MODULE 1

Wave Polarization

The polarization of a wave becomes very important when we consider radio communication systems, and radio wave propagation. The performance of communication systems can be strongly affected by the polarization of a wave, if it is not "matched" to the intended polarization. Along similar lines, propagation of a wave introduces potential changes to its polarization which will in turn affect communication system performance. Hence, it is important to understand how waves are polarized and the different polarization classifications. The polarization of a wave is defined as the figure that the instantaneous electric field traces out with time at a fixed observation point that is normal to the direction of propagation. Perhaps the most common example of polarization you have heard of is linear polarization. A linearly polarized plane wave is illustrate graphically below. We might define this as vertically polarized but in general linear polarization could refer to linear polarization vectors pointed in any direction (e.g. a horizontally polarized wave is also a form of linear polarization).

In general, the figure traced out by the electric field is not a line, but in fact an ellipse, of which a line is a degenerate case. Consider a wave travelling in the +z-direction. Its polarization will then be traced out in the xy-plane, and appears as shown in the figure below. Some important definitions are called for here: • τ is the major axis angle, i.e. how far the major axis of the ellipse is tilted away from the x-axis; • E1 and E2 are the two components of the electric field, which will be defined momentarily;

• γ is the auxilliary angle defined by $\tan^{-1}$ E2/E1, $0^\circ \leq \gamma \leq 90^\circ$; • ε is the ellipticity angle defined by $\tan \varepsilon$ = OB OA , $-45^\circ \leq \varepsilon \leq 45^\circ$. The ratio of the major axis electric field component to that along the minor axis is called the axial ratio (AR), which is the ratio of the length of the major axis length of the polarization ellipse to the length of the minor axis length, AR = OA OB , $1 \leq AR < \infty$, (1) or $\cot \varepsilon = AR$. (2) Axial ratio is related to ε through $\varepsilon = \cot^{-1}(AR)$. (3) Axial ratio is a measure of how close the polarization is to circular; if AR = 1, the polarization traced out is a circle. More specifically, a wave can be defined as being right hand circularly polarized (RHCP) or left hand circularly polarized (LHCP) if AR = 1. The "handedness" of the polarization is observed by viewing the rotation of the wave vector as it travels. If your thumb points in the direction of propagation, your fingers should curl in the direction of polarization, hence the use of "hand" in the polarization description. A sign can be arbitrarily added to the axial ratio to be more specific as to the handedness of the wave it is referring to. A positive AR indicates a right-hand polarized wave while a negative AR indicates a left-hand polarized wave (note, not necessarily circularly-polarized). Note that the sign is simply used to indicate the handedness of the wave; it is not possible to generate a negative AR from the formulae shown above. Coming back to the general elliptically polarized case, we can write the time varying electric field at z = 0 as follows, assuming the phase angle Ex = 0: E(z = 0, t) = Exxˆ + Eyyˆ = E1 cos(ωt)xˆ + E2 cos(ωt + δ)yˆ. (4) The equivalent phasor representation is E = E1xˆ + E2e jδyˆ. (5)

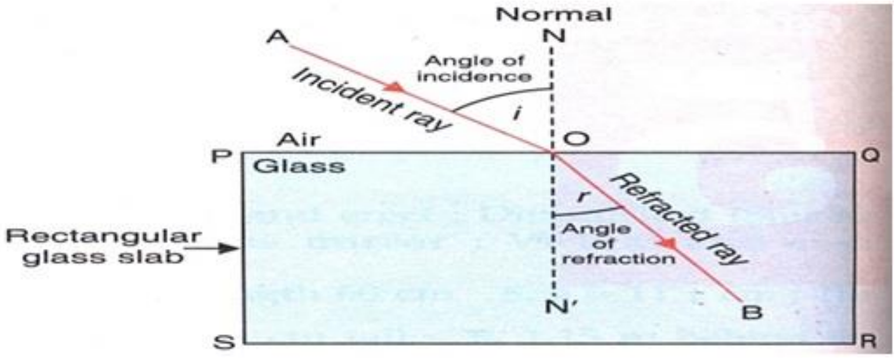
Refraction of Light

Refraction of light takes place when light travels from one medium to another. It takes place at the boundary between the two mediums. Also, we know that speed of light is different in different mediums. So, it occurs due to the change in speed of light on going from one medium to another.

When the light rays either bend or change their direction while passing from one medium to another it is called refraction of light. The refraction of light takes place when light travels from air into glass, from glass into air, from air into water or from water into air.

The example of optical instruments that work on the basis of refraction of light are camera, microscope etc.

Incident ray: The light rays passing from air into glass or water are called incident rays.
Refracted ray: When the light rays bend after passing into another medium, they are called refracted rays.
Normal: The point of incidence is called normal.
Angle of incidence: The angel between incident ray and normal is called angel of incidence.
Angle of refraction: The angel between refracted ray and normal is called angle of refraction.
The angle of refraction is either smaller or greater than angle of incidence.



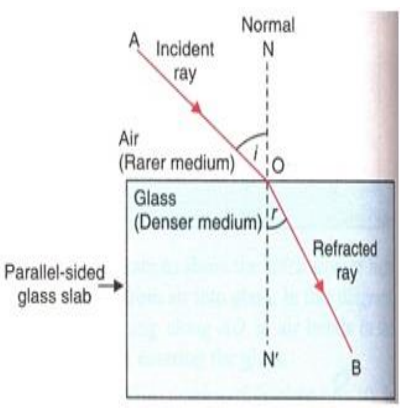
Causes of refraction
Light travels in different speed in different mediums. For example light travels faster in air than in a glass. Therefore, it is due to the change of speed of light in different medium that the light rays are refracted.

Optically rarer medium
A transparent substance (medium) in which the speed of light is more is called optically rarer medium.

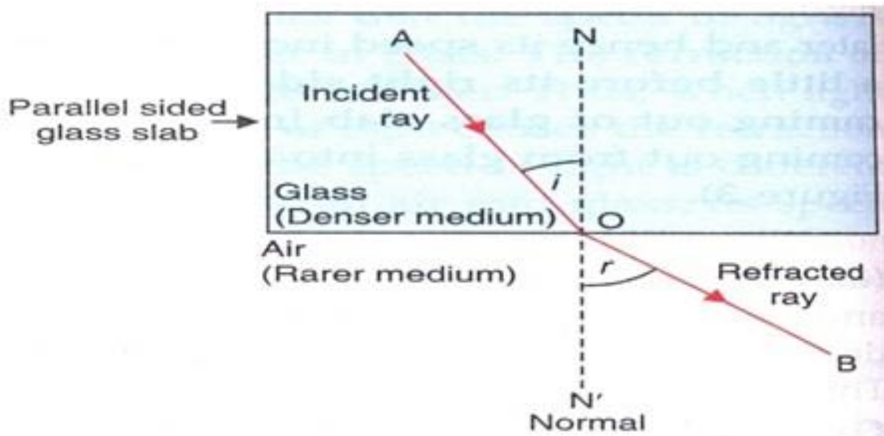
Optically denser medium
A transparent substance (medium) in which the speed of light is less is known as optically denser medium.

Glass is an optically denser medium than air and water.

Rules for refraction of light
Case 1: When light rays travel from optically rarer medium to denser medium then they bend towards normal. In this case angle of refraction is smaller than angel of incidence.
When light rays travel from air into glass or from air into water, it bends towards normal. This is because the speed of light rays decrease while travelling from air into glass or water.



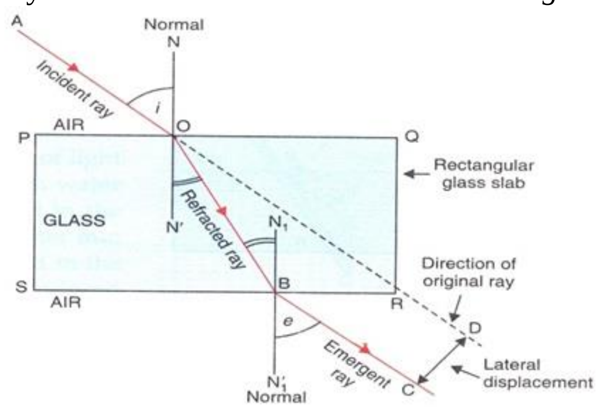
Case 2: When light rays travel from optically denser medium to rarer medium then they bend away from the normal. In this case the angle of refraction is greater than angle of incidence.
When light rays travel from glass into air or from water into air they bend away from the normal. The speed of light rays increase while travelling from glass or water into air.



Case of light going from air into glass and again into air
In this case refraction of light takes place two times. One when it enters the glass slab from air and second time when it enters the air through glass slab.

When light rays travelling through air enters glass slab, they get refracted and bend towards the normal. Now the direction of refracted ray changes again when it comes out of the glass slab into air. Since the ray of light I know travelling from denser medium to rarer medium, it bends away from the normal.

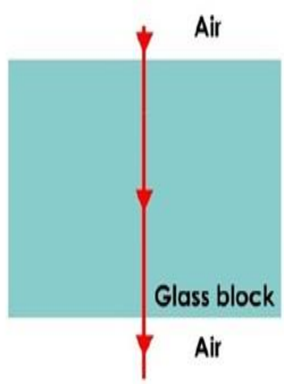
In this case incident ray and the emergent ray are parallel to each other. The perpendicular distance between the original path of incident ray and the emergent ray coming out of the glass slab is called *lateral displacement of the emergent ray of light* and the angle which the emergent ray makes with the normal is called the *angle of emergence*.



Light falling perpendicularly on glass slab

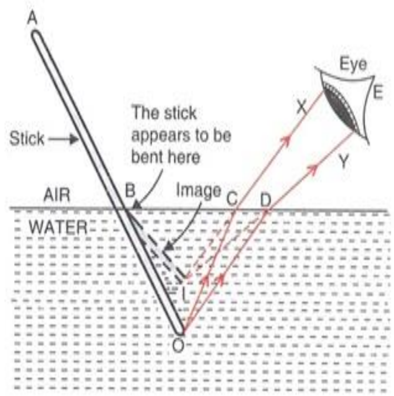
When light falls perpendicularly or normally on the surface of a glass slab, it goes straight. There is no bending of ray of light on entering the glass slab or coming out of it. In this case angle of incidence and angle of refraction is zero.

The same happens if the ray of light falls perpendicularly on the surface of water.



Effects of refraction of light

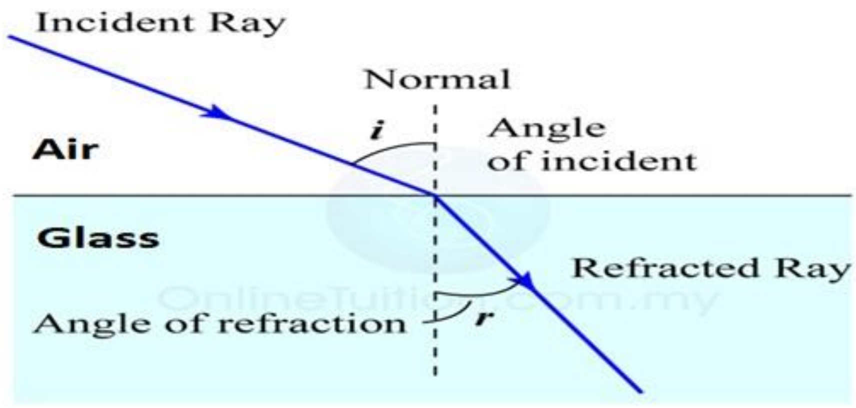
- It is due to refraction of light that when we hold a stick obliquely and partially immersed in water it appears to be bend at the surface of water.



- An object appears to be raised when paced under water.
- Pool of water appears less deep than it actually is.
- If a lemon is kept in a glass of water it appears to be bigger when viewed from the sides of glass.
- It is due to refraction of light that stars appear to twinkle at night.

Laws of refraction of light

1) The incident ray, refracted ray and normal at the point of incidence, all lie in the same plane, i.e. the surface.



2) The ratio of sine of angle of incidence to the sine of angle of refraction is constant for a given pair of media.

Sine of angle of incidence/ sine of angle of refraction = Constant

Constant is called refractive index.

Or Sine i/ Sine r = constant

The refractive index of a medium helps to know the light-bending ability of that medium.

Refractive index and speed of light
Refractive index of medium 2 with respect to medium 1 is equal to the ratio of speed of light in medium 1 to the speed of light in medium 2.

Relative refractive index
When light travels from one medium to another other than vacuum and air, then the value of refractive index is called relative refractive index.

