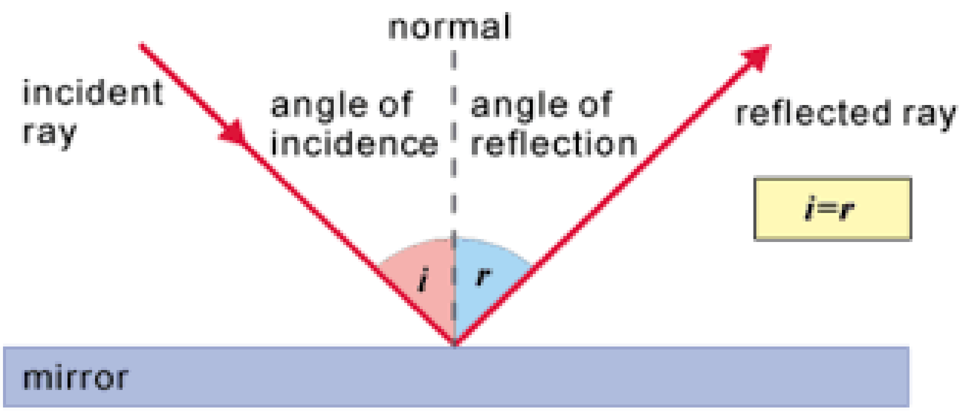
OPTICAL PRINCIPLES

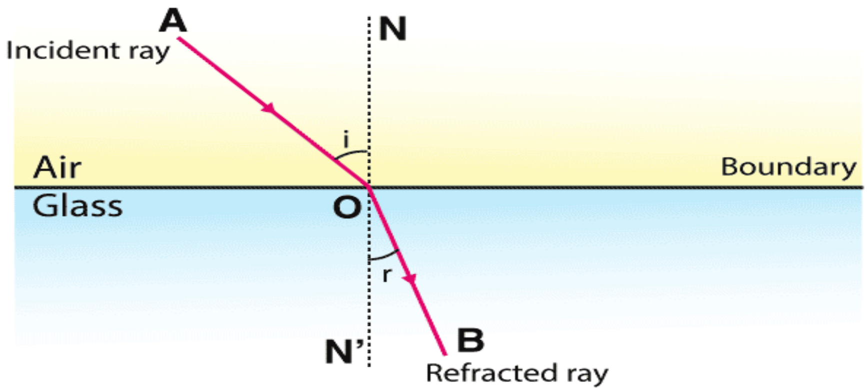
Law Of Reflection:

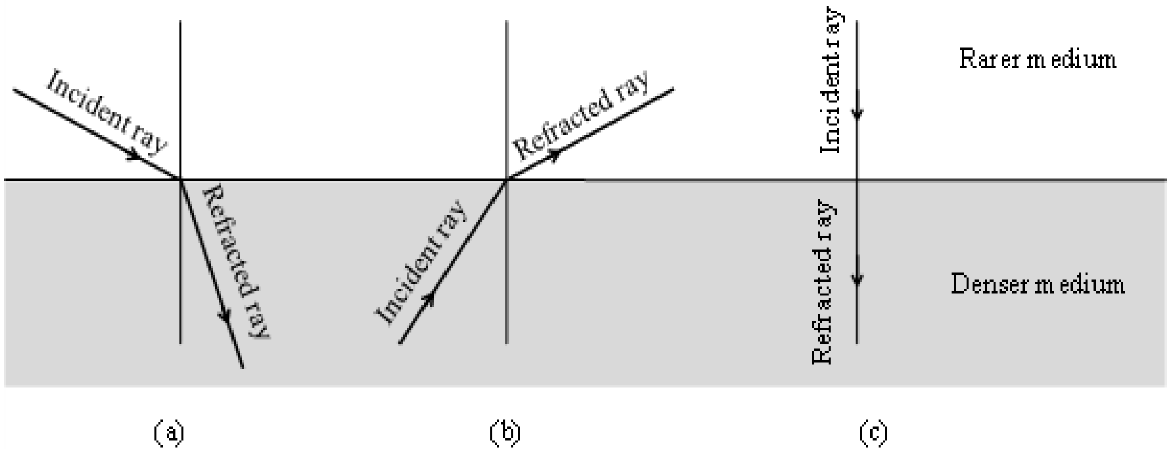
The law of reflection states that the incident ray, the reflected ray, and the normal to the surface of the mirror all lie in the same plane. Furthermore, the angle of reflection is equal to the angle of incidence. A light ray incident upon a reflective surface will be reflected at an angle equal to the incident angle.



Refraction:

The refraction of light is the bending of light rays as they pass from one medium to another, thereby changing the path of the rays. Refraction occurs due to a change in the speed of the light ray or wave.The speed of light is greatest in a vacuum. When the light rays travel from a rarer to a denser medium, they bend towards the normal. If the light rays travel from a denser to a rarer medium, they bend away from the normal.The greater the density of the media, the higher the refractive index. Snell’s law, or the law of refraction, quantitatively defines the amount of bending of waves dependent on the refractive index of the two media.



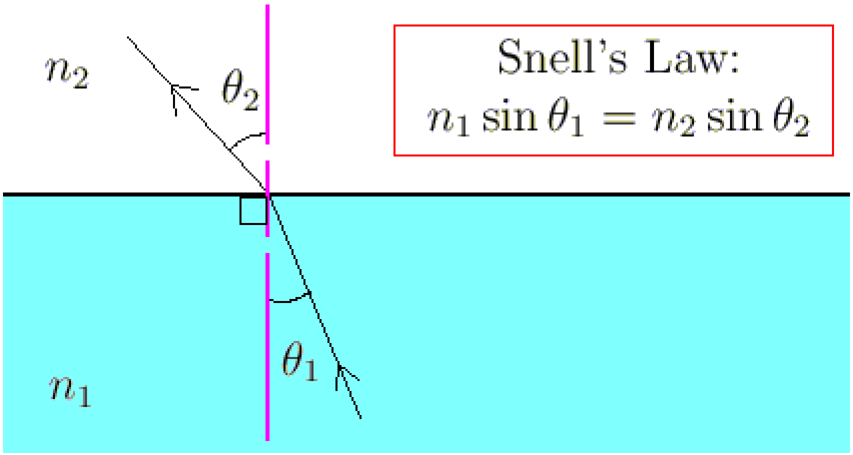


Behaviour of a light ray when it moves from one medium to another

Snell's Law:

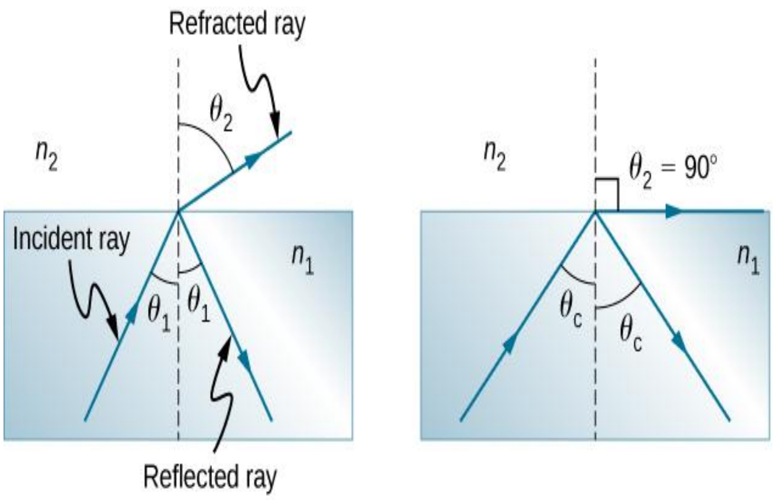
Like with reflection, refraction also involves the angles that the incident ray and the refracted ray make with the normal to the surface at the point of refraction. Unlike reflection, refraction also depends on the media through which the light rays are travelling. This dependence is made explicit in Snell's Law via refractive indices, numbers which are constant for given media.

