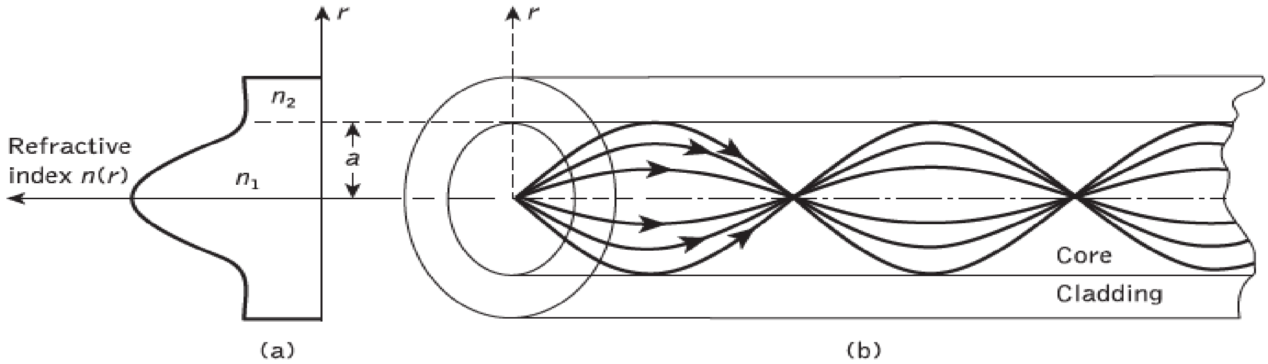


Figure: The refractive index profile and ray transmission in a multimode graded index fiber.

- Δ = RRID
- α = profile parameter
- If $\alpha = \bar{\alpha}$ ... S I Profile
- If α = 2 ... Parabolic RI profile
- If α = 1 ... Triangular RI profile.
- Generally parabolic index profile is used for best results.

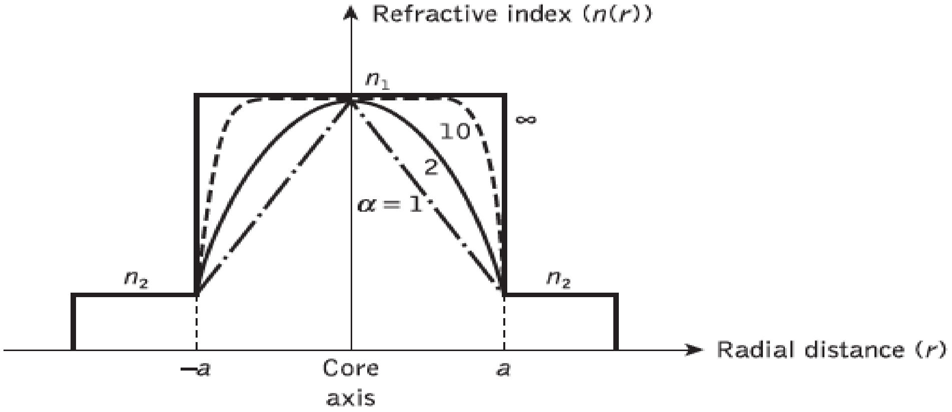


Figure: Possible fiber refractive index profiles for different values of α

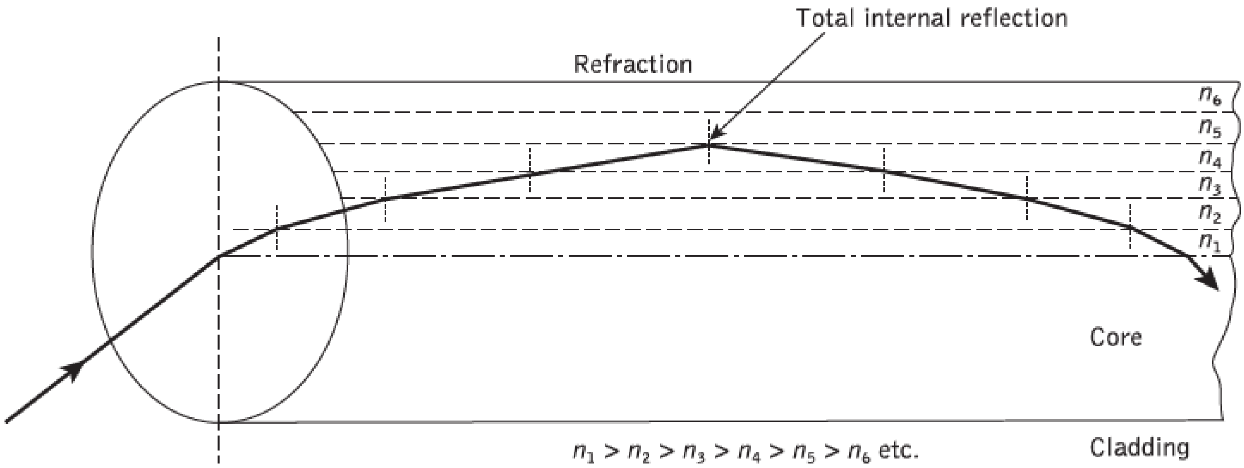


Figure: An expanded ray diagram showing refraction at the various high to low index interfaces within a graded index fiber, giving an overall curved ray path

- The rays travelling close to the fiber axis have shorter path when compared with rays which travel in to outer regions of the core.
- The rays travelling near region of higher RI & therefore travel with the lower velocity than the more extreme rays.

A similar situation exists for skew rays which follow longer helical paths.

