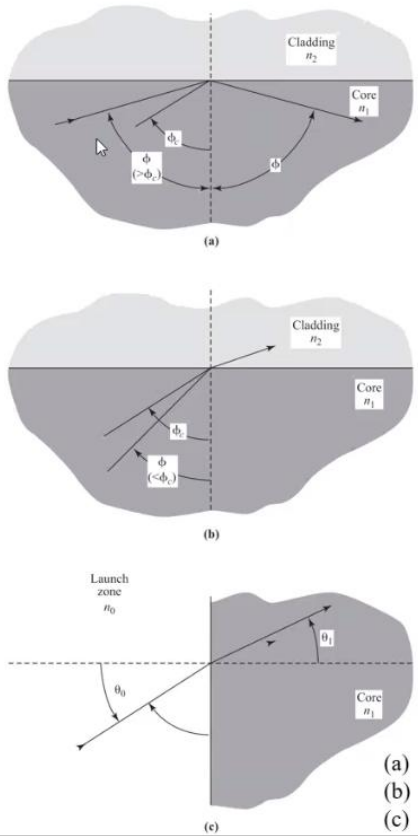
Types of Optical Fibers

Depending upon the material composition of the core, there are two types of fibers used commonly. They are –

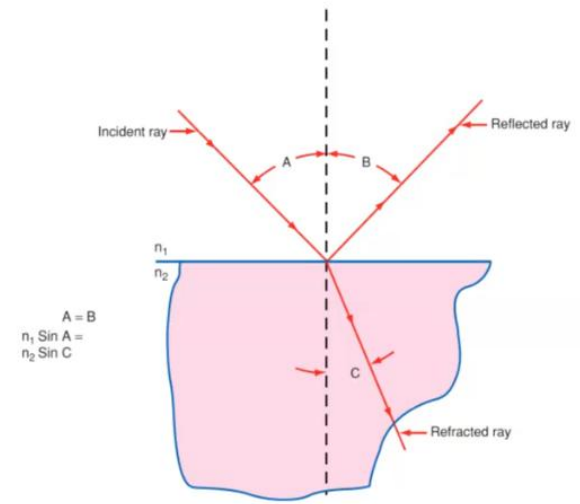
- **Step-index fiber** – The refractive index of the core is uniform throughout and undergoes an abrupt change (or step) at the cladding boundary.
- **Graded-index fiber** – The core refractive index is made to vary as a function of the radial distance from the center of the fiber.

Both of these are further divided into –

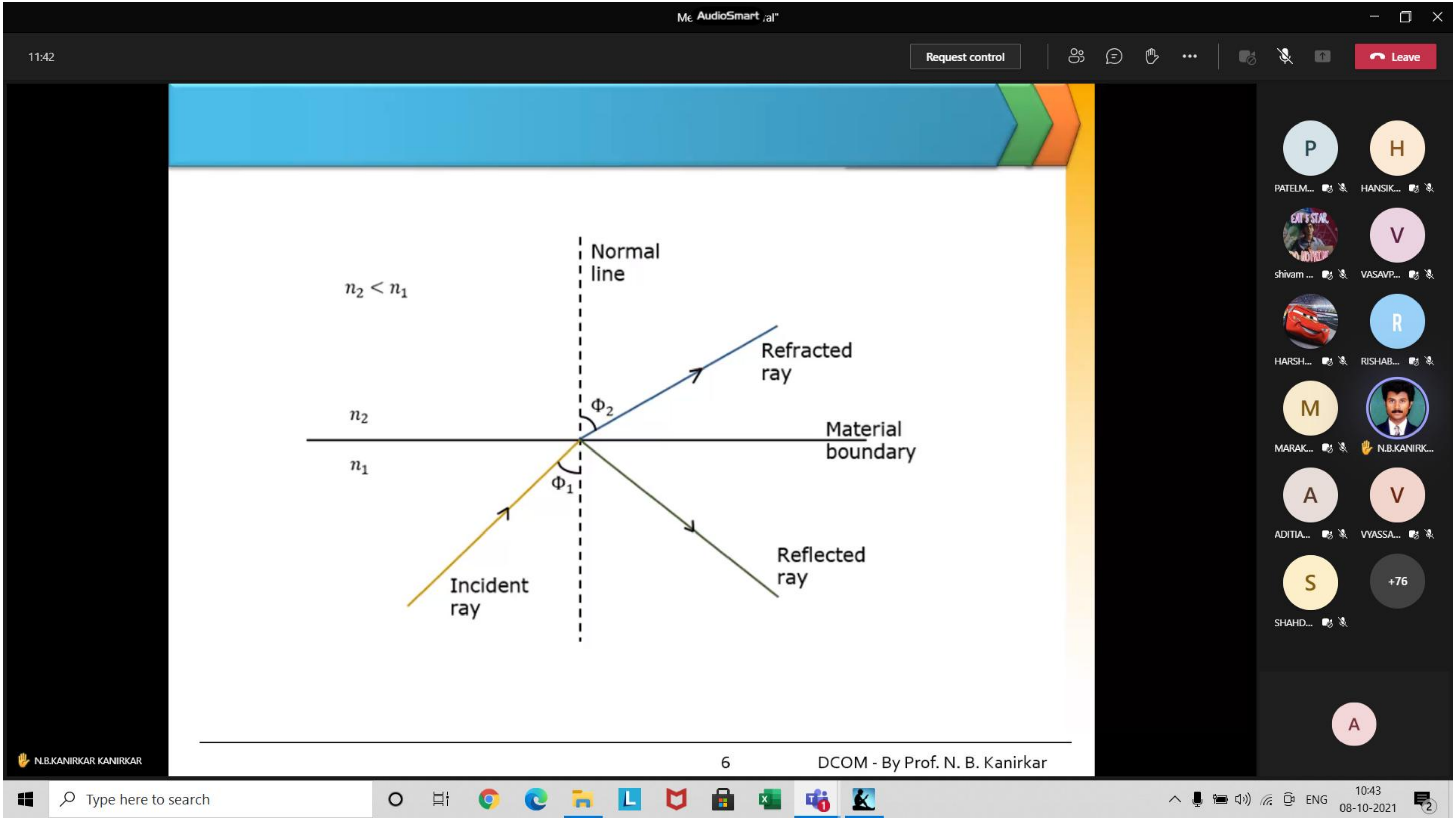
- **Single-mode fiber** – These are excited with laser.
- **Multi-mode fiber** – These are excited with LED.