Snell's Law is given in the following diagram.



As in reflection, we measure the angles from the normal to the surface, at the point of contact. The constants n are the indices of refraction for the corresponding media.

Critical angle:
When the angle of incidence at the interface reaches a certain critical value, the refracted ray lies along the boundary, having an angle of refraction of 90 degrees. This angle of incidence is known as the critical angle; it is the largest angle of incidence for which refraction can still occur.



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

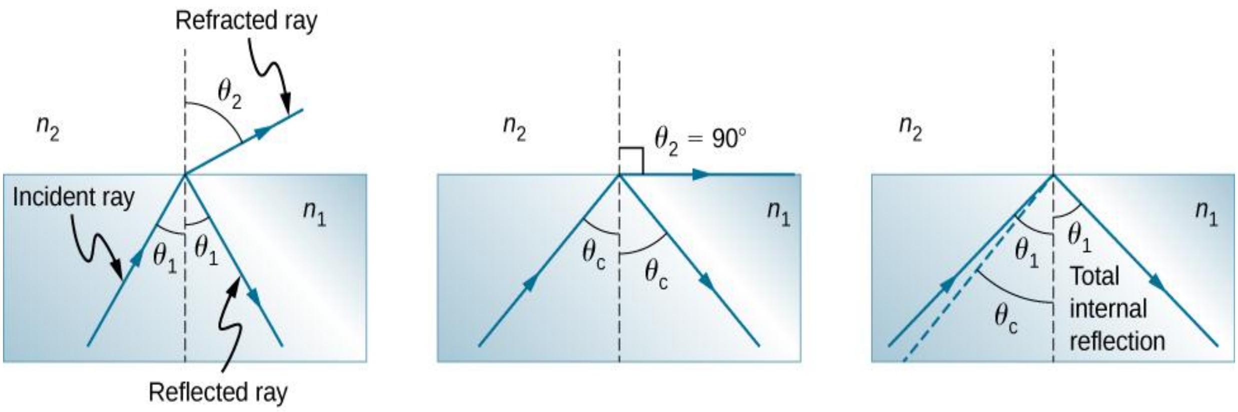
$$\text{Substitute } \theta_2 = 90 \; degrees$$
$$n_1 \sin\theta_1 = n_2 \sin(90)$$
$$n_1 \sin\theta_1 = n_2(1)$$
$$n_1 \sin\theta_1 = n_2(1)$$

$$\text{When } \theta_2 = 90 \; degrees, \theta_1 \; becomes \; the \; critical \; angle, \theta_c$$
$$n_1 \sin\theta_c = n_2$$

$$The \; equation \; for \; the \; critical \; angle, \theta_c \; becomes:$$
$$\theta_c = \sin^{-1}\frac{n_2}{n_1}$$

Total Internal Reflection:

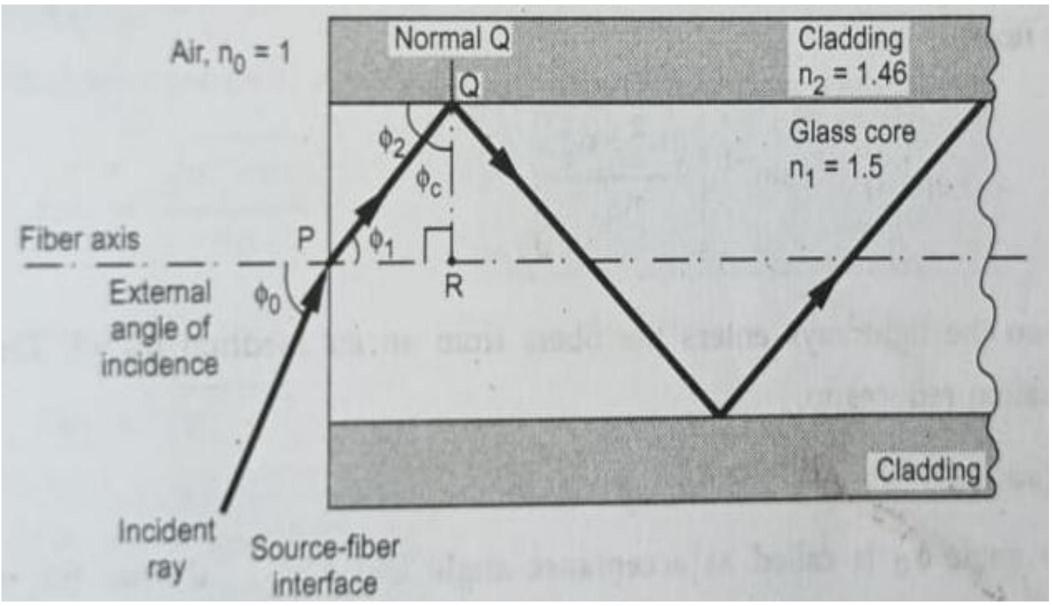
If the incident angle is greater than the critical angle, as shown in then all of the light is reflected back into medium, a condition called total internal reflection (TIR) occurs.



The conditions required for total internal reflection (TIR) to occur are:
1) The light must be travelling from a more dense medium into a less dense medium (ie glass to air)
2) The angle of incidence must be greater than the critical angle.

<u>Acceptance Angle</u>:

To ensure the critical angle of incidence in core-cladding boundary inside the optical fibre, the light should be incident at a certain angle at the end of the optical fiber while entering into it. This angle is called acceptance angle.



.The fig shows the condition exist at the launching end of optic fiber. The light source is surrounded by air and the refractive index of air is $n_0 = 1$. Let the incident ray makes an angle ϕ_0 with fiber axis. The ray enters into glass fiber at point P making refracted angle ϕ_1 to the fiber axis, the ray is then propagated diagonally down the core and reflect from the core wall at point Q. When the light ray reflects off the inner surface, the angle of incidence is equal to the angle of reflection, which is greater than critical angle.In order for a ray of light to propagate down the cable, it must strike the core cladding interface at an angle that is greater than critical angle ϕ_c.

Applying Snell's law to the air to core interface mediums,

$$n_0 sin\phi_0 = n_1 sin\phi_1$$

But $\phi_1 = 90^0 - \phi_c$

$$n_0 sin\phi_0 = n_1 sin(90^0 - \phi_c)$$

$$n_0 sin\phi_0 = n_1 cos\phi_c$$

But $cos^2\phi_c + sin^2\phi_c = 1$

$$cos^2\phi_c = 1 - sin^2\phi_c = 1 - (\frac{{n_2}^2}{n_1^2})$$

$$cos\,\phi_c = \sqrt{1 - (\frac{{n_2}^2}{n_1^2})}$$

$$n_0 sin\phi_0 = n_1 cos\phi_c$$

$$sin\phi_0 = \frac{n_1}{n_0} cos\phi_c$$

$$sin\phi_0 = \frac{n_1}{n_0}\sqrt{1 - (\frac{{n_2}^2}{n_1^2})} = \left[\frac{\sqrt{n_1^2 - n_2^2}}{n_0}\right]$$

$$\phi_0 = \sin^{-1}\left[\frac{\sqrt{n_1^2 - n_2^2}}{n_0}\right]$$

The angle ϕ_0 is called as acceptance angle

When the light rays enters the fiber from air medium(n_0=1) then above equation reduces to

$\phi_{0(max)}=\sin^{-1}\left[\sqrt{n_1^2 - n_2^2}\right]$. This angle defines the maximum angle in which the light ray may incident on fiber to propagate down the fiber.