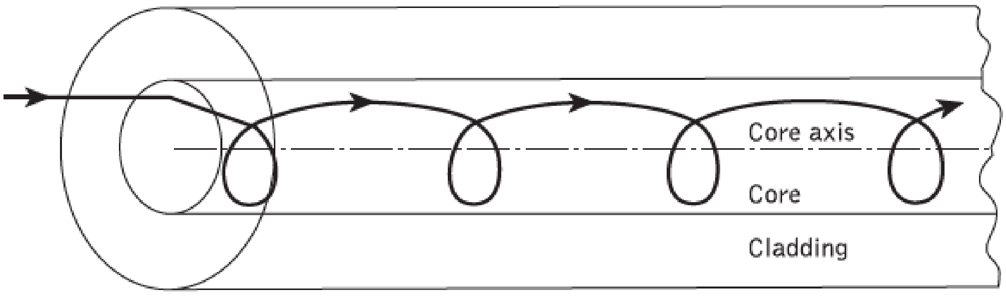


Figure: A helical skew ray path within a graded index fiber

ELECTROMAGNETIC MODE THEORY FOR OPTICAL PROPAGATION:

- For the propagation of light in an optical fiber, EM wave theory must be considered.
- EM wave propagation is provided by Maxwell's equations.

For medium with zero conductivity, vector relationships may be written in terms of electric field E, magnetic field H, electric flux density D, magnetic flux density B as

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t}$$

$$\nabla \cdot \mathbf{D} = 0$$

$$\nabla \cdot \mathbf{B} = 0$$

The four field vectors are related by the relations:

$$\mathbf{D} = \varepsilon \mathbf{E}$$
$$\mathbf{B} = \mu \mathbf{H}$$

where ε is the dielectric permittivity and μ is the magnetic permeability of the medium.

Substituting for **D** and **B** and taking the curl of Equations gives:

$$\nabla \times (\nabla \times \mathbf{E}) = -\mu\varepsilon \frac{\partial^2 \mathbf{E}}{\partial t^2}$$

$$\nabla \times (\nabla \times \mathbf{H}) = -\mu\varepsilon \frac{\partial^2 \mathbf{H}}{\partial t^2}$$

Then using the divergence conditions of Equations with the vector identity:

$$\nabla \times (\nabla \times \mathbf{Y}) = \nabla(\nabla \cdot \mathbf{Y}) - \nabla^2(\mathbf{Y})$$

We obtain the nondispersive wave equations:

$$\nabla^2 \mathbf{E} = \mu\varepsilon \frac{\partial^2 \mathbf{E}}{\partial t^2}$$

and

$$\nabla^2 \mathbf{H} = \mu\varepsilon \frac{\partial^2 \mathbf{H}}{\partial t^2}$$

- PROPAGATION VECTOR/CONSTANT: The propagation vector which gives the direction of propagation and rate of change of phase with distance.

If λ is optical wave length in a vacuum then propagation constant k=2π/ λ

KEY MODAL CONCEPTS [MODES IN PLANAR GUIDE]:

Before progressing with a discussion of mode theory in circular optical fibers, let us qualitatively examine the appearance of modal fields in planar dielectric slab waveguide shown in figure.

- The planar guide is the simplest form of optical wave guide.
- It consists of a slab of direction with Refractive Index n_1 sandwiched between 2 regions of low Refractive Index n_2
- Consider a plan wave propagating in the direction of the ray path with in the guide.
- If the RI with in the guide is n_1 , the optical wave length in this region is reduced to λ / n_1 and propagation constant is increased to kn_1

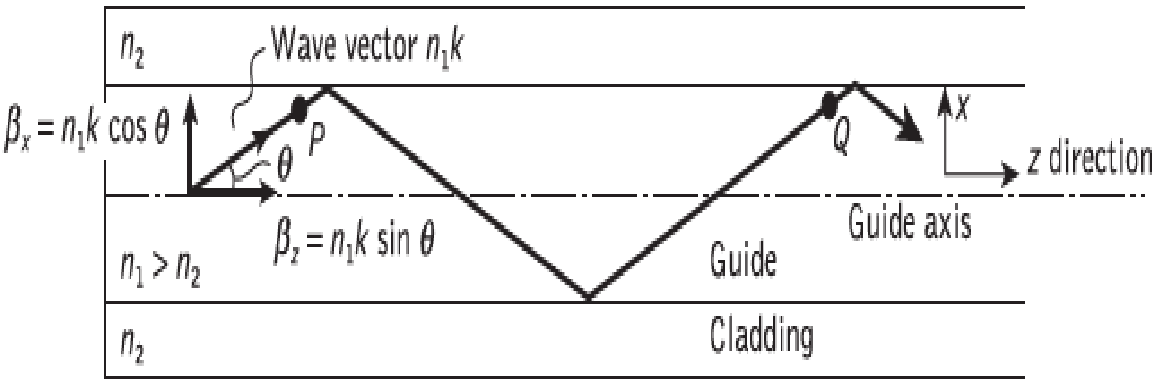


Figure: The formation of a mode in a planar dielectric guide - a plane wave propagating in the guide shown by its wave vector or equivalent ray – the wave vector is resolved into components in the *z* and *x* directions

- If θ is angle between the wave propagation vector & guide axis, the plane wave can be resolved into 2 components.
- Plane wave propagates in Z & X directions.
- The component of propagation constant in Z-direction is given by $\beta_z = n_1 k \text{ Cos}\theta$
- The component of propagation constant in X-direction is given by $\beta_x = n_1 k \text{ Sin}\theta$

The component of plane wave in x-direction is reflected at interface between higher and lower RI media.

- When total phase change [after 2 successive reflections at the upper and lower interfaces] is equal to $2m\pi$ radians, standing wave will be obtained.
- Interference of 2 plan waves is shown in figure below.
  - Interference forms the lowest order standing wave where the electric field is maximum at the canter of the guide decaying towards zero at boundary between the guide & cladding.
- The electric field penetrates some distance into cladding.

