MODULE 1: LASER AND OPTICAL FIBERS

Syllabus content (As per VTU)

Chapter 1: LASER

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- Interaction of radiation with matter(Induced Absorption, Spontaneous Emission, Stimulated Emission)
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- LASER Action and the Conditions for LASER action (Population Inversion and Pumping, meta-stable state)
- Requisites of a LASER system(Energy Source or Pumping Mechanism, Active medium and Resonant cavity (or) LASER cavity)
- Semiconductor LASER or Diode LASER (Principle, construction and working)
- Applications of LASER (LASER Barcode Reader, LASER Printer, LASER Cooling)
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Chapter 2: OPTICAL FIBERS

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LASER

Introduction: Laser is a highly monochromatic and coherent light. LASER is an acronym for Light Amplification by Stimulated Emission of Radiation. The first LASER was built by Theodore H Maiman in the year 1960. Laser finds various applications starting from industries to communication.

Characteristics of a LASER beam: The LASER beam has the following characteristics.

1. LASER beam is highly monochromatic:
2. LASER beam is highly coherent.
3. LASER beam is highly directional.
4. LASER is a high intensity beam of light.

Interaction of radiation with matter:

The interaction between radiation and matter occurs through the following three processes.

1. Induced absorption
2. Spontaneous emission
3. Stimulated emission

Let us consider, any two energy levels of an atom, say E1 and E2 (E2>E1). When light of certain frequency v is incident on it, there are three processes takes place.

1. Induced Absorption:

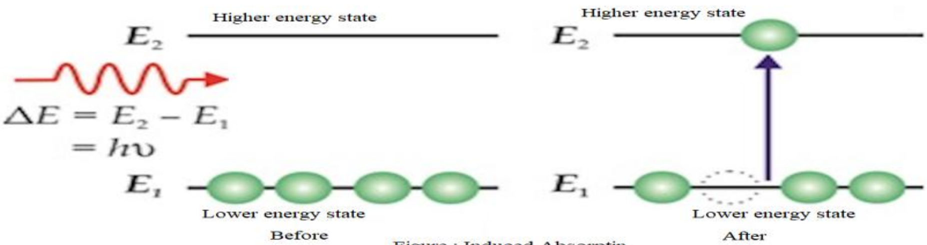


Figure : Induced Absorptin

When a photon of energy is incident on the atom and this photon can be absorbed. This process is induced by the photon and hence it is called Induced Absorption.

Consider an atom in a lower energy states E_1, it will excite to higher energy states E_2 by absorbing the incident photon of energy $E = h\nu = E2 - E1$.

Here, h is the Planck's constant and ν is the frequency of photon.

The process can be expressed as $A + h\nu = A^*$

Where A^* is the atom in the energy state E_2 and A is the atom in the lower energy state E_1.

2. Spontaneous Emission:

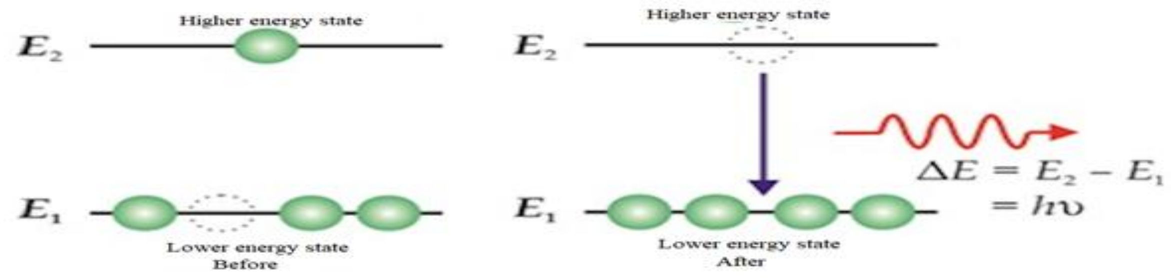


Figure: Spontaneous emission

An atom in the excited state emits photon when atom transit from higher energy level to lower energy level without aid of external energy. This is known as spontaneous emission. The emitted photons are not coherent as they are not directional. The lifetime of atom in the excited state is few nanoseconds.

The process can be expressed as, $A^{*}=A+ h\nu$

After spending time interval of few nanoseconds, atom goes to ground level by emitting energy ($E = h\nu = E2 - E1$) in the form of photons as shown in figure above.

3. Stimulated Emission:

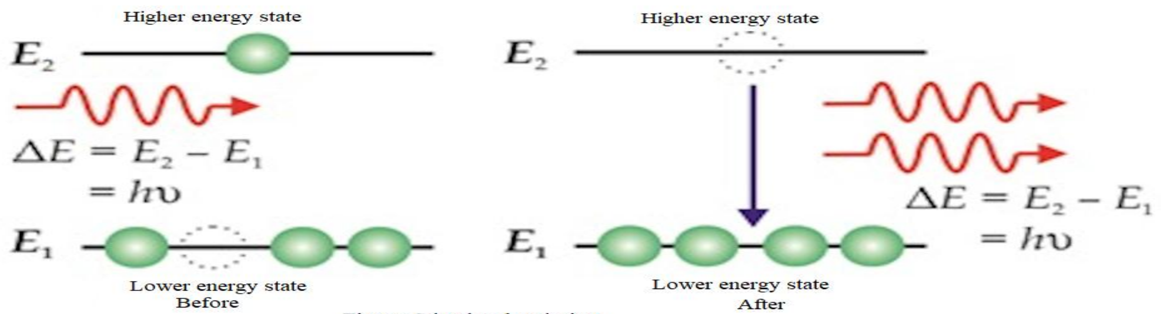


Figure: Stimulated emission

If an atom in the excited state, then the incident photon may stimulate this atom to transit to lower energy level with the emission of identical photons. This is known as stimulated emission. The emitted photons are coherent as they travel in the same direction. The lifetime of atom in this case is few milliseconds.

The process can be expressed as $A^{*}+ h\nu =A+ h\nu$

When a photon of energy $h\nu = E2 - E1$ interacts with an atom in the higher energy state , stimulated emission takes place with the emission of two photons of same energy as shown in figure above.

Einstein's A and B co-efficients and expression for energy density:

Consider two energy states of an atom say E_1 and E_2 (E2>E2). E1 be the lower energy state and E2 be the higher energy state.

Let $N1$ be the number of atoms in the state E1 and $N2$ number of atoms in the state E2.

When light of frequency ν and its energy density of the radiation $E\nu$ is incident on it, there will be three possibilities.

i) **Induced absorption**: Atoms in the energy state E1 can absorb incident photon and excited to E2 state. The probability this process occurs per second is directly proportional to number of atoms N1 in E1 state and energy density $E\nu$.

Rate of induced absorption α $N_1 E_\nu$

Rate of induced absorption = $B_{12} N_1 \, E_\nu$ --------------1

Here $B12$ is proportionality constant called Einstein's coefficient of Induced absorption

ii) **Spontaneous emission:** Atoms in the energy state E2 state have probability of emitting photon spontaneously. The rate of spontaneous emission depends only on the number of atoms N2 in the higher energy state E2.

Rate of spontaneous emission α N_2

Rate of spontaneous emission = $A_{21} N_2$ ------------------2

Here $A21$ is the proportionality constant called Einstein's co-efficient of spontaneous emission.

iii) **Stimulated emission**: The incident photon stimulates the atoms in the energy state E2 state to make transition to E1 level.

Rate of stimulated emission depends upon, Number of atoms $N2$ in the higher energy state and energy density ($E\nu$).

Rate of stimulated emission α $N_2 E_\nu$ ▶

Rate of stimulated emission = $B_{21} N_2 E_\nu$ -------------------3

Here the proportionality constant called $B21$ is Einstein's coefficient of stimulated emission.