Illustrating reflection and refraction at the interface of two optical materials.



(a) Reflection from the inside of the core wall.
(b) Ray escaping through the core wall by refraction.
(c) Ray entering the fiber end by refraction.


Normal line
$n_2 < n_1$
Refracted ray
Φ_2
n_2
Material boundary
n_1
Φ_1
Incident ray
Reflected ray
6
DCOM - By Prof. N. B. Kanirkar

The propagation of light in a fiber can be understood from an analysis process called *geometric ray tracing*, in which the paths of individual rays are geometrically traced along the guide path.

Light stays inside the fiber because it is totally reflected by the inside surface of the fiber. Light entering the end of the fiber at a slight angle to the axis follows a zigzag path through a series of reflections down the length of the fiber. *Total internal reflection* at the fiber wall can occur only if two conditions are met. The first is that the glass inside the fiber core must have a slightly higher index of refraction n_1 than the index of refraction n_2 of the material (cladding) surrounding the fiber core. The second is that the light must approach the wall with an angle of incidence ϕ (between the ray path and the normal to the fiber wall) that is greater than the critical angle ϕ_c, which is defined as

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

The reflected ray will leave the fiber wall at the same angle ϕ as it struck the wall before reflection. These conditions are illustrated in Fig. (a).

Refraction occurs when the angle of incidence is *less than* the critical angle. A ray approaching the inside of the core wall at an angle of incidence that is less than the critical angle will pass through the wall into the cladding region by refraction and become lost. This is illustrated in Fig (b).

In Fig. (c), a ray of light enters the core n_1 through the end face from the n_0 launch region with an angle of incidence θ_0 and leaves the interface at an angle of refraction θ_1, which is smaller than the angle of incidence. It is bent closer to the normal to the interface. Snell's law says that the incidence angle θ_0 is related to the refraction angle θ_1 by the relationship

$$n_0 \sin\theta_0 = n_1 \sin\theta_1$$

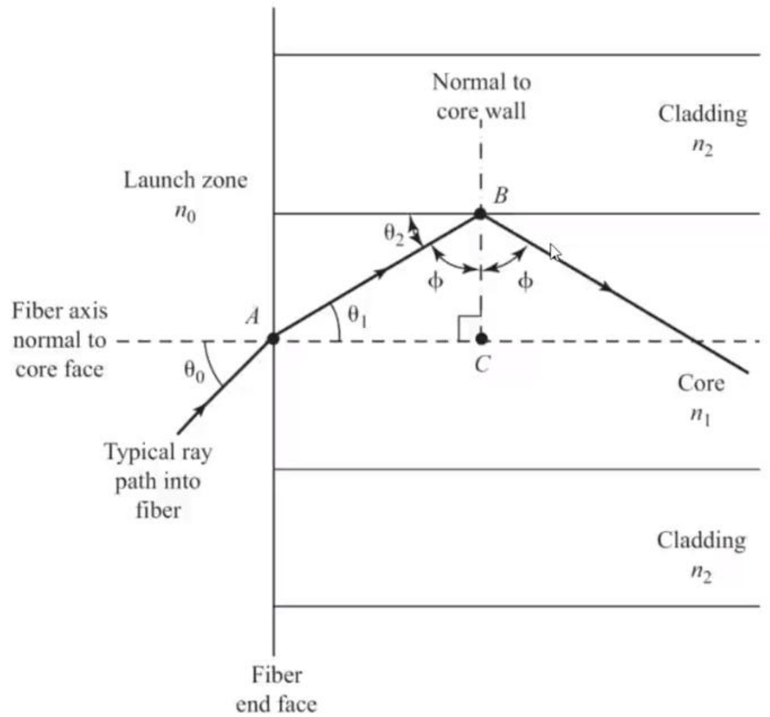
Figure shows a longitudinal cross section of the launch end of a fiber with a ray entering it. The core of the fiber has a refractive index n_1 and is surrounded by a cladding of material with a lower refractive index n_2. Light is launched into the end of the fiber from a launch region with a refractive index n_0. If the launch region is air, then $n0 = 1$. The ray enters with an angle of incidence to the fiber end face of θ_0 to the fiber axis (the normal to the end face). This particular ray enters the core at its axis point A and proceeds at the refraction angle θ_1 from the axis. It is then reflected from the core wall at point B at the internal incidence angle ϕ.

