44 Lasers

Learning Objectives:

By the end of this chapter, you will be able to:

- Learn about basic concepts of Laser.
- Identify different components of Laser.
- Describe concept of Threshold Conditioning.
- Understand Pumping Method and its types – Electrical and Optical.
- Explain different types of Laser.

44.1 INTRODUCTION

Laser is one of the outstanding inventions of the 20^{th} century. The word 'LASER' is the acronym for *Light Amplification through Stimulated Emission of Radiation*. However, laser is not a simple amplifier of light but is a generator of light. It is an artificial light source that differs vastly from the traditional light sources. Laser is more akin to radio and microwave transmitters and produces a highly directional coherent monochromatic polarized light beam. Einstein gave the theoretical basis for the development of laser in 1916, when he predicted the possibility of stimulated emission. In 1954, C.H.Townes and his co-workers put Einstein's prediction for practical realization. They developed a microwave amplifier based on stimulated emission of radiation. It was called a **MASER**.

Shortly thereafter, in 1958, A. Schawlow and C.H. Townes extended the principle of masers to light and T.H. Maiman built the first laser device in 1960. In 1961, A. Javan and associates developed the first gas laser, the helium-neon laser. Laser is a high technology device and is the most sought after tool in a wide variety of fields such as metalworking, entertainment, communications, surgery, and ophthalmology and weapon guidance in wars.

44.2 INTERACTION OF LIGHT WITH MATTER AND THE THREE QUANTUM PROCESSES

It is familiar to us that when light travels through a medium, it undergoes absorption and scattering processes. Light absorption means the transfer of energy from light to atoms and light scattering involves change in the direction of travel of waves. As a result of these two processes, light intensity decreases with distance in the medium. Transfer of energy from atom to light is not conceivable from classical point of view. However, it is found to be possible when the interaction of light with medium is considered from the point of view of quantum mechanics. The transfer of energy from atom to light results in ***light amplification***. A light amplifier can be further converted into a source of light having superior characteristics compared to traditional light sources. A ***laser is a monochromatic coherent light source*** that depends on quantum processes for its operation. It is therefore necessary to first understand the quantum processes in order to understand the operation of a laser.

Let us consider a material medium, which is composed of *identical atoms*. Atoms are characterized by many energy levels but for the sake of simplicity to understand, let us assume that the atoms of the material medium under consideration be characterized by only two energy levels, namely energy level E_1 and energy level E_2. E_1 is the ground state while E_2 is the excited state. As the atoms of the material are identical, majority of them occupy the energy level E_1 and the others the energy level E_2.

The number of atoms per unit volume at an energy level is called the ***population density***. *Let the populations at the two energy levels E_1 and E_2 be N_1 and N_2 respectively.*

Under normal conditions higher the energy, lesser is its population. Hence,

$$N_1 > N_2$$

Now, let light radiation be incident on the material and we assume that the radiation and the medium are in thermal equilibrium. The incident radiation may be viewed as a stream of photons, and let the photon density be $\rho(\nu)$. Let each photon carry an energy E, where $E = E_2 - E_1 = h\nu$. When photons travel through the medium, they are likely to cause three different processes. They are absorption, spontaneous emission and stimulated emission.

44.2.1 Absorption

Suppose an atom is in the lower energy level E_1. If a photon of energy $(E_2 - E_1)$ is incident on the atom, it imparts its energy to the atom and disappears. Then we say that the atom absorbed the incident photon. As a result of absorption of adequate energy, the atom jumps to the excited state E_2 (Fig. 44.1). This is known as an **absorption transition**. In each absorption transition, one atom is excited and one photon is lost from the incident light beam. We may express the process as

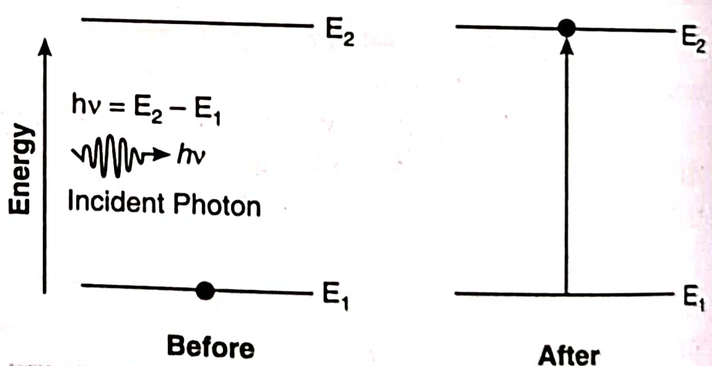


Fig. 44.1: Process of Absorption of photons

$$A + h\nu = A^*$$

where A is an atom in the lower state and A^* is an excited atom.

The probability that an absorption transition occurs is proportional to the photon density $\rho(\nu)$.

$$P_{12} \propto \rho(\nu)$$

or

$$P_{12} = B_{12}\rho(\nu) \qquad ...(44.1)$$

where B_{12} is the constant of proportionality.

B_{12} is known as the *Einstein coefficient for induced absorption*. It is a constant characteristic of the atom and represents the properties of the energy states E_1 and E_2.

The number of absorption transitions occurring in the material at any instant will be equal to the product of the number of atoms at the energy level E_1 and the probability P_{12} for the absorption transition. Thus, the number of atoms, N_{ab}, excited during the time Δt is

$$N_{ab} = B_{12}N_1\rho(\nu)\Delta t \qquad ...(44.2)$$

where N_1 is the population of atoms at E_1.

When the atoms are more at the lower energy level, then more atoms can jump into the excited state. Similarly, when more photons are incident on the assembly of atoms, then more atoms can get excited to the higher energy level. Induced absorption involves the excitation of the atom to the fixed higher level only. As a result of this absorption, N_1 decreases while N_2 increases. But under normal conditions N_2 cannot be greater than N_1.

44.2.2 Spontaneous Emission

When an atom at lower energy level is excited to a higher energy level, it cannot stay in the excited state for a relatively longer time. In a time of about 10^{-8}s, the atom reverts to the lower energy state by releasing a photon of energy $h\nu$ where $h\nu = E_2 - E_1$. The emission of photon occurs on its own and without any external impetus given to the excited atom (Fig. 44.2).

Emission of a photon by an atom without any external impetus is called ***spontaneous emission.***

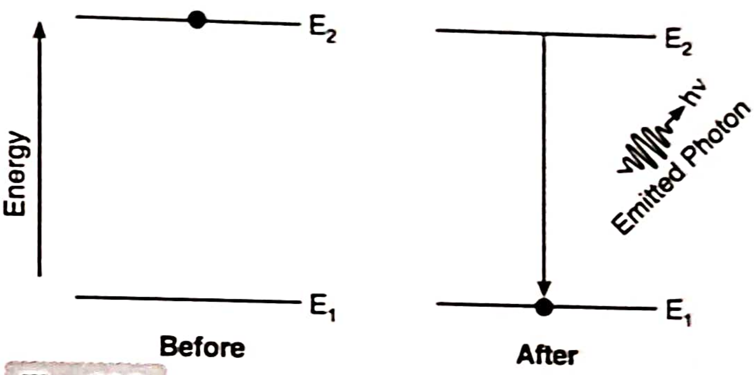


Fig. 44.2: Process of Spontaneous emission of photons

We may write the process as

$$A^* \rightarrow A + h\nu$$

The probability that a spontaneous transition occurs depends only on the properties of energy states E_2 and E_1 and is independent of the photon density. It is equal to the lifetime of level E_2. Thus,

$$(P_{21})_{\text{Spont.}} = A_{21} \qquad ...(44.3)$$

where A_{21} is a constant and known as the *Einstein coefficient for spontaneous emission.*

A_{21} is a constant characteristic of the atom. *$1/A_{21}$ is a measure of the lifetime of the upper state against spontaneous transition to the lower state.*

The number of spontaneous transitions, N_{sp}, taking place during the time Δt depends *only* on the number of atoms N_2 staying at the excited state E_2. Thus,

$$N_{sp} = A_{21}N_2\Delta t \qquad ...(44.4)$$

It is the process of spontaneous emission that dominates in conventional light sources.

44.2.3 Stimulated Emission

In 1916, Einstein showed the existence of equilibrium between matter and radiation required a new radiation process called stimulated radiation. It requires the presence of external radiation. If an atom in the excited state interacts with a photon with energy $h\nu = E_2 - E_1$, the photon induces the excited atom to make a downward transition well before the atom can make a spontaneous transition. The atom emits the excess energy in the form of a photon,

$h\nu = E_2 - E_1$, as it drops to the lower energy state. The passing photon is not affected while the excited atom emits a photon (Fig. 44.3).

The phenomenon of forced photon emission by an excited atom due to the action of an external agency is called ***stimulated emission.***

It is also known as induced emission. The process may be expressed as

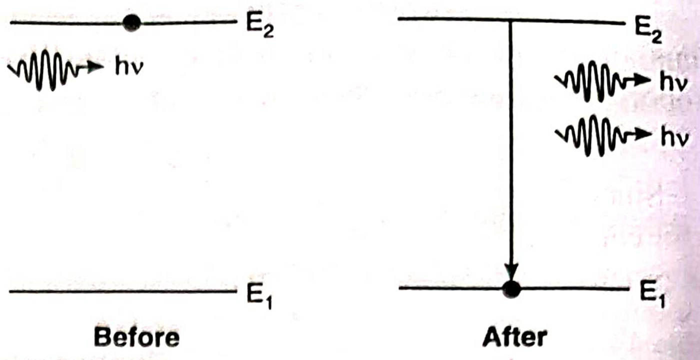


Fig. 44.3: Process of Stimulated Emission of photons

$$A^* + h\nu \rightarrow A + 2h\nu$$

The probability that a stimulated transition occurs is given by

$$(P_{21})_{\text{stimulated}} \propto \rho(\nu)$$

or

$$(P_{21})_{\text{stimulated}} = B_{21}\rho(\nu) \qquad ...(44.5)$$

where B_{21} is the constant of proportionality and is known as the *Einstein coefficient for stimulated emission.*

It is a constant characteristic of the atom and represents the properties of the energy states E_1 and E_2.

The number of stimulated transitions occurring in the material at any instant will be equal to the product of the number of atoms at the energy level E_2 and the probability P_{21} for the stimulated transition. Thus, the number of atoms, N_{st}, that undergo downward transition during the time Δt is

$$N_{st} = B_{21}N_2\rho(\nu)\Delta t \qquad ...(44.6)$$

44.2.4 Multiplication of Stimulated Photons

The photon induced in this process propagates in the *same direction* as that of stimulating photon. The induced photon has features identical to that of the inducing photon. It has the *same frequency, phase and plane of polarization* as that of the stimulating photon. The outstanding feature of this process is the *multiplication of photons.*

For one photon interacting with an excited atom, there are two photons emerging. The two photons travelling in the same direction interact with two more excited atoms and generate two more photons and produce a total of four photons. These four photons in turn stimulate four excited atoms and generate eight photons, and so on. The number of photons builds up in an avalanche like manner, as shown in Fig. 44.4.

All the light waves generated in the medium are due to one initial wave and all of the waves are in phase.

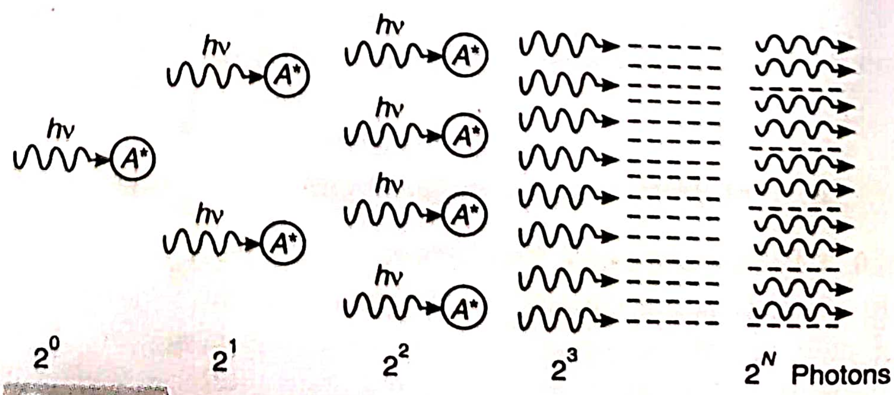


Fig. 44.4: Multiplication of Stimulated photons into an avalanche

Thus, the waves are coherent and interfere constructively. The net intensity of light will be proportional to the square of the number of atoms radiating light. Thus,

$$I_{total} = N^2 I$$

Since the number of atoms in the material medium is very large, coherent emission leads to an enormously high intense light and we say that the incident *light is amplified*. Therefore, the process of stimulated emission is the key to the operation of a laser.

Table 44.1: *Distinction between Spontaneous and Stimulated Emission*

Sl. No.	Spontaneous emission	Stimulated emission
1.	Spontaneous emission is a random and probabilistic process.	Not a random process.
2.	Not amenable for control from outside.	Amenable for control from outside.
3.	The photons are emitted haphazardly. The instant of emission, direction of emission, phase, polarization state of photon are all random quantities and cannot be controlled.	The stimulating photon imposes its characteristics on the photon emitted.
4.	Photons are emitted uniformly in all directions from an assembly of atoms. As a result, the light is ***non-directional***.	The photons emitted in the process travel in the same direction as that of stimulating photon. The light produced by the process is essentially ***directional***.
5.	Photons of slightly different frequencies are generated. As a result, the light is ***not monochromatic***.	The spread of photon frequencies is relatively very narrow. As such the light is nearly ***monochromatic***.
6.	Photons do not have any correlation in their phases, which fluctuate randomly. Therefore, the light produced by this process is ***incoherent***.	The photons emitted by this process are all in phase and therefore, the light is ***coherent***.
7.	In this process multiplication of photons does not take place. Hence there is **no amplification** of light due to the process.	One stimulating photon causes emission of two more photons. These two produce four photons, which in turn generate eight photons and so on. Thus, if there are N excited atoms, 2^N photons will be produced. ***Light amplification*** occurs due to such multiplication of photons.
8.	The net intensity of the generated light is given by $$I_T = N\,I$$ where N is the number of atoms emitting photons and I is the intensity of each photon.	As all the photons are in phase, they constructively interfere and produce an intensity $$I_T = N^2\,I$$
9.	The planes of polarization of the photons are oriented randomly. Hence, light from the source is ***unpolarized***.	The planes of polarization are identical for all photons. Consequently, light is ***polarized***.

44.2.5 Steady State

The three processes described above occur simultaneously (Fig. 44.5). Under steady state condition the absorption and emission balance each other. Thus,

$$N_{absorption} = N_{spont.emission} + N_{stim.emission} \qquad ...(44.7)$$

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

$$B_{12} N_1 \rho(\nu) = A_{21} N_2 + B_{21} N_2 \rho(\nu) \quad ...(44.8)$$

If we consider a medium in thermal equilibrium, there would be more atoms in the lower level than at higher level. That is $N_1 >> N_2$. As the probability for absorption transition is equal to the probability for stimulated transition, a photon traveling through the medium is *more likely to get absorbed* than to stimulate an excited atom to emit a photon. Therefore, usually the process of absorption dominates the process of stimulated emission. Similarly, an atom that is at the excited state is more likely to jump to the lower level on its own than being stimulated by a photon. It is due to the fact that the photon density in the incident beam is not sufficient to interact with the excited atoms; and the photons interact with atoms at lower level because of the large population available at that level. Owing to this, the spontaneous emission dominates the stimulated emission.

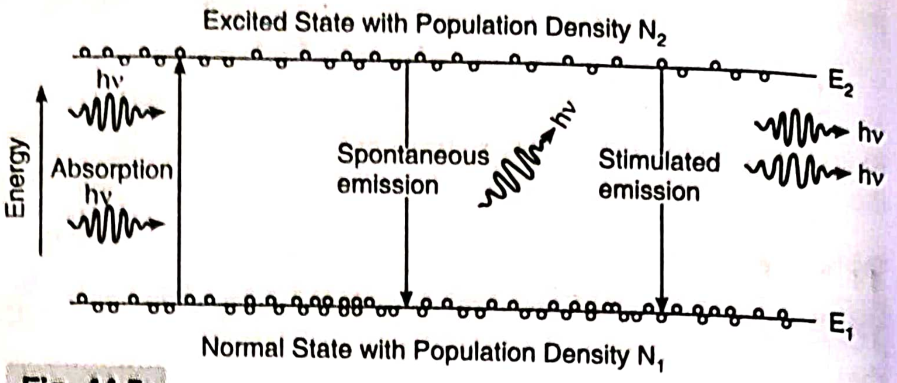


Fig. 44.5: Absorption, spontaneous and stimulated emission processes

44.3 EINSTEIN COEFFICIENTS AND THEIR RELATIONS

44.3.1 Einstein Coefficients

We summarize here the three Einstein coefficients, which are the proportionality constants introduced in the above discussions.

