Introduction to Fiber Optics

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Milestones in Electrical Communication

- 1838 - Samuel F.B. Morse invented Telegraphy
- 1866 - first transatlantic telegraph cable
- 1876 - Alexander Graham Bell invented Telephone
- 1905 - Triode based Electronic amplifier
- 1940 - first coaxial-cable system (3 MHz – 3,000 voice channels or ONE television channel)
- 1948 - first microwave system (4 GHz)
- 1975 - the most advanced coaxial system with a bit rate of 274 Mb/s

Communication Systems of the 20th Century

- Wire – Telegraphy (2 wires for telegraph transmission – simplex & duplex)
- Wire – Telephony (2 wires for telephone transmission of 1 channel)
- Carrier telephony (long-distance telephony for multiple channels – 4,8,16)
- Coaxial cable systems (for 32 channel PCM systems – 32x64kb/s = 2.048 Mb/s)

Problems of Electrical Communication systems

- Affected by EMI
- Low bandwidth (4 kHz – telephone,
  100-500 MHz per km – coaxial cable)
- High attenuation (20 dB/km – typically)
- High system cost
  - due to too many repeaters for a given Bandwidth/ data rate
  - Eg. 32 channel (2.048 Mbps) PCM link required one repeater every 2 km
- Prone to tapping
- Bulky

History of Fibre Optics

- 1954 – first demonstration of Glass Optical fiber (Kapany)
- 1966 – suggestion to use optical fiber (Kao & Hockham)
- 1970 – Corning Glass optical fiber with 20 dB/km near 1 μm
- 1970 - Semiconductor Laser with CW operation at room temp.
- 1980 onwards – wide spread use of Optical Fiber Communication using SMF and MMF
- 1990 – used Optical amplification (for increased repeater spacing) and Wavelength-division multiplexing (WDM) for increased data rate.
  - Resulted in a data rate of 10 Tb/s by 2001.

Advantages of Optical Fiber Communication (Fiber Optics)

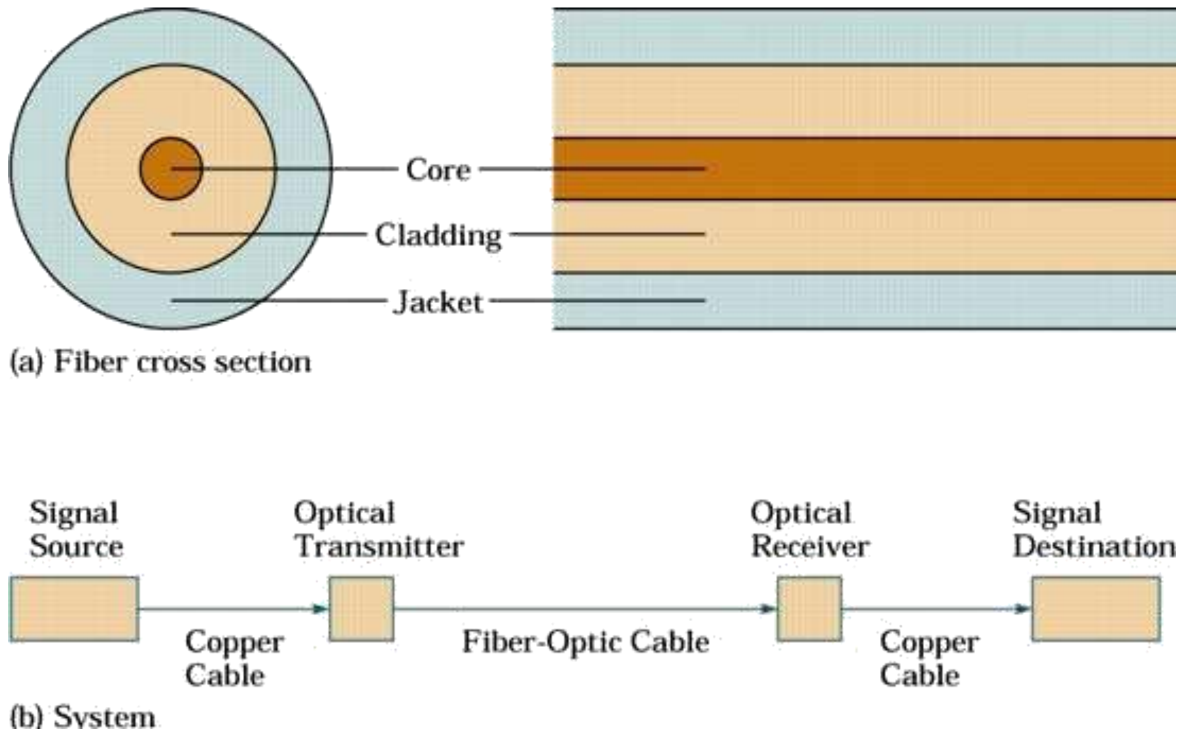
- Very high bandwidth (10 - 500 GHz, typ.)
- Very low attenuation (lowest 0.16 dB/km)
- Immune to EMI
- Data security (almost impossible to tap information)
- Lower system cost (fewer repeaters due to low attenuation of fibers)
- Small size and low weight
- Very low Bit Error Rate ($< 10^{-10}$ typically)

Basics

- An optical fiber is essentially a waveguide for light
- It consists of a **core** and **cladding** that 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

Optical Communications System

- Sources
- Transmission medium
- Detectors



What are optical fibers

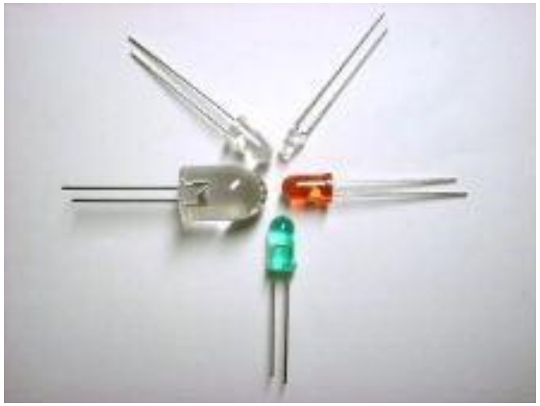
- Thin strands of pure glass
- Carry data over long distances
- At very high speeds
- Fiber can be bent or twisted

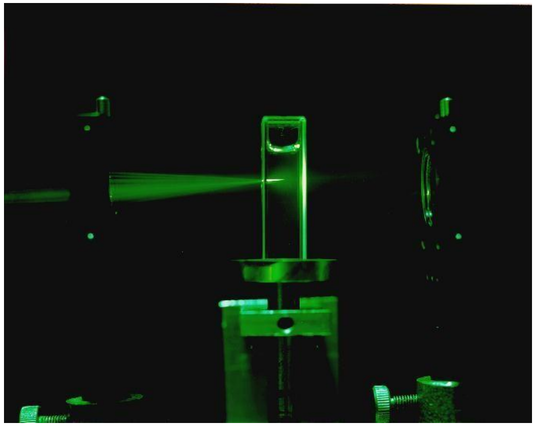
Optical Fiber

- 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

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

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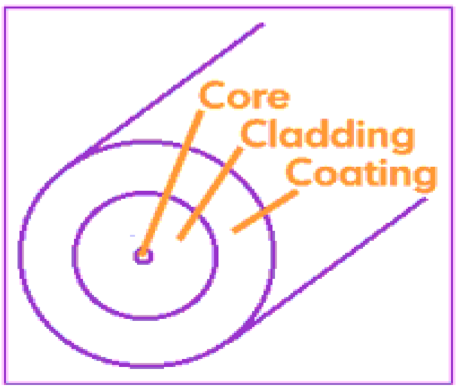
Transmission media