Under thermal equilibrium condition, total energy of the system is unchanged, therefore,

Rate of induced absorption = Rate of spontaneous emission+ Rate of stimulated emission

$$B_{12} N_1 E_\nu = A_{21} N_2 + B_{21} N_2 E_\nu$$

$$B_{12} N_1 E_\nu - B_{21} N_2 E_\nu = A_{21} N_2$$

$$E_\nu = \frac{A_{21} \, N_2}{(B_{12} \, N_1 - B_{21} \, N_2)}$$

$$E_\nu = \frac{A_{21}\,N_2}{N_2\left(B_{12}\frac{N_1}{N_2} - B_{21}\right)}$$

$$E_\nu = \frac{A_{21}}{B_{21}}\left[\frac{1}{\frac{B_{12}}{B_{21}}\left(\frac{N_1}{N_2}\right) - 1}\right] \text{--------------------------4}$$

From Boltzmann factor, the ratio of number of atoms between the energy states is

$$\frac{N_1}{N_2} = e^{\left(\frac{h\nu}{kT}\right)}$$

Here h is the Planck's constant, $\boldsymbol{\nu}$ the frequency of the photon, k is the Boltzmann constant and T is the absolute temperature. Substituting for $\frac{N_1}{N_2}$ in equation (4)

$$E_\nu = \frac{A_{21}}{B_{21}}\frac{1}{\left(\frac{B_{12}}{B_{21}}\ e^{\left(\frac{h\nu}{kT}\right)}\ -1\right)} \text{ --------------------------5}$$

According to Planck's radiation law, the equation for energy density in the frequency domain is given by

$$E_\nu = \frac{8\pi h\nu^3}{c^3}\frac{1}{\left(e^{\left(\frac{h\nu}{kT}\right)} - 1\right)} - - - - - - - - 6$$

on comparing equations 5 and 6 we can get

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} \quad - - - -7$$

and $\frac{B_{12}}{B_{21}} = 1$, $B_{12} = B_{21}$ $- - - 8)$

ie $B_{12} = B_{21}$This means that Probability of Induced absorption is equal to Probability of Stimulated emission. Hence $A21$ & $B21$ can be replaced by A & B.

$$\frac{A}{B} = \frac{8\pi h\nu^3}{c^3}$$

Thus equation (5) can be written as

$$E_\nu = \left(\frac{\boldsymbol{A}}{\boldsymbol{B}}\right)\left[\frac{\mathbf{1}}{\left(e^{\left(\frac{h\nu}{kT}\right)} - \mathbf{1}\right)}\right]$$

This is the expression for energy density in terms of Einstein's co-efficient A and B.

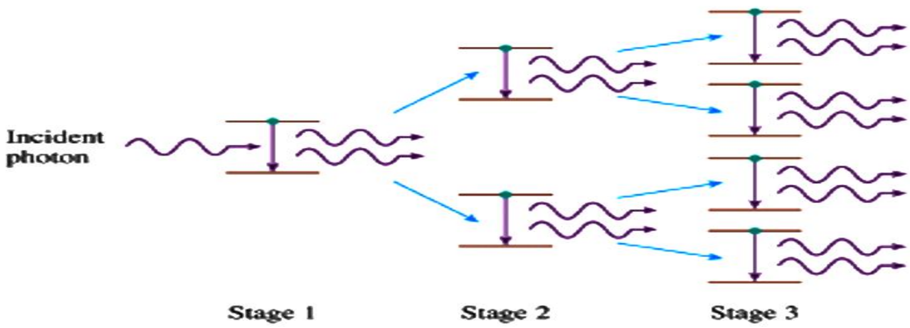
Conclusions:

i) From equation (8), ie $B_{12} = B_{21}$. This means that Probability of Induced absorption is equal to Probability of Stimulated emission. So that amplification is not possible with only two states. This suggests that the necessity of 3rd level for laser.

ii) From equation (7), $A_{21} \propto \nu^3$ means that the probability of spontaneous emission rate is more rather than stimulated emission.

LASER Action and the Conditions for LASER action:

i) LASER Action: Consider a LASER system. Let an atom in the excited state is stimulated by a photon of right energy so that atom makes stimulated emission. Two coherent photons are obtained. These two coherent photons stimulate two atoms in the exited state to make emission of four coherent photons and so on. This process continues to increases the emission of number of coherent photons. These coherent photons constitute an intense beam of LASER and this phenomenon is called lasing action.



ii) Conditions for LASER action :

For lasing action, number of stimulated emission must be more when compared to induced absorption and spontaneous emission. This is possible only if population inversion condition is satisfied.

a) Population Inversion:

Population inversion is the condition in which the number of atoms in the higher energy state is more than the number of atoms in the lower energy state (N2>N1). Let N1 is the number of atoms in the energy state E1 and N2 is the number of atoms in the state E2

From Boltzmann factor,

$$\frac{N_2}{N_1} = e^{-\left(\frac{h\nu}{kT}\right)}$$

$$\frac{N_2}{N_1} = e^{-\left(\frac{hc}{\lambda kT}\right)}$$

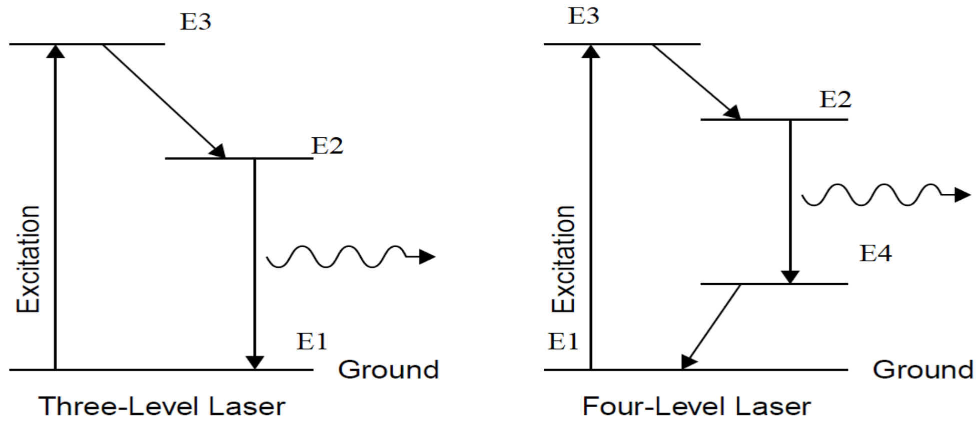
Where k is called Boltzmann constant=$1.38X10^{-23}$ JK^{-1} and T is the temperature in K.

Pumping: Pumping is a process of supplying energy in order to achieve population inversion. Pumping processes such as Electric discharge, optical pumping, chemical pumping etc.

Metastable state: In addition, to have more stimulated emissions, excited state of relatively longer life time of about few milliseconds (10^{-3} to 10^{-2} s) is needed to achieve population inversion. Such excited states are named as **metastable state**. Hence, population inversion could be achieved with the help of 3 energy states or 4 energy states with one of them is a meta-stable state as shown in the figure below.

In 3 energy levels, the population inversion is achieved between metastable state and ground state, energy state $E2$ is a meta-stable state.

In 4 energy levels, the population inversion is achieved between the metastable state E2 and intermediate state E4. The state $E2$ is a meta-stable state.



Requisites of a LASER system:

The three requisites for a Lasing action:

1. Excitation source for pumping action.
2. Active medium.
3. LASER cavity

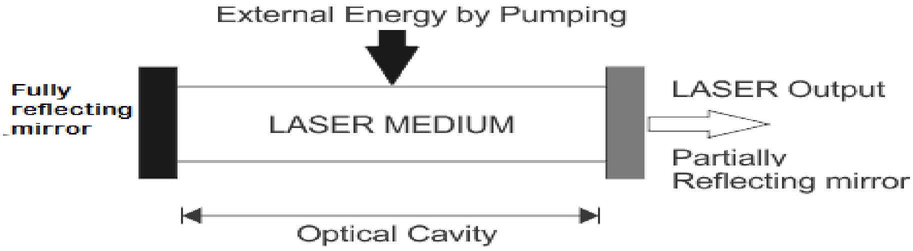
1. **Excitation source for pumping action:**

The excitation source supplies the energy in order to achieve the population inversion. This is achieved by supplying suitable energy using an energy source. If optical energy is used then the pumping action is called optical pumping and if electrical energy is used then the pumping is called electrical pumping.