(*i*) The probability that an absorption transition occurs is given by

$$P_{12} = B_{12}\rho(\nu)$$

where B_{12} is the constant of proportionality known as the *Einstein coefficient for induced absorption.* It is a constant characteristic of the atom and represents the properties of the energy states E_1 and E_2.

(*ii*) The probability that a spontaneous transition occurs is given by

$$(P_{21})_{\text{Spontaneous}} = A_{21}$$

where A_{21} is a constant known as the *Einstein coefficient for spontaneous emission.* A_{21} is a constant characteristic of the atom and is known as the *radiative rate* measured in units of s^{-1}. $1/A_{21}$ *is the lifetime of the upper state against spontaneous decay to the lower state.*

(*iii*) The probability that a stimulated transition occurs is given by

$$(P_{21})_{\text{stimulated}} = B_{21}\rho(\nu)$$

where B_{21} is the constant of proportionality known as the *Einstein coefficient for stimulated emission.* It is a constant characteristic of the atom and represents the properties of the energy states E_1 and E_2.

We may note the following points here regarding the Einstein coefficients.

(*a*) The coefficients indicated by B are related to the induced transitions, i.e., transitions induced by external photons. Thus, B_{12} represents the transition induced by a photon from lower energy level E_1 to the higher energy level E_2, whereas B_{21} denotes the transition induced by a photon from higher energy level E_2 to the lower energy level E_1. It turns out that B_{12} and B_{21} are equal under the special condition that the quantum states E_1 and E_2 are single energy levels (i.e., nondegenerate levels).

(b) The coefficient indicated by A is related to the spontaneous transition, i.e., transition occurred on its own without the assistance of external agent. Since a spontaneous transition cannot take place from lower energy state E_1 to the higher energy state E_2, we do not have the coefficient A_{12}. In other words, $A_{12} = 0$.

44.3.2 Relation between the Einstein Coefficients

The Einstein coefficients A_{21}, B_{12} and B_{21} are interrelated. To find out the relation, we assume that

(i) The atoms and the radiation are in thermal equilibrium.

(ii) The radiation is identical with black body radiation and consistent with Planck's radiation law for any value of T.

(iii) The population densities N_1 and N_2 at the lower and upper energy levels respectively are constant in time and are distributed according to Boltzmann law in the energy levels.

The above conditions require that the rate of change of atoms at the level E_2 must equal to zero. It means that the number of transitions from E_2 to E_1 must be equal to the number of transitions from E_1 to E_2 (see Fig. 44.5).

Thus,

$$\left.\begin{array}{l}\text{The number of atoms absorbing}\\ \text{photons per second per unit volume}\end{array}\right\} = \left\{\begin{array}{l}\text{The number of atoms emitting}\\ \text{photons per second per unit volume}\end{array}\right.$$

The number of atoms absorbing photons per second per unit volume $= B_{12}\,\rho(\nu)\,N_1$

The number of atoms emitting photons per second per unit volume $= A_{21}N_2 + B_{21}\,\rho(\nu)\,N_2$

As the number of transitions from E_1 to E_2 must equal the number of transitions from E_2 to E_1, we have

$$B_{12}\,\rho(\nu)\,N_1 = A_{21}N_2 + B_{21}\,\rho(\nu)\,N_2 \qquad ...(44.9)$$

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

$$\therefore \qquad \rho(\nu) = \frac{A_{21}N_2}{[B_{12}N_1 - B_{21}N_2]} \qquad ...(44.10)$$

By dividing both the numerator and denominator on the right hand side of the above equation with $B_{12}N_2$, we obtain

$$\rho(\nu) = \frac{A_{21}/B_{12}}{\left[\dfrac{N_1}{N_2} - \dfrac{B_{21}}{B_{12}}\right]} \qquad ...(44.11)$$

But

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

As $E_2 - E_1 = h\nu$,

$$\frac{N_2}{N_1} = e^{-h\nu/kT} \quad \text{or} \quad \frac{N_1}{N_2} = e^{h\nu/kT}$$

$$\therefore \qquad \rho(\nu) = \frac{A_{21}}{B_{12}}\left[\frac{1}{e^{h\nu/kT} - B_{21}/B_{12}}\right] \qquad ...(44.12)$$

To maintain thermal equilibrium, the system must release energy in the form of electromagnetic radiation. It is required that the radiation be identical with black body radiation and be consistent with Planck's radiation law for any value of T. According to Planck's law

$$\rho(\nu) = \left(\frac{8\pi h\nu^3\mu^3}{c^3}\right)\left[\frac{1}{e^{h\nu/kT}-1}\right] \quad ...(44.13)$$

where μ is the refractive index of the medium and c is the velocity of light in free space.

Energy density $\rho(\nu)$ given by Eq. (44.12) will be consistent with Planck's law Eq. (44.13), only if

$$\frac{A_{21}}{B_{12}} = \frac{8\pi h\nu^3\mu^3}{c^3} \quad ...(44.14)$$

and

$$\frac{B_{21}}{B_{12}} = 1 \quad \text{or} \quad B_{12} = B_{21} \quad ...(44.15)$$

Eq. (44.14) and Eq. (44.15) are known as the **Einstein relations.** It follows that the coefficients are related through

$$B_{12} = B_{21} = \frac{c^3}{8\pi h\nu^3\mu^3}A_{21} \quad ...(44.16)$$

Eq. (44.15) shows that the coefficients for both absorption and stimulated emission are numerically equal. The equality implies that when an atom with two energy levels is placed in the radiation field, the probability for an upward (absorption) transition is equal to the probability for a downward (stimulated) transition.

Eq. (44.14) shows that the ratio of coefficients of spontaneous versus stimulated emission is proportional to the third power of frequency of the radiation. This is why it is difficult to achieve laser action in higher frequency ranges such as x-rays.

44.4 LIGHT AMPLIFICATION

Light amplification requires that stimulated emission occur almost exclusively. In practice, absorption and spontaneous emission always occur together with stimulated emission. The laser operation is achieved when stimulated emission exceeds in a large way the other two processes. Let us now look at the conditions under which the number of stimulated transitions can be made larger than the other two transitions.

44.4.1 Condition for Stimulated Emission to Dominate Spontaneous Emission

The ratio of Eq. (44.6) to Eq. (44.4) gives

$$\frac{\text{Stimulated transitions}}{\text{Spontaneous transitions}} = \frac{B_{21}N_2\rho(\nu)}{A_{21}N_2} = \frac{B_{21}}{A_{21}}\rho(\nu) \quad ...(44.17)$$

Eq. (44.17) indicates that stimulated transitions will dominate the spontaneous transitions if the radiation density $\rho(\nu)$ is very large. Thus, the presence of a large number of photons in the active medium is required. However, it will lead to more absorption transitions. Hence, large photon density alone will not guarantee more stimulated emissions.

44.4.2 Requirement of States of Larger Lifetimes

Eq. (44.17) further indicates that stimulated transitions will dominate the spontaneous transitions if the value of the ratio B_{21}/A_{21} is also large. To increase the probability of stimulated emissions, the lifetime of atoms at the excited state should be larger. In other words, it is necessary that the excited state has a longer lifetime (remember that $1/A_{21}$ represents the lifetime of the excited state).

44.4.3 Condition for Stimulated Emission to Dominate Absorption Transitions

The ratio of Eq. (44.6) to Eq. (44.2) yields

$$\frac{\text{Stimulated transition}}{\text{Absorption transition}} = \frac{B_{21}N_2\rho(\nu)}{B_{12}N_1\rho(\nu)} = \frac{N_2}{N_1} \qquad \text{...(44.18)}$$

We used here the fact that $B_{12} = B_{21}$.

The above condition indicates that the stimulated transitions will overwhelm the absorption process if N_2 is greater than N_1. It means that there should be more atoms present in the higher energy level than in the lower energy level for stimulated emissions to dominate over the spontaneous emissions.

A medium amplifies light only when the above ***three conditions*** are fulfilled. Therefore to achieve high percentage of stimulated emissions, an artificial situation known as *population inversion* is to be created in the medium.

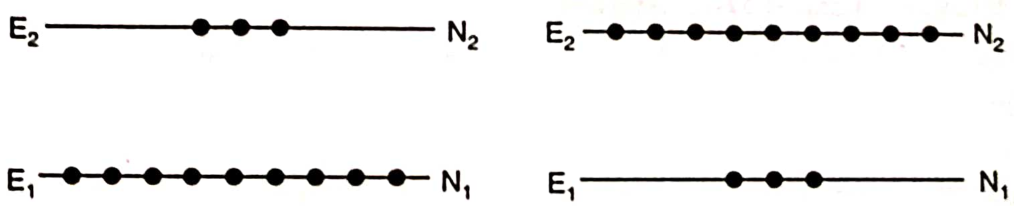
44.5 MEETING THE THREE REQUIREMENTS

44.5.1 Population Inversion

When the material is in thermal equilibrium condition, the population ratio is governed by the Boltzmann factor according to the following equation:

$$\frac{N_2}{N_1} = e^{-[E_2-E_1]/kT} \qquad \text{...(44.19)}$$

It means that the population N_2 at the excited level E_2 will be far smaller than the population N_1 at the level E_1. For example, if we take typical values for E_1 and E_2, the population N_1 would be 10^{30} times of N_2. The condition in which there are more atoms in the lower energy level and relatively lesser number of atoms in the higher energy level is called *normal state or equilibrium state* (Fig. 44.6 a).



(a) Normal state,
Thermal equilibrium condition
$N_1 >> N_2$

(b) Inverted state,
Non-equilibrium condition
$N_1 << N_2$

Fig. 44.6: Illustration of Population Inversion (a) Normal state (b) Inverted state

Thus, under thermal equilibrium condition, $N_1 >> N_2$.

Population inversion *is a non-equilibrium state and exists only for a short time. This is the condition of the material in which population of the upper energy level N_2 far exceeds the population of the lower energy level, N_1* (Fig. 44.6 b).

That is,

$$N_2 >> N_1 \quad ...(44.20)$$

In this condition the population distribution between the levels E_1 and E_2 is inverted and hence it is known as the *inverted state*. This is a *non-equilibrium state* and exists only for a short time. Population inversion is obtained by employing *pumping techniques*, which transfer large number of atoms from lower energy level to higher energy level.

Example 44.1: *A 10 mW He-Ne laser has efficiency of 1%. Assume that all input energy is utilized in pumping the atoms from the ground state to the excited state, which is 20 eV above the ground state. Find how many atoms are promoted to the excited state in one second.*

Solution: Efficiency of laser = 1% = 0.01

$$\text{Power input} = \frac{\text{Power output}}{\text{Efficiency}} = \frac{10\,mw}{0.01} = 1\text{ W.}$$

Therefore, energy input in one second = 1 J.

$$\text{Number of atoms excited in one second} = \frac{1\text{J}}{20\,\text{eV}} = \frac{1\text{J}}{20\times 1.602\times 10^{-19}\,\text{J}} = \mathbf{3.12 \times 10^{17}}.$$

Example 44.2: *Find the ratio of populations of the two states in a He-Ne laser that produces light of wavelength 6328Å at 27°C.*

Solution: The ratio of population is given by $\dfrac{N_2}{N_1} = e^{-(E_2-E_1)/kT}$

$$E_2 - E_1 = \frac{12400}{6328}\text{eV} = 1.96\text{ eV}$$

$$\therefore \quad \frac{N_2}{N_1} = \exp\left[\frac{-1.96eV}{(8.61\times 10^{-5}\,eV)\,(300\text{K})}\right] = e^{-75.88} = \mathbf{1.1 \times 10^{-33}}$$

44.5.2 Metastable States

An atom can be excited to a higher level by supplying energy to it. Generally, excited atoms have very short lifetimes and spontaneously give out their energy in a few nanoseconds (10^{-9}s). Thus, atoms do not stay for long enough time at the excited state. Even though the pumping agent continuously raises the atoms to the excited level, they undergo spontaneous transition and quickly return to the lower energy level. Population inversion cannot be attained under such circumstances. In order to achieve the condition of population inversion, the excited atoms are to be made to 'wait' at the upper energy level without undergoing spontaneous transition till a huge number of atoms build up at that level.

Such an opportunity would be provided by metastable states.

Metastable state *is an excited state of atoms where atoms remain excited for an appreciable time, which is of the order of 10^{-6} to 10^{-3}s. This is 10^3 to 10^6 times the lifetimes of the ordinary excited energy levels. Therefore, the metastable state allows accumulation of a large number of excited atoms at that level.*

The metastable state population can exceed the population at a lower level and establish the condition of population inversion in the lasing medium. It would be impossible to create the state of population inversion without a metastable state.

Metastable state can be readily obtained in a crystal system containing impurity atoms. These levels lie in the forbidden band gap of the host crystal. Population inversion readily takes place as the lifetimes of these levels are large, and secondly, there is no competition in filling these levels, as they are localized levels. For example, **phosphorescent** materials are made up of atoms with metastable states.

There could be no population inversion and hence no laser action, if metastable states do not exist.

44.5.3 Confining Radiation within the Medium

According to Eq. (42.17) a high radiation density $\rho(\nu)$ is required to be present in the active medium so that stimulated emission dominates spontaneous emission. If laser medium is enclosed in between a pair of optically plane parallel mirrors, photon density builds up to a very high value through repeated reflections of photons which remain within the medium. Such an arrangement is known as an ***optical resonant cavity*** or ***optical resonator***.

44.6 COMPONENTS OF LASER

The essential components of a laser are (*i*) an active medium; (*ii*) a pumping agent and (*iii*) an optical resonator (see Fig. 44.7).

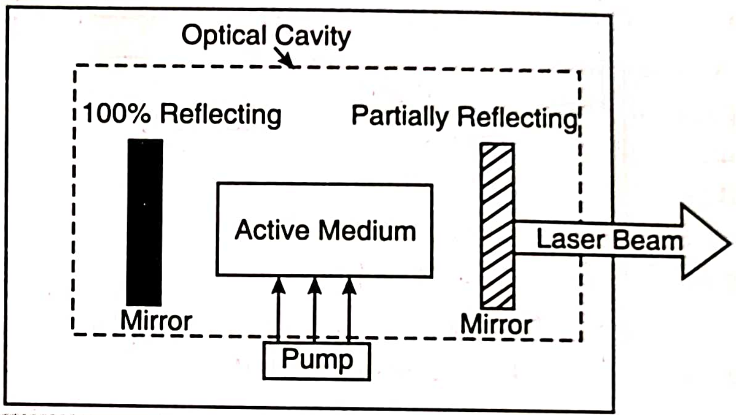


Fig. 44.7: Components of a Laser

44.6.1 Active Medium

Active ***medium*** *is the material in which the laser action takes place. The most important requirement for the laser medium is that we should be able to obtain population inversion in it.*

Atoms are in general characterized by a large number of energy levels. However, all types of atoms are not suitable for laser operation. Even in a medium consisting of different species of atoms, only a small fraction of atoms of a particular type have energy level system suitable for achieving population inversion. Such atoms can produce more stimulated emission than spontaneous emission and cause amplification of light. Those atoms, which cause laser action, are called *active centers*. The rest of the medium acts as host and supports active centers. The medium hosting the active centers is called the ***active medium***. An active medium is a medium which when excited reaches the state of population inversion and promotes stimulated emissions leading to light amplification.

44.6.2 The Pump

For achieving and maintaining the condition of population inversion, we have to raise continuously the atoms in the lower energy level to the upper energy level. It requires energy to be supplied to the system. Pumping is the process of supplying energy.

The pump is an external source that supplies energy needed to transfer the laser medium into the state of population inversion.

There are a number of techniques for pumping a collection of atoms to an inverted state. Optical pumping, electrical discharge and direct conversion are some of the methods of pumping. In optical pumping, a light source such as a flash discharge tube is used. This method is adopted in solid-state lasers. In electrical discharge method, the electric field causes ionization of the medium and raises it to the excited state. In semiconductor diode lasers, a direct conversion of electrical energy into light energy takes place.