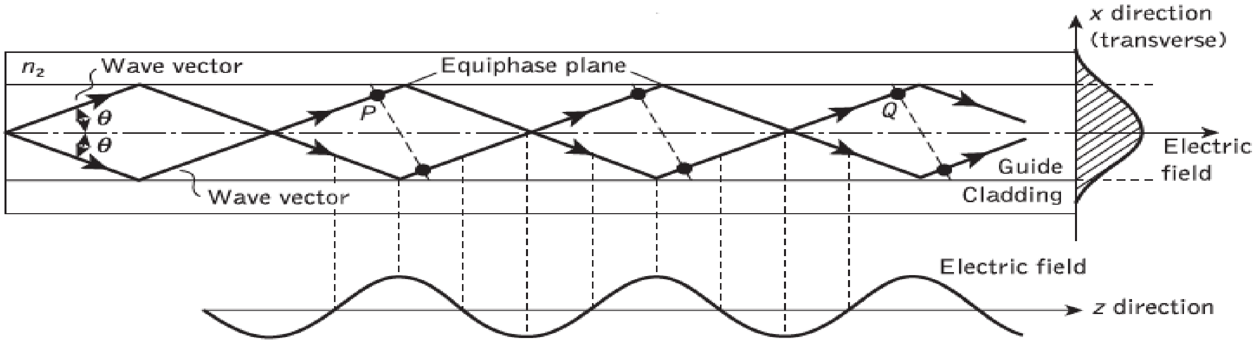


Figure: The formation of a mode in a planar dielectric guide - the interference of plane waves in the guide forming the lowest order mode (m = 0)

- When light is described as an electromagnetic wave it consists of a periodically varying electric field E & magnetic field H which are oriented at right angles to each other.
- The traverse modes:
  TE: When the electric field is perpendicular to the direction of propagation, E_z =0, but magnetic field H is in direction of propagation, then it is known as TE mode.
  TM: When the magnetic field is perpendicular to the direction of propagation, H_z =0, but magnetic field E is in direction of propagation, then it is known as TM mode.
- TEM: When both E_z & H_z are zeros then it is known as TEM mode.
- In TE_m, TM_m modes, m specifies the order of mode.
- The order of a mode is equal to the number of field zero's across the guide.
- The plot shows that the electric fields of the guided modes are not completely confined to the central dielectric slab. But, instead, they extend partially into the cladding.

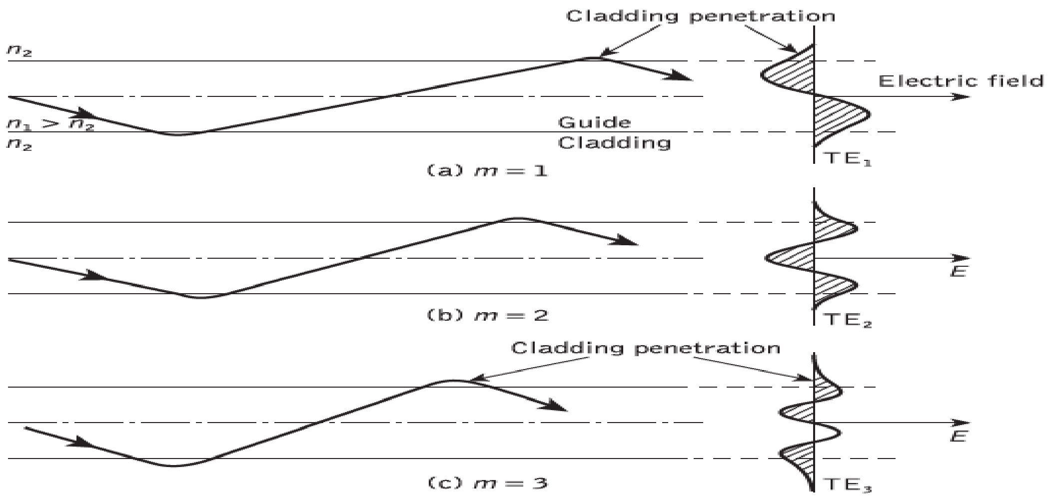


Figure: Physical model showing the ray propagation and the corresponding transverse electric (TE) field patterns of three lower order models (m = 1, 2, 3) in the planar dielectric guide

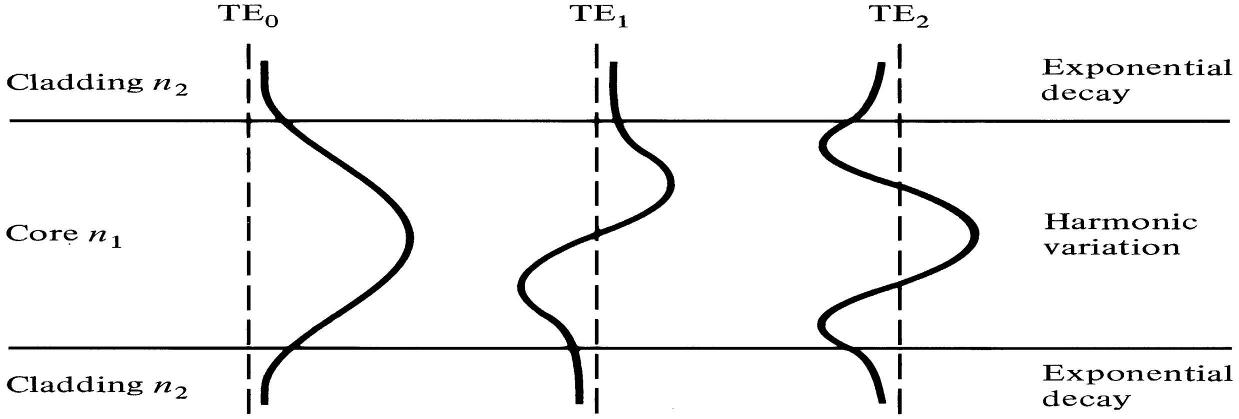


Figure: Electric field distributions for several of the Low-order guided mode fields in a symmetrical-slab waveguides

For lower order modes the fields are tightly concentrated near the center of the slab, with little penetration into the cladding region.

