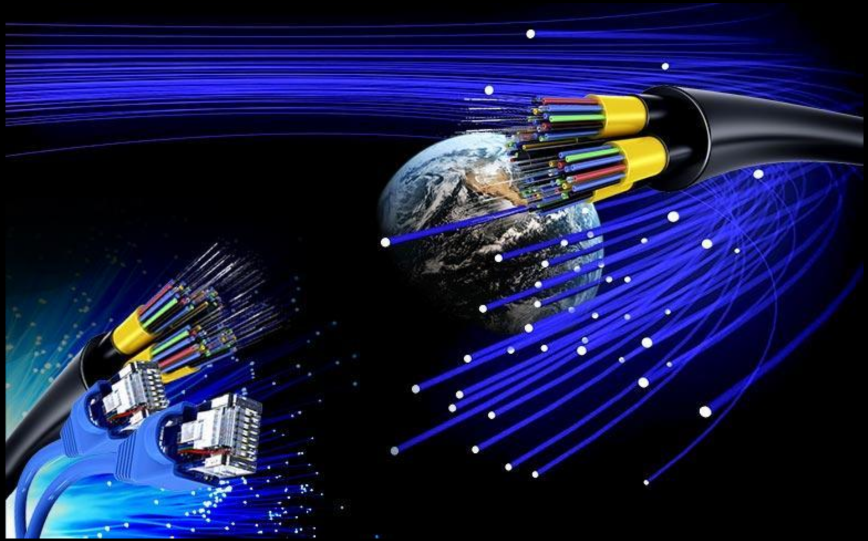
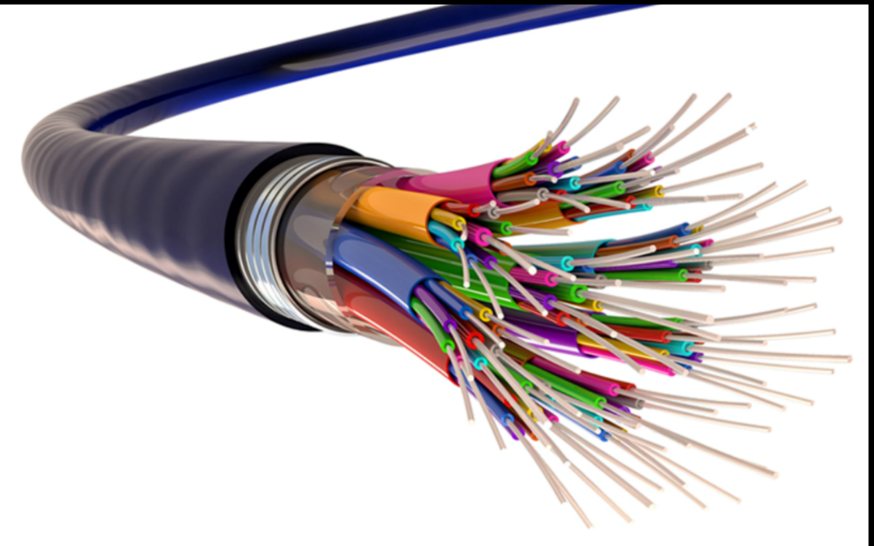
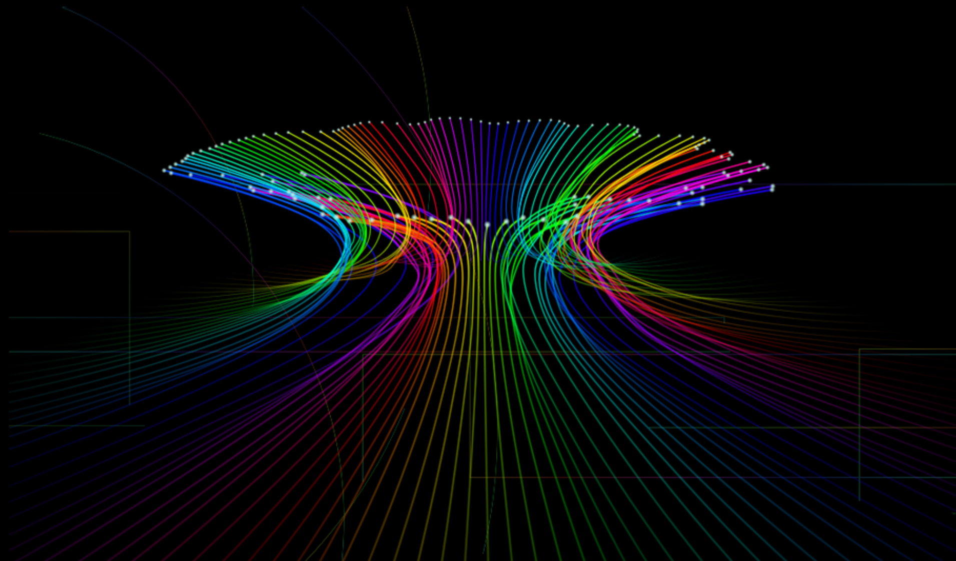


FIBRE OPTICS

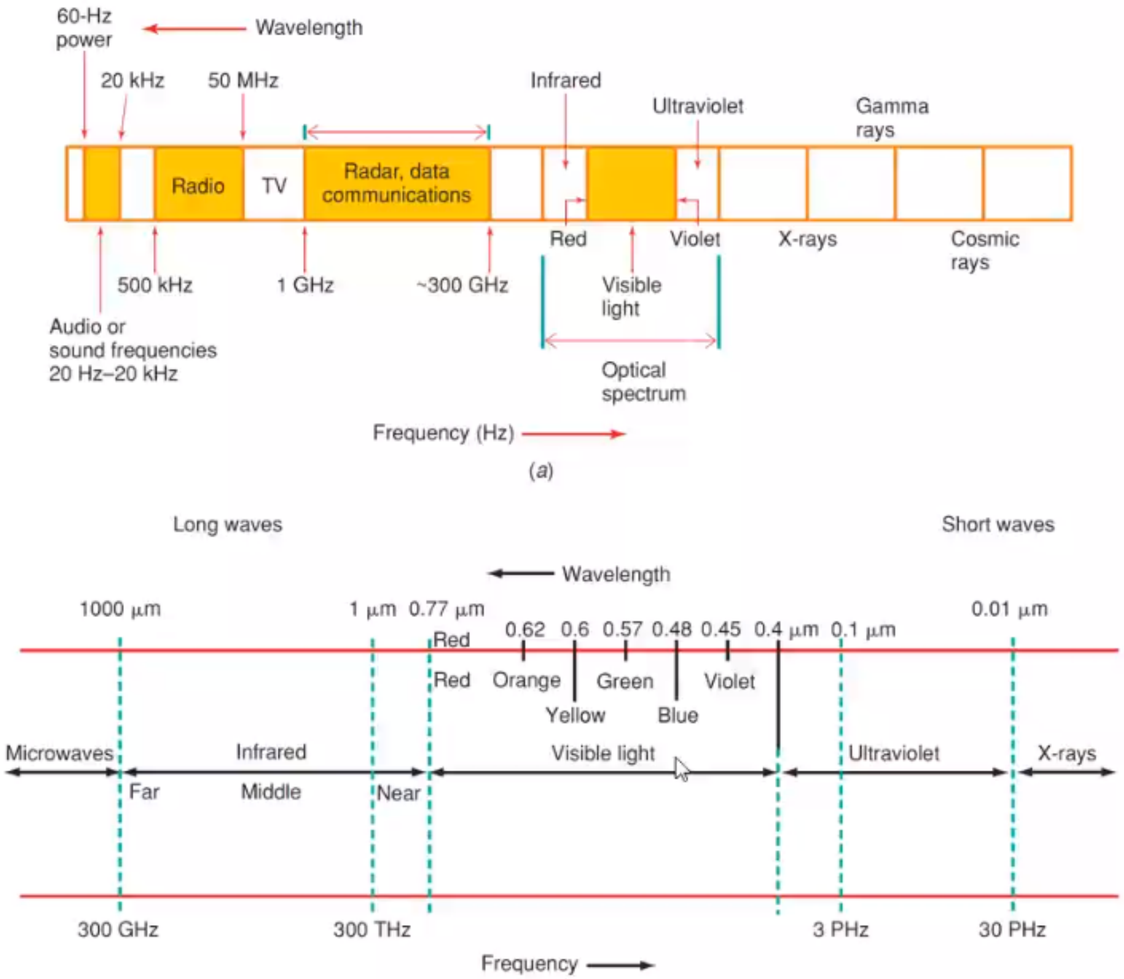




Made By: Bhagya Rana

Optical Spectrum

The optical spectrum. (*a*) Electromagnetic frequency spectrum showing the optical spectrum. (*b*) Optical spectrum details.



GHz = gigahertz = 10^9 Hz, THz = terahertz = 10^{12} Hz, PHz = petahertz = 10^{15} Hz

(*b*)

Light

Light, radio waves, and microwaves are all forms of electromagnetic radiation. Light frequencies fall between those of microwaves and X-rays, as shown in Fig.
Radio frequencies range from approximately 10 kHz to 300 GHz. Microwaves extend from 1 to 300 GHz. The range of about 30 to 300 GHz is generally defined as millimeter waves.

Further up the scale is the *optical spectrum,* made up of infrared, visible, and ultraviolet light. The frequency of the optical spectrum is in the range of 3×10^{11} to 3×10^{16} Hz. This includes both the infrared and the ultraviolet bands as well as the visible parts of the spectrum. The visible spectrum is from 4.3×10^{14} to 7.5×10^{14} Hz.

An **optical fiber** is a flexible, transparent fiber made by drawing glass (silica) or plastic to a diameter slightly thicker than that of a human hair. Optical fibers are used most often as a means to transmit light between the two ends of the fiber and find wide usage in fiber-optic communications, where they permit transmission over longer distances and at higher bandwidths (data transfer rates) than electrical cables.

Fibers are used instead of metal wires because signals travel along them with less loss; in addition, fibers are immune to electromagnetic interference, a problem from which metal wires suffer. Fibers are also used for illumination and imaging, and are often wrapped in bundles so they may be used to carry light into, or images out of confined spaces, as in the case of a fiberscope.

Specially designed fibers are also used for a variety of other applications, some of them being fiber optic sensors and fiber lasers.

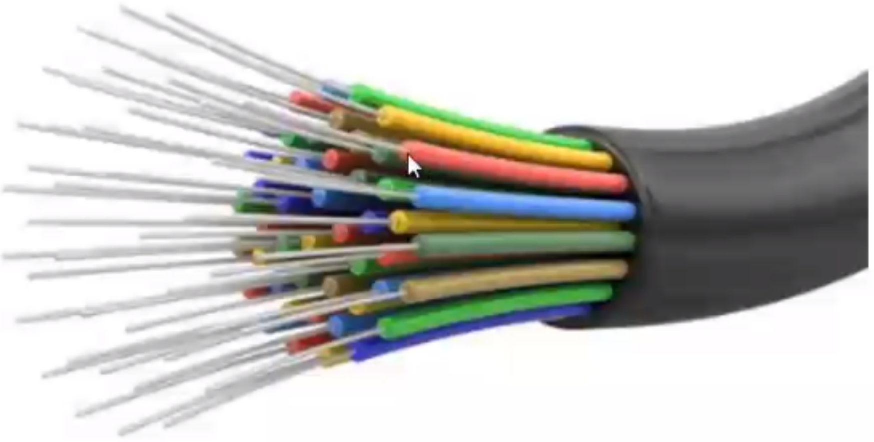
Optical fibers typically include a core surrounded by a transparent cladding material with a lower index of refraction. Light is kept in the core by the phenomenon of total internal reflection which causes the fiber to act as a waveguide.

Fibers that support many propagation paths or transverse modes are called multi-mode fibers, while those that support a single mode are called single-mode fibers (SMF).

Multi-mode fibers generally have a wider core diameter and are used for short-distance communication links and for applications where high power must be transmitted. Single-mode fibers are used for most communication links longer than 1,000 meters (3,300 ft).

