Government College of Engineering and Research

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Educational Resource Material (ERM)

Class:Fist year (Common)

Subject:Engineering Physics (107002)

Unit-II: Laser and Optical Fibre

Lectures required:8

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Syllabus:

Laser & Optical Fibre

1. **Lasers**
    - Basics of laser and its mechanism
    - Characteristics of laser
    - Semiconductor laser: Single Hetro-junction laser
    - Gas laser: CO2laser
    - Applications of lasers: Holography, IT, industrial, medical
2. **Optical Fibre**
    - Introduction
    - Important parameters: i) Acceptance Angle ii) Acceptance Cone iii) Numerical Aperture
    - Types of optical fiber-step index and graded index
    - Attenuation and reasons for losses in optic fibers (qualitative)
    - Communication system: basic building blocks
    - Advantages of optical fiber communication over conventional methods.

0.1 Introduction:

LASER, is acronym of **Light Amplification by Stimulated Emission of Radiation** is an artificial light source.It is highly monochromatic, coherent, energetic, directional intense beam of light. Possibility of such light

source and theoretical estimations of probabilistic coefficients (Einstein coefficients) was given by Einstein in the year 1917. Charles H. Townes designed the first successful MASER (microwave amplification and stimulated emission of radiations) in the year 1953 for which Nobel prize was awarded in 1964. T. Maiman in year 1960 demonstrated the first practical laser (Slolid State Ruby Laser) which was based on optical pumping of synthetic ruby crystal that generated pulsed red laser radiation at 694 nm. First gas laser was made by Ali Javan and Bennett using a mixture of He and Ne gases in the ratio of 1 : 10 in the 1960. The first semiconductor diode laser was demonstrated by R.N.Hall in 1962 which was made up of gallium arsenide (GaAs), later in the same year Nick Holonyak developed the first semiconductor visible-light-emitting laser.
Laser has applications in numerous fields. advancements in laser has brought miraculous changes in our life specially in communication, medical, industrial, IT and entertainment fields, and with the help of lasers the quantum computing facilities will be possible in near future.

0.2 Mechanism of laser:

Emission of light from the source is a quantum mechanical process where de-excitation of electron from higher energy level to lower energy level is responsible for emission of radiation (photon) from the source. Material medium is composed of very large number ($\sim$ Avogadro's number, $N_A = 6.02 \times 10^{23}$) of atoms/molecules in a close proximity and every atom is characterized by discrete energy levels. Acording to Bhor's theory, atom can either absorb a photon of energy, $h\nu = E_2 - E_1$ to excite to higher level ($E_1 \rightarrow E_2$) or emit a photon to de-excite at lower level ($E_2 \rightarrow E_1$). Therefore, it is essential to understand these interactions to know about laser radiations. There are following three basic processes which are continuously happening in atomic system.

1. **Absorption**:If the radiation (photon) of frequency, $\nu = (E_2 - E_1)/h)$ interacts with atom in the lower energy state, say E_1, the atom absorbs this photon and get excited to the higher energy state E_2 by a process called as stimulated absorption see the figure (1).
   Such transitions are called as stimulated absorption or induced absorption or simple absorption.

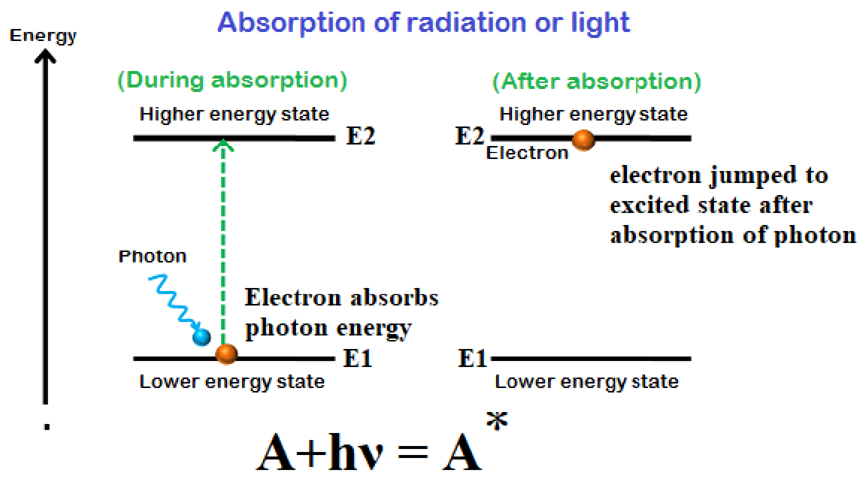

Figure 1: Stimulated absorption of radiation

2. **Spontaneous emission:** The atom already in exited state E_2 stays in excited state for a short duration known as life time,$\tau = 10^{-8} sec$ and after that it spontaneously de-excites to lower energy state E_1 by radiating a photon of frequency, $\nu = (E_2 - E_1)/h)$ as shown in the figure (2). Such Radiations are known as spontaneous emission and emitted photons are incoherent (out of phase), less intense, move in all directions and are random in nature. Moreover, stimulated emissions cannot be controlled from the outside. All natural sources of light emit radiations spontaneously.

3. **Stimulated emission:** If a photon of frequency, $\nu = (E_2 - E_1)/h$ interacts with atom in excited state, (E_2) before spontaneous emission

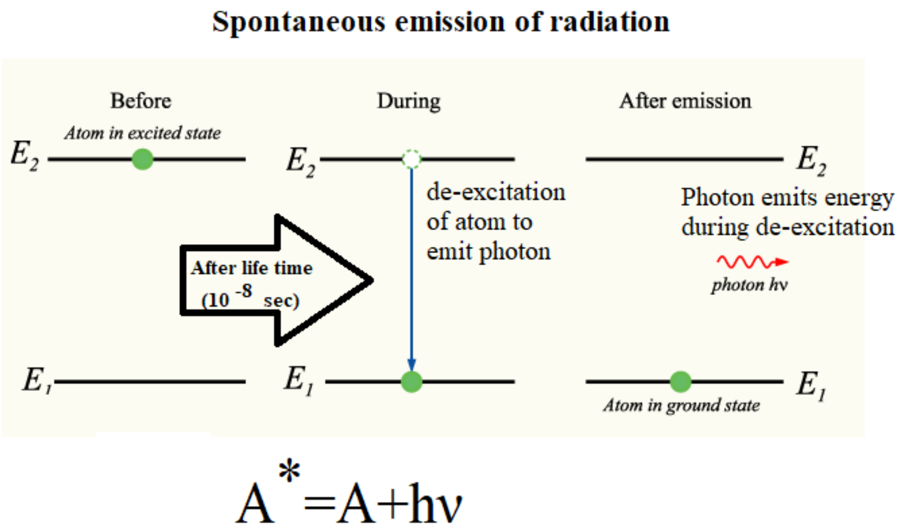

Figure 2: Spontaneous emission of radiation

($\tau \sim 10^{-8} sec$) then de-excitation from higher to lower energy state, E_1 occurs with emission of two photons see the figure (3). Stimulated emission causes amplification of light and hence it is the process responsible for laser action provided other requirements are satisfied.

The notable characteristic of stimulated emission compared spontaneous emission (natural sources) is that the emitted photons have the same frequency, phase, sate of polarization, and direction of propagation as that of incident photons. Interesting fact about stimulated emission is that it can be controlled from outside hence it is artificial source of light and is responsible for the laser.

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0.2.1 Conditions for light amplification

In side any atomic system all the three transitions namely, stimulated absorption, spontaneous emission, and stimulated emission occurs simultaneously.

Let N_1 and N_2 are the number of atoms per unit volume with energy E_1

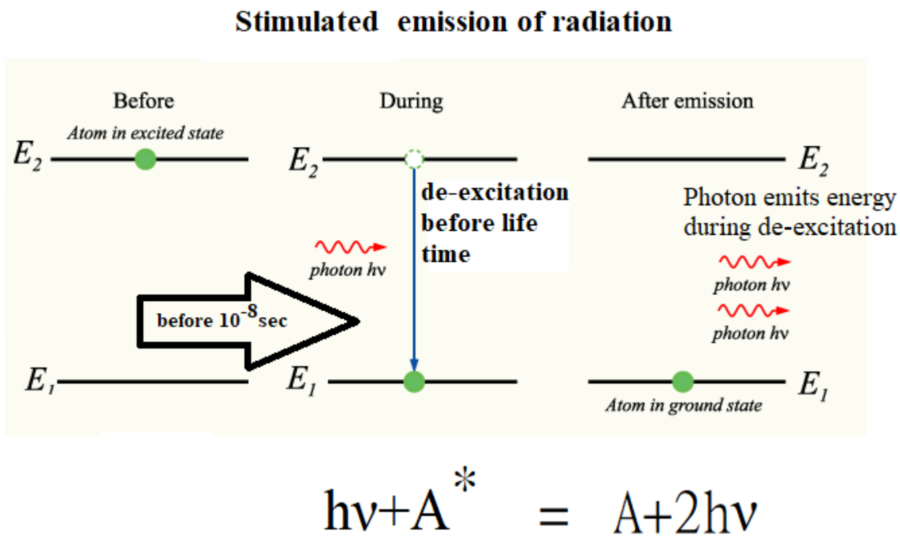


Figure 3: Stimulated emission of radiation

and E_2 respectively. With 'n' be the number of photons per unit volume at frequency ν such that, $h\nu = E_2 - E_1$ then the energy density of interacting photons $\rho(\nu)$ is given by;

$$\rho(\nu) = nh\nu \tag{1}$$

When these photons interact with atomic system, then upward transitions (absorption) and downward transition (spontaneous emission and stimulated emission) takes place simultaneously. At equilibrium these transition rates must be equal.