For higher order modes, the fields are distributed more towards the edges of the guide and penetrate farther into the cladding region.

MODE THEORY FOR CIRCULAR WAVEGUIDES

- At the time of solving Maxwell's equations for planar waveguide, only TE & TM modes are obtained.
- But cylindrical waveguides are obtained in 2 dimensions rather than one. Core Cladding boundary conditions leads to a coupling between electric and magnetic field components. This gives rise to hybrid modes.
- The hybrid modes are designed as HE_{lm} or EH_{lm} depending up on whether the components of H or E make the large contribution to the transverse field & required 2 integers, l & m to specify the modes.

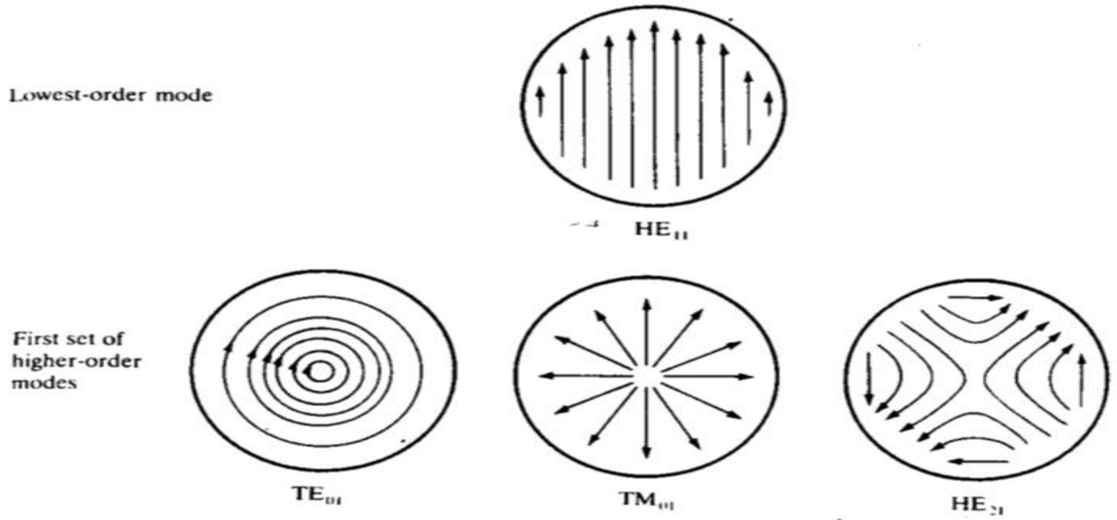


Figure: Cross sectional views of the transverse electric field vectors for the four lowest-order modes in a step-index fiber.

LINEARLY POLARIZED MODES:

- These modes can be analyzed by weakly guiding fiber approximation.
- In this approximation propagation constant of mode pairs $HE_{l-1,m}$ & $EH_{l+1,m}$ are very similar.
- This means that these modes are degenerate modes.
- The superposition of these degenerative modes characterized common propagation constant corresponds to particular LP modes.
- The linear combination of degenerate modes forms LP modes.

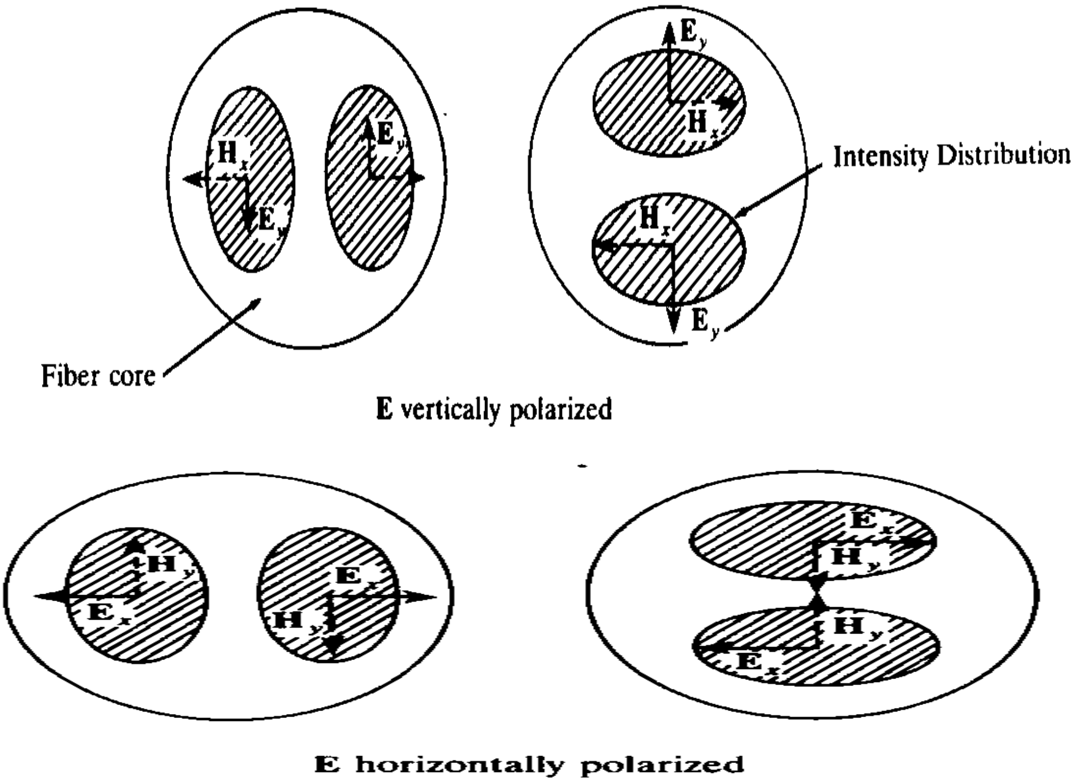
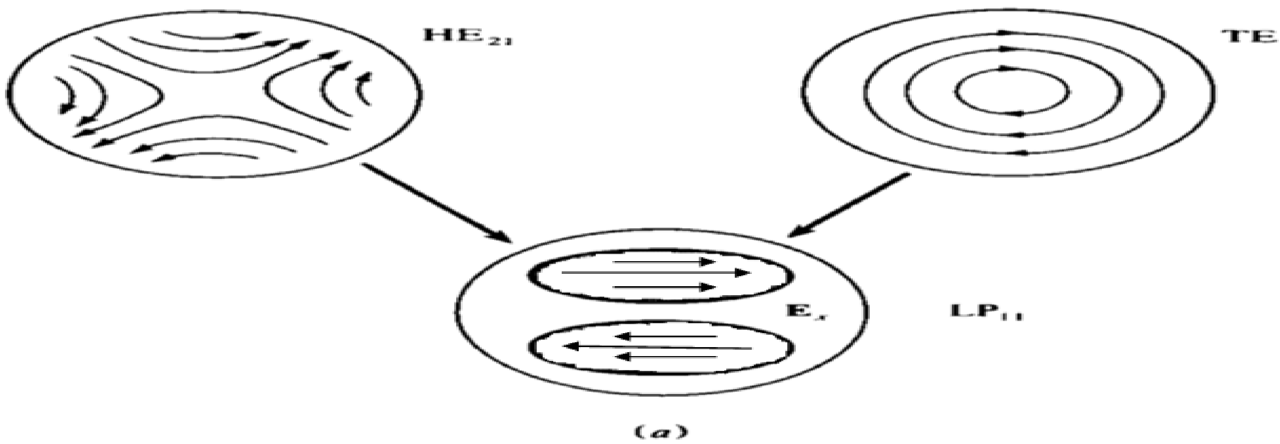