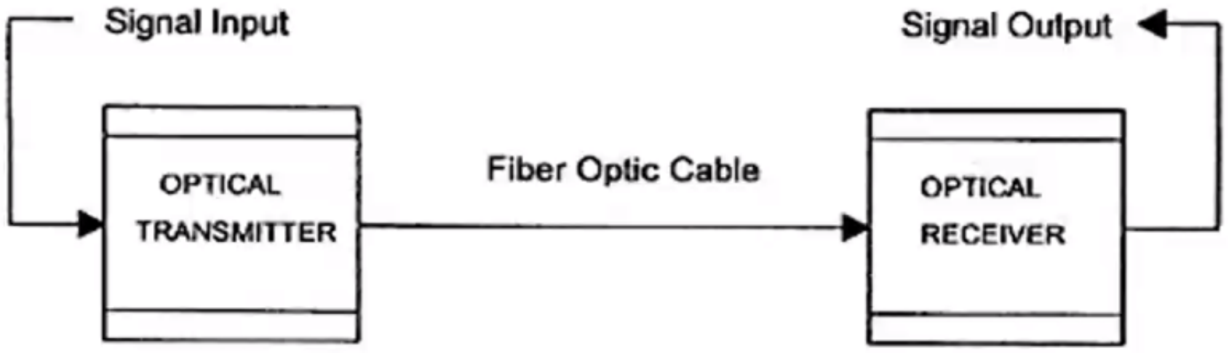
What are optical fibers

- Thin strands of pure glass
- Carry data over long distances
- At very high speeds
- Fiber can be bent or twisted



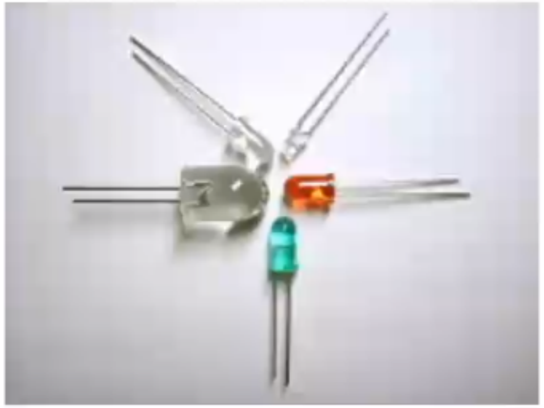
Fiber optic technology

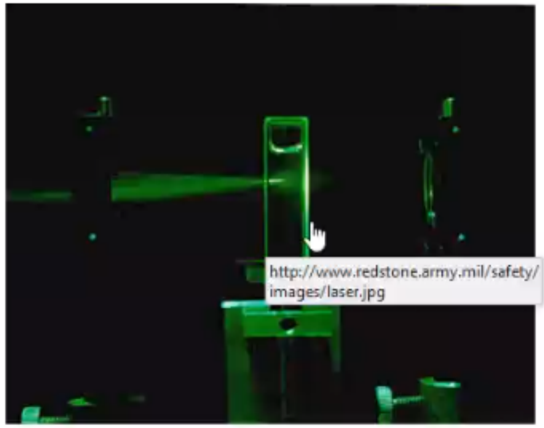
- Sources
- Transmission medium
- Detectors



Sources of light

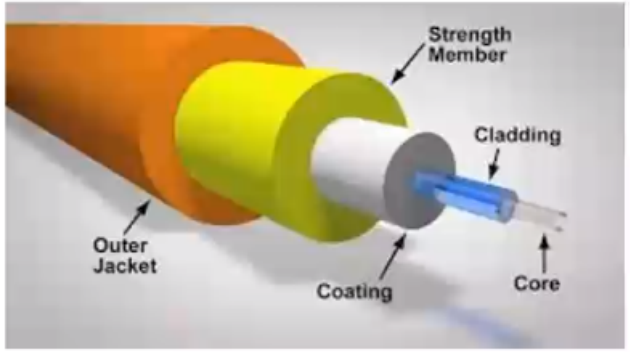
- ✓ Light emitting diodes
- ✓ Lasers





Sources

- Modulate electrical signals into optical signals
- Mostly modulate at 850nm, 1300nm and 1550 nm
- Lasers give high intensity, high frequency light
- LEDs are economical



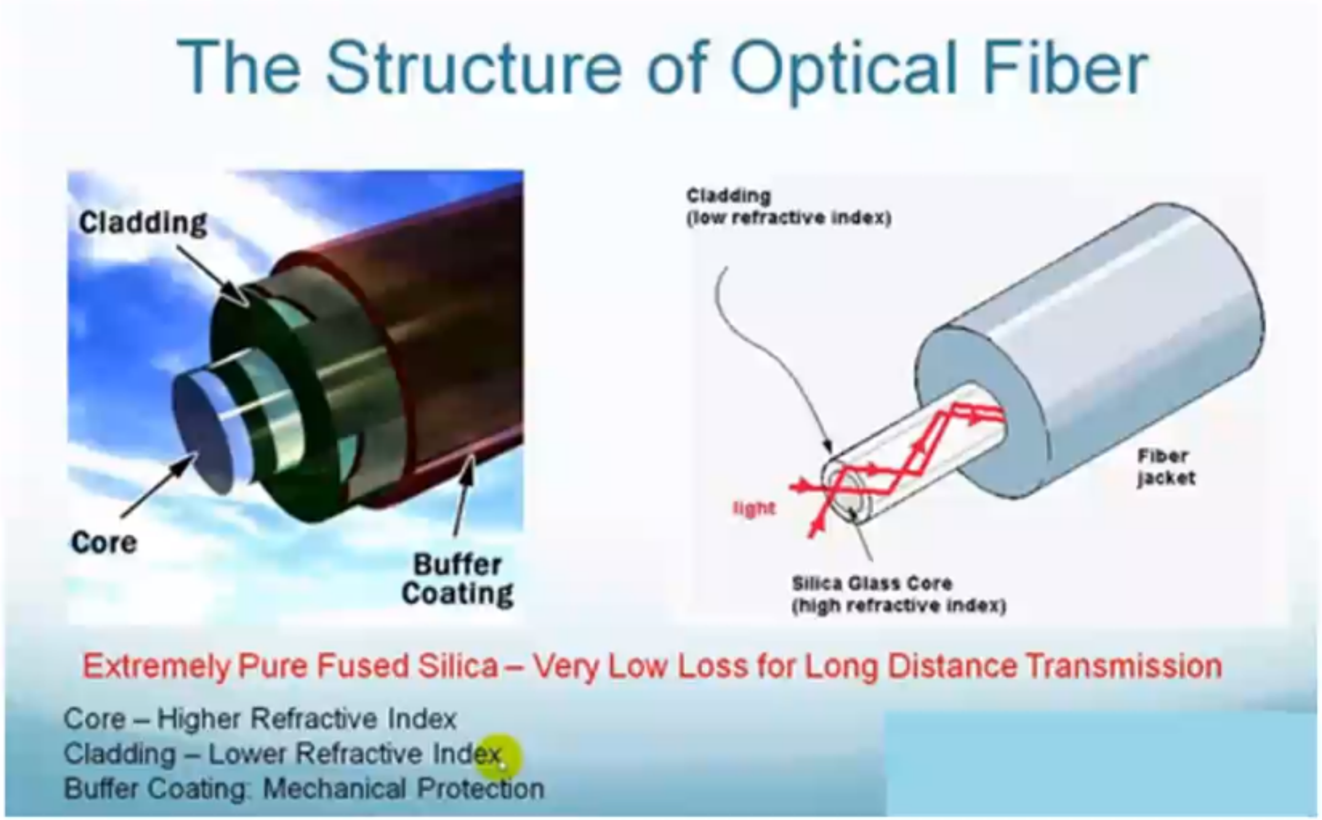
Transmission medium

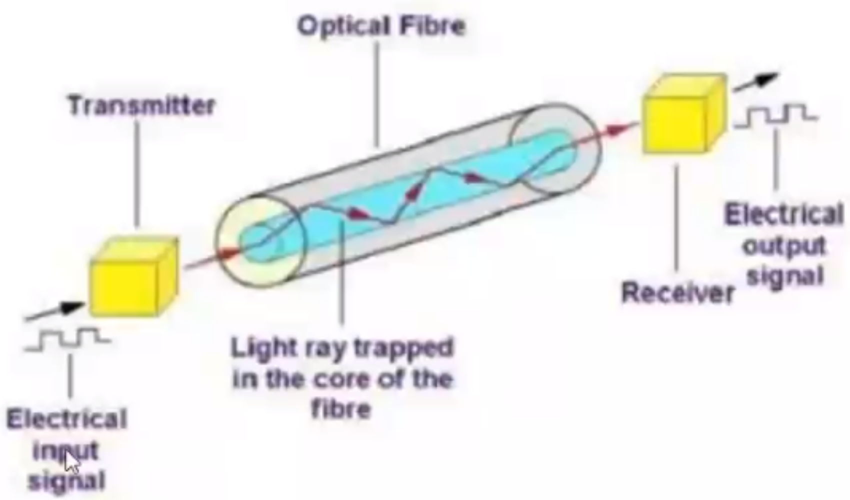
- ❑ Optical fiber is replacing copper
- ❑ Light is used as the carrier of information
- ❑ Much higher data rate

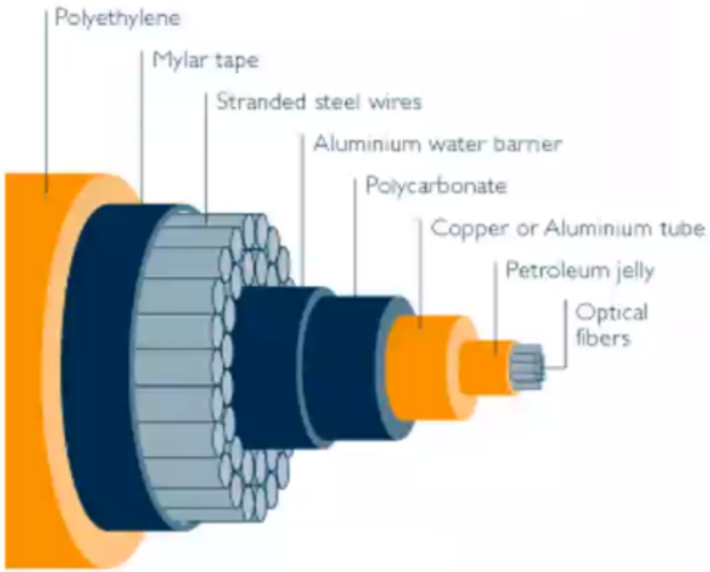
Physics of optical fibers

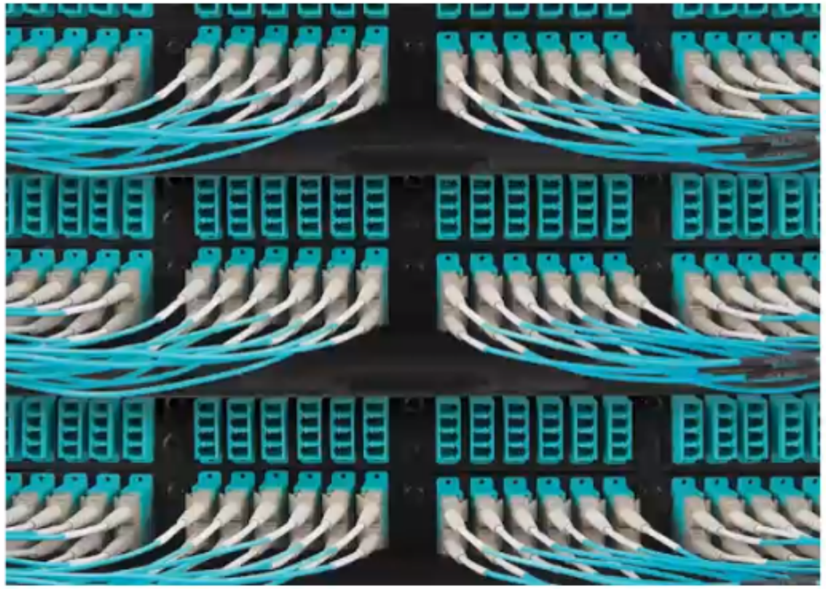
Index of refraction of material : ratio of speed of light in vacuum to speed of light in medium