44.6.3 Optical Resonator

Laser is a light source and it is analogous to an electronic oscillator. An electronic oscillator is essentially an amplifier supplied with a positive feed back. A part of the output of the amplifier is taken and fed back at its input. Then, electrical noise signal of appropriate frequency present at the input gets amplified; the output is again fed back to the input and amplified. It goes on till a stable output is reached. At this stage the oscillator acts as a source of a particular frequency.

In laser the active medium is the amplifier, which is converted into an oscillator through the feed back mechanism established by an optical resonator. A pair of optically plane parallel mirrors, enclosing laser medium in between them (Fig. 44.8), is known as an ***optical resonant cavity***. One of these mirrors is partially reflecting and the other is made fully reflecting.

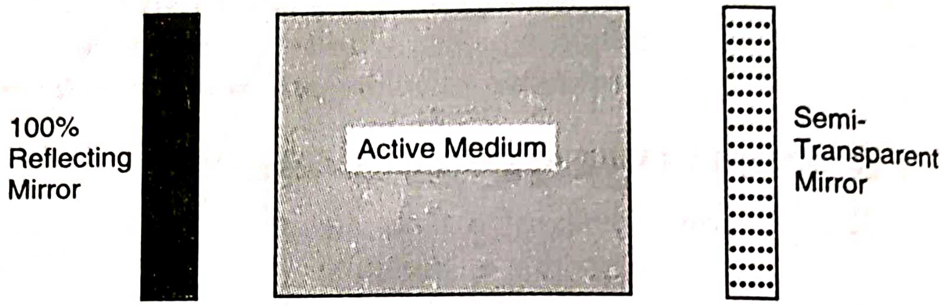


Fig. 44.8:
Fabry-Perot Optical resonator

In laser, the role of noise is played by chance photons emitted spontaneously. The photons emitted along the optic axis of the resonant cavity travel through the medium and trigger stimulated emissions. They are reflected by the end mirror and reverse their path. The photons are thus fed back into the medium and travel toward the opposite end mirror causing more stimulated emissions. The photons are once more reflected at the mirror and travel toward the opposite mirror. Substantial light amplification takes place because the light beam is reflected several times at the mirrors and gains strength in each passage. Ultimately, when the amplification balances the losses in the cavity, the laser beam emerges out from the front – end mirror. *In the absence of resonator cavity, there would be no amplification of light.*

Role of the Optical Resonator

(*i*) The primary function of the optical resonator is to provide positive feed back of photons into the medium so that stimulated emission is sustained and the laser acts as a generator of light.

(*ii*) The laser oscillation is initiated by photons spontaneously emitted by some of the excited atoms. Each spontaneous photon can trigger many stimulated transitions along the path of its travel. As the initial spontaneous photons are emitted in different directions, the stimulated photons would travel in different directions. The optical resonator selects the direction in which the light is to be amplified; the direction being the optical axis of the pair of mirrors. Thus, optical cavity makes the laser beam directional.

(*iii*) In order to make the stimulated emission dominate spontaneous emission, a high radiation density $\rho(\nu)$ is required to be present in the active medium. The optical cavity builds up the photon density to a very high value through repeated reflections of photons and confines them within the medium.

(*iv*) Optical cavity selects and amplifies only certain frequencies causing the laser output to be highly monochromatic.

44.7 LASING ACTION

Fig.44.8 shows the active medium enclosed in optical resonator and being excited by a pumping agent. The resulting laser action, which is shown in Fig. 44.9, consists of the following steps:

Step-1: Pumping: The atoms (active centers) in the medium are in the ground state initially, as shown in Fig. 44.9 (a). By supplying energy from an external source, the atoms are excited from the ground level to an excited state.

Step-2: Population inversion: The lifetime of atoms at the excited state is extremely small, of the order. of 10^{-8} sec. Therefore, the atoms drop spontaneously from the excited state to the metastable state. As the lifetime of atoms at the metastable state is comparatively longer (10^{-3} sec), the atoms go on accumulating at the metastable state. As soon as the number of atoms at the metastable state exceeds that of the ground state, the medium goes into the state of population inversion (Fig. 44.9 b).

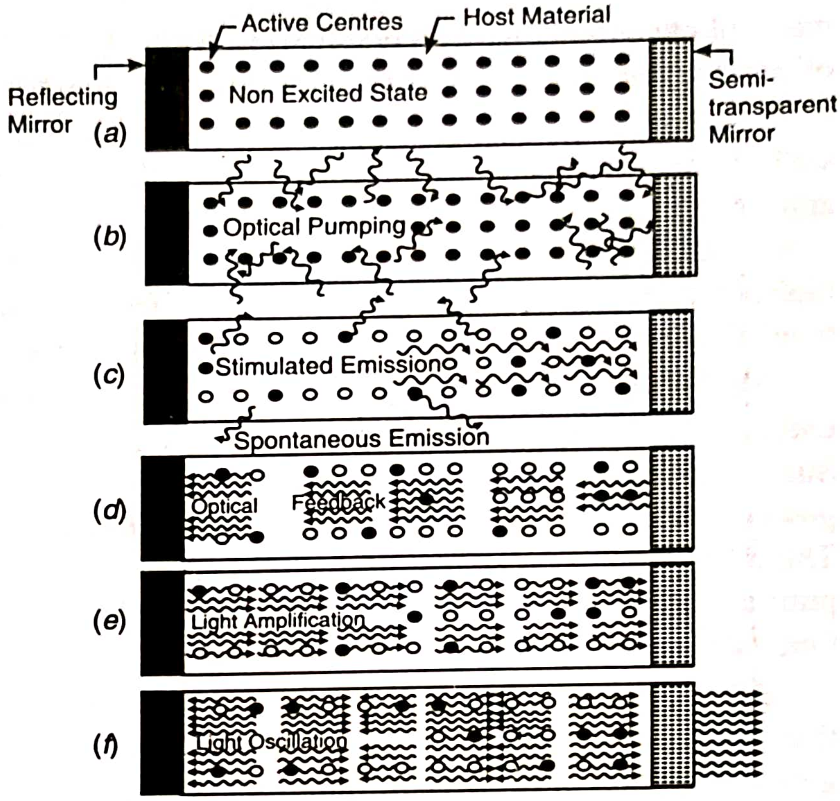


Fig. 44.9: Light amplification and oscillations due to the action of optical resonator

Step-3: Spontaneous emissions: Some of the excited atoms at the metastable state may emit photons spontaneously in various directions (Fig. 44.9 c). Each spontaneous photon can trigger many stimulated transitions along the direction of its propagation. As the initial spontaneous photons are moving in different directions, the photons stimulated by them also travel in different directions. Many of such photons leave the medium without reinforcing their strength. The photons emitted in a direction other than the axial direction will pass through the sides of the medium and are lost forever.

Step-4: Amplification: A majority of photons traveling along the axis cause stimulated emission and on reaching the end mirror they are reflected back into the medium. On their way to opposite mirror, stimulates more and more atoms and boost up the photon strength, Fig. 44.9 (d). The photons that reach the opposite mirror are reflected once again into the medium, as shown in Fig. 44.9 (e). The photons travel once more through the medium generating more photons and more amplification. The photons are then reflected again at the mirror and travel through the medium. As the photons are reflected back and forth between the mirrors, stimulated emission sharply increases and the amplification of light takes place. The mirrors thus provide *positive feed* back of light into the medium so that stimulated emission acts are sustained and the medium operates as an oscillator.

Step-5: Oscillations: On every reflection at the front-end mirror, light is partly transmitted through it. It is a *loss of energy* from the resonator. When the losses occurring at the mirrors and within the medium together balance the gain a stable and strong laser beam will come out from the front-end mirror as shown in Fig. 44.9 (*f*).

44.8 PUMPING METHODS

In order to create the state of population inversion in an active medium, the atoms in the material have to be pumped (excited) to particular energy levels. The most common methods of pumping are optical pumping and electrical pumping.

(a) Optical pumping: Optical pumping uses photons to excite the atoms. A light source such as a flash discharge tube is used to illuminate the laser medium and the photons of appropriate frequency excite the atoms to an upper energy level. From there, they drop to a metastable level to create the state of population inversion. The pump photon must have higher frequency than the emitted photon. This is because the atoms are to be excited to a level above the metastable level from the ground level or a lower energy level.

The pumping level of the atom must be a broader level. It should span a range of energies. If the level is narrow, one can use a pump photon of only one specific frequency. Such a situation severely restricts the choice of sources and also a large portion of the source power would go wasted. Fortunately, in a majority of cases the pump levels are wide bands. Therefore, light sources like flash lamps emitting a broad range of frequencies can be used for pumping. Optical pumping is suitable for any laser medium that is transparent to pump light. Optical pumping is used in solid state lasers.

(b) Electrical pumping: Electrical pumping can be used only in case of laser materials that can conduct electricity without destroying lasing activity. This method is limited to gases. In case of a gas laser, a high voltage pulse initially ionizes the gas so that it conducts electricity. An electric current flowing through the gas excites atoms to the excited level from where they drop to the metastable level leading to population inversion.

44.8.1 Principal Pumping Schemes

Atoms in general are characterized by a large number of energy levels. Among them only three or four levels will be pertinent to the pumping process. Therefore, only those levels are depicted in the pumping scheme diagrams. Two important pumping schemes are widely employed. They are known as three-level and four-level pumping schemes.

Two levels scheme is not generally feasible for laser action. The main reason is that the energy being used to pump the atoms into the upper laser state has an equal probability of stimulating them back down. Therefore, it is not possible in general to pump more than half of atoms into the excited state.

1. Three-Level Pumping Scheme: In the *three levels scheme* the atoms are first pumped to a state higher in energy than the upper laser state. The pumped state should have a shorter lifetime for spontaneous emission so that the atoms can spontaneously come down to the upper laser state. The upper laser state is selected such that it has as long a lifetime as possible. Then the atoms stay in the upper laser state long enough to be stimulated.

A typical *three-level pumping scheme* is shown in Fig. 44.10. The state E_1 is the ground state; E_3 is the pump state and E_2 is upper lasing level, which is a metastable state. When the medium is exposed to pump frequency radiation, a large number of atoms will be excited to E_3 level. However, they do not stay at that level but rapidly undergo downward transitions to the metastable state E_2 through non-radiative transitions. The atoms are trapped at this state as spontaneous transition from the level E_2 to the level E_1 is forbidden. The pumping continues and after a short time there will be a large accumulation of atoms at the level E_2. When more than half of the ground state atoms accumulate at E_2, the population inversion condition is achieved between the two states E_1 and E_2. Now a chance photon can trigger stimulated emission.

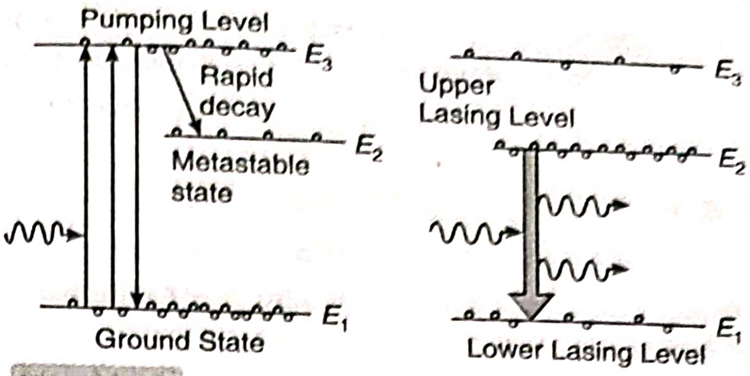


Fig. 44.10:

A typical three level pumping scheme (a) Pumping (b) Lasing action

(*a*) In this scheme, the terminal state of the laser transition is simultaneously the ground state. Therefore, population inversion is achieved only when more than half of the ground state atoms are pumped to the upper state. Thus, the scheme requires very high pump power.

(*b*) The three levels scheme produces light only in pulses. Once stimulated emission commences, the metastable state is quickly emptied and the population of the ground state increases rapidly. As a result, the population inversion ends. One has to wait till the population inversion is re-established. Thus, the three-level lasers operate in pulsed mode.

2. Four-Level Pumping Scheme: A typical *four level pumping scheme* is shown in Fig. 44.11. The state E_1 is the ground state, E_4 the pumping level, E_3 the metastable upper lasing level and E_2 the lower lasing level. E_2, E_3 and E_4 are the excited states. When light of pump frequency ν_p is incident on the lasing medium, the active centers are readily excited from the ground state to the pumping level E_4. The atoms stay at the E_4 level for only about 10^{-8}s, and quickly drop down to the metastable state E_3. As spontaneous transitions from the level E_3 to level E_2 cannot take place, the atoms get trapped in the state E_3. The population at the state E_3 grows rapidly. The level E_2 is well above the ground state such that $(E_2 - E_1) > kT$.

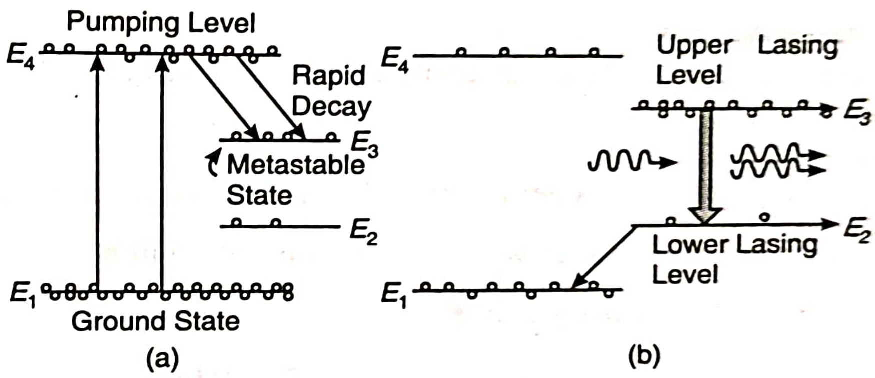


Fig. 44.11:

Illustration of fourlevels pumping scheme (a) Pumping (b) Lasing Action.

Therefore, at normal temperature atoms cannot jump to level E_2 on the strength of thermal energy. As a result, the level E_2 is virtually empty. Therefore, population inversion is attained between the states E_3 and E_2. A chance photon of energy hv = $(E_3 - E_2)$ emitted spontaneously can start a chain of stimulated emissions, bringing the atoms to the lower laser level E_2. From state E_2, the atoms subsequently under go non–radiative transitions to the ground state E_1 and will be once again available for excitation, making it possible for light to be emitted continuously.

(a) The lower laser transition level in this scheme is nearly vacant. Therefore, less pump power is sufficient to achieve population inversion.

(b) Four level lasers operate in continuous wave (cw) mode.

44.9 THRESHOLD CONDITION FOR LASING

Light, as it travels back and forth in the optical resonator, gets amplified and it suffers various losses. The losses occur due to the scattering and diffraction of light within the active medium and also due to transmission at the output mirror. For the buildup of oscillations to the required level, it is necessary that the amplification between two consecutive reflections of light from rear end mirror balance the losses. The threshold gain can be found by considering the change in intensity of a beam of light undergoing a round trip within the resonator.

Let us assume that the laser medium fills the space between the mirrors M_1 and M_2 (see Fig. 44.12), which have reflectivity r_1 and r_2 respectively. Let the mirrors be separated by a distance L. Further, let the intensity of the light beam be I_0 at M_1. Then, in travelling from mirror M_1 to mirror M_2, the beam intensity increases from I_0 to $I(L)$, which is given by

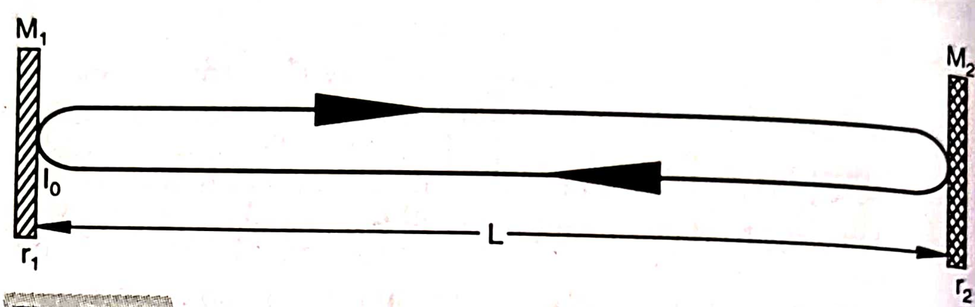


Fig. 44.12: Round trip path of the radiation through the laser cavity

$$I(L) = I_0 e^{(\gamma-\alpha_s)L} \quad ...(44.21)$$

where γ is the gain coefficient and α the loss coefficient of the active medium.

