Course Material

Module 3: Laser and Optical Fibres

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MODULE 3: Lasers and Optical Fibers

Introduction:

Gordon Gould (July 17, 1920 – September 16, 2005) was an American physicist who is sometimes credited with the invention of the laser and the optical amplifier. (Credit for the invention of the laser is disputed, since Charles Townes and Arthur Schawlow were the first to publish the theory and Theodore Maiman was the first to build a working laser). Gould is best known for his thirty-year fight with the United States Patent and Trademark Office to obtain patents for the laser and related technologies. He also fought with laser manufacturers in court battles to enforce the patents he subsequently did obtain.

Course syllabus: Lasers & Optical Fibers Lasers: Interaction of radiation with matter, Einstein's coefficients (derivation of expression for energy density). Requisites of a Laser system. Conditions for Laser action. Principle, Construction, and working of CO2 and semiconductor Lasers. Application of Lasers in Defence (Laser range finder) and medical applications- Eye surgery and skin treatment.

Optical Fibers: Propagation mechanism, angle of acceptance, Numerical aperture, Modes of propagation, Types of optical fibers, Attenuation, and Mention of expression for attenuation coefficient. Discussion of a block diagram of point-to-point communication, Optical fiber sensors- Intensity-based displacement sensor and Temperature sensor based on phase modulation, Merits, and demerits, Numerical problems

3.1. LASERS

The word Laser stands for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. It is a device which amplifies light. It has properties like coherence, uni-directionality, mono-chromaticity, focussability etc.

3.2. INTERACTION OF AN ELECTROMAGNETIC RADIATION WITH MATTER

Radiation interacts with matter under appropriate conditions. The interaction leads to transition of an atom or a molecule from one energy state to another. If the transition is from lower state to higher state it absorbs the incident energy. If the transition is from higher state to lower state it emits a part of its energy.

If ΔE is the difference between the two energy levels,

Then $\Delta E = (E_2 - E_1)$ Joule

According to Max Planck, energy of incident photon is $h\nu$

The interaction of radiation with matter will happen when,

$$\Delta E = h\nu$$

i.e., $\nu = (E_2 - E_1)/h$ Hz.

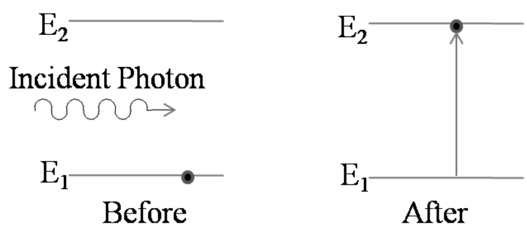
Three types of interactions, which are possible:

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

1. Induced absorption :

Let E_1 and E_2 be the two energy levels of an atom, in which $E_2 > E_1$. When a photon of energy $h\nu = (E_2 - E_1)$ is incident on an atom at level E_1, the atom goes to a higher energy level by absorbing the energy of the incident photon. The transition from the lower energy level to the higher energy level, i.e. the excited state is called induced absorption and it is represented as

$$\text{Atom} + \text{Photon} \rightarrow \text{Atom}^*$$

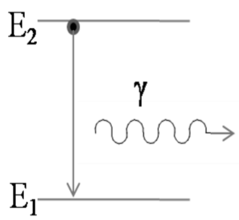


2. **Spontaneous Emission:**

The emission of a photon by the transition of an atom from a higher energy state to a lower energy state without the aid of an external energy is called spontaneous emission.

The process is represented as

$$\text{Atom}^* \rightarrow \text{Atom} + \text{Photon}$$



The photons emitted in spontaneous emission may not have same direction and phase similarities. It is incoherent.

Ex: Glowing electric bulbs, Candle flame etc.

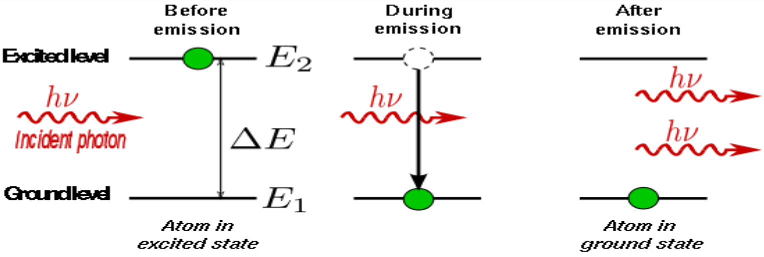
3. Stimulated Emission:

Stimulated emission is the emission of a photon by an atom under the influence of a incident photon due to which the system transits from a higher energy state to a lower energy state.

The photon thus emitted is called stimulated photon and will have the same phase, energy and direction of movement as that of the incident photon called the stimulation photon.

The process is represented as,

$$\text{Atom}^* + \text{Photon} \rightarrow \text{Atom} + 2\ \text{Photons}$$

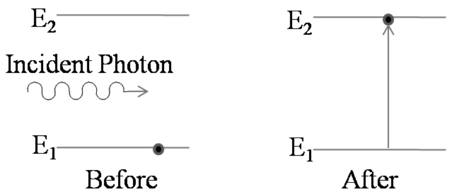


$$E_2 - E_1 = \Delta E = h\nu$$

3.2. EINSTEIN'S A & B COEFFICIENTS: (DERIVATION OF EXPRESSION FOR ENERGY DENSITY)

Consider two energy states E_1 and E_2 of a system of atom. Let there be N_1 number of atoms with energy E_1 and N_2 number atoms with energy E_2 per unit volume of the system. N_1 and N_2 are called the number density of atoms in the states E_1 and E_2 respectively.

Case of Induced absorption:



In this case the atom in E_1 level absorb radiations of frequency $\nu = (E_2\text{-}E_1)/h$ and get excited to E_2 level.

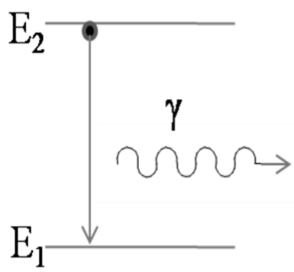
The rate of absorption depends on number density of lower energy state and the energy density U_ν

Rate of absorption $\propto N_1 U_\nu$

Rate of absorption = $B_{12} N_1 U_\nu$

Where 'B_{12}' is the proportionality constant called Einstein Coefficient of induced absorption.

Case of Spontaneous Emission:



In this case, the atom undergoes downward transition from E_2 to E_1 spontaneously, i.e., by itself without the help of external agency. It is independent of energy density.

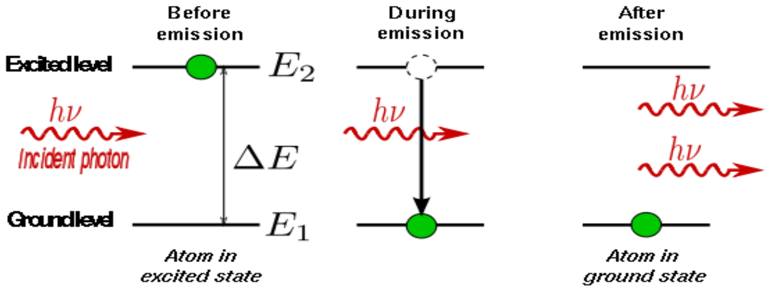
Spontaneous emission depends on N_2 which is the number of atoms present in the higher level.

The rate of spontaneous emission $\propto N_2$

The rate of spontaneous emission = $A_{21} N_2$

Where, 'A_{21}' is the proportionality constant and is called Einstein coefficient of spontaneous emission

Case of Stimulated Emission:



The rate of stimulated emission depends on N_2 and the energy density U_ν .

The rate of stimulated emission $\propto N_2U_\nu$

The rate of stimulated emission = $B_{21}N_2U_\nu$

Where 'B_{21}' is the proportionality constant called Einstein's Coefficient of stimulated emission.