Refractive Index = Speed of light in vacuum/ Speed of light in medium

Or Refractive index = Speed of light in medium 1/ Speed of Light in medium 2

For example, light travelling from water into glass.

Absolute refractive index
When light travels from vacuum to another medium, it is called absolute refractive index.

The substance that has higher refractive index is optically denser than another substance having lower refractive index.

Also, the refractive index for light going from medium 1 to medium 2 is equal to the reciprocal of the refractive index of light going from medium to 2 to medium 1.

Numerical Aperture of Optical Fiber

Definition: Numerical Aperture is the measure of the ability of an optical fiber to collect or confine the incident light ray inside it. It is among the most basic property of optical fiber.

Numerical aperture is abbreviated as **NA** and shows the efficiency with which light is collected inside the fiber in order to get propagated.

We know light through an optical fiber is propagated through **total internal reflection**. Or we can say multiple TIR takes place inside the optical fiber for the light ray to get transmitted from an end to another through an optical fiber.

Basically when the light is emitted from an optical source, then the fiber must be highly efficient so as to collect the maximal emitted radiation inside it.

Thus we can say that the light gathering efficiency of an optical fiber is the key characteristic while transmitting a signal through an optical fiber.

NA is related to **acceptance angle**. As acceptance angle is that max angle through which light enters the fiber. Hence the acceptance angle and numerical aperture are related to each other.

Propagation through Optical fiber

As we have already discussed that light through an optical fiber is propagated by several continuous total internal reflections.

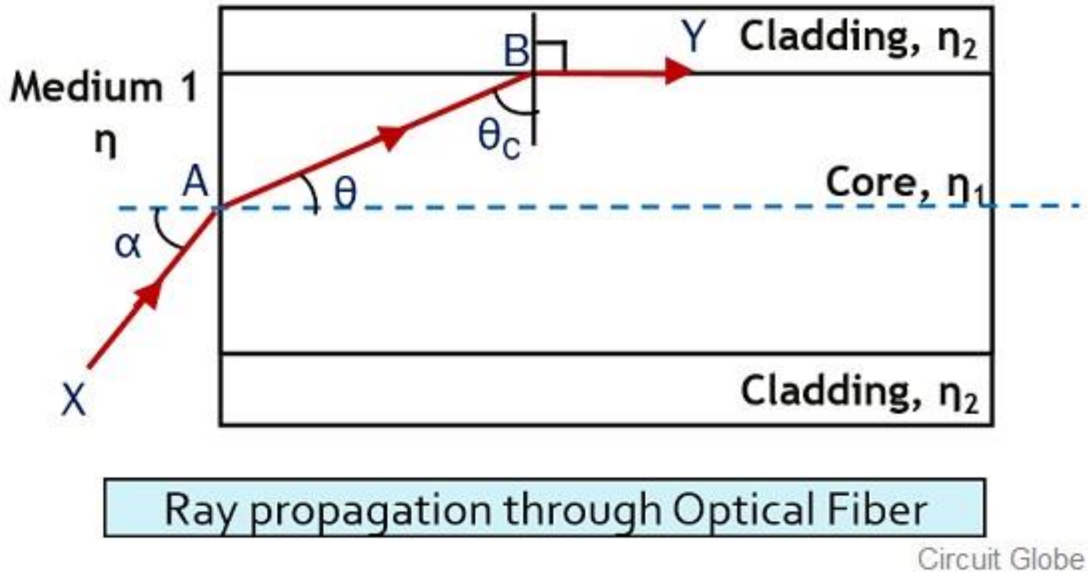
As we know that an optical fiber is composed of a core which is made up of a very pure form of glass silica and is surrounded by a glass cladding. So, the light is propagated inside the fiber by performing continuous reflections from the cladding.

But the condition of total internal reflection for the propagation of light ray comes into action only when most of the light is collected inside the fiber. So, let us now understand the numerical aperture for optical fiber in detail.

Derivation for Numerical Aperture of Optical Fiber

Consider a light ray XA, that incident inside the optical fiber. The refractive index of the core is $\eta 1$ and that of cladding is $\eta 2$.

The figure below shows an optical fiber inside which light ray is focused.



Ray propagation through Optical Fiber

So, the ray XA is launched from denser medium to rarer medium by making an angle α with the fiber axis. This angle α is known as the acceptance angle of the fiber.

This incident ray propagates inside the fiber and gets reflected completely by the core-cladding interface.

But for this, the angle of the incident should be more as compared to the critical angle. Otherwise, if the incident angle is less the critical angle then rather being reflected, the ray gets refracted.

According to Snell's law, the incident and refracted ray propagate in the same plane. Hence, on applying Snell's law at medium 1 (usually air) and core interface. Then

$$\eta \sin\alpha = \eta_1 \sin\theta \qquad \text{-------------- eq}^n\ 1$$

From the above figure, we can write

$$\theta = \frac{\pi}{2} - \theta_C \qquad \text{-------------- eq}^n\ 2$$

On putting the value of θ from the above equation in equation 1, we get,

$$\eta \sin\alpha = \eta_1 \sin\left(\frac{\pi}{2} - \theta_C\right)$$

$$\eta \sin\alpha = \eta_1 \cos\theta_C \qquad \text{(by trigonometric identity)}$$

$$\sin\alpha = \frac{\eta_1}{\eta} \cos\theta_C \qquad \text{-------------- eq}^n\ 3$$

Since we know

$$\cos\theta_C = \sqrt{1 - \sin^2\theta_c} \qquad \text{------------- eq}^n\ 4$$

Applying Snell's law at core-cladding interface, we get

$$\eta_1 \sin\theta_C = \eta_2 \sin 90° \qquad \text{------------- eq}^n\ 5$$

$$\eta_1 \sin\theta_C = \eta_2$$

$$\sin\theta_C = \frac{\eta_2}{\eta_1} \qquad \text{------------- eq}^n\ 6$$

Substituting the above value in equation 4

$$\cos\theta_C = \sqrt{1 - \left[\frac{\eta_2}{\eta_1}\right]^2}$$

Substituting the above value in equation 3, we get

$$\sin\alpha = \frac{\eta_1}{\eta}\sqrt{1 - \left[\frac{\eta_2}{\eta_1}\right]^2}$$

$$\sin\alpha = \sqrt{\frac{\eta_1^2 - \eta_2^2}{\eta}} \qquad \text{------------- eq}^n\ 7$$

As we have already discussed that medium 1 is air, thus refractive index i.e., η will be 1.

$$\sin\alpha = \sqrt{\eta_1^2 - \eta_2^2}$$

So more specifically we can say
$$NA = \sqrt{\eta_1^2 - \eta_2^2}$$

This is the expression for the numerical aperture of an optical fiber, having η1 as the refractive index of core and η2 as the refractive index of the cladding. So we can conclude that as the numerical aperture shows the light collecting ability of the fiber thus its value must be high. As higher the value of NA, better will be the optical fiber.

However, the greater value of NA will be achieved only when the difference between the two refractive indices is high and for this either, η1 is to be high or η2 to be low.But no such material exists that has lower refractive index than 1. So, an option stands that if we remove the cladding present over the core then greater NA can be achieved.

While, for optical signal propagation, the only motive is not to have high accepting range but also to propagate the accepted signal with minimal attenuation.

This is so because an optical fiber that has the greatest light gathering efficiency but does not allow light propagation through it properly, is not of any use.

Thus several parameters must be taken into consideration, for selecting the appropriate optical fiber for signal propagation.

What Is A Step Index Fiber?

In optical fiber, **a step index fiber** is a fiber characterized by a uniform refractive index within the core and a sharp decrease in refractive index at the core-cladding interface so that the cladding is of a lower refractive index. In a step index fiber, the light rays propagate in zig-zag manner inside the core. The rays travel in the fiber as meridional rays and they cross the fiber axis for every reflection.

It is important to note that, Step index fiber is found in two types, that is **mono mode fiber and multi mode fiber.** Signal distortion is more in case of high-angle rays in multimode step index fiber. In single mode step index fiber, there is no distortion. The Step index fiber has a lower bandwidth. The bandwidth is about **50 MHz km** for multimode step index fiber whereas it is more than **100 MHz km** in case of single mode step index fiber.

What You Need To Know About Step Index Fiber

1. Step index fiber is a fiber in which the core is of a uniform refractive index and there is a sharp decrease in the index of refraction at the cladding.
2. Step index fiber is found in two types, that is mono mode fiber and multi mode fiber.
3. Index profiles are in the shape of step.
4. The light rays propagate in *zig–zag* manner inside the core. The rays travel in the fiber as meridional rays and they cross the fiber axis for every reflection.
5. Signal distortion is more in case of high-angle rays in multimode step index fiber. In single mode step index fiber, there is no distortion.
6. The fiber has lower bandwidth. The bandwidth is about 50 MHz km for multimode step index fiber whereas it is more than 100 MHz km in case of single mode step index fiber.
7. The diameter of the core is between 50-200µm in the case of multimode fiber and 10µm in the case of single mode fiber.
8. Used for short distance communication.
9. Attenuation of light rays is more in multimode step index fibers but for single mode step index fibers, it is very less.
10. Less expensive.
11. NA of multimode step index fiber is more whereas in single mode step index fibers, it is very less.
12. Pulse broadening and inter modal dispersion is present.

What Is Graded Index Fiber?

Graded index fiber is a type of optical fiber where the refractive index of the core is uniform at the center core and then it decreases towards core-cladding interface. The uniformity is present because the refractive index is higher at the axis of the core and continuously reduces with the radial movement away from the axis. However, the refractive index of the cladding is constant in the case of graded index fiber; hence the nature of the refractive index is somehow parabolic.

The light rays in graded index fiber, propagate in the form of skew rays or helical rays. They will not cross the fiber axis. Also, it is important to note that inside the fiber, signal distortion is very low even though the rays travel with different speeds. The graded index fiber has a higher bandwidth. The bandwidth of the fiber lies in between **200 MHz Km to 600 MHz** km even though theoretically it has an infinite bandwidth.

Advantages of Graded Index Fiber

- It can transmit a large amount of information.
- The distortion is comparatively small than step index fiber.

Disadvantages of Graded-index Fiber

- These fibers possess low light coupling efficiency.
- It is costly when compared to step index fiber.

What You Need To Know About Graded Index Fiber

1. Graded index fiber is a type of fiber where the refractive index of the core is uniform at the center core and then it decreases towards core-cladding interface.
2. Graded index fiber is of only one type, that is, multi mode fiber.
3. Index profiles is in the shape of a parabolic curve (for α=2).
4. The light rays propagate in the form of skew rays or helical rays. They will not cross the fiber axis.
5. Signal distortion is very low even though the rays travel with different speeds inside the fiber.
6. The fiber has higher bandwidth. The bandwidth of the fiber lies in between 200 MHz Km to 600 MHz km even though theoretically it has an infinite bandwidth.
7. The diameter of the core is about 50μm in the case of multimode fiber.
8. Used for long distance communication.
9. Attenuation of light rays is less in graded index fibers.
10. Highly expensive.
11. NA of graded index fibers is less.
12. No pulse broadening and inter modal dispersion due to periodic self focusing.

Difference Between Step Index Fiber And Graded Index Fiber In Tabular Form

BASIS OF COMPARISON	STEP INDEX FIBER	GRADED INDEX FIBER
Description	Step index fiber is a fiber in which the core is of a uniform refractive index and there is a sharp decrease in the index of refraction at the cladding.	Graded index fiber is a type of fiber where the refractive index of the core is maximum at the center core and then it decreases towards core-cladding interface.
Types	Step index fiber is found in two types, that is mono mode fiber and multi mode fiber.	Graded index fiber is of only one type, that is, multi mode fiber.
Index Profiles	Index profiles are in the shape of step.	Index profiles is in the shape of a parabolic curve (for α=2).
Light Rays Propagation	The light rays propagate in *zig–zag* manner inside the core.	The light rays propagate in the form of skew rays or helical rays. They will not cross the fiber axis.
Signal Distortion	Signal distortion is more in case of high-angle rays in multimode step index fiber. In single mode step index fiber, there is no distortion.	Signal distortion is very low even though the rays travel with different speeds inside the fiber.
Bandwidth Size	The fiber has lower bandwidth.	The fiber has higher bandwidth.
Diameter Of The Core	The diameter of the core is between 50-200µm in the case of multimode fiber and 10µm in the case of single mode fiber.	The diameter of the core is about 50µm in the case of multimode fiber.
Application	Used for short distance communication.	Used for long distance communication.
Attenuation Of Light Rays	Attenuation of light rays is more in multimode step index fibers but for single mode step index fibers, it is very less.	Attenuation of light rays is less in graded index fibers.
Cost	Less expensive	Highly expensive.
NA	NA of multimode step index fiber is more whereas in single mode step index fibers, it is very less.	NA of graded index fibers is less.