Refraction of light : bending of light as it travels from one media to another




Optical Fibre
Transmitter
Electrical output signal
Receiver
Light ray trapped in the core of the fibre
Electrical input signal


Polyethylene
Mylar tape
Stranded steel wires
Aluminium water barrier
Polycarbonate
Copper or Aluminium tube
Petroleum jelly
Optical fibers

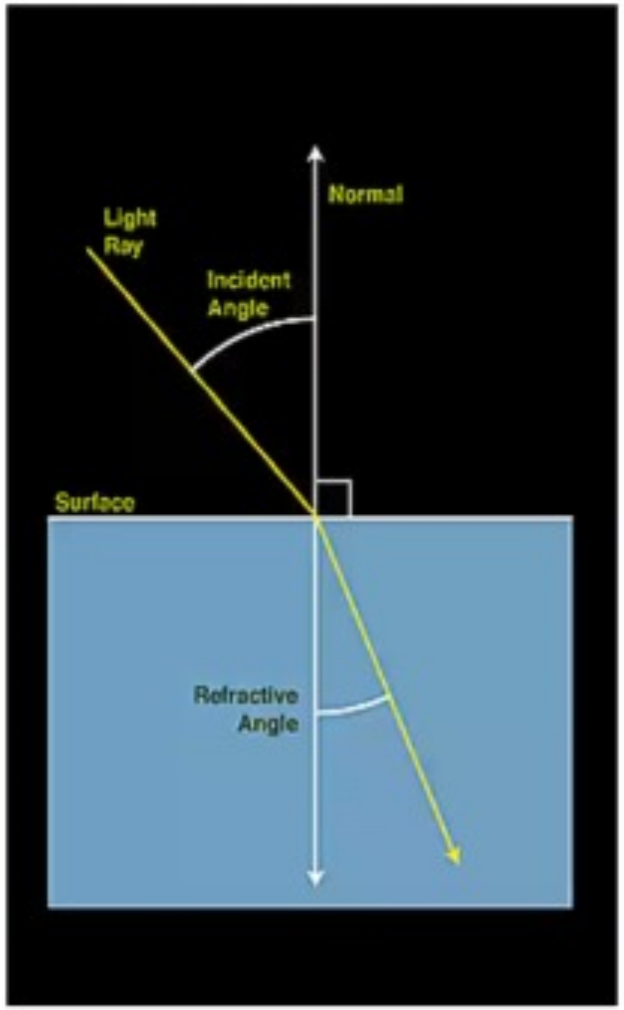


Refraction of light

Speed of light changes as it across the boundary of two media Angles w.r.t normal

Refraction Indices

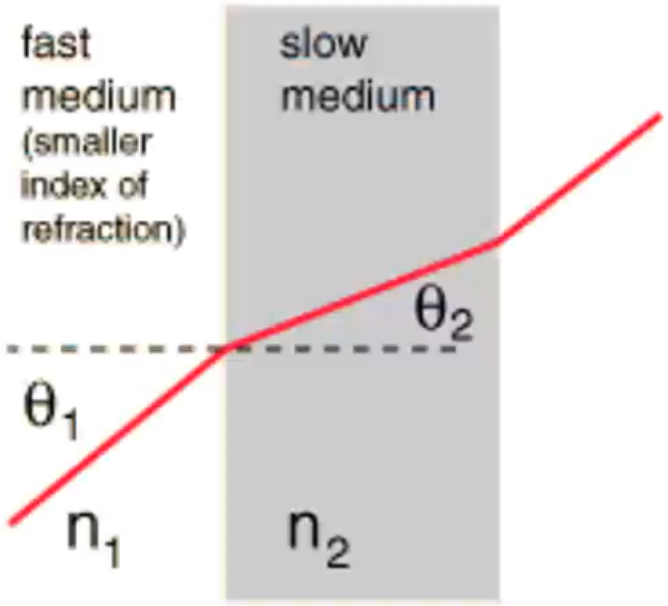
- Vacuum…….1.00000 (exactly)
- Air ……1.00029
- Alcohol……1.329
- Diamond 2.417
- Glass 1.5
- Ice 1.309
- Sodium Chloride (Salt) 1.544
- Sugar Solution (80%) 1.49
- Water (20 C) 1.333



Snell's Law

Snell's Law

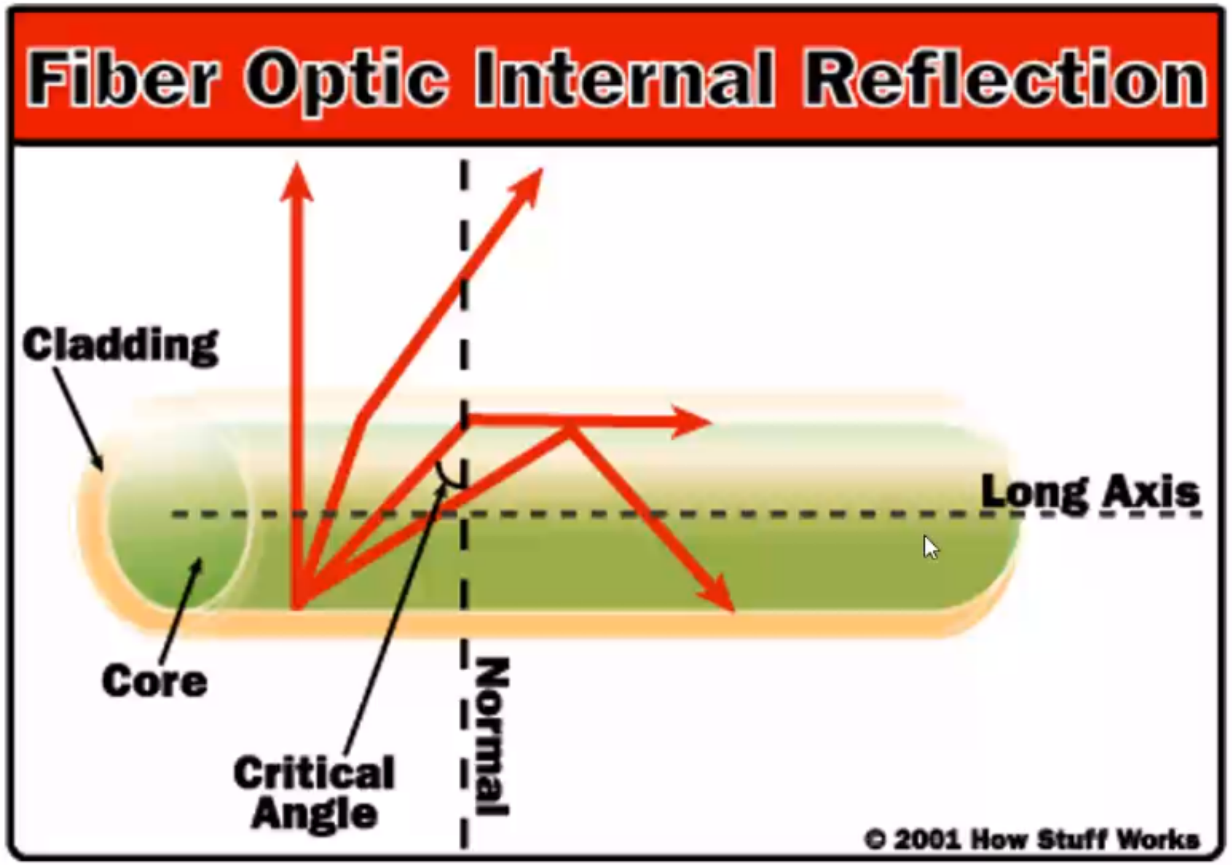
$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1}$$



Critical angle: Angle of incidence at which angle of refraction = 90^0

Total internal reflection

Trapping light in the fiber



Fibers can be bent!!

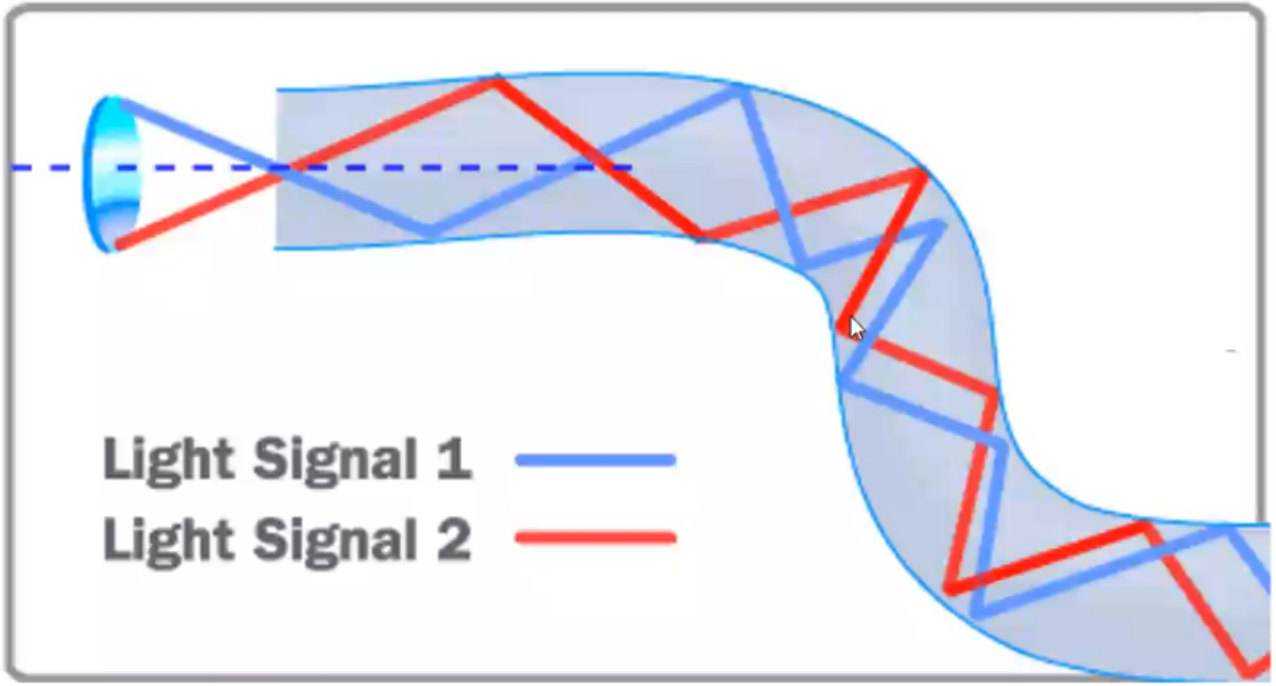


Fig: illustration of total internal reflection

Types of optical fibers

- Single mode
  - only one signal can be transmitted
  - use of single frequency
- Multi mode
  - Several signals can be transmitted
  - Several frequencies used to modulate the signal

Losses in optical fibers

- **Attenuation loss**
- **Dispersion loss**
- **Waveguide loss**
- **Rayleigh Scattering Losses**
- **Absorption Losses**
- **Leaky Modes**
- **Mode Coupling Losses**
- **Bending Losses**
- **Combined Fiber Losses**

Splices and Connectors

- ✓ To connect to fibers mechanically or by fusion
- ✓ Lot of signal loss possible
- ✓ Very accurate alignment necessary
- ✓ Most important cost factor
- ✓ Now being replaced by optical amplifiers

Optical Receivers

- Must be very sensitive
- Capable of picking up and amplifying signals of nanowatts
- Photodiodes and phototransistors
- These devices get ‘turned ON’ by light
- Produce photocurrent

Advantages of optical fibers

- ✓ Can carry much more information
- ✓ Much higher data rates
- ✓ Much longer distances than co-axial cables
- ✓ Immune to electromagnetic noise
- ✓ Light in weight
- ✓ Unaffected by atmospheric agents

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- Reflection & Refraction in Fiber
- Losses in Fiber Optic Communication