For every upward transition a photon is absorbed from incident beam which can be written as;

$$A + h\nu = A^* \tag{2}$$

where A and A^* represents atomic system in lower and higher (excited) energy states respectively. The rate of stimulated absorption depends on the number of atoms, N_1 available in the lower energy state, E_1 and the energy density,$\rho(\nu)$ of interacting radiation;

$$N_{abs} \propto N_1$$
$$N_{abs} \propto \rho(\nu)$$
$$N_{abs} \propto \Delta t$$
$$\therefore N_{abs} = B_{12} N_1 \rho(\nu) \Delta t \tag{3}$$

Where, B_{12} is the Einstein's coefficient of absorption or probability of stimulated absorption.

Similarly, for each downward transition there are have two possibilities;

1) Spontaneous emission - if de-excitation occurs after life time ,$\tau = 10 \times 10^{-8} sec$ then single photon is emitted.

$$A^* = A + h\nu \tag{4}$$
$$N_{sp} \propto N_2$$
$$N_{sp} \propto \Delta t$$
$$\therefore \; N_{sp} = A_{21} N_2 \Delta t \tag{5}$$

Where A_{21} is the Einstein's coefficient for spontaneous emission OR probability of spontaneous emission.

2) Stimulated emission - if de-excitation occurs before the life time due to the presence other photon then two photons of exactly same frequency, phase, amplitude, direction and same sate of polarization emitted simultaneously. We can write as following;

$$h\nu + A^* = A + 2h\nu \tag{6}$$

$$N_{st} \propto N_2$$

$$N_{st} \propto \rho(\nu)$$

$$N_{st} \propto \Delta t$$

$$\therefore \; N_{st} = B_{21} N_2 \rho(\nu) \Delta t \tag{7}$$

Where, B_{21} are the Einstein's coefficient for stimulation OR probability of stimulated emission.

For a system in equilibrium, the upward and downward transition rates must be equal and hence we have;

$$N_{abs} = N_{sp} + N_{st} \tag{8}$$

$$B_{12} N_1 \rho(\nu) \Delta t = A_{21} N_2 \Delta t + B_{21} N_2 \rho(\nu) \Delta t$$

$$B_{12} N_1 \rho(\nu) = A_{21} N_2 + B_{21} N_2 \rho(\nu) \tag{9}$$

At thermal equilibrium, the ratio of stimulated transitions to spontaneous transitions is in general very small and stimulated emissions are negligible which can be written as following;

$$\frac{Stimulated\ transition}{Spontaneous\ transition} = \frac{B_{21} N_2 \rho(\nu)}{A_{21} N_2} = \frac{B_{21}}{A_{21}} \rho(\nu) \tag{10}$$

From above equation (10) it is clear that in order to enhance stimulated emissions the radiation density ,$\rho(\nu)$ in medium should be large.

At the same time ratio of stimulated emission to absorption can be written as;

$$\frac{Stimulated\ transition}{Stimulated\ absorption} = \frac{B_{21}N_2\rho(\nu)}{B_{12}N_1\rho(\nu)}$$
$$= \frac{N_2}{N_1} \quad (Assuming\ B_{21} = B_{12}) \tag{11}$$

Equation (11) indicates that stimulated emissions will be larger absorption if $N_2 > N_1$. As long as $N_1 > N_2$ absorption process will dominates stimulated emission process and in this situation medium itself absorb radiations instead of amplification.

Thus, for any medium to amplify the light conditions given by equations (10) and (11) should be fulfilled simultaneously, *i.e.,* radiation density,$\rho(\nu)$ in medium should be very high and number electrons in excited state must be very high with respect to lower state ($N_2 >> N_1$). This can be made possible by feedback of photons in medium and raising large no. of atoms in exited state.

0.2.2 Requirements for laser action:

1. Population inversion: Population inversion is a state of a atomic system where number of electron in exited state (E_2) are much more ($N_2 >> N_1$) than in lower energy level(E_1) or a higher-lying energy level is more strongly populated than a lower-lying level. This cannot occur under thermal equilibrium because the level populations are described by a Boltzmann distribution ($N = N_0 e^{\frac{-E}{K_B T}}$). However, a population inversion is possible and it achieved by applying suitable pumping mechanism see figure (4).

   The population inversion condition required for light amplification is a non-equilibrium distribution of atoms among the various energy levels of the atomic system. By Boltzman distribution the population

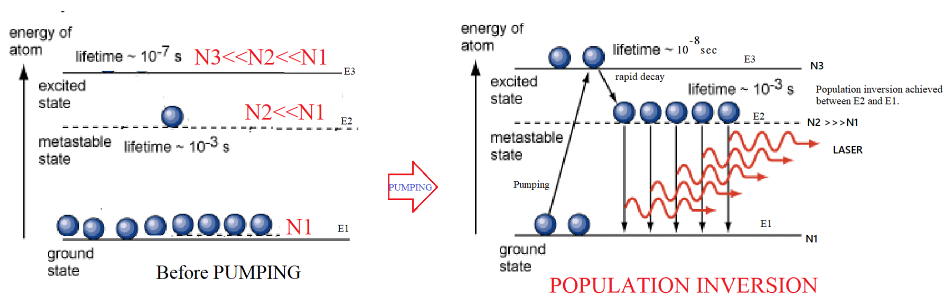


Figure 4: population inversion

for two sates with E_1, *and* E_2 and number of electrons N_1 *and* N_2 respectively can be written as;

$$N_1 = N_0 e^{\left[\frac{-E_1}{K_B T}\right]} \quad \& \quad N_2 = N_0 e^{\left[\frac{-E_2}{K_B T}\right]} \tag{12}$$

$$\therefore \frac{N_2}{N_1} = e^{\left[\frac{-(E_2-E_1)}{K_B T}\right]} \tag{13}$$

The negative exponent in above equation simply indicates that at thermal equilibrium $N_2 <<< N_1$ *i.e.,* Number of electrons in lower energy state are much more that number of electrons in higher energy state. This is called as **normal state**.

When situation is apposite *i.e.,* $N_2 >> N_1$ this condition is known as population inversion which is just apposite to normal state and sometimes described as a state with a **negative temperature**. It does not mean that temperature drops below absolute zero $(0K)$ but it is **non-equilibrium state**.This is because a Boltzmann distribution would lead to such a situation for negative temperatures, which of course cannot occur in reality.

Generally light intensity decreases exponentially when it propagates through any medium this is because radiations are absorbed by lower level electrons *i.e.,* $I = I_0 e^{-\alpha L}$ where α is absorption coefficient and L- length of medium. The phenomenon of population inversion can be understood by considering negative absorption coefficient *i.e.,* $I =$

$I_0e^{-(-\alpha)L} = I_0e^{\alpha L}$. Such medium is medium of negative absorption coefficient and light amplification is referred as **negative absorption**.

2. Pumping: The process by which population inversion can be achieved. There are following mechanisms can be applied to pump the atoms of the active medium to higher energy states to create population inversion.

    - Optical pumping: Optical energy generated by flash lamp can be used to populate higher energy levels . Examples of optically pumped lasers are Ruby, Nd:YAG,Nd:Glass lasers.
    - Electric discharge: In case of gas lasers absorption band of lasing material is very narrow so pumping by flash lamp is not possible. In most of the cases inversion is created by means of electric discharge. Examples of such systems are HE-NE lasers, Argon Ion Laser, CO2 Laser.
    - Chemical reaction: Chemical reaction can also use to excite system in higher level to create of population inversion in few systems. Examples of such systems are HF,DF and atomic iodine lasers.
    - Injection current:In semiconductor lasers, the injection current through the junction results in creation of population inversion among charge carriers.

3. Active system: Atomic system where population inversion is achieved and ready for laser action is known as an active system.

