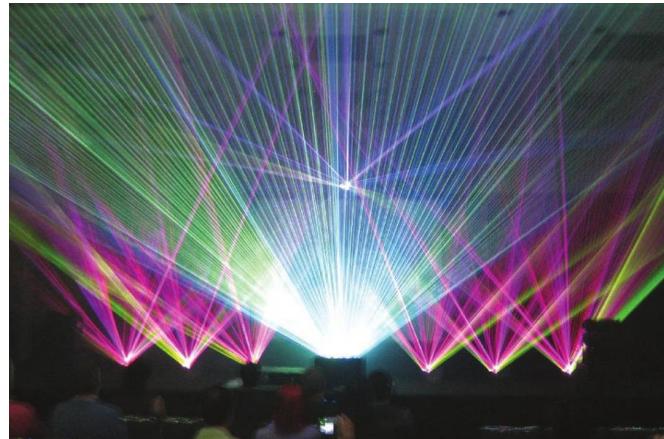


22

CHAPTER

Lasers



22.1. INTRODUCTION

Laser is one of the outstanding inventions of the 20th century. Laser is a **photonic device**, which is actually responsible for the resurgence of interest in optical technology and for the birth of a new field, namely *photonicis*. 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 actually a generator of light. In fact, the device should have been called a LOSER signifying Light Oscillation through Stimulated Emission of Radiation; this name was avoided because of its bad connotation and the name laser has been preferred. Though it is a source of light, laser differs vastly from the traditional light sources. It is not used for illumination purposes as we use other light sources. Laser is more akin to radio and microwave transmitters and produces a highly directional coherent monochromatic 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.

At a Glance

- Introduction
- Attenuation of Light in an Optical Medium
- Thermal Equilibrium
- Interaction of Light with Matter
- Einstein Coefficients and Their Relations
- Light Amplification
- Meeting the three Requirements
- Components of Laser
- Lasing Action
- Principal Pumping Schemes
- Role of Resonant Cavity
- Modes of the Laser Beam
- Transverse Modes
- Types of Lasers
- Semiconductor Laser
- Laser Beam Characteristics
- Applications

22.2 ATTENUATION OF LIGHT IN AN OPTICAL MEDIUM

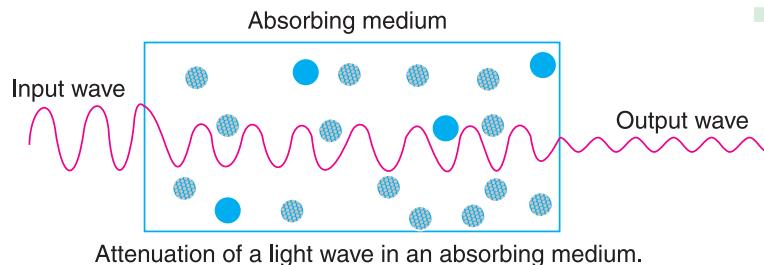


Fig. 22.1

When light travels through a medium, a gradual reduction in its intensity occurs mainly because of the processes of absorption and scattering of light in the medium. (i) Light *absorption* occurs because part of the incident light is transformed into the energy of motion of the atoms in the medium; and (ii) light is scattered when it encounters obstacles of sizes smaller than a wavelength. The reduction in intensity with distance in a medium is called **attenuation of light**. The following relation governs the attenuation of light in a transparent medium.

$$I = I_0 e^{-\alpha x} \quad (22.1)$$

where x is the distance in the medium, I_0 is the value of intensity at $x = 0$, and α is the *coefficient of attenuation* or *absorption coefficient* of the material at frequency v .

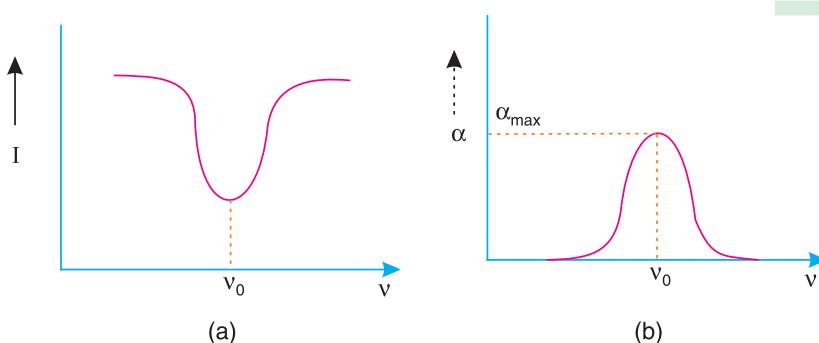


Fig. 22.2

Fig. 22.2(a) shows the variation of intensity I with frequency v at a fixed distance x in the medium. Fig. 22.2 (b) shows the variation of the attenuation coefficient α with frequency v . In general α is a positive quantity and we say that the material has a *positive coefficient of absorption*.