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



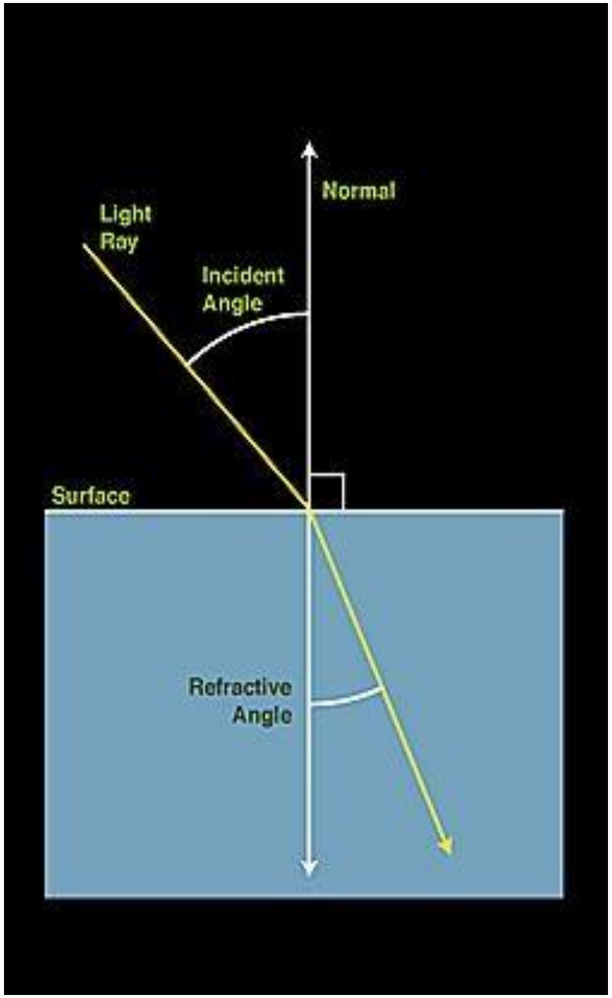
The optical fiber

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

Refraction of light

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



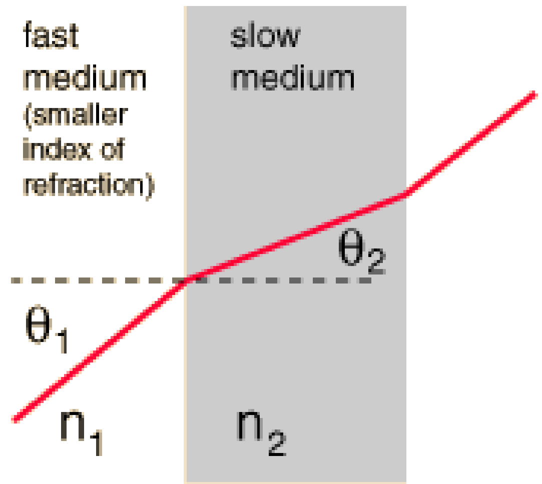
Refraction Indices

- 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

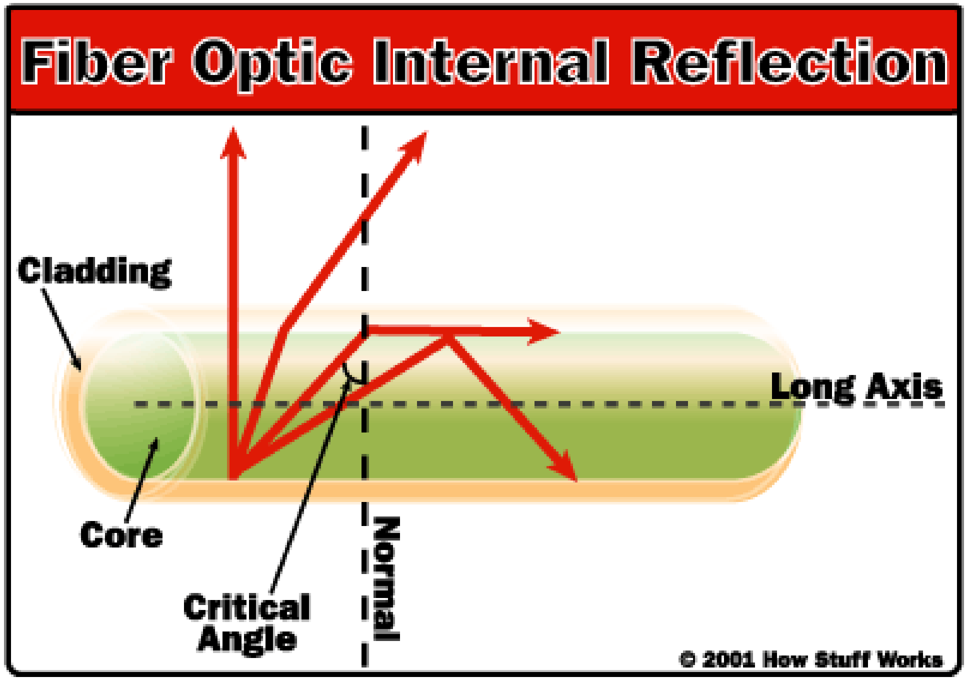
$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1}$$



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

Total internal reflection

- Trapping light in the fiber

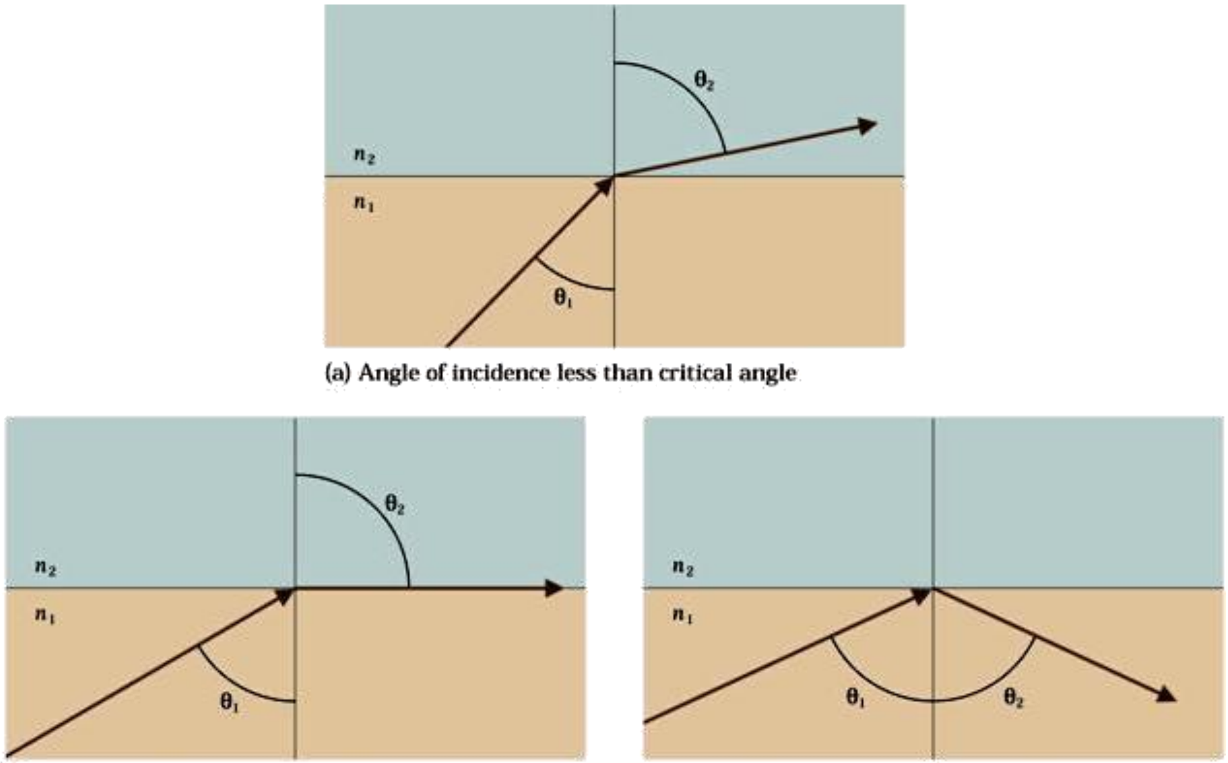


Total Internal Reflection

- Optical fibers work on the principle of **total internal reflection**
- With light, the refractive index is listed
- The **angle of refraction** at the interface between two media is governed by Snell's law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Refraction & Total Internal Reflection



