LASER and Fiberoptics 1

1.1 Introduction to LASER

LASER, which stands for *"Lignt Amplification by Stimulated Emission of Radiation."* , is a technology that has revolutionized various fields, from medicine to telecommunications to manufacturing. It harnesses the unique properties of light to create a focused, intense, and coherent beam of light that can be precisely controlled and manipulated.
The invention of the laser in the 1960s has paved the way for numerous applications, ranging from cutting-edge scientific research to everyday consumer products. With its diverse range of uses and incredible precision, lasers have become an integral part of modern society and continue to push the boundaries of what is possible in many different industries.
In this unit, we will explore the fundamental principles of laser technology, different laser systems, and its wide-ranging applications, showcasing the remarkable impact that lasers have had on our world.

Characteristics of LASER

LASER has important characteristics over ordinary light.

1. **Monochromaticity**
   The laser light is highly monochromatic, i.e., the line width of laser beams are extremly narrow. So the laser beam is more or less single wavelength (Color).
2. **Directionality**
   Spreading of light is called divergence. The divergence is more in ordinary light and lesser in laser light.
3. **Coherence**
   The group of photons coming from the laser are in phase with other photons this property is called coherence. Laser light is more coherent than ordinary light.
4. **Brightness or Hight intensity**
   Intensity of a wave is defines as energy per unit time flowing through a unit normal area. In Laser light, energy is concentrated in small region of space with with greater intensity. A laser beam has brightness many times in magnitude greater than that of conventional sources.

1.2 Interaction of light with matter

The interaction of light with matter is associated with mainly three phenomenon i.e., Absorption, Spontaneous and Stimulated emission of radiation. To describe the phenomenon of absorption, spontaneous or stimulated emission, let us consider two energy levels, 1 and 2, of atoms or molecules of a given material, their energies being E_1 and E_2 ($E_1 < E_2$).

Absorption

Let us now assume that the atom is initially in the ground level,

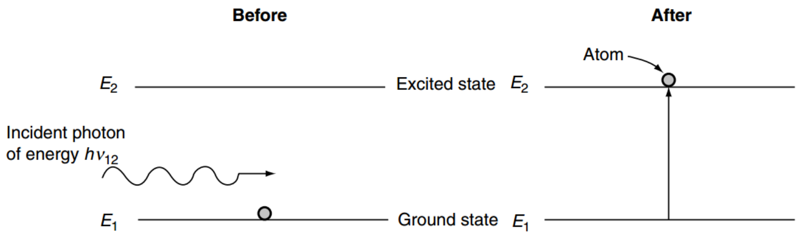

Figure 1.1: Absorption.

the atom will remain in this level unless some external stimulus (photons) is applied to it. We shall assume that, a photon of frequency ν is incident on the material. In this case there is a finite probability that the atom will be raised to level 2. The energy difference $E_2 - E_1$ required by the atom to undergo the transition is obtained from the energy of the incident photon. This is the absorption process.

Spontaneous emission

Let us now assume that the atom is initially in level 2. Since E_2

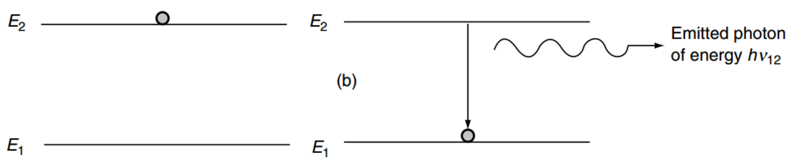

Figure 1.2: Spontaneous emission.

$> E_1$, the atom will tend to decay to level 1. The corresponding energy difference, $E_2 - E_1$, must therefore be released by the atom. When this energy is delivered in the form of an electromagnetic wave called photon, the process will be called spontaneous (or radiative) emission.

Stimulated emission

Let us now suppose that the atom is found initially in level 2 and that a photon of frequency ν is incident on the material (Adjacent

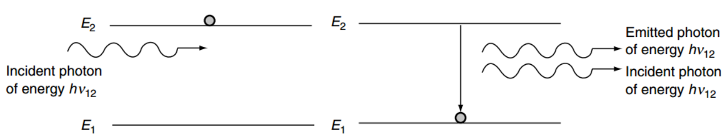

Figure 1.3: Stimulated emission.

Fig.). Since this photon has the same frequency as the atomic frequency, there is a finite probability that this photon will force the atom to undergo the transition 2$\longrightarrow$ 1. In this case the energy difference $E_2 - E_1$ is delivered in the form of a photon. The emitted photon is in phase with the incident photon. These are coherent. This is the phenomenon of stimulated emission.

1.3 The Einstein A & B coefficients

Einstein coefficients are proposed based on the quantum theory of radiation to describe the rates at which atoms or molecules interact with electromagnetic radiation.There are three Einstein coefficients: B_{12}, A_{21}, and B_{21}, each representing a specific type of interaction.
Consider an assembly of N_1 and N_2 atoms per unit volume with energies E_1 and E_2 ($E_2 > E_1$) is irradiated with photons of density $\rho(\nu) = nh\nu$, where n is the number of photons of frequency ν per unit volume. When these photons of energy $h\nu = (E_2 - E_1)$ interact with atoms, both upward (absorption) and downward (emission) transitions occur. At equilibrium these transition rates are equal.

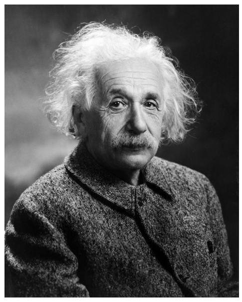

Figure 1.4: Albert Einstein.

Stimulated Absorption or Absorption

When the photons interact with the atoms present in the energy level E_1 then it leads to absorption which is called as stimulated absorption. Stimulated absorption rate depends upon the number of atoms available in the lowest energy state as well as the energy density of photons.
The rate of change of population N_1 due to absorption,

$$\text{The stimulated absorption rate} \quad \frac{dN_1}{dt} \propto N_1$$
$$\frac{dN_1}{dt} \propto \rho(\nu)$$

$$\text{The rate of absorption } (R_{abs}) = \frac{dN_1}{dt} = B_{12}N_1\rho(\nu) \qquad (1.1)$$

Where the constant of proportionality B_{12} is the Einstein coefficient for stimulated absorption.

Spontaneous Emission

Once the atoms are excited by stimulated absorption, they stay in the excited state for a short duration of time called the lifetime of the excited state. After their life time they move to the lower energy level spontaneously by emitting photons. This spontaneous emission rate depends on the number of atoms in the excited energy state. The rate of change of population N_2 due to spontaneous emission,

$$\text{The spontaneous emission rate} \quad \frac{dN_2}{dt} \propto N_2$$

$$\text{The rate of spontaneous emission } (R_{spont}) = \frac{dN_2}{dt} = A_{21}N_2 \quad (1.2)$$

Where the constant of proportionality A_{21} is the Einstein coefficient for spontaneous emission.

Stimulated Emission

Before the de excitation of atoms from excited state to lower energy state they may interact with photons coming from spontaneous emission. Due to this the stimulated emission of photons takes place. Therefore stimulated emission rate depends on the number of atoms available in the excited state as well as the energy density of interacting photons. The rate of change of N_2 due to stimulated emission,

$$\text{The stimulated emission rate } \frac{dN_2}{dt} \propto N_2$$

$$\frac{dN_2}{dt} \propto \rho(\nu)$$

$$\text{The rate of stimulated emission } (R_{stim}) = \frac{dN_2}{dt} = B_{21}N_2\rho(\nu) \quad (1.3)$$

Where the constant of proportionality B_{21} is the Einstein coefficient for spontaneous emission.

During stimulated emission, the interacting photon called the stimulating photon and the photon due to stimulated emission are in phase with each other. Please note that during stimulated absorption, the photon density decreases whereas during stimulated emission it increases.

For an ideal material with only two non-degenerate energy levels, at thermal equilibrium,

Absorption = Spontaneous emission + Stimulated emission

$$R_{\text{abs}} = R_{\text{spont}} + R_{\text{stim}}$$

$$B_{12}N_1\rho(\nu) = A_{21}N_2 + B_{21}N_2\rho(\nu) \quad (1.4)$$

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

$$[B_{12}N_1 - B_{21}N_2]\rho(\nu) = A_{21}N_2$$

$$\rho(\nu) = \frac{A_{21}N_2}{[B_{12}N_1 - B_{21}N_2]}$$

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

$$\rho(\nu) = \frac{A_{21}}{B_{21}}\frac{1}{\left[\frac{N_1}{N_2}\frac{B_{12}}{B_{21}} - 1\right]} \quad (1.5)$$

The population of various energy levels in thermal equilibrium is given by Boltzmann distribution law

$$N_i = N_0 e^{\frac{-E_i}{k_B T}} \tag{1.6}$$

Where, N_0 is population of atoms at temperature $T = 0K$ and k_B is the Boltzmann's constant.

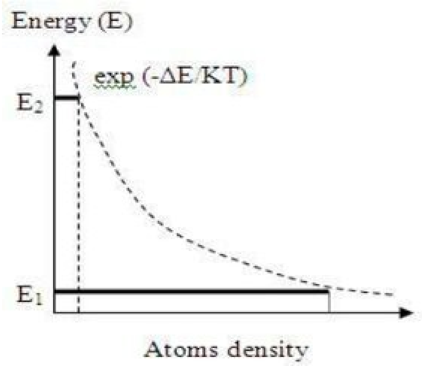

Figure 1.5: Boltzman distribution.

From Boltzmann distribution law,

$$\frac{N_1}{N_2} = e^{\frac{E_2-E_1}{k_B T}} = e^{\frac{h\nu}{k_B T}} \tag{1.7}$$

Substituting 1.19 in 1.17, we get

$$\rho(\nu) = \frac{A_{21}}{B_{21}} \frac{1}{\left[e^{\frac{h\nu}{k_B T}} \frac{B_{12}}{B_{21}} - 1\right]} \tag{1.8}$$

According to Plank's law of black body radiation, the energy density $\rho(\nu)$ at frequency ν and temperature T is,

$$\rho(\nu) = \frac{8\pi h \nu^3}{c^3} \frac{1}{\left[e^{\frac{h\nu}{k_B T}} - 1\right]} \tag{1.9}$$

Comparing 1.20 and 1.21, we get

$$\boxed{\frac{A_{21}}{B_{21}} = \frac{8\pi h \nu^3}{c^3}} \tag{1.10}$$

$$\boxed{\frac{B_{12}}{B_{21}} = 1} \tag{1.11}$$

Equations 1.10 and 1.11 shows the relations between Einstein's coefficients B_{12}, B_{21} and A_{21}.