Numerical Aperture:

The Numerical Aperture(NA) of a fiber is a figure of merit which represents its light gathering capability. Larger the NA ,the greater the amount of light accepted by fiber.

$$NA=\sin\phi_{0(max)}=\sqrt{n_1^2 - n_2^2}$$

The relative refractive index difference(Δ) is given by

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

$$NA=\sqrt{n_1^2 - n_2^2}=\sqrt{(n_1+n_2)(n_1-n_2)}$$

Multiplying and dividing with n_1 and considering $n_1 \approx n_2$

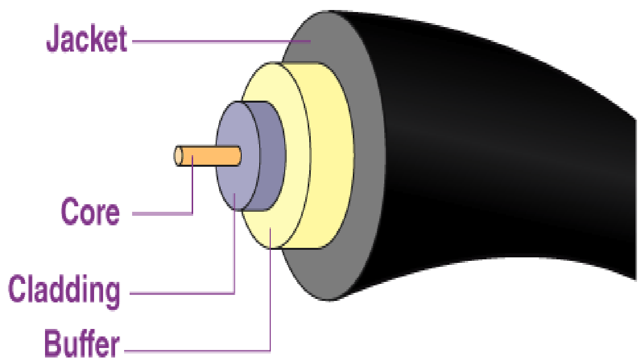
$$NA = \sqrt{\frac{(n_1+n_2)(n_1-n_2)(n_1)}{n_1}}$$

$$= \sqrt{\frac{(2n_1)(n_1-n_2)(n_1)}{n_1}}$$

$$= \sqrt{(2n_1^2)(\Delta)}$$

$$=n_1\sqrt{2\Delta}$$

OPTICAL FIBER CABLE:



Core:

This is the glass core of very thin size consists of optically transparent dielectric medium which carries the light from the transmitter to the receiver.The core diameter varies from 5µm to 100µm.

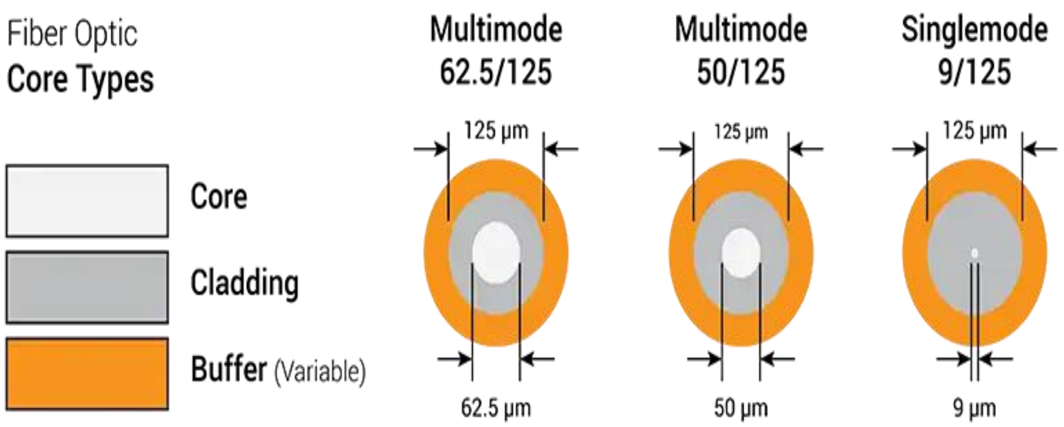
Cladding:
This is the outer optical material surrounding the core having refractive index less than that of core.The cladding diameter varies from 100µm to 200µm.The glass cladding is also important material in fiber optic technology because it helps to keep the light within the core through the phenomenon of Total Internal Reflection.

Plastic Buffer Coating:
This is made of plastic rubber which protects the fiber cable.
The typical diameter of fiber after coating is 250µm to 300µm.

Jacket:
Optical fiber cables comes in number of cores that starts from a single core to thousands of cores. These cores are arranged in bundles in optical cables. These optical cables are protected by the cable's outer covering which is known as fiber optic jacket.It also protects the cores from weathering effects and also from heat and fire as per its application.

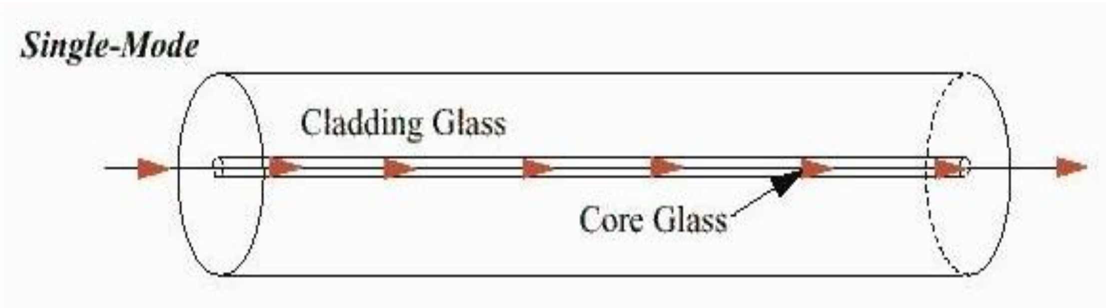
FIBER OPTIC CABLES:

Optical Fiber Cables are divided into two types depending upon the mode. Light rays propagate as an electromagnetic wave along the fiber. The two components, the electric field and the magnetic field form patterns across the fiber. These patterns are called mode of transmission.The mode of a fiber refers to the number of paths for the light rays within the cable. According to modes optic fibers can be classified into two types.
i) Single mode fiber
ii) Multimode fiber.



Single mode fiber:

This fiber allows the propogation of light ray by only one path. This type of fiber has a small core diameter (9µm) and high cladding diameter (125µm) and the difference between the refractive index of core and cladding is very small. There is no dispersion i.e. no degradation of the signal during traveling through the fiber.

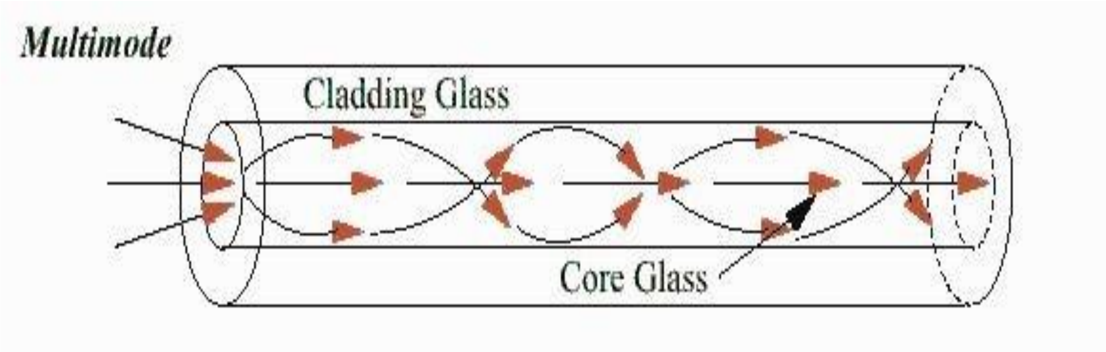


Single Mode Fiber Optical Cable uses strong and brighter light sources with lower attenuation. At the same time, it can deliver unlimited bandwidth, making it a preferred choice in this high-paced world.