Pulse Broadening	Pulse broadening and inter modal dispersion is present.	No pulse broadening and inter modal dispersion due to periodic self focusing.

MODULE 2

Light Emitting Diode

Red, green and blue LEDs

What is it??

As is evident from its name, LED (Light Emitting Diode) is basically a small light emitting device that comes under "active" semiconductor electronic components. It's quite comparable to the normal general purpose diode, with the only big difference being its capability to emit light in different colors. The two terminals (anode and cathode) of a LED when connected to a voltage source in the correct polarity, may produce lights of different colors, as per the semiconductor substance used inside it.

Working Principle:

A light-emitting diode is a two-lead semiconductor light source. It is a p–n junction diode that emits light when activated. When a suitable voltage is applied to the leads, electrons are able to recombine with electron holes within the device, releasing energy in the form of photons. This effect is called electroluminescence, and the color of the light (corresponding to the energy of the photon) is determined by the energy band gap of the semiconductor.

Working in a nutshell:

- The material used in LEDs is basically aluminum-gallium-arsenide (AlGaAs). In its original state, the atoms of this material are strongly bonded. Without free electrons, conduction of electricity becomes impossible here.

- By adding an impurity, which is known as doping, extra atoms are introduced, effectively disturbing the balance of the material.
- These impurities in the form of additional atoms are able either to provide free electrons (N-type) into the system or suck out some of the already existing electrons from the atoms (P-Type) creating "holes" in the atomic orbits. In both ways the material is rendered more conductive. Thus in the influence of an electric current in N-type of material, the electrons are able to travel from anode (positive) to the cathode (negative) and vice versa in the P-type of material. Due to the virtue of the semiconductor property, current will never travel in opposite directions in the respective cases.
- From the above explanation, it's clear that the intensity of light emitted from a source (LED in this case) will depend on the energy level of the emitted photons which in turn will depend on the energy released by the electrons jumping in between the atomic orbits of the semiconductor material.
- We know that to make an electron shoot from lower orbital to higher orbital its energy level is required to be lifted. Conversely, if the electrons are made to fall from the higher to the lower orbitals, logically energy should be released in the process.
- In LEDs, the above phenomena is well exploited. In response to the P-type of doping, electrons in LEDs move by falling from the higher orbitals to the lower ones releasing energy in the form of photons i.e. light. The farther these orbitals are apart from each other, the greater the intensity of the emitted light.
  Different wavelengths involved in the process determine the different colors produced from the LEDs. Hence, light emitted by the device depends on the type of semiconductor material used.
  Infrared light is produced by using Gallium Arsenide (GaAs) as a semiconductor. Red or yellow light is produced by using Gallium-Arsenide-Phosphorus (GaAsP) as a semiconductor. Red or green light is produced by using Gallium-Phosphorus (GaP) as a semiconductor.

Advantages of LEDs:

1. Very low voltage and current are enough to drive the LED.
Voltage range – 1 to 2 volts. Current – 5 to 20 milliamperes.
2. Total power output will be less than 150 milliwatts.
3. The response time is very less – only about 10 nanoseconds.
4. The device does not need any heating and warm up time.
5. Miniature in size and hence lightweight.

6. Have a rugged construction and hence can withstand shock and vibrations.
7. An LED has a lifespan of more than 20 years.

Disadvantages:

1. A slight excess of voltage or current can damage the device.
2. The device is known to have a much wider bandwidth compared to the laser.
3. The temperature depends on the radiant output power and wavelength.

Lasers:-Fundamental Approach

A laser consists of two fundamental elements:

- An amplifying or gain medium (this can be a solid, a liquid or a gas). This medium is composed of atoms, molecules, ions or electrons whose energy levels are used to increase the power of a light wave during its propagation. The physical principle involved is called stimulated emission.
- A system to excite the amplifying medium (also called a pumping system). This creates the conditions for light amplification by supplying the necessary energy. There are different kinds of pumping system: optical (the sun, flash lamps, continuous arc lamps or tungsten-filament lamps, diode or other lasers), electrical (gas discharge tubes, electric current in semi-conductors) or even chemical.

These two components are sufficient to amplify an existing light source. This is known as a laser amplifier. However, most lasers also incorporate an optical resonator (or cavity) in order to produce a very special radiation. Technically, the whole device is known as a laser oscillator, but this term is often shortened to simply “laser”. The laser oscillator uses reflecting mirrors to amplify the light source considerably by bouncing it back and forth within the cavity. It also has an output beam mirror that enables part of the light wave in the cavity to be removed and its radiation used.

Oscillations :-

Oscillations are unbiquitous. It would be difficult to find something which never exhibits oscillations. Atoms in solids, electromagnetic fields, multi-storeyed buildigs and share prices all exhibit oscillations. In this course we shall restrict our attention to only the simplest possible situations, but it should be borne in mind that this elementary analysis provides insights into a diverse variety of apparently complex phenomena. Periodic Motion : The mation in which the particle repeats itself after a regular interval of time is known as periodic motion. Ex: Motion of a pendulum motion of a swing. The periodic motion in which a particle moves to and fro motion about the mean position over the same path is known as Oscillator. Eg- Pendulum, balance wheel of a clock, Beating of heart etc. Mechanism of ascillation: Each oscillator has an equlibrium position, when it displaced from the mean position, it experiences a force which is called restoring force which bring it back to the original position However on reaching the position, it overshoots to the other side due to inertia of motion. It again experiences restoring force and oscillation continues. Types of Oscillator : There are 4 types of oscillator i. Simple Harmonic oscillator ii. Damp harmonic oscillators iii. Forced oscillator iv. Copupled oscillators.

A particle is said to execute simple Harmonic Motion if the restoring force is directed towards the mean position and its magnitude is directly proportional to the displacement of particle from the mean position.

According to the definition of SHM, – x i.e. [– sign because F is opposite to x]αF F = – kx [where k is a force constant]

ma = – kx

⇒ m (d2x/dt2)=-kx

⇒(d2x/dt2)+w2=0, where w=$\sqrt{(\frac{k}{m})}$

Damped harmonic oscillator:-

The oscillator whose amplitude in successive oscillation goes on decreasing due to presence of damping force or dissipative force is known as Damped Harmonic Osilator. If the velocity of the particle increases, then damping force also increases (Fd). Hence damping forceΘ [– αF V d & velocity are opposite to each other] F b V d– = ⇒ where b = damping constant. In damped harmonic oscillator, when a particle displaces a displacement x, it experiences two opposing forces. First one is restoring fore (Fr) and another

m (d2x/dt2)=-kx

m (d2x/dt2)=-kx-b (dx/dt)

⇒(d2x/dt2)+(b/m) (dx/dt)+(k/m)x=0

⇒(d2x/dt2)+(2β) (dx/dt)+(w2)x=0 where b 2m = damping coefficient.= β

Semiconductor Diode laser:

Definition:

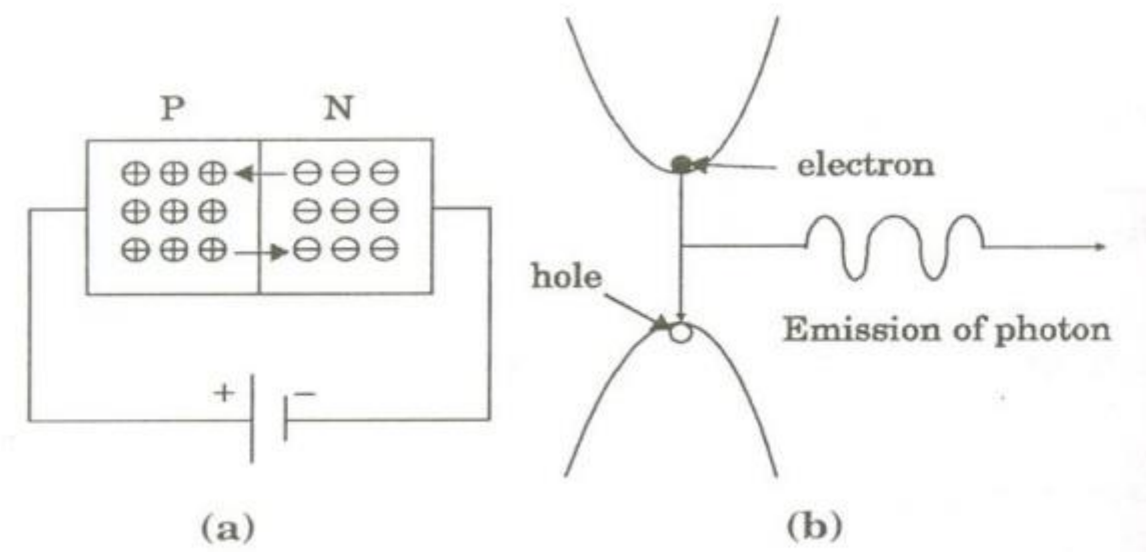
It is specifically fabricated p-n junction diode. This diode emits laser light when it is forward biased.

Principle:

When a p-n junction diode is forward biased, the electrons from n – region and the holes from the p- region cross the junction and recombine with each other.

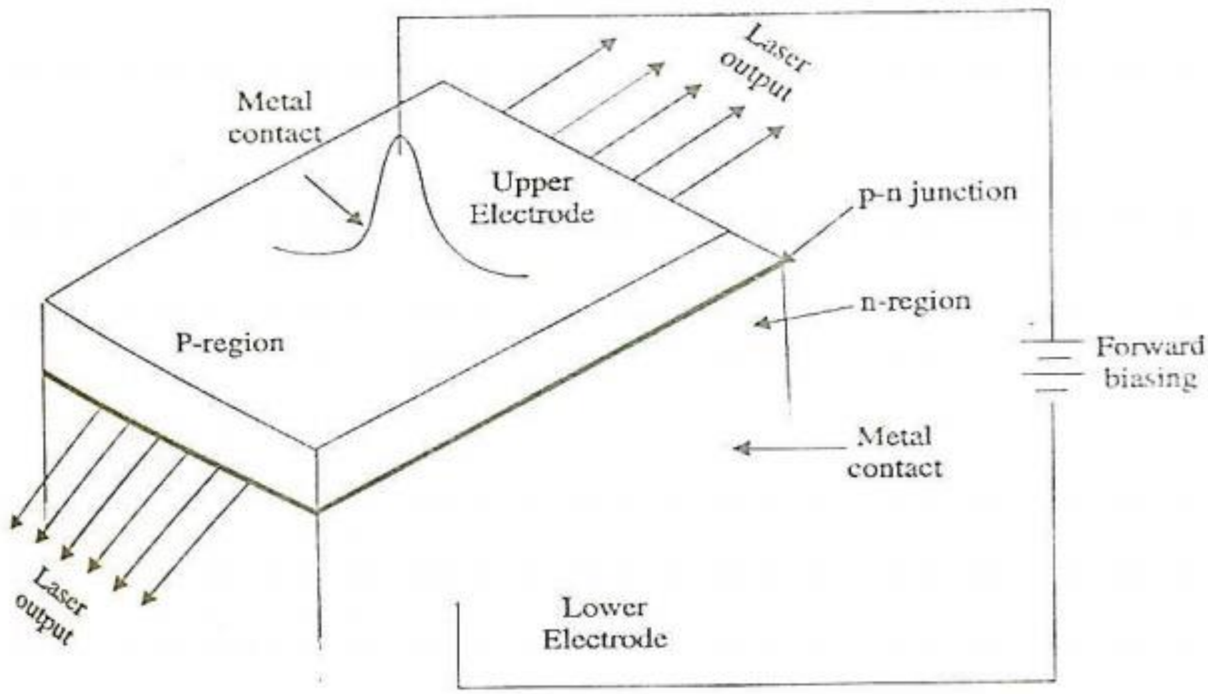
During the recombination process, the light radiation (photons) is released from a certain specified direct band gap semiconductors like Ga-As. This light radiation is known as recombination radiation.

The photon emitted during recombination stimulates other electrons and holes to recombine. As a result, stimulated emission takes place which produces laser.