(a) Angle of incidence less than critical angle

(b) Angle of incidence equal to critical angle

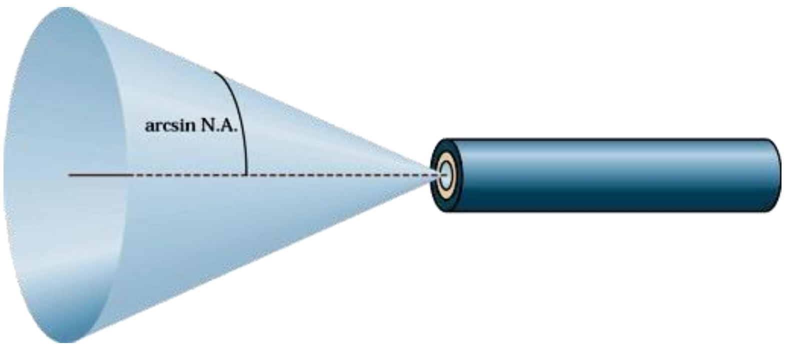
(c) Angle of incidence greater than critical angle

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:

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

- The **angle of acceptance** is twice that given by the numerical aperture



Modes and Materials

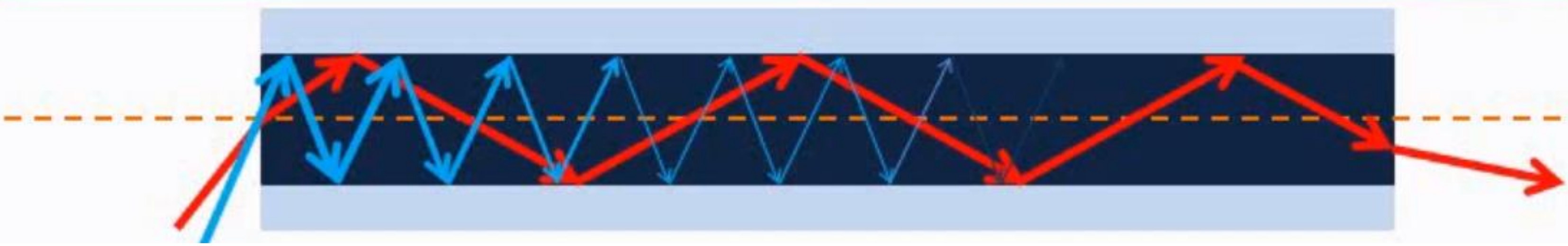
- Since optical fiber is a waveguide, light can propagate in a number of modes
- If a fiber is of large diameter, light entering at different angles will excite different modes while narrow fiber may only excite one mode
- Multimode propagation will cause **dispersion**, which results in the spreading 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

Modes of Propagation

The light ray paths along which the waves are in phase inside the fibre are known as modes.

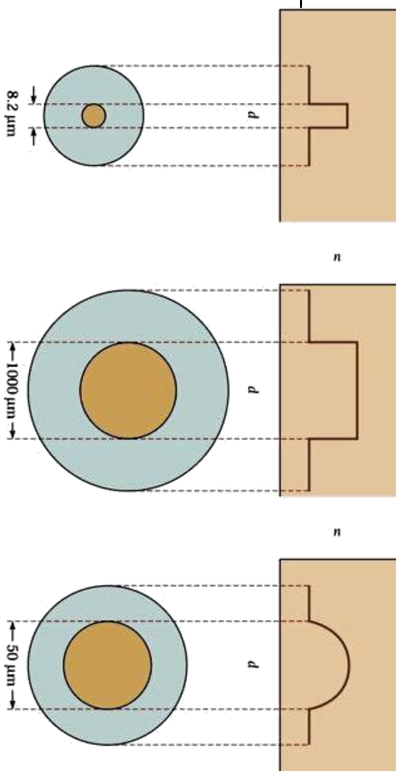
In simple words the allowed paths for the light ray inside the fibre are known as modes of propagation.

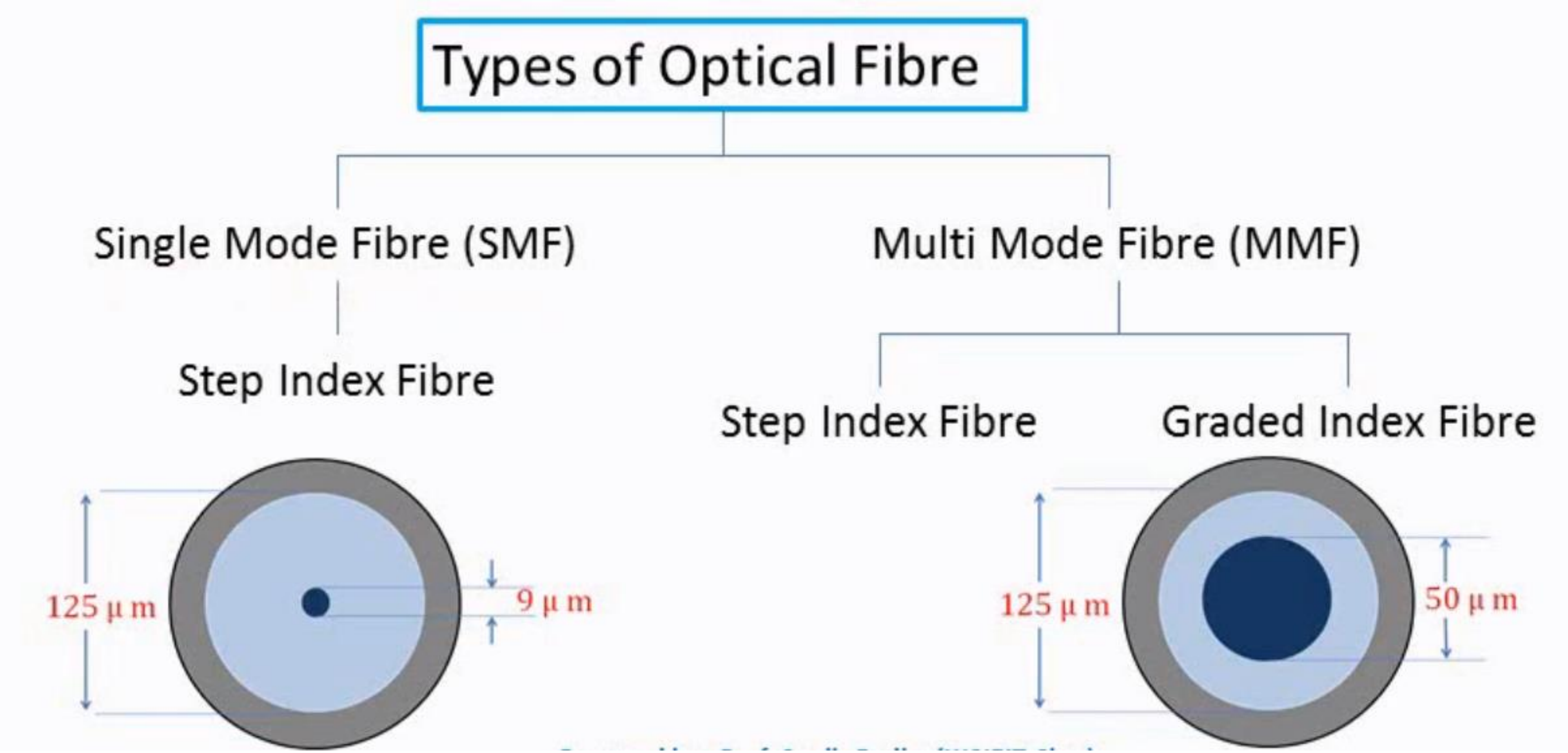
$$\textbf{Number of modes} \propto \frac{d}{\lambda}$$