The entry incidence angle θ_0 can be related to the internal reflection angle ϕ by the right triangle ABC and Snell's law as follows. First, from the triangle ABC

$$\theta_1 = 90^\circ - \phi$$

Now substituting from Snell's law,

$$\sin\theta_0 = \frac{n_1}{n_0}\sin(90^\circ - \phi) = \frac{n_1}{n_0}\cos\phi$$



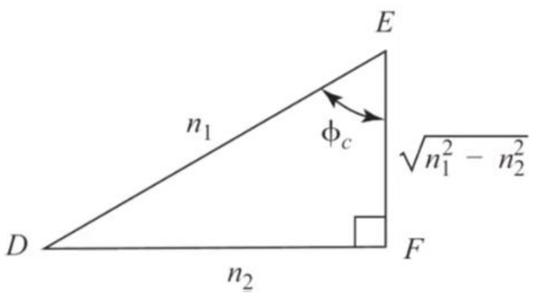
Path of a typical light ray launched into a fiber.

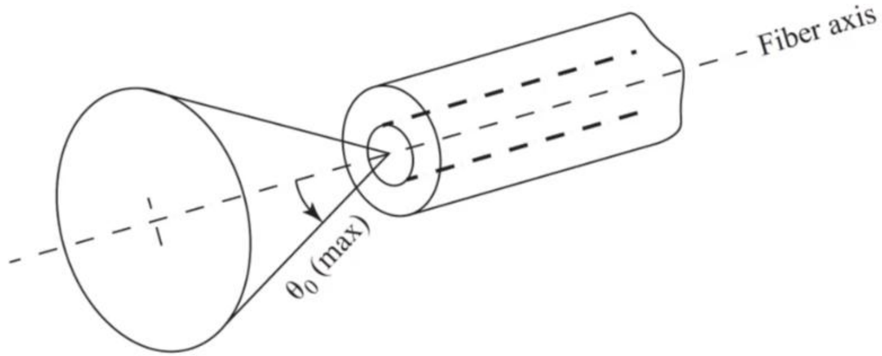
Applying Pythagoras' theorem and the cosine definition gives

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

Substituting Eq. (2 to Eq. (20. s the maximum value of the external incidence angle for which light will propagate in the fiber as

$$\theta_0(\max) = \sin^{-1}\left(\frac{\sqrt{n_1^2 - n_2^2}}{n_0}\right)$$





Acceptance cone obtained by rotating the acceptance angle about the fiber axis.

This maximum angle is called the *acceptance angle* or the *acceptance cone half-angle.* Rotating the acceptance angle about the fiber axis as shown in Fig. above describes the *acceptance cone* of the fiber.

Any light aimed at the fiber end within this cone will be accepted and propagated to the far end. Larger acceptance angles make easier launching.

The *numerical aperture* (NA) of the fiber is used as a figure of merit and is defined as the sine of the maximum acceptance angle, or

$$\mathrm{NA} = \sin\theta_0(\max) = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

If the light in the fiber is launched from air, as is often the case, $n_0 = 1$ and the numerical aperture becomes

$$\mathrm{NA} \approx \sqrt{n_1^2 - n_2^2}$$

The normalized difference Δ between the indexes of the core and cladding is

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

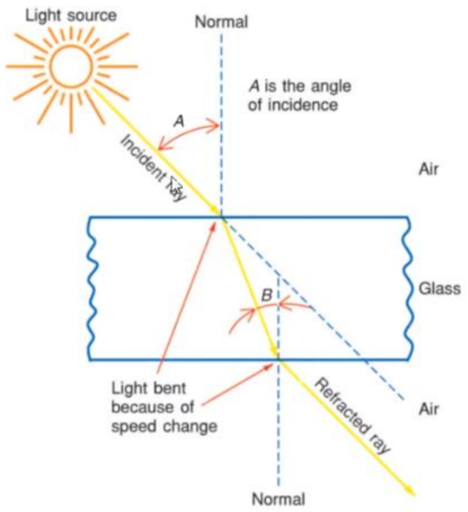
Substituting this in Eq. and noting that $n_1 \approx n_2$ for all practical fibers, the numerical aperture becomes

$$\mathrm{NA} \approx \frac{n_1\sqrt{2\Delta}}{n_0}$$

which if $n_0 = 1$ reduces to

$$\mathrm{NA} \approx n_1\sqrt{2\Delta}$$

How light rays are bent when passing from one medium to another.