At thermal equilibrium,

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

$$B_{12}N_1U_\nu = A_{21}N_2 + B_{21}N_2U_\nu$$

$$U_\nu (B_{12}N_1 - B_{21}N_2) = A_{21}N_2$$

$$U_\nu = \frac{A_{21}N_2}{(B_{12}N_1 - B_{21}N_2)}$$, Multiply and divide the denomination by $B_{21}N_2$

$$\text{i.e. } U_\nu = \frac{}{B_{21}N_2}\left[\frac{A_{21}N_2}{\left(\frac{B_{12}}{B_{21}}\frac{N_1}{N_2} - 1\right)}\right]$$

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

By Boltzmann's law,

$$N_2 = N_1\, e^{-h\nu/KT}$$

i.e., $N_1/N_2 = e^{h\nu/KT}$

Eqn. (1) becomes

$$U_{\upsilon} = \frac{A_{21}}{B_{21}}\left[\frac{1}{\left(\frac{B_{12}}{B_{21}}e^{\left(\frac{h\upsilon}{kT}\right)}-1\right)}\right] \frac{A_{21}}{B_{21}}\left[\frac{1}{\left(\frac{B_{12}}{B_{21}}e^{h\gamma/KT}\right)-1}\right] \rightarrow (2)$$

By Planck's law,

$$U_{\upsilon} = \frac{8\pi h\upsilon^3}{c^3}\left[\frac{1}{\left(e^{\left(\frac{h\upsilon}{kT}\right)}-1\right)}\right] \rightarrow (3)$$

Comparing equation (2) & (3)

$\frac{A_{21}}{B_{21}} = 8\pi h\nu^3/c^3$ & $\frac{B_{12}}{B_{21}} = 1$ i.e. $B_{12} = B_{21}$

It implies that the probability of induced absorption is equal to the probability of stimulated emission. Because of the above identity the subscripts could be dropped and A_{21} and B_{21} can be simply represented as A &B

$U_{\nu} = \frac{A}{B}$ $[1/ e^{h\nu/kT} -1]$

3.3. CONDITIONS FOR LASER ACTION:-

Population inversion and the metastable states are the two conditions required for laser action.

Under normal conditions at thermal equilibrium in the atomic system there are more number of atoms in the ground state than in the excited state. Hence the probability of absorption is more than that of stimulated emission. The number of atoms in each energy state is given by Boltzmann statistical law as

$$N_2/N_1 = e^{-h\nu/KT}$$

This equation implies that the population is maximum in the ground state and decreases exponentially as one goes to the higher energy state i.e., $N_2 < N_1$.

Hence stimulation emission is very weak under thermal equilibrium condition.

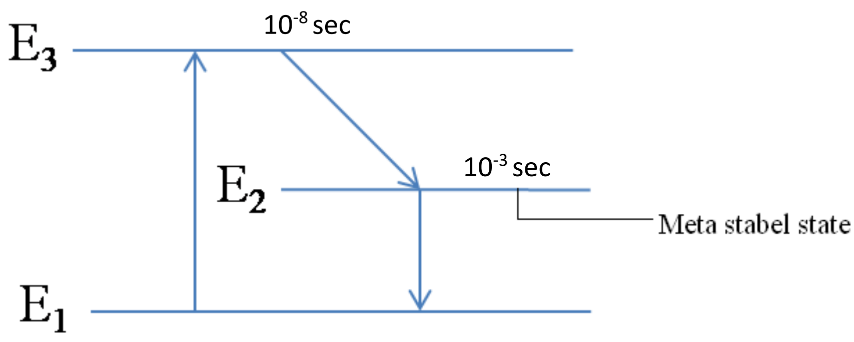
But for amplification N_2 has to be greater than N_1

Therefore, the required conditions are,

1. **Population Inversion:**
 "The situation in which the number of atoms in the higher energy state exceeds that in the lower energy state is known as population inversion".

2. **Meta Stable State:**

It is the state where the atoms get excited and remains in the excited state for longer time than the normal state.



This state plays an important role in lasing action. In metastable state, atoms stay of the order of 10^{-3} to 10^{-2} second. This property helps in achieving the population inversion in the following way.

Consider 3 energy levels E_1, E_2, & E_3 of a quantum system, such that $E_3>E_2>E_1$, Let E_1 be the ground state, E_2 be the Meta stable state & E_3 be the excited state respectively. Let the atoms are excited (pumped) from E_1 to E_3 state. The atoms from E_3 state undergo non-radiative transitions to E_2 states rapidly.

Since E_2 is a metastable state, those atoms which get into that state stay there over a very long duration ie.,10^{-3} sec. Because of which the population of E_2 state increases steadily. Under these conditions a stage will be reached where in the population of E_2 state overtakes that of E_1, which is known as population inversion.

Once the population of E_2 exceeds E_1, the stimulated emissions out number the spontaneous emissions, & soon stimulated photons, all identical in respect of phase, wavelength & direction, grow to a very large number which build up the laser light. The process which leads to emission of stimulated photons after establishing the population inversion is often referred to as Lasing. Hence the condition for laser action is achieved by means of population inversion with the help of a metastable state.

3.4. REQUISITES FOR LASER SYSTEM:-

The following are the requisites of a laser system

1. An excitation source for pumping action.
2. An active medium which supports population inversion and
3. A laser cavity.

- **Pumping:** It is the process of exciting atoms from lower energy level to higher energy level. It can be achieved by different methods.

  Optical pumping, Electric Discharge, forward bias current, etc

- **Active medium for population inversion:**
  The quantum system between whose energy levels the pumping & the lasing action occur, is called an active system. A part of the input energy is absorbed by the active medium in which population inversion occurs at a certain stage. After this stage the medium attains capability to issue laser light.

- **Laser cavity:**
  A laser cavity is formed by an active medium bounded by two mirrors.
  The laser cavity provides the feedback necessary to tap certain permissible part of laser energy from the active medium.

  A laser device consists of an active medium bound between 2 mirrors. The mirrors reflect the photons to & fro through the active medium. A photon moving in a particular direction represents a light wave moving in the same direction. Thus the two mirrors along with the active medium form a cavity inside which two types of wave exists, one type comprises of waves moving to the right & the other moving to the left.

  The two waves interfere constructively if there is no phase difference between the two. But their interference becomes destructive if the phase difference is $\pi/2$. For constructive interference to happen the length (L) of the laser cavity has to be equal to $n\lambda/2$.,

  i.e., $L= n\lambda/2$

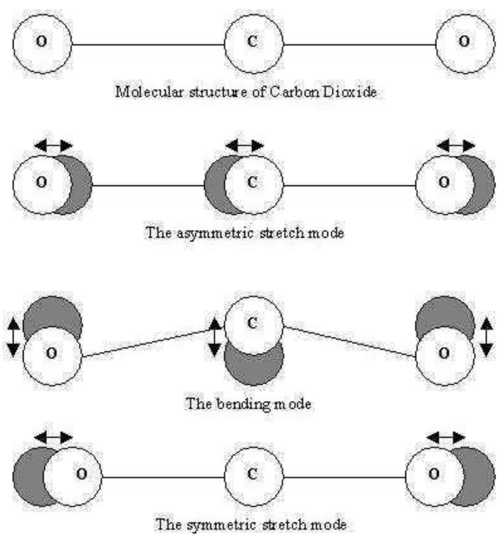
  where λ is the wavelength of the laser beam.

3.5. CARBON DIOXIDE LASER:

In addition to the electronic energy levels in atoms, the gas molecules possess vibrational and rotational energies which are quantized.

Vibrational energy levels a Carbon dioxide molecule:

Carbon dioxide molecule has three modes of vibration as shown in Fig.

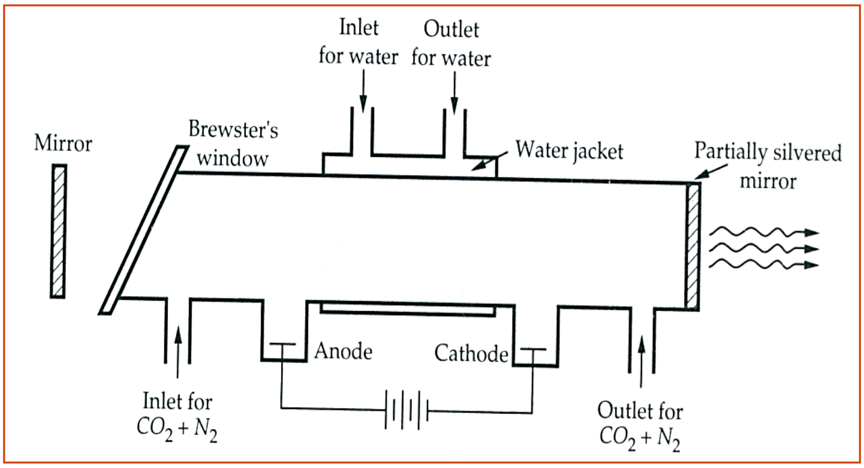


1. Symmetric Stretching mode:
   In Symmetric Stretching mode, the two Oxygen atoms either simultaneously move towards or away from the Carbon atom.
2. Asymmetric Stretching mode:
   In this mode, both the oxygen atoms move in one direction while the carbon atoms moves in the opposite direction along the molecular axis.
3. Bending mode:

In the bending mode, the three atoms vibrate perpendicular to the axis of the molecule in such a way that the Carbon atom moves in opposite direction to the Oxygen atom.