Conclusions from Einstein's relations:

1. The ratio of Einstein's coefficients (A_{21}) and (B_{21}) is proportional to cube of the frequency of the incident photon,

$$\frac{A_{21}}{B_{21}} \propto \nu^3$$

   This shows that the probability of spontaneous emission increases rapidly with the frequency of incident radiation.
2. The second relation shows that the probability of stimulated absorption is equal to the stimulated emission when the system is in thermal equilibrium.

$$B_{12} = B_{21}$$

Conditions to have LASER

Let us calculate the ratio of rates of spontaneous emission to stimulating emission,

$$R = \frac{\text{Rate of spontaneous emission}}{\text{Rate of stimulated emission}}$$
$$R = \frac{A_{21}N_2}{B_{21}N_2\rho(\nu)}$$
$$R = \frac{A_{21}}{B_{21}\rho(\nu)}$$

Substituting Eq.1.9 and Eq.1.10

$$R = e^{\frac{h\nu}{k_BT}} - 1$$

Case (i): $h\nu \gg K_BT$

Consider a Tungsten filament lamp operating at a temperature of $T = 2000K$ with average frequency $5 \times 10^{14} Hz$,

$$h\nu = 6.626 \times 10^{-34} \times 5 \times 10^{14}$$
$$h\nu = 33.13 \times 10^{-20} J$$
$$K_BT = 1.38 \times 10^{-23} \times 2000$$
$$K_BT = 2.76 \times 10^{-20} J$$
$$h\nu \gg K_BT$$

$$R = e^{\frac{h\nu}{k_BT}} - 1$$
$$R = 1.6 \times 10^5$$
$$\frac{A_{21}}{B_{21}\rho(\nu)} = 1.6 \times 10^5$$
$$A_{21} \gg B_{21}$$

From above result, it can be understood that under conditions of thermal equilibrium, sources operating at higher temperatures and higher frequencies, spontaneous emission predominates.

Case (ii): $h\nu \ll K_BT$

Consider a source at $T = 300K$ and with frequency $3 \times 10^9 Hz$,

$$h\nu = 6.626 \times 10^{-34} \times 3 \times 10^9$$
$$h\nu = 0.0019 \times 10^{-21} J$$
$$K_BT = 1.38 \times 10^{-23} \times 300$$

$$K_BT = 4.14 \times 10^{-21} J$$
$$h\nu \ll K_BT$$
$$R = e^{\frac{h\nu}{k_BT}} - 1$$
$$R = 5 \times 10^{-4}$$
$$\frac{A_{21}}{B_{21}\rho(\nu)} = 5 \times 10^{-4}$$
$$A_{21} \ll B_{21}$$

From above result, it can be understood that under conditions of thermal equilibrium, sources operating at lower temperatures and lower frequencies, stimulated emission predominates.

Case (ii)

Let us consider another case, the ratio of rate of stimulated absorption to stimulated emission,

$$R = \frac{\text{Rate of absorption}}{\text{Rate of stimulated emission}}$$
$$R = \frac{B_{12}N_1\rho(\nu)}{B_{21}N_2\rho(\nu)} \quad (From Eq.(1.11))$$
$$R = \frac{N_1}{N_2}$$

Under normal condition population of lower energy level N_1 is grater than N_2 (i.e., $N_1 \gg N_2$).

From the analysis of Einstein coefficients and relation between them, it is important to maintain conditions to have a LASER,

(a) $B_{21} \gg A_{21}$ i.e., stimulated emission process should be dominating among other phenomenon.

(b) Population inversion should be maintained i.e., $N_2 \gg N_1$.

1.4 Population inversion and Metastable states

Population inversion

The number of atoms present in the excited (or higher) state is greater than the number of atoms present in the ground energy state (or lower state) is called as population inversion.
Let us consider two level energy systems of energies E_1 and E_2 (E_2 > E_1) as shown in figure. Let N_1 and N_2 be the population (means number of atoms per unit volume) of E_1 and E_2 respectively.

According to Boltzmann's distribution law, the population of an particular energy level E_i, at temperature T is given by

$$N_i = N_0 e^{\frac{-E_i}{k_BT}} \tag{1.12}$$

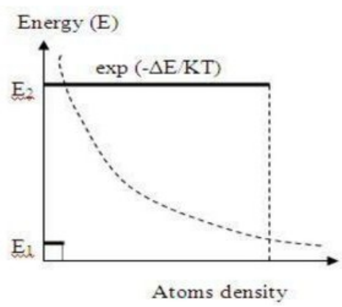

Figure 1.6: Boltzman distibution for population inverted state.

Where, N_0 is the number of atoms at temperature $T = 0K$ and k_B is the Boltzmann's constant. From the above equation the population of energy levels E_1 and E_2 are given by

$$N_1 = N_0 e^{\frac{-E_1}{k_B T}}$$
$$N_2 = N_0 e^{\frac{-E_2}{k_B T}}$$
$$\frac{N_1}{N_2} = e^{\frac{E_2 - E_1}{k_B T}} = e^{\frac{h\nu}{k_B T}}$$

Since $E_2 > E_1$ at ordinary conditions (i.e. at thermal equilibrium) $N_1 > N_2$ i.e., the population in the ground or lower energy state is always greater than the population in the excited or higher energy states.

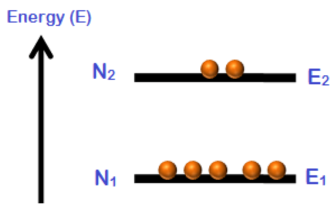

Figure 1.7: A two-level lasing system.

The state of creating, population of higher energy level greater than the population of lower energy level is called population inversion. i.e., $N_2 \gg N_1$.
The system in which population inversion is achieved is known as "active system" or "active medium".
Metastable states
Meta-stable state is an excited state of an atom or a system with a longer lifetime than the typical excited states. However, it has a shorter lifetime than the stable ground state. Normally an atom in the excited state has short life time in the order of 10^{-8} sec. Whereas atoms in the meta-stable state remain excited for a considerable time in the order of 10^{-6} to 10^{-3} sec.
In meta stable state, atoms have greater lifetime so large number of excited atoms are accumulated as a result the population in this state can exceed the population at a lower level thereby establishing population inversion in a lasing medium. Population inversion could not be created without a meta-stable state.

1.5 Pumping

The process of achieving the population inversion by sending the atoms from lower level to higher levels (excited level) through supply of energy to the lower level atoms is called laser pumping. Energy can be supplied in different forms. The supply of energy is usually provided in the form of light (Optical) or electric current (Electrical). But, more exotic sources such as chemical or nuclear reactions can also be used.
Optical Pumping: Optical pumping is a process in which light is used to raise or pump atoms from lower energy level to higher energy level. Xenon flash tube is usually used as source in optical pumping. Solid state lasers are optically pumped using Xenon flash lamps. Since these materials have very broad absorption, thus sufficient amount of energy is absorbed from the emission band of flash lamp and population inversion created. In modern solid state

lasers flash lamps are being replaced by laser diodes for making systems more efficient and reliable.
Examples of lasers which employ optical pumping are Ruby, Nd:YAG, etc.
Electrical Pumping: Gas lasers have very narrow absorption band, hence pumping them using any flash lamp is not possible. Therefore electric discharge method is commonly used in gas lasers. In this method of pumping, electric discharge acts as the pump source or energy source. A high voltage electric discharge (flow of electrons, electric charge, or electric current) is passed through the laser medium or gas. The intense electric field accelerates the electrons to high speeds and they collide with neutral atoms in the gas. As a result, the atoms in the lower energy state gains sufficient energy from external electrons and jumps into the higher energy state.
Examples of lasers which employ electrical pumping technique are He-Ne, Argon ion, etc.

1.6 Three and four level laser schemes

Three level laser scheme:

A three-level laser system is a type of laser in which there are three energy levels involved in the lasing action as shown in Fig.1.8. If collection of atoms are intensely pumped (using Xenon flash lamp) a large number of atoms from E_1 are excited through stimulated absorption to the highest energy level E_3. Because of short life time of atoms in E_3, the atoms decay fast to level E_2. If the level E_2 is a meta stable state then atoms tend to accumulate at E_2. With intense pumping from E_1 to E_3 and because of rapid decay to E_2, it is possible to bring E_2 more populated than E_1 and laser transition takes place between level E_2 (called upper laser level) and E_1 (called lower laser level) as illustrated in Fig.1.8.
Since ground level E_1 happens to be the lower laser level, hence three level pumping schemes generally require very high pump power.
Furthermore, it is not possible to continuously maintain the upper laser level more populated than the lower laser level. Therefore such a system result in a pulsed laser emission.
The Ruby laser is best example for a three level system.

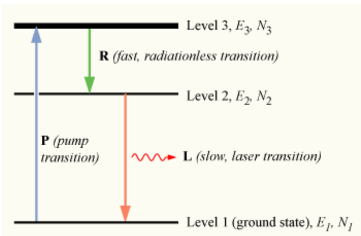

Figure 1.8: A three-level lasing system.

Four level laser scheme:

A four-level laser system is a type of laser in which there are four energy levels involved in the lasing action as shown in Fig.1.9. We start with all the atoms in the ground state 1, and none in the excited states 2, 3 and 4 (E_2<E_3<E_4). Level 4 is chosen so that it has a fast decay to level 3. If level 3 is a meta stable state, then pumping between levels 1 and 4 immediately produces a population

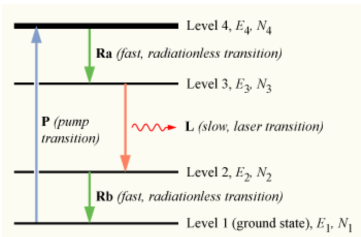

Figure 1.9: A four-level lasing system.

inversion between levels 3 and 2. As level 2 begins to fill up by stimulated emission at the frequency $(E_2 - E_1)/h\nu$, the population inversion will decrease.
To minimize this, level 2 is chosen so that it has a fast decay to the ground state. Since ground level is not the lower laser level there is no need to more than one-half of the population to the higher level.
Furthermore, level E_2 is the lower laser level, it is relatively easier to maintain population inversion between levels E_3 and E_2 continuously with moderate pumping and get continuous wave output. He-Ne laser is a best example for four level laser.