22.3 THERMAL EQUILIBRIUM

A material medium is composed of *identical atoms*, which are characterized by a specific system of energy levels. These energy levels are common to all atoms in the medium. We can therefore say that a certain number of atoms occupy a certain energy level. The number of atoms per unit volume that occupy a given energy level is called the **population** of that energy level. We make a simple assumption here that a particular medium has atoms, which are characterized by only two

energy levels (see Fig.22.3). Let them be E_1 the *ground level* and E_2 the *excited level*. Atoms are distributed differently in these two energy levels. Let the populations at the levels E_1 and E_2 be N_1 and N_2 respectively.

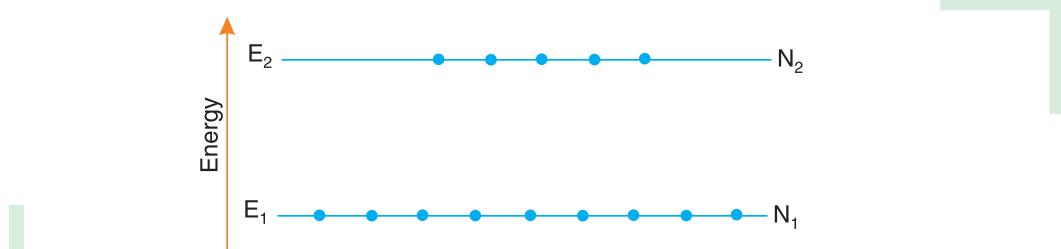


Fig. 22.3

At thermal equilibrium, the population at the energy levels can be found with the help of Boltzmann law.

$$N_1 = e^{-E_1/kT} \quad (22.2)$$

$$N_2 = e^{-E_2/kT} \quad (22.3)$$

The relative population N_2 / N_1 is given by

$$\frac{N_2}{N_1} = e^{-(E_2 - E_1)/kT} \quad (22.4)$$

Equ.(22.4) shows that the relative population N_2 / N_1 is dependent on two factors: (i) the temperature T and (ii) the energy difference $(E_2 - E_1)$. We conclude that the fraction of excited atoms would be large if the temperature is very high or if the energy levels are close.

Effect of temperature

Let us now make an estimate of the population in the energy level N_2 . Let us take the example of hydrogen gas and assume it to be a monatomic gas. In case of hydrogen atoms,

$$E_1 = -13.6 \text{ eV} \text{ and } E_2 = 3.39 \text{ eV}$$

$$\therefore (E_2 - E_1) = 10.21 \text{ eV}$$

$$\text{At room temperature, } T = 300 \text{ K, } kT = 0.025 \text{ eV and } \frac{N_2}{N_1} = e^{-\frac{10.21 \text{ eV}}{0.025 \text{ eV}}} = e^{-408.4} \approx 0 \text{ or } N_2 \approx 0.$$

It means that at room temperature all atoms are in the ground state. Now, suppose the temperature is raised say to 6000K,

$$\frac{N_2}{N_1} = e^{-\frac{10.21 \text{ eV}}{0.516 \text{ eV}}} = e^{-19.79} \cong \frac{4}{10^{10}}$$

It means that roughly 4 atoms out of 10^{10} atoms are excited to higher energy level at 6000K. This is a very small number. We thus find that even at very high temperatures the fraction of excited atoms is very small. The number of atoms in the lower energy level is *always larger* than that in the higher energy level. Under normal conditions higher the energy of the energy level, lesser is its population. Hence $N_1 > N_2$. Such distribution of atoms among the energy levels is termed **normal distribution** (also see Fig. 22.10a).

