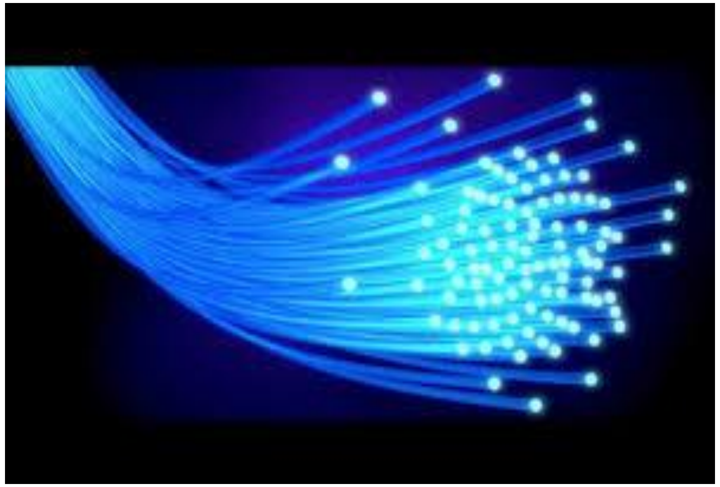
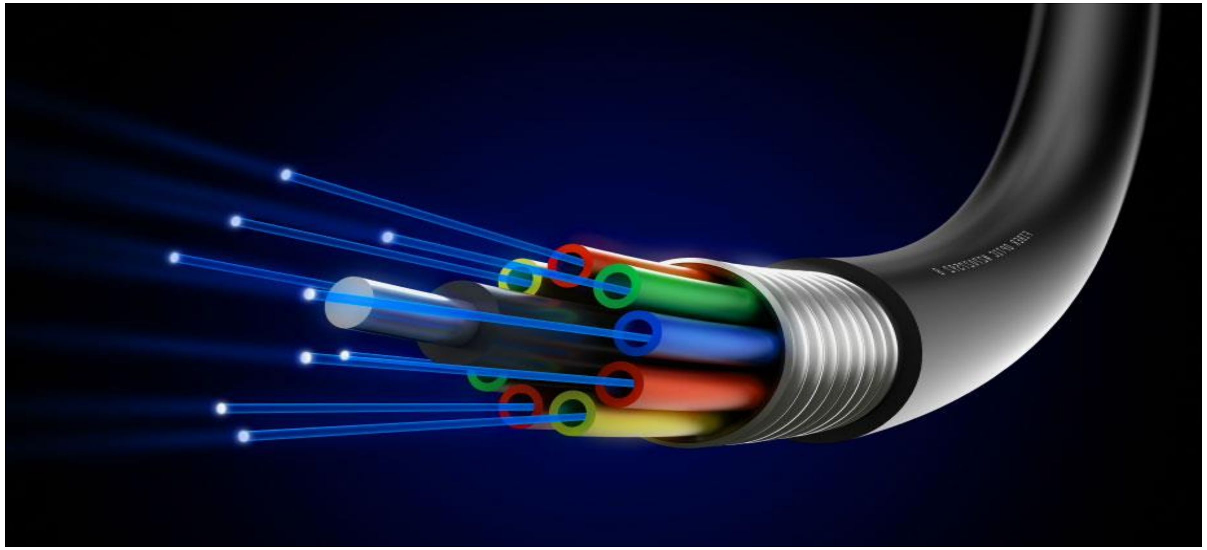
Fiber Optics History

Narinder Singh Kapany (born 31 October 1926) is an Indian-born American physicist known for his work in fiber optics. He was named as one of the seven 'Unsung Heroes' by Fortune in their 'Businessmen of the Century' issue (1999-11-22). He is also known as "**Father of Fiber Optics**". The term fibre optics was coined by Singh Kapany in 1956.

At Imperial College, Kapany worked with **Harold Hopkins** on transmission through fibers, achieving good image transmission through a large bundle of optical fibers for the first time in 1953. Optical fibers had been tried for image transmission before, but Hopkins and Kapany's technique allowed much better image quality than could previously be achieved.

Narinder Singh Kapany





Fiber Optics History

- **1840s:** Swiss physicist **Daniel Colladon** (1802–1893) discovered that he could shine light along a water pipe. The water carried the light by internal reflection.
- **1870:** An Irish physicist called **John Tyndall** (1820–1893) demonstrated internal reflection at London's Royal Society. He shone light into a jug of water. When he poured some of the water out from the jug, the light curved round following the water's path. This idea of "bending light" is exactly what happens in fiber optics. Although **Colladon** is the true grandfather of fiber-optics, **Tyndall** often earns the credit.
- **1930s: Heinrich Lamm** and **Walter Gerlach**, two German students, tried to use light pipes to make a gastroscope—an instrument for looking inside someone's stomach.
- **1950s:** In London, England, Indian physicist **Narinder Kapany** (1926–) and British physicist **Harold Hopkins** (1918–1994) managed to send a simple picture down a light pipe made from thousands of glass fibers. After publishing many scientific papers, Kapany earned a reputation as the "father of fiber optics."
- **1957:** Three American scientists at the University of Michigan, **Lawrence Curtiss**, **Basil Hirschowitz**, and **Wilbur Peters**, successfully used fiber-optic technology to make the world's first gastroscope.
- **1960s:** Chinese-born US physicist **Charles Kao** (1933–) and his colleague **George Hockham** realized that impure glass was no use for long-range fiber optics. Kao suggested that a fiber-optic cable made from very pure glass would be able to carry telephone signals over much longer distances and was awarded **the 2009 Nobel Prize** in Physics for this ground-breaking discovery.
- **1960s:** Researchers at the **Corning Glass Company** made the first fiber-optic cable capable of carrying telephone signals.
- **~1970: Donald Keck** and colleagues at Corning found ways to send signals much further (with less loss) prompting the development of the first low-loss optical fibers.
- **1977:** The first fiber-optic telephone cable was laid between **Long Beach and Artesia, California**.
- **1997:** A huge transatlantic fiber-optic telephone cable called FLAG (Fiber-optic Link Around the Globe) was laid **between London, England and Tokyo, Japan.**

http://www.explainthatstuff.com/fiberoptics.html

Advantages

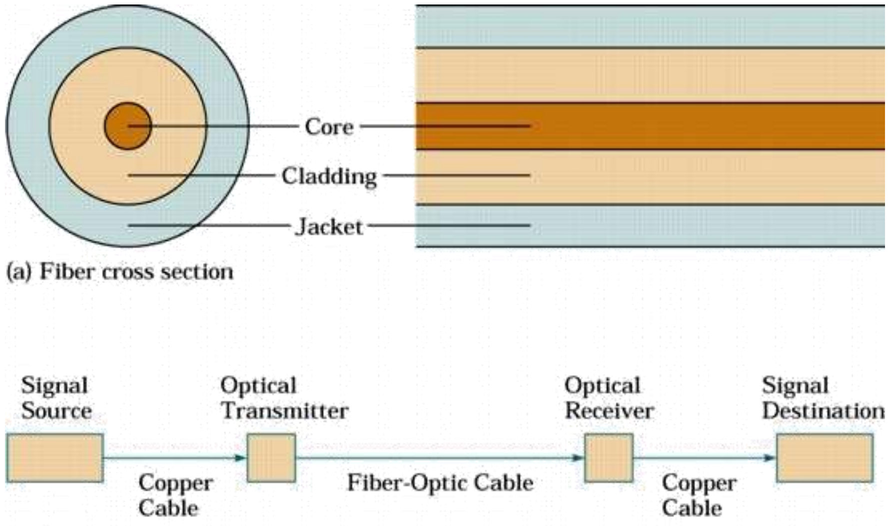
- The bandwidth is high and thus optical fiber can carry more data.
- optical fiber cable is less susceptible to interference than metal cables.
- Thinner and lighter than the metal cables.
- Digital data transmission is possible.
- Very low attenuation through fiber over long distance transmission, so there is no need of repeaters.