1.7 Construction and working of laser systems

1.7.1 Construction and working of Ruby laser system

The first working laser was built in 1960 by T.H. Maiman using a Ruby crystal and is called the Ruby Laser. This is also called solid state laser or three level laser. Ruby belongs to the family of gems consisting of Al_2O_3 with various types of impurities. In Ruby laser pink ruby crystal is used which contains 0.05% Cr atoms (Al_2O_3+0.05%Cr_2O_3).

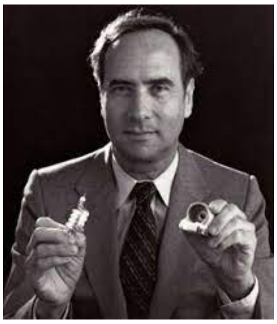

Figure 1.10: Theodore Maiman (1932-2007) was an American physicist and inventor who is best known for creating the first working laser.

Construction:
The Ruby laser consists of a Ruby rod whose length is 2 to 30 cm and diameter is 0.5 to 2 cm. This is made up of with chromium (Cr^{3+}) doped with Al_2O_3. Both the ends of the Ruby rod are silvered such that one end (M_1) is fully reflecting and the other end (M_2) is partially reflecting. Ruby rod with two faces M_1 and M_2 is constitues the resonant cavity, in which the light intensity can be built up by multiple reflections and through stimulated emission. The Ruby rod is surrounded by helical Xenon flash lamp tube which provides the optical pumping to raise Cr^{3+} ions to upper energy level. The schematic diagram of the Ruby laser is shown in Fig.1.11.

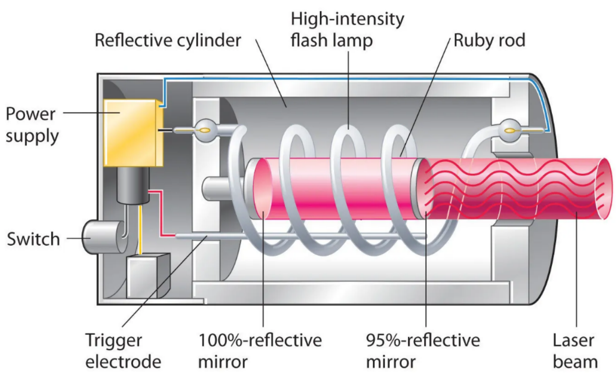

Figure 1.11: Schematic diagram of Ruby laser.

Working:
In Ruby laser Cr ions are active centers which are responsinle

for laser action. A simplified energy level diagram of Cr ions in Ruby crystal as shown in Fig.1.12. In the normal state all the Cr ions are in the ground state E_1. When the light from Xenon flash lamp falls on Ruby rod, Cr ions absorb wavelength of 5500Åfrom incident photons and rise to energy level E_3. Then Cr ions move to E_2 via fast non-radiative transition by giving up energy to the Ruby crystal. The life time of E_2 is around 3 ms act as metastable state, therefore number of ions in this energy level goes on increasing and number of ions in the ground state goes on decreasing. Thus population inversion is achieved by optical pumping.

When Cr ion returns spontaneously from metastable state E_2, it emits a photon of wavelength 6943Å. This photon travels parallel to the axis of Ruby rod and stimulates the Cr ions in the metastable state by which stimulated emission takes place and emitted photons are in phase with stimulating photons. By successive reflection of these photons at fully silvered end M_1 of the Ruby rod, every time the stimulated emission is achieved, we obtain an intense, coherent and unidirectional laser beam of wavelength 6943Åfrom the partially silvered face M_2.
The Ruby laser produce a beam of a pulse of very short duration (about a millisecond) with efficency around 1%.

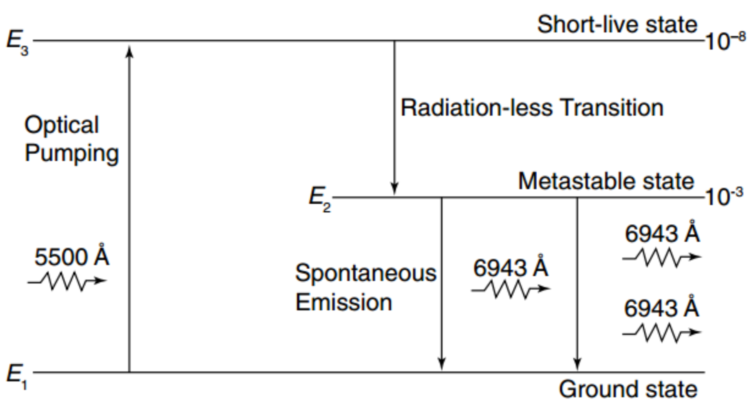

Figure 1.12: Three-level laser system in Ruby laser.

Characteristics of Ruby Laser:

1. **Type:** This is a three level solid state laser
2. **Active medium:** Ruby rod (Al_2O_3+0.05%Cr_2O_3)
3. **Pumping method:** Optical pumping
4. **Optical resonator:** The two ends of Ruby rod which are polished with silver (One is fully reflected while other is partially reflected) are used as optical resonator
5. **Power output:** The power output 10^4 to 10^5 Watt
6. **Frequency output:** 10^4 Hz
7. **Wavelength of output:** 6943 Å

8. **Nature of output:** Pulsed beam of light

Applications: Ruby lasers used in a number of applications where short pulses of red light are required

1. Holography's around the world produce holographic portraits with ruby lasers, in sizes up to a meter squared.
2. Many non-destructive testing labs use ruby lasers to create holograms of large objects such as aircraft tires to look for weaknesses in the lining.
3. Ruby lasers were used extensively in tattoo and hair removal.

Drawbacks:

1. The laser requires high pumping power because the laser transition terminates at the ground state and more than half of ground state atoms must be pumped to higher state to achieve population inversion.
2. The efficiency of ruby laser is very low because only green and blue component of the pumping light is used while the rest of components are left unused
3. The laser output is not continuous but occurs in the form of pulses of millisecond duration

1.7.2 Construction and working of He-Ne laser system

The He-Ne laser was the first gas laser to be operated successfully. It was invented by Ali Javan, W. Bennett and D. Herriott in 1961 using $He - Ne$ gas mixture as a active medium. Ever since its invention it has become on of the most common and popular gas lasers.

Construction:
He-Ne laser consists of a long narrow quartz tube of length $30cm$ and diameter of $1.5cm$. The tube is filled with a mixture of Ne under a pressure of $0.1mm$ of Hg and He under the pressure of $1mm$ of Hg. He-Ne gas mixture is maintained at 10:1 ratio so that the pressure on He atoms is greater than Ne atoms.
The gas mixture is enclosed between a set of parallel mirrors forming a resonating cavity. In which one of the mirrors is completely reflecting and the other is partially reflecting in order to amplify the output laser beam. The energy or pump source of the laser is provided by a high-voltage electrical discharge passed through the gas between electrodes (anode and cathode) within the tube. A DC current of 3 to 20 mA is typically required for CW operation. The schematic diagram of He-Ne laser is shown in Fig.1.13.

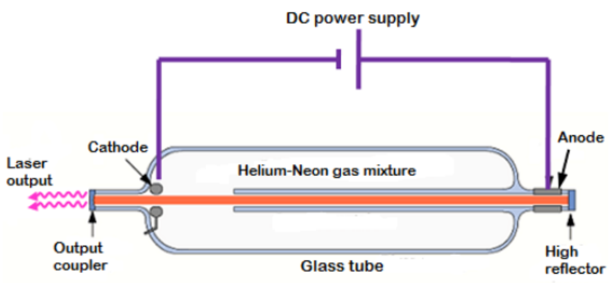

Figure 1.13: Schematic diagram of *He-Ne* laser.

Working:

In the *He-Ne* laser, electrical discharge in the gas tube makes inelastic collision of energetic electrons with ground-state *He* atoms. Due to collions, *He* atoms are excited to the energy level of 20.61 eV which is close to *Ne* higher energy level at 20.66 eV. This makes the energy transfer easier from the *He* to *Ne* atoms. *He* does not directly produce laser light but it acts as a buffer gas, its main purpose to excite *Ne* atoms to produce lasing action.

The active energy levels of *He* and *Ne* atoms are show in the above Fig.1.14. The excited *He* atoms do not return to their ground state by spontaneously emitting photons rather they transfer their energy to the *Ne* atoms through collisions. Thus, the *He* atoms help achieving a population inversion of *Ne* atoms at metastable state 20.66 eV.

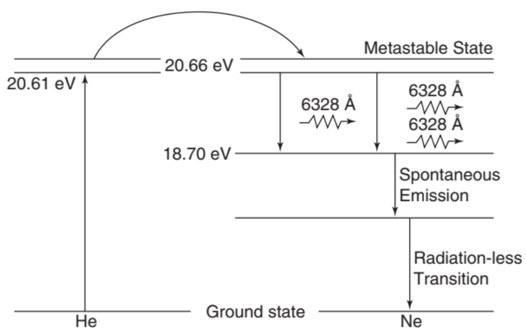

Figure 1.14: Energy level diagram of *He-Ne* laser.

An excited *Ne* atom passes spontaneously from the meta stable state at 20.66 eV to the excited state at 18.70 eV by emitting a photon of wavelength 6328Å. This photon travels through the gas mixture parallel to the axis of the tube and stimulates the surrounding *Ne* atoms present in the meta stable state. In this way photons emitted are in the phase with the stimulating photons. These photons are reflected back and forth by the silvered ends and the number of photons gets amplified through stimulated emission. Finally, a portion of these intensified photons passes through the partially silvered end.

The *He-Ne* laser is the most common and inexpensive gas laser.

Usually it is constructed to operate in the red light at 6328Åand in the infrared at 15,230 Å.

Characteristics of He-Ne Laser:

1. **Type:** This is a four level gas state laser
2. **Active medium:** He-Ne gas mixture
3. **Pumping method:** Electrical pumping
4. **Optical resonator:** A pair of plane mirrors facing each other
5. **Power output:** The power output 1 to 50 mWatt
6. **Frequency output:** 4.7×10^{14} Hz
7. **Wavelength of output:** 6328 Å
8. **Nature of output:** Continuous beam of light

Applications:

1. The narrow red beam of He-Ne laser is used in supermarkets to read bar codes (Barcode scanners)
2. The He-Ne laser is used in Holography in producing the 3D images of objects.
3. He-Ne lasers have many industrial and scientific uses, and are often used in laboratory demonstrations of optics.