After reflection at M_2, the beam intensity will be $r_2 I_0 e^{(\gamma-\alpha_s)L}$ and after a complete round trip the final intensity will be

$$I(2L) = r_1 r_2 I_0 e^{(\gamma-\alpha_s)2L} \quad ...(44.22)$$

The amplification obtained during the round trip is

$$G = \frac{I(2L)}{I_0} = r_1 r_2 e^{(\gamma-\alpha_s)2L} \quad ...(44.23)$$

The product $r_1 r_2$ represents the losses at the mirrors whereas α_s includes all the distributed losses such as scattering, diffraction and absorption occurring in the medium. The losses are balanced by gain, when $G \geq 1$ or $I(2L) = I_0$. It requires that

$$r_1 r_2 e^{2(\gamma-\alpha_s)L} \geq 1$$

or

$$e^{2(\gamma-\alpha_s)L} \geq \frac{1}{r_1 r_2} \quad ...(44.24)$$

Taking logarithms on both sides, we get

$$2L(\gamma - \alpha_s) \geq -\ln r_1 r_2$$

$$\gamma - \alpha_s \geq -\frac{1}{2L} \ln r_1 r_2$$

$$\gamma \geq \alpha_s - \frac{1}{2L} \ln r_1 r_2 \qquad ...(44.25)$$

$\therefore$

$$\gamma \geq \alpha_s + \frac{1}{2L} \ln \frac{1}{r_1 r_2} \qquad ...(44.26)$$

or

Eq. (44.26) is known as the ***condition for lasing***. It shows that the initial gain must exceed the sum of the losses in the cavity. This condition is used to determine the threshold value of pumping energy for lasing action.

γ will be dependent on how hard the laser medium is pumped. As the pump power is slowly increased, a value of γ_{th} called ***threshold value*** is reached and the laser starts oscillating. The threshold value γ_{th} is given by

$$\gamma_{th} = \alpha_s + \frac{1}{2L} \ln \frac{1}{r_1 r_2} \qquad ...(44.27)$$

Eq. (44.27) states the condition when the net gain would be able to counteract the effect of losses in the cavity and is known as the ***threshold condition for lasing***. The value of γ must be atleast γ_{th} for laser oscillations to commence.

44.10 MODES OF THE LASER BEAM

The laser beam radiated from the laser cavity is not random but is determined by the dimensions of the cavity. The dimensions of the cavity determine certain discrete resonant conditions. They are known as *resonant modes*. The light waves oscillating at modes that match the oscillation modes of the cavity are sustained. The laser modes governed by the axial dimensions of the resonant cavity are called the ***longitudinal modes***, and the modes determined by the cross-sectional dimensions of the laser cavity are called ***transverse modes***.

(a) Longitudinal Modes: A light wave which moves inside the laser cavity from right to left is reflected by the left mirror. Reflected light moves to the right and is reflected from the right mirror, and so forth. So, two waves of the same frequency and amplitude moving in opposite directions creates a standing wave.

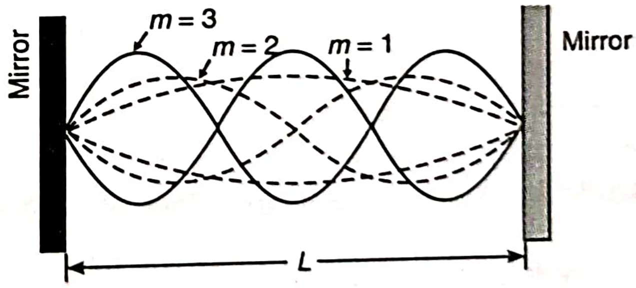


Fig. 44.13: Longitudinal Modes

In order to create a standing wave, the wave must start with the same phase at the mirror (Fig. 44.13). Therefore, the optical path from one mirror to the other and back must be an integer multiplication of the wavelength. Thus,

$$2\mu L = m\lambda_m \qquad (m = 1, 2, 3, ...)$$

or

$$\lambda_m = \frac{2\mu L}{m} \qquad ...(44.28)$$

Light waves are amplified strongly if, and only if, they satisfy the above condition. Only those wavelengths that satisfy Eq. (44.28) can exist inside the cavity. Waves of other wavelengths interfere destructively with each other as they pass back and forth between the mirrors. Thus, they attenuate very quickly. Because of its relatively longer length as compared to the wavelength of light, the resonator may support simultaneously several standing waves.

These standing waves are known as the ***longitudinal modes***.

$$\nu_m = \frac{mc}{2\mu L} \quad \text{...(44.29)}$$

Thus, frequency difference between two adjacent modes (m and $m \pm 1$) is

$$\Delta\nu = \frac{c}{2\mu L} \quad \text{...(44.30)}$$

The frequencies given by the Eq. (44.29) are the *allowed frequencies* inside a laser cavity of length L. However, all these allowed frequencies will not be emitted from the laser, since there are other limiting conditions. Only those frequencies (modes) that have amplification above the lasing threshold, to overcome absorption will be emitted out of the laser (see Fig. 44.14)

Fig. 44.14 shows the gain versus frequency curve of a certain active medium. The ***lasing threshold*** and ***possible longitudinal modes of the laser*** are indicated therein. The region under the curve and above the lasing threshold encloses the lasing range. For example, Fig. 44.14 consists of only 5 frequencies out of those allowed inside the cavity and which are above the lasing threshold. So, only these 5 frequencies can exist at the output of this laser.

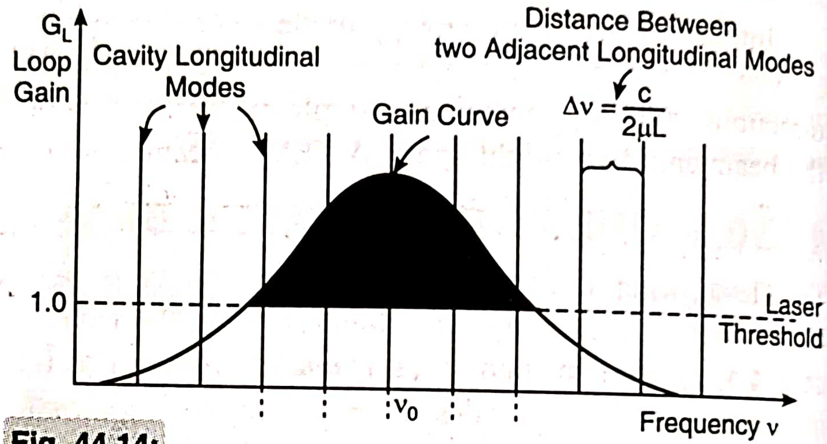


Fig. 44.14: Gain curve of a laser and allowed frequencies.

Example 44.3: *Because of the interaction of chromium ion with ruby lattice, the transitions responsible for ruby-laser-emission are spread over an energy, resulting in wavelength spread of 0.53 mm around 694.3 nm. If the length of ruby rod is 2 cms (refractive index 1.75) how many longitudinal cavity modes would the ruby-laser emission contain?*

Solution: Mode separation $= \dfrac{c/\mu}{l} = \dfrac{3\times10^8/1.75 \text{ m/s}}{2\times10^{-2}\text{m}} = 8.6 \times 10^9$ Hz

Frequency spread of laser emission

$$\Delta\nu = (c/\lambda^2)\Delta\lambda = \frac{3\times10^8(\text{m/s})\times0.53\times10^{-9}(\text{m})}{(694.3\times10^{-9}\text{m})^2} = 330 \times 10^9 \text{ Hz.}$$

No. of cavity modes $= \Delta\nu$ / mode separation $= 330 \times 10^9 / 8.6 \times 10^9 = 38.5$

i.e., $=$ **38 modes**

Example 44.4: *If the half-width of the He-Ne laser operating at wavelength 6328Å is 1500 MHz, what must be the length of the laser cavity to ensure that only one longitudinal mode oscillates?*

Solution:

The length of cavity is given by $L = \dfrac{mc}{2\Delta\nu}$

$$= \frac{1 \times 3 \times 10^8 \text{ m/s}}{2 \times 1.5 \times 10^9 \text{ / s}} = \mathbf{0.1 \text{ m.}}$$

(b) Transverse Modes: The transverse modes illustrate the intensity distribution across the cross-section of the laser beam. The shape of the optical cavity determines the transverse modes. The allowed modes in an optical cavity are designated as TEM_{mn}, where T, E, and M stand for transverse, electric, and magnetic modes, respectively, and m and n are integers. The simplest transverse mode is TEM_{00}, which has a smooth cross-section profile with a Gaussian peak in the middle, as shown in Fig. 44.15.

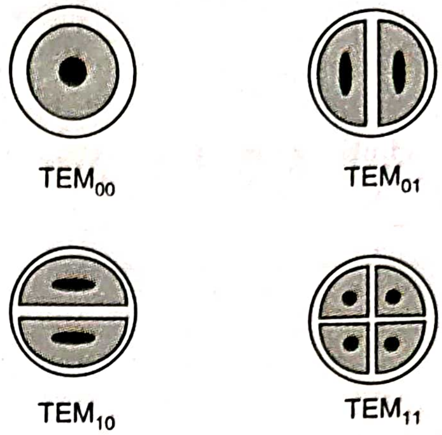


Fig. 44.15: Beam profiles of transverse modes

Integers m and n of TEM_{mn} mode stand for minima between the edges of the beam in two perpendicular directions. A TEM_{01} beam has a single minimum dividing the beam into two bright spots. A TEM_{11} beam has two perpendicular minima one in each direction, dividing the beam into four bright spots. The larger the values of m and n, the more bright spots are contained in the laser beam. Most laser cavities are designed to produce only the TEM_{00} mode.

44.11 TYPES OF LASERS

Lasers are divided into different types basing on different considerations. We divide them here on the basis of the material used. Some of the important types of lasers are

(*i*) Solid-state lasers	Examples: Ruby laser, Nd:YAG laser etc
(*ii*) Gas lasers	Examples: Helium-Neon laser, CO_2 laser etc
(*iii*) Semiconductor diode lasers	Examples: GaAs laser, InP laser etc

Most lasers emit light in the red or IR regions. Lasers work in continuous mode or in a pulsed mode.

44.11.1 Ruby Laser

Ruby laser belongs to the class of solid-state lasers. Ruby is basically Al_2O_3 crystal containing about 0.05% of chromium atoms. Cr^{3+}ions are the actual active centers while aluminum and oxygen atoms are inert. Chromium ions have absorption bands in the blue and green regions.

(a) Construction: Ruby rod is taken in the form of a cylindrical rod of about 4 cm in length and 1 cm in diameter. Its ends are grounded and polished such that the end faces are exactly parallel and are also perpendicular to the axis of the rod. The end faces of the ruby rod are silvered so that they form the optical resonator. The rear face is made totally reflecting while the front face is made partially reflecting.

The laser rod is surrounded by a helical photographic flash lamp filled with xenon (Fig. 44.16a). Whenever activated by the power supply the lamp produces flashes of white light.

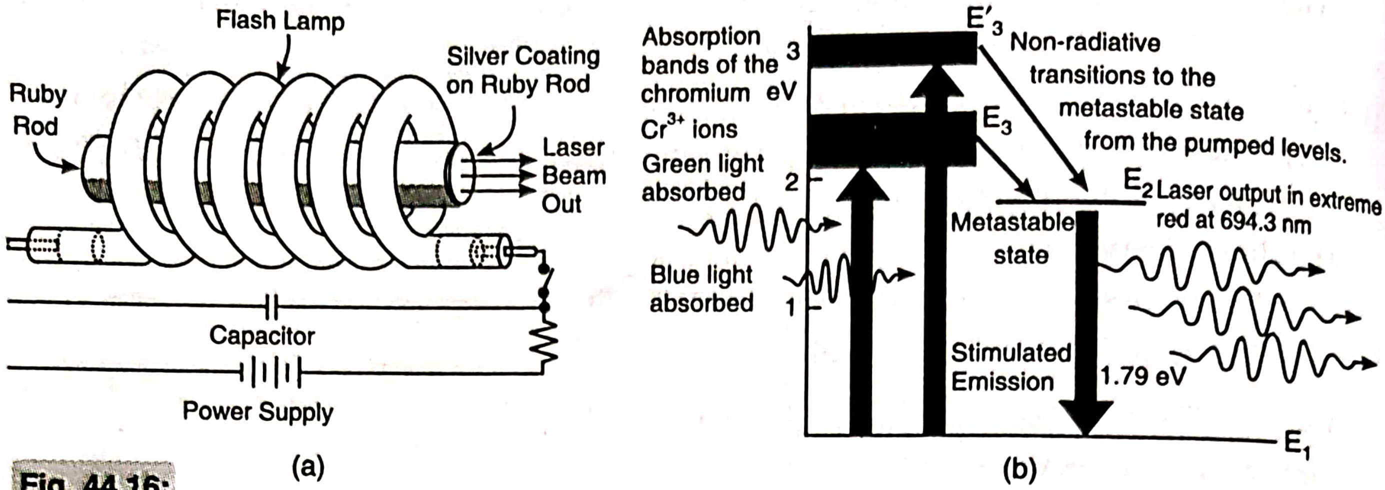


Fig. 44.16: (a) Schematic of a ruby laser (b) Energy levels and transitions in a ruby laser

(b) Working: The energy levels of Cr^{3+} ions in the crystal lattice are shown in Fig. 44.16 (b). The energy level structure of the Cr^{3+} ions is characterized by two absorption bands and a metastable state.

(c) The Pumping Mechanism

(*i*) When the xenon flash lamp is switched on, the discharge generates an intense burst of white light lasting for a few milliseconds.

(*ii*) The Cr^{3+} ions are excited to the energy bands E_3 and E_3' by the green and blue components of white light.

(*iii*) The Cr^{3+} ions undergo non – radiative transitions from these energy levels to level E_2. E_2 is a metastable state.

(*iv*) The metastable state E_2 has a lifetime of approximately 1000 times more than the lifetime of E_3 and E_3' levels. Therefore, Cr^{3+} ions accumulate at E_2 level.

(*v*) The metastable level E_2 is the upper laser level, while E_1 is the ground level and constitutes the lower laser level.

(d) Population Inversion

(*i*) The upper laser level E_2 will be rapidly populated, as the excited Cr^{3+} ions quickly make downward transitions from the upper energy bands.

(*ii*) When more than half of the Cr^{3+} ion population accumulates at E_2 level, the state of population inversion is established between E_2 and E_1 levels.

(e) Lasing action

(*i*) A chance photon is produced when a Cr^{3+} ion makes a spontaneous transition from E_2 level to E_1 level.

(*ii*) This spontaneous photon stimulates another excited ion to make a downward transition.

(*iii*) This stimulated photon and the initial photon trigger many excited ions to emit photons.

(*iv*) Red photons of wavelength 6943 Å travelling along the axis of the ruby rod are repeatedly reflected at the end mirrors and light amplification takes place.

(*v*) On attaining sufficient energy, the laser beam emerges out through the partially reflecting mirror.

(*vi*) The laser emission occurs in the visible region at a wavelength of 6943 Å.

(vii) Once stimulated transitions commence, the metastable state gets depopulated very rapidly and the state of population inversion disappears and lasing action ceases.

(viii) The laser becomes active once again when population inversion state is reestablished.

(ix) Therefore, the output of the laser is not a continuous wave but occurs in the form of pulses of microsecond duration.

(f) Salient Features

(i) Uses three-level pumping scheme

(ii) The active centers are Cr^{3+} ions

(iii) Light from a xenon flash lamp is the pumping agent

(iv) Poor efficiency

(v) Operates in pulsed mode

44.11.2 Nd: YAG Laser

Nd: YAG laser is one of the most popular types of solid state laser. It is a four-level laser. Yttrium aluminium garnet, $Y_3Al_5O_{12}$, commonly called YAG is an optically isotropic crystal. Some of the Y^{3+} ions in the crystal are replaced by neodymium ions, Nd^{3+}. Doping concentrations are typically of the order of 0.725% by weight. The crystal atoms do not participate in the lasing action but serve as a host lattice in which the active centres, namely Nd^{3+} ions reside.

(a) Construction: Fig. 44.17 illustrates a typical design of Nd: YAG laser. The system consists of an elliptically cylindrical reflector housing the laser rod along one of its focus line and a flash lamp along the other focus line. The light leaving one focus of the ellipse will pass through the other focus after reflection from the silvered surface of the reflector. Thus the entire flash lamp radiation gets focused on the laser rod. The YAG crystal rods are typically of 10 cm in length and 12 mm in diameter. The two ends of the laser rod are polished and silvered and constitute the optical resonator.