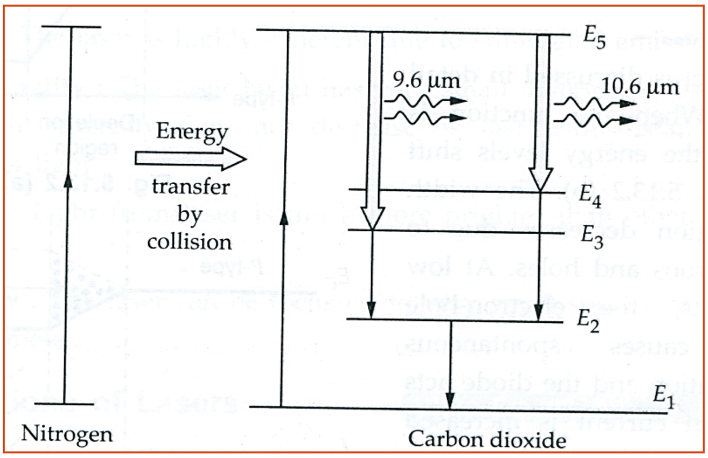
3.5.1. Construction and Working of Carbon Dioxide Laser:

Construction:



A typical CO_2 laser consists of a discharge tube of 2.5 cm in diameter and of 5cm length. The tube is water cooled and is filled with a mixture of CO_2, N_2 and He gases in the ratio 1:2:3. One end of the tube has a partially silvered mirror and other the other end has a Brewster's windows. A completely silvered mirror is kept beyond the Brewster's windows.

Working: The high voltage across the electrodes excites the gas molecules. The Nitrogen molecules in the gas are excited to higher levels and transfer energy to CO_2 molecules by collisions.



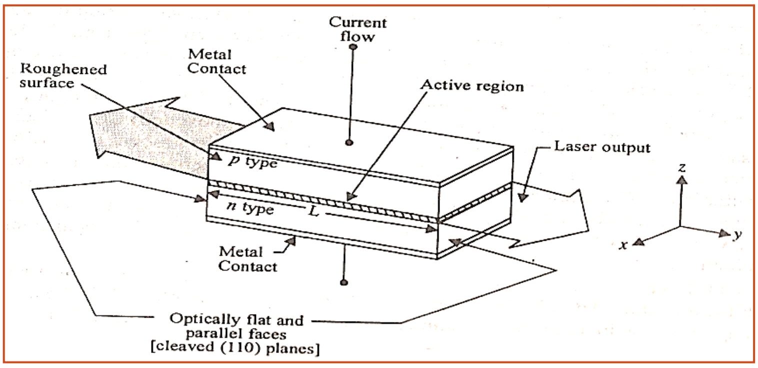
The CO_2 molecules are excited to the metastable state E_5 where population inversion takes place with respect to the two lower lasing levels E_4 and E_3. Transition from E_5 to E_4 gives rise to 10.6 μm wavelength laser and the transition from E_5 to E_3 gives rise to 9.6 μm wave length which are both in the far infra red region. Helium depopulates the lower energy levels in CO_2 which facilitates population inversion.

3.5.2. Applications of CO_2 laser:

Because of the high power levels available (combined with reasonable cost for the laser), CO_2 lasers are frequently used in industrial applications for cutting and welding. They are used for pollution monitoring and remote sensing (LIDAR) applications. Due to minimal atmospheric attenuation, they find applications in communication systems.

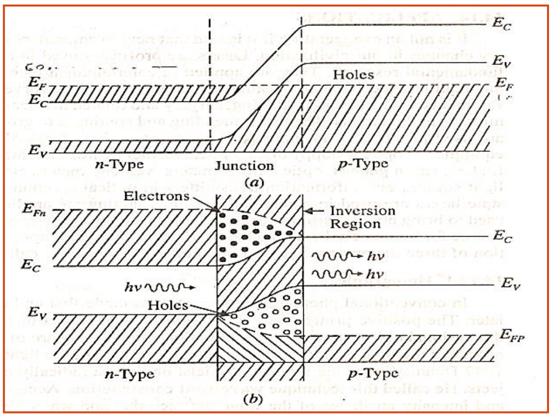
3.6. GALLIUM-ARSENIDE LASER: SEMICONDUCTOR LASER:

A Semiconductor diode laser is a specially fabricated p-n junction device that emits coherent light when it is forward biased. In the case of germanium and silicon based diodes, this energy is released in the form of heat because of recombination of carriers take place through interaction with the atoms of the crystal. But in the case of GaAs, the energy is released in the form of photons as the atoms of the crystal are not involved in the release of energy. The wavelength of the emitted photon depends upon the activation energy of the crystal.



3.6.1. Construction: A schematic diagram of semiconductor laser is as shown in the figure. The diode is very small size with sides of the order of 1mm. The junction lies in a horizontal plane. The *n*-section is formed by doping with tellurium whereas the *p*-section, is obtained by doping with zinc. The doping concentration is of the order of 10^{17} to 10^{19} dopant atoms/cm^3. The top and bottom surfaces are metalized and ohmic contacts are provided for external connection. The front and rear faces are polished. The polished faces constitute the laser cavity. The other two faces are roughened to prevent lasing action in that direction. The active region consists of a layer of about 1μm thickness.

3.6.2. Working: The energy band diagram of heavily doped pn-junction is as shown unbiased condition. At thermal equilibrium, the Fermi level is uniform across the junction. Because of very high doping on n-side, Fermi level is pushed into the conduction band and electrons occupy the portion of the conduction band lying below the Fermi level. On P-side, the Fermi level lies within the valence band and holes occupy the portion of the valence band that lies above the Fermi level. When the junction is forward biased electrons and holes are injected into the junction region in high concentrations. At low forward current, the electron-holes recombination results in spontaneous emission of photons and the junction acts as a LED. As the forward current is increased gradually and when it reaches a threshold value the carrier concentration in the junction region there will be large concentrations of electrons within the band. As a result condition of population inversion is attained in the narrow region. This narrow zone in which population inversion occurs is called as an active region, at that stage a photon emitted spontaneously triggers stimulated emission. This stimulated electron-hole recombination produces coherent radiation.



Energy level diagram of p-n junction diode laser
(a) Before biasing (b) After biasing.

The stimulated electron-hole recombination causes emission of coherent radiation of very narrow bandwidth. At room temperature, GaAs laser emits light of wavelength $9000A^0$ and GaAsP laser radiates at $6500A^0$.

3.6.3. Advantages of semiconductor laser:

1. They are compact
2. They are efficient
3. They are highly stable

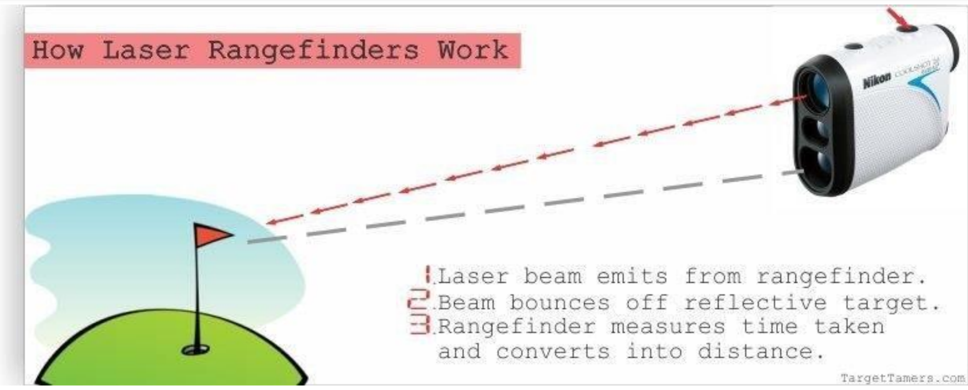
3.7. APPLICATION OF LASERS:

3.7.1. Application of Lasers in Defense (Laser range finder):

Military operations often demand a secure and timely transmission of a massive amount of information from one place to another. Until now, the military has relied on the radio spectrum for effective communication, which is vulnerable to security threats and susceptible to electromagnetic interference (EMI). The probability of intercepting a laser signal is verylow due to its narrow beam divergence and coherent optical beam, making the laser a suitable candidate for secure military tactical operations. Besides the communication aspect, the highlydirective nature of a laser beam is also used as a directed energy laser weapon. These highly powerful and light weighted directed energy laser weapons are very cost-effectivecountermeasures for airborne threats. Furthermore, laser sensors are deployed in the battlefield or in space for tracking the path of a wide range of military vehicles like missiles, unmanned aerial vehicles, fighter aircraft, warships, submarines, and so on.

3.7.2. Working of Rangefinders:

Laser rangefinders work pretty much the way that radar works, except that the beam diverges much less than a radar beam would, hence the range finder can specifically target much smaller objects than a radar beam could.