Advantages:
1) Can be used for very long access system distances, up to 100 km.
2) It supports high bandwidths and high speeds up to 10Gbps for about 10Km.

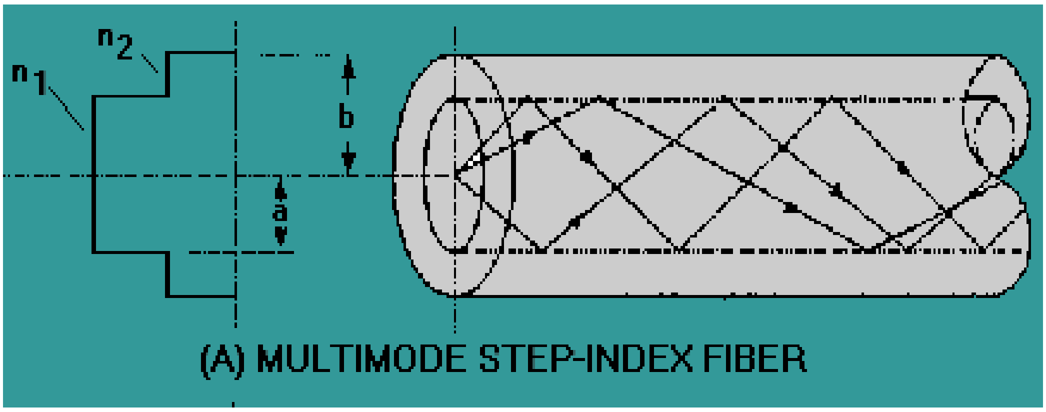
Disadvantages:
1) Single-mode requires more expensive laser diodes rather than LEDs
2)
3) Because of the smaller core diameter, Single-mode fiber manufacture need more time an effort.

Multimode Fiber:
Multi mode fiber allows many modes for the light rays traveling through it. The core diameter is generally 5µm-100µm and that of cladding is 100µm-200µm.There is signal degradation due to multimode dispersion. It is not suitable for long-distance communication due to the large dispersion and attenuation of the signal.



There are two categories of Multi-mode fiber i.e. Step Index Fiber and Graded Index Fiber. These are categories under the types of optical fiber based on the Refractive Index profile which is the graphical representation of value of refractive index across the core diameter.

Multimode Step Index Fiber:
Multimode step index fiber is most widely used type. It is easy to manufacture. Its core diameter is 50 to 1000 µm i.e. large aperture and allows more light to enter the cable.The light rays are propagated down the core in zig-zag manner. There are many paths that a light ray follow during the propagation.The light ray is propagated using the principle of Total Internal Reflection (TIR)..Light rays passing through the fiber are continuously reflected off the glass cladding towards the centre of the core at different angles and lengths, limiting overall bandwidth.

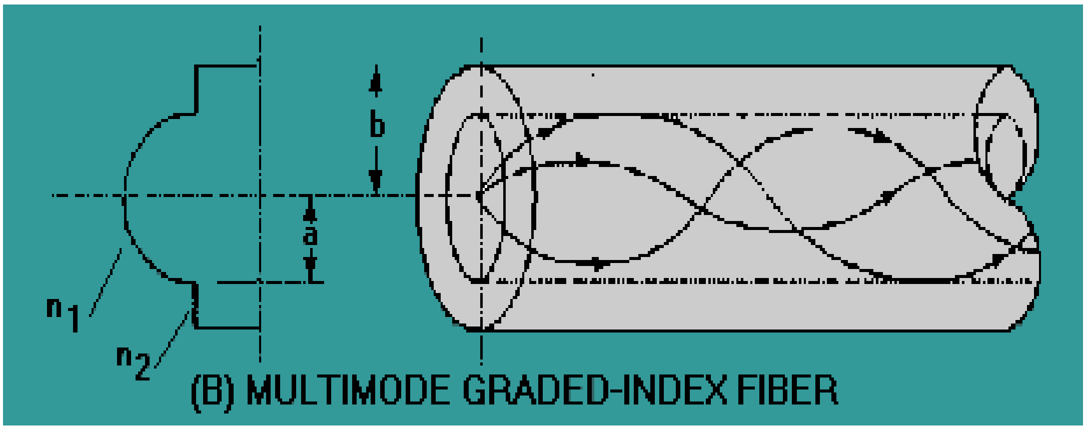


Advantages:
1) Inexpensive and easy to manufacture
2) It is easy to couple light into the fiber as this optical fiber cable has large Numerical Aperture.

Disdvantages:
1) Pulse dispersion is more in this cable

2) Bandwidth and the rate of data transfer is low.
3) Higher attenuation

Multimode Graded Index Fiber:
The core size of multimode graded index fiber cable is varying from 50 100 µm range.The light ray is propagated through the refraction. The light ray enters the fiber at many different angles. As the light propagates across the core toward the center it is intersecting a less dense to more dense medium. Therefore the light rays are being constantly being refracted and ray is bending continuously shown in fig below. This cable is mostly used for long distance communication.

