Basics of optics

Dr. Deblina Biswas

Assistant Professor

I&C Engineering

Dr. B. R Ambedkar National Institute of Technology, Jalandhar

Electromagnetic mode theory for optical propagation

- **Electromagnetic waves**
- The basis for the study of electromagnetic wave propagation is provided by Maxwell's equations
- For a medium with zero conductivity these vector relationships may be written in terms of the electric field E, magnetic field H, electric flux density D and magnetic flux density B as the curl equations:

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

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

the divergence conditions:

$$\nabla \cdot \mathbf{D} = 0 \qquad \text{(no free charges)} \quad \text{(c)}$$

$$\nabla \cdot \mathbf{B} = 0 \qquad \text{(no free poles)} \quad \text{(d)}$$

where ∇ is a vector operator.

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

Cont.

- Substituting for D and B and taking the curl of Eqs (a) and (b) 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 Eqs (c) and (d) 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:

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

where ∇^2 is the Laplacian operator. For rectangular Cartesian and cylindrical polar coordinates the above wave equations hold for each component of the field vector, every component satisfying the scalar wave equation:

$$\boxed{\nabla^2 \psi = \frac{1}{\upsilon_p^2} \frac{\partial^2 \psi}{\partial t^2}}$$

where ψ may represent a component of the E or H field and Vp is the phase velocity(velocity of propagation of a point of constant phase in the wave) in the dielectric medium.

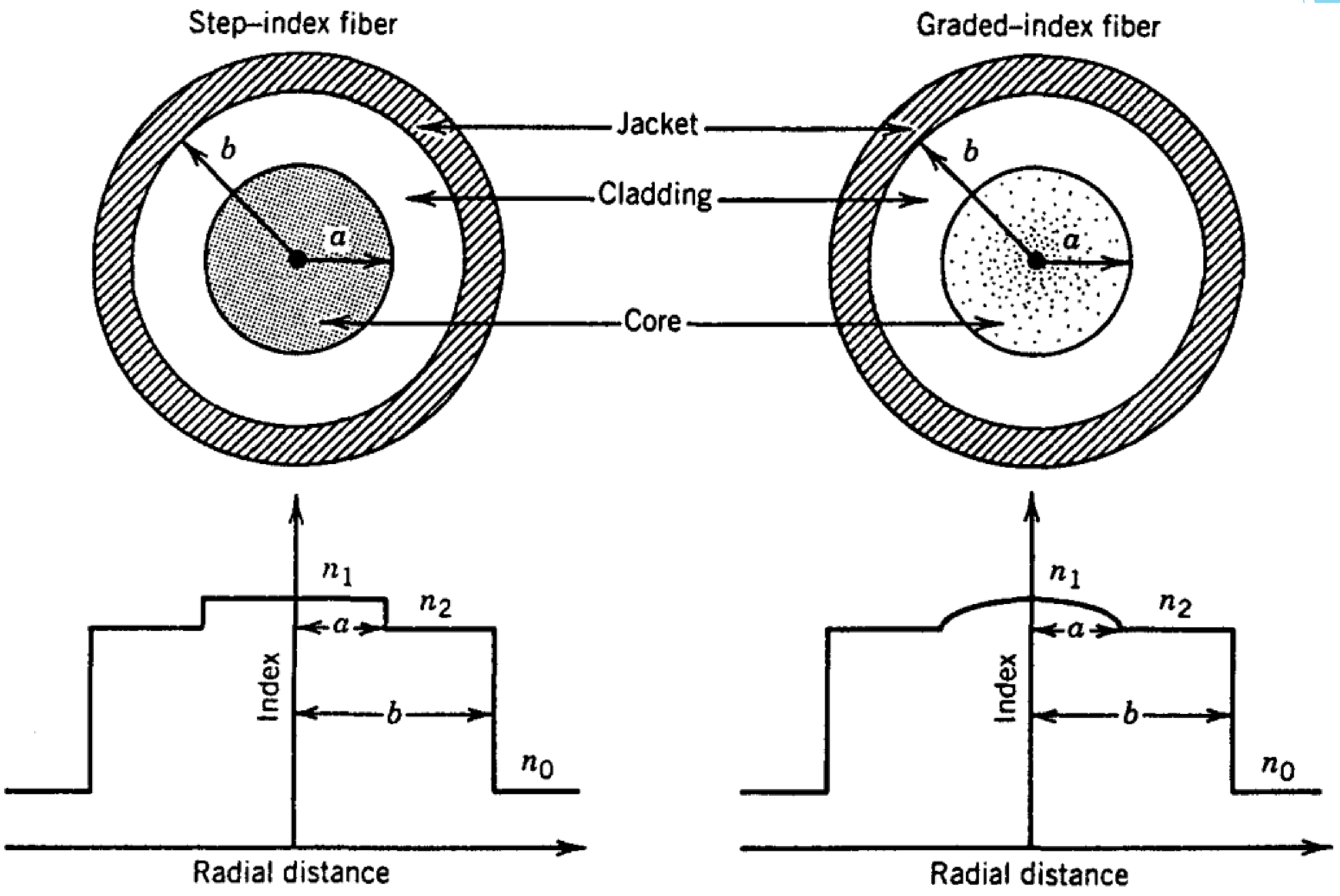
Types of fibers

- Based on index change at the core-cladding interface
- **Step Index**
- **Graded index**

- Based on modes:
- **Single modes**
- **Multi modes**

- Due to an abrupt index change at the core-cladding interface, such fibers are called step-index fibers.
- In a different type of fiber, known as graded-index fiber, the refractive index decreases gradually inside the core.

Cont.