4. Metastable state: Life-time of excited hydrogen atom is about 10^{-8} second. However, some of the excited states have relatively longer lifetime than this *i.e.* about 10^{-3} seconds, such states are known as

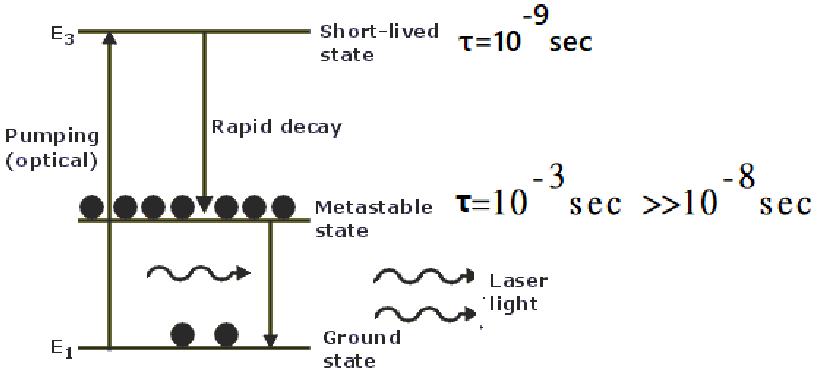


Figure 5: Metastable state a need for population inversion

metastables tates. **In other words, a metastable state can be defined as a state where excited atom can remain for a longer time than normal excited state.** An atom can stay in metastable state for second, minute or even hours also. Metastable states play an important role in laser operation For Example an electron in a state with life time $10^{-3}sec$ can stay about 10^5 times longer than the duration for which it can stay in level with conventional life time $\tau = 10^{-8}sec$ refer figure(5).

5. Resonant cavity:For amplification of radiations there should large number of photons available for stimulation purpose and it will be possible if photons generated in system are fed back by some mechanism. Resonator mirrors are generally coated with multi layer dielectric materials to reduce the absorption loss in the mirrors. Moreover these resonators act as frequency selectors and also give rise to directionality to the output beam. Since the resonator mirrors provide feedback to the photons amplification is possible.

0.3 Characteristics of laser

Laser light has following four unique characteristics that differentiate it from ordinary light.

1. High Monochromaticity: Laser beam is highly monochromatic because its band with (spread of the wavelength (frequency) about the wavelength of maximum intensity) is very small than ordinary light. Where band width, $\Delta\lambda \sim 1000A^o$ for ordinary light it is about $10A^o$ for the laser. This narrow band width of a laser makes it vry special and this property is called as monochromacity $(\zeta = \Delta\lambda/\lambda = \Delta\nu/\nu)$.
   Since Laser is monochromatic source large amount energy can be concentrated and it is very high at extremely small band width.

2. Coherence: A light is said to be coherent if there is a fixed phase relationship between the electric field values at different locations (space) or at different times (temporal). **Photons in laser beam are produced due to stimulated emission therefore, they have the same phase, energy, frequency or wavelength hence laser is highly coherent beam**.
   Coherence can be spacial (space) and temporal (time) coherence, where spatial coherence means a strong correlation (fixed phase relationship) between the electric fields at different locations across the beam profile and Temporal coherence means a strong correlation between the electric fields at one location but at different times.
   The two light fields at different point in space maintain a constant phase difference over any time (t) they are said to be spatial coherence. Coherence length ($L_{coh} = c \times \tau_{coh}$) is the distance for which the phase difference is maintained over any time see figure (6). The Coherence time (τ_{coh}) can be used for quantifying the degree of temporal

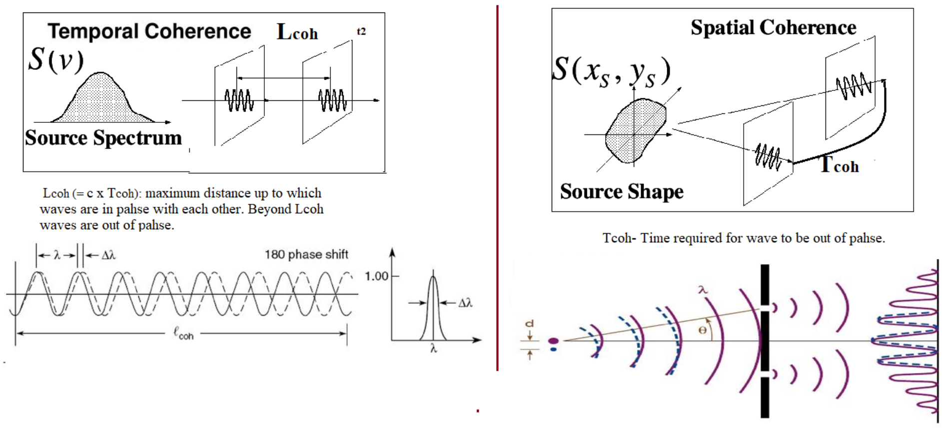


Figure 6: Spatial and temporal coherence

coherence of light. It is the time required for beam to get out of phase by a full cycle see figure (6). or it is the ratio of coherence length ,L_{coh} to phase velocity, v of light in medium. $\tau_{coh} = 1/\Delta\nu = \frac{L_{coh}^2}{c\Delta L_{coh}}$
Due to its coherence only it is possible to create very high power (10^{12} watts) in space with laser beam of $1\mu m$ diameter.

3. High Directionality: The conventional light sources like lamp, torch light, sodium lamp emits light in all directions. This spreading is called as divergence. Laser on the other hand emits light only in one direction so laser is highly directional source of laser light. Where light from ordinary light spreads about few kilometers light from laser spreads about diameter less than 1 cm after many kilometers. The directionality of laser beam is given by (or) expressed in divergence. The divergence $\Delta\theta = \frac{r_2 - r_1}{d_2 - d_1}$ Where r_2, r_1 are the radii of laser beam spots at distances d_2 ,d_1 from the laser source respectively.

4. High Intensity: Intensity of a wave is the energy per unit time flowing through a unit area. Laser light is much brighter and more intense than that from any conventional source. This is due to emitted and

incident photons are perfectly in phase. A laser of $10mW$ power can produce an image of intensity 10^5 watt/cm^2 this property makes it useful in drilling, welding and cutting works.

0.4 Types of laser

Broadly lasers are classified as following.

- Solid state lasers: For eg. Ruby, Nd:YAG, Nd:glass;
- Gas lasers:For eg. He-Ne, Argon ion, and CO2
- Liquid lasers:For eg, dyes, chemical lasers
- Excimer lasers
- Semiconductor Lasers: For eg. diode laser

These laser systems are in widespread use today for different applications

0.4.1 CO2 Laser

The carbon gas Laser is very useful and efficient Laser. It is a four-level molecular Laser and operated at 10.6 mum in the far IR region. CO2 Molecule is bound state of two one carbon atom and two oxygen atoms. In addition to electronic motion constituent atoms in CO_2 molecule can perform vibrational motion and molecule as whole can perform rotational motion. Thus, CO_2 is characterized by vibrational and rotational levels along with electronic levels. In a CO_2 laser the transitions occurring between different vibrational states of the CO_2 molecule can be used for laser action. Various modes of vibrations of CO_2 molecule are shown in fig(7(a)) it shows the CO_2 molecule consisting of a central carbon atom with two oxygen atoms attached on either side. Such a molecule can vibrate with three independent

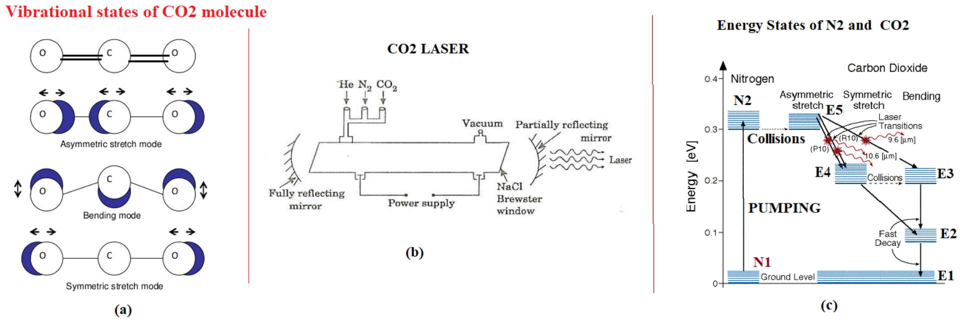


Figure 7: Vibrational modes of CO_2 molecule

modes of vibration shown in fig.(7(a)). These correspond to the symmetric stretch, the bending and the asymmetric stretch modes. Each of these modes is characterized by a definite frequency of vibration. **Construction and working:** CO2 laser consists of a quartz tube about 5m long and 2.5 cm in the diameter. This discharge tube is filled with a gaseous mixture of CO2(active medium), helium (He) and nitrogen (N2) with suitable partial pressures as shown in the figure(7(b)).The terminals of the discharge tubes are connected to a D.C power supply. The ends of the discharge tube are fitted with $NaCl$ Brewster windows so that the laser light generated will be polarized.Two concave mirrors one fully reflecting and the other partially form an optical resonator. The active medium is a gas mixture of CO2, N2 and He. The laser transition takes place between the vibrational states of CO2 molecules.