Figure 1.15: Semiconductor diode laser.

1.7.3 Construction and working of semiconductor diode laser

A semiconductor diode laser, often referred to simply as a laser diode or diode laser, is a type of laser device that uses a semiconductor material as the gain medium to produce coherent light. It operates on the same principles as other lasers but has unique characteristics and applications due to its compact size, efficiency, and ease of modulation.

A semiconductor laser is a semiconductor diode whose active medium is a forward-biased PN junction diode, which produces light of certain wavelength by recombination of charge carrier when forward biased.

If a p-n junction is formed by a single crystalline material such that the basic material is same on both sides of the junction then it is known as **homo-junction** semiconductor diode laser (e.g. GaAs/GaAs).

Whereas if a p-n junction is formed by two dissimilar semiconductor materials is called **hetero-junction** semiconductor diode laser (e.g. GaAs/GaAlAs)

Principle:

A semiconductor diode laser operates on the principle that, in a direct band gap semiconductor recombination of electron and hole emits photon is called radiative recombination. For example GaAs is a direct band gap (1.44 eV) semiconductor and hence it is used to make lasers. The wave lengths of the emitted light depend on the band gap of the semiconductor material.

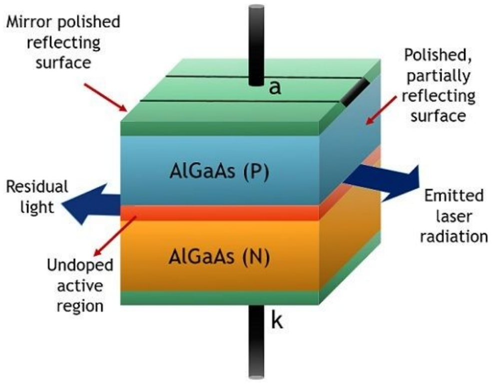

Figure 1.16: Schematic diagram of semiconductor diode laser.

Construction:

In semiconductor diode laser P+ and N- regions of the diode are obtained by heavily doped p-and n-sides of GaAs homo junction. The narrow junction region of GaAs p-n junction diode act as active medium and responsible for laser emission. Well polished side walls of the junction which are parallel to each other constitue a resonating cavity like structure. Since the refractive index of GaAs is high, the reflectance at the material air interface is sufficiently large so that the external mirrors are not required to produce multiple reflections. The p-n junction is forward biased by connecting positive terminal to p-type and negative terminal to n-type.

Working:

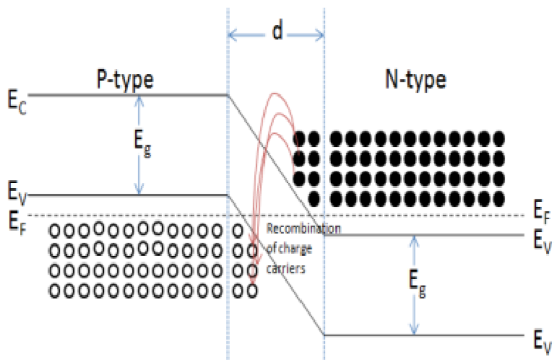

Figure 1.17: Energy level diagram of semiconductor diode laser.

When the p-n junction is not connected in forward bias, there are no electrons and holes present in the junction region or active region. When a small forward bias voltage is given to the $p-n$ junction then small number of electrons and holes will be injected into the active region.
When forward current is I greater than critical current or lasing threshold, injection of more charge carriers into the active region creates the population inversion at the junction which sets the stage for the laser action via stimulated emission.

When electron from conduction band and holes from the valance band recombine at the junction region will emit photon. As these photons move back and forth within junction, they stimulate other excited electrons to undergo recombination which leads to the emission of more photons that have the same frequency and are in phase with the stimulating photons. This results in the amplification of light which is emitted through the partially reflective side of the junction as a highly collimated and coherent laser beam.

Characteristics of semiconductor diode Laser:

1. **Type:** It is a solid state semiconductor laser
2. **Active medium:** p-n junction
3. **Pumping method:** Direct conversion
4. **Optical resonator:** The two ends of the junction which are polished (One is fully reflected while other is partially reflected) are used as optical resonator
5. **Power output:** The output power from the laser is 1mW
6. **Wavelength of output:** 8300 to 8500 Å
7. **Nature of output:** Continuous wave or Pulsed beam of light

Applications:

Semiconductor lasers are the cheapest, smallest lasers, they can be produced in mass scale. Laser output can be modulated by controling the current through the laser diode, and they are highly efficient. These properties have made these lasers well suited for may applications.

1. Telecommunications: Used in optical fiber communication systems for data transmission.
2. Optical Storage: Found in CD, DVD, and Blu-ray players for reading and writing data.
3. Medical Devices: Employed in laser surgery, dermatology, and ophthalmology.
4. Industrial and Scientific Instruments: Used in laser pointers, barcode scanners, and scientific research instruments.
5. Printing: Used in laser printers for high-quality document printing.
6. Material Processing: Applied in cutting, welding, and engraving of materials in industrial processes.
7. LiDAR (Light Detection and Ranging): Utilized in autonomous vehicles, drones, and mapping for precise distance measurement.
8. Optical Sensing: Employed in sensors for detecting various physical parameters like distance, temperature, and pressure.
9. Display Technology: Used in laser projection displays and laser TVs for vivid and high-resolution imagery.
10. Spectroscopy: Applied in analytical chemistry and physics for studying the interaction of light with matter.

1.8 Applications of laser

Due to high intensity, high mono-chromaticity and high directionality of lasers, they have found a multitude of applications across a wide range of industries and fields.

Industrial applications of laser:

Lasers have become an invaluable tool in industrial settings, providing unique advantages over traditional manufacturing processes. Here are some common industrial applications of lasers:

1. **Laser Cutting:** Lasers are widely used for cutting a wide variety of materials, such as metals, plastics, ceramics, and composites. Laser cutting offers high precision, fast cutting speeds, and minimal material wastage compared to traditional cutting methods. It is widely used in industries such as automotive, aerospace, electronics, and sheet metal fabrication to produce complex shapes with tight tolerances.
2. **Laser Welding:** Laser welding is a precise and efficient method for joining materials together. It offers high welding speeds, narrow heat-affected zones, and minimal distortion. Laser welding is commonly used in industries such as automotive, aerospace, and electronics for joining components made of metals, plastics, and other materials.
3. **Laser Marking and Engraving:** Lasers are used for marking and engraving a wide range of materials, including metals, plastics, glass, and ceramics. Laser marking and engraving offer permanent, high-quality, and precise marking solutions for product identification, branding, and traceability in industries such as automotive, electronics, and medical devices.
4. **Additive Manufacturing/3D Printing:** Lasers play a crucial role in additive manufacturing or 3D printing, where successive layers of material are built up to create three-dimensional objects. Lasers are used for melting, sintering, or polymerizing materials in powder or liquid form to produce complex parts with high precision and customization in industries such as aerospace, automotive, and healthcare.
5. **Surface Treatment:** Lasers are used for surface treatment processes such as laser cleaning, surface hardening, and surface texturing. Laser surface treatment can modify the surface properties of materials to improve their performance, durability, and aesthetics. It is used in industries such as automotive, aerospace, and electronics.
6. **Quality Control and Inspection:** Lasers are used for non-destructive testing (NDT) and inspection of manufactured components, such as welds, coatings, and surface defects. Laser-based inspection methods offer high speed, accuracy,

and repeatability, allowing for efficient quality control in industries such as automotive, aerospace, and electronics.

7. **Packaging and Labeling:** Lasers are used for precision cutting, marking, and perforating of packaging materials, such as cardboard, films, and foils. Laser-based packaging and labeling solutions offer high-quality, clean, and permanent marks, and are widely used in the food and beverage, pharmaceutical, and consumer goods industries.

Defence applications of laser:

Lasers have found several applications in the defense and military sectors due to their unique properties and capabilities. Here are some common defense applications of lasers:

1. **Directed Energy Weapons (DEWs):** Lasers can be used as directed energy weapons, also known as DEWs, for defense and security purposes. High-energy lasers can be used to destroy or disable targets such as drones, missiles, rockets, and unexploded ordnance. DEWs offer precise targeting, fast engagement times, and reduced collateral damage compared to traditional kinetic weapons, making them attractive for defense against various threats.
2. **Laser Guided Weapons:** Lasers are used for guidance and targeting of missiles, bombs, and other munitions. Laser-guided weapons use lasers to illuminate a target, and the reflected laser light is detected by sensors on the weapon to accurately guide it to the target. Laser guidance offers high precision and accuracy, allowing for effective engagement of targets with minimal collateral damage.
3. **Countermeasures:** Lasers are used for defensive countermeasures against threats such as missiles, rockets, and drones. Laser-based systems can detect, track, and disable or destroy incoming threats in real-time, providing an effective defense mechanism against potential attacks.
4. **Target Designation:** Lasers are used for target designation, which involves marking or illuminating targets to guide other weapons or assets to the target. Laser target designation is used in applications such as artillery, close air support, and naval targeting, enabling precise and coordinated engagement of targets.
5. **Situational Awareness:** Lasers can be used for enhancing situational awareness on the battlefield. Laser-based sensors, such as LIDAR (Light Detection and Ranging), can provide accurate and real-time information about the environment, terrain, and objects, enabling better decision-making and tactical planning for military operations.
6. **Communication and Sensing:** Lasers are used for secure communication and sensing in defense applications. Laser-

based communication systems offer high data rates, low probability of interception, and enhanced security compared to traditional communication methods. Lasers are also used for remote sensing, such as LIDAR for mapping, reconnaissance, and surveillance purposes.

7. **Countermeasure Jamming:** Lasers can be used for jamming or disrupting enemy sensors and communication systems. High-power lasers can interfere with enemy electro-optical and infrared (EO/IR) sensors, disrupting their ability to detect, track, and target friendly assets.