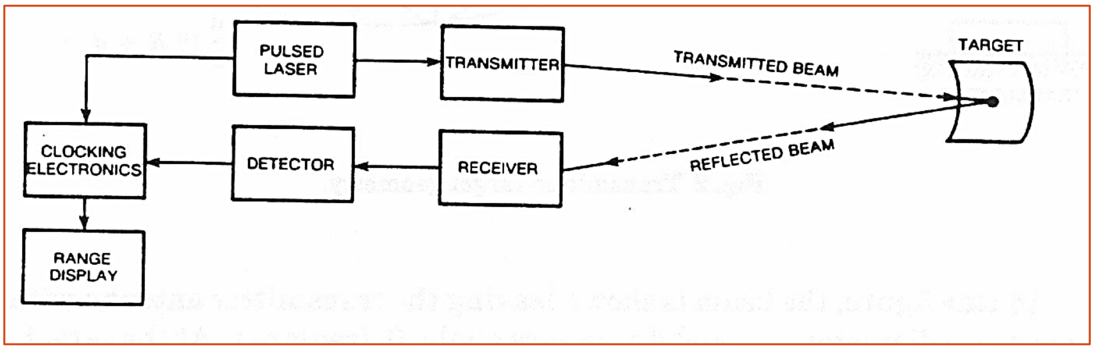


Fig: Block diagram of ranging system

These laser ranging systems are used to measure the distance (or range) between the sourceand the target. This is accomplished by:

1. Irradiating the target with a laser pulse from the source transmitter.
2. Detecting a reflection of the beam off of the target.
3. Measuring the time required for the laser signal to travel from the source to the target andback to the detector.

The electronic circuitry measures the interval from the time the signal leaves the laser transmitter until it is received back at the detector, and converts the result to a range.

3.8. MEDICAL APPLICATIONS OF LASERS

3.8.1. Eye surgery

Laser eye surgery is a medical procedure that involves the use of laser to reshape the surface of the eye. This is done to improve or correct myopia (short-sightedness), hypermetropia (long-sightedness) and astigmatism (uneven curvature of the eye's surface). It can also be helpful in overcoming presbyopia (difficulty seeing up close as we get older).

During laser eye surgery, a computer-controlled excimer laser is used to remove microscopic amounts of tissue from the cornea. The aim is to restore normal eyesight, without the need for glasses or contact lenses. In one of the operations using the excimer laser, the thin outer layer of the cornea (called the corneal epithelium) is removed and the underlying layers are reshaped. This procedure is known as photorefractive keratectomy (PRK).

3.8.2. Skin treatment

Today, there are more medical and aesthetic dermatological procedures utilizing laser technology than ever before. Applications range from mildly invasive procedures such as laser-assisted lipolysis to completely non-invasive ones such as photobiomodulation. This wide spectrum includes skin resurfacing, non-invasive body contouring, hair and tattoo removal, treatment of vascular and pigmented lesions, to name a few. Success in each of these applications is largely dependent on correct choice of laser type, wavelength, and pulse width.

With ablative lasers such as the CO_2 laser, it is possible to destroy superficial layers of the skin (i.e. the epidermis). On the other hand, the pulsed dye laser (PDL) can target blood vessels because the wavelength corresponds to the absorption spectrum of haemoglobin and penetrates to the level of the dermis, while the pulse duration can be set to be shorter than the thermal relaxation time of a small cutaneous blood vessel.

3.9. OPTICAL FIBERS

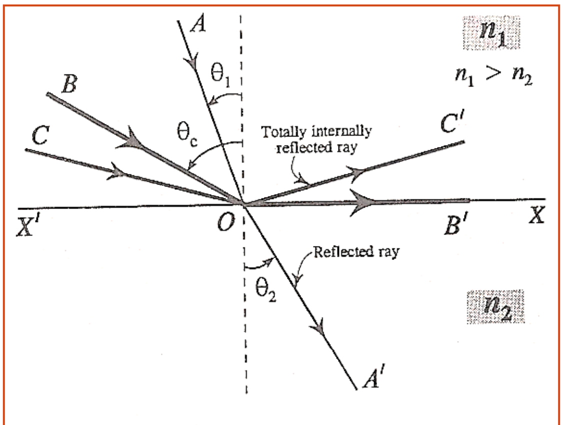
3.9.1. Total Internal Reflection:

When a ray of light travels from denser to rarer medium it bends away from the normal. As the angle of incidence increases in the denser medium, the angle of refraction also increases. For a particular angle of incidence called the "*critical angle*", the refracted ray grazes the surface separating the media or the angle of refraction is equal to 90°. If the angle of incidence is greater than the critical angle, the light ray is reflected back to the same medium. This is called *"Total Internal Reflection"*.

In total internal reflection, there is no loss of energy. The entire incident ray is reflected back.

XX^1 is the surface separating medium of refractive index n_1 and medium of refractive index n_2, $n_1 > n_2$.

AO and OA^1 are incident and refracted rays. θ_1 and θ_2 are angle of incidence and angle of refraction, $\theta_2 > \theta_1$. For the ray BO, θ_c is the critical angle. OB^1 is the refracted ray which grazes the interface. The ray CO incident with an angle greater than θ_c is totally reflected back along OC^1.



TOTAL INTERNAL REFLECTION

From Snell's law,

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

For total internal reflection,

$$\theta_1 = \theta_c \text{ and } \theta_2 = 90°$$

$$n_1 \sin\theta_c = n_2 \quad \text{(because } \sin 90° = 1\text{)}$$

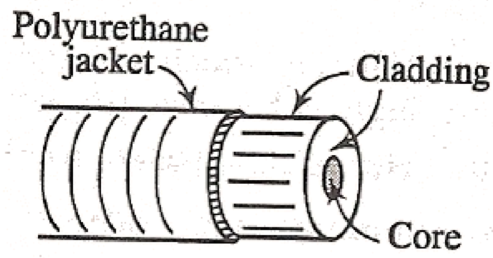
$\theta_c = \sin^{-1}(n_2/n_1)$

In total internal reflection there is no loss or absorption of light energy.

The entire energy is returned along the reflected light. Thus is called Total internal reflection.

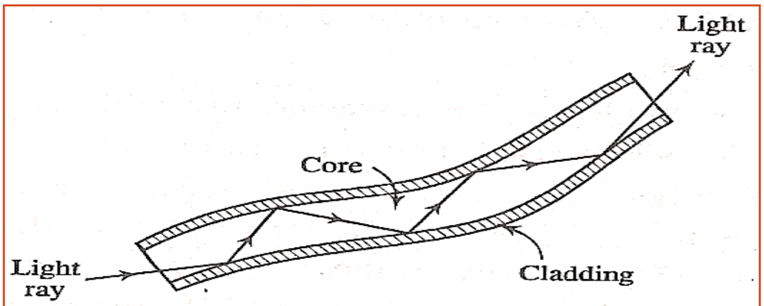
3.9.2. Construction and working of Optical Fiber:

Optical fiber works based on the principle of Total internal reflection (TIR). Optical fiber is made from transparent materials. It is cylindrical in shape. The inner cylindrical part is called as core of refractive index n_1. The outer part is called as cladding of refractive index n_2, $n_1 > n_2$. There is continuity between core and cladding. Cladding is enclosed inside a polyurethane jacket. Number of such fibers is grouped to form a cable.



OPTICAL FIBER

The light entering through one end of core strikes the interface of the core and cladding with angle greater than the critical angle and undergoes total internal reflection. After series of such total internal reflection, it emerges out of the core. Thus the optical fiber works as a waveguide. Care must be taken to avoid very sharp bends in the fiber because at sharp bends, the light ray fails to undergo total internal reflection.



FIBER AS A WAVEGUIDE

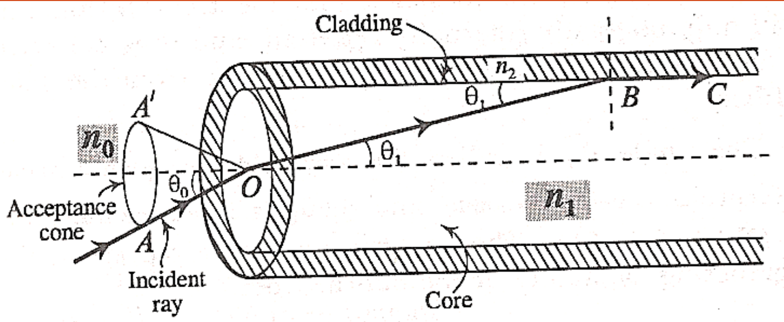
3.10. ANGLE OF ACCEPTANCE AND NUMERICAL APERTURE:

Consider a light ray AO incident at an angle 'θ_0' enters into the fiber. Let 'θ_1' be the angle of refraction for the ray OB. The refracted ray OB incident at a critical angle ($90^\circ - \theta_1$) at B grazes the interface between core and cladding along BC. If the angle of incidence is greater than critical angle, it undergoes total internal reflection. Thus θ_0 is called the waveguide acceptance angle and $\sin\theta_0$ is called the numerical aperture.