2. **Active medium**

A medium which supports population inversion for lasing action is known as active medium. Medium can be gaseous, liquid, or solid. These could include atoms, molecules. Ex: GaAs in semiconductor laser.

3. **Resonant cavity (or) LASER cavity:**



Laser cavity is main part of the device which accounts for directionality and amplification of the beam.

The LASER Cavity consists of an active medium bound between two highly parallel mirrors. So that photons bounce back and forth between the mirrors lead to amplifications. It is also called resonant cavity because of the output will be maximum when the distance L between the mirrors is equal to an integral multiple of $\lambda/2$ .i.e $L = m\frac{\lambda}{2}$

Here λ is the wavelength of incident radiation and 'm' is an integer.

Semiconductor LASER or Diode LASER:

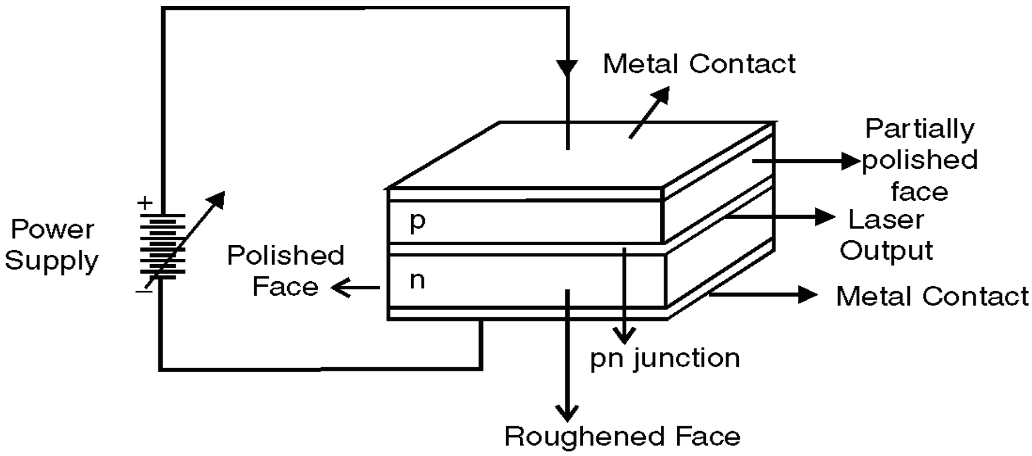
Semiconductor diode LASER is an LED with heavily doped P and N sections. First semiconductor LASER was fabricated in 1962 using $GaAs$. It is a low cost and high efficiency LASER.

i) Principle:

Semiconductor diode laser emits highly coherent laser beam when a p-n junction of the diode is forward biased. A photon is emitted by spontaneously during recombination process induce more number of stimulated emission which produces laser.

ii) **Construction:**

Figure shows the basic construction of $GaAs$ semiconductor laser. GaAs is a highly doped p-n junction. Active medium is a p-n junction made from the single crystal of GaAs. This crystal is cut in the form of a thin layer of about 0.5mm. The two faces are perpendicular to p-n junction are polished and silvered. They act as optical resonator and laser beam finally comes out from partially silvered face as shown in the figure. The other two faces parallel to p-n junction are fused with metal contacts across which forward voltage is applied using power supply.



Working:

Figure shows the energy level diagram of semiconductor laser. The energy band consists of valence band Ev and conduction band Ec separated by energy gap, where conduction band contains electrons and valence band contains holes. For semiconductor laser, heavily doped p-type and n-types are fused to form p-n junction. The Fermi level is pushed into VB (p-type) and CB (n-type) to attain equilibrium as shown in fihure.

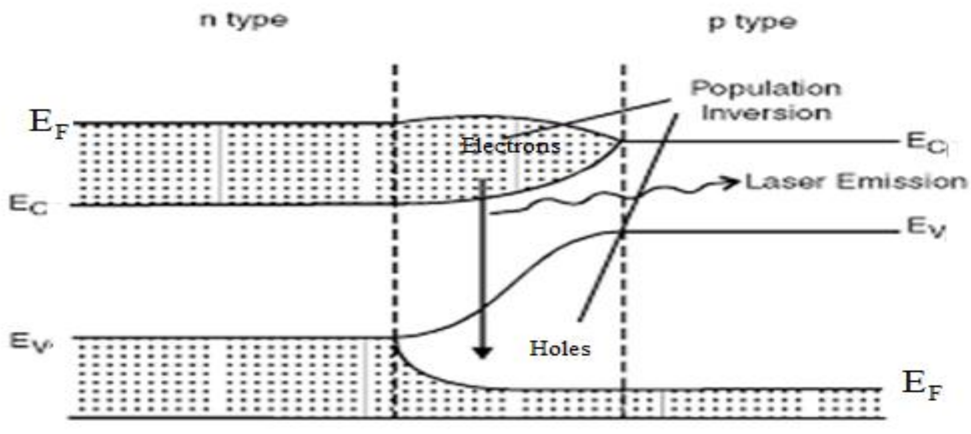


Figure: Energy level diagram

When forward voltage is applied across the junction, electrons from n-type enter into p-region where they recombine with holes causing spontaneous emission. This could be considered as the transition of electron from conduction band to valance band. The concentration of electron and hole is relatively less.

Now if the forward current is sufficiently high, more number of electrons is injected into the p-region and carrier concentration in the active region increases to high value. Hence population inversion can be achieved. The photons emitted initially due to spontaneous emissions which in induce further stimulated emissions. The LASER cavity helps in the amplification of light and finally LASER beam is comes out from partially silvered face.

The wavelength of the LASER emitted can be calculated by using the relation,

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

Where E_g is the energy band gap of semiconductor.

For GaAs semiconductor, the energy gap is E_g =1.4eV

$$\lambda = \frac{6.626X10^{-34}X3X10^{8}}{1.4X1.609X10^{-19}}$$

$$\lambda = 8824\text{Å}$$

iii) Advantages

1. It has excellent efficiency
2. The output can be modulated
3. It produces both continuous wave output and pulsed output.
4. It is highly economical

v) Applications

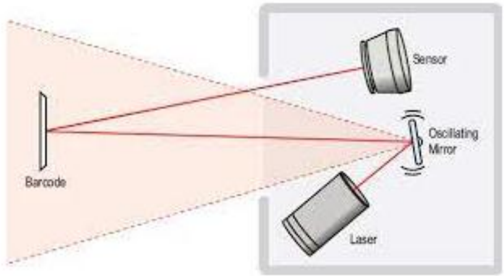
1. It is used in optical fiber communication.
2. It is used in commercial CD recording and reading.
3. It is used in Barcode Reader, Laser printing and Laser Cooling.

Applications of LASER

LASER has wide range of applications pertaining to all disciplines of engineering.

1. LASER Barcode Reader:

A barcode is a printed series of parallel bars or lines of varying width that is used for entering data into a computer system. A barcode scanner/reader is a device with lights, lenses, and a sensor that decodes and captures the information contained in barcodes. Laser scanners use a laser beam as a light source and typically employ oscillating mirrors or rotating prisms to scan the laser beam back and forth across the barcode. A photodiode then measures the reflected light from the barcode. An analog signal is created from the photodiode, and is then converted into a digital signal.

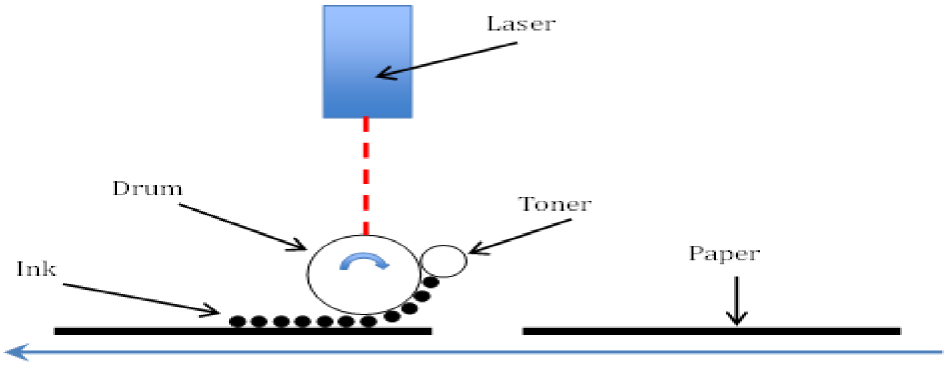


Barcode scanner

barcode

2. LASER Printer

Laser printers ware invented at XEROX in 1969 by by researcher Gary Starkweather. Laser Printers are digital printing devices that are used to create high quality text and graphics on plain printer. A Diode Laser is used in the process of printing in LASER Printer.