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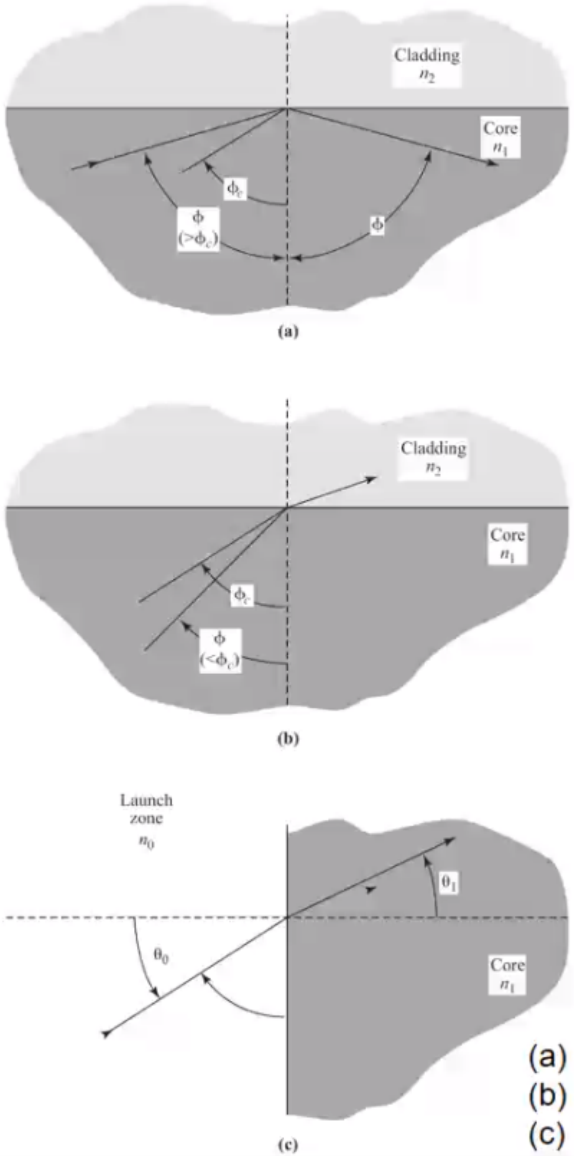
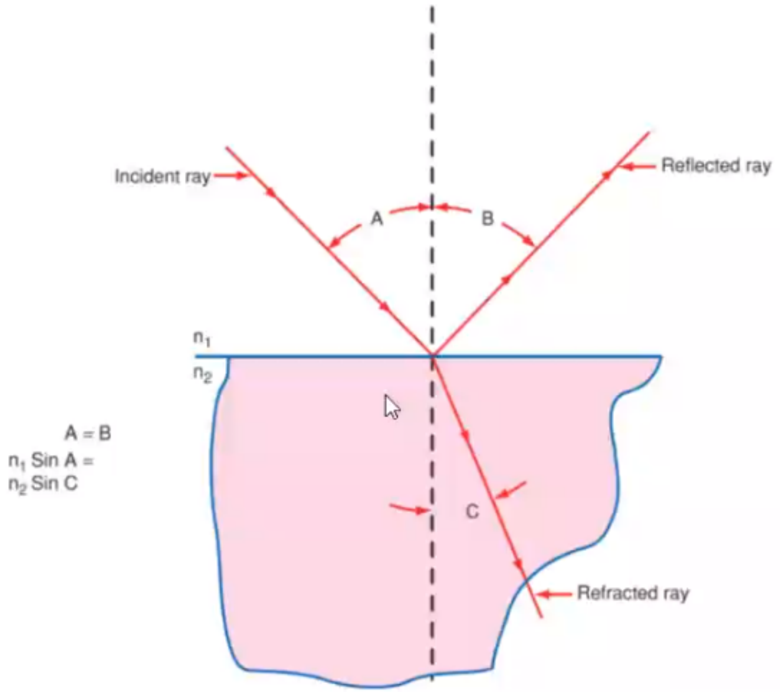


Illustrating reflection and refraction at the interface of two optical materials.



(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.

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

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

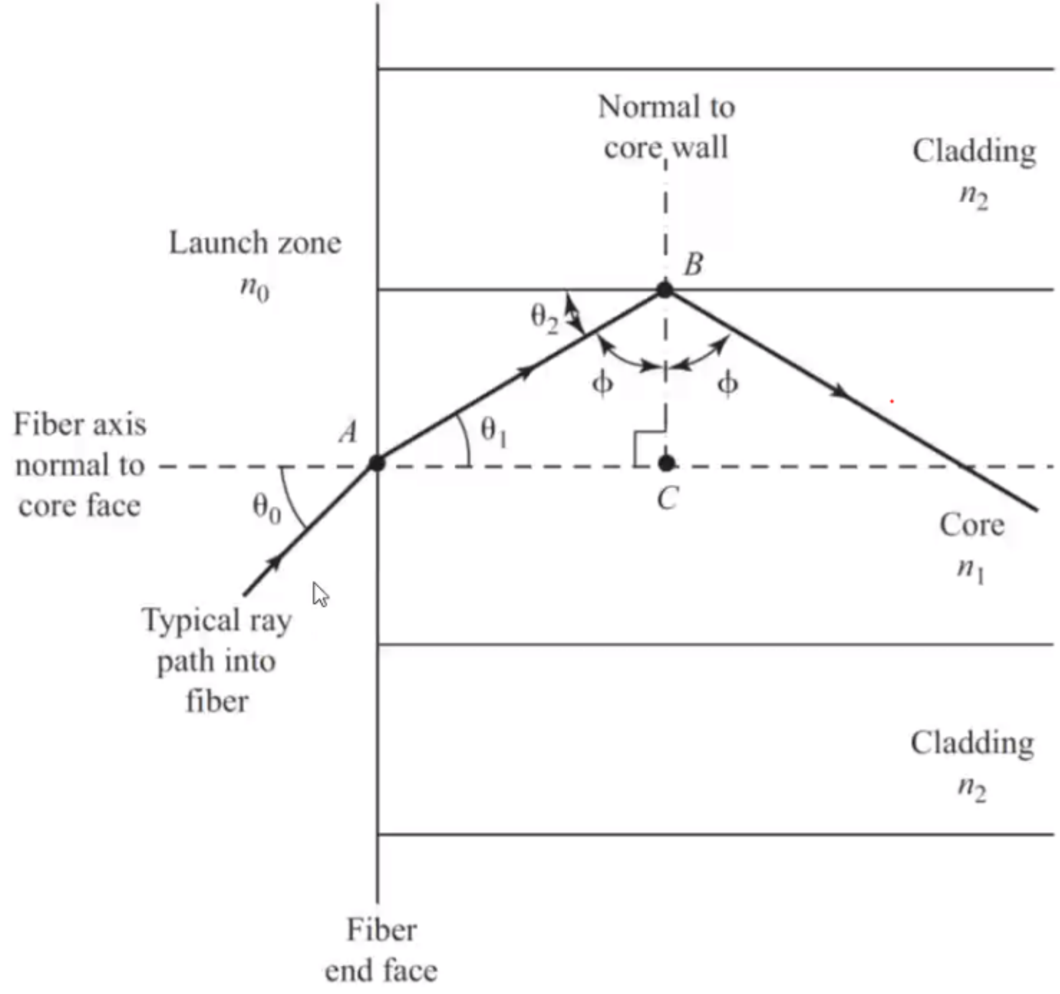
Figure shows a longitudinal cross section of the launch end of a fiber with a ray entering it. The core of the fiber has a refractive index n_1 and is surrounded by a cladding of material with a lower refractive index n_2. Light is launched into the end of the fiber from a launch region with a refractive 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,

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



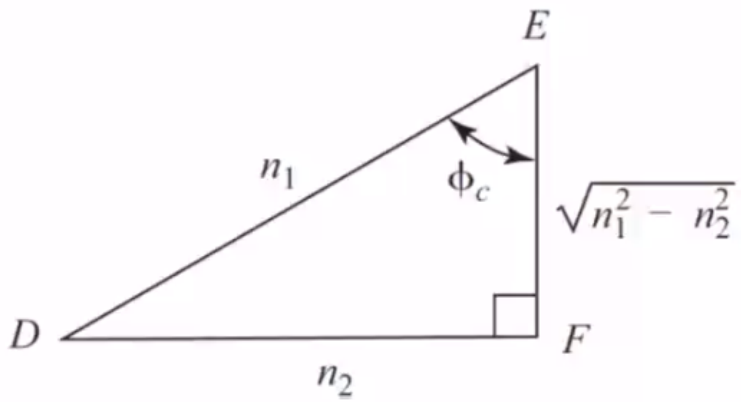
Path of a typical light ray launched into a fiber.

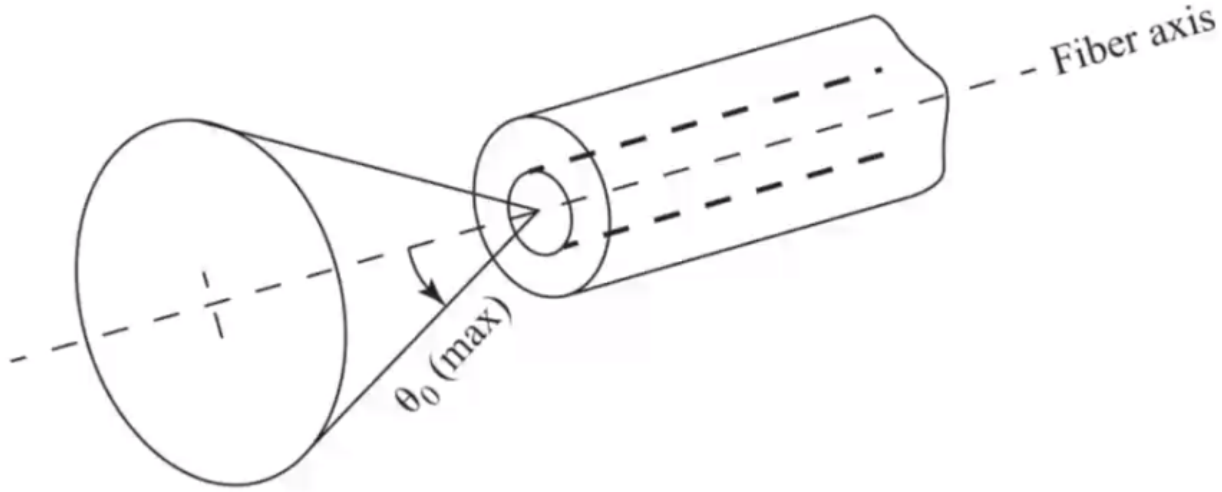
Applying Pythagoras' theorem and the cosine definition gives

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

Substituting Eq. into Eq. gives 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

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

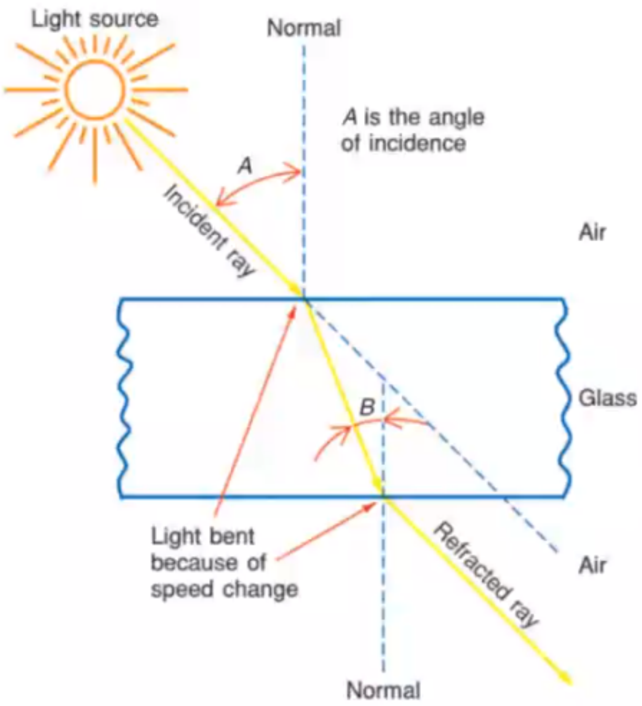
Substituting this in Eq. and noting that $n_1 \approx n_2$ for all practical fibers, the numerical aperture becomes