Micro-Trench Fiber Laying

Introduction

- An optical fiber is essentially a waveguide for light
- It consists of a **core** and **cladding. Cladding** surrounds the core.
- The **index of refraction** of the cladding is less than that of the core, causing rays of light leaving the core to be refracted back into the core
- A **light-emitting diode** (LED) or **laser diode** (LD) can be used for the source
- Advantages of optical fiber include:
  - Greater bandwidth than copper
  - Lower loss
  - Immunity to **crosstalk**
  - No electrical hazard

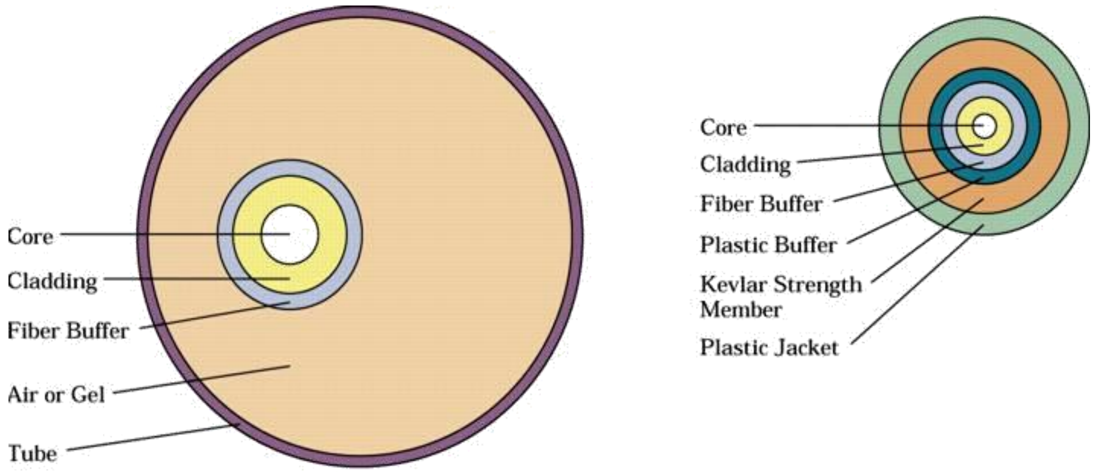
Introduction: Construction



(a) Fiber cross section

(b) System

There are three main regions of an optical fiber namely **Core**, **Cladding** and **Sheath**.



(a) Loose-tube construction

(b) Tight-buffer construction

Core: It is the innermost region of the fiber having the specific property of conducting an optical beam. It is generally made of glass or plastic. It is the actual working structure of the fiber.

Cladding: The core is covered with another layer of glass or plastic having slightly different chemical composition known as cladding. It has lower refractive index than the core.

Sheath: The sheath is the outermost section of the optical fiber. It is made up of plastic or special type of polymer which is opaque in nature. It protects the core from abrasion, interaction with environment, moisture, absorption, crushing, and other adversities of the terrestrial atmosphere and thus enhances the tensile strength.

Introduction

- Optical fiber is made from thin strands of either glass or plastic
- It has little mechanical strength, so it must be enclosed in a protective jacket
- Often, two or more fibers are enclosed in the same cable for increased bandwidth and redundancy in case one of the fibers breaks
- It is also easier to build a full-duplex system using two fibers, one for transmission in each direction

Optical Fiber as Dielectric wave guide

- A waveguide is a structure that guides waves, such as electromagnetic waves or sound, with minimal loss of energy by restricting expansion to one dimension or two.

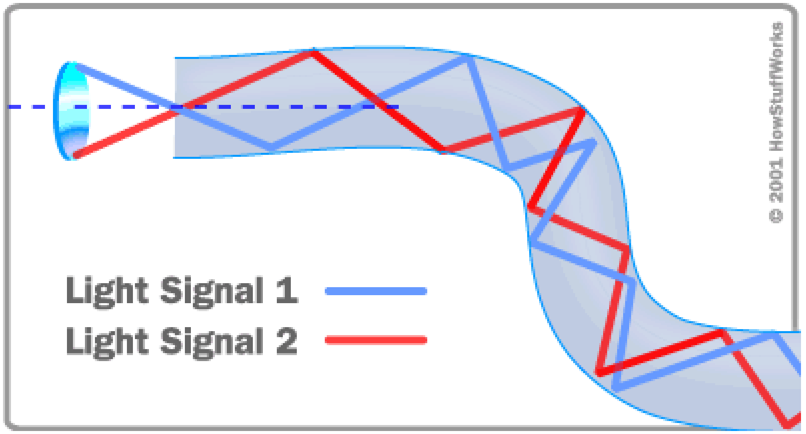
- An optical waveguide is a physical structure that guides electromagnetic waves in the optical spectrum.

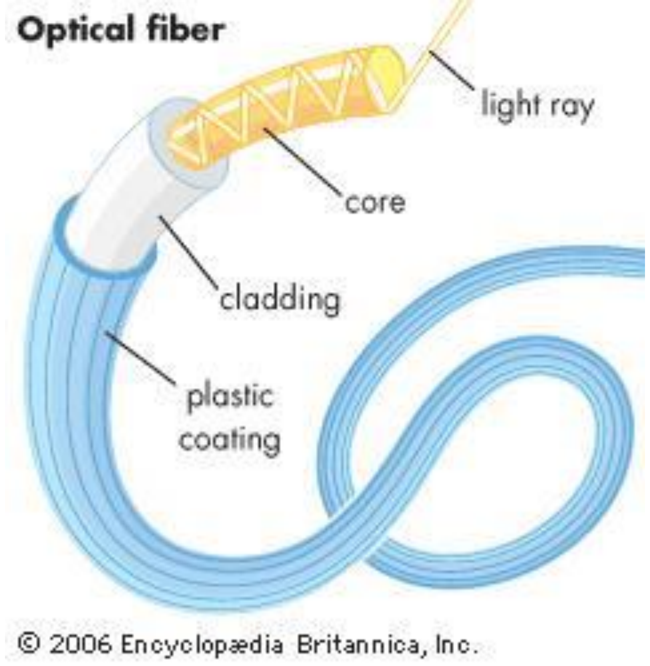
Optical fibers transmit light by the principle of total internal reflection (**TIR**).

The most common optical fibers used in communications are 0.25 to 0.5 mm in diameter, but that includes a coating that protects the fiber from plastic mechanical damage. The cladding, the outer part of the fiber proper, normally is 125 microns across.

https://hypertextbook.com/facts/1997/LaurenBoyd.shtml

VIDEO





Optical Fiber as Dielectric wave guide

Basics of refraction

Refraction: In physics, the change in direction of a wave passing from one medium to another, caused by its change in speed.

Critical Angle: The critical angle is the angle of incidence for which the angle of refraction is 90°.

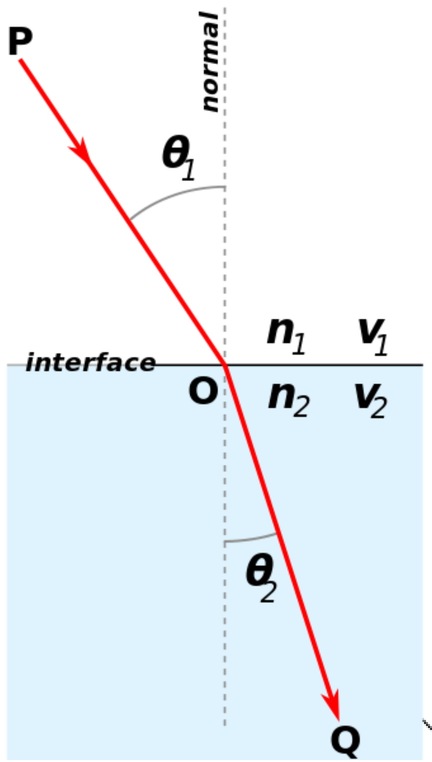
Total Internal Reflection (TIR): Total internal reflection is the phenomenon which occurs when a propagated wave strikes a medium boundary at an angle larger than a particular critical angle with respect to the normal to the surface. If the refractive index is lower on the other side of the boundary and the incident angle is greater than the critical angle, the wave cannot pass through and is entirely reflected into the same medium.