Medical applications of laser:

Lasers have revolutionized various aspects of medicine and healthcare, offering advanced and precise tools for diagnosis, treatment, and research. Here are some common medical applications of lasers:

1. **Laser Surgery:** Lasers are widely used in various surgical procedures, offering several advantages such as minimal invasiveness, reduced bleeding, faster recovery, and improved precision. Laser surgery is used in various fields, including ophthalmology (eye surgery), dermatology (skin surgery), gynecology (gynecologic surgery), urology (prostate surgery), and many other specialties.
2. **Laser Therapy:** Lasers are used for therapeutic purposes, such as photocoagulation, where the laser energy is used to selectively destroy abnormal or diseased tissue while minimizing damage to surrounding healthy tissue. Laser therapy is used in various medical conditions, including cancer treatment, vascular diseases, skin conditions, and many others.
3. **Laser Diagnostics:** Lasers are used for diagnostic purposes, offering non-invasive and highly sensitive methods for imaging and detection. Laser-based diagnostic techniques, such as optical coherence tomography (OCT), laser-induced fluorescence (LIF), and Raman spectroscopy, are used for early detection, monitoring, and characterization of diseases, including cancer, cardiovascular diseases, and neurological disorders.
4. **Laser Dentistry:** Lasers are used in various dental procedures, such as gum surgery, tooth whitening, cavity removal, and soft tissue surgeries. Laser dentistry offers advantages such as minimal bleeding, reduced pain, and faster healing, making it a popular choice in modern dental practice.
5. **Ophthalmology:** Lasers are extensively used in ophthalmology for vision correction procedures such as LASIK (Laser-Assisted In-Situ Keratomileusis), PRK (Photorefractive Keratectomy), and cataract surgery. Laser-based techniques

are also used for the treatment of various eye conditions, such as glaucoma, retinal disorders, and corneal diseases.

6. **Dermatology:** Lasers are used in dermatology for various skin treatments, such as removal of birthmarks, tattoos, scars, and unwanted hair, as well as for skin rejuvenation and resurfacing. Laser dermatology offers precise and effective treatments with minimal scarring and downtime.
7. **Photodynamic Therapy (PDT):** Lasers are used in conjunction with photosensitizing drugs in a technique called photodynamic therapy (PDT), which is used for the treatment of cancer, as well as certain skin conditions. The laser energy activates the photosensitizing drug, leading to the destruction of targeted cells or tissues.
8. **Research and Biotechnology:** Lasers are used in research and biotechnology for various applications, such as DNA sequencing, gene editing, tissue engineering, and drug delivery. Lasers provide precise and controlled tools for manipulating biological materials, enabling advancements in research and biotechnology fields.

IT applications of laser:

Lasers are widely used in information technology (IT) for various applications, offering high-speed, precise, and reliable solutions. Here are some common IT applications of lasers:

1. **Optical Fiber Communication:** Lasers are the key components in optical fiber communication systems, which form the backbone of modern telecommunications and internet infrastructure. Lasers are used to generate and transmit light signals through optical fibers, enabling high-speed and long-distance communication for data, voice, and video.
2. **Data Storage:** Lasers are used in various data storage technologies, such as CDs, DVDs, Blu-ray discs, and holographic storage. Lasers are used to read and write data on these storage media by using their precise and focused light beams to encode and retrieve information.
3. **Laser Printing:** Lasers are used in laser printers, which are widely used in offices and homes for high-quality printing. Lasers are used to generate a static charge on a photosensitive drum, which attracts and transfers toner onto paper, creating text and images with high precision and resolution.
4. **Laser Cutting and Engraving:** Lasers are used for precision cutting and engraving of various materials, such as metal, wood, plastic, and fabric. Laser cutting and engraving offer high accuracy and speed, making them ideal for manufacturing, prototyping, and customization in the IT industry.
5. **Laser Scanning and Sensing:** Lasers are used in scanning and sensing technologies, such as barcode scanners, LIDAR

(Light Detection and Ranging) systems, and 3D scanners. Lasers are used to emit and detect light to capture and process information from the environment, enabling applications in logistics, mapping, robotics, and virtual reality.

6. **Laser Display and Projection:** Lasers are used in display and projection technologies, such as laser projectors, laser TVs, and holographic displays. Lasers offer high brightness, color accuracy, and long lifespan, making them suitable for large-scale displays, entertainment, and immersive experiences.
7. **Optical Sensors and Detectors:** Lasers are used in various optical sensors and detectors, such as photodiodes, phototransistors, and spectrometers. Lasers are used to generate light signals that are detected and processed to measure physical quantities, such as light intensity, distance, and chemical composition, enabling applications in automation, sensing, and monitoring.
8. **Laser Security and Encryption:** Lasers are used in security and encryption technologies, such as optical security systems and quantum key distribution (QKD) systems. Lasers are used to generate and transmit encrypted information, offering high levels of security and confidentiality in data communication and storage.

1.9 Introduction to optical fiber

Fiber optics is a branch of science and technology that deals with the transmission of light through thin, flexible strands of glass or transparent plastic known as optical fibers. It involves the use of light as a carrier of information for communication, sensing, imaging, and other applications.
The concept of using light for communication dates back to ancient times, but the modern era of fiber optics began in the 1960s with the development of low-loss optical fibers and the invention of the laser, which made it possible to generate and manipulate light in a controlled manner. Since then, fiber optics has rapidly evolved and revolutionized various fields, including telecommunications, data communications, medicine, aerospace, defense, and more.

Fiber optics has numerous advantages over traditional copper-based communication systems. Optical fibers are capable of transmitting signals over much longer distances without significant signal degradation, have higher bandwidth and data capacity, are immune to electromagnetic interference, and are more secure as they do not radiate or leak signals.

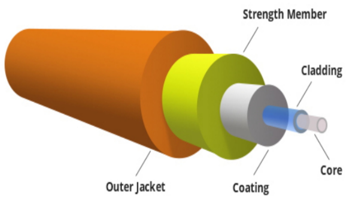

Figure 1.18: Optical fiber.

1.10 Construction and working principle of an optical fiber

Optical Fiber: A very thin, long, flexible, transparent, cylindrical dielectric medium which guides the light signal propagated through it.
It consists of three parts:

1. **Core**
2. **Cladding**
3. **Outerjacket**

(i) The core is the inner part of the fiber, which guides the light signal.
(ii) The cladding surrounds the core completely.
(iii) The refractive index of the core (n_1) is greater than the cladding (n_2) to satisfy the total internal reflection ($n_1 > n_2$).
(iv) The outer jacket provides the mechanical protection to the fiber.

Working principle of an optical fiber
The transmission of light in optical fiber is based on the principle of total internal reflection. Let n_1 and n_2 be the refractive indices of core and cladding respectively such that $n_1 > n_2$. Let a light ray travelling from the medium of refractive index n_1 to the refractive

index n_2 be incident with an angle of incidence θ_1 and the angle of refraction θ_2.

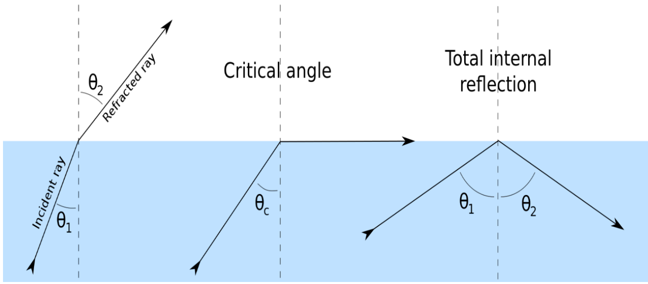

Figure 1.19: Total internal reflection.

From Snell's law,

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{1.13}$$

In optical fiber, the light ray travels from core (denser) to cladding (rarer) medium, there is possibility of total internal reflection, if the angle of incidence is greater than the critical angle (θ_c).

Critical angle (θ_c): When a light ray moves from high refractive index (core) medium to low refractive index (cladding) medium and for a particular angle of incidence the refraction angle(θ_2) is $90°$ then the angle of incidence is known as critical angle (θ_c).

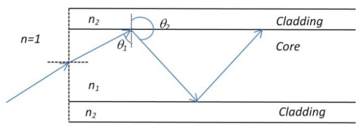

Figure 1.20: Propagation of light in optical fiber.

1. When $\theta_1 < \theta_c$, then the ray refracted into the second medium as shown in figure.
2. When $\theta_1 = \theta_c$, then the ray travels along the interface of two media as shown in the above figure.1.20.
3. When $\theta_1 > \theta_c$, then the ray totally reflects into the same medium (core) as shown in the above figure.1.20.

The critical angle can be calculated from Snell's law, suppose if $\theta_1 = \theta_c$ then $\theta_2 = 90°$, hence

$$n_1 \sin\theta_c = n_2 \sin 90°$$

$$\sin\theta_c = \frac{n_2}{n_1}$$

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

This is known as critical angle for mediums of refractive indices n_1 and n_2 ($n_1 > n_2$). The light signal once entered the fiber with greater than critical angle makes total internal reflection within the core as shown in Fig.1.20. and it will propagate to other end of the fiber.

1.11 Acceptance angle and numerical aperture

The maximum angle of incidence to launch the light beam to enable the entire light to pass through the core is called acceptance angle.

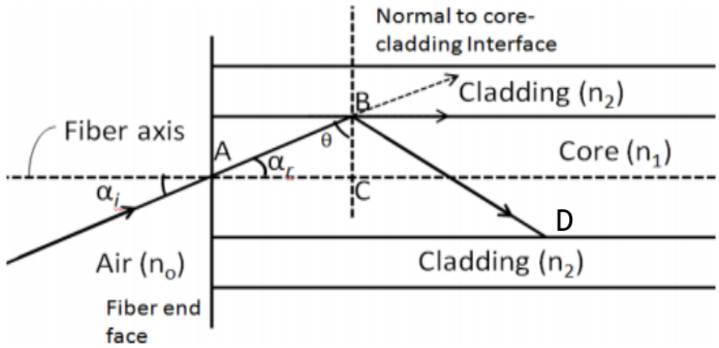

Figure 1.21: Cross section of an optical fiber.

When we launch the light beam in to the fiber at its one end the entire light may not pass through the core and propagate. Only the rays which make the angle of incidence greater than critical angle undergo total internal reflection and propagate through the core and all other rays are lost.
Let us consider a ray enters the core of refractive index n_1 from air medium of refractive index n_0 with an angle of incidence α_i at the interface of air and core.
The incident beam at the interface of core and cladding makes an angle θ as shown in Fig.1.21.