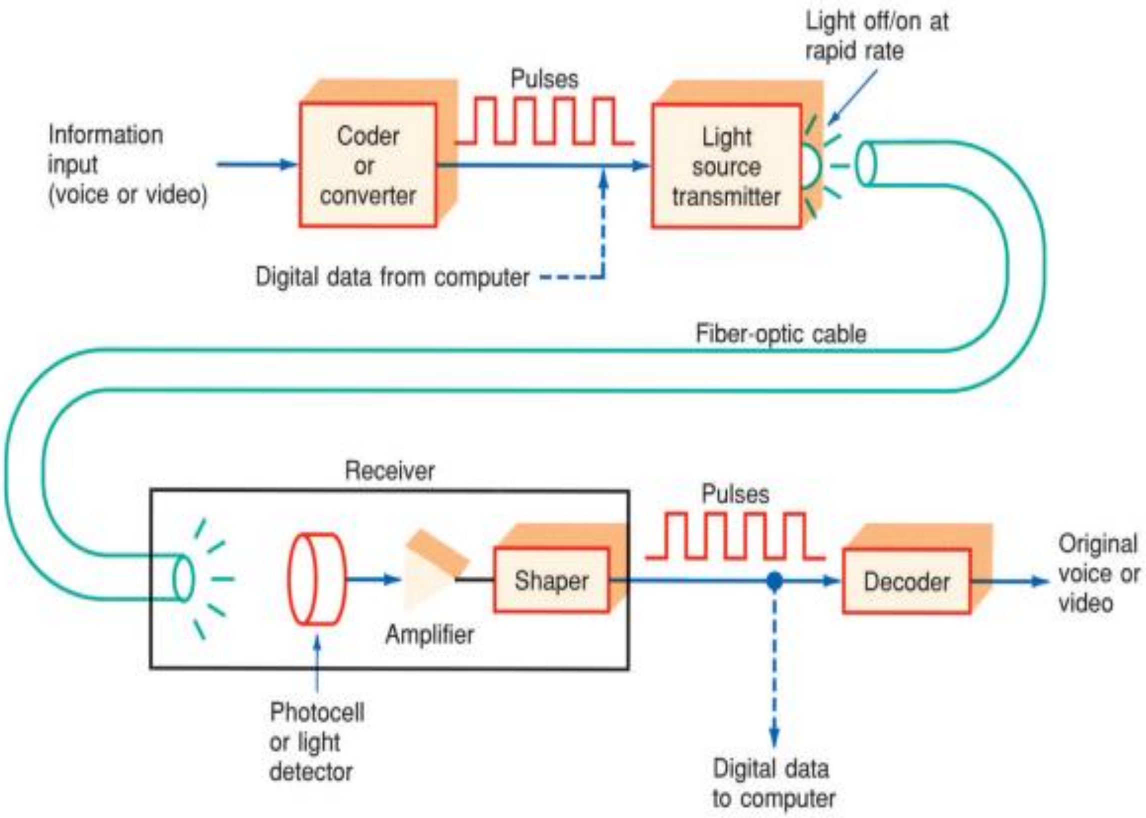


(B) MULTIMODE GRADED-INDEX FIBER

Advantages:
1) Pulse dispersion is less in this cable
2)Bandwidth and the rate of data transfer is high.
Disadvantages:
1) Expensive and difficult to manufacture
2) Lower coupling of light due lo less Numerical Aperture

<u>Optical Communication System:</u>

The components of a typical fiber-optic communication system are shown in Fig.below



The information signal to be transmitted may be voice, video, or computer data. The first step is to convert the information to a form compatible with the communication medium, usually by converting continuous analog signals such as voice and video (TV) signals to a series of digital pulses. An A/D converter is used for this purpose.These digital pulses are then used to flash a powerful light source off and on very rapidly. In simple low-cost systems that transmit over short distances, the light source is usually a light-emitting diode that emits a low-intensity infrared light beam. Infrared beams such as those used in TV remote controls are also used in transmission.

The light beam pulses are then fed into a fiber-optic cable, which can transmit them over long distances. At the receiving end, a light-sensitive device known as a photocell,or light detector, is used to detect the light pulses. It converts the light pulses to an electric signal. The electrical pulses are amplified and reshaped back into digital form. They are fed to a decoder, such as a D/A converter, where the original voice or video is recovered.

OPTICAL TRANSMITTERS

In an optical communication system, transmission begins with the transmitter, which consists of a carrier generator and a modulator. The carrier is a light beam that is usually modulated by turning it on and off with digital pulses. The basic transmitter is essentially a light source.

Light Sources:

Conventional light sources such as incandescent lamps cannot be used in fiber-optic systems because they are too slow. To transmit high-speed digital pulses, a very fast light source must be used. The two most commonly used light sources are light-emitting diodes (LEDs) and semiconductor lasers.

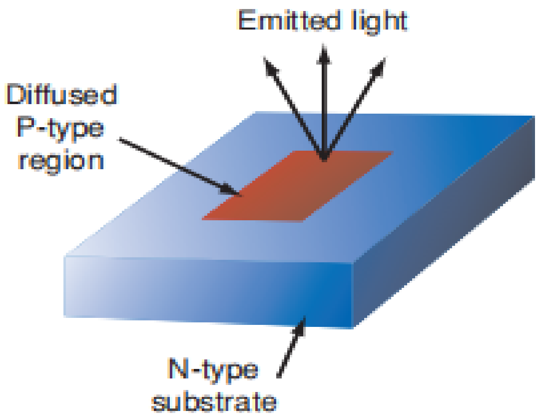
Light-Emitting Diodes:

A light-emitting diode (LED) is a PN-junction semiconductor device that emits light when forward-biased. When a free electron encounters a hole in the semiconductor structure, the two combine, and in the process they give up energy in the form of light. Semiconductors such as gallium arsenide (GaAs) are superior to silicon in light emission. Most LEDs are GaAs devices optimized for producing red light. The n type materials used are Sulphur, Selenium, Tellurium and the p type materials used are Zinc, Cadmium, Magnesium.

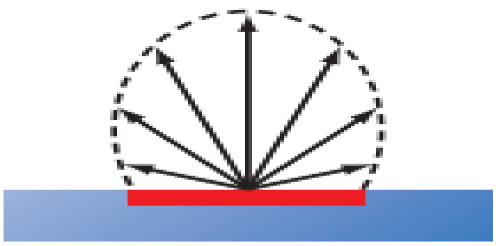
LEDs are widely used for displays indicating whether a circuit is off or on, or for displaying decimal and binary data. However, because an LED is a fast semiconductor device, it can be turned off and on very quickly and is capable of transmitting the narrow light pulses required in a digital fiber-optics system.

LEDs can be designed to emit virtually any color light desired. The LEDs used for fiber-optic transmission are usually in the red and near-infrared ranges because these wavelengths have significantly lower absorption (attenuation) in standard telecommunication glass optical fibers. This allows the longest distance transmission of data from point to point with minimal loss of power. Typical wavelengths of LED light commonly used are 0.85, 1.31, and 1.55 µm, more commonly designated 850, 1310, and 1550 nm where 1 micrometer (µm) equals 1000 nm. These frequencies are all in the near-infrared range just below red light, which is not visible to the naked eye.

One physical arrangement of the LED is shown in Fig.below.



A P-type material is diffused into the N-type substrate, creating a diode. Radiation occurs from the P-type material and around the junction. The fig shows a common light radiation pattern

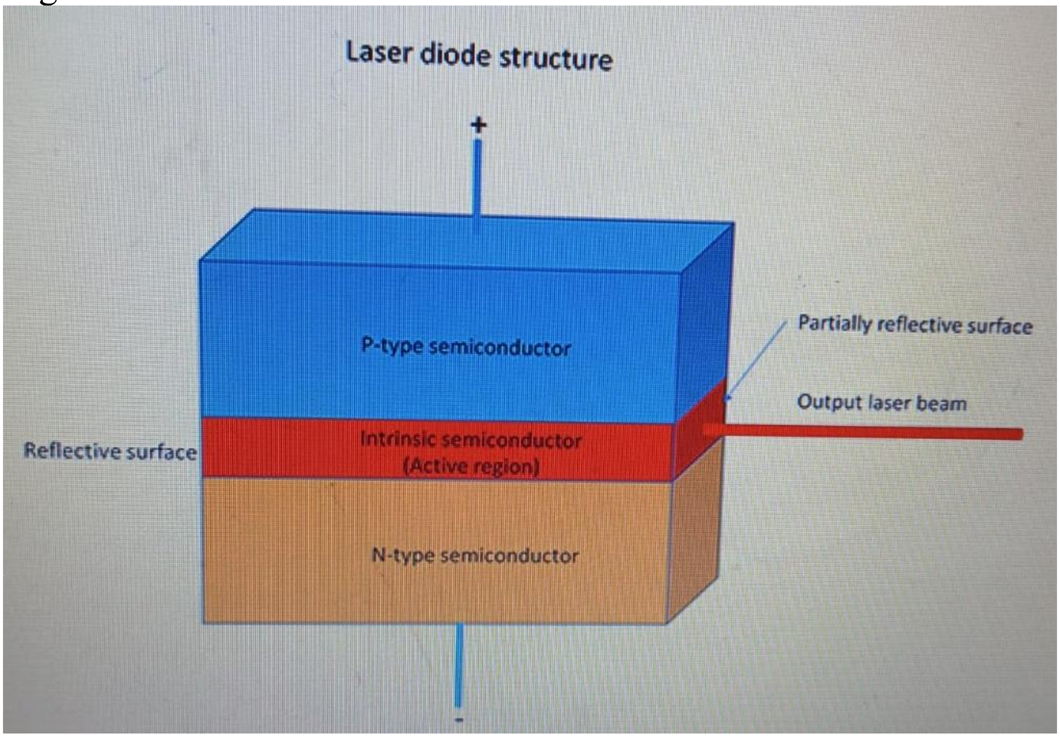


The light output from an LED is expressed in terms of power. Typical light output levels are in the range of few mW for small LEDs upto seveal Watts for high power LEDs.A standard visible LED typically outputs only a few milliWatts.