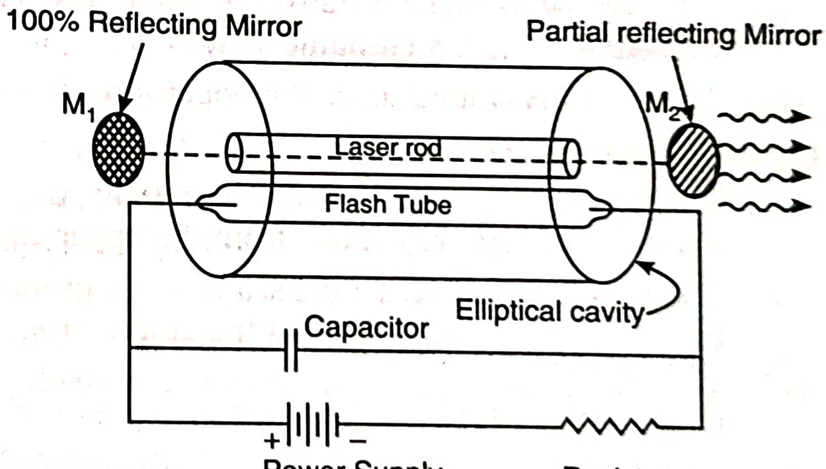


Fig. 44.17: Schematic of a Nd:YAG Laser

(b) Working: A simplified energy level diagram for the neodymium ion in YAG crystal is shown in Fig. 44.18. The energy level structure of the free neodymium atom is preserved to a certain extent because of its relatively low concentration. However, the energy levels are split and the structure is complex.

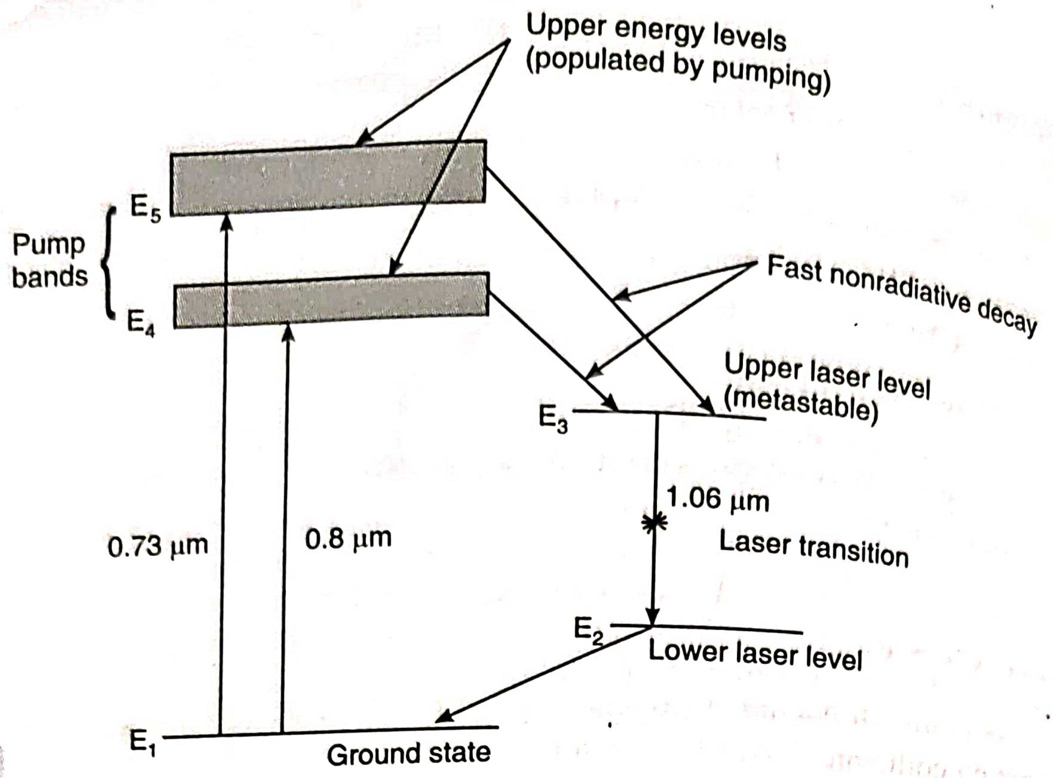


Fig. 44.18: Energy levels and transitions in a Nd : YAG laser

(c) The Pumping Mechanism

(*i*) When the krypton flash lamp is switched on, the Nd^{3+} ions are excited to the upper energy bands E_4 and E_5.

(*ii*) The Nd^{3+} ions make a transition from these energy levels to level E_3 by non-radiative transition. E_3 is a metastable state.

(*iii*) The metastable level E_3 is the upper laser level, while E_2 forms the lower laser level.

(d) Population Inversion

(*i*) The upper laser level E_3 will be rapidly populated, as the excited Nd^{3+} ions quickly make downward transitions from the upper energy bands.

(*ii*) The lower laser level E_2 is far above the ground level and hence it can not be populated by Nd^{3+} ions through thermal transitions from the ground level.

(*iii*) Therefore, the population inversion is readily achieved between the E_3 level and E_2 level.

(e) Lasing action

(*i*) A chance photon is produced when an Nd^{3+} ion makes a spontaneous transition from E_3 level to E_2 level.

(*ii*) This spontaneous photon stimulates another excited atom to make a downward transition.

(*iii*) This stimulated photon and the initial photon trigger many excited atoms to emit photons.

(*iv*) Photons thus generated travel back and forth between the two end mirrors and gain in strength very rapidly.

(*v*) On attaining sufficient energy, the laser beam emerges out through the partially reflecting mirror.

(*vi*) The laser emission occurs in infrared (IR) region at a wavelength of about 10,600 Å (1.06 μm).

(*vii*) The Nd^{3+} ions return to the ground state E_1 from the lower lasing level E_2, on their own through non-radiative transitions.

(f) Salient Features

(*i*) Uses four-level pumping scheme

(*ii*) The active centers are Nd^{3+} ions

(*iii*) Light from a xenon or krypton flash lamp is the pumping agent

(*iv*) Low efficiency (1%) and moderate power output (watts)

(*v*) Operates in CW/pulsed mode

44.11.3 Helium-Neon Laser

Gas lasers are the most widely used lasers. They range from the low power helium-neon laser used in college laboratories to very high power carbon dioxide laser used in industrial applications.These lasers operate with rarefied gases as the active media and are excited by an electric discharge. In gases, the energy levels of atoms involved in the lasing process are narrow and as such require sources with sharp wavelength to excite atoms. Finding an appropriate optical source for pumping poses a problem. Therefore optical pumping is not used in gas lasers. The most common method of exciting gas laser medium is by passing an electric discharge through the gas. Electrons present in the discharge transfer energy to atoms in the laser gas by collisions.

The first gas laser was He-Ne laser, which was invented in 1961 by Ali Javan, William R. Bennett, Jr. and Donald R.Herriott.

(a) Construction: A Helium - Neon laser is illustrated in Fig. 44.19. It is made of a long discharge tube filled with a mixture of helium and neon gases in the ratio 10:1. Neon atoms are the active centers and have energy levels suitable for laser transitions while helium atoms help in exciting neon atoms.

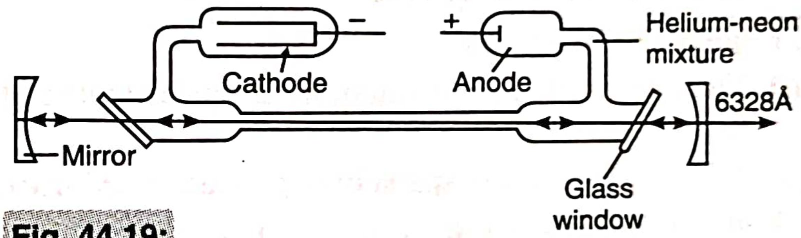


Fig. 44.19:

Schematic of a He-Ne laser

Electrodes are provided in the discharge tube to produce discharge in the gas. They are connected to a high voltage power supply. The tube is hermetically sealed by inclined windows arranged at its two ends. On the axis of the tube, two mirrors are arranged externally, which form the Fabry-Perot optical resonator. The distance between the mirrors is adjusted to be $m\lambda/2$ such that the resonator supports standing wave pattern.

(b) Working: The energy levels of helium and neon are shown in Fig. 44.20.

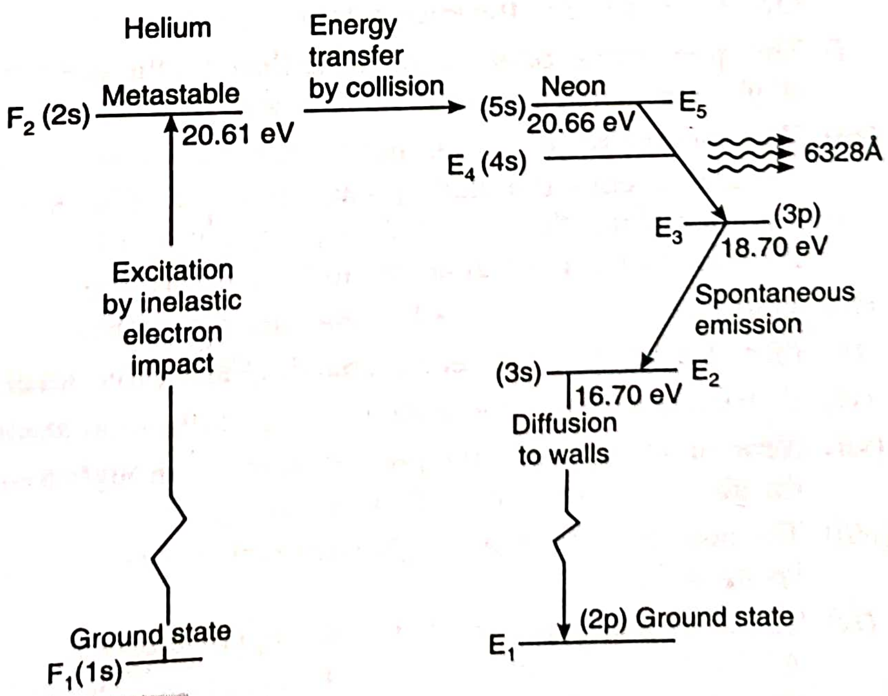


Fig. 44.20:

Energy levels of helium and neon and Laser transitions.

(c) Pumping Mechanism

(*i*) When the power is switched on, a high voltage of about 10 kV is applied across the gas mixture. It ionizes the gas.

(*ii*) The electrons and ions produced in the process of discharge are accelerated towards the anode and cathode respectively. They collide with helium and neon atoms on the way.

(*iii*) The energetic electrons excite helium atoms more readily, as they are lighter.

(*iv*) One of the excited levels of helium F_2 (2s) is at 20.61 eV above the ground level. It is a metastable level and the excited helium atom cannot return to the ground level through spontaneous emission.

(*v*) However, the excited helium atom can return to the ground level by transferring its excess energy to a neon atom through collision. Such an energy transfer can take place when the two colliding atoms have identical energy levels. Such an energy transfer is known as **resonant energy transfer**.

(*vi*) The neon energy level E_5 (5s) is at 20.66 eV, which is close to the excited energy level F_2 of helium atom. Therefore, resonant transfer of energy occurs between the excited helium atom and ground level neon atom. The kinetic energy of helium atoms provides the additional 0.05 eV required for excitation of the neon atoms.

(*vii*) Helium atoms drop to the ground state after exciting neon atoms. This is the pumping mechanism in He-Ne laser.

(d) Population Inversion

(*i*) The upper state of neon atom E_5 is a metastable state. Therefore, neon atoms accumulate in this upper state.

(*ii*) The E_3 (3p) level is sparsely populated at ordinary temperatures.

(*iii*) As the population at the higher energy level E_5 is greater than the population at the lower level E_3, a state of population inversion is established between E_5 and E_3 levels.

(e) Lasing Action

(*i*) Random photons of red colour of wavelength 6328 Å are emitted spontaneously by a few of the atoms at the energy level E_5.

(*ii*) The spontaneous photons traveling through the gas mixture prompt stimulated emission of photons of red colour of wavelength 6328 Å.

(*iii*) The photons bounce back and forth between the end mirrors, causing more and more stimulated emission during each passage. The strength of the stimulated photons traveling along the axis of the optical cavity (discharge tube) builds up rapidly while the photons traveling at angles to the axis are lost.

(*iv*) Thus, the transition $E_5 \rightarrow E_3$ generates a laser beam of wavelength 6328 Å.

(*v*) From the level E_3 the neon atoms drop to E_2 (3s) level spontaneously.

(*vi*) E_2 level is a metastable state. Consequently, neon atoms tend to accumulate at E_2 level.

(*vii*) Neon atoms return to the ground state E_1 through frequent collisions with the walls of the glass tube holding the helium-neon gas mixture.

(*viii*) The neon atoms are once again available for excitation to higher state and participate in lasing action.

(*ix*) The neon atoms are excited to the upper lasing level continuously through collisions. As the population inversion can be maintained in the face of continuous laser emission, the laser operates in continuous wave mode.

(f) Role of helium atoms: The role of helium atoms in the laser is to excite neon atoms and to cause population inversion. The probability of energy transfer from helium atoms to neon atoms is more, as there are 10 helium atoms per 1 neon atom in the gas mixture. The probability of reverse transfer of energy from neon to helium atom is negligible.

(g) Necessity of narrow glass tube: During the operation of the laser, it is necessary that the atoms accumulating at the metastable level E_2 are brought to the ground state $E_1(2p)$ quickly; otherwise the number of atoms at the ground state will go on diminishing and the laser ceases to function. The only way of bringing the atoms to the ground state is through collisions. Therefore, to increase the probability of atomic collisions with the tube walls, the discharge tube is made narrow.

(h) Salient Features

(*i*) Uses four-level pumping scheme

(*ii*) The active centers are neon atoms

(*iii*) Electrical discharge is the pumping agent

(*iv*) Low efficiency and low power output

(*v*) Operates in CW mode

44.11.4 Carbon Dioxide Laser

The carbon gas laser is a very useful and efficient laser. It is a four-level molecular laser and operates at 10.6 μm in far IR region.

(a) Construction: The schematic of typical CO_2 laser is shown in Fig. 44.21. It is basically a discharge tube having a bore of cross section of about 1.5 mm^2 and a length of about 260 mm. The discharge tube is filled with a mixture of carbon dioxide, nitrogen and helium gases in 1:4:5 proportions respectively. CO_2 molecules are the active centres. Lasing transitions occur between the vibrational levels of the electronic ground state.

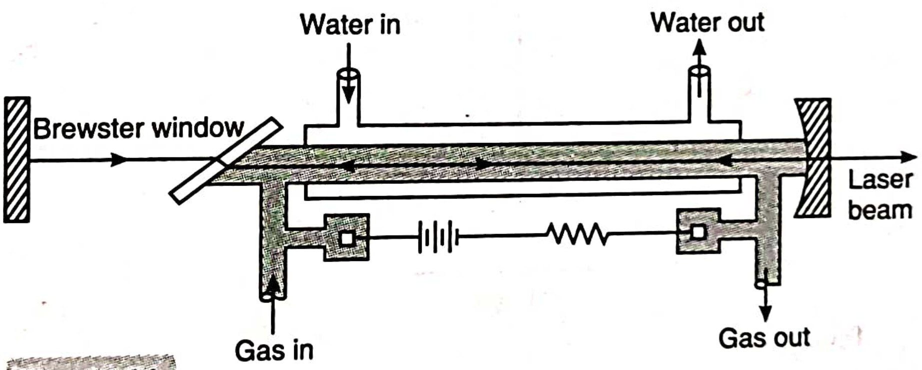


Fig. 44.21: Schematic of a carbon dioxide laser

(b) Energy levels of CO_2 molecule: Fig. 44.22 shows the vibrational modes and rotations of CO_2 molecule.

(*i*) The electron energy levels of an isolated atom are discrete and narrow. However, in case of molecules the energy spectrum is complicated due to many additional features.

(*ii*) Each electron energy level is associated with nearly equally spaced vibrational levels and each vibrational level in turn has a number of rotational levels.