Let n_0, n_1 and n_2 be the refractive indices of the medium, core and cladding respectively.

From Snell's law,

$n_o \sin\theta_0 = n_1 \sin\theta_1 \rightarrow (1)$



ACCEPTANCE CONE

At B the angle of incidence is $(90^o - \theta_1)$

From Snell's law,

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

$$n_1 \cos\theta_1 = n_2$$

$$\cos\theta_1 = n_2 / n_1 \rightarrow (2)$$

From eqn (1)

$\sin\theta_i = \frac{n_1}{n_o}\sin\theta_1$ $Sin\theta_0 = \frac{n_1}{n_0}\sin\theta_1$

$= \frac{n_1}{n_o}\sqrt{1 - cos^2\theta_1} \rightarrow (3)$

Using eqn (2) in (3)

$$Sin\theta_0 = \frac{n_1}{n_0}\sqrt{1 - \frac{n_2^2}{n_1^2}} \quad \sin\theta_i = \frac{n_1}{n_o}\sqrt{1 - \frac{n_2^2}{n_1^2}}$$

$$= \frac{\sqrt{n_1^2 - n_2^2}}{n_o} \rightarrow (4)$$

The surrounding medium is air, $n_o = 1$

$$Sin\theta_0 = \sqrt{n_1^2 - n_2^2} \quad \sin\theta_i = \sqrt{n_1^2 - n_2^2}$$

Where $\sin\theta_i$ is called numerical aperture.

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

Therefore for any angle of incidence equal to θ_i equal to or less than θ_0, the incident ray is able to propagate.

$\theta_i < \theta_0$

$$\text{Sin}\,\theta_i < \text{Sin}\,\theta_0$$

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

$sin\theta_i < N.A$is the condition for propagation.

3.11. MODES OF PROPAGATION:

3.11.1. V-number:

The number of modes supported for propagation in the fiber is determined by a parameter called V-number.

If the surrounding medium is air, then

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

Where'd' is the core diameter, n_1 and n_2 are refractive indices of core and cladding respectively, 'λ' is the wavelength of light propagating in the fiber.

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

If the fiber is surrounded by a medium of refractive index n_0, then,

$$V = \frac{\pi d}{\lambda}\frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

For V >1, the number of modes supported by the fiber is given by, number of modes ≈ $V^2/2$.

3.12. TYPES OF OPTICAL FIBERS:

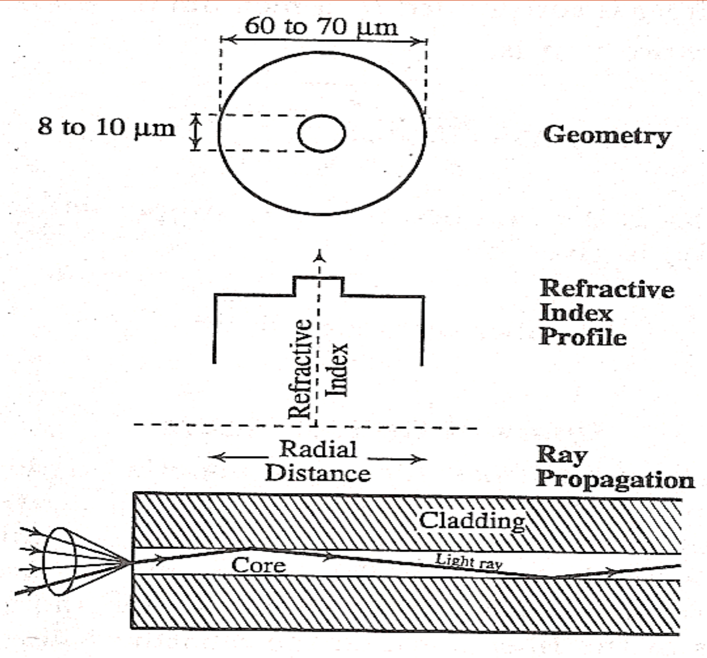
In an optical fiber the refractive index of cladding is uniform and the refractive index of core may be uniform or may vary in a particular way such that the refractive index decreases from the axis, radically.

Following are the different types of fibers:

1. Single mode fiber
2. Step index multimode fiber
3. Graded index multimode fiber

1. Single mode fiber:

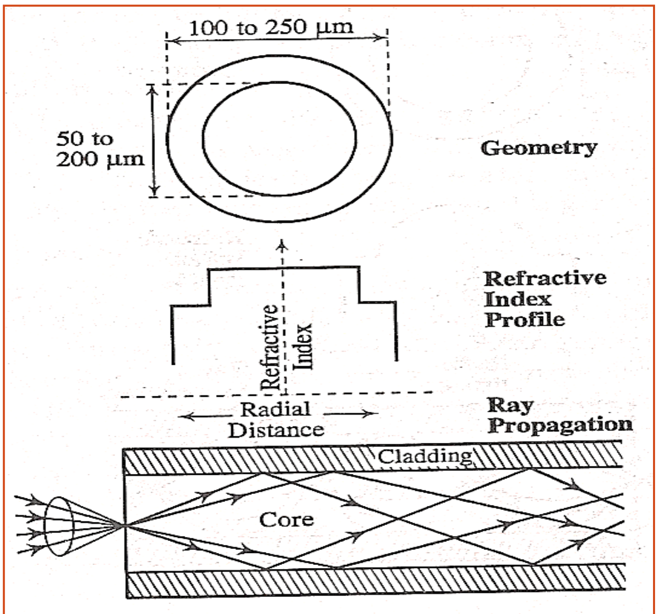
Refractive index of core and cladding has uniform value; there is an increase in refractive index from cladding to core. They are used in submarine.



SINGLE MODE FIBER

2. Step index multimode fiber:

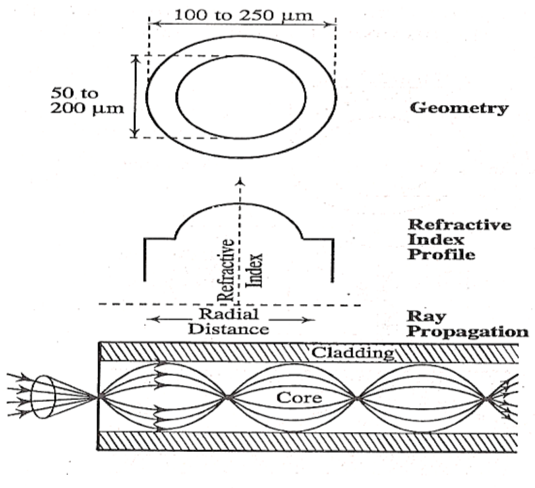
It is similar to single mode fiber but core has large diameter. It can propagate large number of modes as shown in figure. Laser or LED is used as a source of light. It has an application in data links.



STEP - INDEX MULTIMODE FIBER

3. Graded index multimode fiber:

It is also called GRIN. The refractive index of core decreases from the axis towards the core cladding interface. The refractive index profile is shown in figure. The incident rays bends and takes a periodic path along the axis. The rays have different paths with same period. Laser or LED is used as a source of light. It is the expensive of all. It is used in telephone trunk between central offices.



GRADED - INDEX MULTIMODE FIBER

3.12. SIGNAL ATTENUATION IN OPTICAL FIBERS:

Attenuation is the loss of optical power as light travels through a fiber. It is expressed in decibel/kilometer [db/km].A fiber with lower attenuation will allow more power to reach its receiver than a fiber with higher attenuation. If P_{in} is the input power and P_{out} is the output power after passing through a fiber of length 'L', the mean attenuation constant or coefficient 'α' of the fiber, in units of db/km is given by

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

Attenuation can be caused by three mechanisms.

1. Absorption:- Absorption of photons by impurities like metal ions such as iron, chromium, cobalt and copper in the silica glass of which the fiber is made of. During signal processing photons interact with electrons of impurity atoms. The atoms are excited and de-excite by emitting photons of different characteristics. Hence it is a loss of energy. The other impurity such as hydroxyl ions (OH) causes significant absorption loss. The absorption of photons by fiber material itself is called intrinsic absorption.