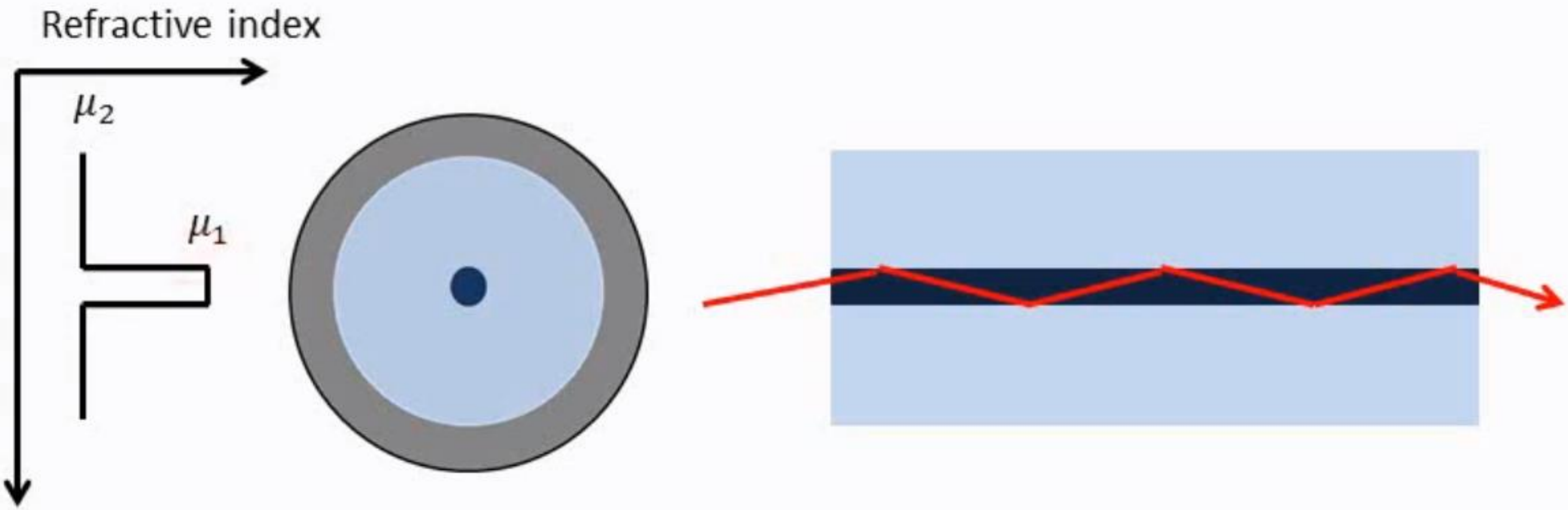
Types of Optical Fiber

- Both types of fiber described earlier are known as **step-index** fibers because the index of refraction changes radically between the core and the cladding
- **Graded-index** fiber is a compromise 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



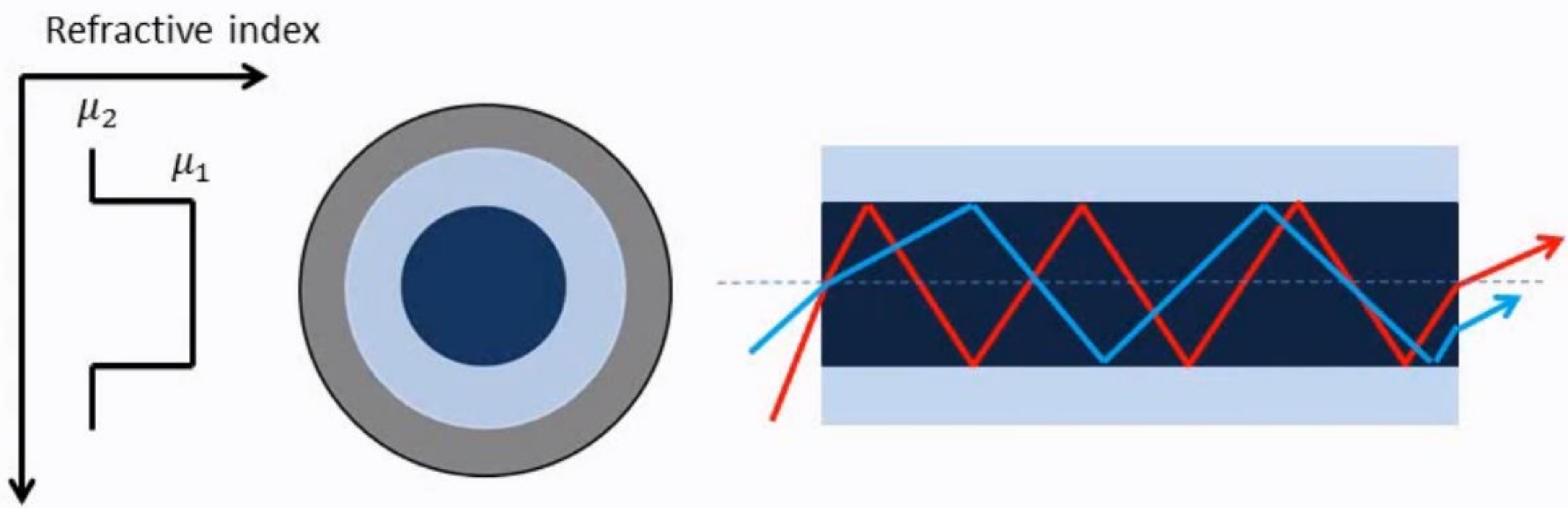

Types of Optical Fibre
Single Mode Fibre (SMF)
Multi Mode Fibre (MMF)
Step Index Fibre
Step Index Fibre
Graded Index Fibre
125 μ m
9 μ m
125 μ m
50 μ m

Single Mode Fibre (SMF)