Working Principle

1. A laser beam projects an image of the page to be printed onto an electrically charged rotating Photo sensitive drum coated with selenium.

2. Photo conductivity allows charge to leak away from the areas which are exposed to light and the area gets positively charged.

3. Toner particles are then electrostatically picked up by the drum's charged areas, which have been exposed to light.

4. The drum then prints the image onto paper by direct contact and heat, which fuses the ink to the paper.

Advantages

1. Laser printers are generally quiet and fast.
2. Laser printers can produce high quality output on ordinary papers.
3. The cost per page of toner cartridges is lower than other printers.

Disadvantages

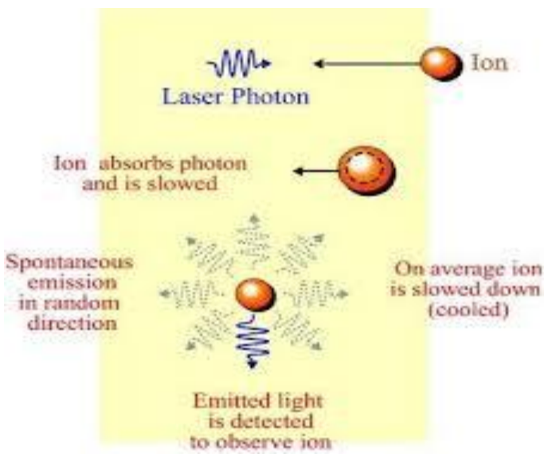
1. The initial cost of laser printers can be high.
2. Laser printers are more expensive than dot-matrix printers and ink-jet printers.

3. LASER Cooling

Principle of LASER Cooling is the use of dissipative light forces for reducing the random motion and thus the temperature of small particles, typically atoms or ions. Depending on the mechanism used, the temperature achieved can be in the millikelvin, microkelvin, or even nanokelvin regime.

If the atom absorbs a photon from the laser beam it will be slowdown by the fact that the photon has momentum. It would take a large number of such absorptions to cool the atoms to near 0K.

The methods of laser cooling; Doppler Cooling, Anti-Stokes cooling, Sisyphus cooling, electromagnetically induced transparency (EIT) cooling..



Numerical Problems:

1. Calculate the number of photons emitted per pulse of duration 1microsecondgiven the power of laser 3mW and the wavelength of laser 632.8nm.
2. Find the population inversion of two energy levels in a medium in thermal equilibrium, if the wavelength of light emitted at 330K is 632.8nm.
3. A pulse from laser with 1mW lasts for 20nS. If the number of photons emitted per pulse is $3.491X10^{7}$. Calculate the wavelength of the laser.
4. Calculate the wavelength of laser emitted from an extrinsic semiconductor laser if the band gap is 0.02eV. To which region of EM spectrum does it belong?
5. A laser operating at 632.8nm emits 3.182×10^{16} photons per second. Calculate the output power of the laser if the input power is 100 watt. Also find the percentage power converted into coherent light energy.
6. Find the ratio of population of two energy levels in a LASER if the transition between them produces light of wavelength 6493 Å, assuming the ambient temperature at 27°C.
7. Find the ratio of population of two energy levels in a medium at thermal equilibrium, if the wavelength of light emitted at 291 K is 6928 Å.
8. The ratio of population of two energy levels out of which one corresponds to metastable state is 1.059×10^{-30}. Find the wavelength of light emitted at 330 K.
9. Find the ratio of population of two energy levels in a medium at thermal equilibrium, if the wavelength of light emitted at 300 K is $10\mu m$. Also find the effective temperature when energy levels are equally populated.
10. The average power output of a LASER beam of wavelength 6500 Å is 10 mW. Find the number of photons emitted per second by the LASER source.
11. The average power of a LASER beam of wavelength 6328 Å is 5mW. Find the number of photons emitted per second by the LASER source.
12. A pulsed LASER has an average power output 1.5mW per pulse and pulse duration is 20 ns. The number of photons emitted per pulse is estimated to be 1.047×10^{8} . Find the wavelength of the emitted LASER.
13. A pulsed LASER with power 1 mW lasts for 10ns. If the number of photons emitted per pulse is 5×10^{7} . Calculate the wavelength of LASER.

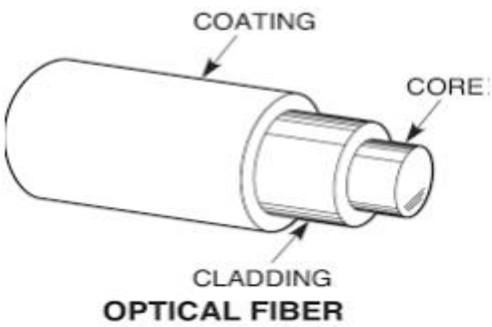
OPTICAL FIBER

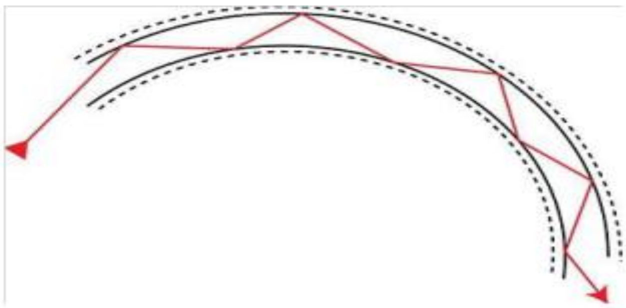
Introduction:

Optical fibers are used to transmit light signal between the two ends of the fiber and find wide usage in fiber-optic communications, where they permit transmission over longer distances and at higher bandwidths (data rates) than electrical cables.

Optical fibers are the wires and strands made of transparent dielectrics such as glass or plastic which guide light over longer distances using the phenomenon of Total Internal Reflection

Construction: The sectional view of a typical optical fiber is as shown in the figure. It has three regions named Core, Cladding and Sheath.



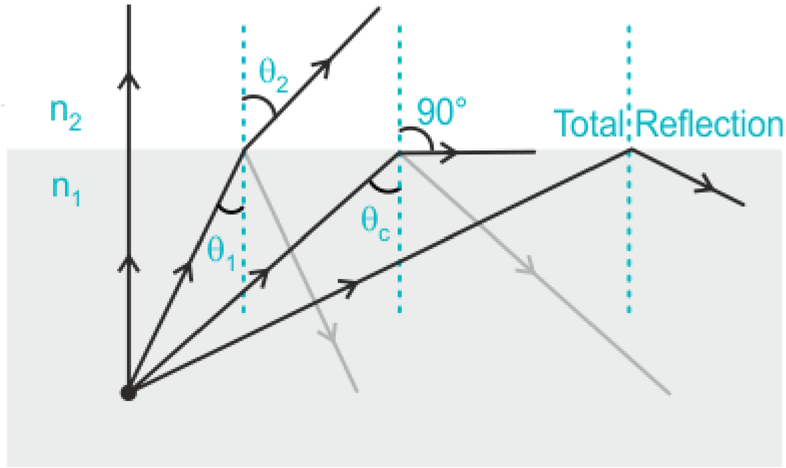


1. The innermost light guiding region is called Core.
2. The layer covering core and helps in total internal reflection of light is called Cladding or Clad.
3. The outermost protective layer is called Sheath (Coating). The sheath protects the fiber from mechanical stress and chemical reactions.

The optical fiber is designed to support total internal reflection and hence the RI of core $n1$ is made greater than the RI of cladding $n2$. A typical fiber will be of the order of few microns.