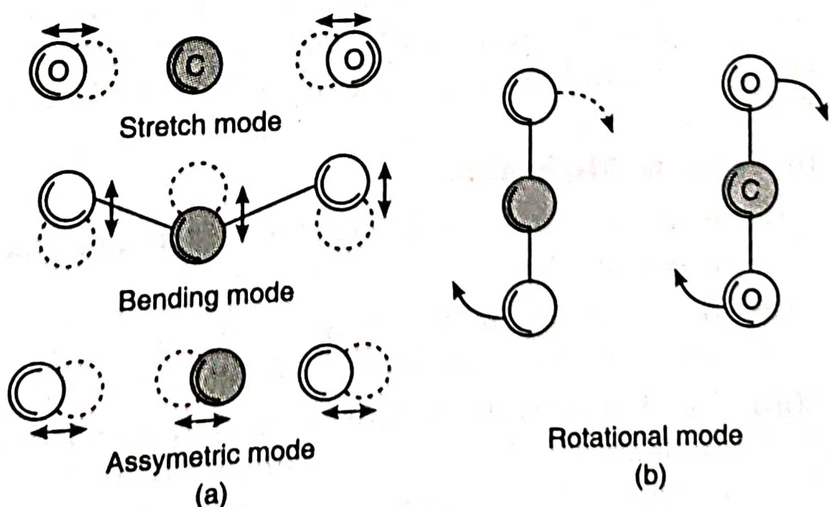


Fig. 44.22: (a) Vibrational modes and (b) Rotational modes of a CO_2 molecule

(c) Pumping Mechanism

(*i*) When the power is switched on, a high voltage of about 10 kV is applied across the gas mixture. It ionizes the gas.

(*ii*) The electrons and ions produced in the process of discharge are accelerated towards the anode and cathode respectively. They collide with helium and neon atoms on the way.

(*iii*) The energetic electrons excite helium atoms more readily, as they are lighter.

(*iv*) One of the excited levels of helium F_2 (2s) is at 20.61 eV above the ground level. It is a metastable level and the excited helium atom cannot return to the ground level through spontaneous emission.

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(*ix*) The neon atoms are excited to the upper lasing level continuously through collisions. As the population inversion can be maintained in the face of continuous laser emission, the laser operates in continuous wave mode.

(f) Role of helium atoms: The role of helium atoms in the laser is to excite neon atoms and to cause population inversion. The probability of energy transfer from helium atoms to neon atoms is more, as there are 10 helium atoms per 1 neon atom in the gas mixture. The probability of reverse transfer of energy from neon to helium atom is negligible.

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(h) Salient Features

(*i*) Uses four-level pumping scheme
(*ii*) The active centers are neon atoms
(*iii*) Electrical discharge is the pumping agent
(*iv*) Low efficiency and low power output
(*v*) Operates in CW mode

44.11.4 Carbon Dioxide Laser

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(a) Construction: The schematic of typical CO_2 laser is shown in Fig. 44.21. It is basically a discharge tube having a bore of cross section of about 1.5 mm^2 and a length of about 260 mm. The discharge tube is filled with a mixture of carbon dioxide, nitrogen and helium gases in 1:4:5 proportions respectively. CO_2 molecules are the active centres. Lasing transitions occur between the vibrational levels of the electronic ground state.

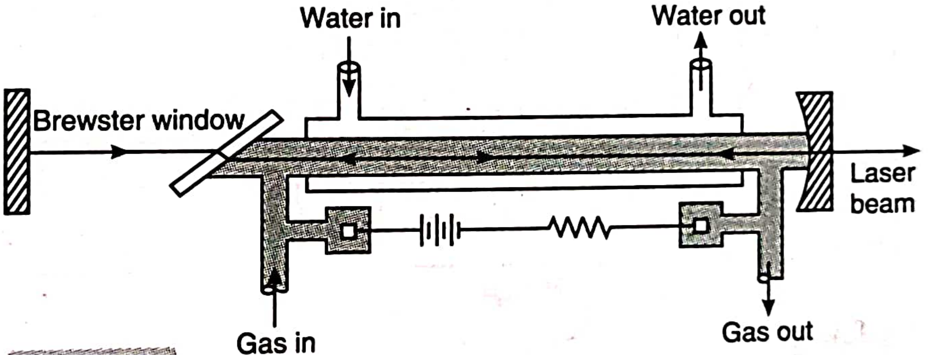

Fig. 44.21: Schematic of a carbon dioxide laser

(b) Energy levels of CO_2 molecule: Fig. 44.22 shows the vibrational modes and rotations of CO_2 molecule.

(*i*) The electron energy levels of an isolated atom are discrete and narrow. However, in case of molecules the energy spectrum is complicated due to many additional features.

(*ii*) Each electron energy level is associated with nearly equally spaced vibrational levels and each vibrational level in turn has a number of rotational levels.

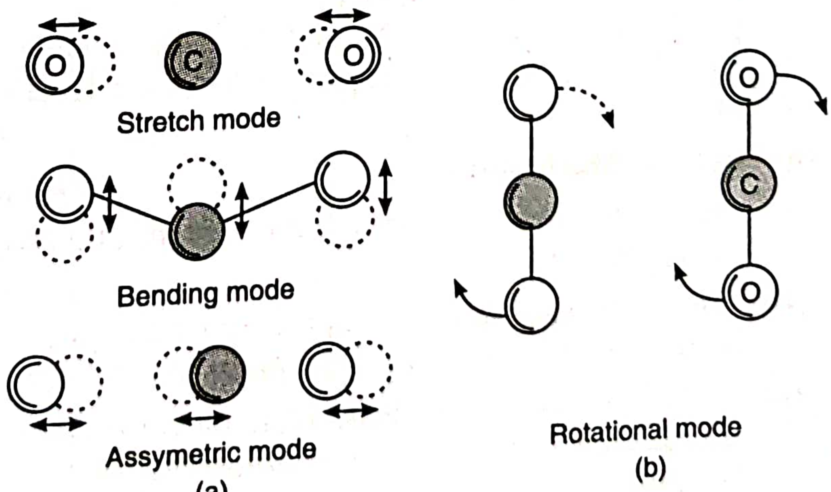

Fig. 44.22: (a) Vibrational modes and (b) Rotational modes of a CO_2 molecule

(iii) CO_2 molecule is a linear molecule consisting of a central carbon atom with two oxygen atoms attached one on either side.

(iv) It undergoes three independent vibrational oscillations known as the ***vibrational modes*** (Fig. 44.20). These vibrational degrees of freedom are quantized. At any one time, a CO_2 molecule can vibrate in a linear combination of three fundamental modes.

(v) The energy states of the molecule are represented by three quantum numbers (m n q).

(vi) These numbers stand for the amount of energy related with each mode. For example, the number (020) shows that the molecule in this energy state is in the pure bending mode with two units of energy.

(vii) Each vibrational state is related with rotational states corresponding to the rotation of CO_2 molecule about its centre of mass. The separations between vibrational-rotational states are to a large extent lesser on the energy scale compared to the separations between electron energy levels.

The nitrogen molecule N_2 is also characterized by similar vibrational levels.

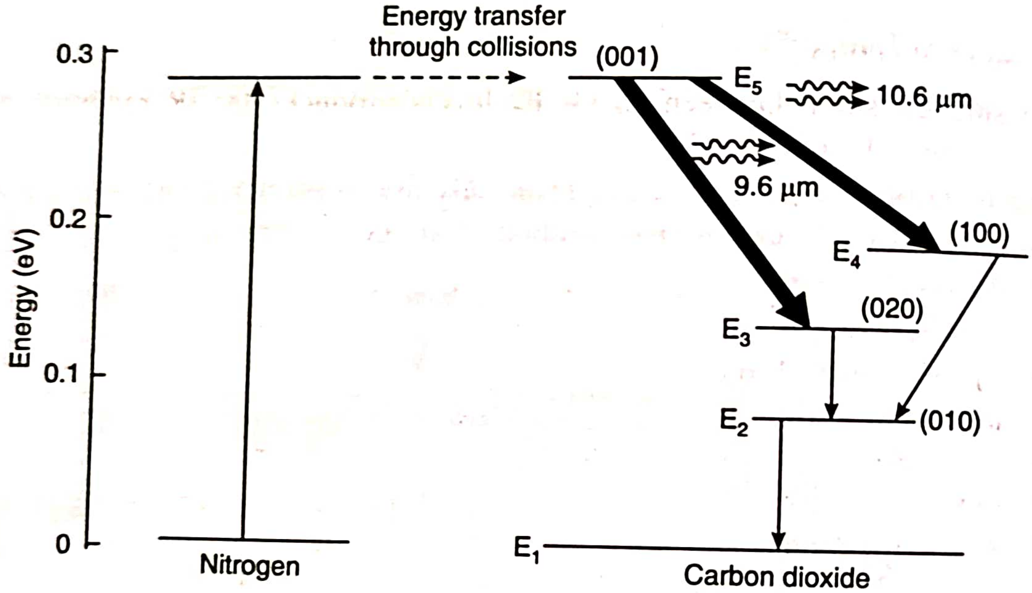

Fig. 44.23:

Energy levels of nitrogen and carbon dioxide molecules and transitions between the levels

(c) Working: Fig. 44.23 shows the lowest vibrational levels of the ground electron energy state of CO_2 molecule and an N_2 molecule. The excited state of an N_2 molecule is metastable and it is identical in energy to (001) vibrational level of CO_2 molecule, indicated as E_5 in Fig. 44.23.

(d) Pumping Mechanism

(i) When current passes through the mixture of gases, the N_2 molecules get excited to the metastable state.

(ii) The excited N_2 molecules cannot spontaneously lose their energy and consequently, the number of N_2 molecules at the metastable level builds up.

(iii) The N_2 molecules undergo inelastic collisions with ground state CO_2 molecules and excite them to E_5 level. Some of the CO_2 molecules are also excited to the upper level E_5 through collisions with electrons.

(e) Population Inversion

(*i*) The E_5 level is the upper lasing level while the (020) and (100) states marked as E_3 and E_4 levels act as the lower lasing levels.

(*ii*) As the population of CO_2 molecules builds up at E_5 levels population inversion is achieved between E_5 level and the levels at E_4 and E_3.

(f) Lasing action

(*i*) Random photons are emitted spontaneously by a few of the atoms at the energy level E_5.

(*ii*) The spontaneous photons traveling through the gas mixture prompt stimulated emission of photons.

(*iii*) The photons bounce back and forth between the end mirrors, causing more and more stimulated emission during each passage. The strength of the stimulated photons traveling along the axis of the optical cavity (discharge tube) builds up rapidly while the photons traveling at angles to the axis are lost.

(*iv*) The laser transition between $E_5 \rightarrow E_4$ levels produces far IR radiation at the wavelength 10.6 μm (1, 06,000Å).

(*v*) The lasing transition between $E_5 \rightarrow E_3$ levels produces far IR radiation at 9.6 μm (96,000Å) wavelength.

(*vi*) E_3 and E_4 levels are also metastable states and the CO_2 molecules at these levels fall to the lower level E_2 through inelastic collisions with normal (unexcited) CO_2 molecules.

(*vii*) This process leads to accumulation of population at E_2 level. As the gaseous mixture heats up, the E_2 level, which is close to the ground state, tends to be populated through thermal excitations. Thus, the de-excitation of CO_2 molecules at the lower lasing level poses a problem and inhibits the laser action.

(*viii*) The helium atoms de-excite CO_2 molecules through inelastic collisions and decrease the population density of CO_2 at E_2 level. It also aids cooling the gaseous mixture through heat conduction.

(*ix*) The CO_2 molecules are once again available for excitation to higher state and participate in lasing action.

(*x*) CO_2 molecules are excited to the upper lasing level continuously through collisions. As the population inversion can be maintained in the face of continuous laser emission, the laser operates in continuous wave mode.

Salient Features

(*i*) Uses four-level pumping scheme

(*ii*) The active centers are CO_2 molecules

(*iii*) Electrical discharge is the pumping agent

(*iv*) High efficiency (40%) and high power output (several kilowatts)

(*v*) Operates in CW mode

44.11.5 Semiconductor Diode Laser

A ***semiconductor diode laser*** is a specifically made *p-n* junction diode that emits coherent light under forward bias. R. N. Hall and his coworkers made the first semiconductor laser in 1962. p-n junction lasers are made to emit light almost anywhere in the spectrum from UV to IR.

Diode lasers are remarkably small in size (0.1mm long). They have high efficiency of the order of 40%. Modulating the biasing current easily modulates the laser output. They operate at low powers. In spite of their small size and low power requirement, they produce power outputs equivalent to that of He-Ne lasers. The chief advantage of a diode laser is that it is portable. Because of the rapid advances in semiconductor technology, diode lasers are mass produced for use in optical fibre communications, in CD players, CD-ROM drives, optical reading, and high speed laser printing etc wide variety of applications.

(i) Semiconductor Materials

(*i*) Among the semiconductors, there are two different groups. They are *direct band gap semiconductors and indirect band gap semiconductors.*

(*ii*) Direct band gap semiconductor is the one in which a conduction band electron can recombine directly with a hole in the valence band.

(*iii*) The recombination process leads to emission of light.

(*iv*) Most of the compound semiconductors belong to this group.

(*v*) Direct recombination of conduction band electron with a hole in the valence band is not possible in indirect band gap semiconductors. Silicon and germanium belong to this group. The recombination of an electron and a hole produces heat in these materials.

(*vi*) Direct band gap semiconductors are formed by group III-V elements and group IV-VI elements.

(*vii*) Lasers are made using direct band gap semiconductors. Gallium Arsenide (GaAs) diode is an example of semiconductor diode laser.

(ii) Principle

(*i*) The energy band structure of a semiconductor consists of a valence band and a conduction band separated by an energy gap, E_g.

(*ii*) The conduction band contains electrons and the valence band contains holes and electrons.

(*iii*) When an electron from the conduction band jumps into a hole in the valence band, the excess energy E_g is given out in the form of a photon.

(*iv*) Thus, the electron-hole recombination is the basic mechanism responsible for emission of light.

(*v*) The wavelength of the light is given by the relation $\lambda = hc/E_g$.

(*vi*) Semiconductors having a suitable value of E_g emit light in the optical region.

(iii) Types of semiconductor diode lasers

Broadly there are two types of semiconductor diode lasers. They are known as *homojunction semiconductor lasers and heterojunction semiconductor lasers.*

(a) Homojunction Semiconductor Laser

A simple diode laser which makes use of the same semiconductor material on both sides of the junction is known as a homojunction diode laser.

Example: Gallium arsenide (GaAs) laser.

(b) Heterojunction Semiconductor Laser

A diode laser which makes use of different semiconductor materials on the two sides of the junction is known as a heterojunction diode laser. These are further classified as single heterojunction diode lasers and double heterojunction diode lasers.

Example: A junction laser having GaAs on one side and GaAlAs on the other side

44.11.5.1 Homojunction semiconductor laser

(a) Construction: Fig. 44.24 shows the schematic of a homojunction diode laser. Starting with a heavily doped *n*-type GaAs material, a *p*-region is formed on its top by diffusing zinc atoms into it. A heavily zinc doped layer constitutes the heavily doped p-region. The diode is extremely small in size. Typical diode chips are 500 μm long and about 100 μm wide and thick. The top and bottom faces are metallized and metal contacts are provided to pass current through the diode. The front and rear faces are polished parallel to each other and perpendicular to the plane of the junction. The polished faces constitute the Fabry-Perot resonator. In practice there is no necessity to polish the faces. A pair of parallel planes cleaved at the two ends of the PN junction provides the required reflection to form the cavity. The two remaining sides of the diode are roughened to eliminate lasing action in that direction. The entire structure is packaged in small case which looks like the metal case used for discrete transistors.

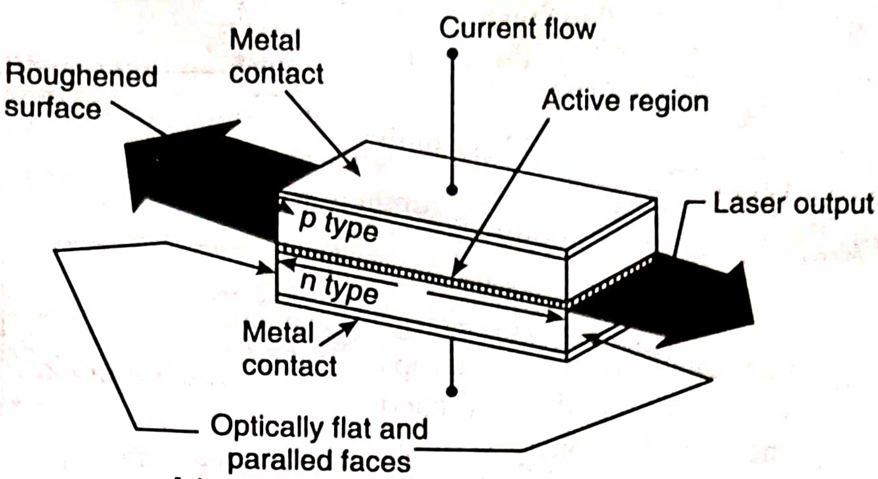

Fig. 44.24: Schematic of homojunction diode laser

(b) Working: The energy band diagram of a heavily doped *p-n* junction is shown in Fig. 44.25.