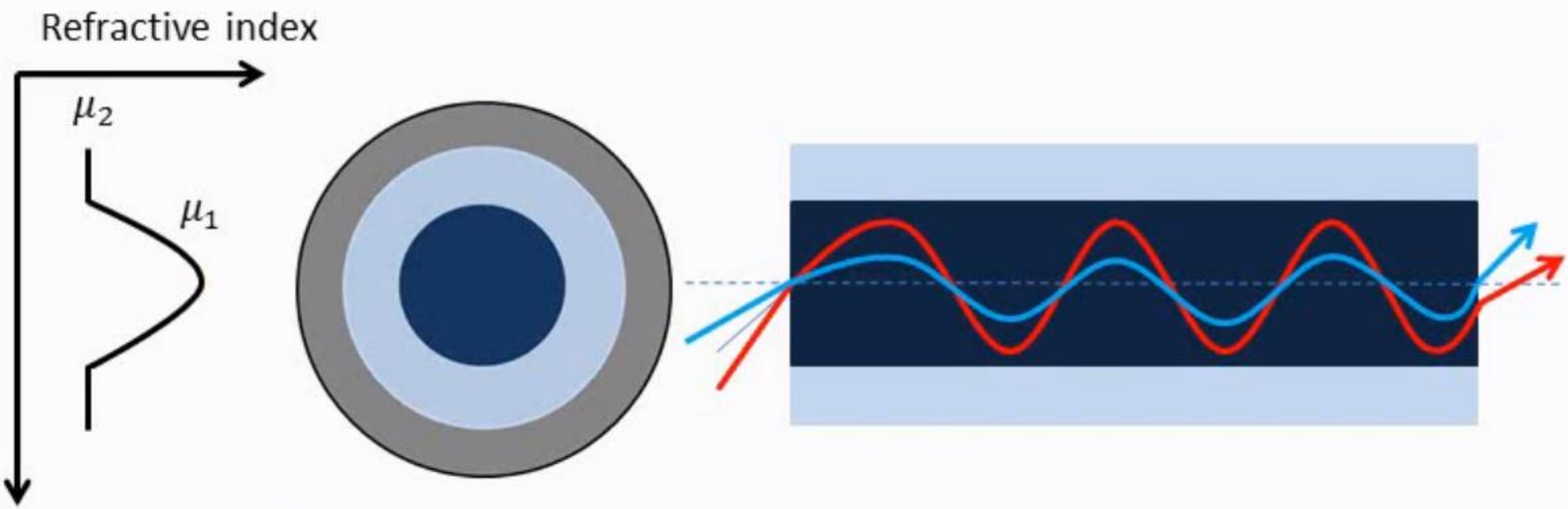
$\mu_1 > \mu_2$

Multi Mode Fibre (MMF) - Step Index Fibre



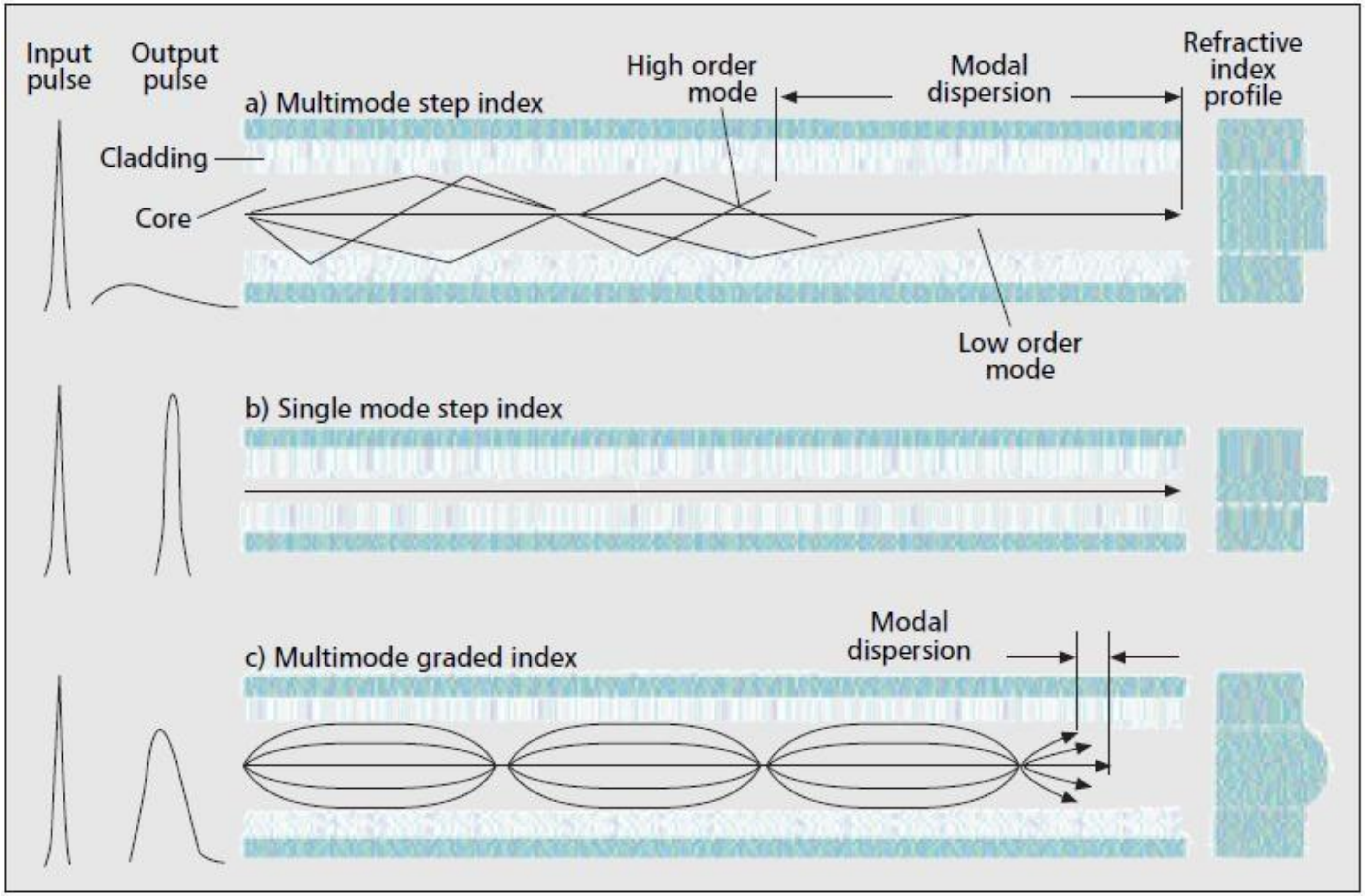
$$\mu_1 > \mu_2$$

Multi Mode Fibre (MMF) - Graded Index Fibre

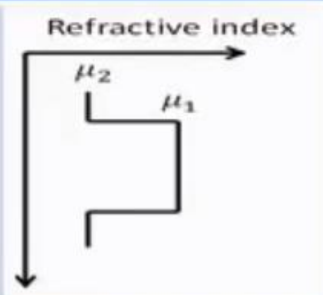
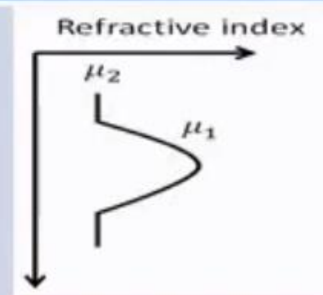
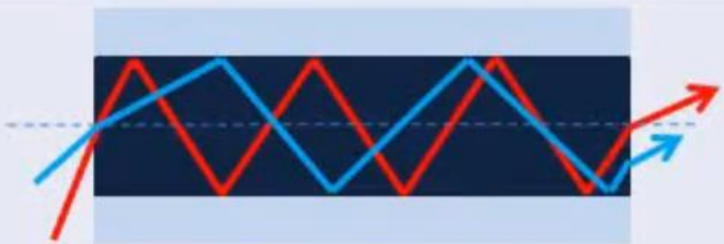
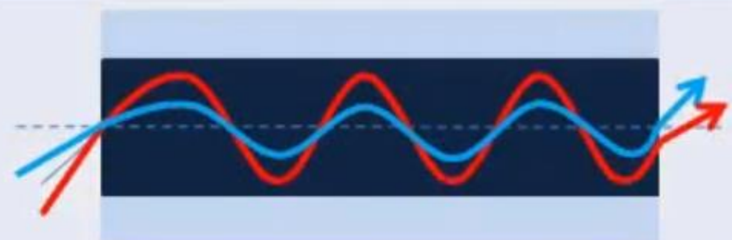


$\mu_1 > \mu_2$

Fibre types – how do they differ?