Special cases of refraction. (*a*) Along the surface. (*b*) Reflection.

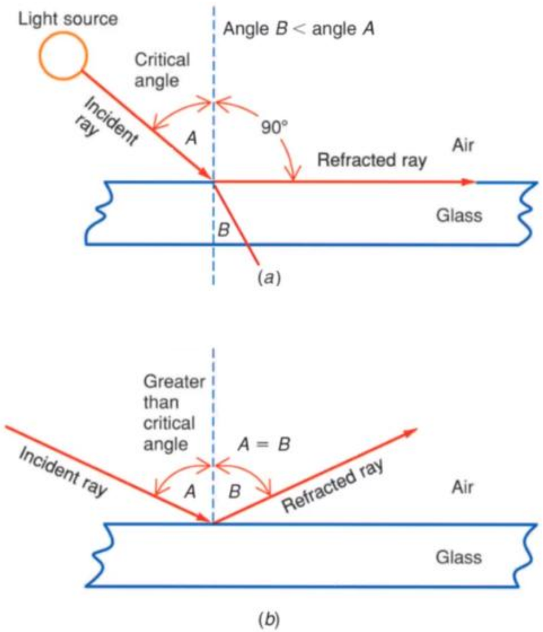
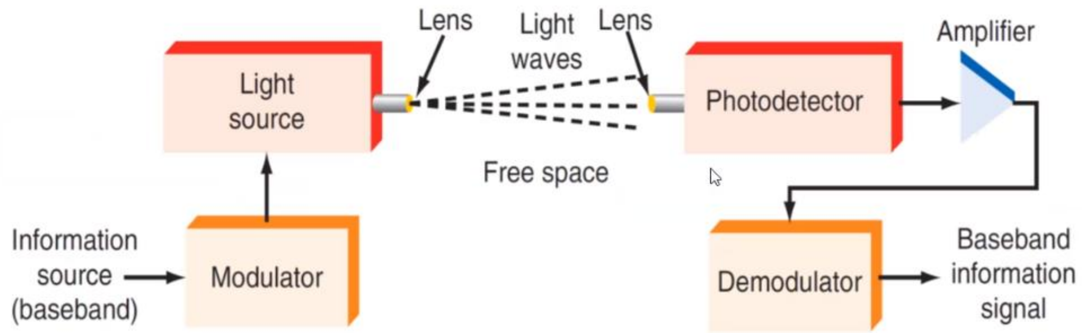
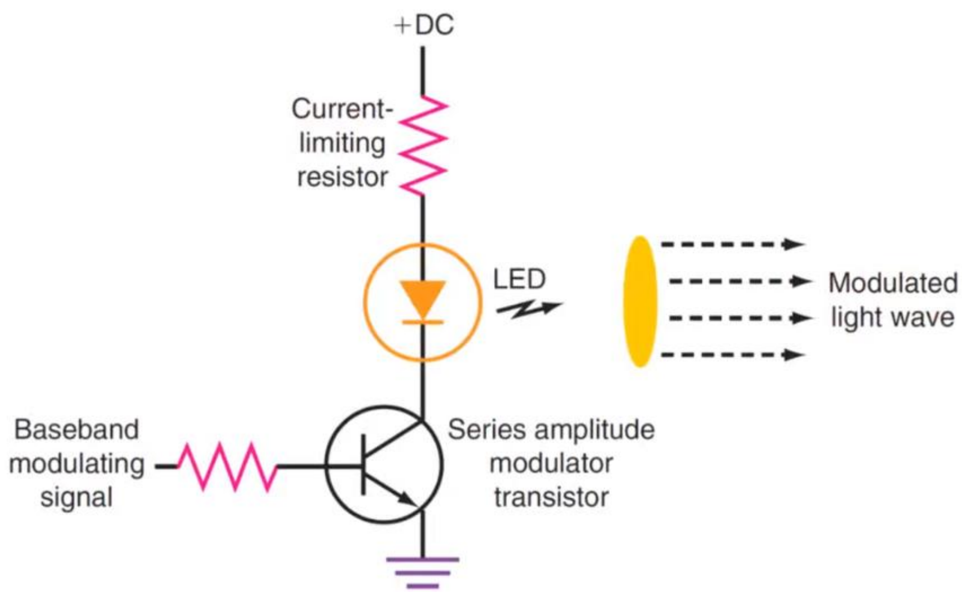