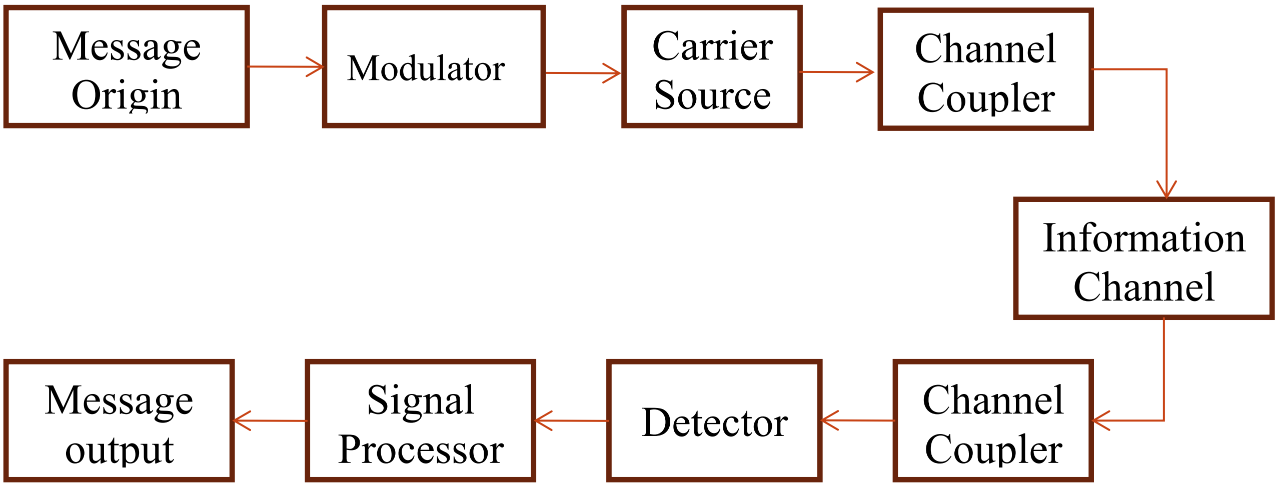
2. Scattering: When the wavelength of the photon is comparable to the size of the particle then the scattering takes place. Because of the non uniformity in manufacturing, the refractive index changes with length leads to a scattering. This type of scattering is called as Rayleigh scattering. It is inversely proportional to the fourth power of wavelength. Scattering of photons also takes place due to trapped gas bubbles which are not dissolved at the time of manufacturing.

3. Radiation losses: Radiation losses occur due to macroscopic bends and microscopic bends.

   (a) Macroscopic bending: All optical fibers are having critical radius of curvature provided by the manufacturer. If the fiber is bent below that specification of radius of curvature, the light ray incident on the core cladding interface will not satisfy the condition of TIR. This causes loss of optical power.

(b) Microscopic bending: Optical power loss in optical fibers is due to non-uniformity of the optical fibers when they are laid. Non uniformity is due to manufacturing defects and also lateral pressure built up on the fiber. The defect due to non uniformity (microbendings) can be overcome by introducing optical fiber inside a good strengthen polyurethane jacket.

3.13. FIBER OPTICS COMMUNICATION SYSTEM: (POINT TO POINT COMMUNICATION)



Optical fiber communication system consists of transmitter, information channel and receiver. Transmitter converts an electrical signal into optical signal. Information channel carries the signal from transmitter to receiver. The receiver converts optical signal to electrical form. The block diagram of optical fiber communication system is shown in fig.

Message origin: It converts a non electrical message into an electrical signal.

Modulator: It converts the electrical message into proper format and it helps to improve the signal onto the wave which is generated by the carrier source.

There are two types of format. They are Analog and digital. Analog signal is continuous and it doesn't make any change in the original format. But digital signal will be either in ON or OFF state.

Carrier source: It generates the waves on which the data is transmitted. These carrier waves are produced by the electrical oscillator. Light emitting diodes (LED) and laser diodes (LD) are the different sources.

Channel Coupler: (Input) The function of the channel coupler is to provide the information-to-information channel. It can be an antenna which transfers all the data.

Information channel: It is path between transmitter and receiver. There are two types of information channel. They are guided and unguided. Atmosphere is the good example for unguided information channel. Co-axial cable, two-wire line and rectangular wave guide are example for guided channel.

Channel Coupler: (Output) The output coupler guides the emerged light from the fiber on to the light detector.

Detector: The detector separates the information from the carrier wave. Here a photo-detector converts optical signal to electronic signal.

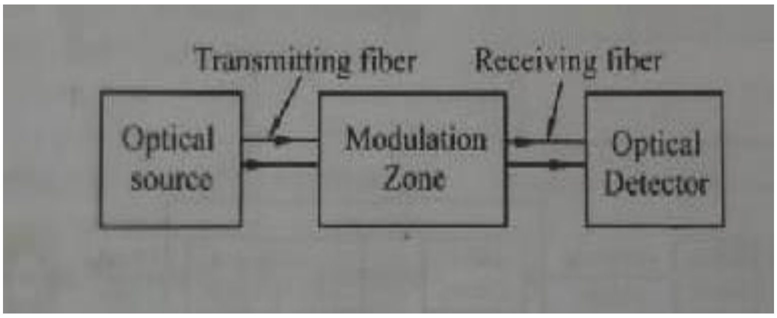
Signal processor: Signal processor amplifies the signals and filters the undesired frequencies.

Message output: The output message will be in two forms. Either person can see the information or hear the information. The electrical signal can be converted into sound wave or visual image by using CRO.

3.14. ACTIVE AND PASSIVE FIBRE SENSORS

Optical sensor is a transducer, which converts any form of signal into optical signal in the measurable form. Here optical fibres are used as a guiding media and hence called as wave-guides. The basic block diagram of a sensor system is shown in figure.

The optical sources used here are light emitting diode and Laser. The optical signals produced by the optical source and is transmitted through the transmitting fibre to the modulation zone.



The optical signals are modulated based on any one of these properties i.e., optical intensity, phase, polarization, wavelength and spectral distribution. These modulated signals with any one of these properties are received by the receiving fibre end and is sent to the optical detector.

3.15. TYPES OF SENSORS:

There are two types of sensors

(i) Intrinsic Sensors or Active Sensors

(ii) Extrinsic Sensors or Passive Sensors

3.15.1. INTRINSIC SENSORS OR ACTIVE SENSORS

In Intrinsic sensors or Active sensors, the physical parameter to be sensed directly acts on the fibre itself to produce the changes in the transmission characteristics.

Examples:

(i) Temperature Pressure Sensor (Phase and Polarization Sensor)

(ii) Liquid Level Sensor

3.15.2. EXTRINSIC SENSORS OR PASSIVE SENSORS

Extrinsic sensors or Passive sensors, separate sensing element will be used and the fibre will act as a guiding media to the sensors.

Examples:

(i) Displacement Sensor and

(ii) Laser Doppler Velocimeter Sensor

3.16. TEMPERATURE / PRESSURE SENSOR OR PHASE AND POLIRIZATION SENSOR – (INTRINSIC SENSOR):

Principle:

It is based on the principle of interference between the beams emerging out from the reference fibre and the fibre kept in the measuring environment.

Construction:

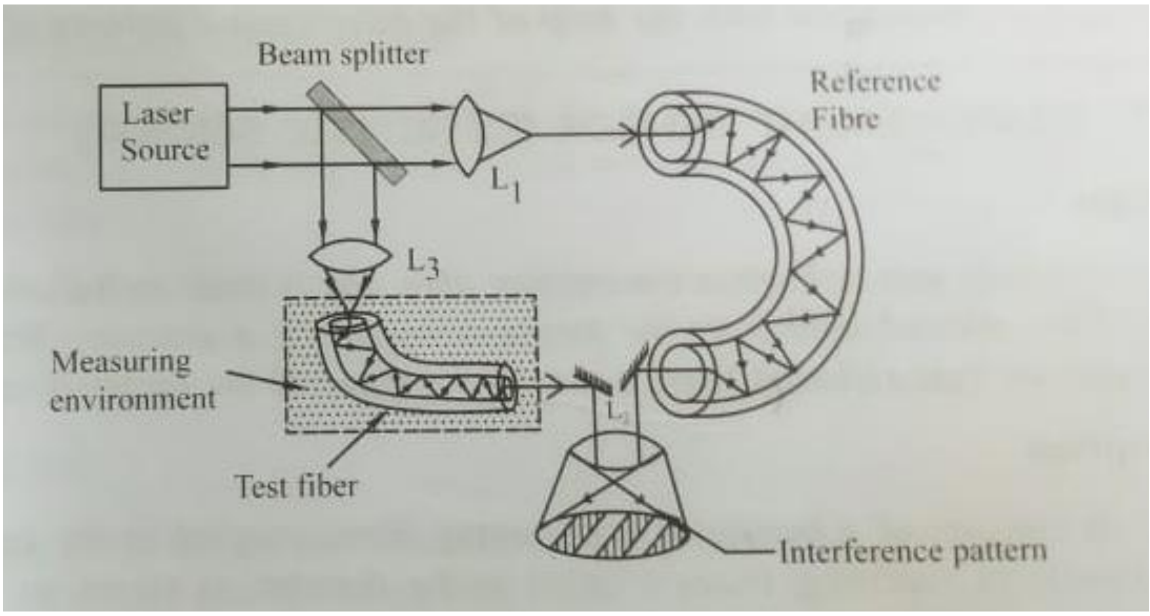
It consists of a laser source to emit light. A beam splitter, made of glass plate is inclined to an angle of 45^{0} with respect to the direction of laser beam. Two fibres

(i) Reference fibre, which is isolated from the environment and

(ii) Test fibre, kept in the environment to be sensed, and are placed as shown in figure. Separate lens system is provided to split and to collect the beam.