Construction:

Figure shows the basic construction of semiconductor laser. The active medium is a p-n junction diode made from the single crystal of gallium arsenide. This crystal is cut in the form of a platter having thickness of 0.5μmm.



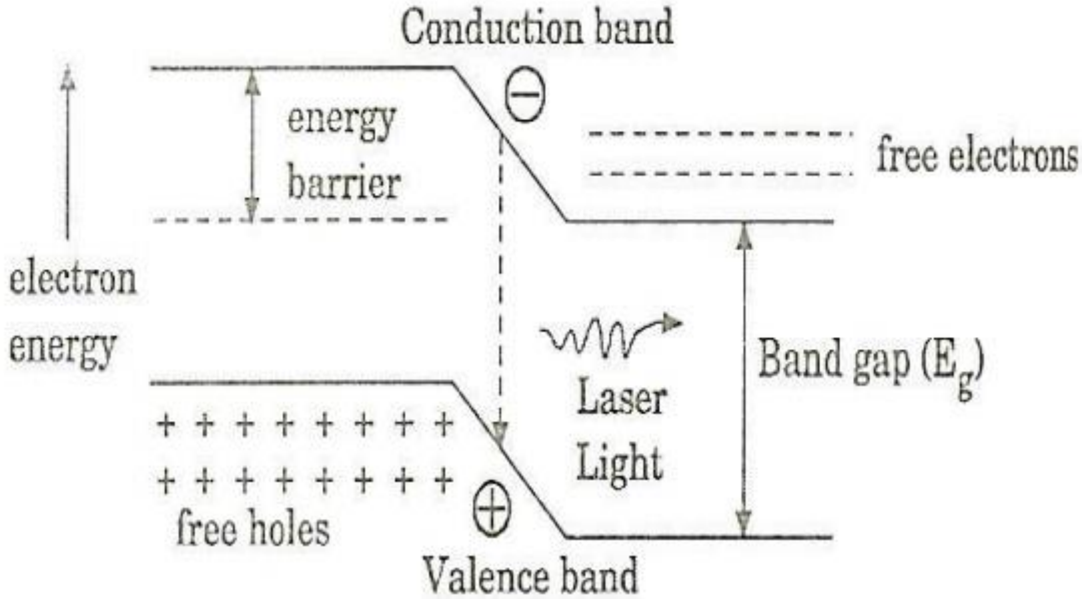
The platelet consists of two parts having an electron conductivity (n-type) and hole conductivity (p-type).

The photon emission is stimulated in a very thin layer of PN junction (in order of few microns). The electrical voltage is applied to the crystal through the electrode fixed on the upper surface.

The end faces of the junction diode are well polished and parallel to each other. They act as an optical resonator through which the emitted light comes out.

Working:

Figure shows the energy level diagram of semiconductor laser.



When the PN junction is forward biased with large applied voltage, the electrons and holes are injected into junction region in considerable concentration

The region around the junction contains a large amount of electrons in the conduction band and a large amount of holes in the valence band.

If the population density is high, a condition of population inversion is achieved. The electrons and holes recombine with each other and this recombination's produce radiation in the form of light.

When the forward – biased voltage is increased, more and more light photons are emitted and the light production instantly becomes stronger. These photons will trigger a chain of stimulated recombination resulting in the release of photons in phase.

The photons moving at the plane of the junction travels back and forth by reflection between two sides placed parallel and opposite to each other and grow in strength.

After gaining enough strength, it gives out the laser beam of wavelength 8400o A .

The wavelength of laser light is given by

$$E_g = h\nu = h\frac{c}{\lambda}$$

$$\lambda = \frac{hc}{E_g}$$

Where Eg is the band gap energy in joule.

Characteristics:

1. Type: It is a solid state semiconductor laser.

2. Active medium: A PN junction diode made from single crystal of gallium arsenide is used as an active medium.

3. Pumping method: The direct conversion method is used for pumping action

4. **Power output:** The power output from this laser is 1mW.

5. **Nature of output:** The nature of output is continuous wave or pulsed output.

6. **Wavelength of Output:** gallium arsenide laser gives infrared radiation in the wavelength 8300 to 8500 ^{o}A .

Advantages:

1. It is very small in dimension. The arrangement is simple and compact.
2. It exhibits high efficiency.
3. The laser output can be easily increased by controlling the junction current
4. It is operated with lesser power than ruby and CO_2 laser.
5. It requires very little auxiliary equipment
6. It can have a continuous wave output or pulsed output.

Disadvantages:

1. It is difficult to control the mode pattern and mode structure of laser.
2. The output is usually from 5 degree to 15 degree i.e., laser beam has large divergence.
3. The purity and monochromacity are power than other types of laser
4. Threshold current density is very large (400A/mm2).
5. It has poor coherence and poor stability.

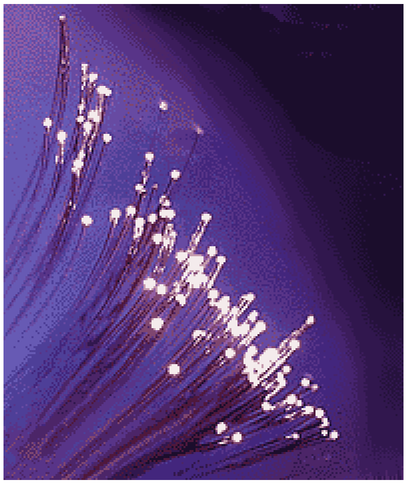
Application:

1. It is widely used in fiber optic communication
2. It is used to heal the wounds by infrared radiation
3. It is also used as a pain killer
4. It is used in laser printers and CD writing and reading.

Module 3

Fiber Optic Splicing

What is Fiber Optic Splicing

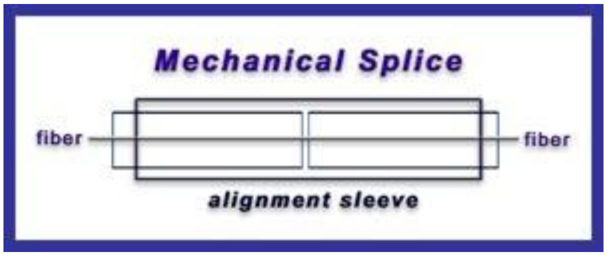


Knowledge of fiber optic splicing methods is vital to any company or fiber optic technician involved in Telecommunications or LAN and networking projects.

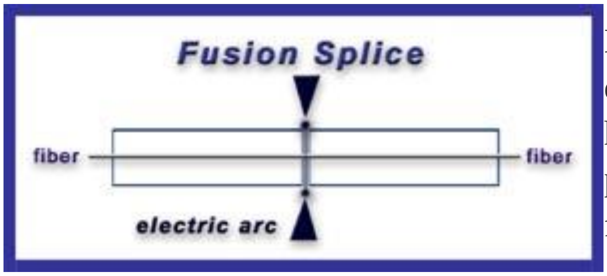
Simply put, fiber optic splicing involves joining two fiber optic cables together. The other, more common, method of joining fibers is called termination or connectorization. Fiber splicing typically results in lower light loss and back reflection than termination making it the preferred method when the cable runs are too long for a single length of fiber or when joining two different types of cable together, such as a 48-fiber cable to four 12-fiber cables. Splicing is also used to restore fiber optic cables when a buried cable is accidentally severed.

There are two methods of fiber optic splicing, fusion splicing & mechanical splicing. If you are just beginning to splice fiber, you might want to look at your long-term goals in this field in order to chose which technique best fits your economic and performance objectives.

Mechanical Splicing vs. Fusion Splicing



� Mechanical Splicing:



Mechanical splices are simply alignment devices, designed to hold the two fiber ends in a precisely aligned position thus enabling light to pass from one fiber into the other. (Typical loss: 0.3 dB)

� Fusion Splicing:

In fusion splicing a machine is used to precisely align the two fiber ends then the glass ends are "fused" or "welded" together using some type of heat or electric arc. This produces a continuous connection between the fibers enabling very low loss light transmission. (Typical loss: 0.1 dB)

� Which method is better?
The typical reason for choosing one method over the other is economics. Mechanical splicing has a low initial investment ($1,000 - $2,000) but costs more per splice ($12-$40 each). While the cost per splice for fusion splicing is lower ($0.50 - $1.50 each), the initial investment is much higher ($15,000 - $50,000 depending on the accuracy and features of the fusion splicing machine being purchased). The more precise you need the alignment (better alignment results in lower loss) the more you pay for the machine.

As for the performance of each splicing method, the decision is often based on what industry you are working in. Fusion splicing produces lower loss and less back reflection than mechanical splicing because the resulting fusion splice points are almost seamless. Fusion splices are used primarily with single mode fiber where as Mechanical splices work with both single and multi mode fiber.

Many Telecommunications and CATV companies invest in fusion splicing for their long haul singlemode networks, but will still use mechanical splicing for shorter, local cable runs. Since analog video signals require minimal reflection for optimal performance, fusion splicing is preferred for this application as well. The LAN industry has the choice of either method, as signal loss and reflection are minor concerns for most LAN applications.

Fusion Splicing Method
As mentioned previously, fusion splicing is a junction of two or more optical fibers that have been permanently affixed by welding them together by an electronic arc.

Four basic steps to completing a proper fusion splice:

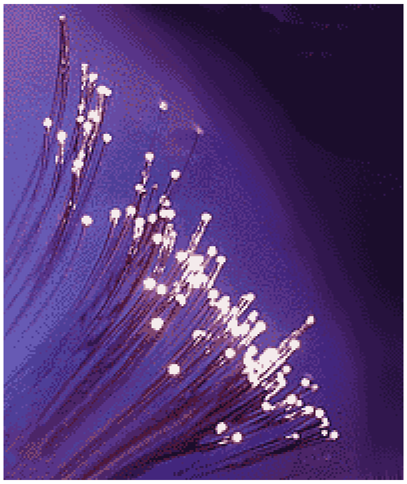
Step 1: Preparing the fiber - Strip the protective coatings, jackets, tubes, strength members, etc. leaving only the bare fiber showing. The main concern here is cleanliness.

Step 2: Cleave the fiber - Using a good fiber cleaver here is essential to a successful fusion splice. The cleaved end must be mirror-smooth and perpendicular to the fiber axis to obtain a proper splice. NOTE: The cleaver does not cut the fiber! It merely nicks the fiber and then pulls or flexes it to cause a clean break. The goal is to produce a cleaved end that is as perfectly perpendicular as possible. That is why a good cleaver for fusion splicing can often cost $1,000 to $3,000. These cleavers can consistently produce a cleave angle of 0.5 degree or less.

Step 3: Fuse the fiber - There are two steps within this step, alignment and heating. Alignment can be manual or automatic depending on what equipment you have. The higher priced equipment you use, the more accurate the alignment becomes. Once properly aligned the fusion splicer unit then uses an electrical arc to melt the fibers, permanently welding the two fiber ends together.

Step 4: Protect the fiber - Protecting the fiber from bending and tensile forces will ensure the splice not break during normal handling. A typical fusion splice has a tensile strength between 0.5 and 1.5 lbs and will not break during normal handling but it still requires protection from excessive bending and pulling forces. Using heat shrink tubing, silicone gel and/or mechanical crimp protectors will keep the splice protected from outside elements and breakage.

What is Fiber Optic Splicing



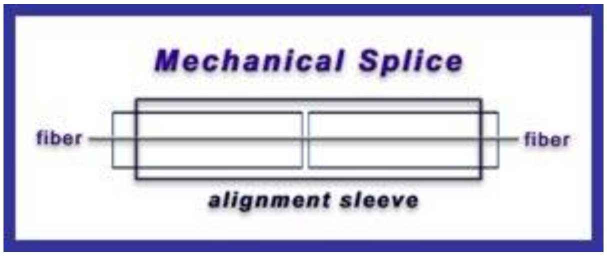
Knowledge of fiber optic splicing methods is vital to any company or fiber optic technician involved in Telecommunications or LAN and networking projects.

Simply put, fiber optic splicing involves joining two fiber optic cables together. The other, more common, method of joining fibers is called termination or connectorization. Fiber splicing typically results in lower light loss and back reflection than termination making it the preferred method when the cable runs are too long for a single length of fiber or when joining two different types of cable together, such as a 48-fiber cable to four 12-fiber cables. Splicing is also used to restore fiber optic cables when a buried cable is accidentally severed.