Figure: The four possible transverse electric field and magnetic field directions and the corresponding intensity distributions for the LP_{11} mode



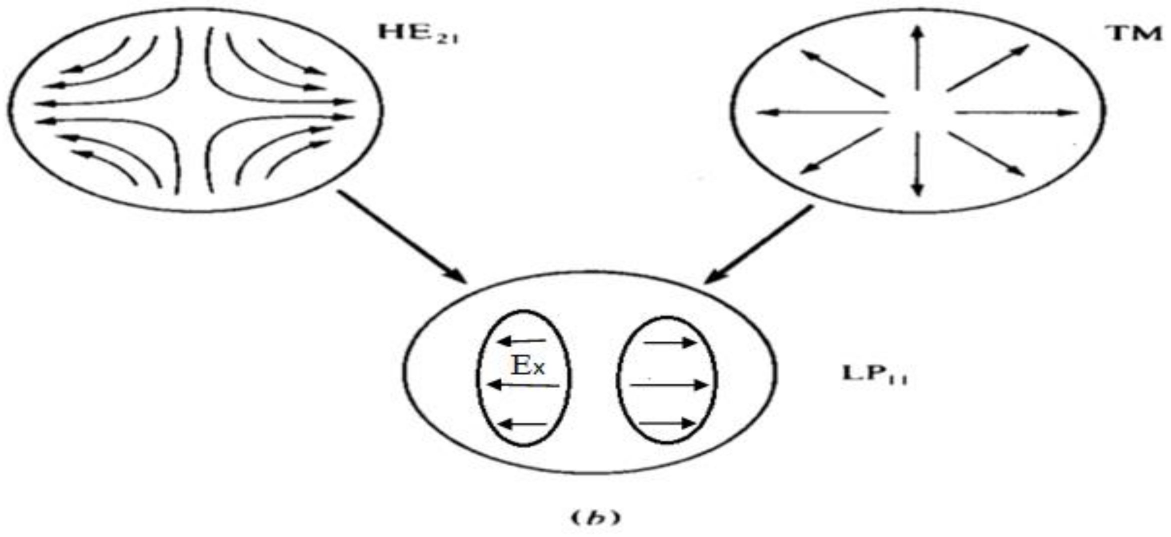


Figure: Composition of two LP_{11} modes from exact modes and their transverse electric field and intensity distributions

- The LP_{0m} mode is derived from HE_{1m} mode.
- Each LP_{1m} modes is derived from TE_{0m} TM_{0m} HE_{0m} modes.

Table Correspondence between the lower order linearly polarized modes and the traditional exact modes from which they are formed

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)	$HE_{l+1,m}$, $EH_{l-1,m}$

LEAKAGE MODES:

- These leakage modes are confined to the core region and attenuated by continuously radiating their power out of the core as they propagating along the fiber.
- The radiation field basically results from the optical power that is outside the fiber acceptance angle being refracted out of the core.
- Because of the finite radius of the cladding, some of this radiation gets trapped in the cladding, thereby causing cladding modes to appear.
- As the core and cladding modes propagates along the fiber, mode coupling occurs between cladding modes and higher order core modes causes Leaky modes.

V-NUMBER [OR] NORMALISED FREQUENCY:

- It is a dimensionless parameter & is defined as $v = ka[n_1^2 - n_2^2]^{1/2}$ where a = radius of core n_1 = RI of core , n_2 = RI of core, k=Bessel function.
- V-number can also be expressed in terms of NA & Δ
- $V = 2\pi a [NA] / \lambda$
- $V = 2\pi a n_1 [2\Delta]^{1/2} / \lambda$

  V-number changes from mode to mode. MODE VOLUME:
- The total no. of guided modes or mode volume for SIF is $M_S = v^2/2$
- For GIF $M_G = [\alpha/\alpha+2]^* v^2/2$
- For α=2, $M_G = [2/2+2]^* v^2/2$
- $= v^2/4$

PROBLEM 1.1:

A MMSIF with a core diameter of 80μm and a RRID of 1.5% is operating at a wave length of 0.85 μm. If the core RI is 1.48. Estimate [a] the normalized frequency for the fiber [b] the no. of guided modes.