Working: When discharge current passes through a mixture of gases, the N2 molecules gets excited to metastable state. Given by $N_2 + e^* \rightarrow N_2^* + e$ where $*$ indicates N_2 in exited state after absorbing energy from excited energy. The excited N_2 molecules cannot spontaneously lose their energy and consequently the number of N_2 molecule at meta-stable level builds up. N_2 molecules undergo inelastic collisions with ground state CO2 molecules and excite them to E level as $N_2^* + CO_2 \rightarrow N_2 + CO_2^*$ where $*$ indicates the excited state. Some of CO2 molecules are also excited to upper level through collisions with electrons. The level E_5 is upper Lasing level while E_3 and E_4 acts as a lower lasing level. As E_5 level becomes highly populated, then population inversion achieved between E_5 level and levels E_3 andE_3. Random photons are emitted spontaneously by few of the atoms from level E_5. These photons traveling through a gas mixture produces stimulated emitted photons. The photons travel back and forth between the end mirror, causing more and more stimulated emission. The strength of stimulating photons traveling along the axis of optical cavity, builds up rapidly, while photons traveling at an angle to the axis are lost. Following are the Laser transitions;

$$E_5^* \rightarrow E_4 + h\nu \quad (\lambda \sim 10.6\mu m) \tag{14}$$

$$E_5^* \rightarrow E_3 + h\nu \quad (\lambda \sim 9.6\mu m) \tag{15}$$

Here E3 and E4 levels are also metastable states and CO2 molecules at these levels fall to lower level E2 through inelastic collisions with normal CO2 molecules. So, level E2 again become populated, as gaseous mixture heated, level E2, which is close to ground state will get populated through thermal excitation. Thus, de-excitation of CO2 molecules at a lower lasing level and causes for lasing action. The helium atoms de-excite CO2 molecules through inelastic collision and decreases population density of CO2 at E2 level. CO2 molecules are once again available for excitation to higher state and produces Laser light. CO2 molecules are excited to the upper lasing level through collisions and CO2 works in continuous wave mode.

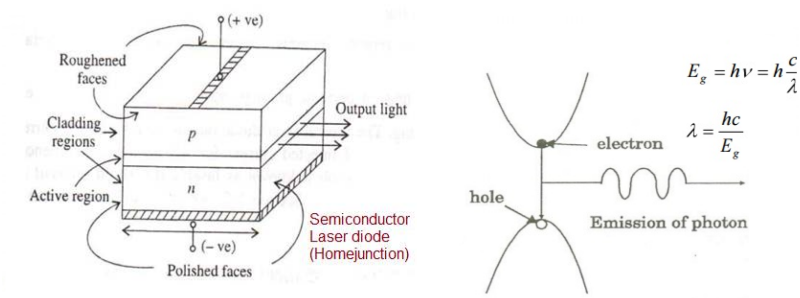
Applications: High power CO2 laser finds applications in material processing, welding, drilling, cutting soldering etc. Due to the low attenuation of 10.6 μm CO2 laser is used in air communication and remote sensing. CO2 is also used in cosmetic surgery.

0.4.2 Semiconductor laser

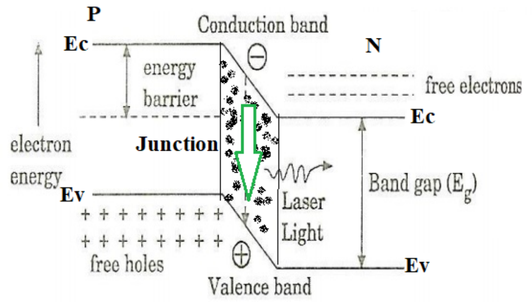
Semiconductor laser is specifically fabricated $P-N$ junction diode with very thin junction. It works in forward biased mode and emit LASER above certain threshold current below which it work as LED.
Direct band gap semiconductors like Ga-As are used for laser diode because the radiations emitted through indirect band gap semiconductors like Si and Ge comes under heat radiations.

In forward biased mode the electrons from N region and the holes from the P region cross the junction and recombine with each other. During the recombination process, the light radiation (photons) is released from a certain specified direct band gap semiconductors like Ga-As. This light radiation is known as recombination radiation see fig.(8(a)). The photon emitted during recombination stimulates other electrons and holes to recombine. As a result, stimulated emission takes place which produces laser.

:Homojunction Semiconductor laser is made from heavily doped PN junction diode. where junction is very thin about $100\mu m$ and apposite sides are polished to form resonator. It is a two level laser where population inversion is achieved due to forward current. Initially under forward voltage large number of electrons and holes enter in junction. Thus very large number of electrons are available in conduction band of N region. After life time recombination of electron hole pair creates spontaneously emitted photons. These photons can be used as simulators to initiate stimulated emission. If forward current increases beyond certain critical value (I_C) population inversion takes place and laser action starts as shown in figure (8(b)). As long as $I > I_C$ radiations are stimulated and laser action continues. The energy



(a)



(b)

Figure 8: Homojunction laser

gap and wavelength of emitted radiation can be written as following;

$$E_g = E_c - E_v = h\nu = h\frac{c}{\lambda} \implies \lambda = \frac{hc}{E_g} \tag{16}$$

0.4.2.1 Hetro-junction-semiconductor laser

Single heterojunction semiconductor laser consists of P-N Junction with different materials on two sides of the junction. For example: GaAS-GaAlAs heterojunction.

Construction: In single hetro-junction LASER, a layer of low band gap material like P-(Ga As) is sandwiched between P-(GaAl)As and n-(GaAl)As

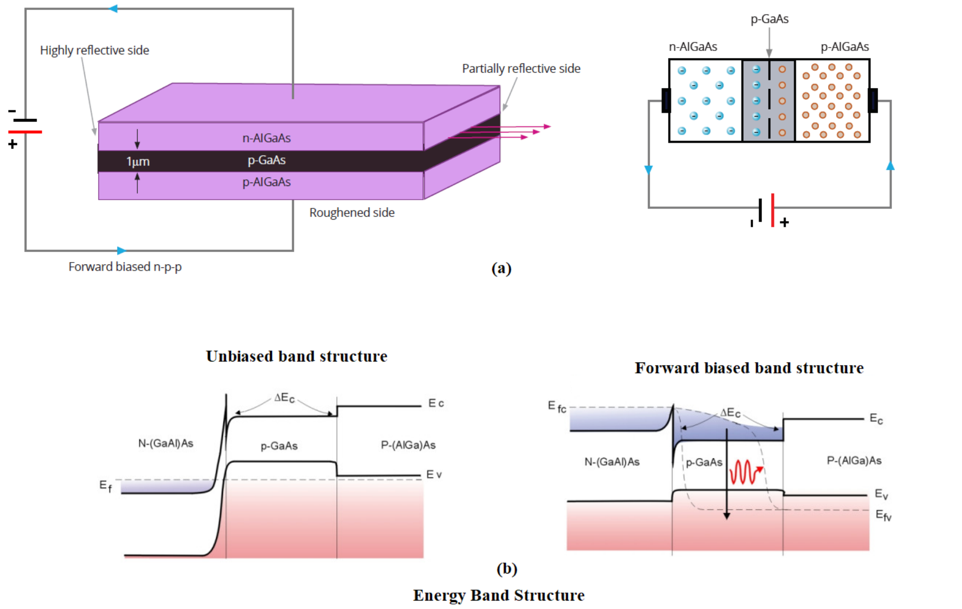


Figure 9: Hetrojunction laser

as shown in the figure (9 (a)). These layers have different refractive indices.The top layer $P-(AlGa)As$ has higher band gap and lower refractive middle $P-GaAs$ layer. The refractive index of middle layer is higher than outer layers. **The middle layer, P-GaAs acts as an active region**. The layer above $P-(GaAl)As$ acts as a barrier for the injected carriers. The top and bottom faces have metal contacts to apply forward biasing. The Front and rear faces are polished, which work as a resonator.

Working: Lasing action occurs in middle $P-GaAs$ layer. When forward voltage is applied large number of electrons and holes are injected in the active region.When diode current $(I \geq I_c)$ *i.e,* threshold current, carrier concentration in the active layer of $P-GaAs$ reaches to maximum. The electrons are injected from the $n-(GaAl)As$ layer in the active layer of $P-GaAS$. Due to change in refractive index at boundary of $P-(GaAl)As$ and $P-(GaAl)$ electrons are reflected back into active region. Therefore, under application of forward voltage population inversion is achieved by shifting large population of electrons and holes in conduction band (CB) and valence band(VB) respectively. The recombination of an electron in CB with holes in VB emits photons due to spontaneous emission. These spontaneous photons propagate in active layer stimulates conduction electrons to jump into vacant states in VB and produce stimulated photons. The reflection of photons from polished ends within the active layer produces further stimulated emissions and laser action starts as shown in figure (9(b)).

Advantages of lasers:

1. It is very small in size,simple and compact and requires little auxiliary equipment.
2. It exhibits high efficiency.
3. The laser output can be controlled by changing junction current.
4. It is operated with lesser power than ruby and CO2 laser.
5. Output can be continuous as well as pulsed.

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

0.5 Applications of lasers

applications of laser are found on various fronts like, communication, entertainment, medical, industry, defense, research and development. Following are some important applications of lasers.

0.5.1 Holography

The word holography is derived from Greek word holos means entire and graphy means recording. Holography is a technique of recording and reconstructing three-dimensional images, which are based on interference phenomena. In holography both amplitude as well as phase of interfering rays are recorded whereas in 2D photography only amplitude is recorded. Hologram is different than photograph where on cannot see the object directly, but it needs the light source of same wavelength when it as recorded and need to be sent in specific angle on a film to reconstruct the image. Even a small piece of hologram can reproduce complete image which not applicable for photograph.