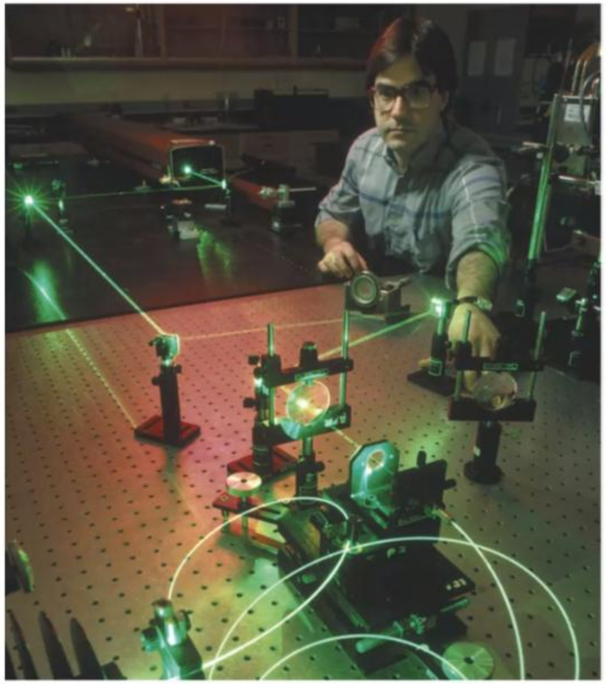
Figure Free-space optical communication system.



A simple light transmitter with series amplitude modulator. Analog signals: Transistor varies its conduction and acts as a variable resistance. Pulse signals: Transistor acts as a saturated on/off switch.



Optical waveguide and laser research created a surge of new products in the communication field.



Light detector (photocell)

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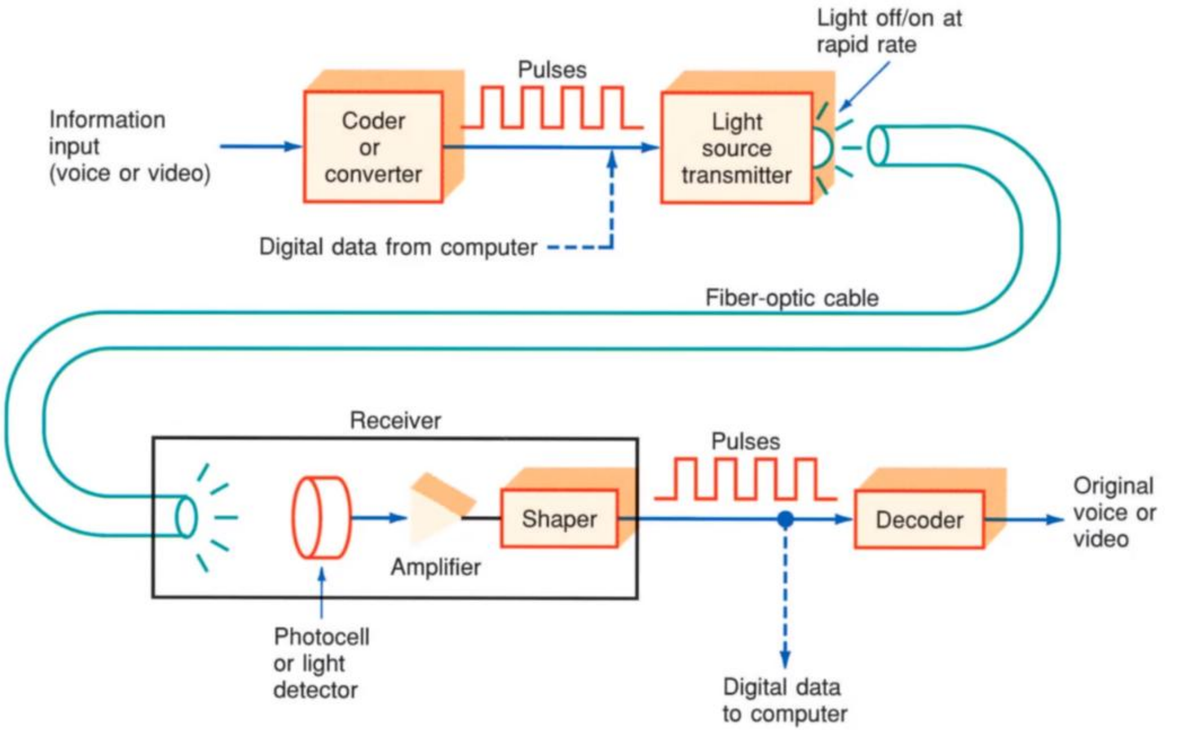
Figure Basic elements of a fiber-optic communication system.