LASER DIODES:

The other commonly used light transmitter is a laser, which is a light source that emits coherent monochromatic light. Monochromatic light is a pure single frequency light. Although an LED emits red light, that light covers a narrow spectrum around the red frequencies. Coherent refers to the fact that all the light waves emitted are in phase with one another. Coherence produces a focusing effect on a beam so that it is narrow and, as a result, extremely intense.

The most widely used light source in fiber-optic systems is the injection laser diode (ILD), also known as a Fabry-Perot (FP) laser which is shown in fig below



Structure:

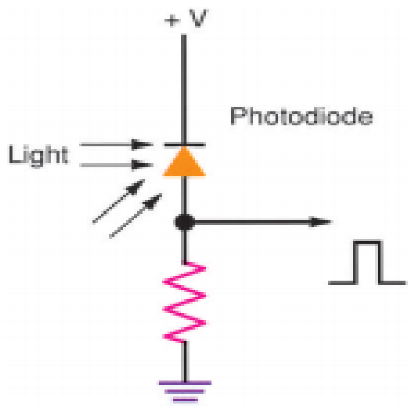
The Laser diode is made up of two layers of Semiconductors i.e. P-type and N-type. Materials like in LEDs. The layers of semiconductors are made up of GaAs doped with materials like selenium(N type), cadmium(P type).Modern laser diodes include an intrinsic compound semi-conductor material between the P-type and N-type materials. Unlike the P-type and N-type materials, the intrinsic material is not doped so that its refractive index is different from that of the other region, which is referred to as the active region of the laser diode. Electrons and holes are pumped into this intrinsic region. The laser diode is designed to allow some light to escape through one end of the active region while allowing a percentage of the light to loop back into the active region to boost the intensity of the light or to contribute to population inversion by exciting more electrons. To achieve this, one end of the region is coated with a reflective material while the other is coated with a partially reflective coating material.

Laser works on the principle of stimulated emission.The process by which electrons in the excited state are stimulated to emit photons while falling to the ground state or lower energy state is called stimulated emission.When a photon passes by an electron that is already excited and is in conduction band, it takes only a small amount of energy from the photon to trigger its downfall. Because only a small amount of energy is lost by the photon,it causes the electron to fall into its valence band.This stimulated emission process results in two identical photons,the original incident photon and the new generated photon. Once the two photons emerge from a single stimulated event, they too may each trigger a stimulation event resulting in four photons and the four photons give rise to eight and so on.This process is known as population inversion which ensures that there is an abundance of excited electrons that will emit light thereby resulting in amplification.

CHARACTERISTIC	LED	LASER DIODE
Cost	Low	High
Data rate	Low	High
Distance	Short	Long
Fiber type	Multimode	Singlemode
Lifetime	High	Low

Light Detectors:
The receiver part of the optical communication system is relatively simple. It consists of a detector that senses the light pulses and converts them to an electric signal. This signal is amplified and shaped into the original serial digital data. The most critical component is the light sensor.

Photodiode:
Photodiode. The most widely used light sensor is a photodiode. It is a silicon PN-junction diode that is sensitive to light. This diode is normally reverse-biased, as shown in Fig below.



The only current that flows through it is an extremely small reverse leakage current. When light strikes the diode, this leakage current increases significantly. This current flows through a resistor and develops a voltage drop across it. The result is an output voltage pulse.

Phototransistor:

The reverse current in a diode is extremely small even when exposed to light. The resulting voltage pulse is very small and so must be amplified.So we use the phototransistor . The base collector junction is exposed to light. The base leakage current produced causes a larger emitter-to-collector current to flow. Thus the transistor amplifies the small leakage current into a larger, more useful output as shown in fig below

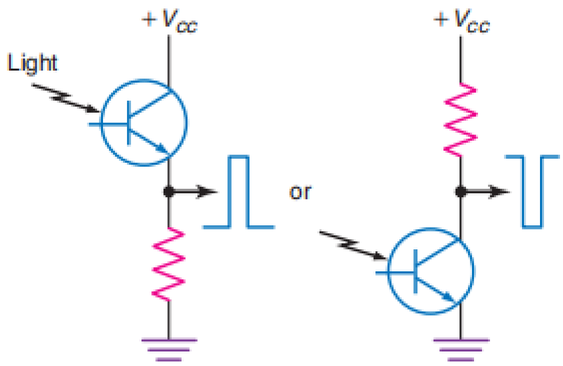
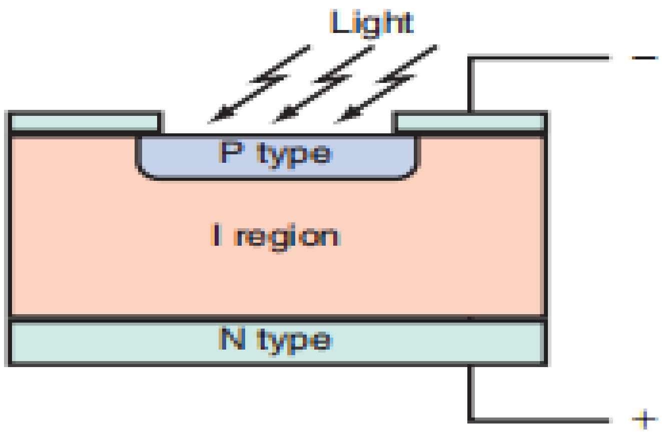


Photo transistor circuits are far more sensitive to small light levels, but they are relatively slow. Thus further amplification and pulse shaping are normally used.