(*i*) Heavily doped *p*- and *n*- regions are used in making a laser diode.

(*ii*) Because of very high doping on n-side, the donor levels are broadened and extend into the conduction band. The Fermi level also is pushed into the conduction band.

(*iii*) Electrons occupy the portion of the conduction band lying below the Fermi level.

(*iv*) Similarly, on the heavily doped p-side the Fermi level lies within the valence band and holes occupy the portion of the valence band that lies above the Fermi level.

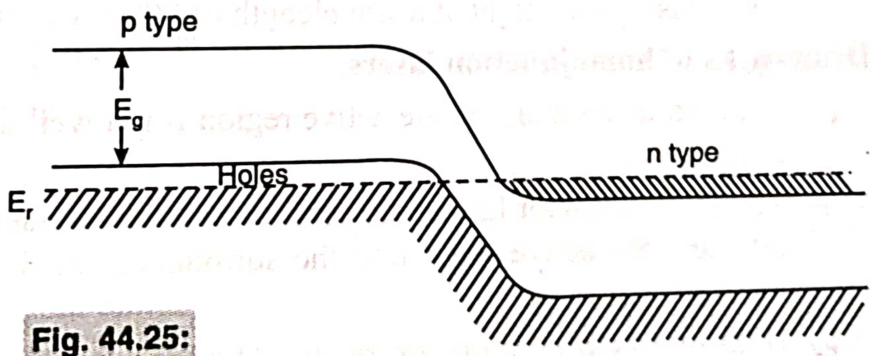

Fig. 44.25: Energy band diagram of a heavily doped *p-n* junction without bias

(*v*) At thermal equilibrium, the Fermi level is uniform across the junction.

(c) The Pumping Mechanism

(*i*) When the junction is forward-biased, electrons and holes are injected into the junction region in high concentrations.

(*ii*) In other words, charge carriers are *pumped* by the dc voltage source.

(*iii*) When the diode current reaches a threshold value (see Fig. 44.26), the carrier concentrations in the junction region will rise to a very high value.

(d) Population Inversion

(*i*) As a result, the region d in Fig. 44.26 (b) contains a large concentration of electrons within the conduction band and simultaneously a large number of holes within the valence band.

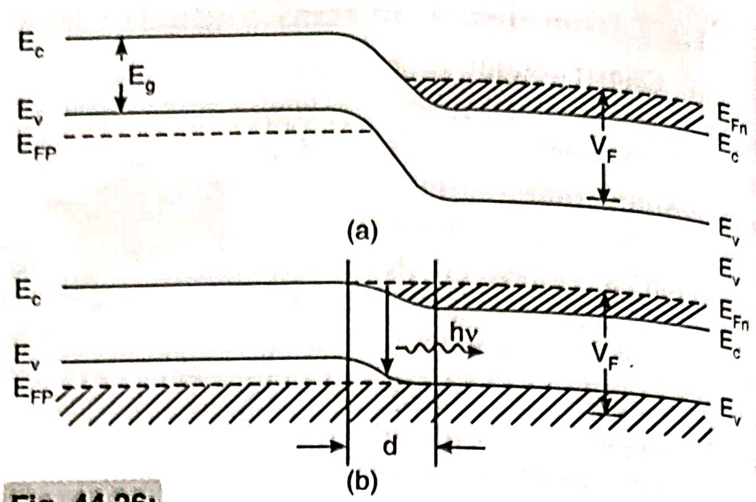

Fig. 44.26: Laser diode under forward bias

(*ii*) Holes represent absence of electrons.

(*iii*) Thus, the upper energy levels in the narrow region are having a high electron population while the lower energy levels in the same region are vacant.

(*iv*) Therefore, the condition of population inversion is attained in the narrow junction region. This narrow zone in which population inversion occurs is called an ***inversion region or active region***.

(e) Lasing action

(*i*) Chance recombination acts of electron and hole pairs lead to emission of spontaneous photons.

(*ii*) The spontaneous photons propagating in the junction plane stimulate the conduction electrons to jump into the vacant states of valence band.

(*iii*) This stimulated electron-hole recombination produces coherent radiation.

(*iv*) GaAs laser emits light at a wavelength of 9000 Å in IR region.

Drawbacks of homojunction lasers:

(*i*) In homojunction lasers, the active region is not well defined due to the diffusion length of the carriers.

(*ii*) The semiconductor has nearly uniform refractive index throughout. Therefore, light can diffuse from active layer into the surrounding medium. As a result the cavity losses increase.

(*iii*) High threshold currents are required and the laser cannot be operated continuously at room temperature.

44.11.5.2 Heterojunction laser

Heterojunction lasers are multilayer-structures designed such that the carriers are confined in a narrow region and population is built up at lower current levels. We study here the structure and working of a double heterojunction (DH) laser.

(a) Construction: In a double heterojunction laser, a GaAs layer is sandwiched between two layers of GaAlAs (Fig. 44.27). The material GaAlAs has a wider energy gap and a lower refractive index than GaAs. Metal contacts on the top and bottom faces provide the passage of current through the diode. The front and rear faces are polished parallel to each other and perpendicular to the plane of the junction and constitutes the Fabry-Perot resonator.

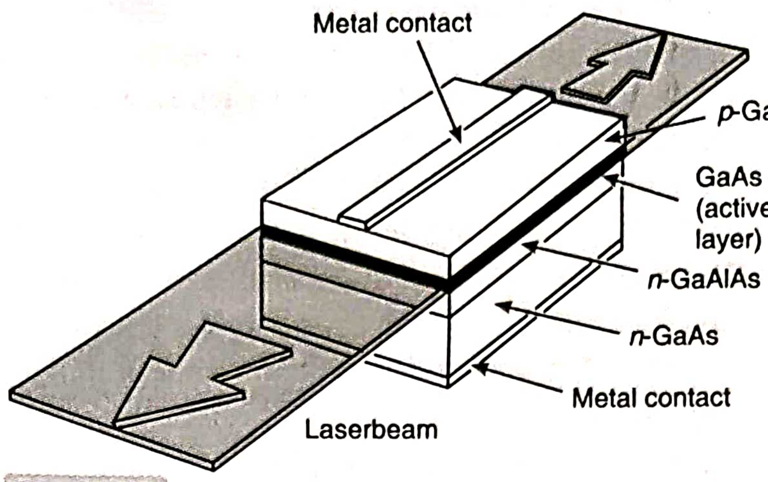

Fig. 44.27: Schematic of heterojunction laser

(b) Working:

(*i*) The basic principle of working of heterojunction diode is similar to that of a homo-junction diode.

(*ii*) P-type narrow band gap GaAs layer at the centre constitutes the active layer in which the lasing occurs.

(*iii*) This layer is flanked by an n-type wide band gap GaAlAs layer on one side and by a *p*-type wide band gap GaAlAs layer on the other side (Fig. 44.28 a).

(*iv*) The refractive indices of GaAlAs layers are smaller than that of GaAs layer (Fig. 44.28c).

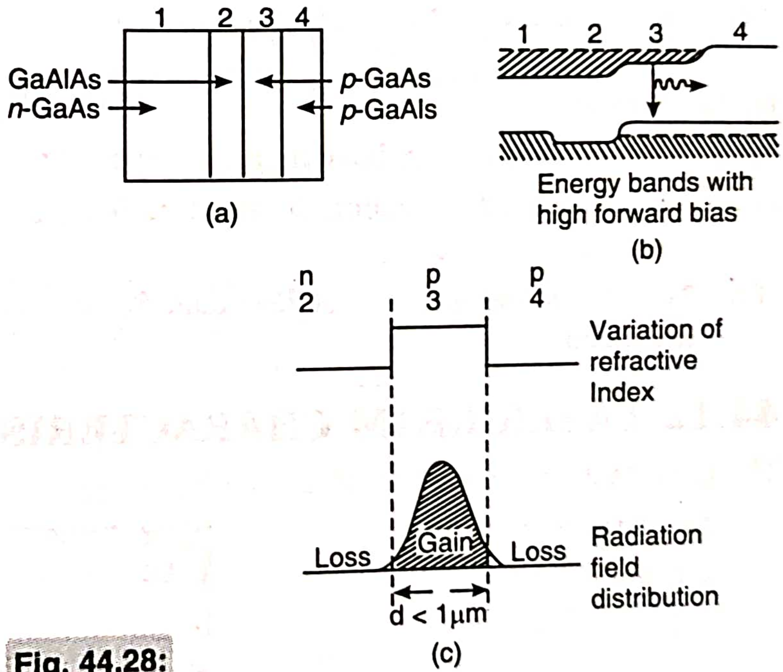

Fig. 44.28: Working of heterojunction laser

(c) Pumping Mechanism

(*i*) When the junction is forward-biased, electrons and holes are injected into the active region in high concentrations.

(*ii*) When the diode current reaches a threshold value, the carrier concentrations in the active region will rise to a very high value.

(*iii*) The electrons injected from the *n*-type GaAlAs layer into the p-GaAs layer confront energy barrier at the junction where p-type GaAs and *p*-type GaAlAs meet and are reflected back into the active region. Similarly, the holes are reflected by the potential barrier provided by the higher band gap *n*-GaAlAs layer. Thus, the layers in heterostructure confine the charge carriers to the GaAs layer.

(d) Population Inversion

(*i*) Due to the forward bias, the active region contains a large concentration of electrons within the conduction band and simultaneously a large number of holes within the valence band.

(*ii*) Thus, the upper energy levels in the active region are having a high electron population while the lower energy levels in the same region are vacant.

(*iii*) Therefore, the condition of population inversion is attained in the narrow active region.

(*iv*) Now the active region thickness is the thickness of *p*-GaAs layer. If its thickness is made small, a smaller drive current can lead to population inversion.

(e) Lasing action

(*i*) Chance recombination acts of electron-hole pairs lead to spontaneous emission of photons.

(*ii*) The spontaneous photons propagating in the active layer stimulate the conduction electrons to jump into the vacant states of valence band and produce stimulated photons.

(*iii*) The reflection at the GaAs – air interface provides sufficient feed back for laser oscillation.

(*iv*) When the diode losses are off-set by the laser gain, the laser oscillations will start.

(*v*) When the radiation attains appropriate strength, laser beam emerges from the diode.

(*vi*) As the refractive index of GaAs is higher than the refractive index of GaAlAs layers, the light is trapped within the active region and travels in one direction only.

(*vii*) The wavelength of the light emitted by the GaAs layer is 800 nm when its band gap is 1.55 eV.

(f) Advantages

(*i*) Heterojunction lasers have high efficiency even at room temperature.

(*ii*) As a result of reduction in the threshold current density, continuous operation is possible.

(*iii*) With operating currents of less than 50 mA, output powers of about 10 mW can be produced.

44.12 LASER BEAM CHARACTERISTICS

The important characteristics of a laser beam are:

(*i*) directionality

(*ii*) negligible divergence

(*iii*) high intensity

(*iv*) high degree of coherence and

(*v*) high monochromaticity.

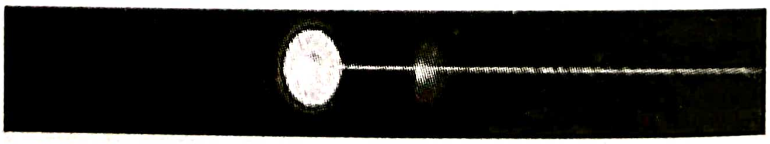

Fig. 44.29: Illustration of Directionality

(*i*) Directionality: The conventional light sources emit light uniformly in all directions. When we need a narrow beam in a specific direction, we obtain it by placing a slit in front of the source of light.

In case of laser, the active material is in a cylindrical resonant cavity. Any light that is travelling in a direction other than parallel to the cavity axis is eliminated and only the light that is travelling parallel to the axis is selected and reinforced. Light propagating along the axial direction emerges from the cavity and becomes the laser beam. Thus, a laser emits light only in one direction.

***(ii)* Divergence:** Light from conventional sources spreads out in the form of spherical wave fronts and hence it is highly divergent.

On the other hand, light from a laser propagates in the form of plane waves. The light beam remains essentially as a bundle of parallel rays. The small divergence that exists is due to the diffraction of the beam at the exit mirror. A typical value of divergence of a He-Ne laser is 10^{-3} radians. It means that the diameter of the laser beam increases by about 1 mm for every meter it travels.

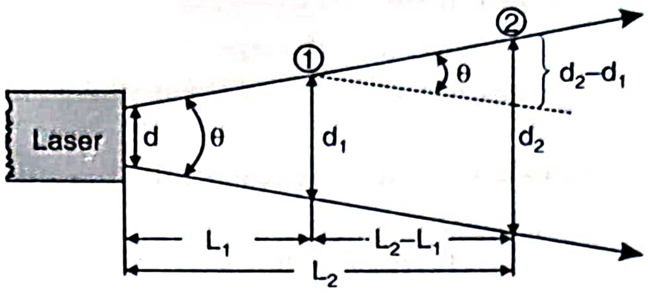

Fig. 44.30:
Illustration of Divergence

The extent of divergence can be estimated in a simple way as follows:

If the diameters of spot produced by the laser on a screen which is held at two different distances from the laser are measured, then the angle of divergence is given by

$$\phi = \frac{d_2 - d_1}{l_2 - l_1} \qquad ...(44.31)$$

where d_1 is the spot diameter at the distance l_1 and d_2 is the spot diameter at the distance l_2.

Example 44.5: *Calculate the divergence of light beam issuing out of He-Ne laser, which produces spot diameters of 4 mm and 6 mm at 1m and 2m distances respectively.*

Solution: Beam divergence $\theta = \frac{d_2 - d_1}{2(l_2 - l_1)} = \frac{(6-4)\times 10^{-3}\,\text{m}}{2(2-1)\text{m}} = \mathbf{10^{-3}}$ **radians**

***(iii)* Intensity:** The intensity of light from a conventional source decreases rapidly with distance as it spreads out in space. Laser emits light in the form of a narrow beam with its energy concentrated in a small region of space. Therefore, the beam intensity would be tremendously large and stays constant with distance. The intensity of a laser beam is approximately given by

$$I = \left[\frac{10}{\lambda}\right]^2 P \qquad ...(44.32)$$

where P is the power radiated by the laser.

To obtain light of same intensity from a tungsten bulb, it would have to be raised to a temperature of 4.6×10^6 K.

Example 44.6: *A 10 mw laser has a beam diameter of 1.6 mm. What is the intensity of the light assuming that it is uniform across the beam?*

Solution: Intensity of light is given by

$$I = \frac{\text{Power of the laser}}{\text{Area of cross section of the beam}} = \frac{P}{A}$$

$$= \frac{10\times 10^{-3}\,\text{W}}{3.143(0.8\times 10^{-3}\,\text{m})^2} = \mathbf{4.97\ kW/m^2}$$

Example 44.7: *A laser beam has a power of 50mW. It has an aperture of 5×10^{-3}m and wavelength 7000Å. The beam is focused with a lens of foal length of 0.2m. Calculate the areal spread and intensity of the image.*

Solution: Angular spread of the beam is $d\theta = \frac{\lambda}{d} = \frac{7000 \times 10^{-10}\,\text{m}}{5 \times 10^{-3}\,\text{m}} = 1.4 \times 10^{-4}$ rad.

$$\text{Areal spread} = (d\theta \times f)^2 = (1.4 \times 10^{-4}\ \text{rad} \times 0.2\text{m})^2 = 4 \times 10^{-9}\ \text{m}^2.$$

$$\text{Intensity} = \frac{\text{Power}}{\text{Area}} = \frac{50 \times 10^{-3}\,\text{watt}}{4 \times 10^{-9}\,\text{m}^2} = \mathbf{12.5\ MW/m^2}.$$

Example 44.8: *With He-Ne laser, fringes remained clearly visible when the path difference was increased upto 8m. Deduce the lower limits for (i) Coherence length, (ii) Coherence time (iii) Spectral half width (iv) Q-factor, $\lambda = 11.5 \times 10^{-7}$ m.*

Solution: (*i*) We know the phase relation will not exist for distance > λ_o.