Total internal reflection

Consider a ray of light moving from a denser medium to rarer medium. As a result the incident ray of light bends away from the normal. Hence the angle of refraction is greater than the angle of incidence. As the angle of incidence increases the angle of refraction also increases. For a particular angle of incidence θc the refracted ray grazes the interface separating the two media. The corresponding angle of incidence θc is called Critical Angle. If the angle of incidence is greater than the critical angle then all the light is turned back into the same medium and is called Total Internal Reflection.



For a optical fiber, consider a ray of light propagate from medium of refractive index of denser medium of n1 to refractive index of rarer medium n2.

Let θ1 be the angle of incidence and θ2 be the angle of refraction,

Then From Snell's law

$$n_1 \sin \theta 1 = n_2 sin\theta 2$$

For total reflection, angle of incidence = critical angle θc and $\theta 2 = 90^0$

$$n_1 \sin \theta c = n_2 \sin 90^0$$

$$n_1 \sin \theta c = n_2 * 1$$

$$\sin \theta c = \frac{n_2}{n_1}$$

$$\boldsymbol{\theta c = sin^{-1}\left(\frac{n_2}{n_1}\right)}$$

Propagation of light: Angle of acceptance and Numerical aperture

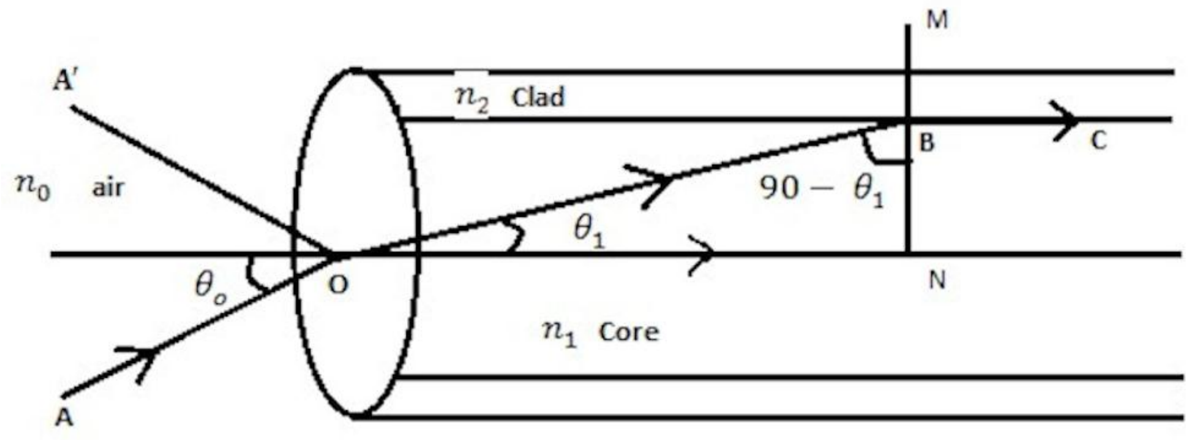
Acceptance angle (θ_0) is the maximum angle of incidence with which the ray is sent into the fiber core which allows the incident light to be guided by the core. It is also called as waveguide acceptance angle or acceptance cone half angle.

Numerical aperture (NA) of an optical fiber is a dimensionless number that characterizes the range of angles over which the fiber can accept light. Numerical aperture represents the light gathering capability of optical fiber and it is given by $NA = sin\theta_0$.

In order to understand the propagation of light through an optical fibre,

Consider an optical fiber with core made of refractive index $n1$ & cladding made of material refractive index $n2$. Let n_0 be the refractive index of the surrounding medium ($n_1 > n_2 > n_0$.).

Let a ray of light AO entering into core at an angle of incidence θ_0 w.r.t fiber axis. Then it is refracted along OB at an angle $\theta 1$ & meet core-cladding interface at critical angle of incidence (θc = 90 − $\theta 1$). Then the refracted ray grazes along BC.



On applying Snell's law at O,

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

$$\sin\theta_0 = \frac{n_1}{n_0} sin\theta_1 - - - - - 1)$$

On applying Snell's law at point B, we get

$$n_1 \sin(90 - \theta_1) = n_2 \sin 90^0$$

$$n_1 \cos\theta_1 = n_2$$

$$\cos\theta_1 = \frac{n_2}{n_1} - - - - - 2)$$

From trigonometric identity

$$sin^2\theta_1 + cos^2\theta_1 = 1$$

$$sin^2\theta_1 = 1 - cos^2\theta_1$$

$$\sin\theta_1 = \sqrt{1 - cos^2\theta_1}$$

using equation 2)

$$\sin\theta_1 = \sqrt{1 - \left(\frac{n_2}{n_1}\right)^2}$$

$$\sin\theta_1 = \sqrt{1 - \frac{{n_2}^2}{{n_1}^2}}$$

$$\sin\theta_1 = \sqrt{\frac{n_1^2 - n_2^2}{n_1^2}}$$

$$\sin\theta_1 = \frac{1}{n_1}\sqrt{n_1^2 - n_2^2} \quad ----3)$$

Substitute equation (3) in equation (1) we get

$$\sin\theta_0 = \frac{n_1}{n_0}\left[\frac{1}{n_1}\sqrt{n_1^2 - n_2^2}\right]$$

$$\sin\theta_0 = \frac{1}{n_0}\left[\sqrt{n_1^2 - n_2^2}\right]$$

Since numerical aperture (NA)= sin θ_0

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

If the fiber is in air $n0$ = 1 then,

$$NA = \boldsymbol{sin\theta_0} = \sqrt{n_1^2 - n_2^2}$$

Light is transmitted through the fiber only when the angle of incidence

$$\boldsymbol{\theta_i \leq \theta_0}$$

$$\sin\theta_i \leq \sin\theta_0$$

$$\sin\theta_i \leq \sqrt{n_1^2 - n_2^2}$$

$$\sin\theta_i \leq NA$$

This is the condition for propagation. Light will be transmitted through the optical fiber with multiple total internal reflections when the above condition is satisfied

Fractional index (Δ):

It is the ratio of difference in the refractive index of core and cladding to the refractive index of the core.

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

Relation between numerical aperture and refractive index:

$$numerical\ aperture = \sqrt{n_1^2 - n_2^2}$$

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

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

$$= \sqrt{2n_1\Delta * \frac{(n_1 + n_2)}{2}}$$

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

Modes of propagation:

The optical fiber supports any numbers of rays for propagation but it is found that it allows only a certain restricted number of rays for propagation. The maximum number of rays or paths supported by the fiber for the propagation of light is called Modes of propagation. Based on the modes of propagation fibers are classified into Single mode and Multi-mode fibers.

In a given optical fiber, the modes propagate along the axial path is called axial ray or zero order mode. The modes propagate at angles close to critical angle are called higher order modes. The modes propagate at angles greater than critical angle are called lower order modes.

The number of modes can be evaluated with help of V-number or normalized frequency, which is given by

$$V = \frac{\pi d}{\lambda}\sqrt{n_1^2 - n_2^2}$$

$$V = \frac{\pi d}{\lambda}(NA)$$

Here d=2r is the diameter of the core (r is the radius of the core) and λ being the wavelength of the light used.

$$\boldsymbol{number\ of\ modes = \frac{V^2}{2}}$$

RI Profile

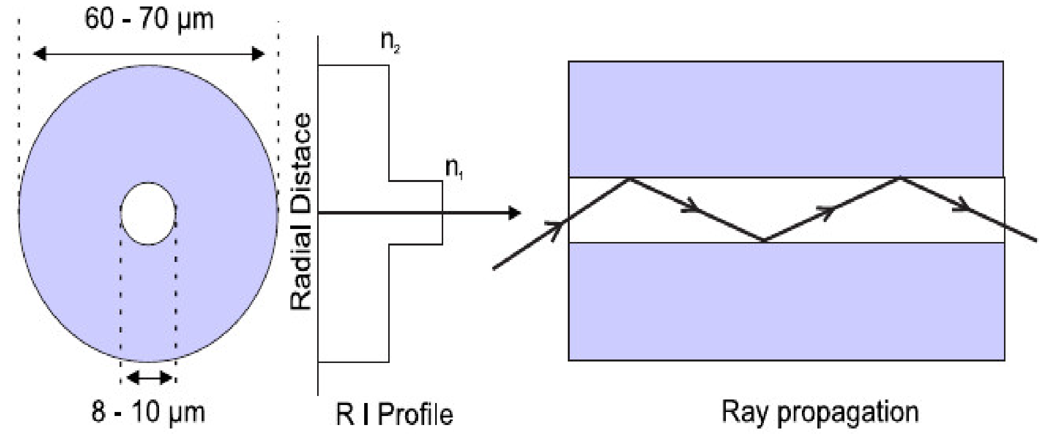
The RI profile is a plot of variation of RI of the fiber with respect to radial distance from the axis of an optical fiber. Based on the RI profile fibers are classified into Step index and Graded index fibers. In case of Step index fibers RI of the core is constant. In case of Graded index fibers the RI decreases radialy outwards.