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

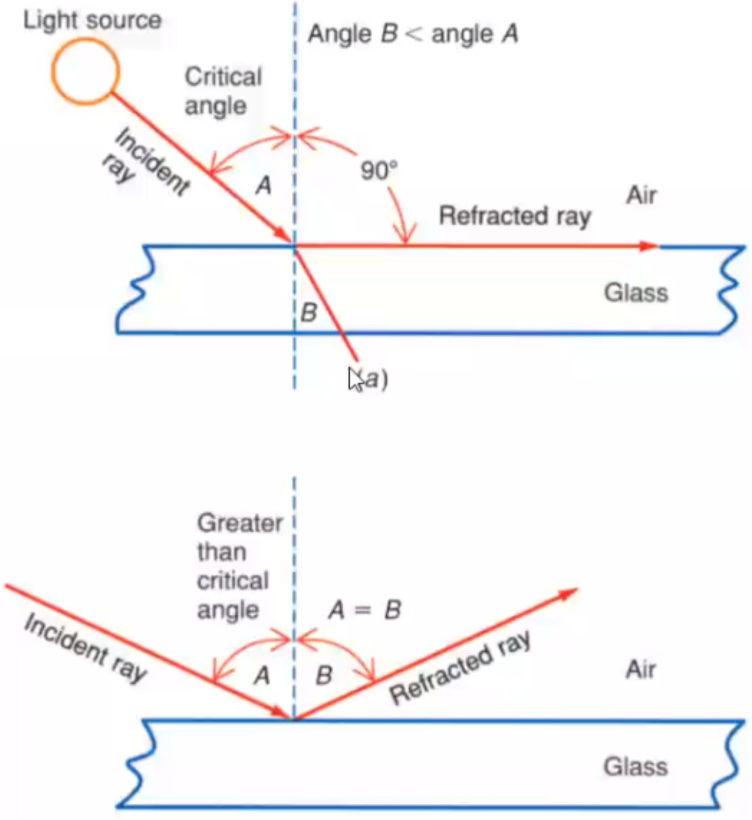
which if $n_0 = 1$ reduces to

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

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

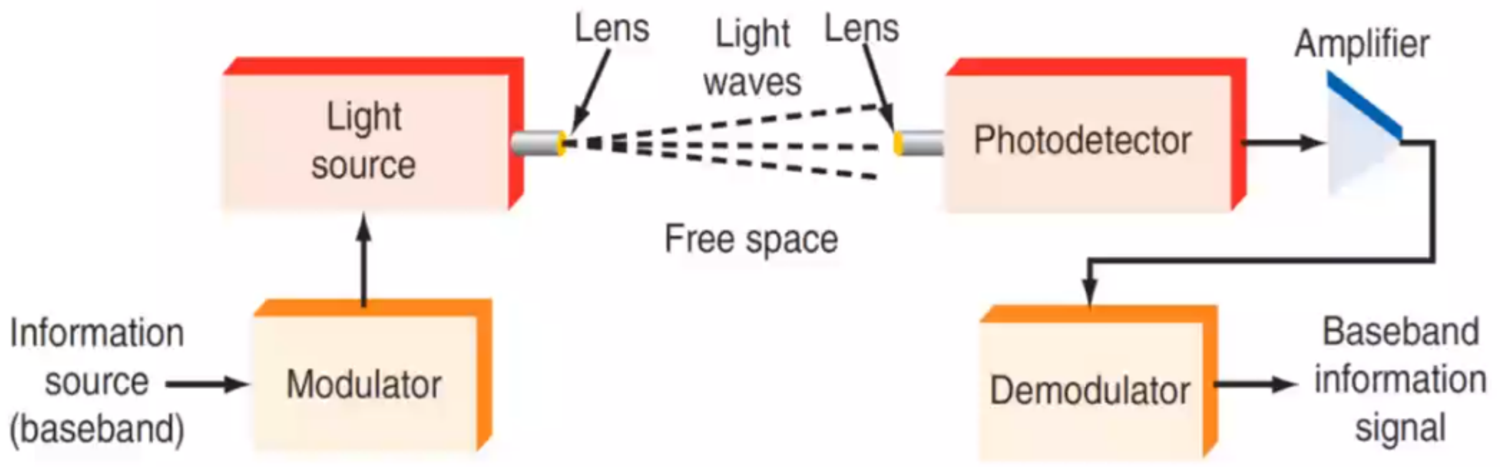


Special cases of refraction. (*a*) Along the surface. (*b*) Reflection.

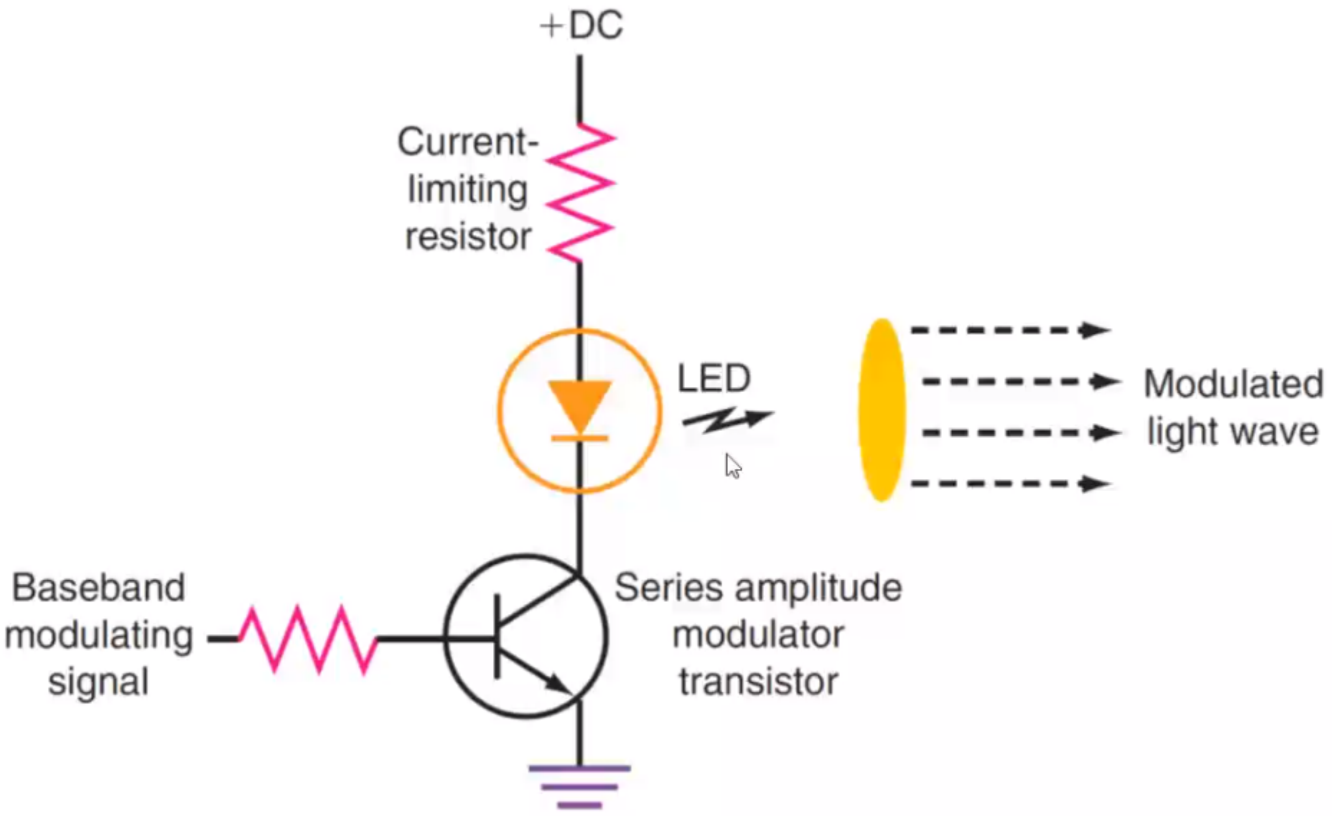


(*b*)

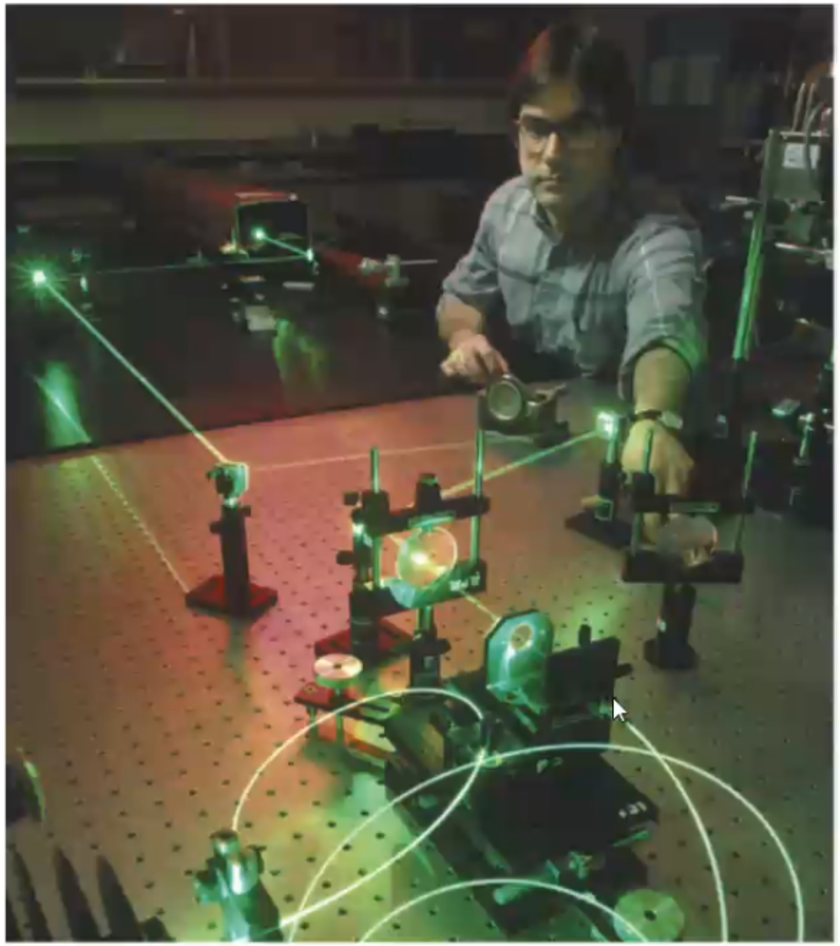
Figure Free-space optical communication system.



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.