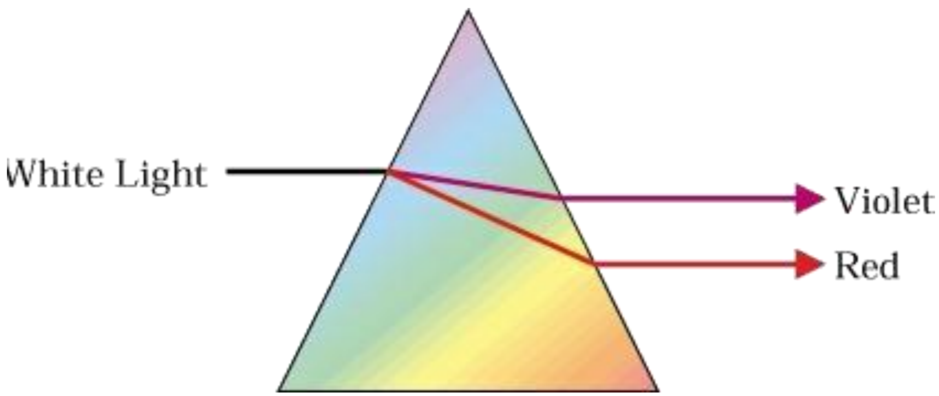
Source: P.Polishuk, "Plastic Optical Fibers Branch Out", IEEE Commn. Mag., Sep.2006, pp. 140-148.

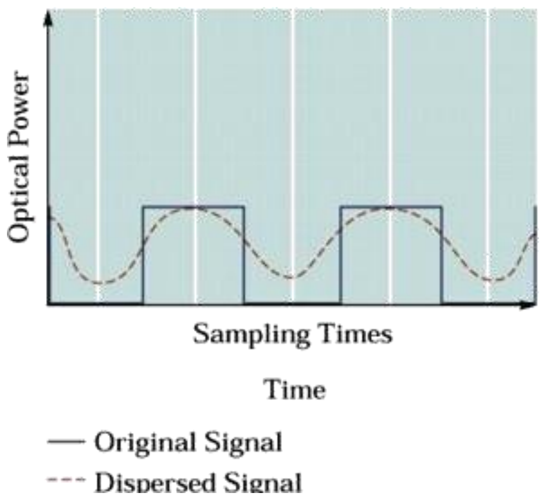
Step Index Fibre	Graded Index Fibre
	
	
Light rays entering at different angles will take different time to arrive at the other end.	Light rays take almost same time to reach other end irrespective of angle of entrance.

Dispersion

- Dispersion in fiber optics results from the fact that in multimode propagation, the signal travels faster in some modes than it would in others
- Single-mode fibers are relatively free from dispersion except for *intramodal dispersion*
- Graded-index fibers reduce dispersion by taking advantage of higher-order modes
- One form of intramodal dispersion is called *material dispersion* because it depends upon the material of the core
- Another form of dispersion is called *waveguide dispersion*
- Dispersion increases with the bandwidth of the light source

Examples of Dispersion

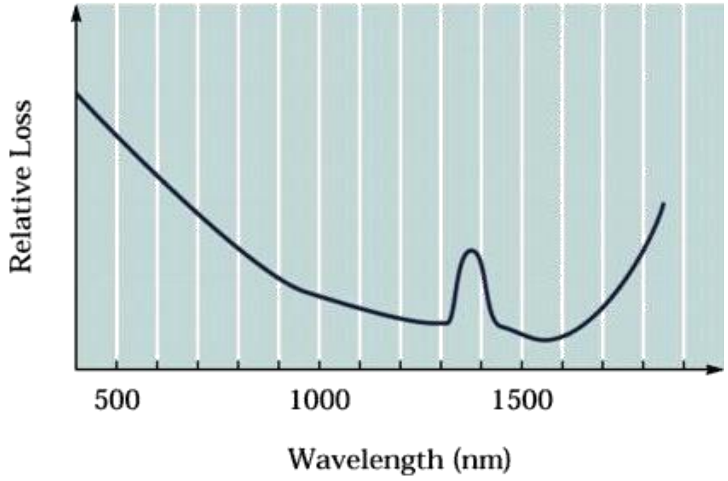


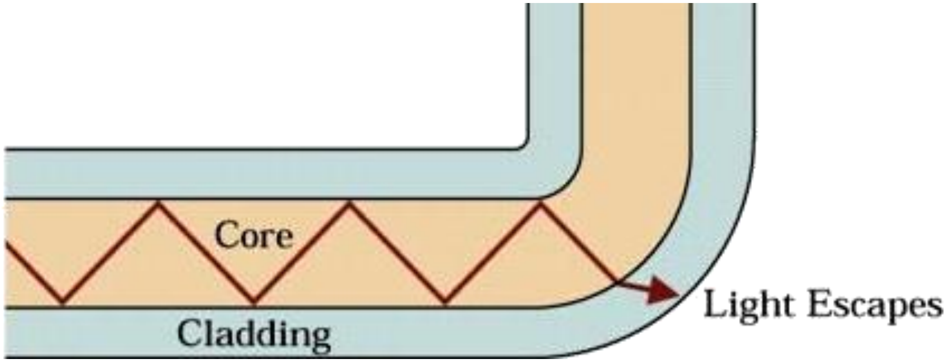


Losses

- Losses in optical fiber result from attenuation in the material itself and from scattering, which causes some light to strike the cladding at less than the critical angle
- Bending the optical fiber too sharply can also cause losses by causing some of the light to meet the cladding at less than the critical angle
- Losses vary greatly depending upon the type of fiber
  - Plastic fiber may have losses of several hundred dB per kilometer
  - Graded-index multimode glass fiber has a loss of about 2–4 dB per kilometer
  - Single-mode fiber has a loss of 0.4 dB/km or less

Types of Losses



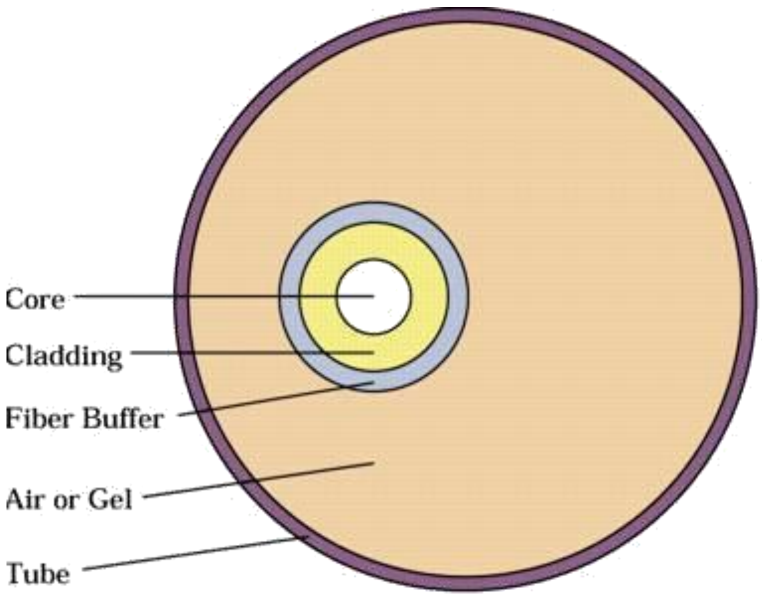


Fiber Optic Technology Elements

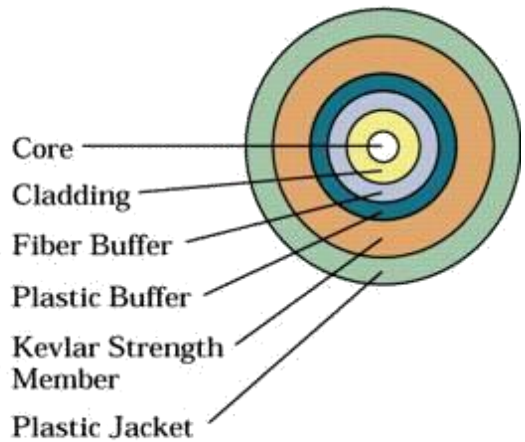
Fiber-Optic Cables

- There are two basic types of fiber-optic cable
  - The difference is whether the fiber is free to move inside a tube with a diameter much larger than the fiber or
  - is inside a relatively tight-fitting jacket
- They are referred to as *loose-tube* and *tight-buffer* cables
- Both methods of construction have advantages
  - Loose-tube cables—all the stress of cable pulling is taken up by the cable's strength members and the fiber is free to expand and contract with temperature
  - Tight-buffer cables are cheaper and generally easier to use