TYPES OF OPTICAL FIBER: The optical fibers are classified under 3 categories,

1. Step index single mode fiber
2. Step index multi-mode fiber
3. Graded index multi-mode fiber

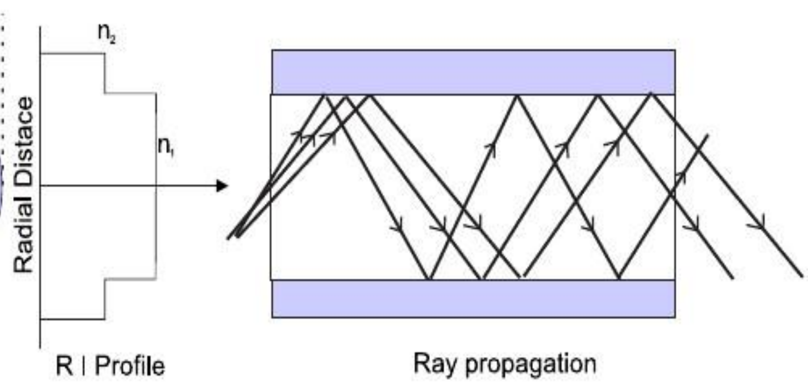
This classification is done depending on the refractive index profile, and the number of modes that the fiber can guide.

1. Step index single mode fiber:



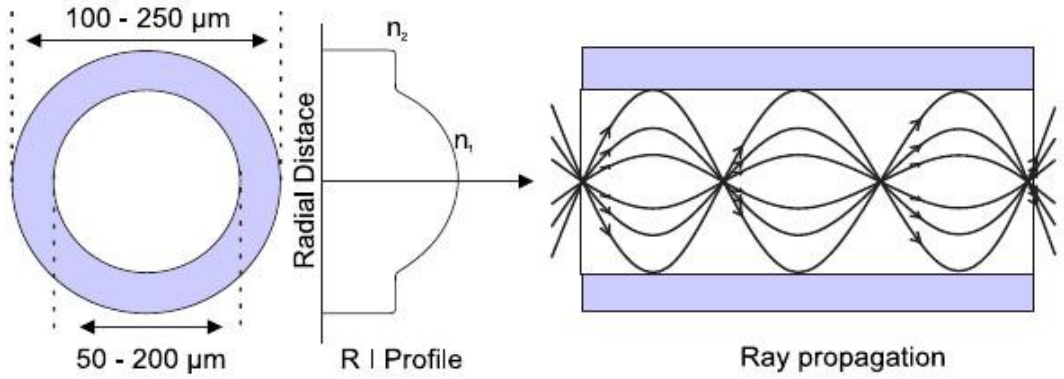
A single mode step index fiber consists of a very fine thin core of uniform RI surrounded by Cladding of RI lower than that of Core. Since there is abrupt change in the RI of Core and Cladding at the interface it is called step index fiber. Since the Core size is small the Numerical aperture is also small and hence support single mode. They accept light from LASER source. They are used in submarine cables.

2. Step index multi-mode fiber:



This is similar to single mode step index fiber with the exception that it has a larger core diameter. The core diameter is very large as compared to single mode optical fiber. The numerical aperture is large because of large core size and thus supports multi-modes. They accept light from both LASER as well as from LED. They are used in data links.

3. **Graded index multi-mode fiber:**



A multi-mode fiber has concentric layers of RI is called GRIN fiber. It means the R I of the Core varies with distance from the fiber axis. The RI is maximum at the center and decreases with radial distance towards to core-cladding interface. In GRIN fibers the acceptance angle and numerical aperture diminish with radial distance. They accept light from both LASER as well as from LED. They are used for medium distance communication for example telephone link between central offices.

ATTENUATION (Fiber loss)

Attenuation is the loss of power suffered by the optical signal as it propagates through the fiber. The optical energy (signal) passing through the optical fiber gets reduced progressively. This is due to attenuation. It is also called the fiber loss. The attenuation is measured in terms of attenuation co-efficient.

The attenuation co-efficient α is defined as the ratio of optical power output to the optical power input for a fiber of length L and for a given wavelength of propagating light. It is expressed in dB/km. Attenuation co-efficient is given by

$$\alpha = -\frac{10}{L} log\left(\frac{P_{out}}{P_{in}}\right) \ dB/km$$

Here L is the length of the cable in km, Pin is Power of optical signal at launching end (input power) & $Pout$ is Power of optical signal at receiving end (output power)

The attenuation in fibers gives is due to the following three losses

1. Absorption losses
2. Scattering loss (due to Rayleigh Scattering)
3. Geometric Effects (Radiation losses)

1. **Absorption loss**: In this type of loss, the loss of signal power occurs due to absorption of photons associated with the signal. Photons are absorbed either by impurities in the glass fiber or by pure glass material itself. Absorption loss is wavelength dependent. Thus absorption loss is classified in to two types namely Extrinsic absorption and Intrinsic absorption.

   In Extrinsic absorption, extrinsic loss in an optical fiber is due to the absorption of light by the impurities such as hydroxide ions and transition metal ions such as iron, chromium, cobalt and copper.

   In intrinsic absorption, intrinsic loss in fiber is due to the absorption of light by the material of the fiber glass itself. The intrinsic losses are insignificant.

2. **Scattering loss:** Light traveling through the core can get scattered by impurities or small regions with sudden change in refractive index. Rayleigh scattering varies as $\frac{1}{\lambda^4}$ and leads to significant power loss at smaller wavelengths. The scattering results in loss of photons. Rayleigh scattering is responsible for maximum losses in optical fibers.

3. **Geometric effects:** These may occur due to manufacturing defects like irregularities in fiber dimensions (microscopic and macroscopic) during drawing process or during coating, cabling or insulation processes. The microscopic bends are the bends with radii greater than fiber diameter. The microscopic bends couple light between the various guided modes of the fiber and some of them then leak through the fiber.