Cross section and refractive-index profile for step-index and graded-index fibers

Step-Index Fibers

- At Air-fiber interface

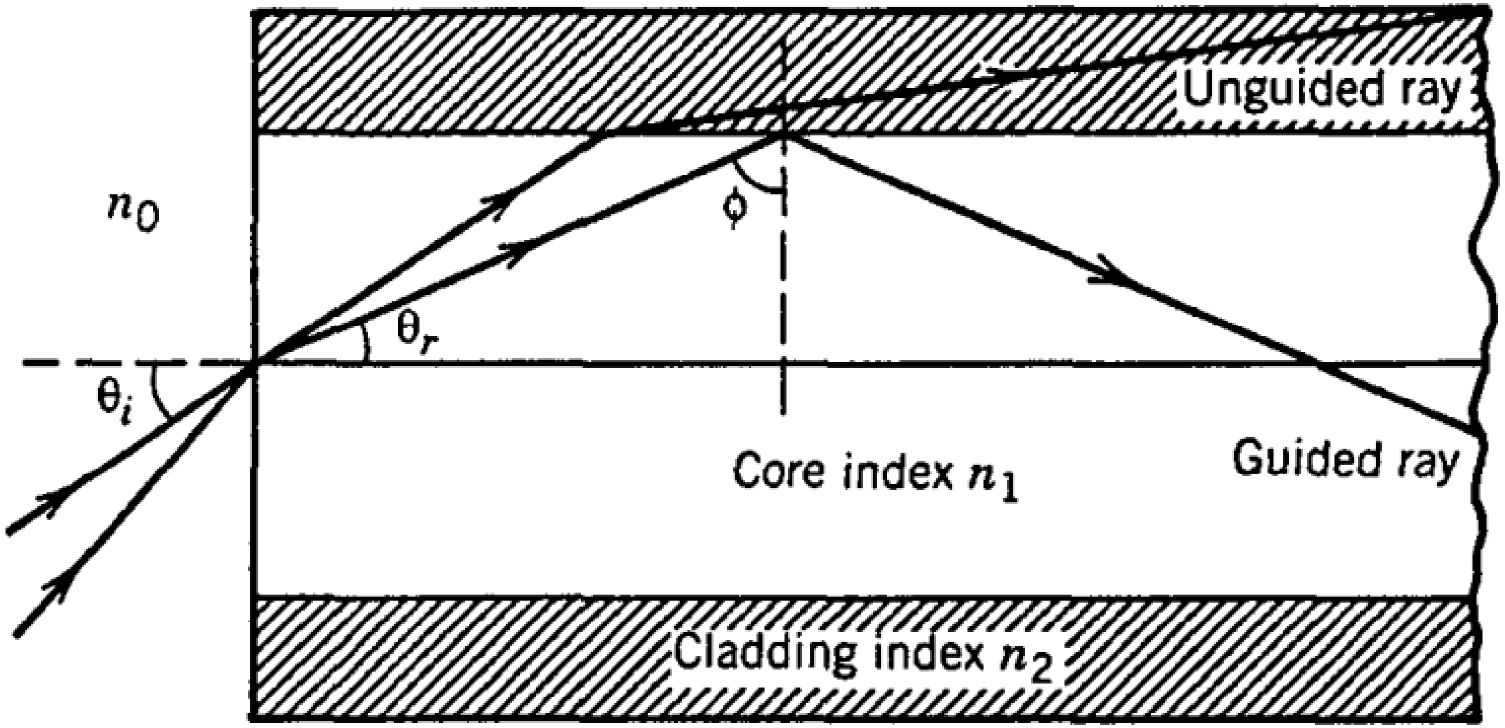
$$n_0 \sin\theta_i = n_1 \sin\theta_r,$$

- critical angle θ_c

$$\sin\phi_c = n_2/n_1,$$

- Putting $\theta_r = \pi/2 - \phi_c$

$$n_0 \sin\theta_i = n_1 \cos\phi_c = (n_1^2 - n_2^2)^{1/2}.$$



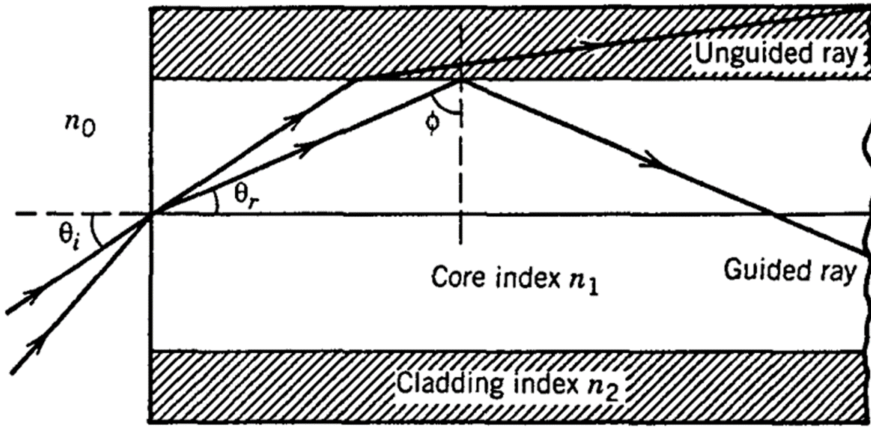
(a)

$$\mathrm{NA} = n_1(2\Delta)^{1/2}, \qquad \Delta = (n_1 - n_2)/n_1,$$

where Δ is the fractional index change at the core-cladding interface. Clearly, Δ should be made as large as possible in order to couple maximum light into the fiber.

Cont.

- However, such fibers are not useful for the purpose of optical communications because of a phenomenon known as multipath dispersion or modal dispersion
- Multipath dispersion can be understood by referring to Figure, where different rays travel along paths of different lengths. As a result, these rays disperse in time at the output end of the fiber even if they were coincident at the input end and traveled at the same speed inside the fiber.
- A short pulse (called an impulse) would broaden as a result of different path lengths.
- Pulse broadening can be estimated by considering the shortest and longest ray paths.
- The shortest path occurs for θi, = 0 and is equal to the fiber length L.
- The longest path occurs for θi, given by Eq. (a) and has a length L/sin θc. By taking the velocity of propagation v = c/n, the time delay is given by



$$n_0 \sin\theta_i = n_1 \cos\phi_c = (n_1^2 - n_2^2)^{1/2}. \quad \text{(a)}$$

$$\Delta T = \frac{n_1}{c}\left(\frac{L}{\sin\phi_c} - L\right) = \frac{L}{c}\frac{n_1^2}{n_2}\Delta.$$

The time delay between the two rays taking the shortest and longest paths is a measure of broadening experienced by an impulse launched at the fiber input.

Cont.