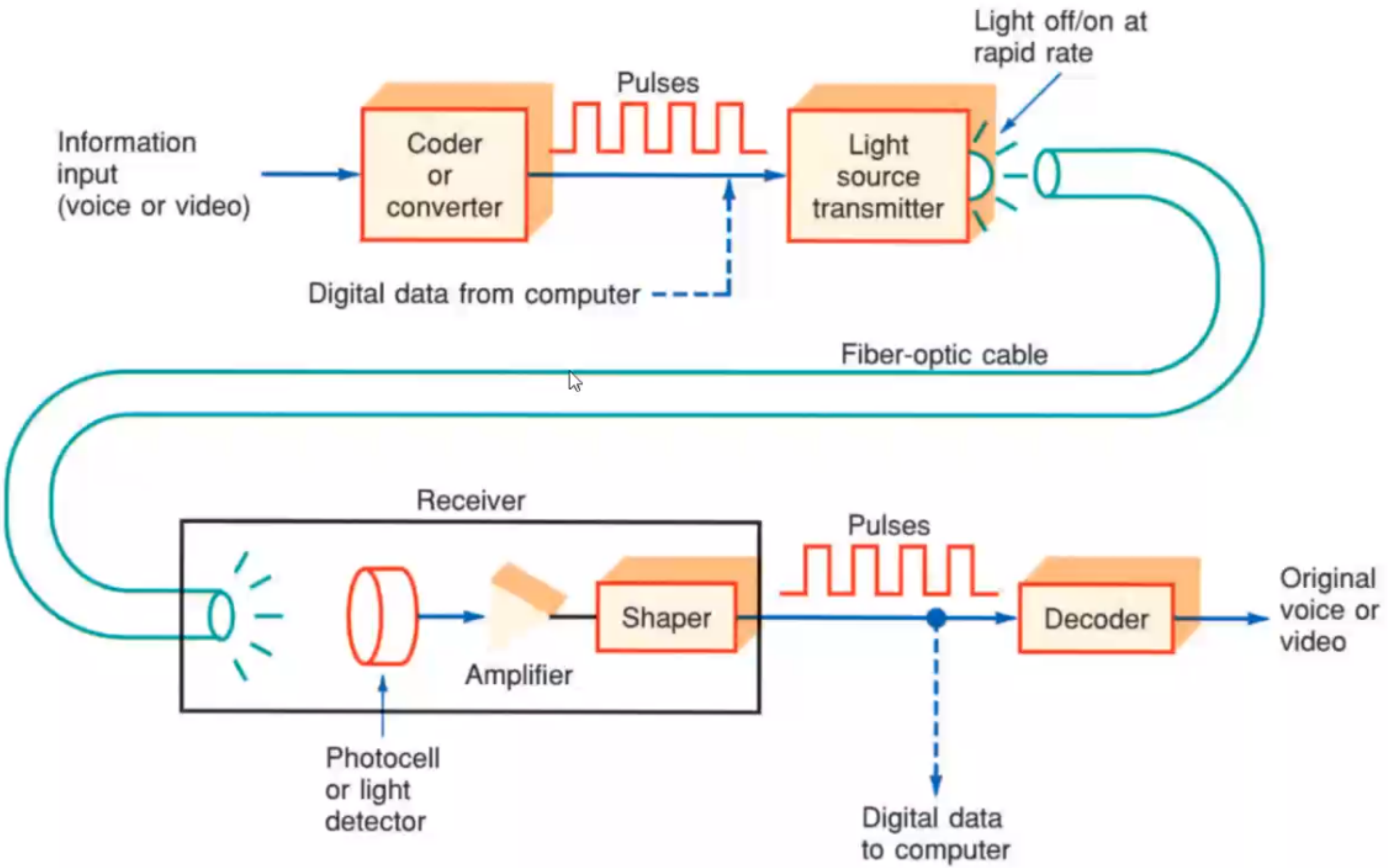


Optical waveguide and laser research created a surge of new products in the communication field.



Light detector (photocell)

Figure Basic elements of a fiber-optic communication system.



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

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

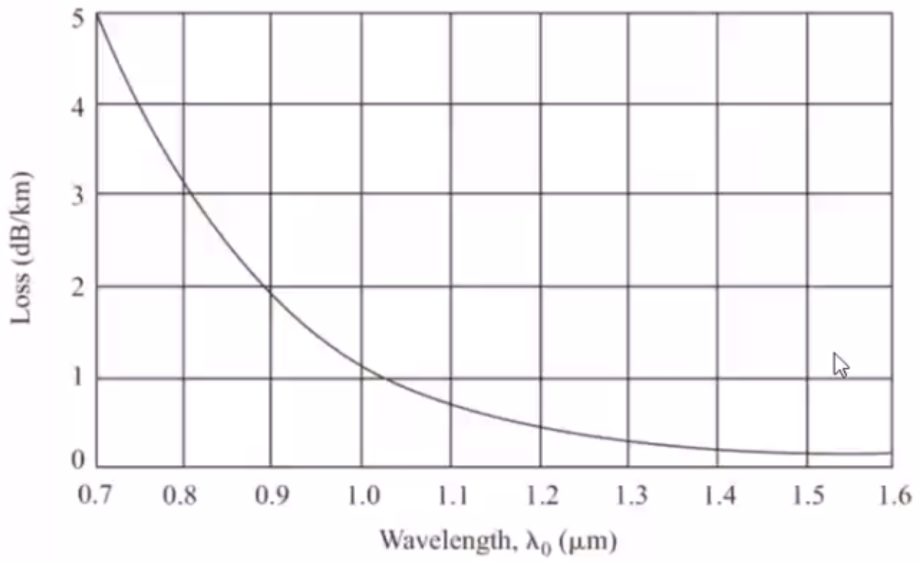
(b) the acceptance angle is

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

Losses in Fibers

Rayleigh Scattering Losses

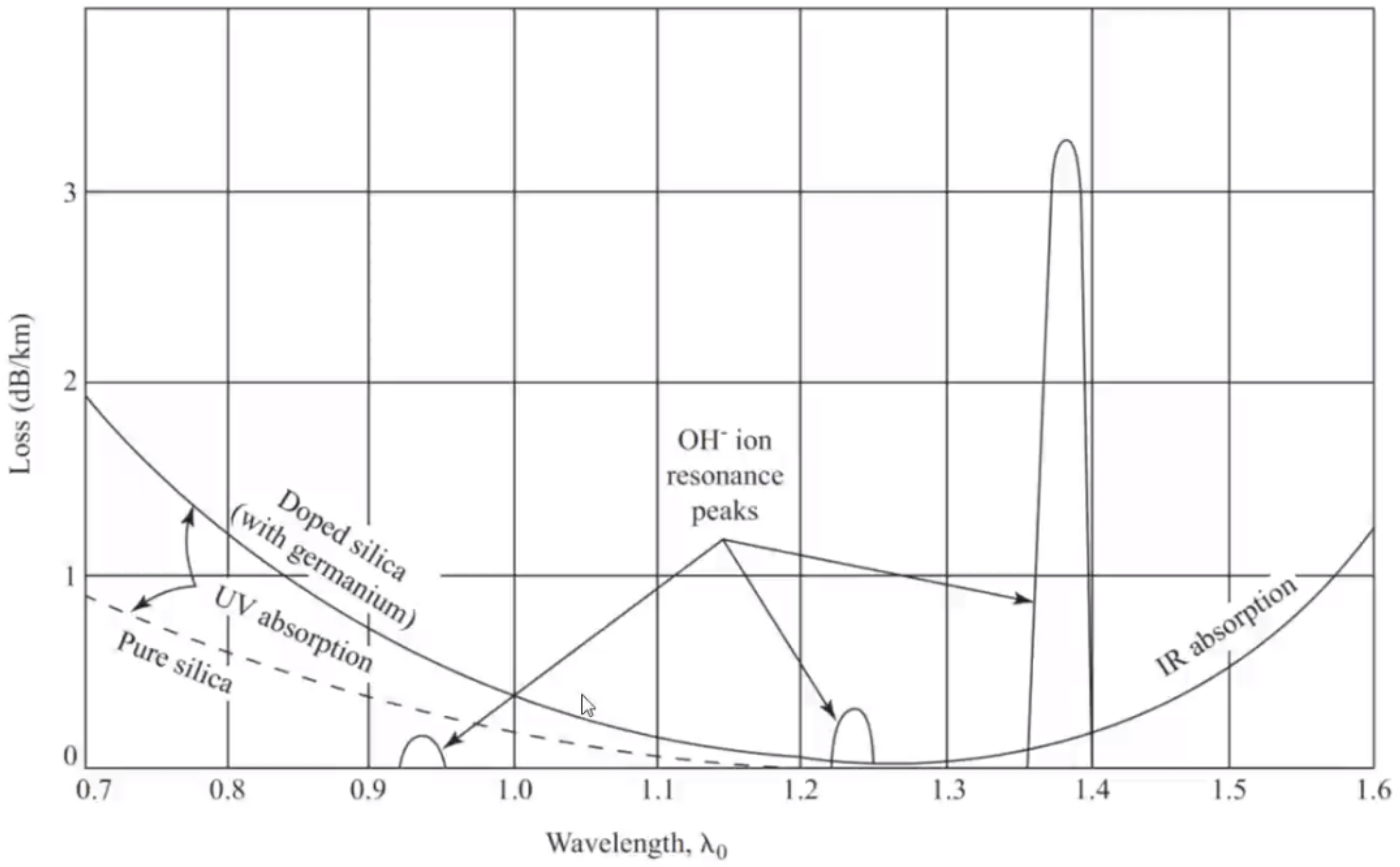
The glass in optical fibers is an amorphous (noncrystalline) solid that is formed by allowing the glass to cool from its molten state at high temperature until it freezes. While it is still plastic, the glass is drawn out under tension into its long fiber form. During this forming process, submicroscopic 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.



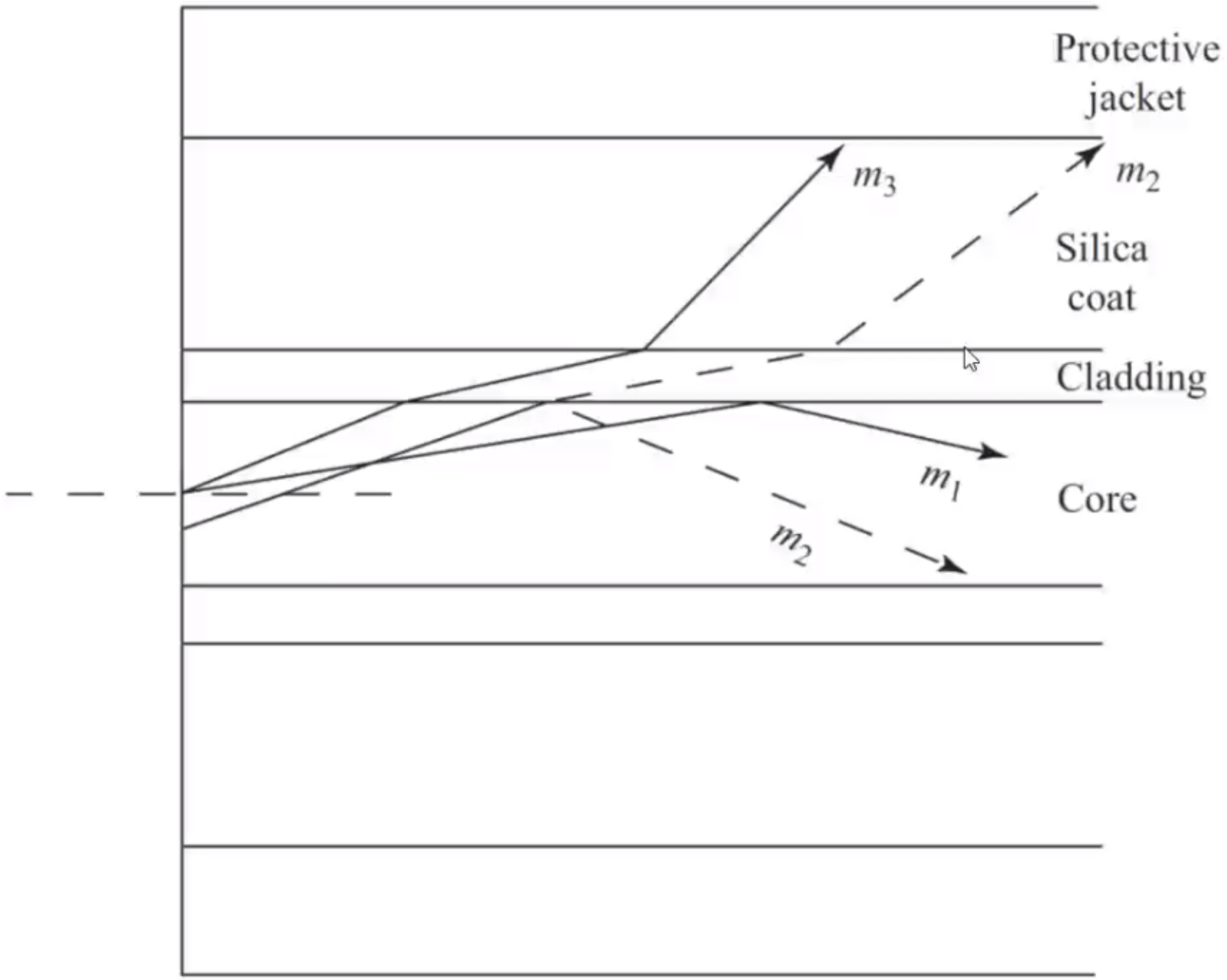
Absorption loss effects in fused silica glass fibers.