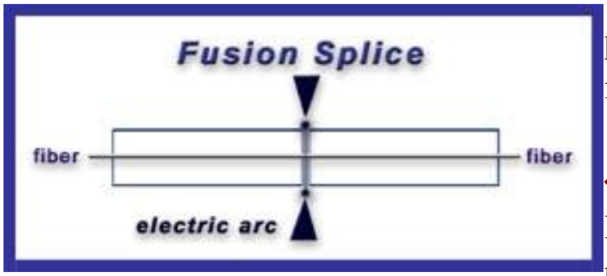
There are two methods of fiber optic splicing, fusion splicing & mechanical splicing. If you are just beginning to splice fiber, you might want to look at your long-term goals in this field in order to chose which technique best fits your economic and performance objectives.

Mechanical Splicing vs. Fusion Splicing

� Mechanical Splicing:



Mechanical splices are simply alignment devices, designed to hold the two fiber ends in a precisely aligned position thus enabling light to pass from one fiber into the other. (Typical loss: 0.3 dB)



� Fusion Splicing:

In fusion splicing a machine is used to precisely align the two fiber ends then the glass ends are "fused" or "welded" together using some type of heat or electric arc. This produces a continuous connection between the fibers enabling very low loss light transmission. (Typical loss: 0.1 dB)

� Which method is better?

The typical reason for choosing one method over the other is economics. Mechanical splicing has a low initial investment ($1,000 - $2,000) but costs more per splice ($12-$40 each). While the cost per splice for fusion splicing is lower ($0.50 - $1.50 each), the initial investment is much higher ($15,000 - $50,000 depending on the accuracy and features of the fusion splicing machine being purchased). The more precise you need the alignment (better alignment results in lower loss) the more you pay for the machine.

As for the performance of each splicing method, the decision is often based on what industry you are working in. Fusion splicing produces lower loss and less back reflection than mechanical splicing because the resulting fusion splice points are almost seamless. Fusion splices are used primarily with single mode fiber where as Mechanical splices work with both single and multi mode fiber.

Many Telecommunications and CATV companies invest in fusion splicing for their long haul singlemode networks, but will still use mechanical splicing for shorter, local cable runs. Since analog video signals require minimal reflection for optimal performance, fusion splicing is preferred for this application as well. The LAN industry has the choice of either method, as signal loss and reflection are minor concerns for most LAN applications.

Fusion Splicing Method

As mentioned previously, fusion splicing is a junction of two or more optical fibers that have been permanently affixed by welding them together by an electronic arc.

Four basic steps to completing a proper fusion splice:

Step 1: Preparing the fiber - Strip the protective coatings, jackets, tubes, strength members, etc. leaving only the bare fiber showing. The main concern here is cleanliness.

Step 2: Cleave the fiber - Using a good fiber cleaver here is essential to a successful fusion splice. The cleaved end must be mirror-smooth and perpendicular to the fiber axis to obtain a proper splice. NOTE: The cleaver does not cut the fiber! It merely nicks the fiber and then pulls or flexes it to cause a clean break. The goal is to produce a cleaved end that is as perfectly perpendicular as possible. That is why a good cleaver for fusion splicing can often cost $1,000 to $3,000. These cleavers can consistently produce a cleave angle of 0.5 degree or less.

Step 3: Fuse the fiber - There are two steps within this step, alignment and heating. Alignment can be manual or automatic depending on what equipment you have. The higher priced equipment you use, the more accurate the alignment becomes. Once properly aligned the fusion splicer unit then uses an electrical arc to melt the fibers, permanently welding the two fiber ends together.

Step 4: Protect the fiber - Protecting the fiber from bending and tensile forces will ensure the splice not break during normal handling. A typical fusion splice has a tensile strength between 0.5 and 1.5 lbs and will not break during normal handling but it still requires protection from excessive bending and pulling forces. Using heat shrink tubing, silicone gel and/or mechanical crimp protectors will keep the splice protected from outside elements and breakage.

Coupler:-

A fiber optic coupler is an optical device capable of connecting one or more fiber ends in order to allow the transmission of light waves in multiple paths. The device is capable of combining two or more inputs into a single output and also dividing a single input into two or more outputs. Compared to a splice or connector, the signal can be more attenuated by fiber optic couplers, as the input signal can be divided amongst the output ports.

Fiber optic couplers can broadly be classified as active or passive devices. An external power source is required for active fiber optic couplers, whereas no power is required for operation of passive fiber optic couplers. There are different types of fiber optic couplers such as X couplers, combiners, splitters, stars and trees. Tree couplers perform both the functions of combiners and splitters in one device. This categorization is mostly based on the number of input and output ports. Combiners combine two signals and provide one output. Splitters supply two outputs while making use of one optical signal. The splitters can further be categorized into Y couplers and T couplers, with the former having equal power distribution and latter an uneven power distribution. Star couplers help in distributing power from inputs to outputs. Tree couplers are either multi-input with a single output or multi-output with a single input. Important parameters when considering a fiber optic coupler are splitting ratio, insertion loss, cable category, coupler type, signal wavelength, input numbers, output numbers and polarization dependent loss. The three major types of manufacturing technologies used in fiber optic couplers are fused-fiber, micro optics and planar waveguide.

There are many benefits of using fiber optic couplers. They have low excess loss, high stability, dual operating window, high reliability and low polarization dependent loss. They also have high directivity and low insertion loss.

Many applications make use of fiber optic couplers such as community antenna networks, optical communication systems and fiber-to-home technology.

Polarizer:

Fiber optics cables are a common and extremely efficient method for data transmission and light guiding applications. Complete fiber optic networks can transmit data over long distances at a wide bandwidth. This makes fibers an ideal technology for a wide range of applications in medical, networking, and military industries. While both polarized and unpolarized light can travel through optical fibers, unpolarized light travels with significant losses and distortions over large distances, which could be critically detrimental to the transmission of information via optical networks.

Fiber optic polarizers are one remedy to this overarching problem and extremely useful in providing the strongest and cleanest output signal. These devices are small pieces of cable placed in-line with fiber that are able to polarize incoming light.

Polarization-controlled fibers produce outputs with maximum intensity and bandwidth without hindering velocity. In this blog post we will learn the basics of polarization in fiber optics and why fiber optic polarizers are the best option for high-speed transmission.

Fiber cables can be single-mode or multimode. The number of modes tells us how light can propagate throughout the fiber. Single-mode fibers can only support a single propagation mode. While waves may contain different frequencies, they are all spatially distributed in the same way. Multimode fibers, however, have a much larger core diameter, allowing for higher light gathering capacity and more modes of propagation along the cable. While these fibers are simpler than the single mode, they are much more limited in bandwidth and travel distance.

Birefringence is is the property within optical materials where the refractive index is dependent on the polarization direction of incoming light. This property is common in most nonlinear crystals and many optical fibers. Ideal fiber cores are perfectly circular, but in practice most fibers experience mechanical stresses due to bending or handling. Shifted geometry within the fiber core then causes polarization-mode distortion along the length of both single and multimode fibers. One polarization mode will then travel at a different space than the other.

How could this affect fiber performance? Lengthened pulses due to birefringence results in more noise and lower quality output light. Different polarizations of light can be absorbed to different degrees by materials. Control over polarization is essential to most optics applications because polarization of light affects the focus of laser beams, influences the cut-off wavelengths of filters, and can be important to prevent unwanted back reflections.

Factors to consider: - **Insertion Loss-** Inserting a fiber optic polarizer (or any optical component) into the system will inevitably cause attenuation. The best polarizers minimize the resultant loss.
Available Bandwidths- Different applications require different (or broader) bandwidths; it is important to choose the polarizer and fiber that matches the accommodates the desired output bandwidth.
Size– Most systems best benefit from smaller polarizers, simply because of constraints on available space. Smaller polarizers also typically prompt lower insertion loss. **Extinction Ratio-** This ratio is likely the most important factor in choosing the best fiber optic polarizer for a given system. Extinction ratio gives the ratio of the transmission of the desired polarization to that of the undesired polarization. This factor is thereby the best indicator of quality for a polarizer.

Applications:-_Fiber optic polarizers are an essential building block for fiber optic networks. These devices make it possible to standardize the inputs and outputs of light for simple construction with fiber couplers without free-space optics. They are therefore ideal in a wide variety of high-density data and measurement applications.

Fiber Amplifiers

While fiber optic polarizers can benefit most fiber systems, they are especially useful for amplification purposes. Doped fibers act as the gain medium in many solid state lasers. Here coherent light pumps the dopant to stimulate emission and then propagates through the fiber. This generation stage for optimal gain is usually polarization-dependent. Polarizers greatly reduce the effects of birefringence and polarization-mode dispersion, therefore allowing for greater amplification and stronger output signal.

Polarization Measurement

Because fiber optic polarizers work as a type of light filter, they are also very efficient in sensing and measurement. Fiber optic polarizers can tell the user a great deal of information about the light passing through and the fiber itself. Polarizers allow for polarization analyses, monitoring and control.

Detectors

PIN:- A p–i–n photodiode, also called PIN photodiode, is a photodiode with an intrinsic (i) (i.e., undoped) region in between the n- and p-doped regions. Most of the photons are absorbed in the intrinsic region, and carriers generated therein can efficiently contribute to the photocurrent. In Figure 1, the electrodes are shown in black: the cathode is a flat electrode, whereas the anode has the form of a ring (of which two opposite parts are seen in the shown cross section). The positive pole of the (reverse) bias voltage is connected to the cathode. On top of the p region, there is an anti-reflection coating.

Advantages of the p–i–n Design

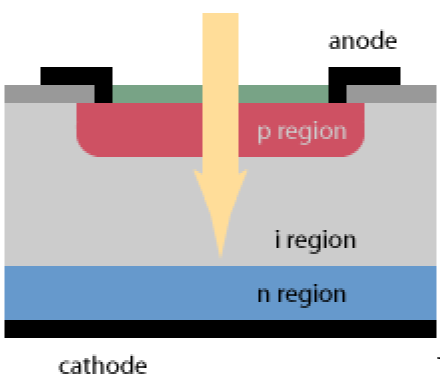


Figure 1: Schematic drawing of a p–i–n photodiode. The green layer is an anti-reflection coating.

Ordinary p–n photodiodes can suffer from the following problems:

- The width of the depletion region may be well below the absorption length, so that only some fraction of the generated photocarriers are generated within the depletion region. The collection of the carriers generated outside the depletion region may be limited, leading to a reduced quantum efficiency.
- Even for those carriers generated outside the depletion region which eventually diffuse into the depletion region and can thus contribute to the photocurrent, that diffusion takes some time; that results in a tail in the impulse response function, which can limit the detection bandwidth.

These problems can be mitigated or avoided with p–i–n photodiode design. There, most carriers are generated in the intrinsic region, because that can be much thicker than the depletion region of a p–n structure. Another effect of the thick intrinsic region can be the reduced capacitance, which allows for a higher detection bandwidth.

Some p–i–n diodes are made from different semiconductor materials, where the band gap energy is below the photon energy only for the intrinsic region, but not for the p and n regions. In that case, any absorption outside the intrinsic region can be avoided.

The fastest p–i–n photodiodes have bandwidths well above 100 GHz. Their active areas typically have a diameter of only a few microns. They are often made in fiber-coupled form and can be applied e.g. in receivers for optical fiber communications; the achieved bit rates can be as high as 160 Gbit/s.

Materials for p–i–n Photodiodes

Some p–i–n diodes are based on silicon. They are sensitive throughout the visible spectral region and in the near infrared up to ≈ 1 μm. At longer wavelengths, the absorption efficiency and thus the responsivity drops sharply, but the parameters of that cut-off depend on the thickness of the intrinsic region.

For longer wavelengths up to ≈ 1.7 μm (or with extended spectral response up to 2.6 μm), InGaAs p–i–n diodes are available, although at significantly higher prices (particularly for large active areas). Small InGaAs photodiodes can be extremely fast.

Germanium p–i–n diodes can be a cheaper alternative to InGaAs diodes, but they have a much slower response and exhibit a much larger dark current.

Avalance Photodiode: - An avalanche photodiode (APD) is a highly sensitive semiconductor photodiode that exploits the photoelectric effect to convert light into electricity. ... APD arrays are becoming commercially available, also lightning detection and optical SETI may be future applications.

An avalanche photodiode (APD) is a highly sensitive semiconductor photodiode that exploits the photoelectric effect to convert light into electricity. From a functional standpoint, they can be regarded as the semiconductor analog of photomultipliers. The avalanche photodiode (APD) was invented by Japanese engineer Jun-ichi Nishizawa in 1952.[1] However, study of avalanche breakdown, microplasma defects in Silicon and Germanium and the investigation of optical detection using p-n junctions predate this patent. Typical applications for APDs are laser rangefinders, long-range fiber-optic telecommunication, and quantum sensing for control algorithms. New applications include positron emission tomography and particle physics. APD arrays are becoming commercially available, also lightning detection and optical SETI may be future applications.