- We can relate ΔT to the information-carrying capacity of the fiber measured through the bit rate B.
- Although a precise relation between B and ΔT depends on many details such as the impulse shape, it is clear that ΔT should be less than the allocated bit slot ($T_B = 1/B$).
- Thus an order-of-magnitude estimate of the bit rate is obtained from the condition $B\Delta T < 1$. We obtain

$$BL < \frac{n_2}{n_1^2}\frac{c}{\Delta}.$$

Graded-index Fibers

- The refractive index of the core in graded-index fibers is not constant but decreases gradually from its maximum value n1 at the core center to its minimum value n2 at the core-cladding interface.
- Most graded-index fibers are designed to have a nearly quadratic decrease and are analyzed by using a-profile, given by

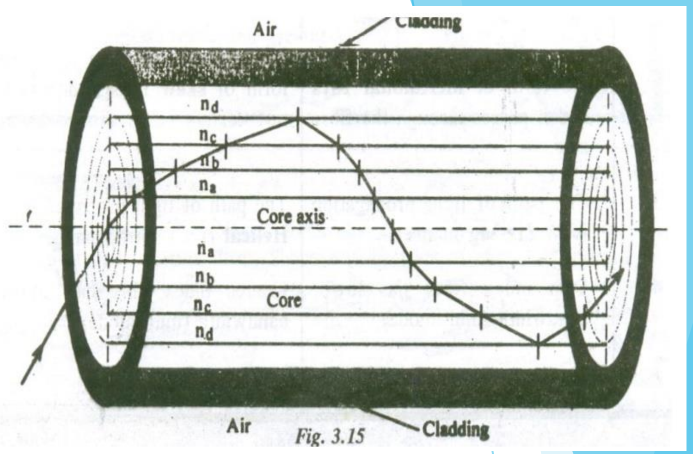
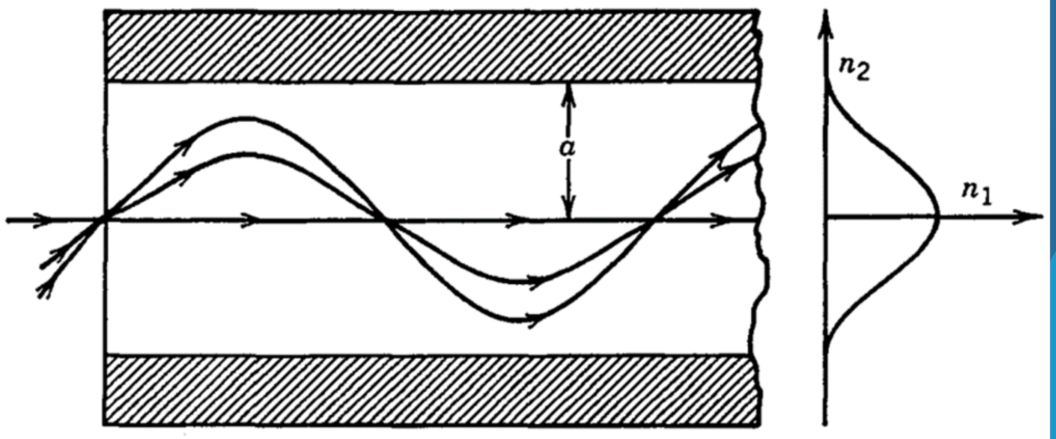


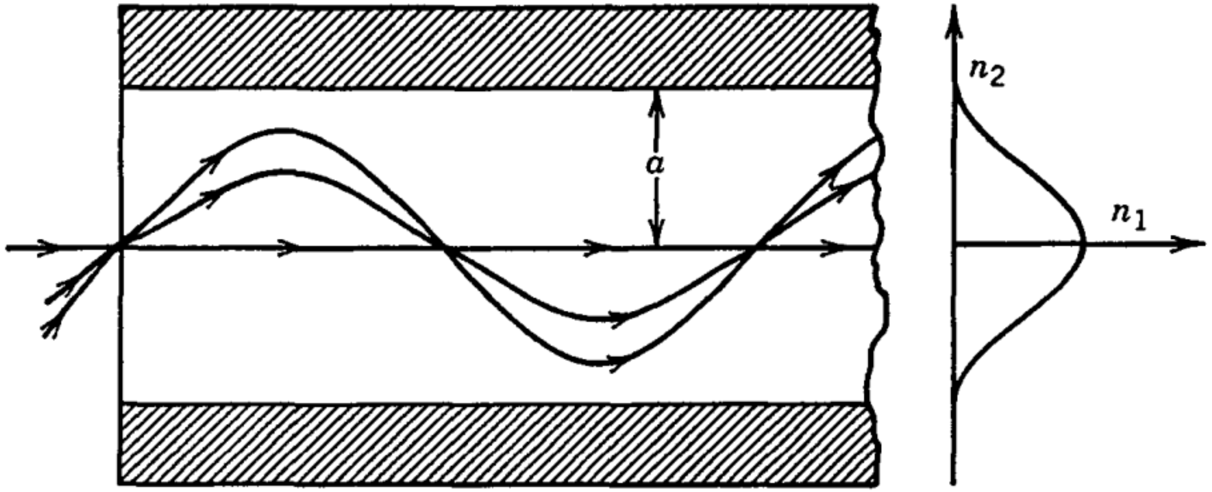
Fig. 3.15



$$n(\rho) = \begin{cases} n_1[1-\Delta(\rho/a)^{\alpha}]; & \rho < a, \\ n_1(1-\Delta) = n_2 \ ; & \rho \geq a, \end{cases}$$

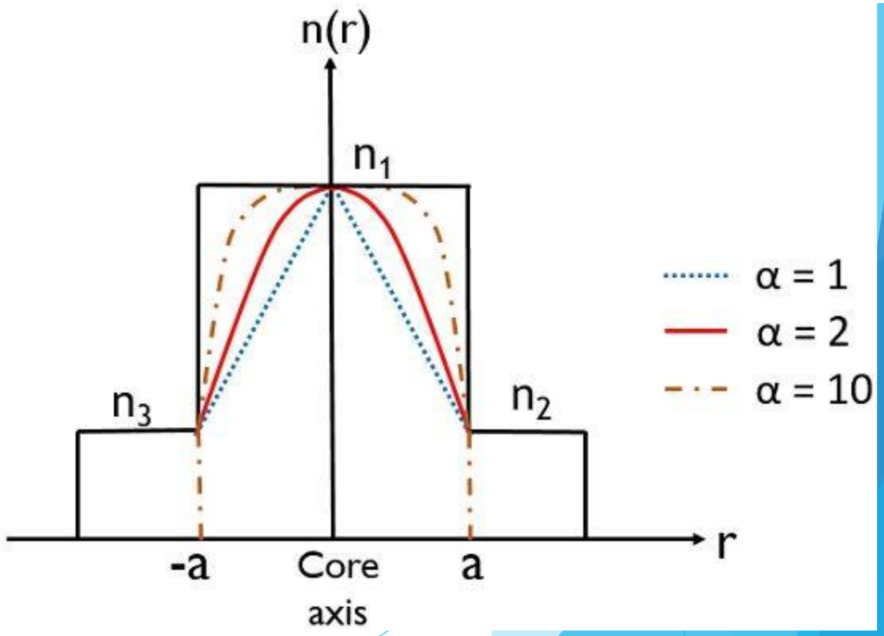
where a is the core radius. The parameter α determines the index profile. A step-index profile is approached in the limit of large α. A parabolic-index fiber corresponds to α = 2. ρ is the radial distance of the ray from the axis

Cont.