SOLUTION:

- Given data 2a=80 μm

  a=40 μm λ=0.85

  μm n_1 = 1.48

  Δ=1.5%=0.015

$V = 2\pi a n_1 [2\Delta]^{1/2} / \lambda$

$= 2\pi\ 40\ \mu m\ 1.48[2*0.015]^{1/2} / 0.85\ \mu m$

$= 76$

$M_S = v^2/2 = [76]^2/2 = 2873 \sim= 3000$ guided modes.

PROBLEM 1.2:

A GIF has a core with a parabolic RIP which has a diameter of 50 µm. The fiber has a NA of 0.2. Estimate the total no. of guided modes propagating in fiber when it is operating at a wave length of 1 µm.

SOLUTION:

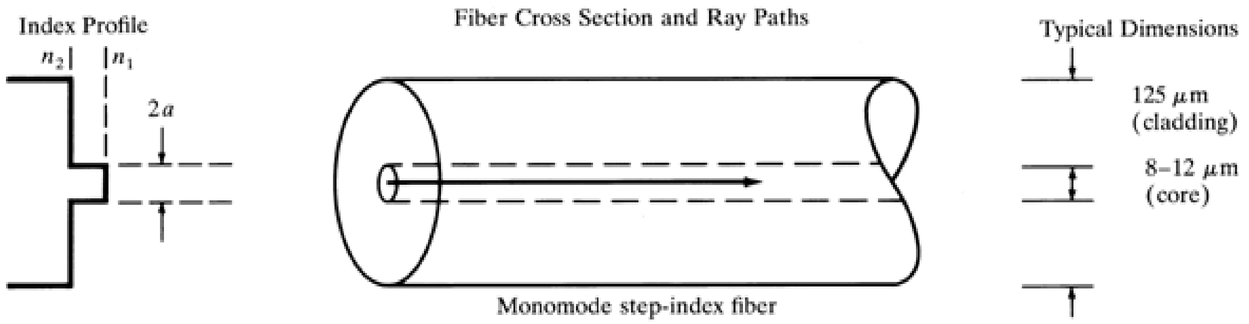
- Given data: $\alpha = 2$, $2a = 50$ µm NA=0.2 $\lambda = 1$ µm.
- Wkt $V = 2\pi a\,[NA] / \lambda$
- $= 2\pi * 25\ \mu m * 0.2 / 1\ \mu m$
- $= 31.4$
- Mode volume For $\alpha=2$, $M_G = v^2/4$
- $= [31.4]^2/4$
- $= 247$

CUT-OFF NORMALIZED FREQUENCY:

- Normalized frequency at cut-off wavelength is known as cut off normalized frequency.
- $V_C = 2\pi a\,[NA] / \lambda_C$
- $= 2\pi a\, n_1\, [2\Delta]^{1/2} / \lambda_C$

SINGLE MODE FIBERS:

- The advantage of single mode propagation over multimode propagation is that the signal dispersion caused by delay difference between different modes may be avoided.



- For the transmission of a single mode the fiber must be designed to allow propagation of only one mode while the other modes are attenuated by leakage or absorption.
  Multimode fibers do not lend themselves to the propagation of single mode due to difficulties of maintaining single mode operation.
- For single mode operation, only the fundamental LP_{01} mode can exist.
- For LP_{11} mode propagation the cut-off normalized frequency $V_C = 2.405$.
- For LP_{01} mode normalized frequency "v" should be in range of $0 \leq v < 2.405$ as there is no cut-off for the fundamental mode.

- "v" for the fiber may be adjusted by reduction of core radius & RRID.
- In order to obtain single mode operation with maximum v number of 2.4, the single mode fiber must have smallest core diameter.
- It is possible to achieve single mode operation with slightly larger core diameter by reducing RRID of the fiber.
- Both these factors create difficulties with single mode fibers.
- Small core diameter rises problem with launching light in to fiber & with field jointing.
- Reduced RRID present difficulties in the fiber fabrication process.
- Graded Index fiber may also be designed for single mode operation.
- The V to support a single mode in a graded index fiber is given by $V_c = 2.405[1 + 2/\alpha]^{1/2}$

PROBLEM 1.3:

- Estimate the maximum core diameter for an OF with RRID 1.5% & core RI 1.48. Fiber is operating at wave length 0.85 μm. Further estimate the new core diameter for single mode operation when RRID is reduced by a factor of 10.
  SOLUTION:
- Given data λ=0.85 μm
  $n_1 = 1.48$
  Δ=1.5%=0.015 V_c
  =2.4

  $V = 2\pi a n_1 [2\Delta]^{1/2} / \lambda$

  $a = v^* \lambda / 2\pi n_1 [2\Delta]^{1/2}$
  $= 2.4^* 0.85\ \mu m / 2\pi\ 1.48 [2^* 0.015]^{1/2}$
  $= 1.3\ \mu m$

  Maximum core diameter for single mode operation = 2*a=2* 1.3 μm = 2.6 μm
- Reducing RRID by 10 ➔ Δ=0.0015
  - $a = v^* \lambda / 2\pi n_1 [2\Delta]1/2$
- $= 2.4^* 0.85\ \mu m / 2\pi\ 1.48 [2^* 0.0015]1/2$
- $= 4.0\ \mu m$

Maximum core diameter for single mode operation = 2*a

=2* 4.0 μm = 8.0 μm

Determine the core diameter for the GIF to exhibit single mode operation when the core RI is 1.5 and wavelength is 1.3μm respectively, with the RRID of 1.0%. Assume α=2.