Working:

Monochromatic source of light is emitted from the laser source. The Beam splitter kept at 45^{0}-inclination divide the beam emerging from the laser source into two beams, (i) Main beam and (ii) Spitted beam, exactly at right angles to each other. The main beam passes through the lens L1 and is focused onto the reference fibre, which is isolated from the environment to be sensed. The Beam after passing through the reference fibre then falls on the lens L2. The splitted beam passes through the lens L3 and is focus onto the first fibre kept in the environment to be sensed. The splitted beam after passing through the test fibre made to fall on the lens L2. The two beams after passing through the fibres, produces a path difference due to the change in parameters such as pressure temperature etc., in the environment. Therefore, a path difference is produced between the two beams, causing the interference pattern as shown in figure. Thus, change in pressure or temperature can be accurately measured with the help of the interference pattern obtain.



Merits:

1. Weather independent like artificial microwave radiation can penetrate clouds, light rain and snow.

2. Sunlight independent can be operated day and night.

Demerits:

1. The pulse power is mostly low and can be influenced or interfered by other radiation sources.

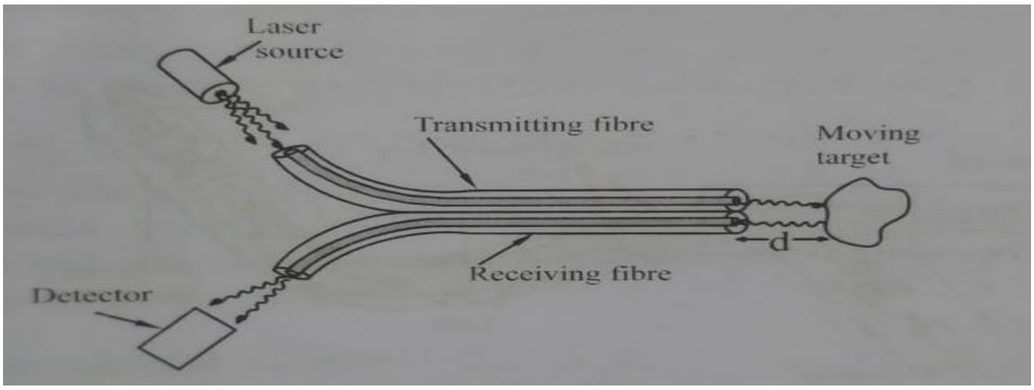
3.17. DISPLACEMENT SENSOR – (EXTRINSIC SENSOR):

Principle:

Light is sent through a transmitting fibre and is made to fall on the moving target. The reflected light from the target is sensed by a detector. With respect to intensity of light reflected from it the displacement of the target is measured.

Construction:

It consists of a bundle of transmitting fibres coupled to the laser source and a bundle of receiving fibres coupled to the detector as shown in figure. The axis of transmitting fibre and the receiving fibre with respect to the moving target can be adjusted to increase the sensitivity of the sensor.



Working:

Light from the source is transmitted through transmitting fibre and is made to fall on the moving target. The light reflected from the target is made to pass through the receiving fibre and the same is detected by the detector. Based on the intensity of light received, the displacement of the target can be measured, i.e., if the received intensity is more then we can say that the target is moving towards the sensor and if the intensity is less, we can say that the target is moving away from the sensor.

Merits:

1. Passive sensors, do not emit energy: they rely on energy that is pre-existing in the environment.

Demerits:

1. Passive sensors can't be detected by observed parties as they only sense what is in the environment rather than relying on a transmitter whose activity might be detected with equipment.

3.18. ADVANTAGES OF OPTICAL COMMUNICATION SYSTEM: (MERITS)

1) It carries very large amount of information in either digital or analog form due to its large bandwidth.
2) The materials used for making optical fiber are dielectric nature. So, it doesn’t produce or receives any electromagnetic and R-F interferences.
3) Fibers are much easier to transport because of their compactness and lightweight.
4) It is easily compatible with electronic system.
5) It can be operated in high temperature range.
6) It does not pick up any conducted noise.
7) Not affected by corrosion and moisture.
8) It does not get affected by nuclear radiations.
9) No sparks are generated because the signal is optical signal.

3.19. DEMERITS

Though fiber optic transmission brings lots of convenience, its disadvantages also cannot be ignored.
1. Fragility: usually optical fiber cables are made of glass, which lends to they are more fragile than electrical wires. In addition, glass can be affected by various chemicals including

hydrogen gas (a problem in underwater cables), making them need more cares when deployed underground.

2. Difficult to install: it's not easy to splice fiber optic cable. And if you bend them too much, they will break. And fiber cable is highly susceptible to becoming cut or damaged during installation or construction activities. All these make it difficult to install.

3. Attenuation & Dispersion: as transmission distance getting longer, light will be attenuated and dispersed, which requires extra optical components like EDFA to be added.

4. Cost Is Higher Than Copper Cable: despite the fact that fiber optic installation costs are dropping by as much as 60% a year, installing fiber optic cabling is still relatively higher than copper cables. Because copper cable installation does not need extra care like fiber cables.

5. Special Equipment Is Often Required: to ensure the quality of fiber optic transmission, some special equipment is needed. For example, equipment such as OTDR (optical time-domain reflectometry) is required and expensive, specialized optical test equipment such as optical probes and power meter are needed at most fiber endpoints to properly provides testing of optical fiber.

Solved Problems

1. Find the ratio of population of two energy levels in a laser if the transition between them produces light of wavelength 694.3 nm. Assume the ambient temperature to be 27ºC.

$$\frac{N_2}{N_1} = e^{-(E_2-E_1)/kT} = e^{-\frac{hc}{\lambda kT}}$$

h = 6.63×10^{-34} J.s
c = 3×10^{8} m/s
λ = 694.3 nm = 694.3×10^{-9} m
k = 1.38×10^{-23} J/K
T = 27ºC = 300 K

$$\therefore \quad \frac{N_2}{N_1} = e^{-\left(\frac{6.63\times10^{-34}\times3\times10^{8}}{694.3\times10^{-9}\times1.38\times10^{-23}\times300}\right)}$$

$$\therefore \quad \frac{N_2}{N_1} = 8.874\times10^{-31}$$

2. A laser beam with power per pulse is 1.0 mW lasts 10 ns. If the number of photons emitted per pulse is 3.941×10^{7}, calculate the wavelength of laser.

$$\mathrm{E} = \mathrm{P}\times\mathrm{t} = \frac{\mathrm{Nhc}}{\lambda}$$

$$\therefore \quad \lambda = \frac{Nhc}{Pt}$$

N = 3.941×10^{7}
h = 6.63×10^{-34} J-s
c = 3×10^{8} m/s
P = 1.0 mW= 1×10^{-3} W
t = 10 ns =10×10^{-9} s

$$\therefore \quad \lambda = \frac{3.941\times10^{7}\times6.63\times10^{-34}\times3\times10^{8}}{1\times10^{-3}\times10\times10^{-9}}$$

= 7.839×10^{-7} m

∴ λ = 7839 Å

3. The average output power of laser source emmiting a laser beam of wavelength 633 nm is 5 mW. Find the number of photons emmitted per second by the laser source.

$$\mathrm{E} = \mathrm{P}\times\mathrm{t} = \frac{\mathrm{Nhc}}{\lambda}$$

$$\mathrm{N} = \frac{\mathrm{Pt}\lambda}{\mathrm{hc}}$$

P = 5 mW = 5×10^{-3} W
t = 1 s
λ = 633 nm = 633×10^{-9} m
h = 6.63×10^{-34} J-s
c = 3×10^{8} m/s

$$\therefore \quad N = \frac{5\times10^{-3}\times1\times633\times10^{-9}}{6.625\times10^{-34}\times3\times10^{8}}$$

∴ N = 1.592×10^{16}

4. The angle of acceptance of an optical fibre is 30º when kept in air. Find the angle of acceptance when it is in medium of refractive index 1.33.
In air,

$$N.A = \sqrt{n_1^2 - n_2^2} = (sin\emptyset_a)_{air}$$

∴ $\sqrt{n_1^2 - n_2^2}$ = sin 30

∴ $\sqrt{n_1^2 - n_2^2}$ = 0.5

In medium of refractive index n_0

$$n_0 sin\emptyset_a = \sqrt{n_1^2 - n_2^2}$$

∴ 1.33 $sin\emptyset_a$ = 0.5

∴ $\emptyset_a$= 22.08°

5. The refractive indices of core and cladding are 1.50 and 1.48 respectively in an optical fiber. Find the numerical aperture and angle of acceptance.