- Geometrical optics can be used to show that a parabolic-index profile leads to nondispersive pulse propagation within the paraxial approximation. The trajectory of a paraxial ray is obtained by solving

$$\frac{d^2\rho}{dz^2} = \frac{1}{n}\frac{dn}{d\rho},$$



- where ρ is the radial distance of the ray from the axis. By using Eq. for ρ < a with a = 2, Eq. reduces to an equation of harmonic oscillator and has the general solution

$$\rho = \rho_0 \cos(pz) + (\rho_0'/p)\sin(pz),$$

where $p = (2\Delta/a^2)^{1/2}$

ρo and ρò are the position and the direction of the input ray, respectively.

Cont.

- The minimum dispersion occurs for a = 2(1 -Δ) and depends on Δ as

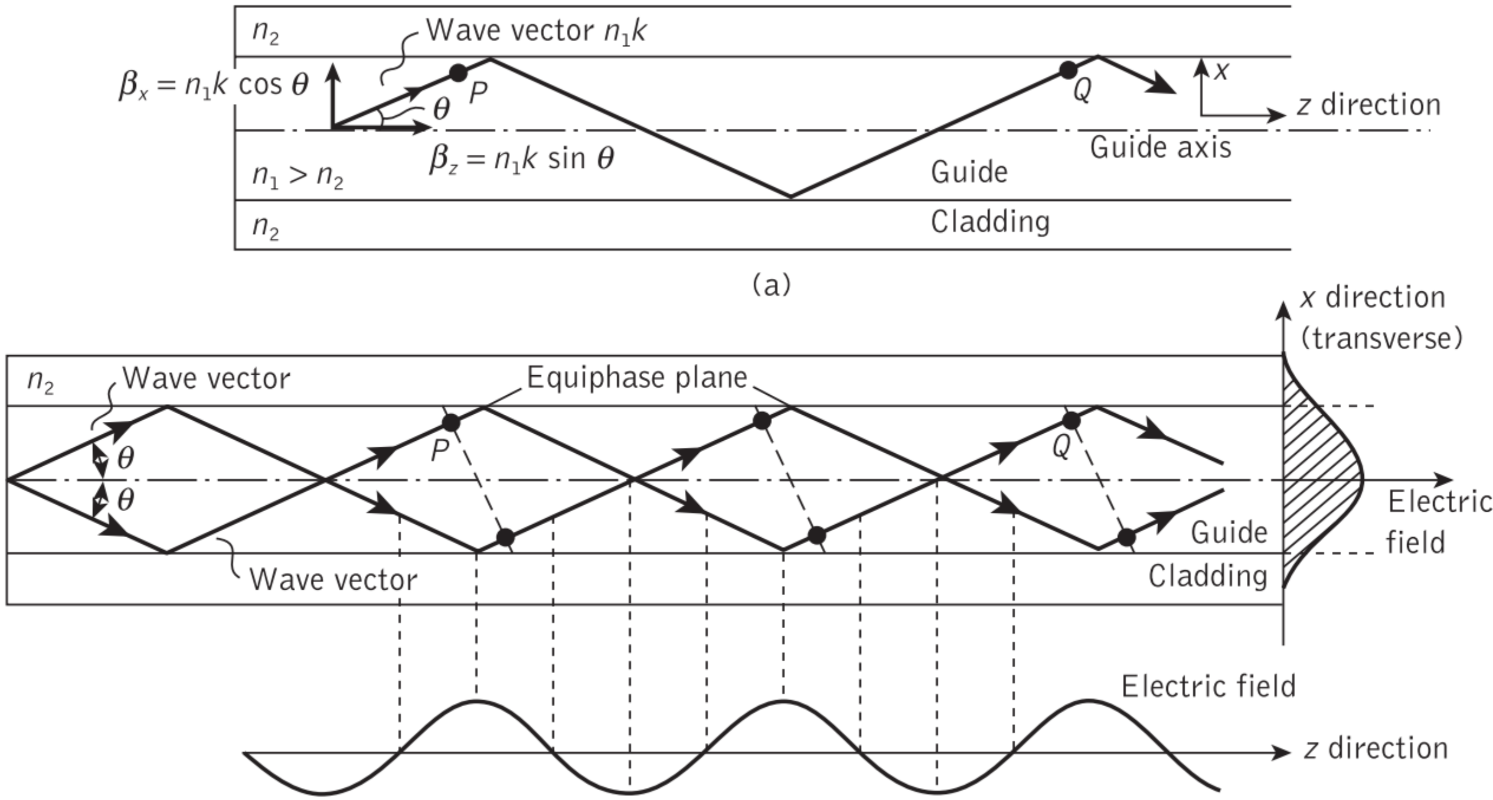
$$\Delta T/L = n_1\Delta^2/8c.$$

- The limiting bit rate-distance product is obtained by using the criterion ΔT < 1/B and is given by

$$BL < 8c/n_1\Delta^2.$$

Modes in a planar guide

- The planar guide is the simplest form of optical waveguide. It may be assumed it consists of a slab of dielectric with refractive index n1 sandwiched between two regions of lower refractive index n2.
- The conceptual transition from ray to wave theory may be aided by consideration of a plane monochromatic wave propagating in the direction of the ray path within the guide
- As the refractive index within the guide is n1, the optical wavelength in this region is reduced to λ/n1, while the vacuum propagation constant is increased to n1k.
- When θ is the angle between the wave propagation vector or the equivalent ray and the guide axis, the plane wave can be resolved into two component plane waves propagating in the z and x directions, as shown in Figure