SOLUTION:

- The maximum value of v for single mode operation is
- $V = 2.405[1 + 2/\alpha]^{1/2}$
  $= 2.405[2]^{1/2}$

λ=1.3 μm

n_1 = 1.5

Δ=1.0%=0.01

- $a = v^* \lambda / 2\pi n_1 [2\Delta]^{1/2}$
  $= 2.4 [2]^{1/2} * 1.3$ μm$/ 2\pi\ 1.5 [2*0.01]^{1/2}$
  = 3.3 μm
- Maximum core diameter for single mode operation = 2*a=2* 3.3 μm = 6.6 μm

CUTOFF WAVE LENGTH:

- The single mode operation only occurs above a theoretical cut-off wave length λ_C given by
- $\lambda_C = 2\pi a n_1 [2\Delta]^{1/2} / v_c$ → [1]
- Cut-off wave length is a wave length above which a particular fiber becomes single mode.
- Wkt $\lambda = 2\pi a n_1 [2\Delta]^{1/2} / v$ → [2]
- [1]/[2] → $[\lambda_C / \lambda] = [v / v_C]$
- Wkt for SIF $v_C = 2.405$
- $\lambda_C = [v \lambda / 2.405]$

- Practical transmitting systems are generally operated close to effective λ_C in order to enhance the fundamental mode confinement.

PROBLEM 1.5:

- Determine the cut-off wave length for the SIF to exhibit single mode operation when the core RI and radius are 1.46 & 4.5μm respectively, with the RRID 0.25%.

  SOLUTION:
- a=4.5 μm n_1 = 1.46

  Δ=0.25%=0.0025
  - $V_C = 2.405$
  - $\lambda_C = 2\pi a n_1 [2\Delta]^{1/2} / V_c$
  - $= 2\pi\ 4.5$ μm$* 1.46* [2\ 0.0025]^{1/2} / 2.405$
  - = 1.214 μm
  - Hence the fiber is single moded to a wavelength of 1.214 μm.

MODE FIELD DIAMETER:

- A fundamental parameter of a single mode fiber is Mode field diameter [MFD].
- MFD is determined from the mode field distribution of fundamental fiber mode, and is function of optical source wave length, core radius & RIF of the fiber.
- In single mode fiber all the light will not propagates through the fiber.
- MFD is used to predict the fiber properties such as splice loss, bending loss, cut-off wave length & wave guide dispersion.
- A variety of models have been proposed for characterizing and measuring MFD. These includes far-field scanning, near-field scanning, transverse offset, variable aperture in the far field, knife-edge & mask methods.
- A standard technique to find the MFD is to measure the far-field intensity distribution $E^2(r)$ and then calculate the MFD using
  MFD=

$$2W_0 = 2\left[\frac{2\int_0^\infty r^3E^2(r)\,dr}{\int_0^\infty rE^2(r)\,dr}\right]^{1/2}$$

- Where $2W_O$ = [spot size or mode field radius] full width of far field distribution.
- E^2 [r]= far field intensity distribution
- r= radius
- E_O = field at zero radius

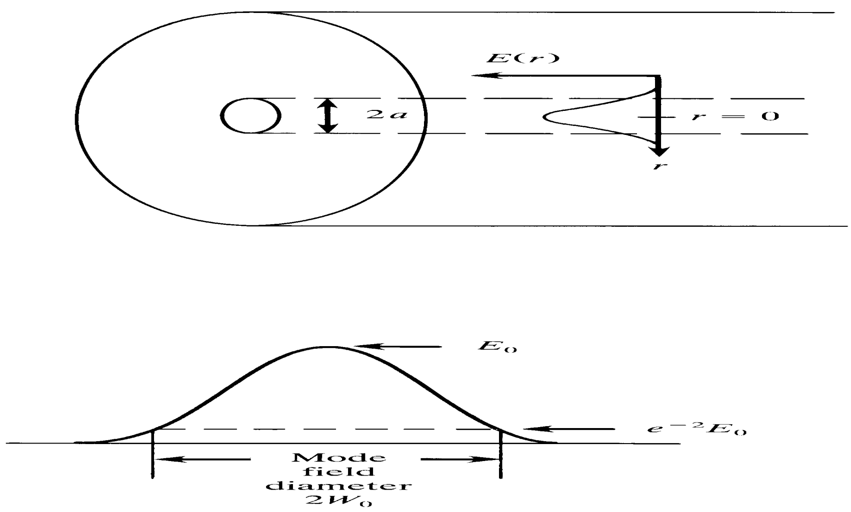


Figure: Distribution of light in a single mode fiber above its cutoff wavelength. For a Gaussian distribution the MFD is given by the 1/e^2 width of the optical power

- MFD is an important parameter for characterizing single mode fiber properties which takes into account that the wavelength dependent field penetration in to fiber cladding.
- The relative spot size $[w_0/a]=0.65+1.619V^{-3/2} + 2.879V^{-1}$
- The condition V=2.405 for single mode operation yields $[w_0/a]=1.1005$. As V decreases from 2.4, the spot size increases. The spot size thus becomes progressively larger than the core radius a and extends father into the cladding.
- As a result V become smaller, most of the optical power losses from the cladding.
- For v=2 only 75% of light confined to core. If v increases this % also increases.