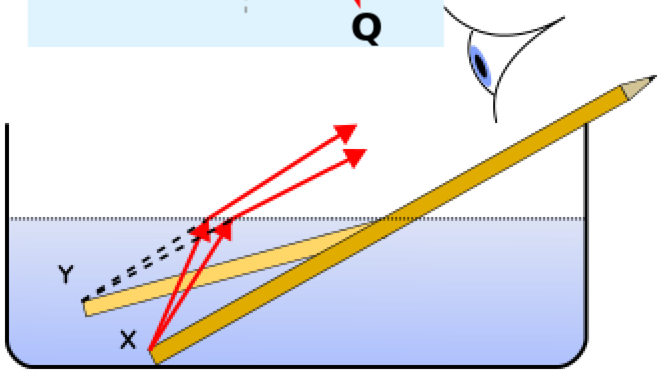
Snell's Law: Snell's law is a formula used to describe the relationship between the angles of incidence and refraction, when referring to light or other waves passing through a boundary between two different isotropic media, such as water, glass, or air.

$$\frac{\sin(\theta_1)}{\sin(\theta_2)} = \frac{\eta_2}{\eta_1}$$

Refractive Index: It is the ratio of the velocity of light in a vacuum to its velocity in a specified medium.

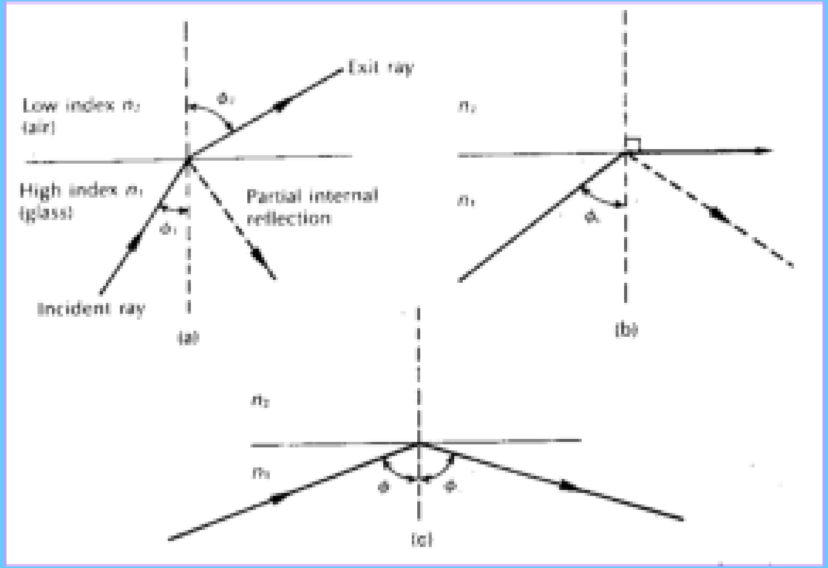
$$\eta = \frac{c}{v}$$





Total Internal Reflection

- Light entering from glass-air interface ($n_1 > n_2$) - **Refraction**



Snell's Law:

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

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

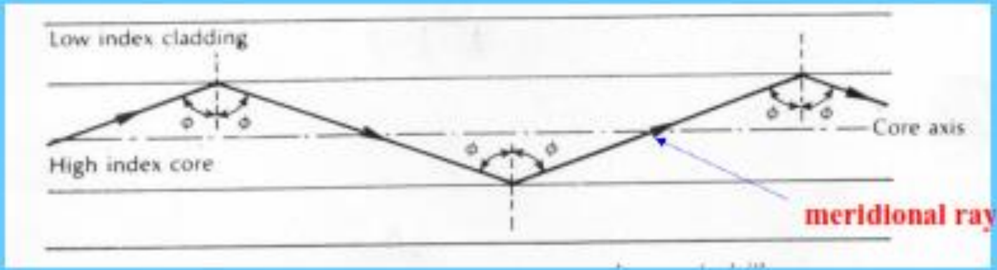
$$\Rightarrow \phi_2 > \phi_1$$

- At $\phi_2 = 90^o$, refracted ray moves parallel to interface between dielectrics and $\phi_1 < 90^o$ - **Limiting case of refraction**

Angle of incidence, $\phi_1 \rightarrow \phi_C$; **critical angle**

Total Internal Reflection

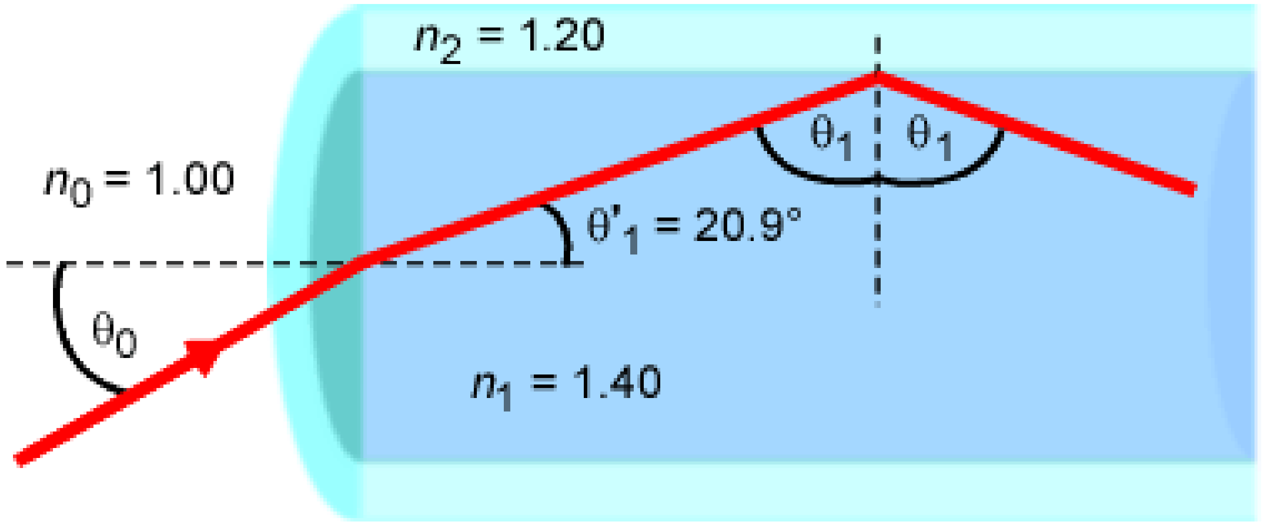
- Value of critical angle (ϕ_C); $\sin \phi_C = n_2/n_1$
  - At angle of incidence greater than critical angle, the light is reflected back into the originating dielectric medium (TIR) with high efficiency ($\approx 99.9\%$)