Attenuation or fiber loss is the sum of the above mechanisms, therefore, Lambert made statement that is " the rate of decrease of intensity of light with distance travelled is directly proportional to initial intensity of light"

$$\frac{dP}{dL} \propto P_{in}$$

$$\frac{dP}{dL} = -\alpha P_{in}$$

Where L is the length of the fiber in km, Pi initial intensity

$$\frac{dP}{P} = -\alpha dL$$

Integrating the above equation with limits @ L=0, to L and P_{in} to P_{out}

$$\int_{P_i}^{P_0} \frac{dP}{P} = -\alpha \int_0^L dL$$

$$\log P_o - log P_i = -\alpha L$$

$$\alpha = \frac{1}{L} log\left(\frac{P_{out}}{P_{in}}\right)$$

Intensity of the light signal can be measured in dB, 1bel=10dB

$$\alpha = -\frac{10}{L} log\left(\frac{P_{out}}{P_{in}}\right) \quad dB/km$$

Applications of Optical Fibers:

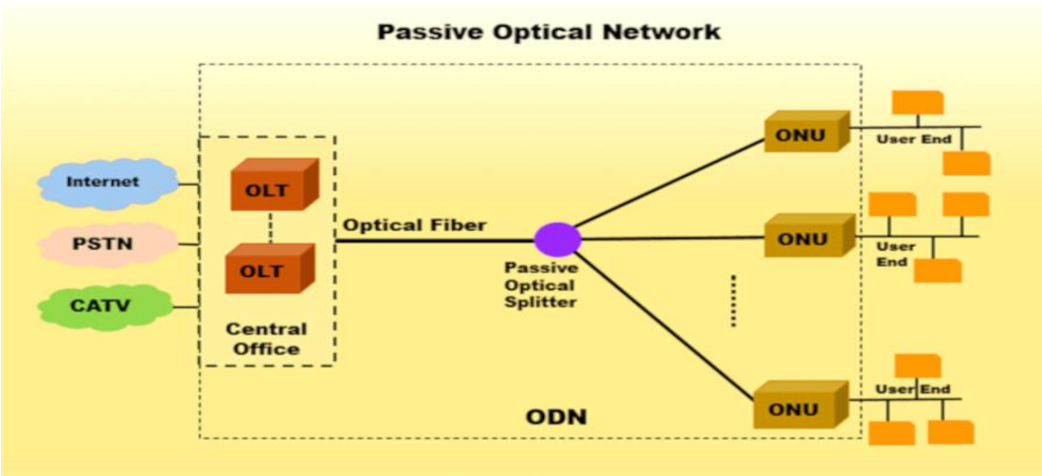
1. **Fiber Optic Networking:**

   Local Area Network: A Local Area Network (LAN) is a type of computer network that interconnects multiple computers and computer driven devices in a particular physical location. Traditionally copper coaxial cables are used for for LAN.

   Abbreviations

   1. PON - Passive Optical Network
   2. ONT - Optical Network Terminal
   3. ODN - Optical Distribution Network
   4. OLT - Optical Line Terminal
   5. ONU - Optical Network Unit

   Passive Optical LAN A passive optical network refers to a fiber-optic network utilizing a point-to-multipoint topology and optical splitters to deliver data from a single transmission point to multiple user endpoints. Passive here refers to the unpowered condition of the fiber and splitting/combining components. Passive optical LANs are built entirely using Optical fiber cables. The passive optical LAN works on the concept of optical network terminals (ONT) and passive optical splitters. Network switches act as passive splitters and the commercial media converters act as optical network terminals in a real-time application of passive optical LAN.

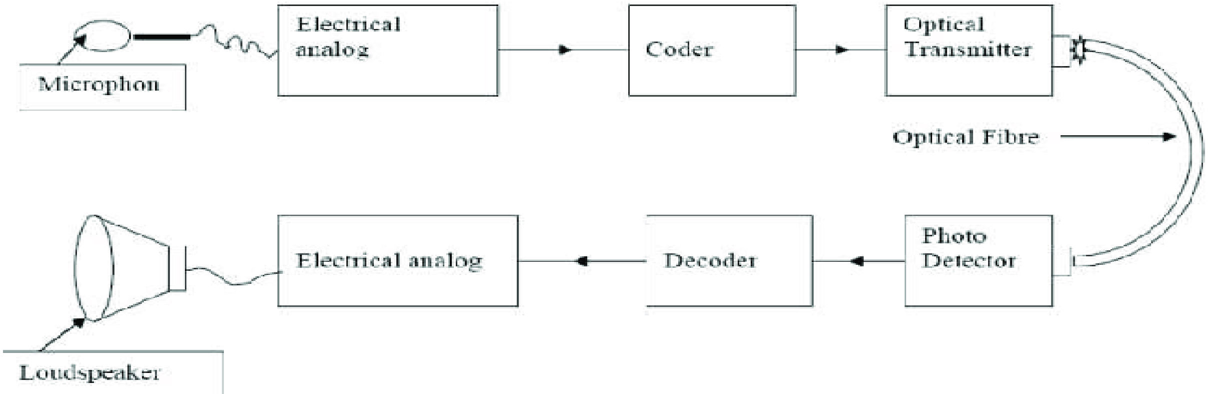


Advantages

1. High speeds and bandwidth
2. Longer distances are possible
3. Less chance of errors

Point to point communication using Optical Fibers:

In an optical fiber communication system, the input signals (audio, video or other digital data) are used to modulate light from a source like a LED or a semiconductor LASER and is transmitted through optical fiber. At the



The communication using Optical fiber is as follows. First voice is converted into electrical signal using a transducer. It is digitized using a Coder. The digitized signal, which carries the voice information, is fed to an optical transmitter. The light source in optical transmitter (LED or LASER Diode) emits modulated light, which is transmitted through the optical fiber. At the other end the modulated light signal is detected by a photo detector and is decoded using a decoder. Finally the information is converted into analog electrical signal and is fed to a loud speaker, which converts the signal to voice (sound).

Advantages and Disadvantages of optical fibers:

Advantages

6. Optical fibers can carry very large amounts of information in either digital or analog form.
7. The raw material for optical fiber is of low cost and abundant.
8. It has low cost
9. Cables are very compact
10. Signals are protected from radiation from lightning or sparking
11. There is no energy radiation from fiber
12. No sparks are generated

Disadvantages

1. The optical connectors are very costly
2. Maintenance cost is high
3. They cannot be bent too sharply
4. They undergo structural changes with temperature

Questions:

Numerical Problems

1. Calculate the numerical aperture and angle of acceptance for an optical fiber having refractive indices 1.563 and 1.498 for core and cladding respectively.
2. The refractive indices of the core and cladding of a step index optical fiber are 1.45 and 1.4 respectively and its core diameter is $45\mu m$. Calculate its fractional refractive index change and numerical aperture.
3. Calculate numerical aperture, acceptance angle and critical angle of a fiber having a core RI 1.50 and cladding RI 1.45.
4. An optical fiber has a numerical aperture of 0.32. The refractive index of cladding is 1.48. Calculate the refractive index of the core, the acceptance angle of the fiber and the fractional index change.
5. An optical signal propagating in a fiber retains 85% of input power after traveling a distance of 500 m in the fiber. Calculate the attenuation coefficient.
6. An optical fiber has core RI 1.5 and RI of cladding is 3% less than the core index. Calculate the numerical aperture, angle of acceptance critical angle.
7. The numerical aperture of an optical fiber is 0.2 when surround by air. Determine the RI of its core, given the RI of the cladding is 1.59. Also find the acceptance angle when the fiber is in water of RI 1.33.
8. The angle of acceptance of an optical fiber is 30^0 when kept in air. Find the angle of acceptance when it is in medium of refractive index 1.33.
9. An optical fiber of 600 m long has input power of 120 mW which emerges out with power of 90 mW. Find attenuation in fiber.

10. The attenuation of light in an optical fiber is 3.6 dB/km. What fraction of its initial intensity is remains after i) 1 km and ii) 3 km ?

11. The attenuation of light in an optical fiber is 2.2 dB/km. What fraction of its initial intensity is remains after i) 2 km and ii) 6 km ?

Model Questions

1. Define the terms: (i) angle of acceptance, (ii) numerical aperture, (iii) modes of propagation & (iv) refractive index profile.
2. Obtain an expression for numerical aperture and arrive at the condition for propagation.
3. Explain modes of propagation and RI profile.
4. What is attenuation? Explain the factors contributing to the fiber loss.
5. Discuss the types of optical fibers based on modes of propagation and RI profile.
6. Explain attenuation along with the expression for attenuation co-efficient and also discuss the types of fiber losses.
7. Explain the Fiber Optic Networking and mention its advantages.
8. Discuss point to point optical fiber communication system and mention its advantages over the conventional communication system.
9. Discuss the advantages and disadvantages of an optical communication.