Recording and reconstruction of Hologram: Coherent beam is the prime requirement for hologram recording, therefore laser is the most suitable light source for this work.

Holographic recording: The arrangement for hologram recording is as shown in figure (**??**) Laser light from source is divided into two beams *i.e.,* object beam and a reference beam. For this beam splitter or mirror mirror is used to obtain the reference beam and object beam. The object beam is allowed to incident on the object on reflection it carries information of object. Then these two beams *i.e.* object beam and reference beams are incident a photographic plate after interference a complex interference pattern is recorded on photographic plate as shown in figure(**??**(a)). The developed photographic plate is known as hologram shown in figure.

Holographic reconstruction: To reconstruct hologram or 3D image the reference beam is allowed to incident on the film with specific angle. The hologram acts as a diffraction grating and secondary waves from hologram interfere constructively or destructively to produce diffraction pattern. The diffraction pattern consists and real and virtual images of object which can be seen as shown in the figure(**??**(b)). The real image is in front of hologram

and virtual image at the back of hologram. When the observer observes a virtual image along with real image can see 3-D image of the object. Holograms are known as Fresnel hologram if object is palced at finite distance from photographic plate. If object is at infinite distance then it is said to be the Fraunhoffer's hologram.
Applications of holography:

- It is used to produce a 3-D image of an object.
- The holograms are capable of storing large amount of data and mainly in ROM devices it can be used to store large information in future.
- It can be used to study air pollution and measurements of size, density distribution, and velocity of a particle.
- It is also used to determine stress in the material.
- It is used to study a certain specimen at the microscopic level

0.5.2 Industrial applications

It is possible to focuss powerful lesser beam on small area with help of lens lasers found useful in industry for various operations. The extreme small beam size and proper control over energy (intensity) lasers are used extensively for drilling, welding and micro-machining.
Drilling: A laser beam is also used to drill holes of micron dimensions of printed circuit boards (PCB). One can drill holes of diameter of 10 micrometer through very hard substances like diamond. Holes can be drilled into materials using high power pulsed lasers of $10^{-4} - 10^{-3}$ sec duration. The laser pulse is capable of evaporating material leaving a hole behind with precise dimensions without any irregularities. As there are no mechanical vibrations, holes can be drilled very close too.
Welding: Lasers are used as a heat source in welding the joints of the metals. A high-power laser is focused on the line of contact. The metal at

the line of contact melt and solidifies on cooling, which causes two plates to stick together. Since it is contact less procedure, possibility of introducing impurities reduces drastically. due to its preciseness laser welding is extremely important in micro-electronics where which thin films are used. Laser welding is commonly used in automobile, ship building and aircraft manufacturing industries. Co2 and Nd-YAG lasers are used for this purpose.

Micro-machining: Lasers are used for machining a surface in a time-consuming and an exact manner to achieve an extraordinary smooth finish. It is based on principle of vaporization of material. In this method, the materials along cut or removed for which pulsed laser issued. The efficiency of operation is increased by using a stream of gas along with the laser beam. For cutting brass, copper v and aluminum Nd-YAG laser is used. Laser is used for splitting the card boards and for cutting of thermoplastic.

0.5.3 Medical applications

The special properties of lasers like high energy, narrow band gap, coherent and powerful beam makes it very special and it is much better than sunlight or other light sources. The beams can be focused to a very small point, giving them a high power density. These properties have led to lasers being used in many areas of medical diagnosis and treatment. Following are few applications of lasers in medical field;

- Lasers are used in eye surgeries as they can be focused to very small area.
- Lasers are widely used in dermatology for things like tumor, tattoo, hair, and birthmark removal.
- It is also used in ophthalmology, in the treatment of detached retinas.

- Blood less and pain less surgery is possible with laser.
- Lasers are used in painless dental surgeries.
- Low level laser therapy (LLLT) is typically used for therapeutic and/or stimulating skin treatments and involves lower laser power doses than those generally used in surgical operations.
- In surgery, lasers are used to cut, coagulate and vaporize.
- When used for surgical and dental procedures, the laser acts as a cutting instrument or a vaporizer of tissue that it comes in contact with.

0.5.4 Applications in IT

Laser communications are far better than radio as light wavelengths are packed much more tightly than the sound waves and they transmit more information per second with a stronger signal, Lasers are used in communication with the optical fibers instead of telephone cables. One can send and receive the data, video and other information, using lasers to encode and transmit the data at rates 10 to 100 times faster than conventional methods. Data exchange is relatively easy with lasers and laser communications are solutions to satisfy increasing bandwidth needs, it can transmit speeds of up to a gigabit per second, with assurance of much faster data traffic at lower power consumption.

0.6 Fiber Optics:

Introduction: Fiber optics is a technology which deals with the transmission of light through thin fiber made from glass or plastic. The total internal reflection principle makes it possible to transfer a light ray over large distances through the optical fiber with minimum losses. Fiber optics plays significant role in the field of communication to transmit audio and/or visual signals from one place to another. Such transmission of light along the thin cylindrical glass fiber was first demonstrated by **John Tyndall in 1870** however, its application in the field of communication was tried first time in the year 1927. In 1950, the transmission of images through optical fibers was realized in practice. The term optical fiber was first time assigned by Kapany when Hopkins and Kapany developed the flexible fiberscope for medical application *i.e. for viewing the interior of human body. The invention of solid state lasers in 1970 made optical communications practicable. Commercial communication systems based on optical fibers are widely used in numerous areas. Fiber-scopes made of optical fibers are widely used in a variety of forms in medical diagnostics. Sensors for detecting electrical, mechanical, thermal energies are made using optical fibers. The Fiber optical communications have transformed the telecommunication industry miraculously. Due to its consistent performance and reliability, fiber optics become the first choice for Ethernet backbone infrastructure, high-speed internet services, and general data networking. Optical fibers can meet the demand for IP-based devices which requires high bandwidth.*

0.6.1 Total Internal reflection:

To understand the working of optical fiber one need to understand the total internal reflection. We know that, when the light ray enters from denser medium to rarer medium the refracted ray bends away from the normal. If angle of incidence (i) is greater than certain critical angle ($i \geq i_C$)*, then the refracted ray again reflects into the same medium. This phenomenon is called total internal reflection (refer fig.10).*

If a light ray traveling from denser medium ($\mu = n_1$) *to rarer medium* ($\mu = n_2$) *with an angle of incidence* i*, then the angle of refraction* r *can be*

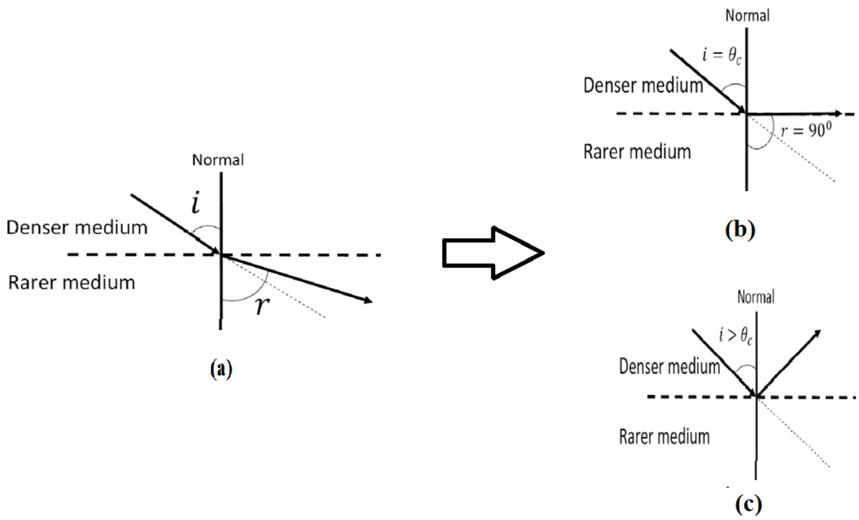


Figure 10: Total internal reflection

obtained by Snell's law (fig.10 a)

$$n_1 sin(i) = n_2 sin(r) \tag{17}$$

When the angle of incidence is increased angle of reflection also increases and for a particular angle of incidence ($i = \theta_c$) the refracted ray travels along the interface of two mediums (fig.10 (b)). This angle of incidence is known as critical angle (θ_c). If angle of incidence further increases ($i > \theta_c$) the refracted ray travels in the same medium as shown in the fig. 10 (c).

$$n_1 sin(\theta_c) = n_2 sin(90) \tag{18}$$

$$n_1 sin(\theta_c) = n_2 \implies sin(\theta_c) = \frac{n_2}{n_1} \tag{19}$$

$$\therefore \theta_c = sin^{-1}\left(\frac{n_2}{n_1}\right) \tag{20}$$

The total internal reflection occurs at the inter-face between two media of different refractive indices. When light is incident on the medium of lower index from the medium of higher index, and the angle of incidence of the ray *exceeds the critical value (fig. 10 (c)). This is the mechanism by which light at a sufficiently shallow angle (less than 90^o) may be considered to propagate down an optical fiber with low loss.*

0.6.2 Typical structure of optical fiber:

The optical fiber mainly consists six parts as shown in the figure (11).