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

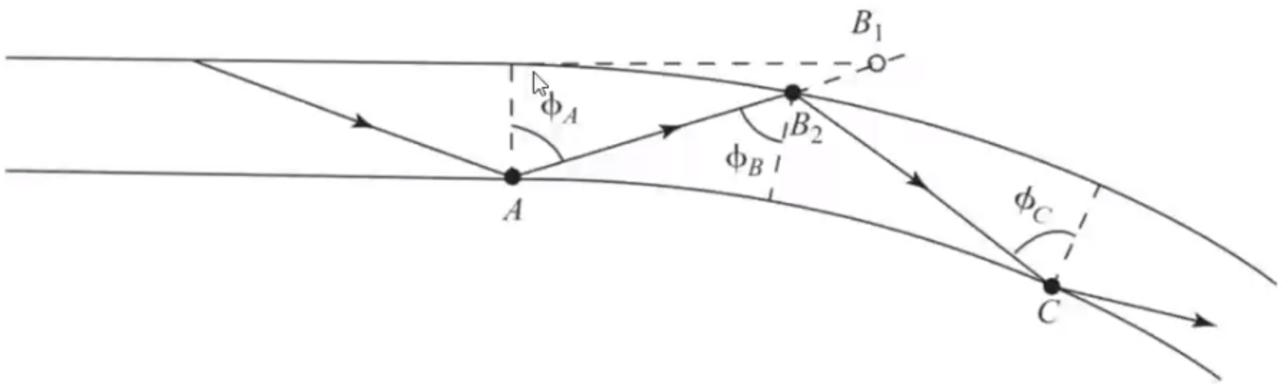
Power that has been launched successfully into a propagating mode may be later coupled into a leaky or radiating mode because of some discontinuity in the fiber. Any variations in the distribution of impurities within the core can cause internal refractions to occur. Any variation in diameter because 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.

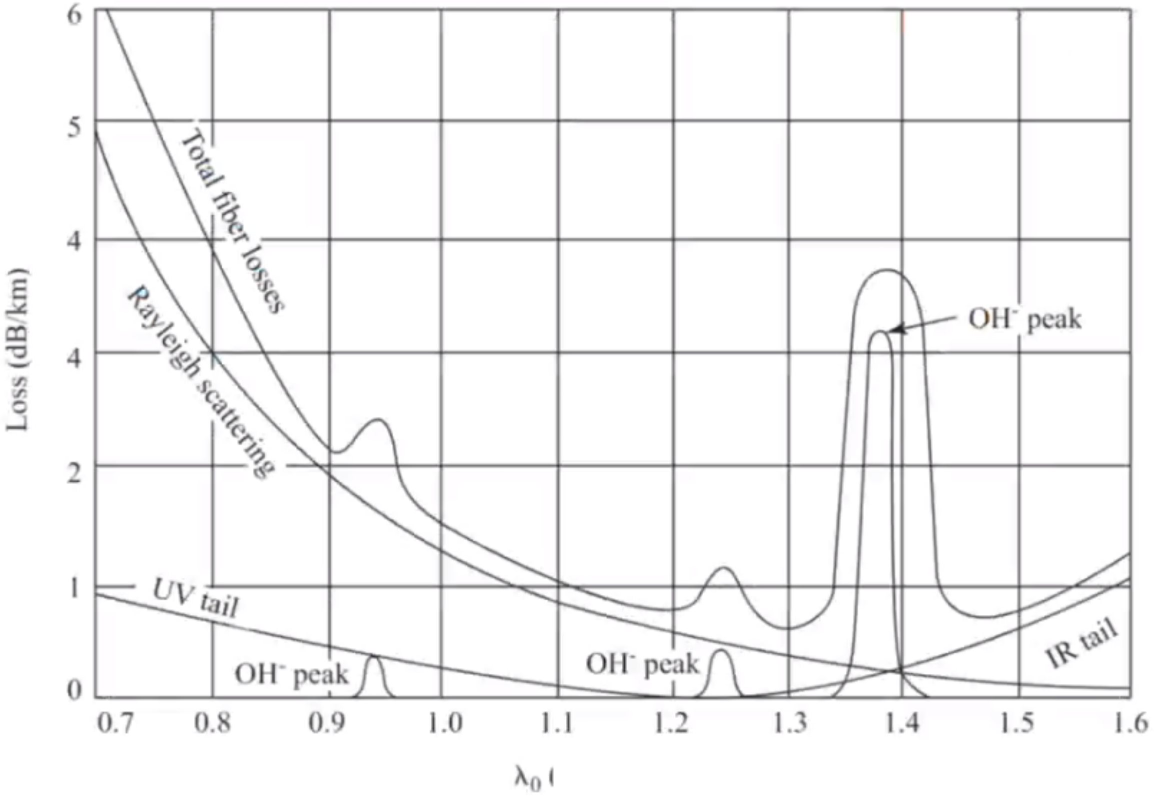
Large radius bending is caused by several things. Fibers are generally combined in multifiber cables, where they are spiraled about a central cable core The spiral creates a constant radius bend that extends the full length of the cable. Aerial cables are hung from poles, and each pole hanger introduces 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.

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Dispersion in Fiber Optic Communication

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Dispersion

Effect of Dispersion on Pulse Transmission

A pulse with a given width and amplitude transmitted into one end of a fiber should theoretically arrive at the far end with its shape and width unchanged and only its amplitude reduced by losses.

However, several effects contribute to time dispersion of the pulse during transmission, which tend to widen out and flatten it, further reducing its amplitude. Besides reduced amplitude, the widening of the pulse may cause it to overlap adjacent pulses, causing intersymbol interference and reducing the upper limit on the pulse transmission rate. At low bit transmission rates the required repeater spacing will be dictated by the loss limits for the fiber. However, at some higher rate the dispersion effects will become predominant and further reduce the repeater spacing. **The product of bandwidth (the maximum allowable transmission rate) and dispersion, or bandwidth-dispersion product (BDP), is used as a quality factor for the fiber.**

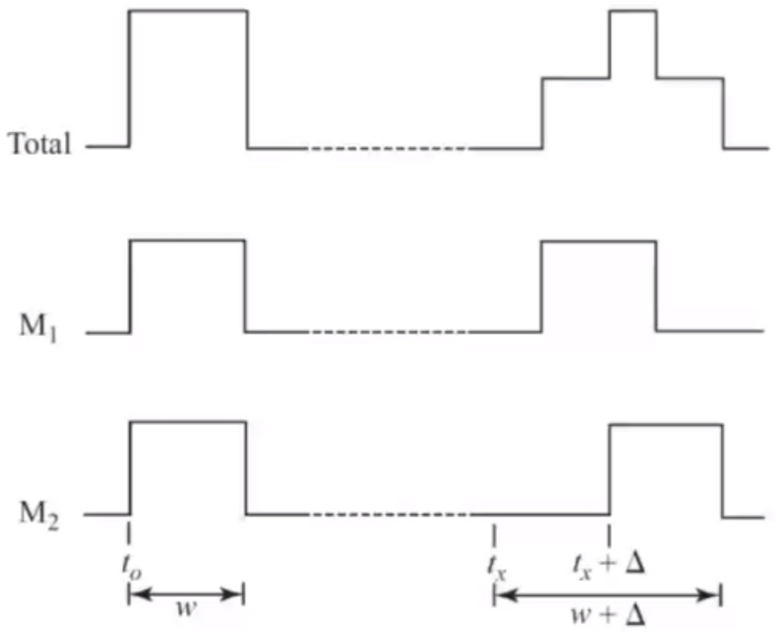
Three separate dispersion mechanisms exist in a fiber.

- Inter-Modal Dispersion
- Material or Chromatic Dispersion
- Waveguide Dispersion

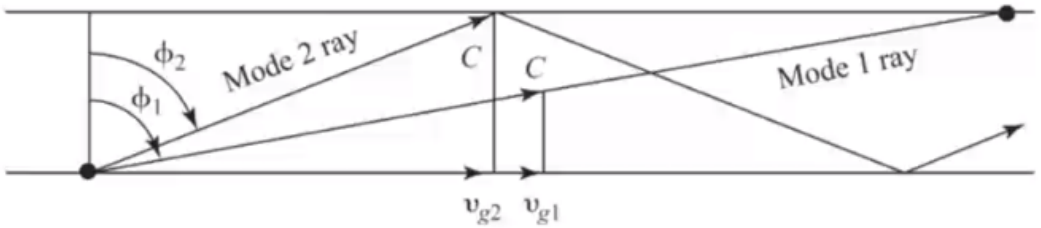
Intermodal Dispersion

Each mode that a step-index fiber supports has a different effective group velocity, even though the phase velocity in each ray path may be identical. This occurs because the total path followed by guided rays is zigzag in nature and has a different length for each mode. The shortest path coincides with the axial length of the fiber for the HE11 mode, while the longest path occurs for the mode nearest the cutoff limit.

A pulse coupled into several modes at the transmitting end becomes several pulses traveling in the several modes at different velocities, which arrive at the receiver at slightly different times. The received pulse is the summation of these mode pulses, each delayed by a different time. Figure shows the effect of dispersion on an ideal pulse transmitted by two modes. The effects of loss are omitted, and only dispersion is accounted for. The received pulse is the summation of the two received modal pulses and has a lower amplitude and wider pulse width than would be the case without dispersion.



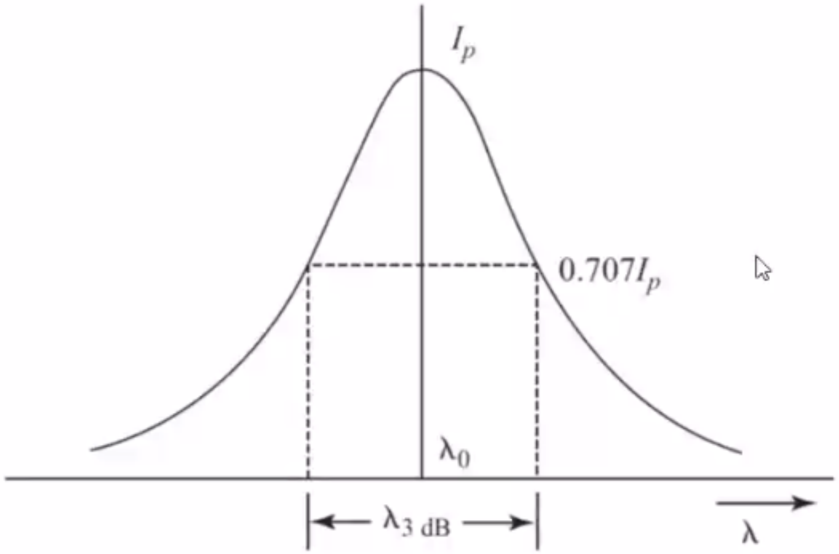
Effect of intermodal dispersion on a transmitted pulse.