Solved Problems:

1. **In an diffraction grating experiment the laser light undergoes second order diffraction if the distance between screen and grating is 20cm and average distance of 2^{nd} order spot 2.7cm, grating constant $1X10^{-5}$m, calculate the wavelength of laser light. (Practical component)**

   Solution:

   Given: Distance between screen and grating is D= 20cm,

   Average distance of 2^{nd} order spot is x = 2.7cm,

   Grating constant, d= $1X10^{-5}$m

   Diffraction order, n=2

   Wavelength of laser light, λ=?

$$\lambda = \frac{d \sin\theta}{n}$$

   Here $\theta = tan^{-1}\left(\frac{x}{D}\right) = tan^{-1}\left(\frac{2.7}{20}\right) = tan^{-1}(0.135)$,

$$\theta = 7.68^0$$

$$\lambda = \frac{1X10^{-5}\sin 7.68^0}{2}$$

$$\lambda = 0.06689 * 10^{-5}$$

$$\lambda = 668.9 * 10^{-9}m$$

2. **A pulse from laser with 1mW lasts for 20nS. If the number of photons emitted per pulse is $3.491X10^{7}$. Calculate the wavelength of the laser.**

   Solution : Given : number of photons emitted per pulse , n= $3.491X10^{7}$

   Pulse duration t= $20\ X10^{-9}$ S

   Power of the laser P=1mW= $1\ X10^{-3}$ W

   Wavelength of laser= λ=?

   Power of the laser $\mathrm{P} * \mathrm{t} = \frac{nhc}{\lambda}$

$$\lambda = \frac{nhc}{\mathrm{P} * \mathrm{t}} = \frac{(6.625X10^{-34}) * 3X10^8}{1 * 10^{-3} * 20 * 10^{-9}}$$

$$\lambda = 694.3 * 10^{-9}$$

$$\lambda = 694.3nm$$

3. **Calculate the wavelength of laser emitted from an extrinsic semiconductor laser if the band gap is 0.02eV. To which region of EM spectrum does it belong?**

   Solution: Energy gap Eg= 0.2eV=$0.2 * 1.609 * 10^{-19}J$

$$\mathrm{E_g} = \frac{hc}{\lambda} = \frac{(6.625X10^{-34}) * 3X10^8}{2 * 1.609 * 10^{-19}}$$

$$E_g = 6.1808 * 10^{-7} m$$

$$E_g = 618.08 * 10^{-9} m$$

$$E_g = 618.08\ nm$$

It belongs to visible region of EM spectrum.

4. **A pulsed laser emits photons of wavelength 780nm with 20mW average power per pulse. Calculate the number of photons contained in each pulse if the pulse duration is 10nS.**

Solution :

Given:

Pulse duration t= 10nS=10 X10^{-9} S

Power of the laser P=20mW= 20 X10^{-3} W

Wavelength of laser= λ=780nm=780 X10^{-9}m

number of photons emitted per pulse , n= ?

Power of the laser $P * t = \frac{nhc}{\lambda}$

$$n = \frac{P * t * \lambda}{hc} = \frac{20 * 10^{-3} * 10 * 10^{-9} * 780 * 10^{-9}}{(6.625X10^{-34}) * 3X10^{8}}$$

$$\mathbf{n = 7.86 * 10^{8}}$$

5. **The ratio of population of two energy levels is $\mathbf{1.059 * 10^{-30}}$. Find the wavelength of light emitted by spontaneous emissions at 330K.**

Solution : Given, Population Inversion is $\frac{N_2}{N_1} = 1.059 * 10^{-30}$

Temperature T= 300K

wavelength of light λ =?

$$\frac{N_2}{N_1} = \exp - \left(\frac{hc}{\lambda kT}\right)$$

Taking log on both sides we get,

$$\ln \frac{N_2}{N_1} = -\frac{hc}{\lambda kT}$$

$$\lambda = -\frac{hc}{kT\ ln\left(\frac{N_2}{N_1}\right)} = -\frac{(6.625X10^{-34}) * 3X10^{8}}{1.38 * 10^{-23} * 300 * \ln 1.059 * 10^{-30}}$$

$$\boldsymbol{\lambda = 632 * 10^{-9} m}$$

6. **The average output power of Laser source emitting a laser beam of wavelength 632.8nm is 5mW. Find the number of photons emitted per second by the laser source.**

Given:

Power of the laser P=5mW= 5 $X10^{-3}$ W

Wavelength of laser= λ=632.8nm=632.8$X10^{-9}$m

Number of photons emitted per pulse , n= ?

Power of the laser $P * t = \frac{nhc}{\lambda}$

$$n = \frac{P * t * \lambda}{hc} = \frac{5 * 10^{-3} * 1 * 632.8 * 10^{-9}}{(6.625X10^{-34}) * 3X10^{8}}$$

$$\mathbf{n = 159.19 * 10^{14}/s}$$

7. **Calculate the acceptance angle and numerical aperture of given optical fiber having diameter of spot is 2.6cm and distance between screen and optical fiber 3.0cm. (Practical component)**

Solution: Given, Diameter of spot is , D=2.6cm

Distance between screen and optical fiber, L= 3cm

Acceptance angle is

Here $\theta_0 = tan^{-1}\left(\frac{D}{2L}\right) = tan^{-1}\left(\frac{2.6}{2*3}\right) = tan^{-1}\left(\frac{2.6}{6}\right) = tan^{-1}(0.433)$

$$\theta_0 = 23.41^0$$

$$Nummerical\ aperture = sin\theta_0$$

$$Nummerical\ aperture = sin\ (23.41^0)$$

$$Nummerical\ aperture = 0.39$$

8. **Calculate numerical aperture, acceptance angle and critical angle of a fiber having a core RI 1.50 and cladding RI 1.45.**

Solution: Given, RI of core n1=1.5, RI of cladding n2= 1.45

$$Nummerical\ aperture = \sqrt{n_1^2 - n_2^2}$$

$$Nummerical\ aperture = \sqrt{1.5^2 - 1.45^2} = 0.384$$

Acceptance angle $\theta_0 = sin^{-1}(Nummerical\ aperture) = sin^{-1}0.384 = 22.5$

Critical angle, $\theta c = sin^{-1}\left(\frac{n_2}{n_1}\right) = sin^{-1}\left(\frac{1.45}{1.5}\right) = sin^{-1}(0.966) = 75.016$

9. The angle of acceptance of an optical fiber is 30^0 when kept in air. Find the angle of acceptance when it is in medium of refractive index 1.33.

Solution: Given, acceptance angle is $\theta_0 = 30^0$, when fiber is kept in air medium of Refractive index $n_0 = 1$

$$\sin\theta_0 = \frac{1}{n_0}\left[\sqrt{n_1^2 - n_2^2}\right]$$

$$\sin 30^0 = \frac{1}{1}\left[\sqrt{n_1^2 - n_2^2}\right]$$

$$\sqrt{n_1^2 - n_2^2} = 0.5$$

Acceptance angle is $\theta_0' =?$ when fiber is kept in a medium of Refractive index $n_0 = 1.33$

$$\sin\theta_0' = \frac{1}{n_0}\left[\sqrt{n_1^2 - n_2^2}\right]$$

$$\sin\theta_0' = \frac{1}{1.33} * 0.5$$

$$\sin\theta_0' = \frac{0.5}{1.33}$$

$$\boldsymbol{\theta_0' = 22^0}$$

10. Given the numerical aperture 0.30 and RI of core 1.49. Calculate the critical angle for the core-cladding interface.

Solution: Given, numerical aperture =0.30 , RI of core n1= 1.49 n2=1

Critical angle θc =? $\theta c = sin^{-1}\left(\frac{n_2}{n_1}\right)$

$$\theta c = sin^{-1}\left(\frac{1}{1.49}\right)$$

$$\theta c = sin^{-1}(0.6711)$$

$$\theta c = 42.15^0$$

11. Obtain the attenuation coefficient of the given fiber of length 1500m given the input and output power of 100mW and 70mW.

Solution: Given, $P_{out} = 70mW \quad and \quad P_{in} = 100mW$, L= 1500m

Attenuation coefficient=? $\alpha = -\frac{10}{L} log\left(\frac{P_{out}}{P_{in}}\right) \ dB/km$

$$\alpha = -\frac{10}{1500} log\left(\frac{70}{100}\right) \ dB/km$$

$$\alpha = 1.412 \ dB/km$$

--------------------------------END OF THE MODULE 1------------------------------------