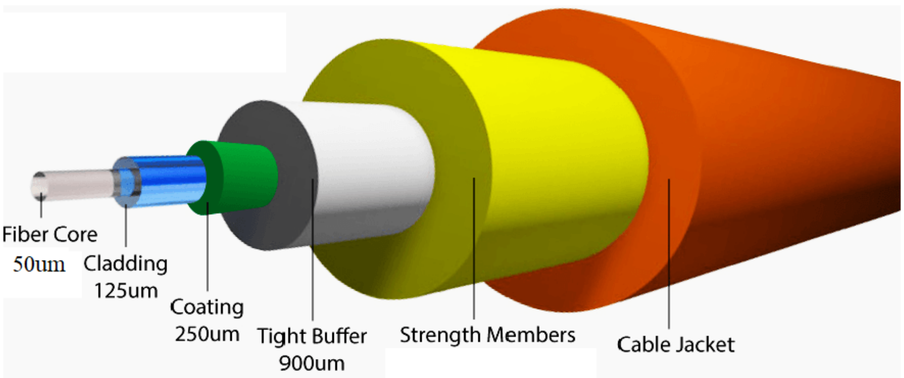


Figure 11: Typical optical fiber

1. ***Core***: *A typical glass fiber consists of a central core material made from glass/silica. Generally core diameter is about $50\mu m$. The core is surrounded by cladding. The core medium refractive is always greater than the cladding refractive index in order to satisfy the total internal reflection.*

2. ***Cladding***: *Cladding covers core and having refractive index is lower than the core. The diameter of cladding is about $125\mu m$ - $200\mu m$. The core cladding boundary plays important role in keeping signal inside the core.*

3. ***Silicon Coating***: *Silicon coating is provided between buffer jacket and cladding. It improves the quality of transmission of light.*

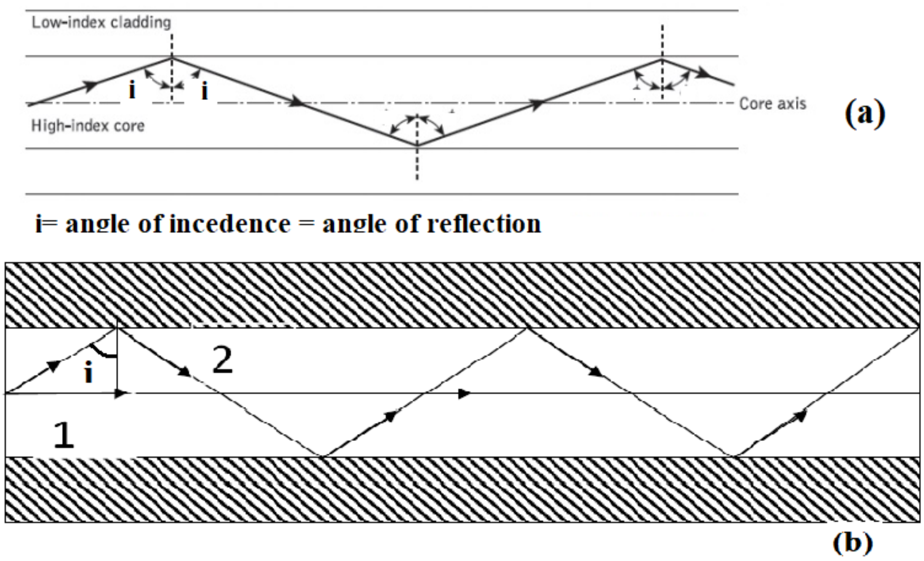


Figure 12: Light ray suffering series of total internal reflection inside the fiber

4. ***Buffer Jacket:*** *Buffer jacket is made of plastic and protects the fiber cable from moisture.*

5. ***Strength Member:*** *Buffer jacket is surrounded by strength member. It provides strength to the fiber cable.*

6. ***Outer Jacket:*** *Finally the fiber cable is covered by polyurethane outer jacket. Because of this arrangement fiber cable will not be damaged during pulling, bending, stretching and rolling through the fiber cable is made up of glasses.*

0.6.3 Transmission of light through optical fiber

Figure (12) illustrates the transmission of a light ray inside an optical fiber. The light ray suffers multiple total internal reflections at the interface of the silica core and the slightly lower refractive index silica cladding. The ray with angle of incidence (i) at the interface greater than the critical angle(θ_c) get reflected at the same angle (i) to the normal. The light ray passes through the axis of fiber as shown in the figure (12 (a)) and is known as a merid-

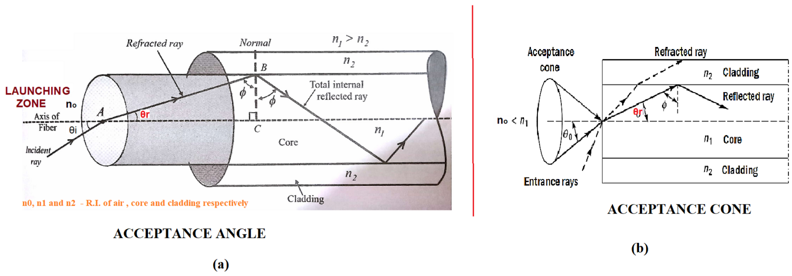


Figure 13: Propagation of light inside optical fiber

ional ray. This type of ray is the simplest to describe and is generally used when illustrating the fundamental transmission properties of optical fibers. It should be noted that the light transmission illustrated in figure (12(b)) assumes a perfect fiber. It may lead to loss of light in case of any discontinuities or imperfections at the core-cladding interface which probably result in refraction rather than total internal reflection.

0.6.4 Acceptance angle, Acceptance cone and Numerical Aperture(NA)

*The function of optical fiber is to accept as maximum as possible optical signal from the source. The light gathering capacity of optical fiber depends on core size (core diameter)**Acceptance angle:**The maximum angle of incidence at the launching interface for which the light ray enters into the core and travels along the fiber.*

Consider light is incident on launching zone of the optical fiber as shown in the figure (13 (a)).

Let n_0, n_1 and n_2 are refractive indices of launching medium, core and cladding respectively with $n_1 > n_2$.

Light ray enters in fiber at angle θ_i and refracts with angle θ_r. The angle of *incidence at core-cladding boundary is ϕ. If ϕ is greater than critical angle ($\phi > \Phi_c$) the ray undergo total internal reflection as shown in the figure (13(a)). As long as $\phi \geq \Phi_c$ ray suffers total internal reflection and travel inside the fiber core.*

To determine the acceptance angle for $\phi \geq \Phi_c$ we can use Snell's law.

$$\frac{sin\theta_i}{sin\theta_r} = \frac{n_1}{n_2} \tag{21}$$

if θ_i increased beyond limit the ϕ will drop below critical value (ϕ_c) and ray no more stay inside the fiber and it will escape from the walls.

The largest value of θ_i for which ray stays inside the fiber occurs when $\phi = \phi_c$

From Δ ABC we can write;

$$sin\theta_r = sin(90 - \phi) = cos\phi \tag{22}$$

From eq. 21 and eq. 22 we get;

$$sin\theta_i = \frac{n_1}{n_0}cos\phi \tag{23}$$

$$When \quad \phi = \phi_c$$

$$sin\theta_i(max) = \frac{n_1}{n_0}cos\phi_c \tag{24}$$

$$But \quad from\ Snell's\ law\ at\ core\ cladding\ Boundary$$

$$\frac{sin\phi_c}{sin(r = 90^0)} = \frac{n_2}{n_1} \implies sin\phi_c = \frac{n_2}{n_1} \tag{25}$$

$$\therefore cos\phi_c = \frac{\sqrt{n_1^2 - n_2^2}}{n_0} \tag{26}$$

$$substituting\ eq.\ 26\ in\ eq.\ 24\ we\ get;$$

$$sin\theta_i(max) = \frac{\sqrt{n_1^2 - n_2^2}}{n_0} \tag{27}$$

$$taking\ n_0 = 1\ forair\ as\ launching\ medium\ we\ get;$$

$$sin\theta_0 = \sqrt{n_1^2 - n_2^2} \implies \theta_0 = sin^{-1}\left[\sqrt{n_1^2 - n_2^2}\right] \tag{28}$$

$$Where\ \theta_0 = \theta_i(max)$$

$$\tag{29}$$

The angle θ_0 is called as acceptance angle which is the maximum angle of incidence for which the light ray enters into the core and travels along the fiber.