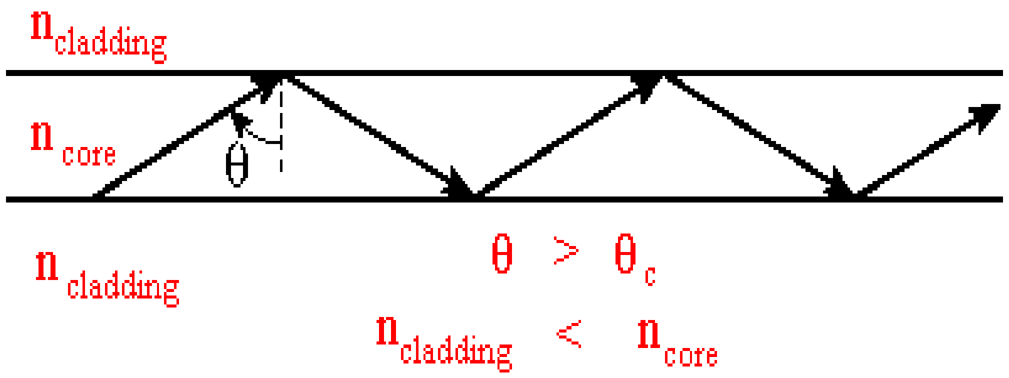


Transmission of light ray in a perfect optical fiber

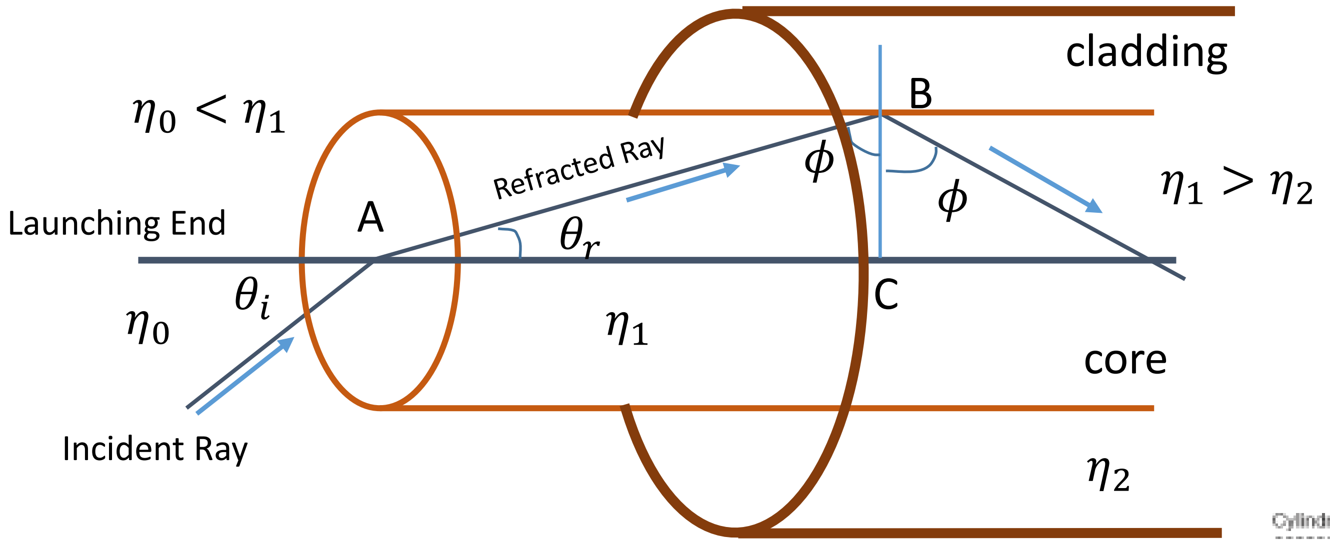
Optical Fiber as Dielectric wave guide

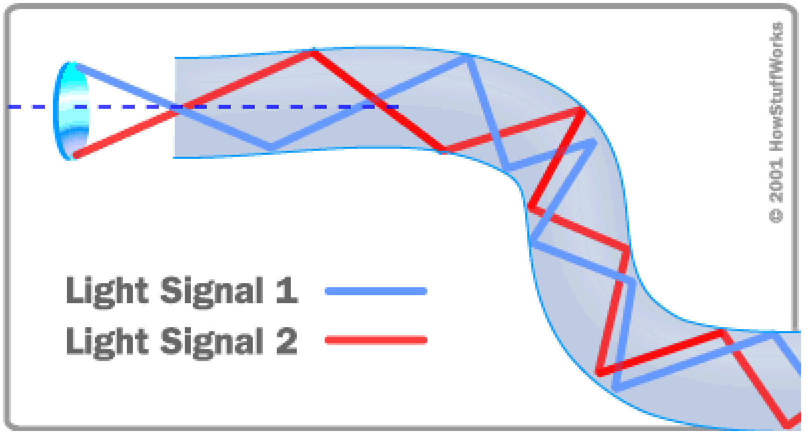
- The incident ray at the core-cladding interface happens to incident at an angle greater than the critical angle. Thus, the ray is no more refracted, but, is totally internally reflected back to the core.
- The ray again hits the bottom of the fiber cable and totally internally reflected once more.
- Thus, by making the zigzag path the ray passes through the fiber.

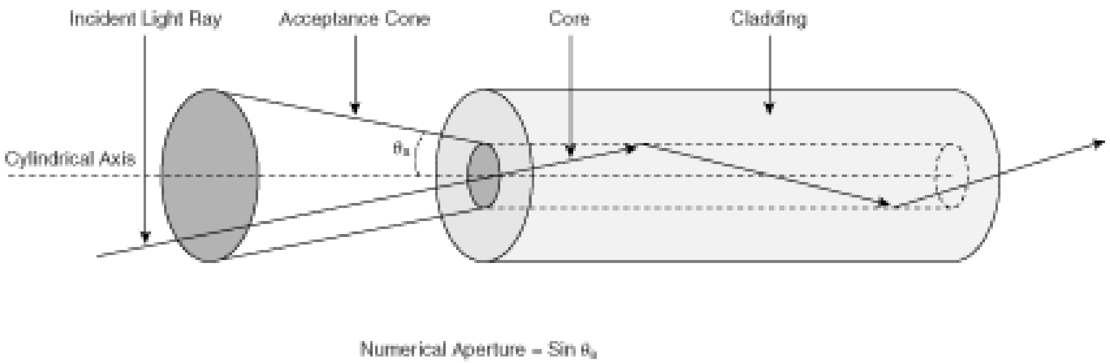




Acceptance Angle





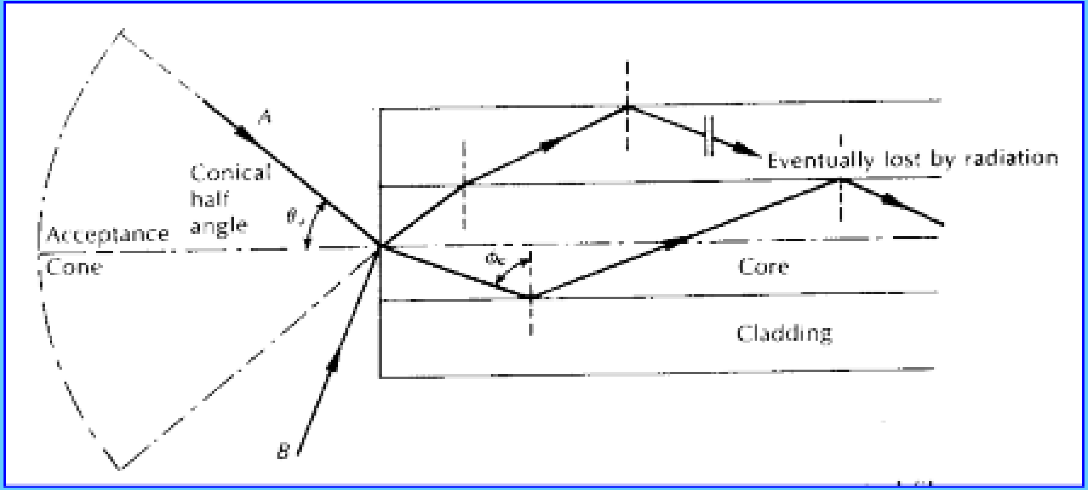


$$\textbf{Acceptance Angle } \theta_m = \sin^{-1}\sqrt{\eta_1^2 - \eta_2^2}$$

ACCEPTANCE ANGLE

- Not all rays entering the fiber core will continue to be propagated down its length

- Only rays with sufficiently shallow grazing angle (i.e. angle to the normal > ϕ_C) at the core-cladding interface are transmitted by TIR.