$\therefore$ Coherence length λ_o > 8 m

(*ii*) Coherence time $$T_o = \frac{l_o}{c} > \frac{8}{3 \times 10^8} s = 2.7 \times 10^{-8} s$$

(*iii*) Spectral half width $$\Delta\lambda = \frac{\lambda^2}{l_o} = \frac{(11.5 \times 10^{-5})^2}{8} = 1.6 \times 10^{-3}\,\text{Å}$$

(*vi*) Quality factor $$Q = \frac{l_o}{\lambda} = \frac{8}{11.5 \times 10^{-5}} = 7 \times 10^6$$

Example 44.9: *A laser beam has a power of 50 mW. It has an aperture of 5×10^{-3} m and wavelength 7000Å. A beam is focused with 1 cm of focal length 0.2 m. Calculate the areal spread and intensity of the image.*

Solution: Given λ = 7000 Å = 7000×10^{-10} m

$d = 5 \times 10^{-3}$ m, focal length of lens f = 0.2 m

$\therefore$ $$\text{Angular Speed } d\theta = \frac{\lambda}{d} = \frac{7 \times 10^{-3}}{5 \times 10^{-3}} = 1.4 \times 10^{-4}\ \text{radians}$$

$$\text{Areal spread } (d\theta \times f)^2 = (1.4 \times 10^{-4} \times 0.2)^2 = 0.4 \times 10^{-8}\ \text{m}^2$$

$$\text{Intensity} = \frac{\text{power}}{\text{speed}} = \frac{50 \times 10^{-3}}{0.4 \times 10^{-8}} = 125 \times 10^5\ \text{W/m}^2$$

(*iv*) **Coherence:** The light that emerges from a conventional light source is a jumble of short wave trains which combine with each other in a random manner. The resultant light is incoherent. Coherence length is one of the parameters used as a measure of coherence. In case of a laser a large number of identical photons are emitted through stimulated emissions and therefore they will be in phase with each other. The resultant light exhibits a high degree of coherence.

The coherence length of light from a sodium lamp, which is a traditional monochromatic source, is of the order of 0.3 mm. On the other hand the coherence length of light emitted by an ordinary helium-neon laser is about 100 m.

(v) Monochromaticity: If light coming from a source has only one frequency (single wavelength) of oscillation, the light is said to be *monochromatic* and the source a *monochromatic source*. Light from traditional monochromatic sources spreads over a wavelength range of 100 Å to 1000 Å. On the other hand, the light from lasers is highly monochromatic and contains a very narrow range of a few angstroms (< 10 Å).

44.13 APPLICATIONS

Lasers find application in almost every field. They are used in mechanical working, industrial electronics, entertainment electronics, communications, information processing, and even in wars to guide missiles to the target. Lasers are used in CD players, laser printers, laser copiers, optical floppy discs, optical memory cards etc. We discuss here a few of the applications in industry.

1. Industrial applications: The large intensity that is possible in the focused output of a laser beam and its directionality makes laser an extremely useful tool for a variety of industrial applications.

(*i*) **Welding:** The laser welding is a contactless process and hence there is no chance of impurities reaching into the joint. As total input power is very small compared to that in conventional welding processes, the work pieces are not spoiled.

The heat-effected zone is relatively small because of rapid cooling. Laser welding can be done even at difficult to reach place. CO_2 lasers are used in welding thin sheets and foils.

(*ii*) **Drilling:** Laser drilling does not require a physical drill bit. Drilling by a laser beam takes place through the intense evaporation of material heated by a sequence of powerful light pulses of short duration of 10^{-4} to 10^{-3}s.

The process is faster and highly reproducible. The drilling operation can be done with extremely high precision and in any direction.

Piercing of holes in a baby bottle nipple and drilling holes in diamond dies are two of the interesting examples of laser drilling.

(*iii*) **Heat treatment for Hardening:** Heat treatment is the process, which is done for some time to harden metals and certain other materials. Heat treatment is common in the tooling and automotive industry. Heat-treating converts the surface layer to a crystalline state that is harder and more resistant to wear. In general CO_2 lasers of about 1 kW output power operating in continuous wave mode are used for heat treatment. As metals are more reflecting at IR frequencies, a heat absorbing coating such as graphite or zinc phosphate is applied on the surface of the work piece to help it absorb laser energy more efficiently. Laser heat treatment requires a low amount of energy input to the work piece. Laser processing is advantageous as it can provide selective treatment of the desirable areas. Heat treatment is used to strengthen cylinder blocks, gears, camshafts etc in the automobile industry. As the method is a non-contact method, stress is not induced in the work-pieces.

(*iv*) **Cutting:** A wide range of materials can be cut by CO_2 lasers. The materials include paper, wood, cloth, glass, quartz, ceramics, steel etc. The advantage of laser cutting is that it is fine and precise. It introduces a minimum mechanical distortion and thermal shock in the material being cut. The process does not introduce any contamination. It is easily automatized and high production rates can be achieved.

(v) **Holography:** Holography is a technique for recording and reproducing an image of an object without the use of lenses. A three-dimensional image of the object is seen when the record is illuminated. The permanent record of the interference pattern on the recording medium is called a ***hologram***.

Holography offers a wide variety of fascinating applications in different fields such as *Holographic interferometry, Acoustical holography, Three-dimensional photography, Microscopy, Holographic optical elements* (diffraction gratings).

(vi) **Electronics Industry:** Electronics industry uses lasers in the manufacture of electronic components and integrated circuits. Lasers have been used to perforate and divide silicon slices having several hundred circuits. They are also used for the isolation of faulty components in a large integrated circuit by disconnecting the conducting paths by evaporation. Trimming of thick and thin film resistors using lasers is a very common application.

(vii) **Measurement of atmospheric pollutants:** Laser is a very useful tool for the measurement of the concentrations of various atmospheric pollutants such as N_2, CO, SO_2 etc gases and particulate matter such as dust, smoke and fly ash. Conventional methods of pollution measurements require that samples of pollutants are to be collected for chemical analysis. Therefore, these methods cannot give real-time data. In contrast, laser methods permit measurements by remotely sensing the composition of atmosphere without the necessity of sample collection or chemical processing.

Another technique uses study of absorption of light beam by pollutants. The existence of specific gases in the atmosphere is detected using absorption spectroscopy techniques. A laser beam is transmitted through polluted sample and the attenuation of intensity of light due to absorption in the sample is detected and recorded. Each chemical absorbs light of characteristic wavelengths and from the absorption spectrum; its existence can be inferred.

A third method uses Raman Effect to detect the pollutants. The Raman Effect involves scattering of light by gas molecules accompanied by a shift in the wavelength of light. Raman shifts are characteristic of each molecular species. Hence, analysis of backscattered laser light reveals the constituents of the gas sample. The ozone concentration high in the atmosphere is determined using this technique.

2. Medical Applications: Lasers are playing nowadays a very important role in diagnostics and surgery. Surgeons use a focused laser beam as a scalpel to perform operations. Laser surgery is a highly sterile process since contact does not occur between the surgical tool and the tissue being cut. Operations are done very fast and the patient does not feel pain.

(i) The first big success of lasers in medicine is in the treatment of eyes. Lasers are used for the ***welding of detached retina***. Retina is the light sensitive layer at the back of the eye. Sometimes it becomes torn and gets detached from the back of the eye ball. The damage can spread and lead to total blindness. Conventional open-eye surgery is very risky. Laser treatment is very simple and fast. An argon laser beam is focused on the desired point of the retina. The green beam of the laser is strongly absorbed by the red blood cells of the retina and causes thermal effects which weld the retina back to the eye ball.

(ii) ***Cataract*** occurs when the natural lens of the eye becomes cloudy and obstructs vision leading to blindness. In traditional open-eye surgery the natural lens is replaced with a plastic lens. A series of laser pulses of high intensity focused to a small spot on the back of lens produce high electric field sparks and ruptures the membrane.

(*iii*) Another interesting eye surgery is the radial keratomy or refractive surgery. Lasers are used to change the shape of the cornea by making small incisions on it. ArF excimer laser ($\lambda = 193$ nm) with a pulse energy of 250 mJ and pulse length of 14 ns is typically used to alter the shape of cornea.

(*iv*) Lasers are employed in destroying kidney stones and gall stones. An optical fibre is used to reache the stone. Laser pulse is launched through the fibre to break the stone into small pieces which can pass through the uterer without pain. Tunable dye lasers are used in this application.

(*v*) Laser canes and spects assist the blind. The laser cane is equipped with three diode lasers. One laser aims its beam downward, the second upward and the third straight ahead. Distance is sensed by vibration of the handle. The obstacle level is indicated by the pitch of vibration.

QUESTIONS

1. What is LASER? How dose a laser beam differ from a point source of light? Mention any three engineering applications of laser.
2. How will you differentiate laser light from ordinary light? Explain in brief.
3. How is laser light different from an ordinary light?
4. Explain with neat diagram, the processes of absorption of light, spontaneous emission and stimulated emission of light. What are the necessary conditions for their occurrence? Why does spontaneous emission dominate over stimulated emission at normal temperature?
5. With the help of neat sketches, explain the three quantum processes that may occur when light radiation interacts with matter.
6. Explain with neat diagram, the processes of absorption of light, spontaneous emission and stimulated emission of radiation.
7. Explain spontaneous and stimulated emission of radiation.
8. With the help of a well labeled diagram explain the interaction of matter and radiation in the processes of (*i*) absorption (*ii*) spontaneous emission and (*iii*) stimulated emission. Which of these processes is maximized for laser operation?
9. Explain the terms: Spontaneous and stimulated emission. Which of the two emission processes is maximized in LASER operation? How?
10. Explain the terms: stimulated emission, population inversion, pumping and metastable states. Highlight their role in working of a laser.
11. With the help of a well-labeled diagram explain the interaction of matter and radiation in the processes of (*i*) absorption (*ii*) spontaneous emission and (*iii*) stimulated emission. Which of these processes is maximized for laser operation?
12. Explain in laser: (*i*) Why the active media should have preferably broad absorption band?, (*ii*) What is the role of metastable state?
13. Explain the terms: (*i*) Stimulated mission, (*ii*) Population inversion, (*iii*) Metastable state, (*iv*) Optical pumping
14. What are Einstein's coefficients? Explain them.
15. State the necessary condition for stimulated emission and explain the Einstein's A and B coefficients.
16. Derive the relation between Einstein's "A" and "B" coefficients.

17. Explain the conditions for light amplification.
18. What is popular inversion? Explain the necessity of population inversion for lasing.
19. Give the applications of laser.
20. What is meant by pumping? Discuss in brief optical pumping.
21. Explain with sketches the basic principle of operation of lasers.
22. Explain the working of a resonant cavity and its role in laser operation.
23. Distinguish between the following: (*i*) Spontaneous and stimulated emission, (*ii*) Three level and four level lasers.
24. What is resonant cavity? Highlight its importance in the production of laser radiation.
25. Why is the optical resonator required in lasers? Illustrate your answer with neat sketches.
26. Explain the role of end mirrors in a laser.
27. What do you understand by a negative temperature state? How it can be achieved?
28. What is the lifetime of charge carrier in metastable state?
29. What is metastable state? What role do such states play in the operation of laser?
30. What is meant by active material in laser?
31. Explain briefly pumping schemes used in Laser. Explain why two levels laser system is not possible.
32. Explain in brief three and four level pumping scheme. Why four levels scheme is preferred over three levels scheme?
33. Explain three level and four level laser systems. What are the advantages of four level laser system over three level laser system?
34. What do you understand by solid-state laser?
35. Explain the production of lasers by Ruby crystal.
36. Explain the working of ruby laser with the help of neat energy level diagram.
37. Describe the construction and working of Nd:YAG laser.
38. What is the main drawback of ruby laser? Explain the operation of a gas laser with the essential components. How stimulated emission takes place with the exchange of energy between helium and neon atoms?
39. Explain the construction and working of He-Ne laser with the help of energy level diagram.
40. Explain the working of He-Ne laser with the help of a neat energy level diagram.
41. Explain with a neat diagram the principle, construction and working of he-Ne laser. What are its merits and demerits?
42. What is the active material in a He-Ne laser? How population inversion is is achieved in a He-Ne laser?
43. With the help of neat energy level diagram, explain how the population inversion is achieved in He-Ne laser. Explain why increase in diameter of He-Ne tube may reduce lasing efficiency.
44. In He-Ne laser, what is the function of He atoms? Why is it necessary to use a tube of narrow diameters?
45. Describe the construction and working of He-Ne laser.
46. Explain the action of a Helium-neon laser. How is it superior to a Ruby laser?
47. What are laser characteristics? Describe the principle and working of he-Ne laser. Why a narrow discharge tube is used in He-Ne laser?
48. Describe the construction and working of CO_2 laser.
49. Explain the modes of vibrations of CO_2 molecule. Describe the construction and working of CO_2 laser with necessary diagrams.
50. Explain with a neat diagram the principle, construction and working of a semiconductor laser. What are its merits and demerits?
51. What are semiconductor diode lasers? Describe with energy band diagram the construction and working of semiconductor diode laser. Mention the uses of diode lasers.
52. What is the role of length of resonant cavity in supporting different frequency modes?
53. Explain longitudinal modes and transverse modes in a laser beam.

54. List out the properties of Laser.
55. State important characteristics of laser beam. Explain construction and working of any one laser.
56. Explain in brief the following typical characteristics of laser: (i) Coherence, (ii) Intensity.
57. What is the reason on monochromaticity of laser beam?
58. Explain in brief the characteristics of a laser beam.
59. Describe briefly the application of lasers in welding, cutting and drilling. Mention the nature and property of the lasers used.
60. Discuss some of the applications of laser in industry.
61. State a few applications of laser.
62. Explain the applications of laser in medical field.

PROBLEMS

1. A three level laser emits laser light at a wavelength of 5500Å. (*i*) In the absence of optical pumping, what will be the equilibrium ratio of the population of the upper level to that of the lower level? Assume T = 300 K., (*ii*) At what temperature for the conditions of (*i*) above would the ratio be ½?, (*iii*) What conclusion can be drawn on the basis of the results obtained by you in relation to choice of pumping mechanism?
2. A typical He-Ne laser emits radiation of λ = 6328 Å. How many photons per second would be emitted by a one milli-watt He-Ne laser? **[Ans:** 3×10^{15}**]**
3. Find the relative populations of the two states in a ruby laser that produces a light beam of wavelength 6943 Å at 300 K and 500 K. **[Ans:** 8.75×10^{-19}**]**
4. Calculate the ratio of spontaneous emission to stimulated emission if the wavelength of the radiation is 5500 Å at 2000K. **[Ans:** 4.6×10^{5}**]**
5. For the He-Ne laser (λ = 10640 Å), estimate the broadening of the wavelength due to Heisenberg uncertainty principle, assuming that the metastable state has a lifetime of 1 ms. **[Ans:** 1.06×10^{-19} m**]**
6. If the pulse width of a laser (λ = 10640 Å) is 25 ms and average output power per pulse is 0.8W, how many photons does each pulse contain? **[Ans:** 107×10^{15} m**]**
7. In an experiment on the divergence of the He-Ne laser beam, the diameters of the beam spot were measured to be 4 mm and 6 mm at distances of 1 m and 2 m respectively. Determine the divergence of the beam. **[Ans: 1 milliradian]**
8. A ruby laser produces a beam of spot diameter 5 mm and divergence of 1 milliradian. It is directed towards the moon. The earth-to-moon distance is 376284 km. Compute the area on the moon that would be illuminated by the laser beam. **[Ans:** 445000 km^2**]**
9. Estimate the angular spread of a laser beam of wavelength 6930 Å due to diffraction, if the beam emerges through a 3 mm diameter mirror. How large would be the diameter of this beam when it is incident on a satellite 300 km above the earth? **[Ans: 84.6m]**
10. A laser beam λ = 6000 Å on earth is focused by a lens of diameter 2m on to a crater on the moon. The distance of the moon is 4×10^{8} m. Hoe big is the spot on the moon? **[Ans:** 3×10^{-7} rad, 1.4×10^{4} m^2**)**
11. A ruby laser emits light of wavelength 694.4 nm. If a laser pulse is emitted for 1.2×10^{-11} s and the energy release per pulse is 0.15 J, (*i*) What is the length of the pulse and (*ii*) How many photons are there in each pulse?