Fiber-Optic Cable Construction



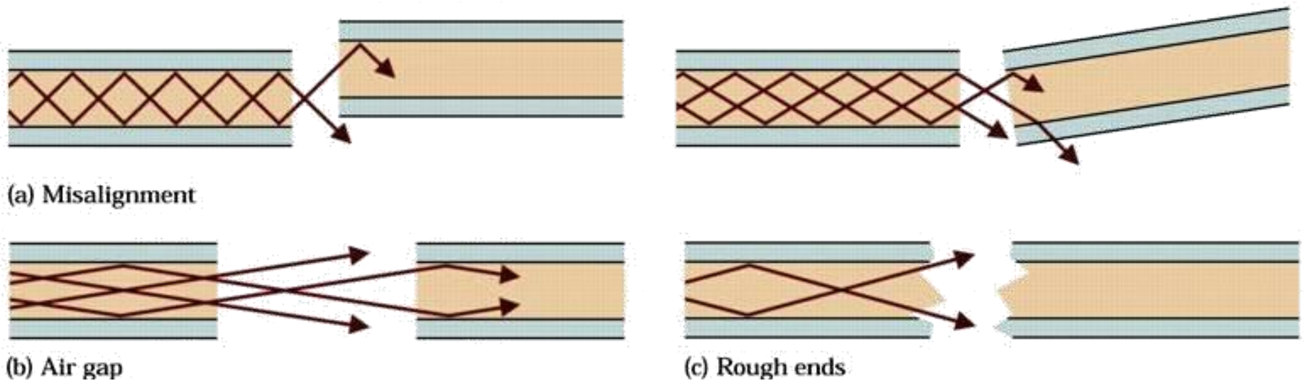
(a) Loose-tube construction



(b) Tight-buffer construction

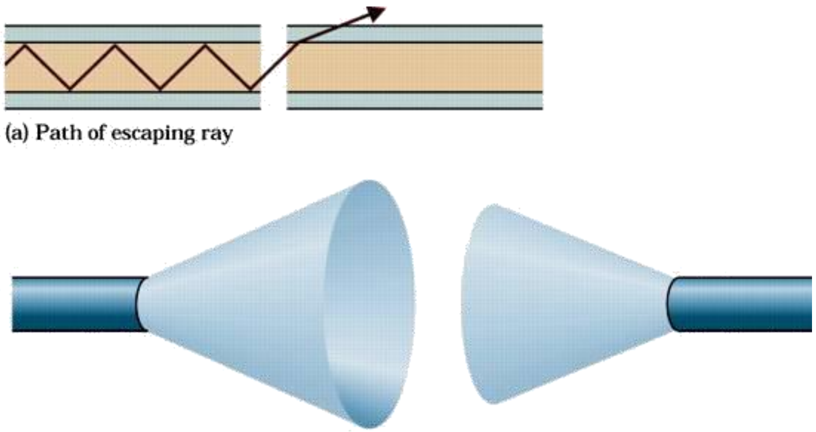
Splices and Connectors

- In fiber-optic systems, the losses from splices and connections can be more than in the cable itself
- Losses result from:
  - Axial or angular misalignment
  - Air gaps between the fibers
  - Rough surfaces at the ends of the fibers



Fiber-Optic Connectors

- Coupling the fiber to sources and detectors creates losses as well, especially when it involves mismatches in numerical aperture or in the size of optical fibers
- Good connections are more critical with single-mode fiber, due to its smaller diameter and numerical aperture
- A *splice* is a permanent connection and a *connector* is removable

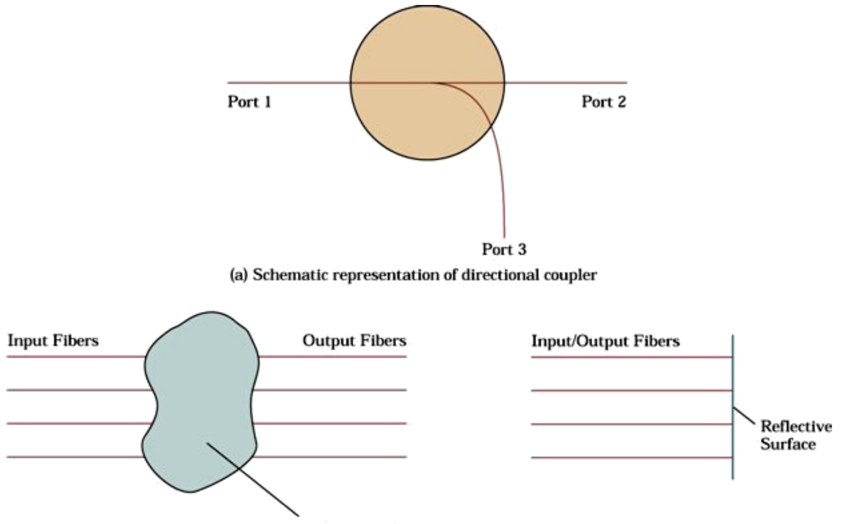


(a) Path of escaping ray

(b) Different cones of acceptance

Optical Couplers and Switches

- As with coaxial cable and microwave waveguides, it is possible to build power splitters and directional couplers for fiber-optic systems
- It is more complex and expensive to do this with fiber than with copper wire
- Optical couplers are categorized as either star couples with multiple inputs and outputs or as tees, which have one input and two outputs



(a) Schematic representation of directional coupler

(b) Transmissive

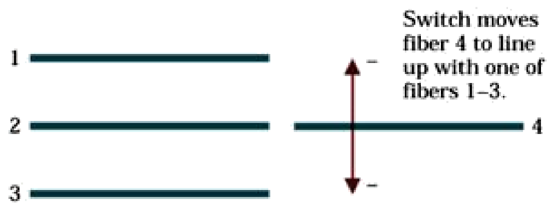
(c) Reflective

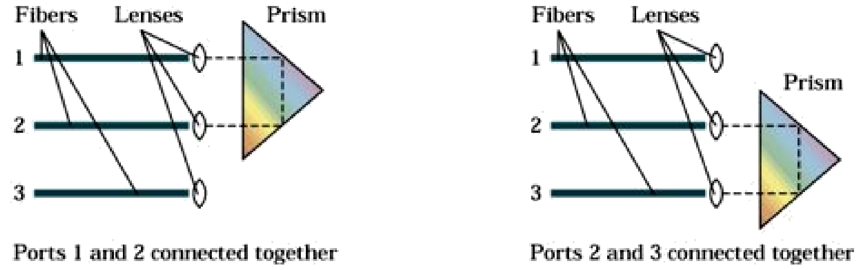
Coupler Construction

- Optical couplers can be made in many different ways:
  - A number of fibers can be fused together to make a transmissive coupler
  - A reflective coupler allows a signal entering on any fiber to exit on all other fibers, so the coupler is bidirectional

Optical Switches and Relays

- Occasionally, it is necessary to switch optical signals from one fiber to another
- The simplest type of optical switch moves fibers so that an input fiber can be positioned next to the appropriate output fiber
- Another approach is direct the incoming light into a prism, which reflects it into the outgoing fiber. By moving the prism, the light can be switched between different output fibers
- Lenses are necessary with this approach to avoid excessive loss of light