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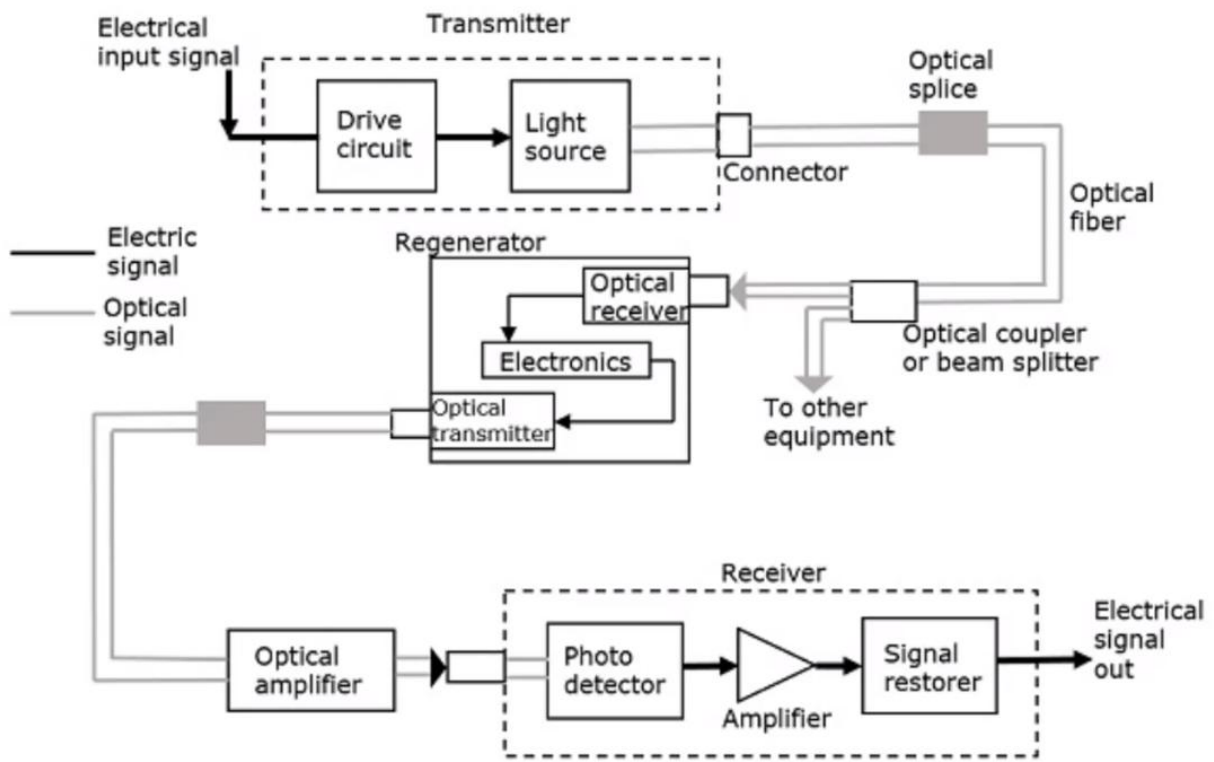
Detailed Fiber Optic Communication Blocks



An optic fiber is made of glass with a refractive index of 1.55 and is clad with another glass with a refractive index of 1.51. Launching takes place from air. (a) What numerical aperture does the fiber have? (b) What is the acceptance angle?

SOLUTION (a) the normalized difference between the indexes is

$$\Delta = \frac{n_1 - n_2}{n_1} = \frac{1.55 - 1.51}{1.55} = 0.0258$$

the numerical aperture is

$$\text{NA} \approx n_1\sqrt{2\Delta} = 1.55\sqrt{2 \times 0.0258} = \mathbf{0.352}$$

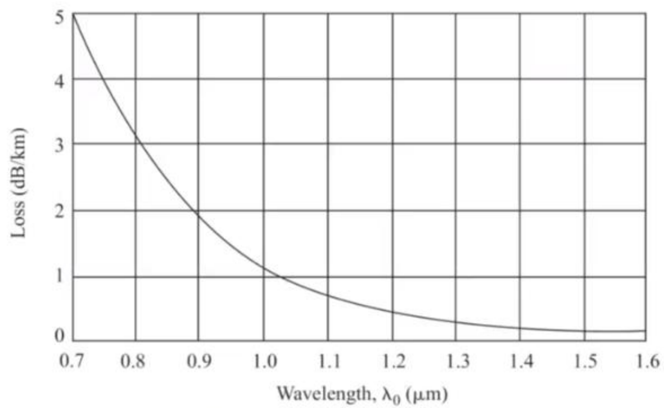
(b) the acceptance angle is

$$\theta_0\,(\text{max}) = \sin^{-1}\text{NA} = \sin^{-1} 0.352 = \mathbf{20.6^{\circ}}$$