Principle of operation- By applying a high reverse bias voltage (typically 100–200 V in silicon), APDs show an internal current gain effect (around 100) due to impact ionization (avalanche effect). However, some silicon APDs employ alternative doping and beveling techniques compared to traditional APDs that allow greater voltage to be applied (> 1500 V) before breakdown is reached and hence a greater operating gain (> 1000). In general, the higher the reverse voltage, the higher the gain. Among the various expressions for the APD multiplication factor (M), an instructive expression is given by the formula

{\displaystyle M={\frac {1}{1-\int _{0}^{L}\alpha (x)\,dx}},} $M = 1/(1 - \int_0^L \alpha(x)dx)$

where L is the space-charge boundary for electrons, and {\displaystyle \alpha } is the multiplication coefficient for electrons (and holes). This coefficient has a strong dependence on the applied electric field strength, temperature, and doping profile. Since APD gain varies strongly with the applied reverse bias and temperature, it is necessary to control the reverse voltage to keep a stable gain. Avalanche photodiodes therefore are more sensitive compared to other semiconductor photodiodes.

If very high gain is needed (105 to 106), detectors related to APDs (single-photon avalanche diodes) can be used and operated with a reverse voltage above a typical APD's breakdown voltage. In this case, the photodetector needs to have its signal current limited and quickly diminished. Active and passive current-quenching techniques have been used for this purpose. SPADs that operate in this high-gain regime are sometimes referred to being in Geiger mode. This mode is particularly useful for single-photon detection, provided that the dark count event rate and afterpulsing probability are sufficiently low.

Module V

Fibre optic Gyroscope

A **fibre-optic gyroscope** (**FOG**) senses changes in orientation using the Sagnac effect, thus performing the function of a mechanical gyroscope. However its principle of operation is instead based on the interference of light which has passed through a coil of optical fibre, which can be as long as 5 kilometres (3 mi).

Operation

Two beams from a laser are injected into the same fibre but in opposite directions. Due to the Sagnac effect, the beam travelling against the rotation experiences a slightly shorter path delay than the other beam. The resulting differential phase shift is measured through interferometry, thus translating one component of the angular velocity into a shift of the interference pattern which is measured photometrically.

Beam splitting optics launches light from a laser diode into two waves propagating in the clockwise and anticlockwise directions through a coil consisting of many turns of optical fibre. The strength of the Sagnac effect is dependent on the effective area of the closed optical path: this is not simply the geometric area of the loop but is enhanced by the number of turns in the coil. The FOG was first proposed by Vali and Shorthill[1] in 1976. Development of both the passive interferometer type of FOG, or IFOG, and a newer concept, the passive ring resonator FOG, or RFOG, is proceeding in many companies and establishments worldwide.

Advantages

A FOG provides extremely precise rotational rate information, in part because of its lack of cross-axis sensitivity to vibration, acceleration, and shock. Unlike the classic spinning-mass gyroscope or resonant/mechanical gyroscopes, the FOG has no moving parts and doesn't rely on inertial resistance to movement. Hence, the FOG is an excellent alternative to a mechanical gyroscope. Because of their intrinsic reliability and long lifetime, FOGs are used for high performance space applications [3] and military inertial navigation systems.

The FOG typically shows a higher resolution than a ring laser gyroscope.

FOGs are implemented in both open-loop and closed-loop configurations.

Like all other gyroscope technologies and depending on detailed FOG design, FOGs may require initial calibration (determining which indication corresponds to zero angular velocity).

Some FOG designs are somewhat sensitive to vibrations[4]. However, when coupled with multiple-axis FOG and accelerometers and hybridized with GNSS data, the impact is mitigated, making FOG systems suitable for high shock environments, including gun pointing systems for 105mm and 155mm howitzers.

Applications

1. FOGs are used in Attitude and Heading Reference System (AHRS) dedicated to aviation, maritime and Defence applications
2. FOGs are used in Fibre optic gyrocompasses.
3. FOGs are used in the inertial navigation systems of some guided missiles, underwater vehicles and other vehicles requiring resilient navigation.
4. FOGs can be a navigation aid in remotely operated vehicles and autonomous underwater vehicles.
5. FOGs are used on surface vessels and submarines as main navigation systems.
6. FOGs are used on land defence vehicles or weapons for accurate pointing and positioning.
7. FOGs are used in surveying.

Optical Time Domain Reflectometer (OTDR)

Definition: OTDR is an acronym used for Optical Time Domain Reflectometer. It is an instrument that is used to detect or analyze the scattered or back reflected light through an optical fiber due to impurities and imperfections in the fiber.

The operating principle of an OTDR is similar to that of radar. OTDR performs timed measurements of reflected light.

OTDR basically determines the characteristics of an optical fiber cable through which optical signal propagates.

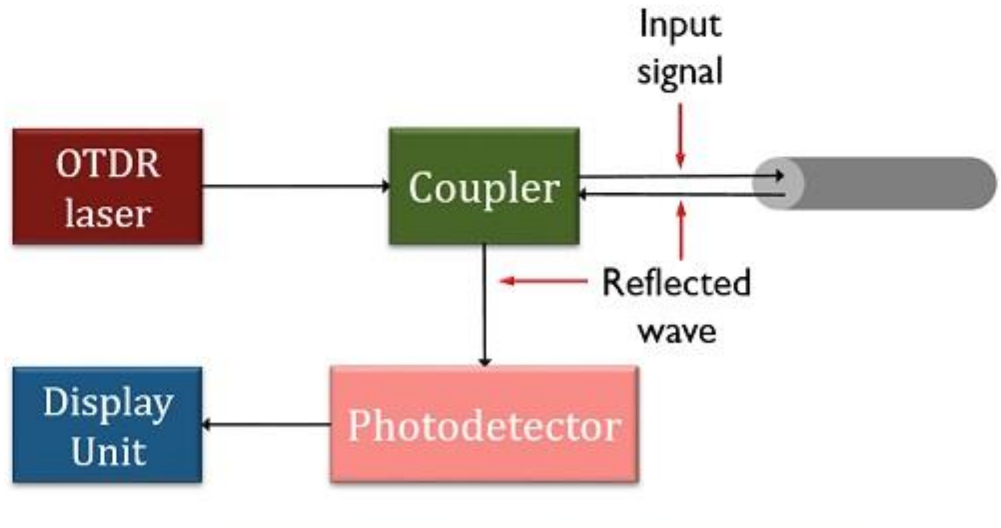
It is also used to evaluate parameters such as splice losses, reflectance angle of a light signal, fiber attenuation etc.
When a signal is transmitted through an optical fiber cable then during transmission some part of the signal gets reflected. This reflection results in signal attenuation that mainly occurs due to defects in the fiber cable.

Thus, an OTDR is used as testing equipment in optical fiber communication system in order to determine the signal loss level inside a fiber cable.

Working of OTDR

An optical time domain reflectometer is test equipment used to evaluate the loss of signal inside an optical fiber by transmitting laser pulses inside the fiber and measures the scattered light signal.

The figure below represents the operational principle of an OTDR:



Operation of OTDR

As we can see in the figure shown above that an optical time domain reflectometer contains a light source (mainly a laser) and a receiver along with a coupler or circulator. The coupler is connected with the fiber under test through a front panel connector.

The laser produces a short and intense light beam. These pulses are directed into the fiber link under test through a fiber optic coupler. A coupler splits the transmitted light pulse into two halves. Due to this, not all the transmitted pulse is directed inside fiber.

However, despite using a coupler if we use a circulator then this wastage of transmitted signal can be avoided. As **circulators are highly directional devices** that direct the overall light signal into the fiber as well as sends the reflected or scattered light signals into the detector.

By inserting circulators in the operational unit of OTDR, the dynamic range of the equipment can be improved. However, it also causes the overall cost of the system to increase considerably as circulator is highly expensive in comparison to couplers.

So, during the propagation of light pulses inside the fiber, due to absorption and Rayleigh scattering, some losses in the transmitted pulse occurs. Also, some losses are introduced due to splicers connected inside the fiber or the bends inside it.

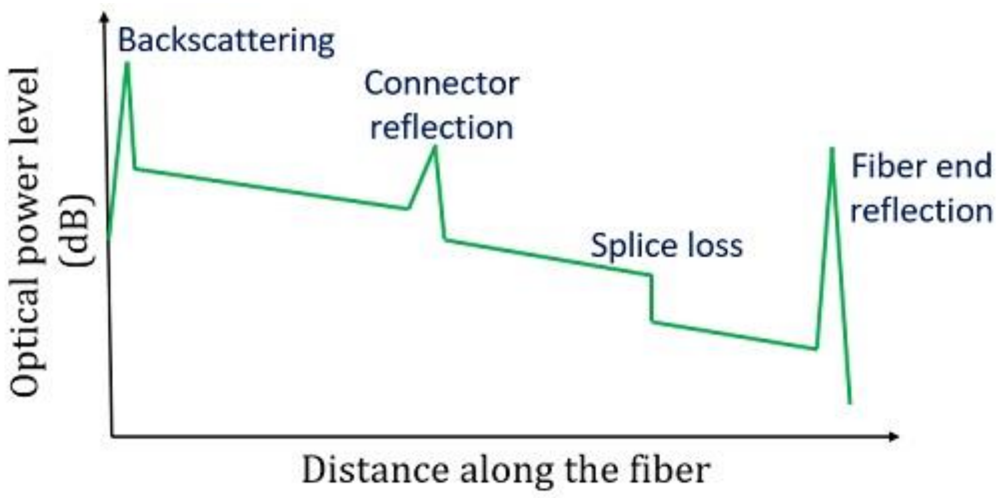
Sometimes variation in the refractive index also causes the light energy to get reflected. This reflected energy reaches the OTDR and in this way, it detects the characteristics of the fiber link.

Specifications of OTDR

The specifications of OTDR are discussed below:

OTDR Trace

The reflected light is traced on the display screen of the reflectometer. The figure below represents the trace of the reflected power on the screen of OTDR:



Representation of trace of OTDR

As we can see that in the above figure that the y-axis represents the optical power level of the reflected signal. While the x-axis represents the distance between the measurement points of the fiber link.

Now, on observing the trace of the OTDR, we can list the features of the reflected wave:

The positive spikes in the trace are the result of Fresnel reflection at the joints of the fiber link and the imperfections in the fiber.

The shifts in the curve are due to losses that occur due to fiber joints.

A deteriorated tail in the curve is the outcome of Rayleigh scattering. As Rayleigh scattering is the result of fluctuations in the refractive index of the fiber and is the major reason for the attenuation of the signal inside the fiber.

OTDR Dead Zone

The dead zone of an OTDR is a crucial parameter. It is the distance in the fiber cable at which the defects cannot be measured properly.

Now the question arises why a dead zone occurs in an OTDR?

In case a very major portion of the transmitted signal is reflected then the received power at the photodetector is highly greater than the backscattered power level.

This saturates the OTDR with the light and hence it needs some duration to overcome the saturation. In this recovery duration, the reflectometer is unable to detect the backscattered reflection, thereby leading to generate a dead zone in the trace of OTDR.

Performance parameter of OTDR

There exist two crucial parameters on which the performance of the OTDR depends. These are as follows:

Dynamic range: This is basically the difference between the backscattered optical power at the front connector and the peak of the noise level at the other end of the fiber. By evaluating the dynamic range one can get an idea about the maximal measured loss inside the fiber link and the time needed for such a measurement.

Measurement range: The measurement range is nothing but provides the distance up to which splice or connection points can be detected by the OTDR. Its value relies on the width of the transmitted pulse and the attenuation.

Hence, we can conclude that an OTDR is a very useful instrument used in an optical communication system. However, certain drawbacks are also associated like dead zone of OTDR.

MODULE IV

Polarization:-

Understanding and manipulating the polarization of light is crucial for many optical applications. Optical design frequently focuses on the wavelength and intensity of light, while neglecting its polarization. Polarization, however, is an important property of light that affects even those optical systems that do not explicitly measure it. The polarization of light affects the focus of laser beams, influences the cut-off wavelengths of filters, and can be important to prevent unwanted back reflections. It is essential for many metrology applications such as stress analysis in glass or plastic, pharmaceutical ingredient analysis, and biological microscopy. Different polarizations of light can also be absorbed to different degrees by materials, an essential property for LCD screens, 3D movies, and your glare-reducing sunglasses.