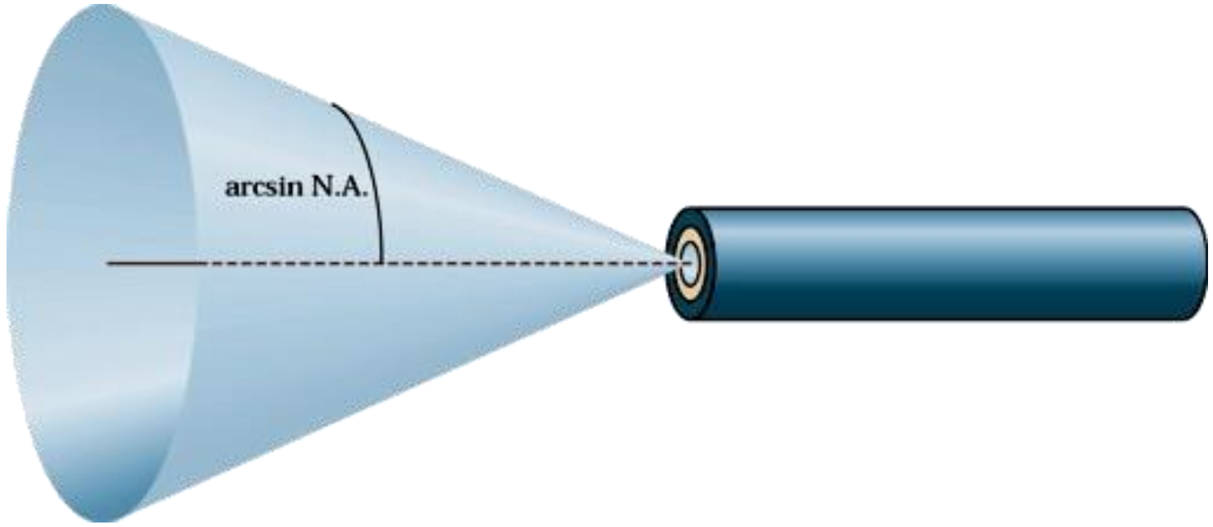
➢ Any ray incident into fiber core at angle > θ_a will be transmitted to core-cladding interface at an angle < ϕ_C and will not follow TIR.

$\Rightarrow$ ***Lost (case B)***

Numerical Aperture

- The **numerical aperture** of the fiber is closely related to the critical angle and is often used in the specification for optical fiber and the components that work with it
- The numerical aperture is given by the formula:
- The **angle of acceptance** is sine inverse of numerical aperture.

$$N.A. = \sqrt{n_1^2 - n_2^2} = \sin \theta a$$



Numerical Aperture

- The larger is the NA, greater the amount of light that can be accepted by fiber. But if NA is too large ,bandwidth of the system degrades.
- NA value is always less than 1.
- Typical values of NA
- 0.11 for single mode
- 0.21 for graded index fiber
- 0.5 for plastic fiber

Modes and Materials

- Since optical fiber is a waveguide, light can propagate in a number of modes
- If a fiber is of large diameter, light entering at different angles will excite different modes while narrow fiber may only excite one mode
- Multimode propagation will cause **dispersion**, which results in the spreading of pulses and limits the usable bandwidth
- **Single-mode** fiber has much less dispersion but is more expensive to produce. Its small size, together with the fact that its numerical aperture is smaller than that of **multimode** fiber, makes it more difficult to couple to light sources

Number of Supported modes

- For step index optical fiber

$$N_\alpha = \frac{2\pi^2 a^2}{\lambda^2}\left(n_1^2 - n_2^2\right)$$

- Where λ is wavelength of light used

  a is radius of the core

V -Number

Normalized wave number
or Normalized frequency

V- Number

- Number of modes supported by optical fiber is obtained by cut-off condition known as Normalized frequency or V-Number
- The number of modes

$$N = \frac{V^2}{2}$$

$$V^2 = 2\,N = \frac{4\pi^2 a^2}{\lambda^2}\left(n_1^2 - n_2^2\right)$$

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} = \frac{2\pi a}{\lambda} NA = \frac{2\pi a n_1}{\lambda}\sqrt{\Delta}$$

V- NUMBER

- No. of modes supported by optical fiber is obtained by cut-off condition known as normalized frequency or V-Number
- Number of modes (N) = ½ V^2
- V- number can be reduced either by reducing numerical aperture or by reducing diameter of fiber

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} \quad = \frac{2\pi a}{\lambda}\mathrm{NA},$$

V-number

- Number of propagating modes in a step-index optical fibre can be determined from the V-number.
- Definition of V-number or normalized frequency

  $V = (2\pi a/\lambda) \times (n_1^2 - n_2^2)^{1/2} = (2\pi a/\lambda) \times (2n_1^2\Delta)^{1/2}$

  – For $V < 2.405$, only one mode (LP_{01}) can propagate through the fibre core.

  – For $V >> 2.405$, Number of modes M $\approx V^2/2$

  – Note: $\Delta = (n_1 - n_2)/n_1 \approx (n_1^2 - n_2^2)/2n_1^2$

NA and Δ (Relative R.I Difference)

- In terms of relative R.I. difference 'Δ' between core and cladding,

$$\Delta = \frac{n_1^{\,2} - n_2^{\,2}}{2n_1^{\,2}} \cong \frac{n_1 - n_2}{n_1} \quad (\text{for } \Delta << 1)$$

$$NA = n_1 (2\,\Delta)^{1/2}$$

- NA ; independent of core and cladding diameters
- Holds for diameters as small as 8 μm

V-Number

- Normalized Frequency, V may be expressed in term Δ, as

$$V = \frac{2\pi}{\lambda} a(NA) = \frac{2\pi}{\lambda} a\, n_1 (2\Delta)^{\frac{1}{2}}$$

- Normalized frequency is a dimensionless parameter and simply called ***V-number*** or ***value of the fiber***.
- It combines in a very useful manner the information about three parameters, **a**, **Δ** and **λ**.
- Limiting parameter for single and multimode propagation in optical fiber.

⇒ V ≤ 2.405 for SM operation

V-number

- Number of propagating modes in a step-index optical fibre can be determined from the V-number.
- Definition of V-number or normalized frequency

  $V = (2\pi a/\lambda) \times (n_1^2 - n_2^2)^{½} = (2\pi a/\lambda) \times (2n_1^2\Delta)^{½}$

  - For $V < 2.405$, only one mode (LP_{01}) can propagate through the fibre core.
  - For $V >> 2.405$, Number of modes M ≈ $V^2/2$
  - Note: $\Delta = (n_1 - n_2)/n_1 \approx (n_1^2 - n_2^2)/2n_1^2$

Modes and Materials

- The term mode refers to mathematical and physical descriptions of the propagation of energy through a medium. A fiber can provide a path for one light ray or hundreds of thousands of light rays.

- Since optical fiber is a waveguide, light can propagate in a number of modes

- If a fiber is of large diameter, light entering at different angles will excite different modes while narrow fiber may only excite one mode

- Multimode propagation will cause **dispersion**, which results in the spreading of pulses and limits the usable bandwidth

- **Single-mode** fiber has much less dispersion but is more expensive to produce. Its small size, together with the fact that its numerical aperture is smaller than that of **multimode** fiber, makes it more difficult to couple to light sources

Fiber Classification

Based on mode the fiber can be classified into two types:

1. **Single Mode Fiber**
2. **Multimode Fiber.**

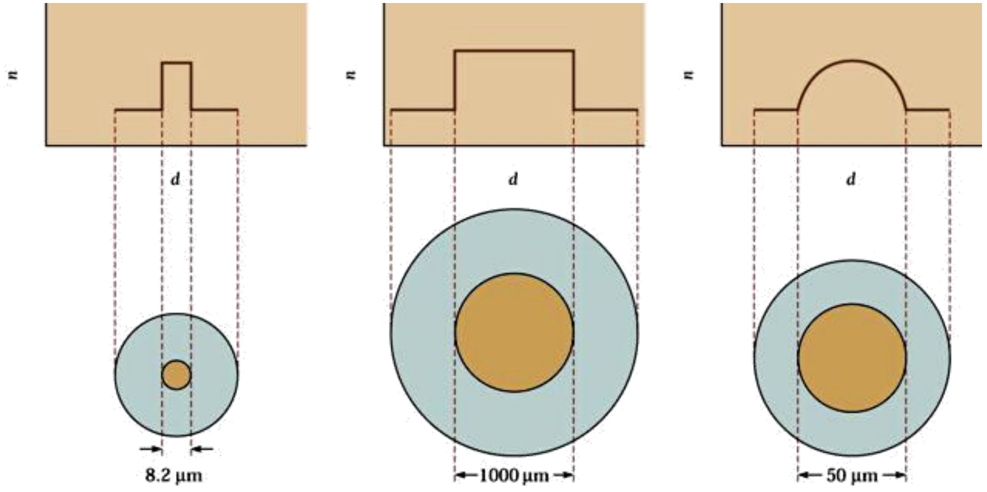
Based on index profile a fiber can be again classified into two types.