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

n_1 = 1.5, n_2 = 1.48

N.A = $\sqrt{1.50^2 - 1.48^2}$

∴ N.A = 0.244

Angle of acceptance θ_0= $\sin^{-1}$(N.A) = $\sin^{-1}$0.244

∴ θ_0 = 14.123°

6. Calculate the number of modes an optical fiber will transmit given the following data: n_{core} = 1.50, n_{clad} = 1.48, core radius = 50 μm, wavelength of light = 1μm

The number of modes propagating through the fibre is

$$N = \frac{\pi^2 d^2}{2\lambda^2} \times (N.A)^2$$

d = 2×50=100 μm = 100×10^{-6} m

$$N.A = \sqrt{n_1^2 - n_2^2} = \sqrt{1.50^2 - 1.48^2}$$

λ = 1μm = 1×10^{-6} m

$$N = \frac{1}{2}\left[\frac{\pi\times100\times10^{-6}\times\sqrt{1.50^2-1.48^2}}{1\times10^{-6}}\right]$$

N= 2941

7. The refractive indices of the core and the cladding of a step index optical fibre are 1.45 and 1.40 respectively and its core diameter is 45 μm. Calculate its relative refractive index difference, V-number at wavelength 1000 nm and the number of modes.

Relative refractive index difference $\Delta = \frac{n_1 - n_2}{n_1}$

n_1= 1.45, n_2=1.40

∴ $\Delta = \frac{1.45-1.40}{1.45}$

∴ Δ =0.0345

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

d= 45μm = 45×10^{-6} m, λ=1000 nm =1000 ×10^{-9} m

$$V = \frac{\pi\times45\times10^{-6}}{1000\times10^{-9}}\sqrt{1.45^2 - 1.40^2}$$

∴ V = 53.37

Number of modes $N = \frac{V^2}{2} = \frac{53.37^2}{2} = 1424.2$

N = 1424

8. The attenuation of light in an optical fibre is estimated as 2.2 dB/km. what fractional initial intensity remains after 2 km and 6km?

The attenuation in dB is

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

$\therefore$ $$\frac{P_{in}}{P_{out}}(10)^{P_L/10}$$

$\therefore$ $$\frac{P_{out}}{P_{in}} = (10)^{-P_L/10}$$

For a length of 2 km,

$$P_L=2.2\times2=4.4 \text{ dB}$$

$\therefore$ $$\frac{P_{out}}{P_{in}} = (10)^{-4.4/10}$$

$\therefore$ $$\frac{P_{out}}{P_{in}} = 0.363$$

$\therefore$ $$P_{out} = 0.363\ P_{in}$$

For 6 km, $P_L = 2.2\times6 = 13.2$ dB

$$\frac{P_{out}}{P_{in}} = (10)^{-13.2/10} = 0.048$$

$\therefore$ $$P_{out} = 0.048\ P_{in}$$

9. A fibre 500 m long has an input power of 8.6 mW and output power 7.5 mW. What is the loss specification in cable?

$$P_L = 10log_{10}\left(\frac{P_{in}}{P_{out}}\right) \text{ in dB}$$

$$P_{in} = 8.6 \text{ mW}$$

$$P_{out} = 7.5 \text{ mW}$$

$\therefore$ $$P_L = 10log_{10}\left(\frac{8.6}{7.5}\right)$$

$\therefore$ $$P_L = 0.5944 \text{ dB}$$

Length of cable L = 500 m = 0.5 km

Loss specification is $\alpha = \frac{P_L}{L} = \frac{0.5944}{0.5}$

$\therefore$ $$\alpha = 1.1888 \text{ dB/km}$$

10. An optical fibre of 600 mts long has input power of 120 mW which emerges out with power of 90 mW. Find attenuation in the fibre.
The attenuation is given by,

$$P_L = 10log_{10}\left(\frac{P_{in}}{P_{out}}\right) \text{ in dB}$$

$$P_{in} = 120 \text{ mW}, P_{out} = 90\text{mW}$$

$\therefore$ $$P_L = 10log_{10}\left(\frac{120}{90}\right)$$

$\therefore$ $$P_L = 1.25 \text{ dB}$$

Numericals:

1. Find the ratio of population of two energy levels in a Laser if the transition between them produces light of wavelength 694.3 nm. Assume the ambient temperature to be 27^0C. (July 2008)

2. A He-Ne laser is emitting a beam with an average power of 4.5mW. Find the number of photons emitted per second by the laser. The wavelength of the emitted radiation is $6328A^0$. (Jan 2008)
3. Find the number of modes of the standing waves and their frequency separation in the resonant cavity of length 1m of He-Ne laser operating at wavelength 632.8nm. (July 2007, July 2011)
4. The average output power of laser source emitting a laser beam of wavelength 633nm is 5mW. Find the number of photons emitted per second by the laser source? (Jan 2011).
5. The ratio of population of two energy states in a laser is $1.059x10^{-30}$. If the temperature of the system is 57^0C, what is the wavelength of the laser (Dec 2010)
6. A ruby laser emits pulse of 20ns duration with average power per pulse being 100kW. If the number of photons in each pulse is $6.981x10^{15}$, calculate the wavelength of photons. (Jan 2010)
7. An optical glass fiber of refractive index 1.50 is to be clad with another glass to ensure internal reflection that will contain light travelling within $5^0$of the fiber axis. What maximum index of refraction is allowed for the cladding?(Jan 2010)
8. An optical glass fiber of refractive index 1.50 is to be clad with another glass to ensure internal reflection that will contain light travelling within $5^0$of the fiber axis. What maximum index of refraction is allowed for the cladding?(Jan 2010)
9. The angel of acceptance of an optical fiber is 30^0 when kept in air. Find the angle of acceptance when it is in a medium of RI 1.33 (July 2011)
10. An optical signal has lost 85% its power after travelling 400 m of fiber. What is the fiber loss? (July 2007)
11. The angle of acceptance of an optical fiber is 30^0 when kept in air. Find the angle of acceptance when it is in a medium of refractive index 1.33 (Jan 2000)
12. Calculate the numerical aperture, fractional index change and V-number for a fiber of core diameter 40μm and with refractive indices of 1.55 and 1.50 respectively for core and cladding. The wavelength of the propagating wave is 1400nm. Assume that the fiber is in air? (Jan 2008)

Descriptive type questions:

1. Mention the Characteristics of laser beam. Derive the expression for energy density of radiation using Einstein's coefficients. Compare the expression with Planck's equation? (July 2007, July 2008, Jan 2009, Jan 2010)
2. Explain the sketches the basic principle of operation of lasers? (Jan 2007)
3. Explain the construction and working of CO_2 laser with the help of energy level diagram.
4. What are semiconductor diode lasers? Describe the construction and working of Semiconductor laser with the help of energy band diagram. Mention the uses and advantages of diode lasers? (Dec 2010, Jan 2009, July 2007)
5. Describe the recording and reconstruction processes in Holography with the help of suitable diagrams (Jan 2008)
6. Describe briefly the application of lasers in welding, cutting, drilling and in air pollutant measurement. Mention the nature and property of the lasers used in these. (July 2007)
7. Write a note on holographic technique. Mention the applications of holography (July 2007, Jan 2011)
8. Explain the requisites and conditions of a laser system. (July 2011)
9. Describe the principle and working of LIDAR used to measure pollutant in atmosphere (July 2011)
10. Describe the recording and reconstruction process in holography, with the help of suitable diagram (Jan 2010)

11. What is meant by acceptance angle for an optical fiber? Show how it is related to numerical aperture. (July 2007)
12. Obtain an expression for numerical aperture and arrive the condition for propagation (Jan 2009)
13. Discuss types of optical fibers and modes of propagation using suitable diagram. (July 2007,July 2011)
14. Describe the point to point communication system, with the help of a block diagram? (Jan 2010)