<u>EFFECTIVE REFRACTIVE INDEX</u>:

- The rate of change of phase of a fundamental LP_{01} mode propagating along a straight fiber is determined by the phase propagation constant β.
- β is directly related to wave length of LP_{01} mode. $\beta \lambda_{01} = 2\pi$.
- The effective RI [or] phase index [or] normalized phase change co-efficient n_{eff} is defined by the ratio of propagation constant of fundamental mode to that of vacuum propagation constant
- $n_{eff} = \beta/k$
- In normal fiber, at long wave lengths, the MFD is large compared to core diameter & hence the electric field extends far into the cladding region. In this case $\beta \sim= n_2k$ & $n_{eff} \sim= n_2$. Most of the power transmitted in cladding material.
- At short wave lengths, the field is concentrated in the core region, $\beta \sim= n_1k$ & $n_{eff} \sim= n_1$.
- The β in single mode fiber varies over interval $n_2k < \beta < n_1k$.
- The n_{eff} in single mode fiber varies over interval $n_2 < n_{eff} < n_1$.
- The relationship between n_{eff} & normalized propagation constant is

$b= ([\beta/k]^2 - n_2^2)/[n_1^2 - n_2^2]$

- $= [\beta^2 - n_2^2k^2]/[n_1^2k^2 - n_2^2k^2]$
- $= ([\beta+n_2k]*[\beta-n_2k])/([n_1k+n_2k]*[n_1k-n_2k])$
- $b= ([\beta+n_2k]*[\beta-n_2k])/([n_1k+n_2k]*[n_1k-n_2k])$
- When field is concentrated in core region $n_1k \sim= \beta$ then
- $b= ([\beta+n_2k]*[\beta-n_2k])/([\beta+n_2k]*[n_1k-n_2k])$
- $b= [\beta-n_2k]/[n_1k-n_2k]$
- $= ([\beta/k]-n_2)/[n_1-n_2]$
- $= (n_{eff}-n_2)/[n_1-n_2]$

b is dimensionless parameter, varies between 0 & 1.

PROPAGATION MODES IN SM FIBERS:

- In a SM fiber there are actually 2 independent, degenerate propagation modes.
- These modes are very similar, but their polarization modes are orthogonal. There may be Horizontal [H] & Vertical [V] polarizations as shown in fig.
- Either one of 2 polarization modes constitutes the fundamental HE_{11} mode.

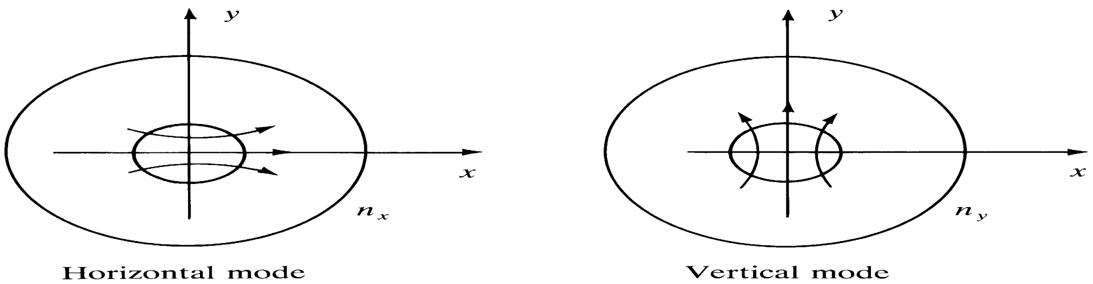


Figure: Two polarizations of the fundamental HE_{11} mode in a single mode fiber

- In general, the electrical field of the light propagating along the fiber is a linear superposition of these two polarization modes and depends on the polarization of the light at the launching point into the fiber.
- In ideal fibers with perfect rotational symmetry, the two modes are degenerative with equal propagation constants & any polarization state injected into the fiber will propagate unchanged.
- In actual fibers there are imperfections, such as asymmetrical lateral stresses, noncircular cores and variations in RI profiles. These imperfections break the circular symmetry of the ideal fiber and lift the degeneracy of the two modes.
- The modes propagate with different phase velocities and the different RI's is called Fiber Birefringence.

- $B_f = n_y - n_x$
- Equivalently we may define as $\beta = k\,[n_y - n_x]$, wkt $k = 2\pi/\lambda$
- If light is injected into the fiber so that both modes are excited, then one will be delayed in phase relative to the other as they propagate. When this phase difference is an integral of 2π, the 2 modes will beat at this point & input polarization state will be reproduced. The length over which this beating occurs is the FIBER BEAT LENGTH $L_p = 2\pi/\beta$
- Wkt $\beta = k\,[n_y - n_x] = kB_f$
- $L_p = 2\pi/kB_f$
- $B_f = \lambda/L_p$

PROBLEM 1.6:

A step index fiber with a suitably large core diameter for ray theory considerations has core and cladding refractive indices of 1.44 and 1.42 respectively. Calculate the acceptance angle in air for skew rays which change direction by 150° at each reflection.

PROBLEM 1.7:

A step index fiber in air has a numerical aperture of 0.16, a core refractive index of 1.45 and a core diameter of 60 μm. Determine the normalized frequency for the fiber when light at a wavelength of 0.9 μm is transmitted. Further, estimate the number of guided modes propagating in the fiber.

PROBLEM 1.8:

A multimode step index fiber has a relative refractive index difference of 1% and a core refractive index of 1.5. The number of modes propagating at a wavelength of 1.3 μm is 1100. Estimate the diameter of the fiber core.

PROBLEM 1.9:

A single mode step index fiber has a core diameter of 4 μm and a core refractive index of 1.49. Estimate the shortest wavelength of light which allows single mode operation when the relative refractive index difference for the fiber is 2%.

PROBLEM 1.10:

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

PROBLEM 1.11:

A graded index fiber with a parabolic index profile supports the propagation of 742 guided modes. The fiber has a numerical aperture in air of 0.3 and a core diameter of 70 μm. Determine the wavelength of the light propagating in the fiber.

Further estimate the maximum diameter of the fiber which gives single mode operation at the same wavelength.

PROBLEM 1.12:

A graded index fiber with a core axis refractive index of 1.5 has a characteristic index profile (α) of 1.90, a relative refractive index difference of 1.3% and a core diameter of 40 μm. Estimate the number of guided modes propagating in the fiber when the transmitted light has a wavelength of 1.55 μm, and determine the cutoff value of the normalized frequency for single mode transmission in the fiber.