1. **Step index and**
2. **Graded index.**

Thus in totality we have the following three classification of the fiber.

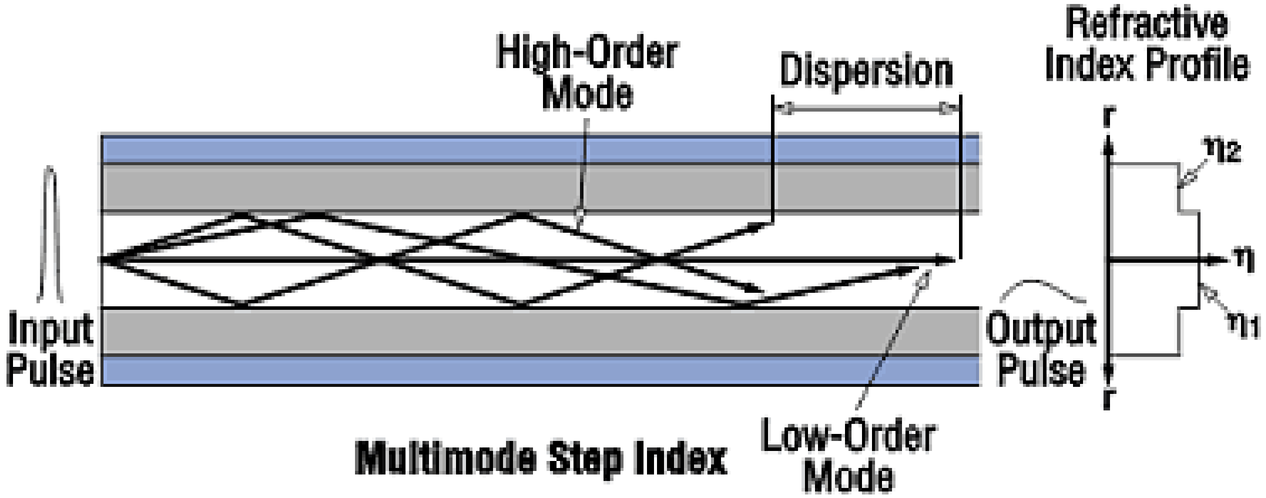
- **Multimode step index fiber (MMSIF).**
- **Multimode graded index fiber (MMGIF).**
- **Single mode step index fiber (SMSIF).**

- Till now the types of fiber described, are the **step-index** fibers because the index of refraction changes radically between the core and the cladding
- **Graded-index** fiber is a multimode fiber, but the index of refraction gradually decreases away from the center of the core
- **Graded-index** fiber has less dispersion than a multimode step-index fiber

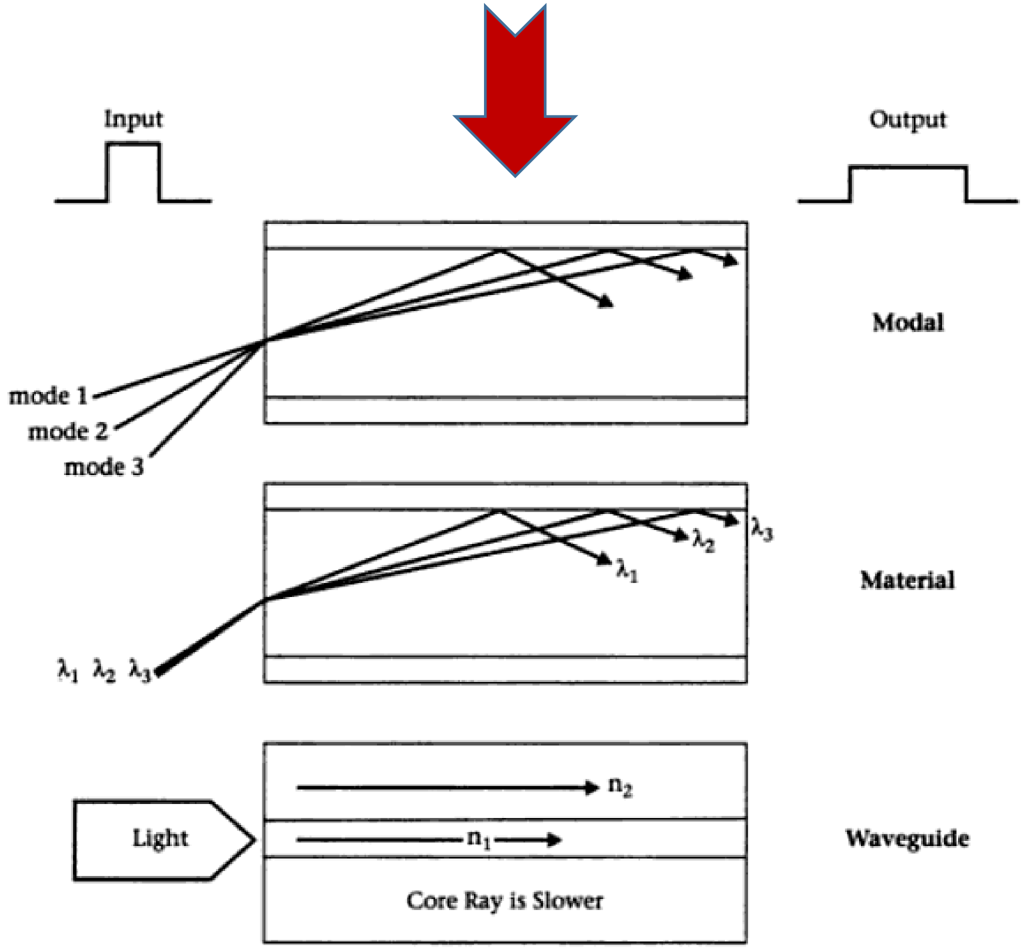


Multimode Step Index Fibers (MMSIF)

- MMSIF has a core diameter ranging from 100 μm to 970 μm.
- Since the diameter is large, there are many paths through which light can travel.
- Therefore, the light ray travelling the straight path through the centre reaches the end before the other rays which follows zigzag path.
- The difference in time length, the various light rays take to exit the fiber is called the modal dispersion.



Dispersions



Multimode Graded Index Fibers (MMGIF)

- MMGIF is an improvement over multimode step index fiber.
- Since light travels faster through the lower index of refraction, light at the fiber core travels more slowly than the light nearer the surface.
- Thus, both the light rays arrive at the exit point almost at the same time. This reduces the modal dispersion.
- A typical graded index fiber has core diameter ranging from 50 to 85 μm and cladding diameter of 125 μm.