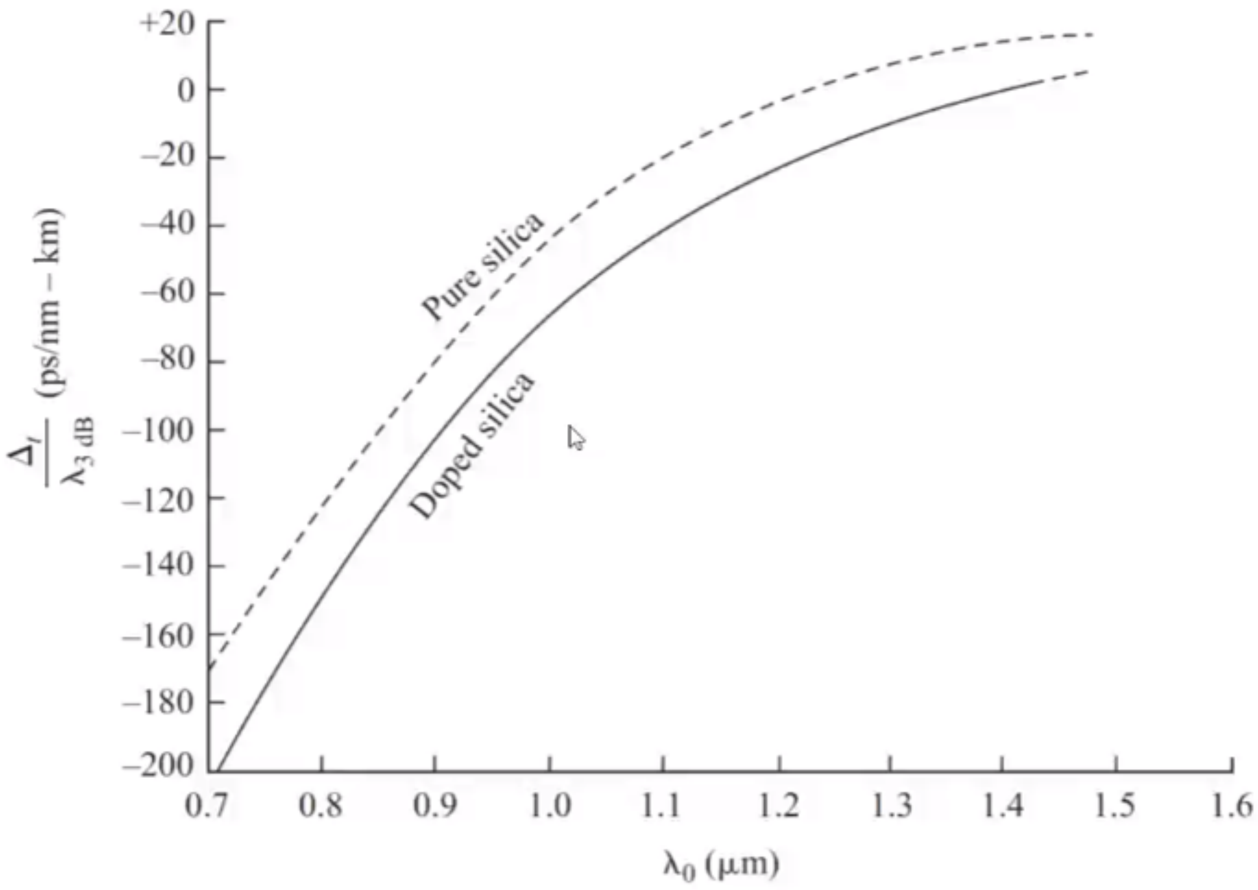
Group velocities for two modes.

Material (or Chromatic) Dispersion

The index of refraction of the core glass is not the same for lights of different wavelengths, but varies across the spectrum. Practical light sources do not put out pure monochromatic light, but produce a spectrum distributed about a central wavelength 0 as shown in Fig. and having a spectral bandwidth 3 dB. Light components of a pulse with shorter wavelengths will experience more delay than will those components of the same pulse with longer wavelengths. The result will be a time dispersion of the pulse at the receiver end of the fiber. A narrow-bandwidth source will produce less dispersion than will a wideband source.



Spectral content of a light source.



Material dispersion coefficient as a function of wavelength for silica fibers.

Waveguide Dispersion

If a fiber can be operated so that intermodal dispersion and material dispersion both disappear (as for a single-mode fiber operated near 1.3m), then a third dispersion mechanism will predominate. This is called *waveguide dispersion* and results only from the guiding characteristics of the fiber.

All practical light sources contain light components of different wavelengths distributed over a spectral bandwidth, as shown in Fig.   A slight spectral shift to higher wavelength will slightly lengthen the path length between successive reflection points (see Fig. __.__) and increase the corresponding incidence angle for each supported mode. This in turn will increase the corresponding group velocity.

Thus each supported mode will suffer a dispersion effect dependent on the spectral width of the source so that, even if the other effects cancel, this one still remains. It too would disappear if a truly monochromatic light source could be developed, but that is not possible.

Total Dispersion and Maximum Transmission Rates

Prof. N. B. Kanirkar
Associate Professor,
ECED, SVNIT.

DIGITAL COMMUNICATION

- Prof. N. B. Kanirkar

Good Morning

Light Sources & Detectors in Fiber Optics

Light Sources for Fiber Optics

Light sources for fiber optics act as light transmitters and must meet certain requirements if they are to be acceptable for the purpose. First, the light produced must be as nearly monochromatic (single frequency) as possible. Most light sources are not single frequency, but emit light at many frequencies distributed over a band or portion of the spectrum, which may be quite broad. A few sources such as gas ionization lamps, light emitting diodes, and lasers emit light over a much narrower band. But even these sources are not truly monochromatic and do emit at several frequencies over a narrow band. The emission spectra of some typical light transmitters are compared in Fig.

Next, the light source should have a high-intensity output so that sufficient energy is transmitted on a fiber to overcome the losses encountered during transmission. Also the sources must be capable of being easily modulated. Although most sources presently available are capable of analog modulation (for example, amplitude modulation), binary on/off modulation with PCM is usually used since it gives good results with much better noise immunity than other methods.

Finally, the devices must be small and easily coupled to fibers so that excessive coupling losses do not occur. They must also be relatively inexpensive to manufacture.

Light emitting diodes and semiconductor lasers are both extensively used for this application. Both emit narrow-band light at fixed center wavelengths as the result of the recombination of hole–electron pairs in the junction area of the diode. Each such recombination is accompanied by the release of a photon of light with a fixed energy content that corresponds to the wavelength of light emitted and to the energy required to free a valence electron from its parent atom in the semiconductor.

Each photon contains an amount of energy that is related to the corresponding electromagnetic frequency by the expression

$$E = hf$$

where E is the energy in joules, h is Planck's constant (6.625×10^{-34} J-s) and f is the frequency in hertz. Light is usually designated by its wavelength instead of frequency. Wavelength is related to frequency by

$$f = \frac{c}{\lambda}$$

where c is the velocity of light in free space (300 Mm/s) and λ is the wavelength in meters. The energy is usually stated in electron voits (eV) found by dividing the energy in joules by the electronic charge q (1.602×10^{-19} C/electron), or

$$E_q = \frac{E}{q}$$

Combining these relationships gives the eV energy in terms of the wavelength as

$$E_q = \frac{hc}{q}\frac{1}{\lambda} = \frac{1.241}{\lambda\,(\mu\text{m})}$$

Fiber-optic Communications

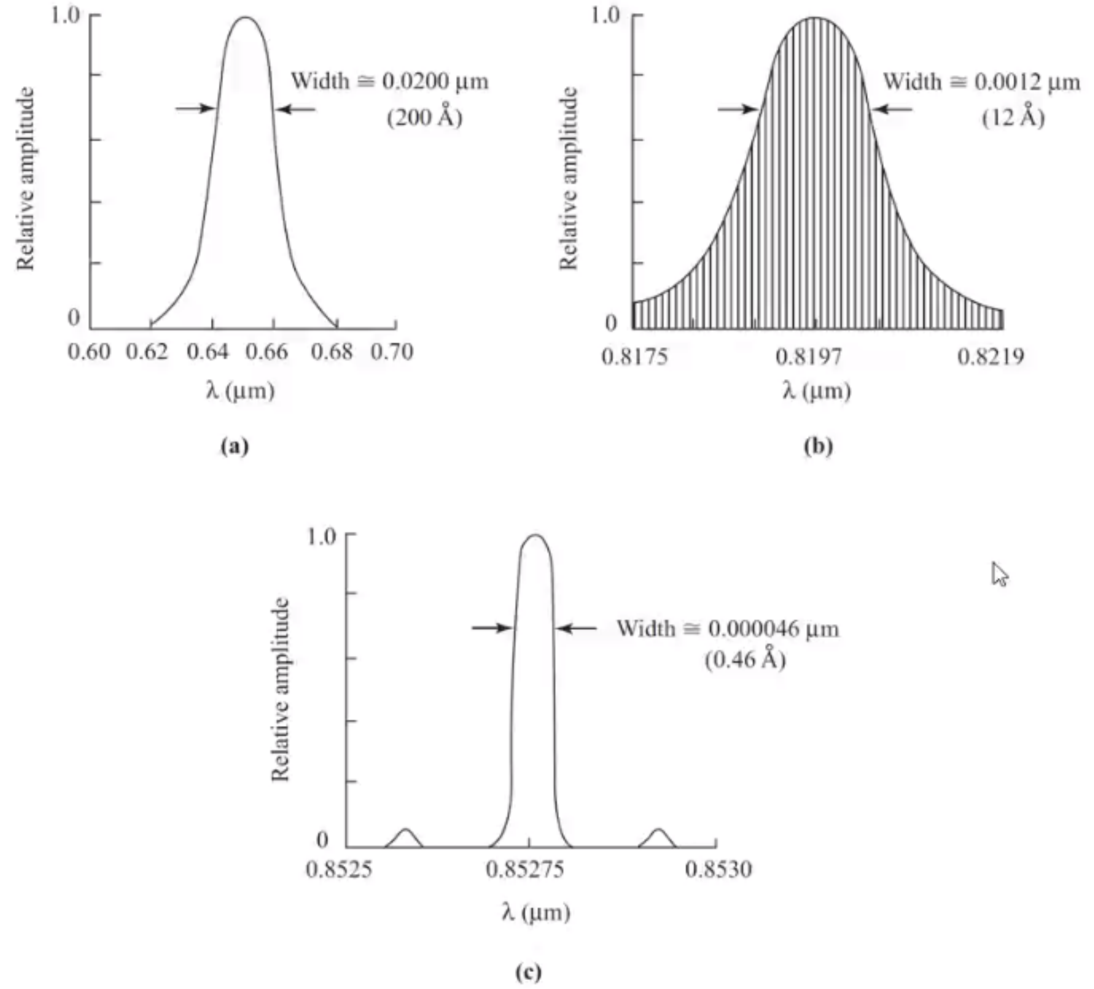


Figure Light emission spectra for typical light transmitters. (a) LED operating at 0.65 μm. (b) Broad-spectrum laser diode at 0.8197 μm. (c) Narrow-spectrum laser diode at 0.85275 μm.

Three semiconductor diodes are made using materials that have energy band gaps of 1.9, 1.46, and 0.954 eV. Find the wavelengths and frequencies of the light produced by them.

SOLUTION (a) The wavelength is

$$\lambda = \frac{1.241}{eV} = \frac{1.241}{1.9} = 0.6532\ \mu\text{m} \quad (= 6532\ \text{angstroms})$$

which emits in the orange-red portion of the visible spectrum. The frequency of this light is

$$f = \frac{c}{\lambda} = \frac{300\ \text{Mm/s}}{0.6532\ \mu\text{m}} - \mathbf{459.3\ THz}$$

(b) $\lambda = 0.850\ \mu\text{m}$ and $f =$ **352.9 THz,** which produces light in the 0.8-μm loss window of silica fibers.
(c) $\lambda = 1.300\ \mu\text{m}$ and $f =$ **230.6 THz,** which produces light in the 1.3-μm loss window of silica fibers.

Light Emitting Diodes

A *light emitting diode* (LED) works by the process of spontaneous emission when it is forward biased and conducting current. One side of the diode junction is *p*-type material containing mostly holes (broken covalent bonds with missing electrons). The other side of the junction is *n*-type material containing mostly free electrons.

At zero bias a depletion zone separates the *p* and *n* regions as shown in Fig. (a). The depletion zone has had all free electrons and holes removed, uncovering two layers of fixed charges of opposite polarities that form a potential barrier across the depletion zone.

When forward bias is applied, the barrier potential is reduced and the depletion zone is narrowed until holes and electrons are free to cross the barrier to conduct current, as shown in Fig (b). Holes injected into the *n* region quickly encounter free electrons and recombine. Electrons injected into the *p* region encounter holes and recombine. External current flow replenishes the lost holes and electrons.