Losses in Fibers

Rayleigh Scattering Losses

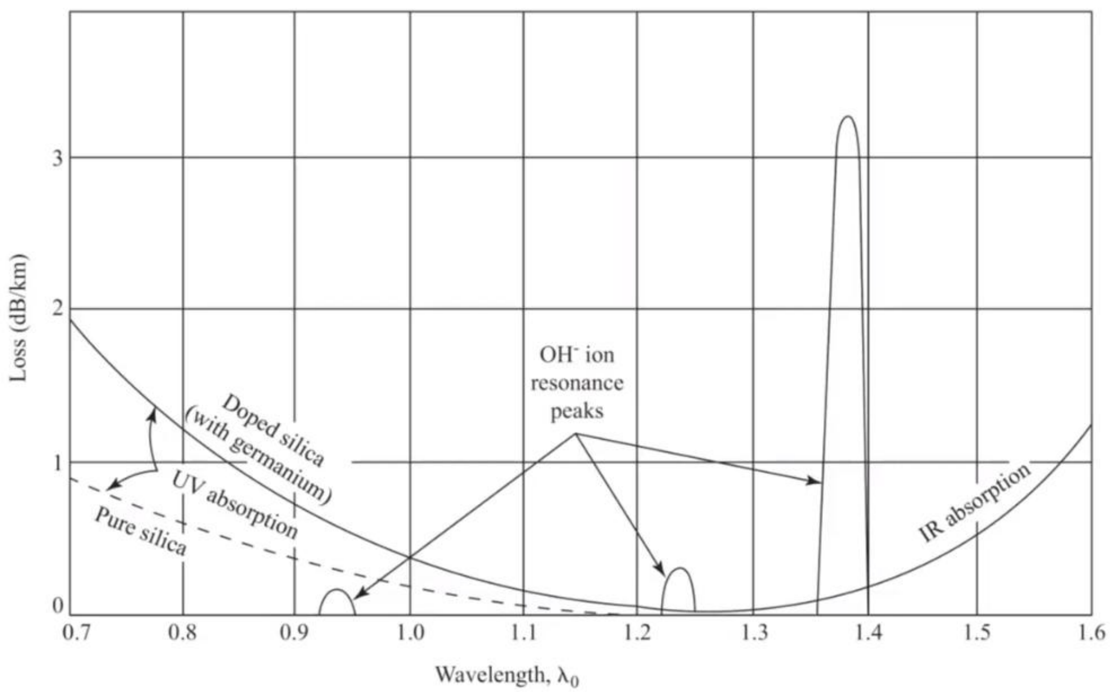
The glass in optical fibers is an amorphous (noncrystalline) solid that is formed by allowing the glass to cool from its molten state at high temperature until it freezes. While it is still plastic, the glass is drawn out under tension into its long fiber form. During this forming process, submicroscopic variations in the density of the glass and in doping impurities are frozen into the glass and then become reflecting and refracting facets to scatter a small portion of the light passing through the glass, creating losses. While careful manufacturing techniques can reduce these anomalies to a minimum, they cannot be totally eliminated.



Rayleigh scattering losses in silica fibers.

Absorption Losses

Three different mechanisms contribute to absorption losses in glass fibers. These are ultraviolet absorption, infrared absorption, and ion resonance absorption Ultraviolet absorption takes place because, for pure fused silica, valence electrons can be ionized into conduction by light with a center wavelength of about 0.14m, corresponding to an energy level of about 8.9 eV. The energy for this ionization is drawn from the light fields being propagated and constitute a transmission loss. The absorption loss does not only occur at this fixed wavelength, but occurs over a broad band that extends up into the visible part of the spectrum, with losses decreasing as wavelength increases. This absorption *tail* becomes negligible in the 1.2- to 1.3-m band.



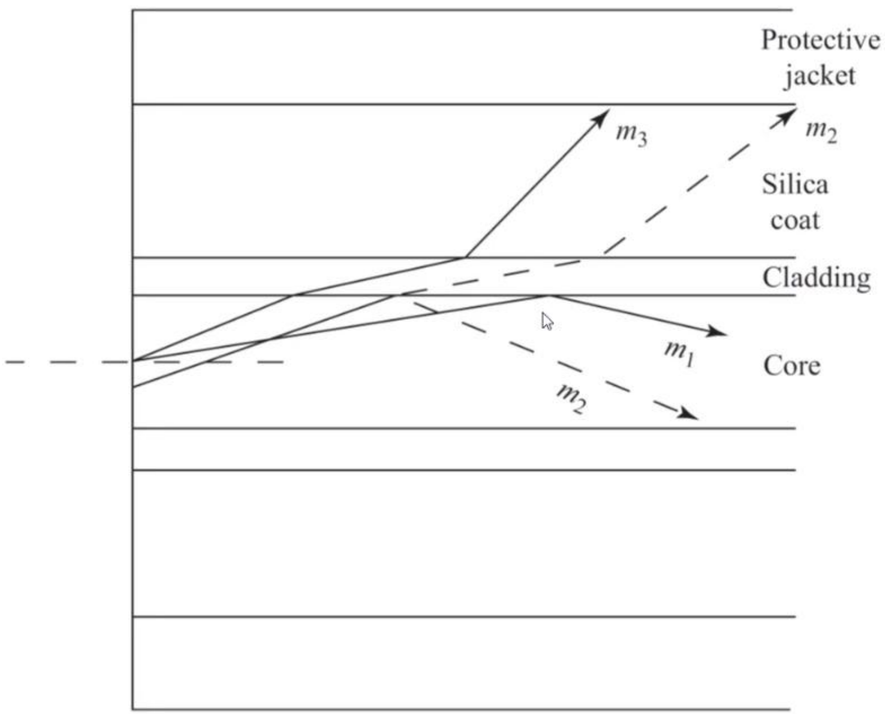
Absorption loss effects in fused silica glass fibers.