PIN Diode:

The sensitivity of a standard PN-junction photodiode can be increased and the response time decreased by creating a new device that adds an undoped or intrinsic (I) layer between the P and N semiconductors. The result is a PIN diode as shown in fig below



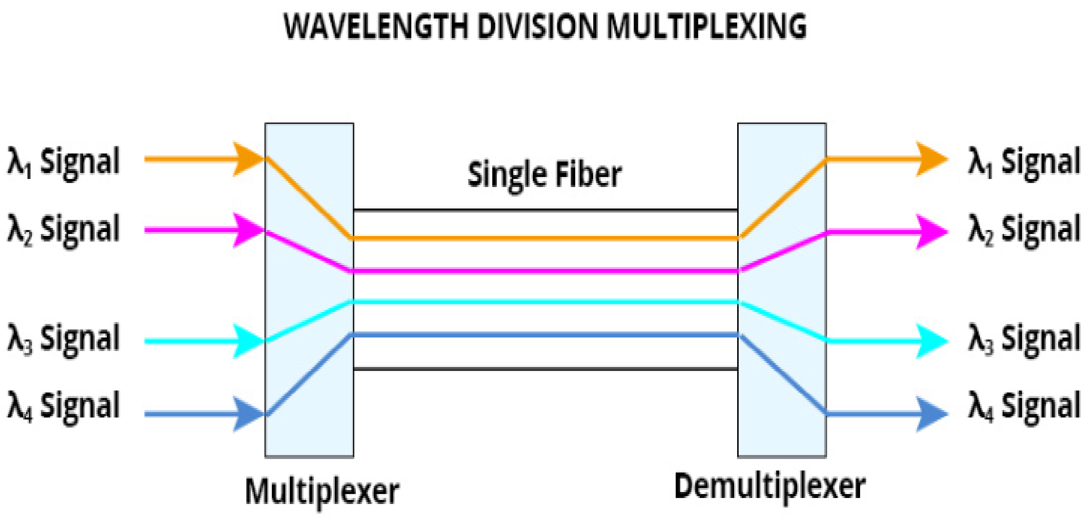
The thin P layer is exposed to the light, which penetrates to the junction, causing electron flow proportional to the amount of light. The diode is reverse-biased, and the current is very low until light strikes the diode, which significantly increases the current. PIN diodes are significantly faster in response to rapid light pulses of high frequency.And their light sensitivity is far greater than that of an ordinary photodiode.

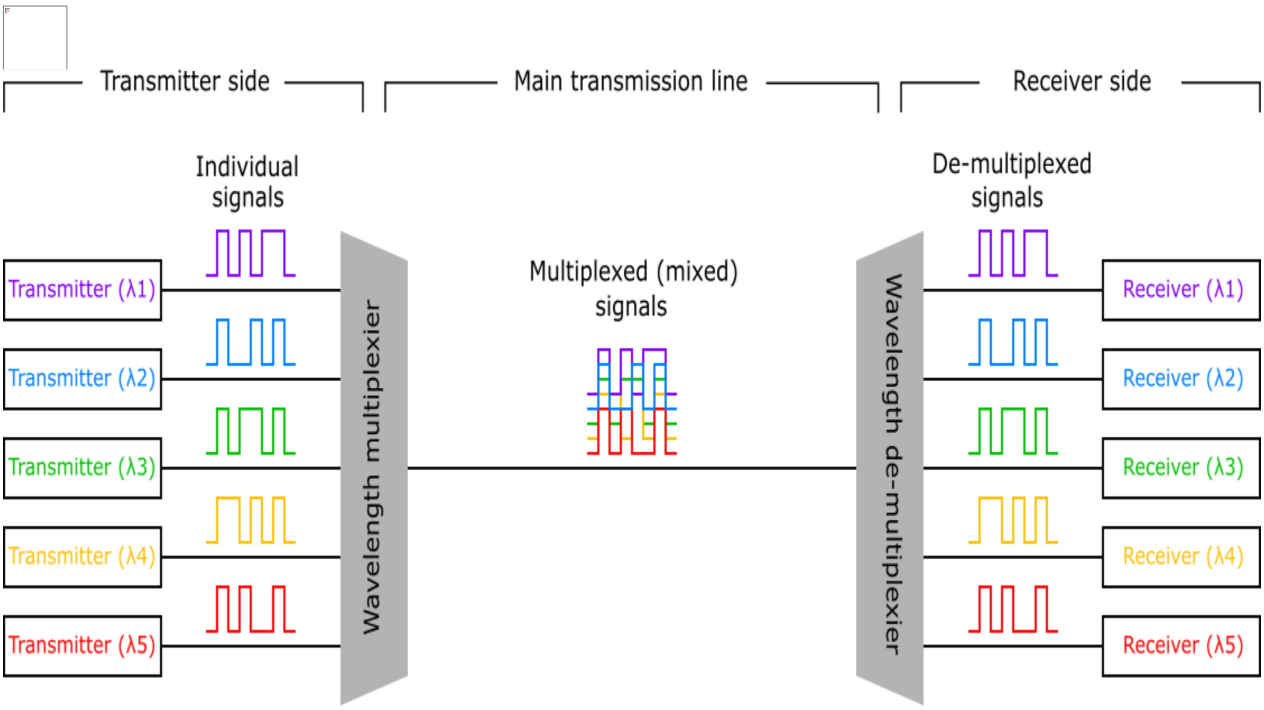
Avalanche Diode: The avalanche photodiode (APD) is a more widely used photo sensor. It is the fastest and most sensitive photodiode available, but it is expensive and its circuitry is complex. Like the standard photodiode, the APD is reverse-biased. However, the operation is different. The APD uses the reverse breakdown mode of operation that is commonly found in zener diodes. When a sufficient amount of reverse voltage is applied, an extremely high current flows because of the avalanche effect. Normally, several hundred volts of reverse bias, just below the avalanche threshold, are applied. When light strikes the junction, breakdown occurs and a large current flows. This high reverse current requires less amplification than the small current in a standard photodiode. Germanium APDs are also significantly faster than the other photodiodes and are capable of handling the very high gigabit-per-second data rates possible in some systems.

Wavelength Division Multiplexing:

Wavelength Division Multiplexing (WDM) is a fiber-optic transmission technique that enables the use of multiple light wavelengths (or colors) to send data over the same medium. Two or more colors of light can travel on one fiber, and several signals can be transmitted in an optical fiber at differing wavelengths or frequencies on the optical spectrum.

Figure below schematically shows a typical WDM transmission system.