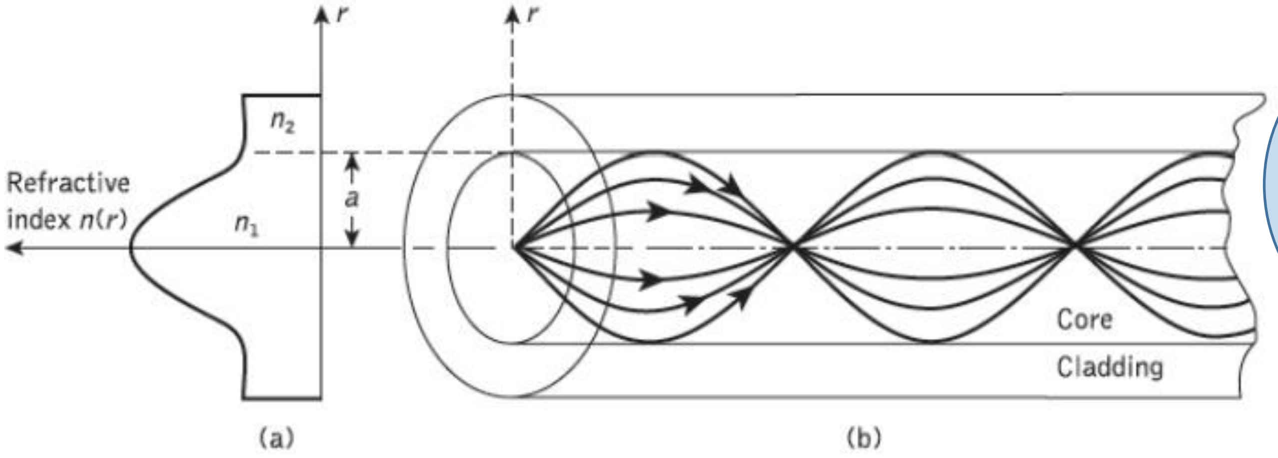
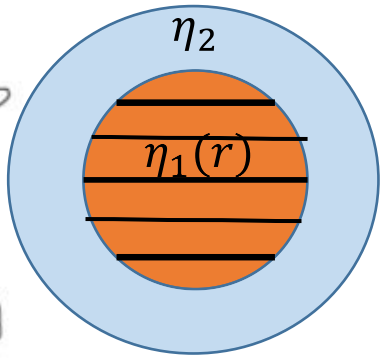


Figure 1.16 The refractive index profile and ray transmission in a multimode graded index fiber



The graded index fibers may be made with a variety of different index profiles. One of the most popular profile is the alpha profile function, in which the index of refraction within the core is made to vary radially as follows:

$$\boldsymbol{\eta(r) = \eta_1\sqrt{1 - 2\Delta\left(\frac{2r}{d}\right)^{\alpha}}}$$

$$\boldsymbol{= \eta_1\sqrt{1 - 2\Delta\left(\frac{r}{a}\right)^{\alpha}}}$$

$$\boldsymbol{NA = \sqrt{\eta(r)^2 - \eta_2^2}}$$

$\Delta = Fractional\ refractive\ index$

$d = core\ diameter$

$r = radial\ ditance\ from\ the\ axis$

$\eta_1 = RI\ of\ the\ core\ axis$

$\boldsymbol{\alpha = 2}$ produces parabolic profile.

Multimode Graded Index Fibers (MMGIF) Mode Support

- The value of α could vary from 1 and ∞, but the most popular use is $\boldsymbol{\alpha = 2}$ which produces parabolic profile.

- Graded index fibers generally do not support as many modes as step index fibers.

- The maximum number of modes supported is reduced according to the equation (for $\alpha = 2$)

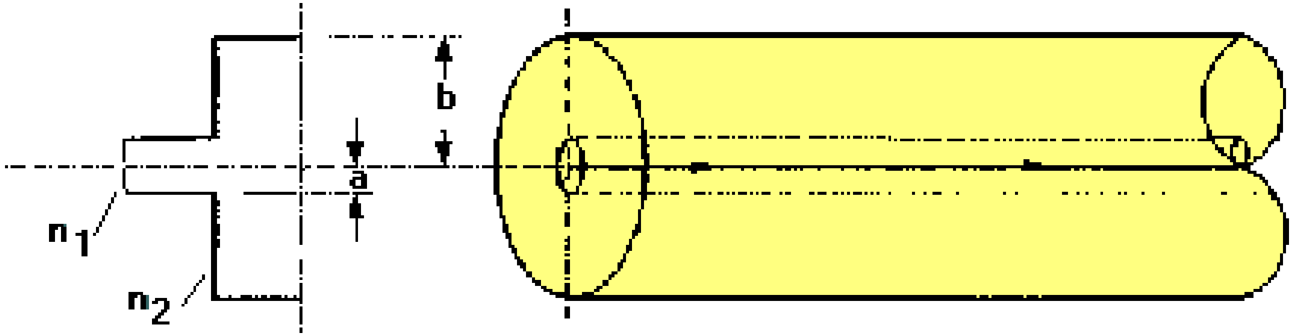
$$N = \left(\frac{\alpha}{\alpha + 2}\right)\frac{V^2}{2}$$

- Graded index fibers are almost always used as multimode fibers.

- A carefully designed graded index fiber will give performance almost as good as a single mode fiber for same application.

Single-mode Step Index Fiber (SMSIF)

- A single-mode optical fiber (SMF) is an optical fiber designed to carry light only directly down the fiber. The core is of uniform refractive index.
- It finds application in today's wide band communication arena.
- Since light travels only in one direction hence, modal dispersion is zero.
- It has a very thin core of $5 - 10\ \mu m$ and cladding of 125 μm.



SINGLE MODE STEP-INDEX FIBER

Losses Associated with Optical Fibers

The losses in optical fibers may be due to the following causes:

1. **Rayleigh Scattering Losses**
2. **Absorption Losses**
3. **Microbend Losses**
4. **Macrobend Losses**

Rayleigh Scattering Loss

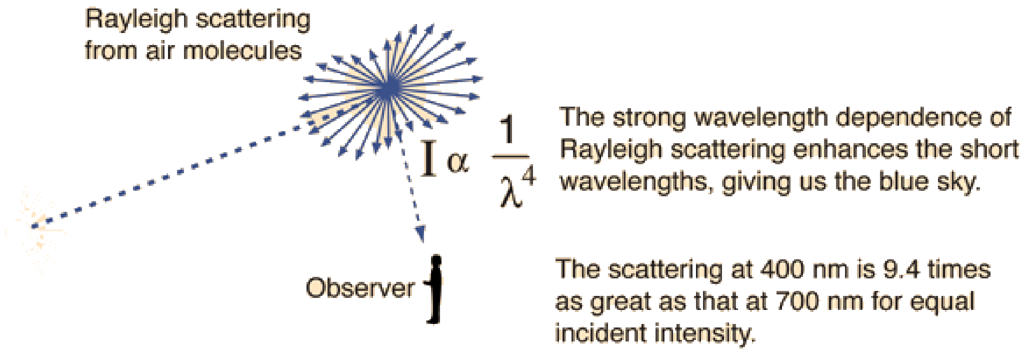
- The glass in optical fiber is an amorphous solid (i.e. non-crystalline)
- It is formed by cooling the glass from the molten state at high temperature until it freezes.
- During this forming process some imperfections are caused in the fiber which allow to scatter a small portion of the light passing through the glass creating losses.
- Since scattering is wavelength dependent process, it affects each wavelength differently.

Some typical scattering loss is as follows:
2.5 dB/km at 0.82 μm
0.24 dB/km at 1.3 μm
0.012 dB/km at 1.55 μm

Rayleigh Scattering

Rayleigh scattering, named after the British physicist Lord Rayleigh is the elastic scattering of light or other electromagnetic radiation by particles much smaller than the wavelength of the radiation.