Understanding Polarization

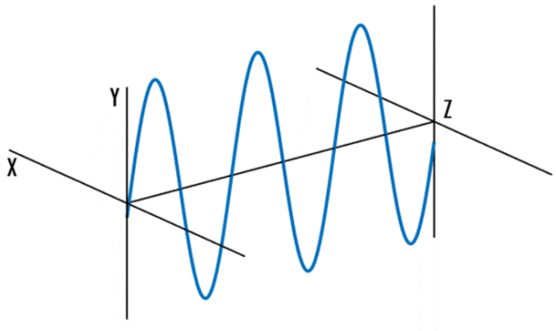
Light is an electromagnetic wave, and the electric field of this wave oscillates perpendicularly to the direction of propagation. Light is called unpolarized if the direction of this electric field fluctuates randomly in time. Many common light sources such as sunlight, halogen lighting, LED spotlights, and incandescent bulbs produce unpolarized light. If the direction of the electric field of light is well defined, it is called polarized light. The most common source of polarized light is a laser.

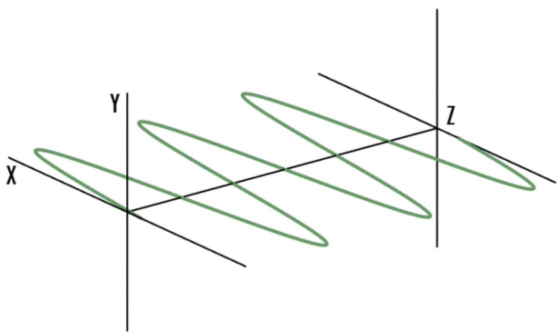
Depending on how the electric field is oriented, we classify polarized light into three types of polarizations:

- Linear polarization: the electric field of light is confined to a single plane along the direction of propagation *(Figure 1)*.
- Circular polarization: the electric field of light consists of two linear components that are perpendicular to each other, equal in amplitude, but have a phase difference of $\pi/2$. The resulting electric field rotates in a circle around the direction

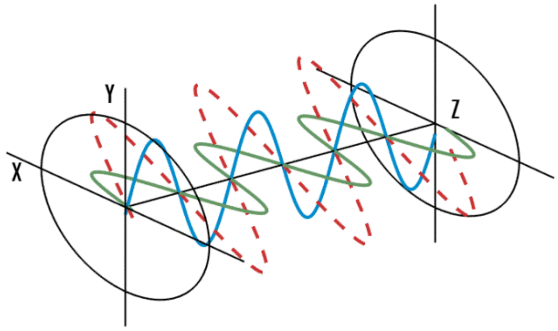
of propagation and, depending on the rotation direction, is called left- or right-hand circularly polarized light *(Figure 2)*.

- Elliptical polarization: the electric field of light describes an ellipse. This results from the combination of two linear components with differing amplitudes and/or a phase difference that is not π/2. This is the most general description of polarized light, and circular and linear polarized light can be viewed as special cases of elliptically polarized light *(Figure 3)*.
-





- Figure 1: The electric field of linearly polarized light is confined to the y-z plane (left) and the x-z plane (right), along the direction of propagation.



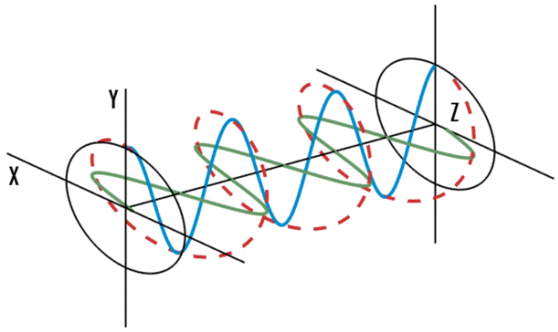
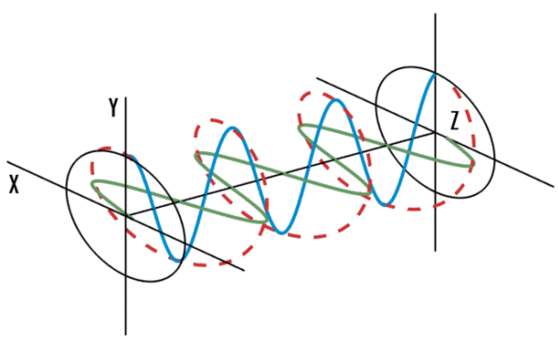
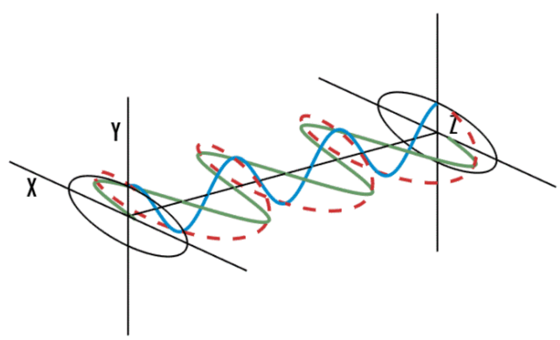
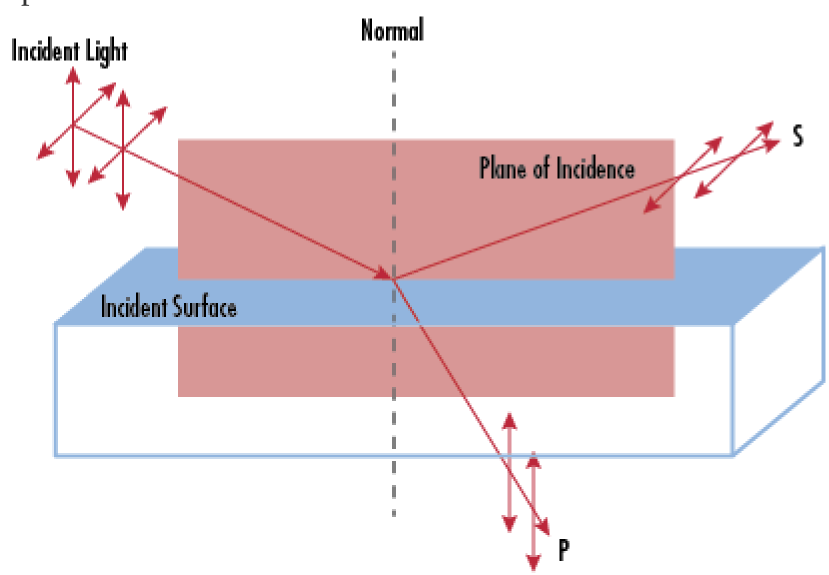
- 

Figure 2: The electric field of linearly polarized light (left) consists of two perpendicular, equal in amplitude, linear components that have no phase difference. The resultant electric field wave propagates along the y = x plane. The electric field of circularly polarized light (right) consists of two perpendicular, equal in amplitude, linear components that have a phase difference of π/2 or 90°. The resultant electric field wave propagates circularly.





- Figure 3: The circular electric field (left) has two components which are of equal amplitude and have a π/2 or 90° phase difference. If the two components however, have differing amplitudes, or if there is a phase difference other than π/2, then then they will create elliptically polarized light (right).
- The two orthogonal linear polarization states that are most important for reflection and transmission are referred to as p- and s-polarization. P-polarized (from the German parallel) light has an electric field polarized parallel to the plane of incidence, while s-polarized (from the German senkrecht) light is perpendicular to this plane.



- Figure 4: P and S are linear polarizations defined by their relative orientation to the plane of incidence.

Manipulating Polarization

Polarizers

In order to select a specific polarization of light, polarizers are used. Polarizers can be broadly divided into reflective, dichroic, and birefringent polarizers. More detailed information on which type of polarizer is right for your application can be found in our Polarizer Selection Guide.

Reflective polarizers transmit the desired polarization while reflecting the rest. Wire grid polarizers are a common example of this, consisting of many thin wires arranged parallel to each other. Light that is polarized along these wires is reflected, while light that is polarized perpendicular to these wires is transmitted. Other reflective polarizers use Brewster’s angle. Brewster’s angle is a specific angle of incidence under which only s-polarized light is reflected. The reflected beam is s-polarized and the transmitted beam becomes partially p-polarized.

Dichroic polarizers absorb a specific polarization of light, transmitting the rest; modern nanoparticle polarizers are dichroic polarizers.

Birefringent polarizers rely on the dependence of the refractive index on the polarization of light. Different polarizations will refract at different angles and this can be used to select certain polarizations of light.

Unpolarized light can be considered a rapidly varying random combination of p- and s-polarized light. An ideal linear polarizer will only transmit one of the two linear polarizations, reducing the initial unpolarized intensity I_0 by half,

(1)$$ I = \frac{I_0}{2} $$

For linearly polarized light with intensity I_0, the intensity transmitted through an ideal polarizer, I, can be described by Malus’ law,

(2)$$ I = I_0 \cos ^2{\theta} $$

Where θ is the angle between the incident linear polarization and the polarization axis. We see that for parallel axes, 100% transmission is achieved, while for 90° axes, also known as crossed polarizers, there is 0% transmission. In real world applications the transmission never reaches exactly 0%, therefore, polarizers are characterized by an extinction ratio, which can be used to determine the actual transmission through two crossed polarizers.

Waveplates

While polarizers select certain polarizations of light, discarding the other polarizations, ideal waveplates modify existing polarizations without attenuating, deviating, or displacing the beam. They do this by retarding (or delaying) one component of polarization with respect to its orthogonal component. To help you determine which waveplate is best for your application, read Understanding Waveplates. Correctly chosen waveplates can convert any polarization state into a new polarization state, and are most often used to rotate linear polarization, to convert linearly polarized light to circularly polarized light or vice versa.

Applications

Implementing polarization control can be useful in a variety of imaging applications. Polarizers are placed over a light source, lens, or both, to eliminate glare from light scattering, increase contrast, and eliminate hot spots from reflective objects. This either brings out more intense color or contrast or helps to better identify surface defects or other otherwise hidden structures.

Reducing Reflective Hot Spots & Glare

In *Figure 5*, a linear polarizer was placed in front of the lens in a machine vision system to remove obfuscating glare such that an electronic chip could be clearly seen. The left image (without polarizer) shows randomly polarized light scattering off of the many glass surfaces between the object and the camera sensor. Much of the chip is obscured by Fresnel reflection of the unpolarized light. The image on the right (with polarizer) shows the chip without glare obscuring any of the object details, allowing the chip to be viewed, analyzed, and measured without obstruction.

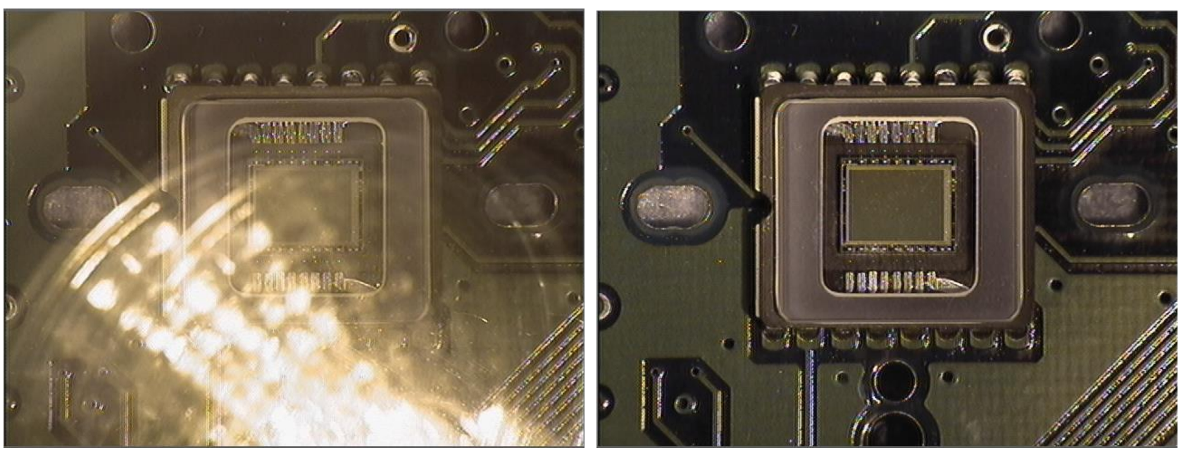


Figure 5: A polarizer is placed in front of the lens of a machine vision camera, reducing the stray light coming from a reflective surface between the lens and electronic chip.