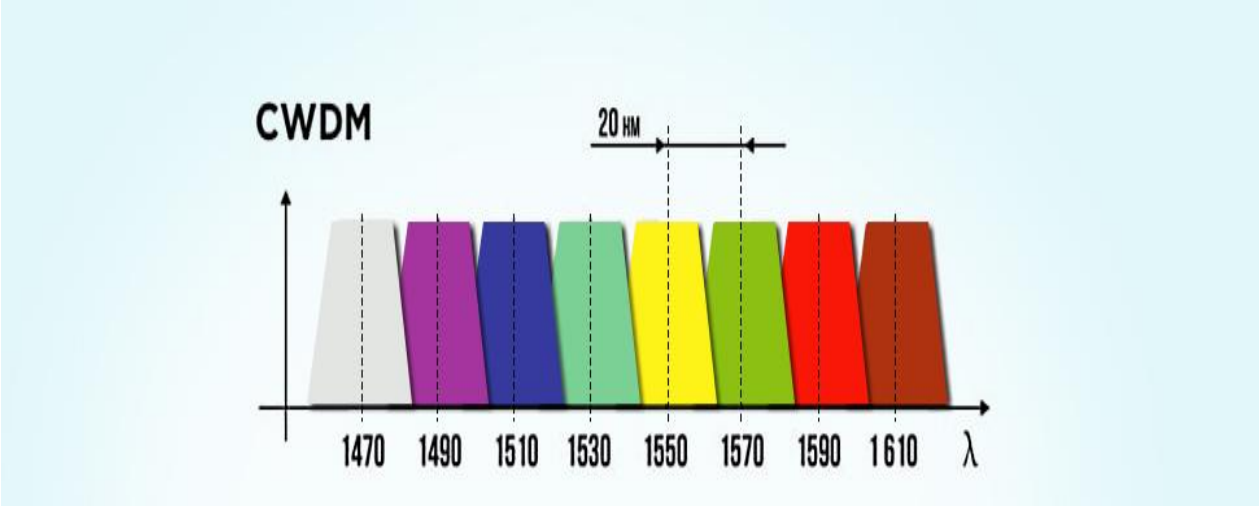




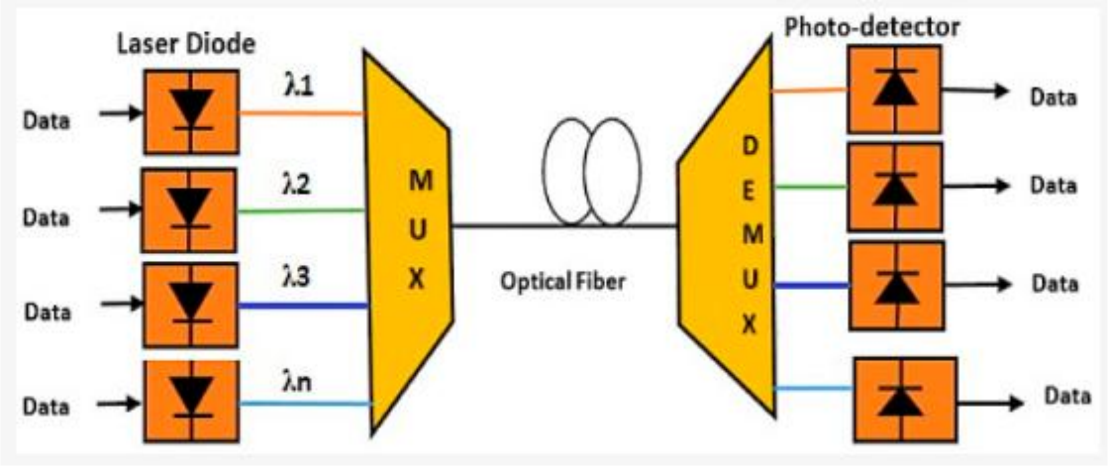
At the transmitter side, multiple optical transmitters – each emitting at a different wavelength – individually send signals and these signals are multiplexed by a wavelength multiplexer (MUX). The multiplexed signals are then transmitted over one main transmission line (optical fiber cable). At the receiver side, the signals are de-multiplexed by a wavelength de-multiplexer (DEMUX) and sent to multiple receivers.

Coarse Wavelength-Division Multiplexing(CWDM):

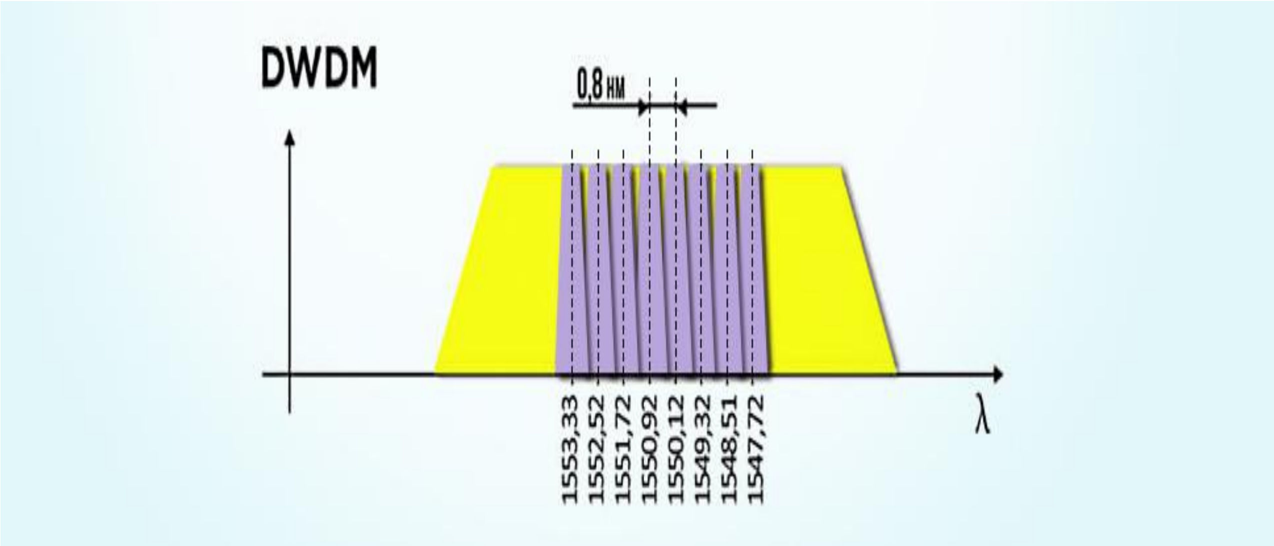
The first coarse WDM (CWDM) systems used two channels operating on 1310 and 1550 nm. Later, four channels of data were multiplexed. The following fig illustrates a CWDM system. A separate serial data source controls each laser. The data source may be a single data source or a multiple TDM source.It uses the wavelengths from 1270 nm to 1610 nm within a 20nm channel spacing shown in fig below.CWDM can support a maximum of 18 channels(wavelengths) and is used for distances upto 80 km.



CWDM supports fewer channels than DWDM, which makes it the ideal solution for short-range communications as it's compact and cost-effective. Current systems use light in the 1550-nm range. A typical four channel system uses laser wavelengths of 1534, 1543, 1550, and 1557.4 nm. Each laser is switched off and on by the input data. The laser beams are then optically combined and transmitted over a single-fiber cable. At the receiving end of the cable, special optical filters are used to separate the light beams into individual channels. Each light beam is detected with an optical sensor and then filtered into the four data streams.



Dense Wavelength-Division Multiplexing:
Dense wavelength-division multiplexing (DWDM) refers to the use of 8, 16, 32, 64, or more data channels on a single fiber. Standard channel wavelengths have been defined by the International Telecommunications Union (ITU) as between 1525 and 1565 nm with a 100-GHz (approximately 0.8-nm) channel spacing shown in fig below



The block of channels between about 1525 and 1565 nm is called the C or conventional band. Most DWDM activity currently occurs in the C band. Another block of wavelengths from 1570 to 1610 nm is referred to as the long-wavelength band, or L band.Wavelengths in the 1525- to 1538-nm range make up the S band.

Current DWDM systems allow more than 160 individual data channels to be carried simultaneously on a single fiber at data rates up to 40 Gbps, giving an overall capacity.of 160x 40, or 6400, Gbps (6.4 Tbps). The potential for future systems is over 200 channels per fiber at a data rate of 40 Gbps. Even more channels can be transmitted on a single fiber as better filters and optical components called splitters become available to permit 50-, 25-, or even 12.5-GHz channel spacing

Advantages of WDM :

a) It has greater transmission capacity.
b) Duplex transmission.
c) Simultaneous transmission of various signals.
d) Easy system expansion.
e) Lower Cost.
f) Faster access to new channels.

g) Higher security.

Disadvantages of WDM:

a)Signals can not be very close.

b)Cost of system increases with addition of optical components.

c)Inefficiency in BW utilization, difficulty in wavelength tuning, difficulty in cascaded topology.