Leaky Modes

For meridional modes in which all rays pass through the core axis, if the axial angle of incidence is greater than critical at each reflection point, it will be reflected and propagate. If the angle of incidence is less than critical, the rays of the mode will be refracted out of the core and lost. Such modes are either propagated or completely lost.

For skew modes, however, each incident ray has two components of its angle of incidence, one axial and the other radial. If both the radial and axial components of the angle of incidence are less than critical as in higher-order modes, the mode will be totally refracted into the cladding and lost. If both the radial and axial components are greater than critical as in lower-order modes, then the mode will be totally reflected Atid propagated within the core.

However, for intermediate-order skew modes, it is possible for the axial component of the incidence angle to be greater than critical while the radial component is less than critical. In this case, some of the mode rays will be refracted into the cladding and lost while the rest are propagated. These modes are called leaky modes.



Leaky mode removed by an additional silica cladding.

Mode Coupling Losses

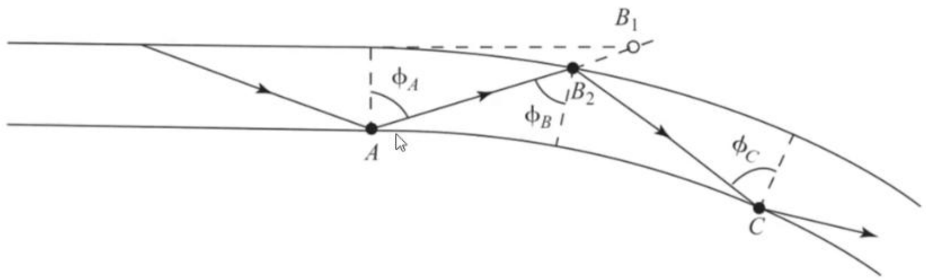
Power that has been launched successfully into a propagating mode may be later coupled into a leaky or radiating mode because of some discontinuity in the fiber. Any variations in the distribution of impurities within the core can cause internal refractions to occur. Any variation in diameter because of splices or bending can cause a shift in the angle of incidence at reflection points Any of these mechanisms can cause energy to be shifted from a fully propagating mode into one of the leaky modes and ultimately lost through leakage.

Bending Losses

Two types of bending can affect a fiber. These are **microbending** and large **radius bending**.

Microbending is a microscopic bending of the core of the fiber that may result from different thermal contraction between core and cladding or because of kinking during handling. These microbends act as scattering facets within the fiber and cause energy from fully propagated modes to be cross-coupled into leaky modes and subsequently lost. Since microbends are randomly distributed over the length of the fiber, losses resulting from them are uniformly distributed and a total figure for the fiber can be obtained. Care in manufacture and handling will minimize microbending losses.

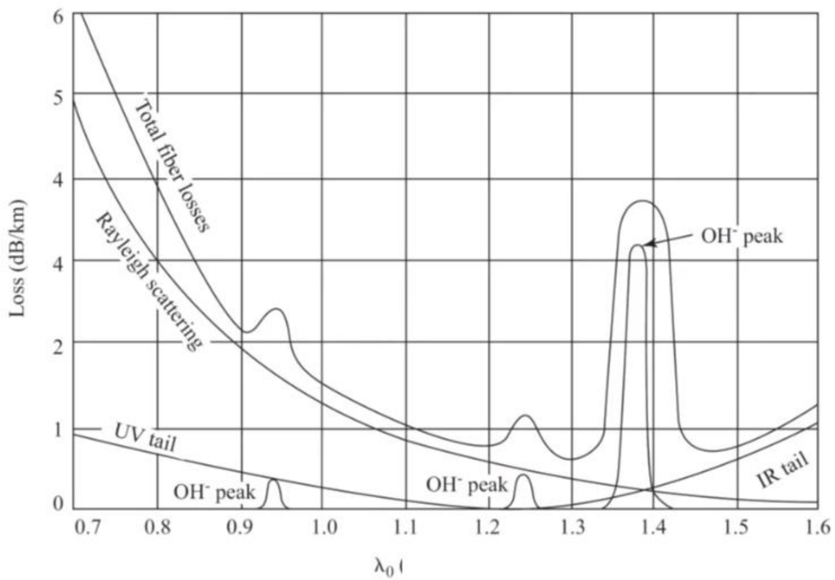
Large radius bending is caused by several things. Fibers are generally combined in multifiber cables, where they are spiraled about a central cable core The spiral creates a constant radius bend that extends the full length of the cable. Aerial cables are hung from poles, and each pole hanger introduces a short, relatively sharp bend in the fiber. Buried ducts or ducts in buildings may be required to negotiate relatively sharp turns. These large radius bends also introduce loss by mode coupling into leaky modes.



Ray propagation in a bent fiber.

Combined Fiber Losses

Four types of losses that must be reduced to a minimum during manufacture are Rayleigh scattering, material absorption, leaky modes, and scattering. Rayleigh scattering and material absorption are the predominant factors, and every effort is made to minimize these during manufacture.



Total loss spectrum for an optical fiber.