At Air-core interface, applying the Snell's law,

$$n_0 \sin\alpha_i = n_1 \sin\alpha_r$$

$$\sin\alpha_i = \frac{n_1}{n_0}\sin\alpha_r$$

$$\text{From} \quad \Delta ABC \quad \alpha_r = (90^\circ - \theta)$$

$$\sin\alpha_i = \frac{n_1}{n_0}\sin(90^\circ - \theta)$$

$$\sin\alpha_i = \frac{n_1}{n_0}\cos\theta$$

The angle of incidence α reaches it's maximum limit α_{max} when incident angle θ at core-cladding interface is equal to critical angle θ_c.
If $\theta = \theta_c$, $\alpha_i = \alpha_{max}$

$$\sin\alpha_{max} = \frac{n_1}{n_0}\cos\theta_c \tag{1.14}$$

At core-cladding interface, when $\theta = \theta_c$ the agle of refraction is 90°.

Applying Snell's law gives,

$$
\begin{aligned}
n_1 \sin\theta_c &= n_2 \sin 90^\circ \\
n_1 \sin\theta_c &= n_2 \\
\sin\theta_c &= \frac{n_2}{n_1}
\end{aligned}
$$

From laws of trignometry,

$$
\begin{aligned}
\cos\theta_c &= \sqrt{1-\sin^2\theta_c} \\
\cos\theta_c &= \sqrt{1-\frac{n_2^2}{n_1^2}} \\
\cos\theta_c &= \frac{\sqrt{n_1^2-n_2^2}}{n_1}
\end{aligned}
$$

Substituting $\cos\theta_c$ in Eq.1.14 ,

$$
\begin{aligned}
\sin\alpha_{max} &= \frac{n_1}{n_0}\frac{\sqrt{n_1^2-n_2^2}}{n_1} \\
\sin\alpha_{max} &= \frac{\sqrt{n_1^2-n_2^2}}{n_0}
\end{aligned}
$$

$$
\alpha_{max} = \sin^{-1}\left(\frac{\sqrt{n_1^2-n_2^2}}{n_0}\right) \tag{1.15}
$$

If we launch light from air medium, then n_0=1 ,

$$
\boxed{\alpha_{max} = \sin^{-1}\left(\sqrt{n_1^2-n_2^2}\right)} \tag{1.16}
$$

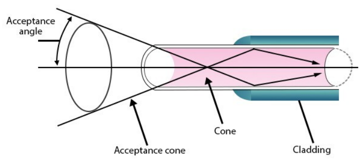

Figure 1.22: Diagram of the light acceptance cone for the optical fibre.

Acceptance cone: The acceptance cone is derived by rotating the acceptance angle about the fiber axis. Light launched at the fiber end within this acceptance cone alone will be accepted and propagated to the other end of the fiber by total internal reflection. Larger acceptance angles make launching easier.

Numerical aperture:

The numerical aperture (NA) of an optical fiber is defined as sin of acceptance angle and is dimensionless quantity that characterizes the range (ability) of angles over which the optical fiber can accept light.

Light collecting capacity of the fiber is expressed in terms of acceptance angle using numerical aperture. Sine of the maximum acceptance angle is called the numerical aperture of the fiber.

$$NA = \sin\alpha_{max} = \left(\frac{\sqrt{n_1^2 - n_2^2}}{n_0}\right) \tag{1.17}$$

For air $n_0 = 1$, then the above equation can be written as

$$\boxed{NA = \sqrt{n_1^2 - n_2^2}} \tag{1.18}$$

Let us define fractional difference in refractive indices

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

The refractive indices difference between core and cladding is very small, $n_1 \approx n_2$.
Thus,

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

$$NA = \left(\frac{\sqrt{n_1^2 - n_2^2}}{n_0}\right) = n_1\frac{\sqrt{2\Delta}}{n_0} \tag{1.19}$$

For air $n_o = 1$, then the above equation can be written as

$$\boxed{NA = n_1\sqrt{2\Delta}} \tag{1.20}$$

Numerical aperture of the fiber depends only on the refractive indices of the core and cladding materials and is not on dimensions of optical fiber.

1.12 Classification of optical fibers

Optical fibers, which are used for transmitting light signals in various applications, can be classified based on different criteria, such as,

1. Mode of propagation
2. Refractive index profile

Modes of fiber:
Optical fibers are used to guide light, during the propagation light can take multiple paths inside the core. The path taken by light during propagation witin the fiber is defined as mode of the fiber. Optical fibers can allow sigle or multple rays inside the fiber depeding on the dimension of fiber.
The number of modes supported by a any kind of fiber is determined by V-number or normalized frequency which is given by,

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} = \frac{2\pi a}{\lambda} NA \tag{1.21}$$

Where,

a = Radius of the optical fiber.

λ = Wavelength of the light.

n_1 = Refractive index of core.

n_2 = Refractive index of cladding.

NA = Numerical aperture.

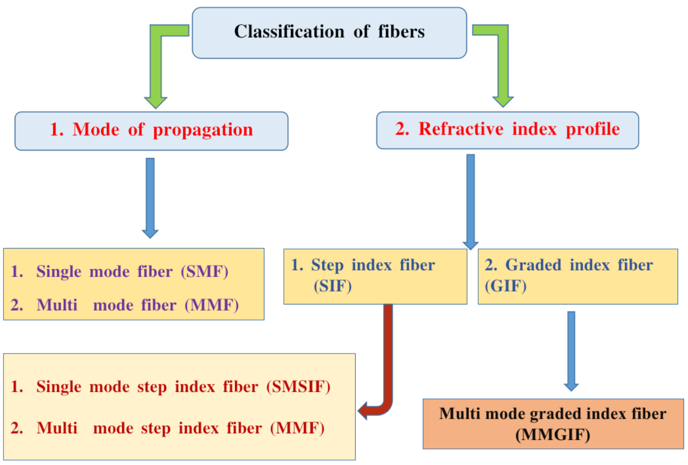

Figure 1.23: Classification of optical fibers.

1.12.1 Classification of optical fibers based on mode of propagation

On the basis of mode of propagation optical fibers are classified into two types,

1. Single mode fiber (SMF)
2. Multi-mode fiber (MMF)

Single mode fiber (SMF):

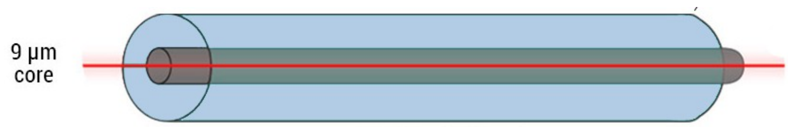

Figure 1.24: Propagation of light in single mode fiber.

A single-mode fiber shown in Fig.1.24 has a narrow core 8–10 μm and the refractive index between the core and the cladding does not change very much throughout the fiber. Because of the narrower core, light travels almost parallel to the axis with less pulse dispersion. Hence, they can carry a higher bandwidth (up to 50 times more distance than a multimode fiber) but require a light source with a narrow spectral width.
The small core and single mode virtually eliminate any distortion that could result from overlapping light pulses, providing the least signal attenuation and the highest transmission speed of any fiber cable type.
However, the cost of a single-mode fiber is high compare to multimode fiber. Typically, in a single-mode fiber, lowest order-bound mode can propagate at the wavelength of approximately 1300–1320nm.

Multimode fiber (MMF):

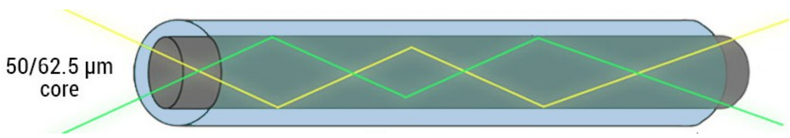

Figure 1.25: Propagation of light in multi mode fiber.

Multimode fiber allows more than one mode to travel through it. As it has to allow more number of modes to travel, the fiber has to have a larger core shown in Fig.1.25. A typical multimode fiber has a core diameter in the order of 50–200 μm. Such a large core not only allows more number of modes to travel but also makes it easier to launch the light into the fiber and also connect two fibers together.
During the propagation of light rays in multimode fiber, some of the rays travel parallel and close to the fiber axis whereas other rays take zig-zag path. These different pathways of light rays makes them reach at different times at a receiving point known as inter modal dispersion.
Because of larger the number of allowed modes casues greater dispersion of light inside the fiber. In longer fiber optic cables (> 3000 ft.) multiple paths of light cause signal distortion at the receiving end, resulting in an unclear and incomplete data transmission. On the contrary, a multimode fiber can provide a higher bandwidth at high speeds over medium or short distances.

1.12.2 Classification of optical fibers based on refractive index

Depending upon the refractive index profile of the core, optical fibers further classified into two types.

1. Step index fiber (SIF)
2. Graded Index fiber (GIF)

Step index fiber (SIF):
In step index fibers, the refractive index uniform throughout the the core region and it undergoes an abrupt (step) change at the core and cladding interface.
The variation of the refractive index mathematically represented as,

$$n(r) = n_1 \quad \text{r< a (inside core)}$$
$$= n_2 \quad \text{r> a (in cladding)}$$

Where,

n_1 = Refractive index at the core

n_2 = Refractive index at the cladding

a = Radius of the optical fiber

Step index fibers are of two types based on light propagation within the fiber core.

a) **Single mode step index fiber (SSIF)**

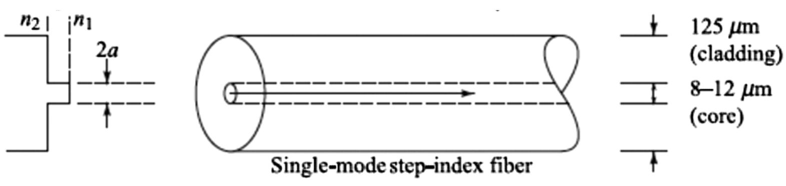

Figure 1.26: Single mode step index fiber.

Single mode step-index fiber, also known as monomode step-index fiber has small core 8 to 10 μm in diameter. The outer diameter of cladding is 60 to 70 μm. It is designed to propagate only a single mode of light. The cross sectional view, refractive index profile and ray propagation are shown in Fig.1.26 and Fig.1.27.
In this fibre, the light ray propagates via sucessive reflections. This small core size ensures that only the fundamental mode, or the lowest-order mode, of light can propagate, while higher-order modes are suppressed. This results in a single, tightly focused optical signal that can travel long distances with minimal signal degradation.