Acceptance cone: *The cone formed with full angle $2\theta_0$ is known as acceptance cone refer figure(**??** (b)) and is defined as **"the cone in which light rays are accepted and transmitted along the optical fiber"**. Beyond this angle (θ_0) light ray enters in fiber but maximum part or light is lost due to refraction at core-cladding boundary.*

Fractional refractive index change(Δ):

The fractional difference between refractive indices of core and cladding is known as fractional refractive index change(Δ).

$$\Delta = \frac{n_1 - n_2}{n_1} \tag{30}$$

Numerical Aperture *In optical fiber Numerical Aperture (NA) is nothing but light gathering ability of the fiber and it is the measure of amount of light that can be accepted by the fiber. NA depends only on refractive indices of core and cladding materials. It plays important role and its value ranges from 0.13 to 0.50 . Large is NA large amount of light is accepted by the fiber. The NA is defined as sin of acceptance angle.*

$$NA = sin\theta_0$$

$$NA = \sqrt{n_1^2 - n_2^2} \tag{31}$$

$$we\ can\ write\ it\ as\ :$$

$$n_1^2 - n_2^2 = (n_1 + n_2)(n_1 - n_2) = \frac{(n_1 + n_2)}{2}\frac{(n_1 - n_2)}{2}2n_1 \tag{32}$$

$$As\ n_1\ and n_2\ are\ close\ to\ each\ other;$$

$$We\ can\ approximate\ \frac{n_1 + n_2}{2} \approxeq n_1$$

$$Thus,\ \left(n_1^2 - n_2^2\right) = 2n_1^2\Delta \tag{33}$$

$$\therefore NA = n_1\sqrt{2\Delta} \tag{34}$$

0.7 Classification of optical fibers

Based on the refractive index of core medium, optical fibers are classified into two categories.

1. ***Step index fiber****: In this type of optical fiber total internal reflections takes place in single step so called as step index fiber. Refer figure (14). The step index fibre can be further classified as 1) Single mode fiber (SMF) which support for single mode and ii) Multimode fiber(MMF) which supports more than one mode.*

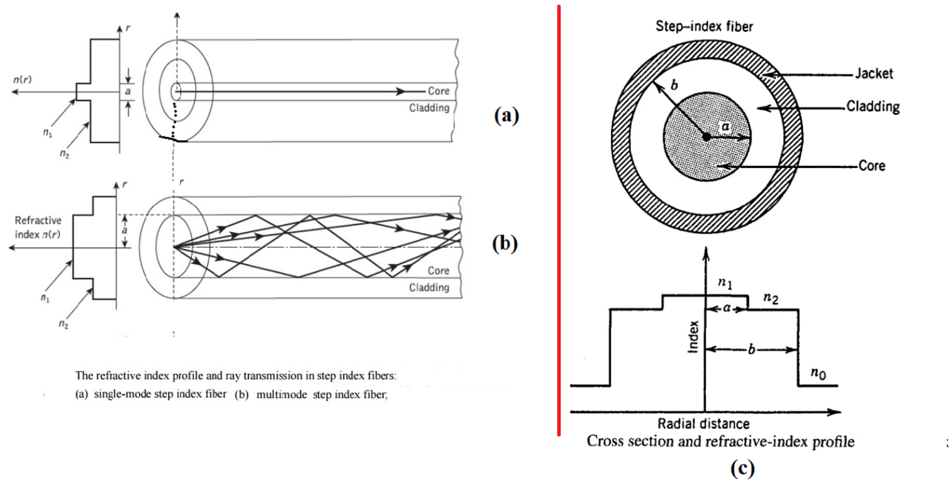


Figure 14: Step index fiber

- *The refractive index of the core is uniform throughout and undergoes on abrupt change at the core cladding boundary.*
- *The diameter of the core 10μm in the case of single mode fiber(SMF).*
- *The path of light propagation is zig-zag in manner*
- *Band width of step index fiber is 50MHz/km.*
- *Numerical aperture is 0.2 to 0.35*
- *Attenuation is high.*
- *SMF has lower bandwidth and the light ray propagation is in the form of meridional rays and it passes through the fiber axis.*

2. ***Graded index fiber(GRIN)****: In graded index fiber, the refractive index gradually decreases farther away from the core, hence making the boundary between cladding and core indistinct.*
   Advantage: The higher index of refraction in the center of the core slows the speed of some light rays, allowing all the light rays to reach the receiving end at approximately the same time, reducing dispersion and increasing bandwidth.

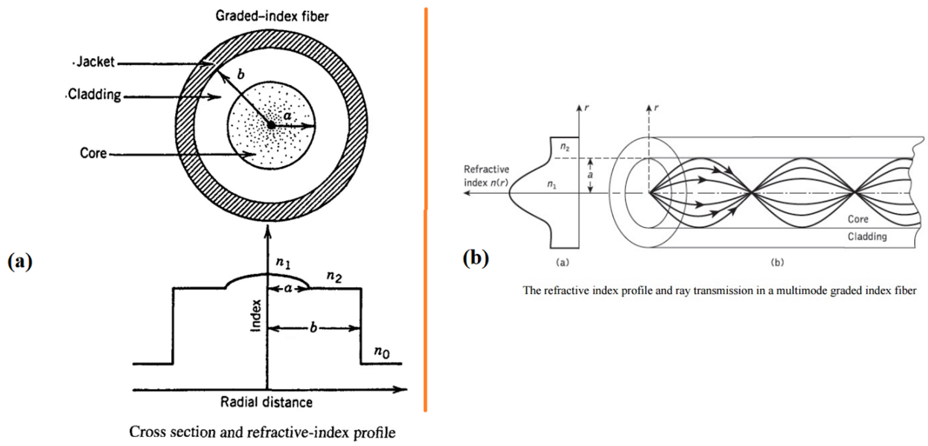


Figure 15: Graded index fiber

- *R.I. of core is not constant but change in parabolic manner see Figure (15).*
- *The diameter of the core is about 50-200 μm.*
- *Bandwidth of GRIN fiber is 200 to 600 MHz/km.*
- *Lower attenuation.*
- *Numerical aperture is 0.16 to 0.2*
- *Pulse dispersion is low because of focusing effect.*

Further, based on the material used, optical fibers are may broadly classified into four categories;
i. All glass fibers
ii. All plastic fibers
iii. Glass core with plastic cladding fibers
iv. Polymer clad silica fibers.

0.8 Attenuation:losses in optical fiber

The attenuation of an optical fiber is the measure of the amount of light lost between input and output or it is the rate at which the light decreases *in intensity. Total attenuation is the sum of all losses. Optical losses of a fiber are usually expressed in decibels per kilometer (dB/km). Attenuation coefficient α is given by following expression;*

$$\alpha = \frac{10}{L} Log \frac{P_i}{P_o} \quad dB \tag{35}$$

Where, P_i is at input of fiber and P_o is power at output end of fiber of length L meters.
Ideally, $P_i = P_o \implies \alpha = 0$ dB/km. Actually typically attenuation is 3 dB/km. The attenuation depends on wavelength of light therefore wavelength should be known well before use of fiber.

0.8.1 Attenuation (losses) mechanisms

The Optical power traveling along the fiber decreases exponentially with distance. There are following important optical fiber losses mechanisms:
1) Absorption,
2) Rayleigh scattering,
3) Macroscopic and microscopic bends
1) Absorption: *As we know that whenever light interact with matter there is absorption of energy even in highly pure glass light is absorbed in specific wavelength range. Especially electronic absorption is dominant at ultraviolet(UV) wavelengths ($\lambda < 0.4\mu$ m and vibrational absorption is dominant it infrared (IR)region i.e.,7-12μ m. Thus, absorption is inherent property of fiber so it is intrinsic absorption. Although intrinsic losses are insignificant. Refer fig. (16).*
Extrinsic losses: impurities present in fiber are main sources of absorption. Transition-metal impurities such as Fe, Cu, Co, Ni, Mn, and Cr absorb strongly in the wavelength range $\lambda 0.6$ 1.6μ u. Their amount should be reduced to below 1 part per billion to obtain a loss level below 1dB/km. Such

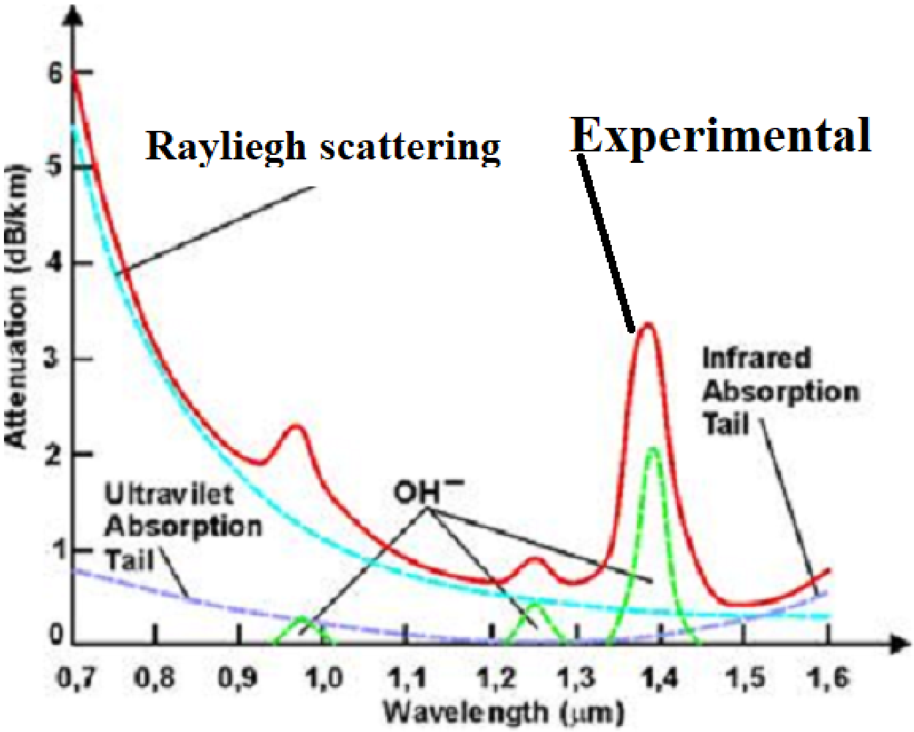


Figure 16: Attenuation in optical fiber

high-purity silica can be obtained by using modern techniques. Refer fig. (16).