vacuum phase propagation constant k (where k = |k|) is given by

$$k = \frac{2\pi}{\lambda}$$

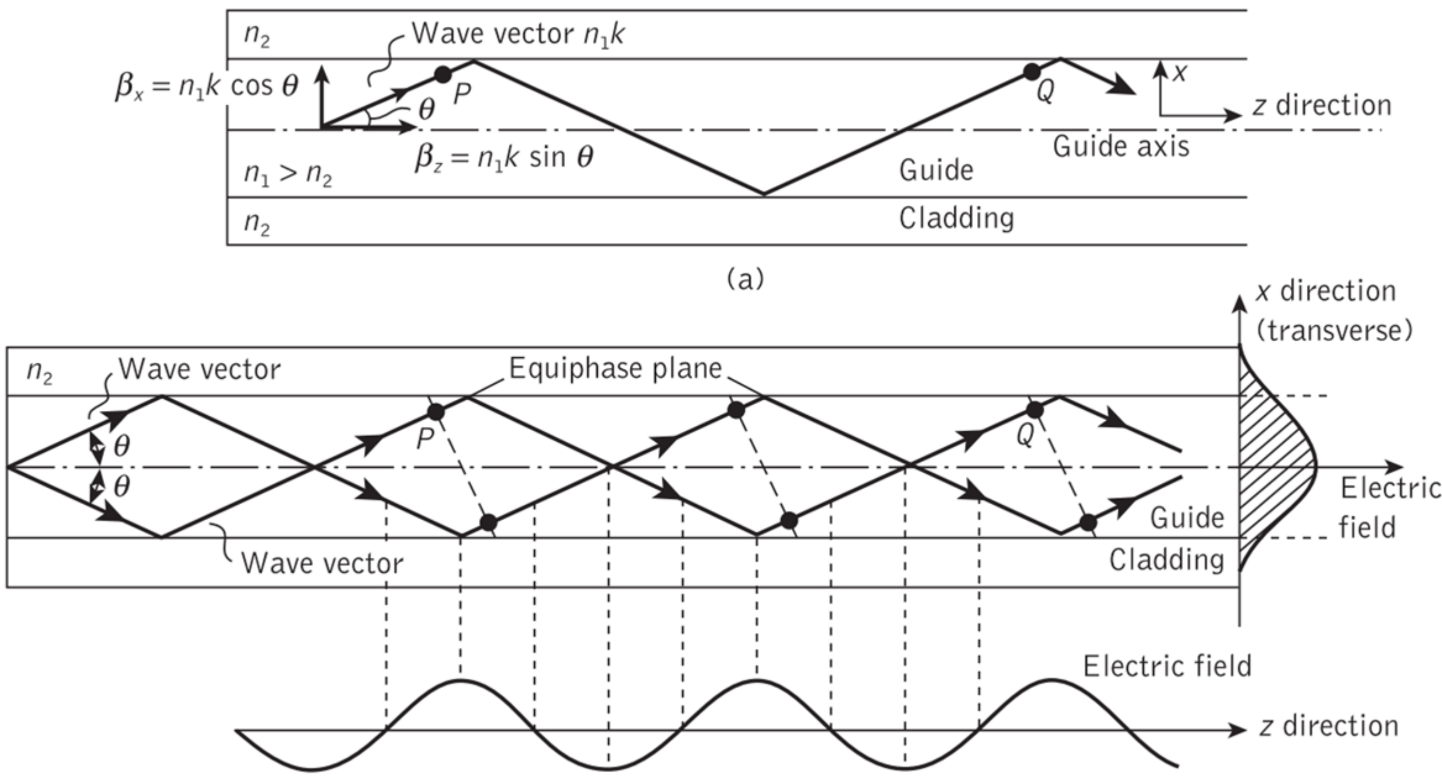
- The component of the phase propagation constant in the z direction βz is given by:

$$\beta_z = n_1 k \cos\theta$$

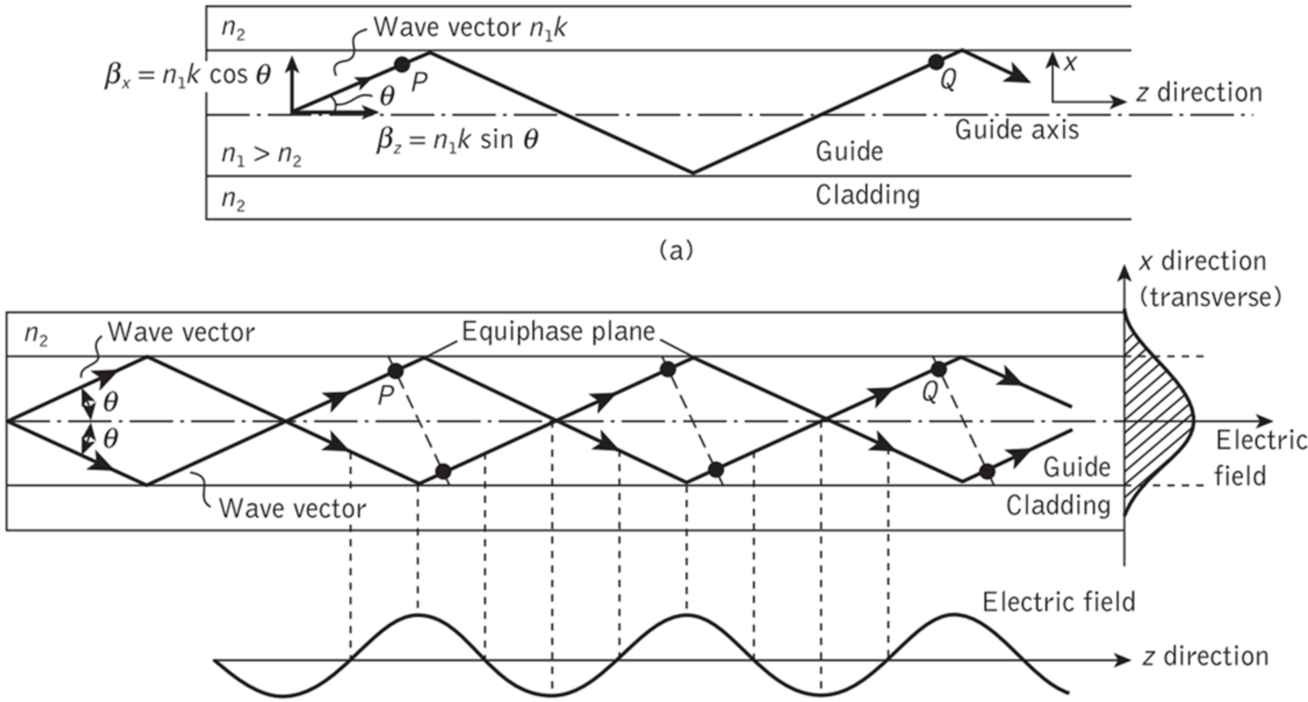
- The component of the phase propagation constant in the x direction βx is:

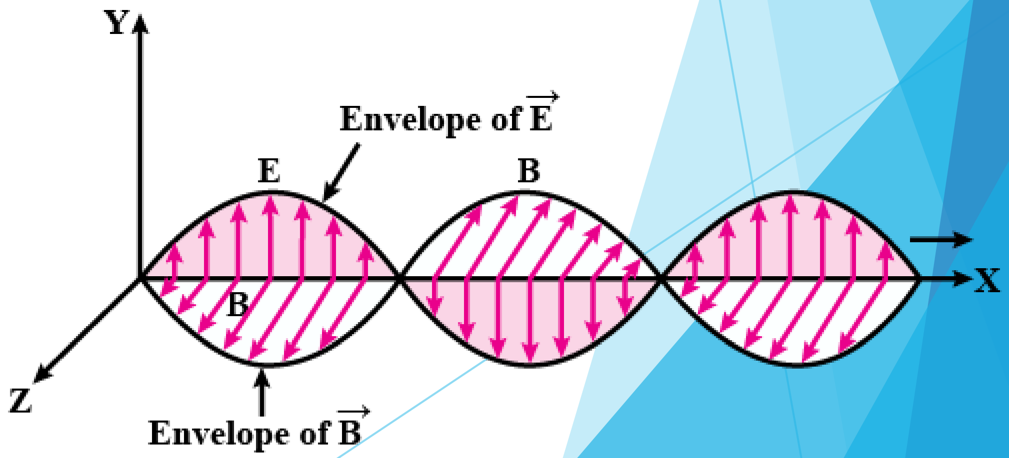
$$\beta_x = n_1 k \sin\theta$$

- The component of the plane wave in the x direction is reflected at the interface between the higher and lower refractive index media.
- When the total phase change* after two successive reflections at the upper and lower interfaces (between the points P and Q) is equal to 2mπ radians, where m is an integer, then constructive interference occurs and a standing wave is obtained in the x direction. This situation is illustrated in Figure (b), where the interference of two plane waves is shown.

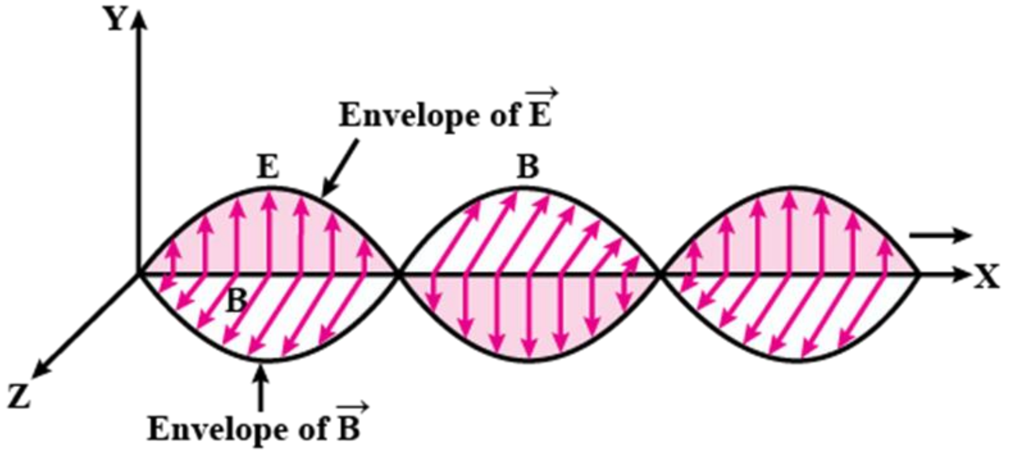


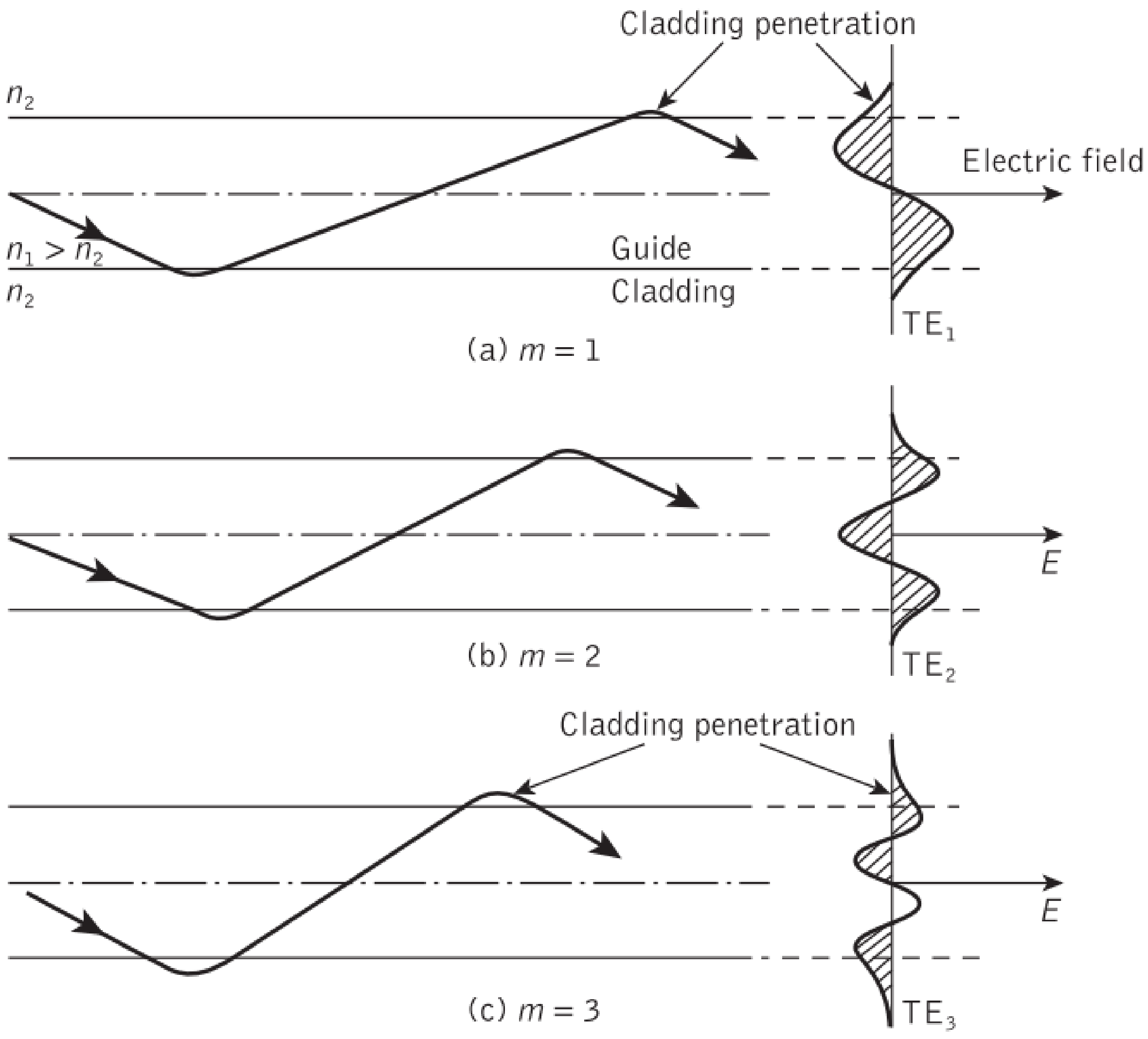
- In this illustration it is assumed that the interference forms the lowest order (where m = 0) standing wave, where the electric field is a maximum at the center of the guide decaying towards zero at the boundary between the guide and cladding.
- However, it may be observed from Figure (b) that the electric field penetrates some distance into the cladding
- The optical wave is effectively confined within the guide and the electric field distribution in the x direction does not change as the wave propagates in the z direction.
- The stable field distribution in the x direction with only a periodic z dependence is known as a mode.
- A specific mode is obtained only when the angle between the propagation vectors or the rays and the interface have a particular value, as indicated in Figure