Figure 1.27: Propagation of light rays in single mode step index fiber.

Single mode step-index fiber typically has a high numerical aperture (NA). A high NA allows for efficient coupling of light into the fiber. High NA and low dispersion making it suitable for applications where high optical power or high bandwidth is required, such as in long-haul telecommunications, fiber optic sensors, and high-speed data communication systems. Single mode step-index fiber requires precise alignment of light into the small core, which can be more challenging compared to multimode fiber.
However, advancements in fabrication techniques and alignment technologies have made single mode step-index fiber widely used in various high-performance fiber optic communication systems.

b) **Multimode step index fiber (MSIF)**

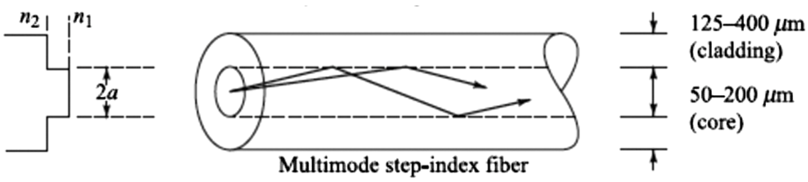

Figure 1.28: Multimode mode step index fiber.

Multimode step-index fiber is another type of optical fiber which is designed to propagate multiple modes of light simultaneously. It has larger core size compared to single mode step-index fiber. The core size ranges from 50 to 100 μm in diameter, allowing for multiple modes of light to propagate. The variation of refractive index profile with radial distance r for the multimode step-index fiber is shown in the above Fig.1.28.
In this fiber, the modes of light take different paths, resulting in dispersion and modal distortion, which can limit the maximum achievable bandwidth and transmission distance of the fiber.
Multimode step-index fiber is commonly used in shorter distance communication applications, such as local area networks (LANs), data centers, and short-range communication systems.
The advantage of multimode step-index fiber is its ease of coupling light into the larger core. However, this fiber has limitations in terms of bandwidth and transmission distance compared to single mode fiber mainly due to the dispersion and modal distortion effects. As a result, for long-haul or high-bandwidth communication applications, single mode fiber is generally preferred over multimode fiber.

Figure 1.29: Propagation of light rays in multimode step index fiber.

The number of modes through single and multi mode step index (SI) fibers is $\frac{V^2}{2}$.

Graded Index fiber (GIF):

Graded-index fibers, also known as gradient-index fibers or GRIN fibers, are a type of optical fiber that has a refractive index that varies gradually along its radial axis. The variation in refractive index is typically achieved by doping the core material with materials of different refractive indices or by designing the core in a geometrically graded manner. The variation of refractive index profile with radial distance r for the GIF fiber is shown in the Fig.1.30.

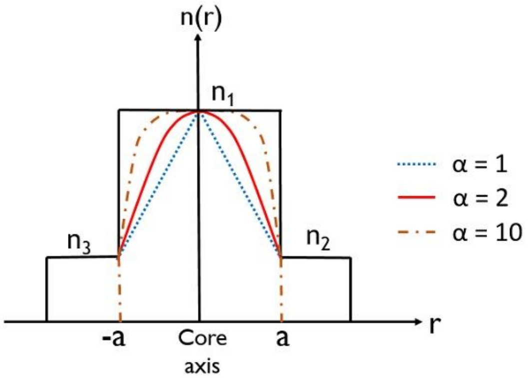

Figure 1.30: Graded Index fiber.

The variation of the refractive index of the core with radius r measured from the center is given by

$$n(r) = n_1\sqrt{1 - 2\Delta[\frac{r}{a}]^{\alpha}} \qquad \text{r<a (inside core)}$$

$$= n_2 \qquad \text{r> a (in cladding)}$$

Where,

n_1 = Refractive index of the core

n_2 = Refractive index of the cladding

a = Radius of the core

Δ = Fractional change of refractive index

α = Grading profile index number which varies from 1 to ∞

When,

α = 1 for linear grading

α = 2 for parabolic grading

$\alpha = \infty$ for step index grading

The main advantage of graded-index fibers is that they can support multiple modes of light propagation, known as multimode operation, while minimizing modal dispersion. By gradually changing the refractive index in the core, graded-index fibers are able to reduce modal dispersion and allow for higher bandwidth and

longer transmission distances compared to step-index fibers in certain applications.
The transmitted light signals travel through the core in the form helical (sine waves) rays, which will not cross the fiber axis at any time. The propagation modes in the GIF fiber are shown in Fig.1.31.

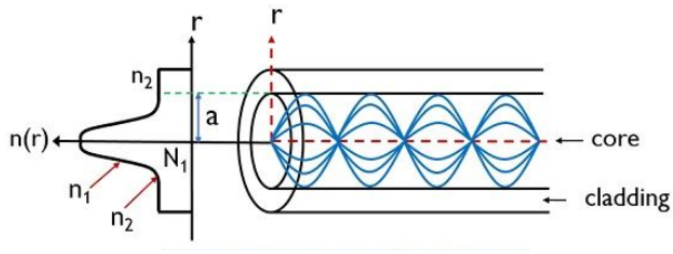

Figure 1.31: Propagation of light rays in multimode graded index fiber.

The number of modes propagated through the GI fiber depends on the radius of the core and NA of the fiber.
The possible number of modes propagated through the GI Fiber is $\frac{V^2}{4}$.

1.13 Attenuation or losses in optical fiber

Attenuation means loss of light energy as the light pulse travels from one end of the fiber cable to the other.

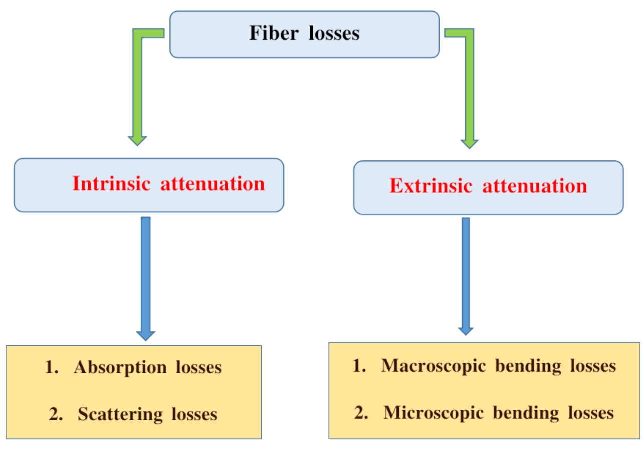

Figure 1.32: Classification of losses in optical fiber.

It is also called as signal loss or fiber loss. It depends on fiber material, wavelength of light and length of the fiber. It limits the optical power which can reach the receiver at the destination end of the fiber.
Attenuation is defined as the ratio of input optical power (p_i) to the output optical power (p_o). The signal attenuation defined for a

unit length of fiber (km),

$$\boxed{\text{Attenuation}(\alpha) = \frac{10}{L}\log_{10}\left(\frac{p_i}{p_o}\right)} \qquad (dB/km)$$

However, there are several factors that can contribute to losses in optical fibers. Attenuation broadly classified into two catagories,

1) Intrinsic attenuation
2) Extrinsic attenuation

Intrinsic attenuation

Intrinsic loss, also known as intrinsic attenuation, refers to the inherent loss of light that occurs within the fiber material itself due to its optical properties. It is one of the factors that contribute to the overall attenuation or loss of an optical fiber.

a) **Absorption loss:**
The most common type of intrinsic loss in optical fibers is absorption loss. The absorption can occur due to various mechanisms, such as electronic transitions, impurities present in the core and fiber material. The fiber material absorbs some of the light energy as it propagates through the fiber is called intrinsic or internal absorptin loss.
The manufacturing process of fibers leaves some impurities in optical fiber which absorb some light is called impurity or extrinsic absorption.
The absorption loss depends on the material used in the fiber core and cladding, as well as the wavelength of the transmitted light. Different materials have different absorption characteristics, and the choice of fiber material can impact the overall intrinsic loss of the fiber.

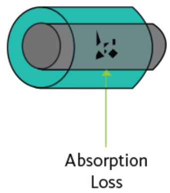

Figure 1.33: Light absorption due to density fluctuations in core.

b) **Scattering loss:**
Scattering occurs when light encounters a change in refractive index, leading to a change in its direction of propagation. Scattering loss is a type of loss that occurs in optical fibers due to the scattering of light off small imperfections or structural irregularities in the fiber material.
These imperfections can include impurities, micro-cracks, density fluctuations of glass and variation of refractive index within the fiber.
If the size of fluctuating regions is of the order of $\frac{\lambda}{10}$ or less, then they act as point source scattering centre. The scattering loss in point sources is inversely proportional to the fourth power of the wavelength of the light $(\frac{1}{\lambda^4})$, meaning that shorter wavelengths are more strongly scattered than longer wavelengths.
This is known as the Rayleigh scattering regime, and it is the

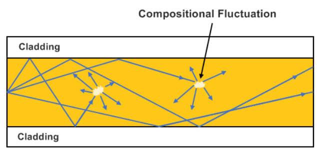

Figure 1.34: Light scattering due to compositional fluctuations.

dominant scattering mechanism in optical fibers for wavelengths in the visible and near-infrared range.

Extrinsic attenuation

Extrinsic attenuation in optical fibers refers to the loss of optical power due to factors that are external to the fiber. These factors can be related to the environment or external components in the optical fiber system such as physical stress or bending.
When an optical fiber is bent, light propagating through the fiber can leak into the cladding due to the change of refractive index at the bent region of optical fiber. This type of losses can contribute to the overall attenuation or loss of optical power in the fiber.

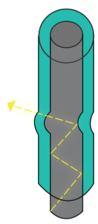

Figure 1.35: Micro bendinng loss.

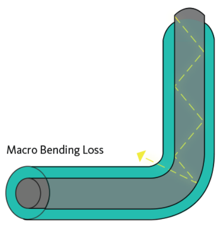

Figure 1.36: Macro bendinng loss.

Bending losses are of two types,

a) **Microscopic bending:** Microscopic bending in optical fibers refers to the bending of the fiber optic cable at a very small scale, typically with a radius of curvature in the millimeter to micrometer range. This bending can occur due to various reasons, such as installation or handling of the fiber, environmental factors, or intentional bending for specific applications.

b) **Macroscopic bending:** Macroscopic bending of optical fibers refers to the intentional bending of fiber optic cables at a larger scale, typically with a radius of curvature in the centimeter to meter range. Unlike microscopic bending, which can occur unintentionally during handling or installation, macroscopic bending is deliberately applied for specific purposes in various applications.