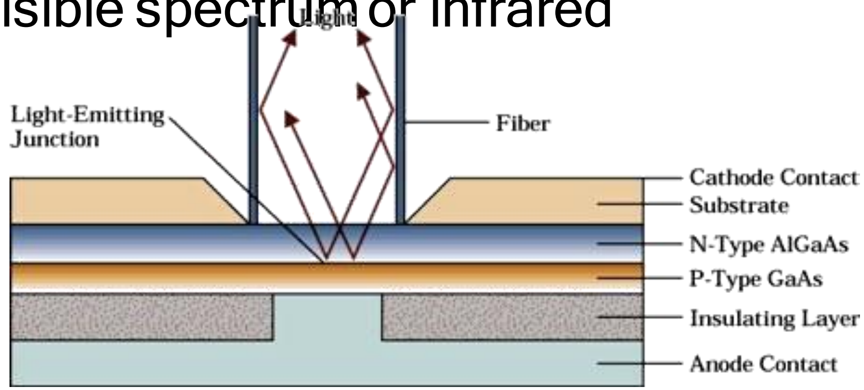


Optical Emitters

- Optical emitters operate on the idea that electromagnetic energy can only appear in a discrete amount known as a **quantum**. These quanta are called **photons** when the energy is radiated
- Energy in one photon varies directly with the frequency
- Typical optical emitters include:
  - Light-Emitting Diodes
  - Laser Diodes

Light-Emitting Diodes

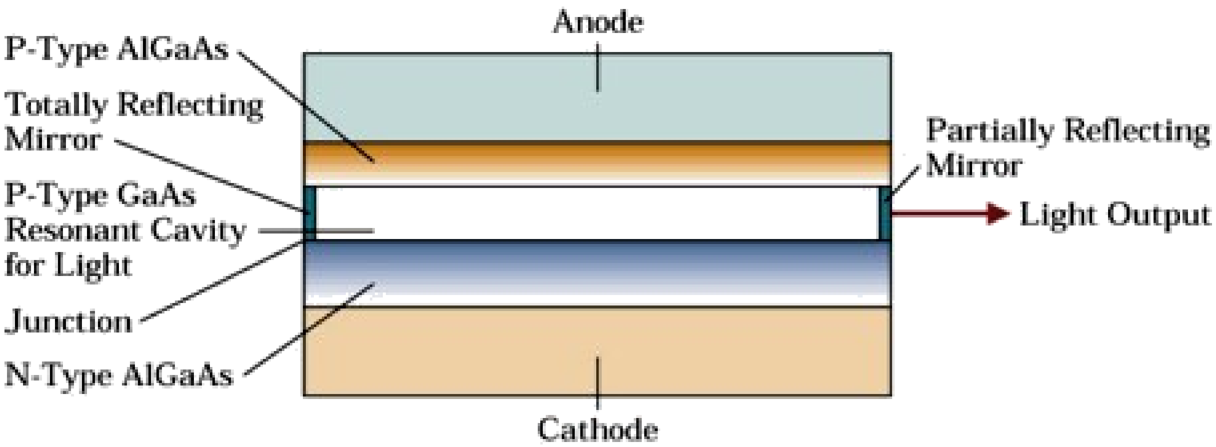
- An LED is form of junction diode that is operated with forward bias
- Instead of generating heat at the PN junction, light is generated and passes through an opening or lens
- LEDs can be visible spectrum or infrared



Laser Diodes

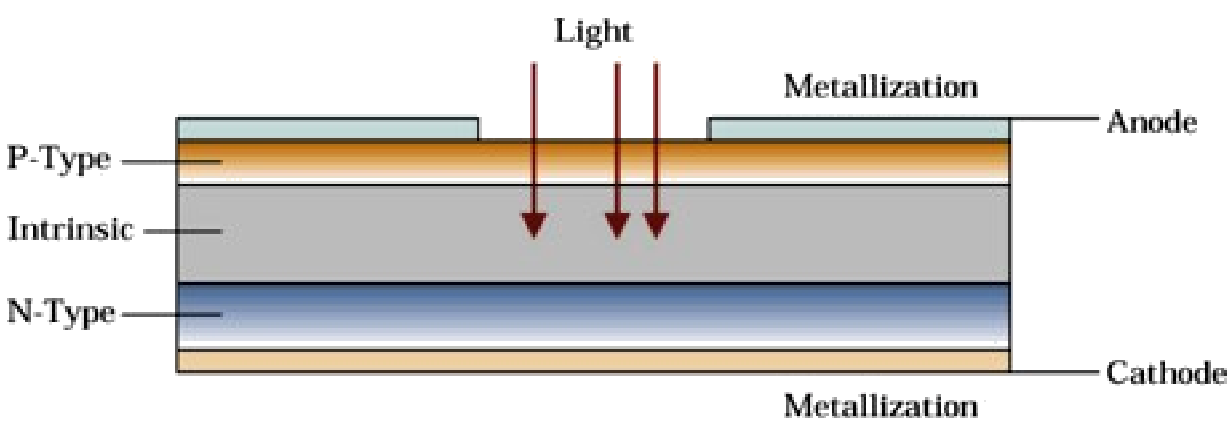
- Laser diodes generate coherent, intense light of a very narrow bandwidth
- A laser diode has an emission linewidth of about 2 nm, compared to 50 nm for a common LED
- Laser diodes are constructed much like LEDs but operate at higher current levels

Laser Diode Construction



Optical Detectors

- The most common optical detector used with fiber-optic systems is the PIN diode
- The PIN diode is operated in the reverse-bias mode
- As a photodetector, the PIN diode takes advantage of its wide depletion region, in which electrons can create electron-hole pairs
- The low junction capacitance of the PIN diode allows for very fast switching



Applications

- Telecom applications
  - Primarily SMFs
- Networking applications
  - Mostly SMFs (FTTH)
- Fibre optic Sensing
  - SMF and MMF
- Medical applications
  - Mostly MMF, or bundle fibres (light pipes
- Industrial applications
  - Mostly MMF

Advantages of POF (over Glass Fibre or Copper Wire)

- Simpler and less expensive components.
- Lighter weight.
- Operation in the visible spectrum.
- Greater flexibility, and resilience to bending, shock, and vibration.
- Immunity to electromagnetic interference (EMI).
- Ease in handling and connecting (POF diameters are 1 mm compared with 8-100 μm for glass).
- Use of simple and inexpensive test equipment.
- GOF is used in telecommunications window wavelength (1310, 1490 and 1550 nm) while the POF operates in the visible spectrum.
- Greater safety than glass fibers or fiber slivers;
- glass requires a laser light source
- Transceivers require less power than copper transceivers.

Disadvantages

- High loss during transmission
- Bandwidths lower than SMFs
- A small number of providers of total systems
- A lack of standards
- A lack of awareness among users of how to install and design with POFs
- Limited production, and Small number of systems and suppliers
- Applications research is incomplete
- Incomplete certification programs from POF installers
- Lack of high temperature fibers (125°C)

	Plastic	Glass	Copper
Component cost	Potentially low	More expensive	Low
Loss	High-medium (short-distance)	Medium-low (long distance)	High
Connections	Easy to connect, requires little training or special tools	Takes longer, requires special tools and training	High
Heandling	Easy	Requires training and care	Easy
Flexibility	Flexible	Brittle	Flexible
Wavelength operating range	Visible	Infrared	N/A
Numerical aperture	High (0.4)	Low (0.1–0.2)	N/A
Bandwidth	High (11 Gb/s over 100m)	Large (40 Gb/s)	Limited to 100 m at 100 Mb/s
Test equipment	Low cost	Expensive	High
System costs	Low overall	High	Medium

Source: P.Polishuk, "Plastic Optical Fibers Branch Out", IEEE Commn. Mag., Sep.2006, pp. 140-148.