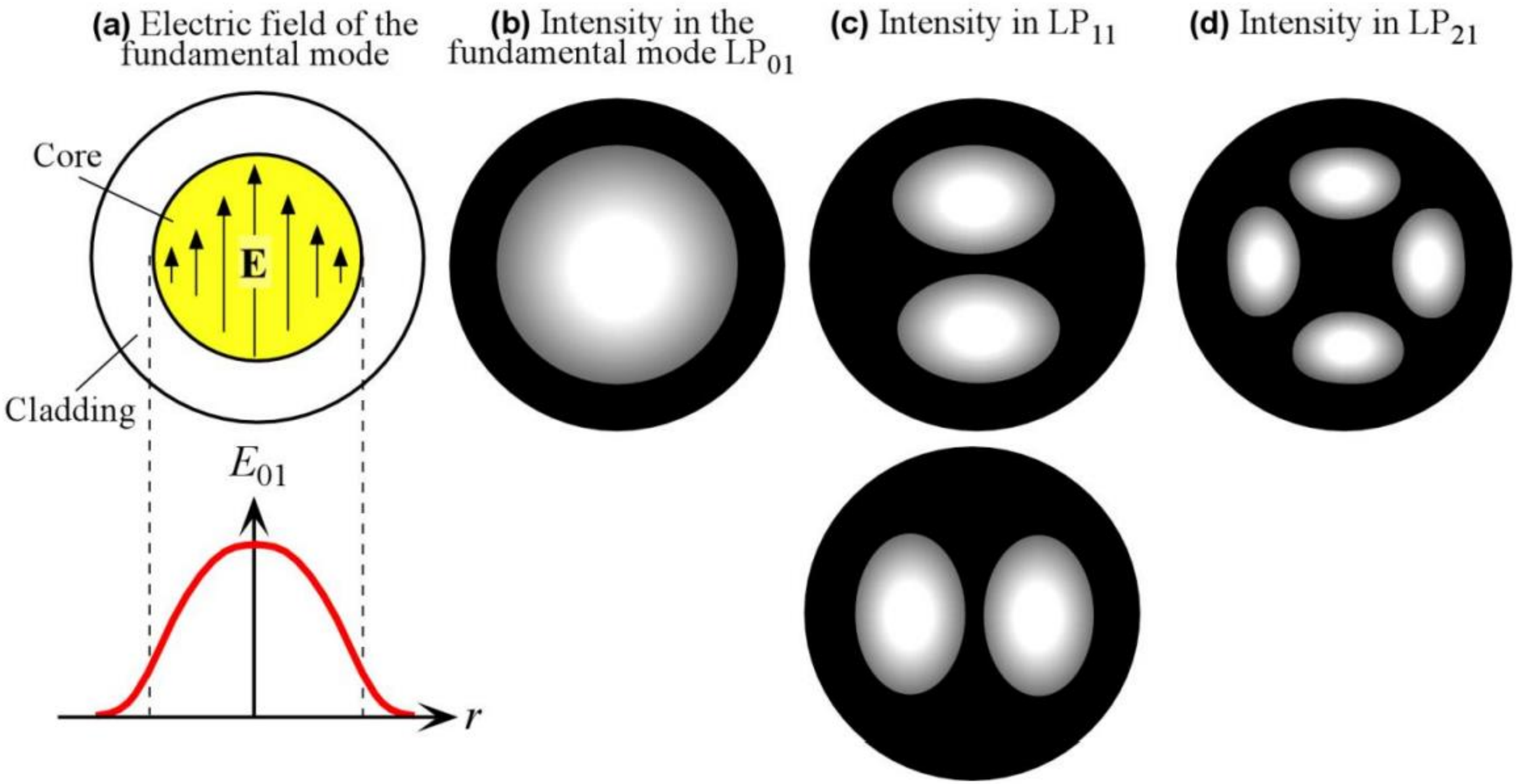


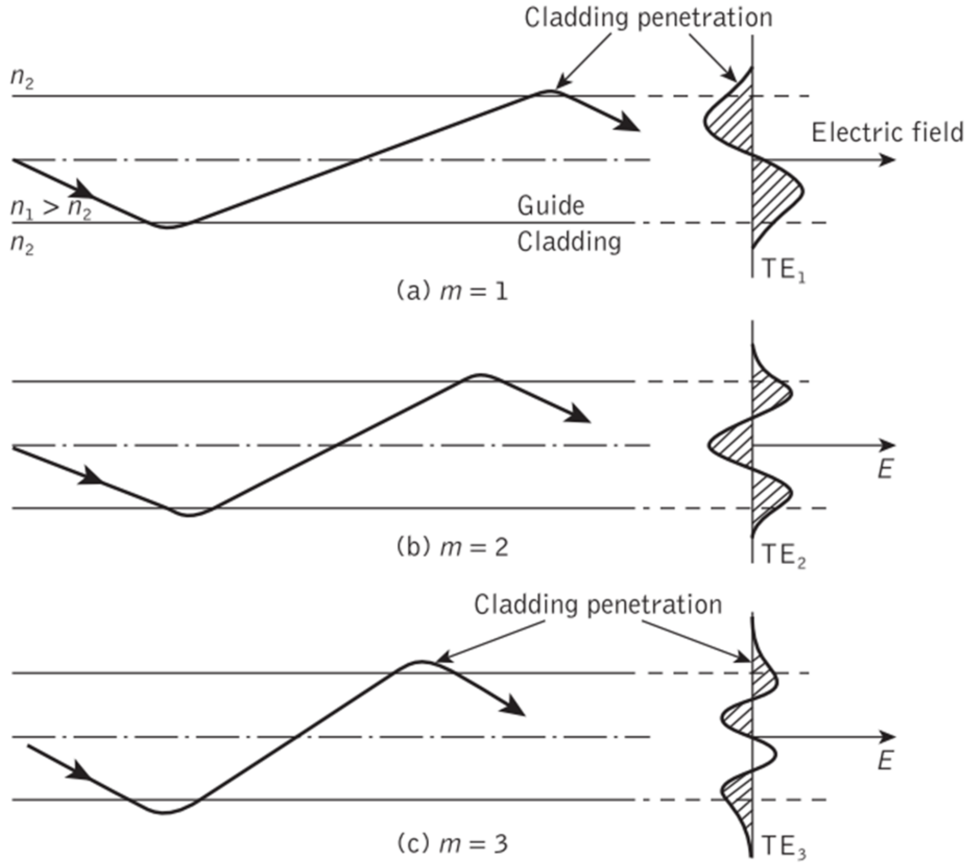
- When light is described as an electromagnetic wave it consists of a periodically varying electric field E and magnetic field H which are orientated at right angles to each other.
- When the electric field is perpendicular to the direction of propagation and hence $E_z = 0$, but a corresponding component of the magnetic field H is in the direction of propagation. In this instance the modes are said to be transverse electric (TE).
- Alternatively, when a component of the E field is in the direction of propagation, but $H_z = 0$, the modes formed are called transverse magnetic (TM).
- The mode numbers are incorporated into this nomenclature by referring to the TE_m and TM_m modes





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





The electric field distribution of the fundamental mode in the transverse plane to the fiber axis z. The light intensity is greatest at the center of the fiber. Intensity patterns in LP01, LP11 and LP21 modes. (a) The field in the fundamental mode. (b)-(d) Indicative light intensity distributions in three modes, LP01, LP11 and LP21.

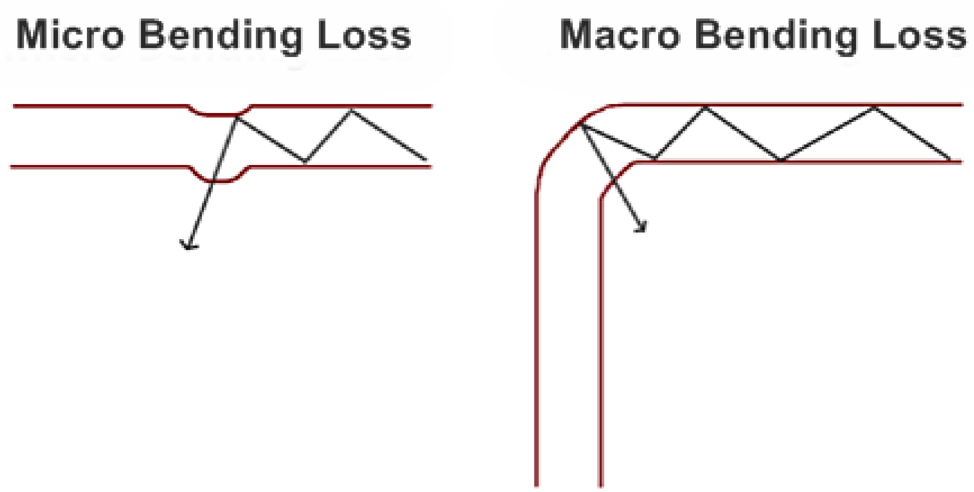
Optical losses

- **Extrinsic Fiber Losses**
- bending losses
- launching losses
- connector losses

- **Intrinsic Fiber Losses**
- Absorption Losses
- Scattering Losses

Bending Losses

- Bending losses are the result of distortion of the fiber from the ideal straight-line configuration.
- While the light is traveling inside the fiber, part of the wave front on the outside of the bend must travel faster than the part of the smaller inner radius of the bend.
- Since this is not possible, a portion of the wave must be radiated away. Losses are greater for bends with smaller radii, particularly for kinks or micro-bends in a fiber.
- An important cause of attenuation is due to micro-bending of the fiber.
- Micro-bending is due to irregularly distributed undulations in the fiber with radii of curvature of a few millimeters and deviations from the mean line of a few micrometers, as exemplified in Figure