Cable designs with appropriate bending characteristics are used in various applications, including data communication networks, telecommunications, and cable television (CATV) systems.
Different types of losses of optical fiber is shown in Fig.1.37.

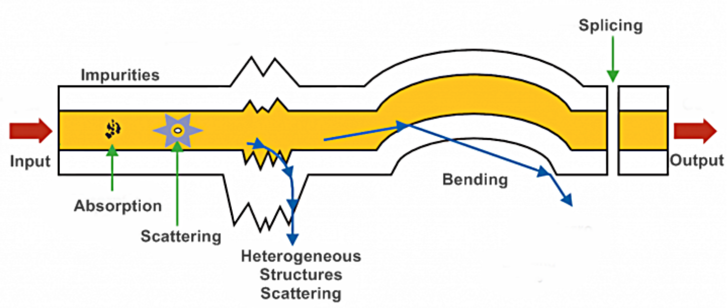

Figure 1.37: Different types of losses in optical fiber.

1.14 Applications of optical fibers

Due to its variety of advantages optical fiber has a wide range of application in different fields namely,

1 Communication
2 Medicine
3 Sensors

1.14.1 Optical fiber communication system

Optical fibers are used as wave guides in the communication system. A typical block diagram of optical fiber communication system (OFCS) is shown in the following Fig.1.38, It mainly consists of the following parts:

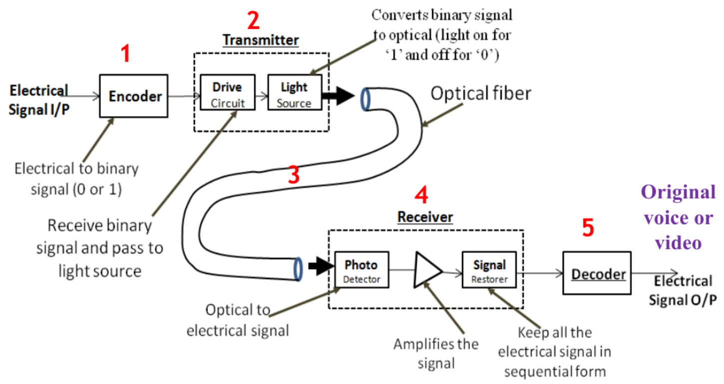

Figure 1.38: Optical fiber communication system.

1. **Encoder:** Encoder is an electronic circuit that converts this analog signal into binary or digital signals. The audio signal (i.e., the words spoken by us) an analog signal is converted into electrical signal.
2. **Transmitter:** The digital signal from the encoder is fed to the transmitter which consists of two parts- a)Drive circuit and b) Light source.
   Drive circuit receives the digital signal from encoder and feeds it to the light source.
   Light source is usually LED or a diode LASER. If digital '0' is received then light source will be turned *off*. If digital '1' is received then the light source will be turned *on*. Thus light source converts electrical signals into optical signals.
3. **Wave guide:** Now the optical signals generated by the transmitter are fed to an optical fiber which acts as a wave guide. The signal travels over longer distances through these wave guides.
4. **Receiver:** On the other side of the wave guide, the optical signal is received by the receiver which consists of photo detector, amplifier and a signal restorer.

The Photo detector receives the optical signal and generates the equivalent electrical signals.
These electrical signals are amplified by the amplifier.
The signal restorer keeps all the electrical signals in a sequential form and supplies to decoder.

5. **Decoder:** It is an electronic system that converts the digital signal to analog signal. Finally, signals will be decoded and sent in the original form.

Advantages of optcal fiber communication system

Optical fiber communication systems have several advantages over other types of communication systems, such as copper-based systems. Here are some key advantages of optical fiber communication systems:

1. **High bandwidth:** Optical fibers have a much higher bandwidth compared to copper cables, allowing for the transmission of large amounts of data over long distances. This makes optical fiber communication systems ideal for high-speed data transmission applications, such as internet connectivity, video streaming, and telecommunication.
2. **Low losses:** Optical fibers have low signal losses, meaning that the transmitted data can travel over long distances without significant degradation. This allows for longer transmission distances without the need for repeaters or signal boosters, reducing costs and improving system performance.
3. **Immunity to electromagnetic interference (EMI):** Unlike copper cables, which can suffer from electromagnetic interference (EMI) that can degrade signal quality, optical fibers are immune to EMI. This makes optical fiber communication systems highly reliable and suitable for use in environments with high levels of electromagnetic interference, such as industrial settings or urban areas.
4. **Enhanced security:** Optical fibers are difficult to tap or intercept, making them more secure for transmitting sensitive data. This makes optical fiber communication systems ideal for applications where data security is critical, such as in government, military, financial, and healthcare sectors.
5. **Lightweight and flexible:** Optical fibers are thin, lightweight, and flexible, making them easy to install and integrate into various environments. They can be installed in tight spaces, bent around corners, and routed through complex pathways, allowing for more versatile and convenient installation options.
6. **Future-proof:** Optical fibers have a high potential for scalability and can support future advancements in communication technology. They are capable of handling ever-increasing

data rates, making them a future-proof choice for communication infrastructure.

7. **Energy Efficient:** Optical fiber communication systems require less energy for transmission compared to copper-based systems, resulting in lower energy consumption and reduced operational costs over time.
8. **Long service life:** Optical fibers are highly durable and can last for decades without significant degradation in performance. This results in a longer service life and lower maintenance costs compared to other types of communication systems.

Overall, optical fiber communication systems offer numerous advantages, including high bandwidth, low losses, immunity to EMI, enhanced security, lightweight and flexible installation options, future-proof scalability, energy efficiency, and long service life, making them a preferred choice for high-speed, reliable, and secure data transmission in various applications.

Questions

Long answer questions

1. Explain the processes of absorption, spontaneous and stimulated emission of light and derive the expression for relation between Einstein's coefficients.
2. Explain the terms: spontaneous and stimulated emission, population inversion, optical pumping.
3. Describe the construction of Ruby laser and its working with the help of energy level diagram.
4. What do you understand by solid state laser? Describe the principle, construction and working of Ruby Laser.
5. Explain the construction and working of Helium-Neon laser with a neat energy level diagram.
6. Explain the concept of coherence in lasers. What are necessary conditions for Lasing action? Give main components of a Ruby or He-Ne laser and principle of laser action.
7. Explain the construction and working of semiconductor diode laser with a neat energy level diagram.
8. Explain the construction and working principle of optical fiber.
9. Define and deduce the expression for acceptance angle and numerical aperture of an optical fiber.
10. Discuss the physical significance of numerical aperture. How does it depend on refractive indices of core and cladding?
11. Explain the structure and propagation of light in step and graded index optical fibers.
12. What are single mode, multimode and graded index fibres? Also explain in detail the difference in structures of single mode step index and multimode graded index fibre.
13. Explain the allowed modes in an optical fibre. How are they related to normalized frequency?
14. Distinguish between step index and graded index optical fibers.
15. Describe the different types of attenuation or losses in the optical fibers.
16. Discuss the optical fiber communication system with a neat block diagram.

Short answer questions

1. What is the principle of laser ?
2. Discuss salient characteristics of laser beam.
3. What do you mean by coherence ?
4. What do you mean by an optical resonator ?

5. What are the necessary conditions for lasing action ?
6. Explain the concept of directionality and monochromaticity as applied to lasers.
7. What is meant by population inversion and how is it achieved in practice
8. What conditions must be fulfilled for a semiconductor laser ? Explain.
9. How does a semiconductor laser differ from other lasers ?
10. Describe various applications of laser ?
11. What is optical fiber ?
12. What is the principle of optical fibers ?
13. How is light transmitted through fiber optics ?
14. What is acceptance angle and numerical aperture ?
15. What do you understand by modes of propagation ?
16. Distinguish between single mode and multi-mode optical fibers.
17. Explain why does fraction of power of a signal get lost due to bending of fibre.
18. Why optical fibre communications are so important ?
19. What are the advantages of using optical fibre communication systems ?
20. Enumerate some applications of optical fibre communication system.

Numerical problems

1. Determine the energy and momentum of a photon of a laser beam of wavelength 6328 Å.
2. Calculate the energy of laser pulse in a ruby laser for 2.8×10^{19} Cr^{3+} ions. If the laser emits radiation of wavelength 6943 Å.
3. A three-level laser emits a light of wavelength of 5500 Å, What will be the ratio of population of upper level (E_2) to the lower energy level (E_1) if the optical pumping mechanism is shut off (Assume T = 300K).
4. A certain ruby laser emits 1.00 J pulses of light whose wavelength is 694nm. What is the minimum number of cr^{+3} ions in the ruby ?
5. The relative population of atoms in two energy levels E_1 and E_2 is 10^{-20}. Calculate the energy level difference in eV. (Assume T = 300K.)
6. A semiconductor diode laser has a peak emission wavelength of 1.55 μ m. Find its band gap in eV.
7. The refractive indices for core and cladding for a step index fibre are 1.52 and 1.41 respectively. Calculate (i) critical angle (ii) numerical aperture and (iii) the maximum incidence angle.

8. Find out the numerical aperture and acceptance angle of an optical fibre, if the refractive indices for core and cladding are 1.6 and 1.5, respectively.
9. A light ray enters from air to a fibre. The refractive index of air is 1.0. The fibre has refractive index of core is equal to 1.5 and that of cladding is 1.48. Find the critical angle, the fractional refractive index,the acceptance angle and numerical aperture.
10. Calculate the numerical aperture and acceptance angle of optical fibre of refractive indices for core and cladding as 1.62 and 1.52, respectively.
11. A step index fiber has core refractive index 1.47, cladding refractive index 1.46. If the operating wavelength of the rays is 0.85 mm, calculate the cut-off parameter or normalized frequency and the number of modes which the fiber will support. The diameter of the core is 50 mm.
12. A graded index fibre has a core diameter of 0.05 mm and numerical aperture of 0.22 at a wavelength of 8500 Å. What are the normalised frequency (V) and number of modes guided in the core?
13. An optical fibre cable 3.0 km long is made up of three 1.0 km length spliced together. The losses due to each length and splice are respectively 5dB and 1.0 dB. What would be out put power if the input power is 5 mW ?