A vibrational resonance of the OH^- ion occurs near 2700 nm but most significant OH^- absorption occurs at the 1380 nm , 1230nm and 950nm . The three spectral peaks seen in above figure occur near these wavelengths and are due to the presence of residual water vapor in silica. Refer fig. (16).

2. Rayleigh Scattering: *Rayleigh scattering is a loss mechanism arising from local microscopic fluctuation in density. These density fluctuation while manufacturing of fibers lead to random fluctuations of the refractive index on a scale smaller than the optical wavelength. Light scattering in such a medium is known as Rayleigh scattering. Rayleigh scattering depends on the size of the particles relative to the wavelength of light. Rayleigh scattering proportional to λ^{-4} so it is significant at lower wavelengths. The* *limiting value of Rayleigh scattering is taken as 0.8 μ m below which it becomes very high. Refer fig. (16).* ***3. Macroscopic and microscopic bends:*** *Macrobending happens when the fiber is bent into a large radius of curvature relative to the fiber diameter (large bends). These bends become a great source of power loss when the radius of curvature is less than several centimeters. Macrobend won't cause significant radiation loss if it has large enough radius. However, when fibers are bent below a certain radius, radiation causes big light power loss as shown in the figure (17).*

Microbendings are the small-scale bends in the core-cladding interface. These are localized bends can develop during deployment of the fiber, or can be due to local mechanical stresses placed on the fiber, such as stresses induced by cabling the fiber or wrapping the fiber on a spool or bobbin. Microbending can also happen in the fiber manufacturing process. It is sharp but microscopic curvatures that create local axial displacement of a few microns (um) and spatial wavelength displacement of a few millimeters. Microbends can cause 1 to 2 dB/km losses in fiber cabling process.

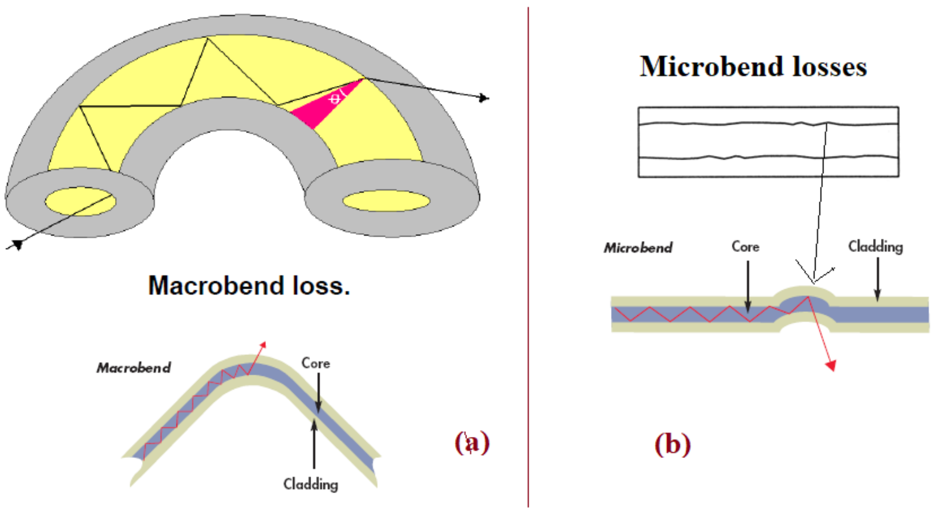


Figure 17: macro bending and micro bending losses

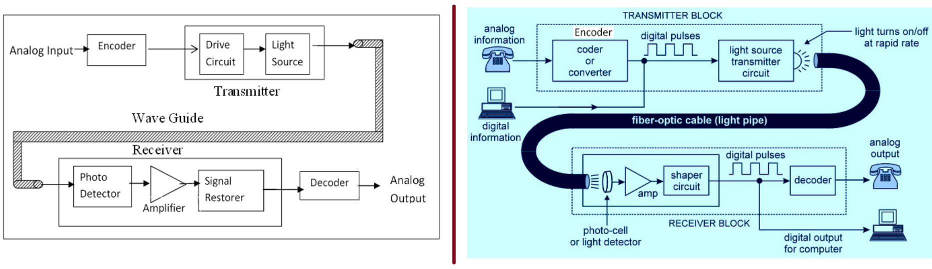


Figure 18: Blocks of Fiber optic communication system

0.9 Optical fiber communication system:

Typical optical fiber communication system mainly consists of the following parts as shown in figure (18).

1. *Encoder: Encoder is an electronic system that converts the analog information like voice, figures, objects etc., into binary data.*

2. *Transmitter:It contain two parts, they are drive circuit and light source. Drive circuit supplies the electric signals to the light source from the encoder in the required form. The light source converts the electrical signals into optical form. With the help of specially made connector optical signals will be injected into wave guide from the transmitter.*

3. *Wave guide: It is an optical fiber which carriers information in the form of optical signals over distances with the help of repeaters. With the help of specially made connector (opto-couplers) optical signals will be received by the receiver from the wave guide.*

4. *Receiver: It consists of three parts; they are photo detector, amplifier and signal restorer. The photo detector converts the optical signal into the equivalent electric signals and supply to hem to amplifier. The amplifier amplifies the electric signals as they become weak during the long journey through the wave guide over longer distance. The signal restorer deeps the electric signals in a sequential form and supplies to the decoder in the suitable way.*

5. *Decoder: It converts electric signals into the analog information.*

0.10 Advantages of optical fiber communication over conventional methods:

1. *Greater bandwidth & faster speed: Fiber-optic cabling is many times faster than traditional copper cabling. The small diameter glass fibers can support bandwidth speeds in-excess of 10-GB speeds per strand. While copper cabling can support these speeds, it would take multitudes of large diameter category 6 cables aggregated together to reach the speeds of one fiber strand. The large amount of information that can be transmitted per unit of optical fiber cable is the most significant advantage.*

2. *Economical: If compared with coaxial cable of equivalent length optical fiber cables are cheaper. moreover they are flexible and easy to handle.*

3. *Thinner and light-weighted: Optical fiber is very thin, and can be drawn to smaller diameters than copper wire. They are of smaller size and light weight than a comparable copper wire cable.*

4. *Higher carrying capacity: As optical fibers are much thinner more fibers can be bundled into a given small diameter cable. This allows more phone lines to go over the same cable or more channels to come through the cable into your cable TV box.*

5. *Secure Communication: Fiber optic cabling is considered one of the most secure means of communication. The construction of the cabling makes interception of the transmission signaling extremely difficult. Any attempts to penetrate the glass cable will cause "light leakage" which in turn will cause noticeable degradation in communications.*

6. *Electromagnetic Compatibility: Fiber optic cabling is resistant electromagnetic interference and is highly recommended where interference due to industrial facilities like large motors, controllers, and air conditioners are constantly starting and stopping are present. Unlike electrical signals transmitted in copper wires, light signals from one fiber do not interfere with those of other fibers in the same fiber cable. This means clearer phone conversations or TV reception.*

7. *Distance: Fiber cable is the ideal means for long-distance, point-to-point hard line communications. The 328ft limit on traditional copper cabling restricts long-distance communication requiring the need of additional equipment to extend the signal. Towards the maximum reach of copper cables, attenuation will start to set in causing a slight reduction of speeds on gigabit transmissions. Fiber cables are far superior and less expensive for long-distance connectivity with the ability to achieve over 10 gigabytes of speed at over 40 km in length.*

8. *Long lifespan:Optical fibers usually have a longer life cycle for over 100 years.*

Disadvantages of Optical Fiber:

- *Low power:Light emitting sources are limited to low power. Although high power emitters are available to improve power supply, it would add extra cost.*
- *Fragility:Optical fiber is rather fragile and more vulnerable to damage compared to copper wires. You?d better not to twist or bend fiber optic cables too tightly.*
- *Distance:The distance between the transmitter and receiver should keep short or repeaters are needed to boost the signal.*

0.11 Numericals:

0.11.1 Numerical based on laser

0.11.2 Numerical based on optical fiber

1.