The cause of scattering can be a particle, a density anomaly or even a surface anomaly.



http://www.differencebetween.com/difference-between-scattering-and-vs-reflection/

Absorption Losses

Three mechanism contribute to the absorption loss

1. Ultraviolet absorption
2. Infrared absorption
3. Ion resonance absorption.

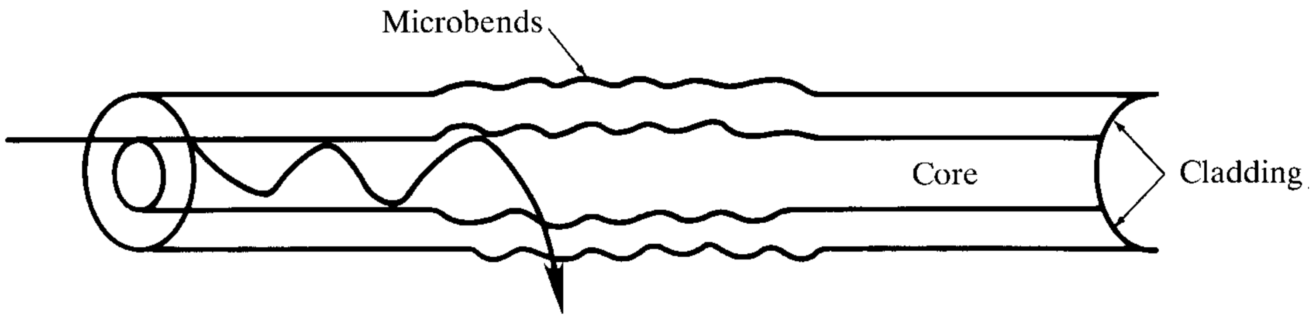
The oxygen ions in pure silica have very tightly bonded electrons and only the ultraviolet light photons have enough energy to be absorbed. However in silica light guide, the dopants and transitional metal impurities have electrons that can be excited in the visible and near infrared light regions.

Infrared absorption takes place because photons of light energy are absorbed by atoms within the glass molecules and converted to the random mechanical vibration type of heating.

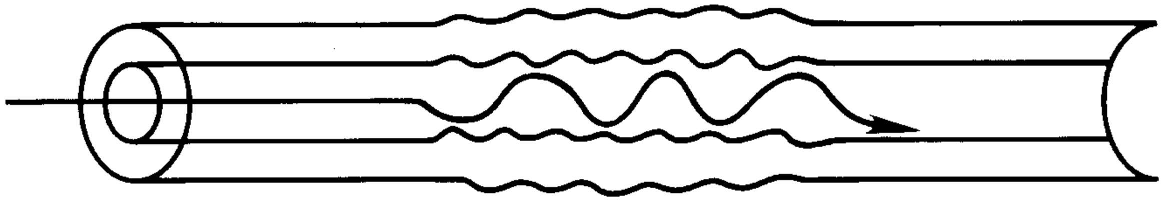
During manufacture some minute quantities of water molecules trapped in the glass contribute hydroxyl ions (OH-) to the material. These ions also absorb energy at peaks of 0.95, 1.23 and 1.3 micro meter with main peak at 1.39 micrometer.

Micro bending Losses

Microbend loss is a loss due to small surface irregularities in the cladding. This causes light to be reflected at angles where there is no further reflection.

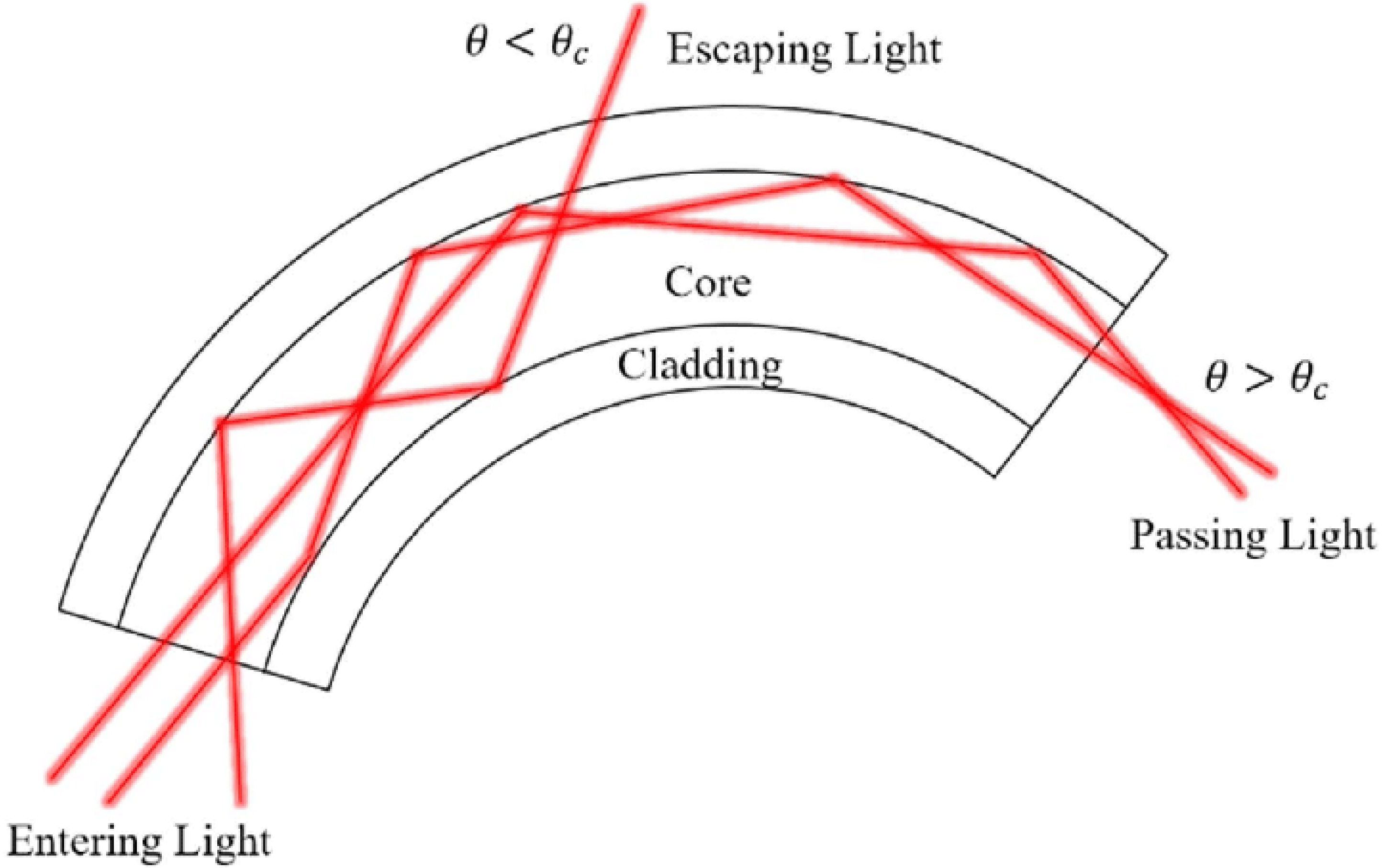


Power loss from higher-order modes


Power coupling to higher-order modes

Macro bending Losses

Macrobend is a bend in the entire cable which causes certain modes not to be reflected and therefore causes loss to the cladding.



Attenuation

Attenuation loss in an optical fiber is defined as the ratio of optical output power P_{out} from a fiber of length L to the optical input power P_{in}. It is measured in **decibel/km.**

$$\boldsymbol{\alpha = \frac{10}{L} log_{10}\left[\frac{P_{in}}{P_{out}}\right]}$$

For ideal case $\alpha = 0$, but in actual practice a low loss fiber may have $\alpha = 3\ dB/km$.

Attenuation

Q. Attenuation loss for a certain fiber is found to be 3.5 dB/km. If initial power is 0.35 mW, what is power output after 4 km?

$$\alpha = \frac{10}{L}\log_{10}\left(\frac{P_{in}}{P_{out}}\right)$$

$$3.5 = \frac{10}{4}\log\left(\frac{0.35\ mW}{P_{out}}\right)$$

Applications of Fiber Optics

- Wide range application is there in the field of communication as information channels.
- In military mobiles such as air-craft, ships, tanks etc., fiber guided missiles, short and long distance communication links.
- Close circuit TV (CCTV) links for traffic controls and security.
- In ophthalmology, a laser beam guided by fibers is used to reattach detached retinas and to correct defects in vision.
- In endoscopy for visualization of internal portions of the human body.
- In sensors and transducers.
- In the signal multiplexing.