The same phenomenon can be seen in the *Figure 6*. In the left image (without polarizer), unpolarized light from the sun is interacting with the windows of the Edmund Optics building and most of this light is reflecting off the windows. In the right image, a polarizing filter has been applied such that the reflected light, rich in one polarization type, is being blocked from the camera sensor and the photographer, using the other polarization type, can see into the building more easily.

Intensity modulation

In optical communications, intensity modulation (IM) is a form of modulation in which the optical power output of a source is varied in accordance with some characteristic of the modulating signal. The envelope of the modulated optical signal is an analog of the modulating signal in the sense that the instantaneous power of the envelope is an analog of the characteristic of interest in the modulating signal.

Recovery of the modulating signal is usually by direct detection, not heterodyning. However, optical heterodyne detection is possible and has been actively studied since 1979. Bell Laboratories had a working, but impractical, system in 1969.[1] Heterodyne and homodyne systems are of interest because they are expected to produce an increase in sensitivity of up to 20 dB[2] allowing longer hops between islands for instance. Such systems also have the important advantage of very narrow channel spacing in optical frequency-division multiplexing (OFDM) systems.[3] OFDM is a step beyond wavelength-division multiplexing (WDM). Normal WDM using direct detection does not achieve anything like the close channel spacing of radio frequency FDM.[4]

Intensity modulation is one of the simplest to measure because it only requires a photodetector to measure the light intensity. The intensity of the light wave traveling through an optical fiber can be modified by microbending of the optical fiber, by a change in coupling of the fiber with the surrounding medium, or the fracture of the optical fiber. A photodetector is used to measure the intensity of the light transmitted through the fiber or reflected back to the input. One drawback of these simple sensors is that they cannot be multiplexed into sensor networks.

Characterization of optical devices

Characterization of Intensity Modulation Response

Intensity modulation response of an optical transmitter can be measured either in frequency domain or in time domain. Usually, it is relative easy for a frequency-domain measurement to cover a wide continuous range of modulation frequencies and provide detailed frequency responses of the transmitter. Time-domain measurement, on the other hand, measures the waveform distortion that includes all the nonlinear effects that cannot be obtained by small-signal measurements in frequency domain. In this subsection, we discuss techniques of frequency-domain and time-domain characterizations separately.

3.2.1.1 Frequency-Domain Characterization

Frequency response is a measure of how fast an optical transmitter can be modulated. Typically, the modulation efficiency of a semiconductor laser or an external modulator is a function of modulation frequency Ω. Frequency-domain characterization is a popular way to find the features of device response such as cutoff frequency, uniformity of inband response, and resonance frequencies. Many time-domain waveform features can be predicted by frequency-domain characterizations. A straightforward way to characterize the frequency-domain response of an optical transmitter is to use an RF network analyzer and a calibrated wideband optical receiver as shown in Figure 3.2.2.

In this measurement, the transmitters have to be properly DC biased so that they operate in the desired operating condition. An RF network analyzer is used and is set to the mode of measuring S_{21} parameter. In this mode, port 1 of the network analyzer provides a frequency swept RF signal, which is fed into the transmitter under test. The transmitter converts this frequency swept RF modulation into the optical domain, and the optical receiver then converts this optical modulation back to the RF domain and sent for detection into port 2 of the network analyzer. To characterize the modulation property of the transmitter, the bandwidth of both the network analyzer and the optical receiver should be wide enough and the receiver should be calibrated in advance so that the transfer function of the receiver can be excluded from the measurement.

Figure 3.2.3 shows an example of the measured amplitude modulation response of a DFB laser under direct modulation of its injection current [10]. With the increase of the average output optical power of the laser, the modulation bandwidth increase and the relaxation oscillation peak become strongly damped. This is due to the fact that at high optical power level, the carrier lifetime is short due to strong stimulated recombination.

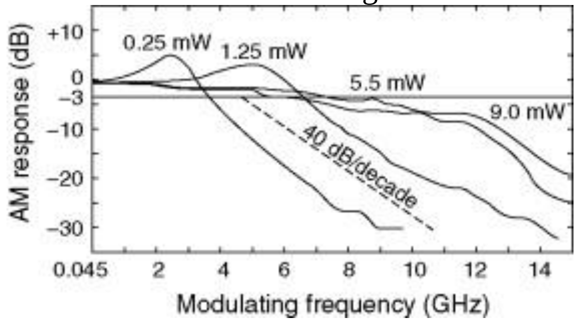


Figure 3.2.3. Example of a direct modulation response of a DFB laser diode at different optical power levels [10].

Used with permission.

The advantage of frequency domain measurement is its simplicity and high sensitivity due to the use of an RF network analyzer. Because the frequency of the interrogating RF signal continuously sweeps across the bandwidth of interest, detailed frequency domain characteristics of the optical transmitter can be obtained through a single sweep. However, in the network analyzer, the receiver in port 2 only selects the very frequency component sent out from port 1. High-order frequency harmonics generated by the nonlinear transfer characteristics of the electro-optic circuits cannot be measured. In general, as a disadvantage, the frequency domain measurement only provides small-signal linear response, while incapable of characterizing nonlinear effects involved in the electro-optic circuits.

To find nonlinear characteristics of an optical transmitter, the measurement of the strengths of high-order harmonics is necessary especially in analog system applications. This measurement can be performed using an RF signal generator (usually known as a *frequency synthesizer*) and an RF spectrum analyzer, as shown in Figure 3.2.4. To measure the nonlinear response, the transmitter is modulated with a sinusoid signal at frequency Ω generated by the synthesizer. Then if the transmitter response is nonlinear, several discrete frequency components will be measured on the RF spectrum analyzer. In addition to the fundamental frequency at Ω, RF energy will exist at the second order, the third order, and higher orders of harmonic frequencies at 2Ω and 3Ω and so on. The k^{th} order harmonic distortion parameter is defined as

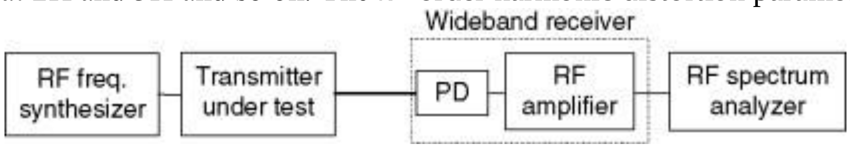


Figure 3.2.4. Frequency domain characterization of an optical transmitter use an RF spectrum analyzer.

$$HD_k = \frac{P(\Omega_k)}{P(\Omega_1)} \quad (3.2.2)$$

where $\Omega_k = k\Omega$, with $k = 2, 3, 4 \ldots$, $P(\Omega_k)$ is the RF power at the k^{th} order harmonic frequency, and $P(\Omega_1)$ is the power at the fundamental frequency, as shown in Figure 3.2.5(a). From this measurement, the *total harmonic distortion* (THD) can be calculated as

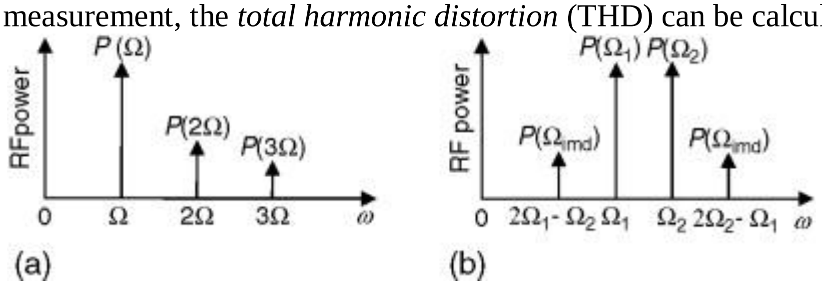


Figure 3.2.5. Illustration of (a) the measurements of second and third orders of harmonic distortions and (b) intermodulation distortion on an RF spectrum analyzer.

$$THD = \sum_{k=2}^{\infty} \frac{P(\Omega_k)}{P(\Omega_1)} \quad (3.2.3)$$

In general, harmonic distortions in directly modulated laser diodes are functions of both modulation frequency and the modulation index *m*. A larger modulation index implies a wider swing of signal magnitude and therefore often results in higher harmonic distortions, as indicated in Figure 3.2.6(a).

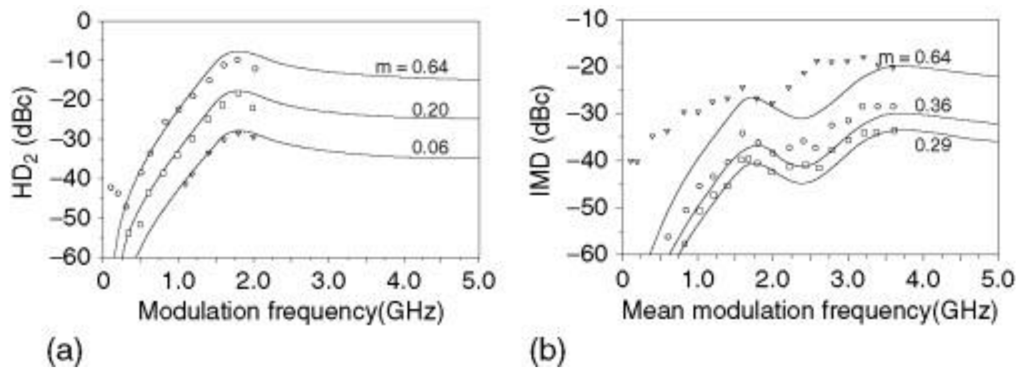


Figure 3.2.6. Examples of (a) measured second-order distortion and (b) intermodulation distortion of a laser diode under direct modulation [11]. Used with permission.

Another type of distortion caused by transmitter nonlinear response is referred to as *intermodulation distortion* (IMD). IMD is created due to the nonlinear mixing between two or more discrete frequency components of the RF signal in the transmitter. In this nonlinear mixing process, new frequency components are created. If there are originally three frequency components at Ω_i, Ω_j, and Ω_k, new frequency components will be created at $\Omega_{ijk} = \Omega_i \pm \Omega_j \pm \Omega_k$, where *i, j,* and *k* are integers. In a simple case, if $i = j$ or $j = k$, only two original frequency components are involved, which is similar to the case of degenerated four-wave mixing in a nonlinear fiber system as discussed in Chapter 1.

For example, two original frequency components at Ω_1 and Ω_2 will generate two new frequency components at $2\Omega_1–\Omega_2$ and $2\Omega_2–\Omega_1$, as shown in Figure 3.2.5(b). These two new frequency components are created by two closely spaced original frequency components which have the highest power compared to others; these are usually the most damaging terms to the optical system performance. The IMD parameter is defined as

$$(3.2.4)\ IMD(\Omega_{imd}) = \frac{P(\Omega_{imd})}{P(\Omega_i)}$$

where Ω_{imd} is the frequency of the new components and $P(\Omega_{imd})$ is the power at this frequency, as shown in Figure 3.2.5(b). Figure 3.2.6(b) shows an example of the measured $IMD(\Omega_{imd})$ versus the average modulating frequency $(\Omega_1 + \Omega_2)/2$ [11]. Again, higher modulation index usually results in higher IMD.

In lightwave CATV systems, a large number of subcarrier channels are modulated onto the same transmitter, and even a low level of intermodulation distortion may generate a significant amount of interchannel crosstalk. For CATV applications, both THD and IMD should generally be lower than –55 dBc.

3.2.1.2 Time-Domain Characterization

In binary modulated digital optical systems, waveform distortions represented by eye-closure penalty may be introduced by limited frequency bandwidth as well as various nonlinear effects in the transmitter. Time-domain measurement directly characterizes waveform distortion, which is most relevant to digital optical systems. In addition, frequency-domain response of the transmitter can be indirectly evaluated from the pulse response measurement performed in time domain.

As shown in Figure 3.2.7, time-domain characterization of an optical transmitter requires a waveform generator, a wideband optical receiver, and a high-speed oscilloscope. A unique advantage of time-domain measurement is the ability to characterize the transient effect during the switch of signal level from low to high, and vice versa. In general, the transient effect not only depends on the frequency bandwidth of the transmitter; it also depends on specific patterns of the input signal waveform. Therefore, pseudorandom waveforms are generally used; they contain a variety of combinations of data patterns. We discussed time-domain waveform characterization in Section 2.8, where both electrical domain sampling and optical domain sampling were presented