- These losses may be avoided by careful cable constructions, avoiding excessive mechanical forces, and controlling the temperature variations of the cable. This is achieved by a loose encasing of the fiber in a plastic sheath or by covering the fiber with soft flexible material



Launching Losses

- The term launching loss refers to an optical fiber not being able to propagate all the incoming light rays from an optical source. These occur during the process of coupling light into the fiber (e.g., losses at the interface stages).
- Rays launched outside the angle of acceptance excite only dissipative radiation modes in the fiber. In general, elaborate techniques have been developed to realize efficient coupling between the light source and the fiber, mainly achieved by means of condensers and focusing lenses.
- The focused input beam of light needs to be carefully matched by fiber parameters for good coupling.
- Equally, once the light is transmitted through the fiber, output fiber characteristics must also match the output target characteristics to be able to couple the largest proportion of the transmitted light.
- This can be done by a suitable focusing lens arrangements in the output end

Connector Losses

- Connector losses are associated with the coupling of the output of one fiber with the input of another fiber, or couplings with detectors or other components.
- The significant losses may arise in fiber connectors and splices of the cores of the joined fibers having unequal diameters or misaligned centers, or if their axes are tilted. Mismatching of fiber diameters causes losses that can be approximated by –10 log(d/D).
- There are other connection losses such as offsets or tilts or air gaps between fibers, and poor surface finishes. Some of these are illustrated in Figure.
- To take full advantage of fiber characteristics in transmission systems of very low intrinsic attenuation, the contribution of losses from other sources must also remain very small. The attenuation as (d) due to coupling efficiency may be expressed as:

$$a_s(d) = -10\ \mathrm{dB}\ \log \eta(d)$$

- where h(d) is the coupling coefficient