Now, if we assume the limiting case of $T \rightarrow \infty$, then $\frac{N_2}{N_1} = e^0 = 1$. Therefore, $N_2 = N_1$. On the

other hand, if the energy difference $(E_2 - E_1) \rightarrow 0$, then also $\frac{N_2}{N_1} = e^0 = 1$. Again, $N_2 = N_1$. Both these limiting cases indicate that *as long as a medium is in thermal equilibrium the population of higher energy level cannot exceed the population of the lower energy level.*

22.4 INTERACTION OF LIGHT WITH MATTER

The process of the transfer of energy from atom to light is not possible from classical point of view. However, the possibility arises if 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 appreciate the quantum processes involved in the development of a laser.

The radiation incident on a material is viewed as a stream of photons, where each photon carries an energy $E = hv$. We assume that the two energy levels of the atoms in the material have an energy difference $(E_2 - E_1) = hv$. When photons travel through the medium, three different processes are likely to occur. They are *absorption, spontaneous emission and stimulated emission*. We study these in detail.

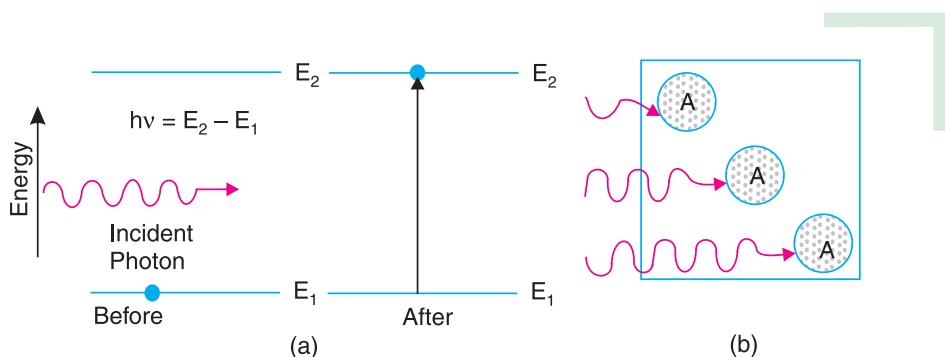
22.4.1 ABSORPTION

Suppose an atom is in the lower energy level E_1 . If a photon of energy $hv = (E_2 - E_1)$ is incident on the atom, it imparts its energy to the atom and disappears. Then we say that the atom absorbed an incident photon. As a result of absorption of adequate energy, the atom jumps to the excited state E_2 (Fig.22.4). The transition is called an **absorption transition**. It is also referred to as **induced absorption**. We may express the process as

$$A + hv = A^*$$

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

In each absorption transition event, an atom in the medium is excited and one photon is subtracted from the incident light beam, which results in attenuation of light in the medium.



Abosorption process (a) Induced absorption (b) Material absorbs photons.

Fig.22.4

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

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

or

$$P_{12} = B_{12}\rho(v) \quad (22.5)$$

where B_{12} is the constant of proportionality. B_{12} is known as the *Einstein coefficient for induced absorption*. It indicates the probability of occurrence of an induced transition from level $1 \rightarrow 2$. B_{12} is a constant characteristic of the atom and represents the properties of the energy states E_1 and E_2 .

The number of atoms per unit volume that undergo absorption transitions per second is called the *rate of absorption transition*. It is denoted by

$$R_{abs} = -\frac{dN_1}{dt} \quad (22.6)$$

where N_1 is the population of atoms at E_1 , and $(-dN_1/dt)$ represents the rate of decrease of population at the lower level E_1 . The rate of absorption can also be represented by the rate of increase of population at the upper level E_2 , as

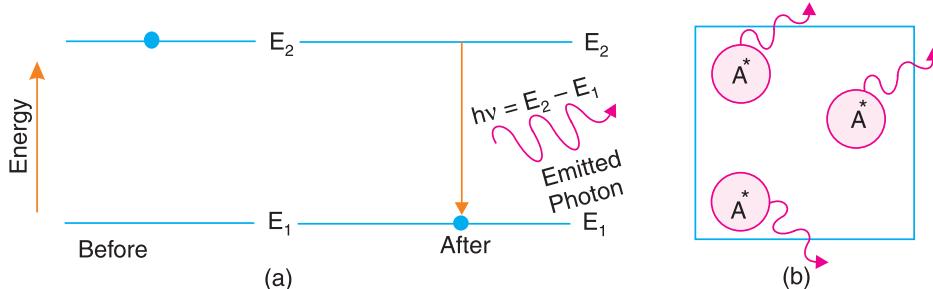
$$R_{abs} = \frac{dN_2}{dt} \quad (22.7)$$

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. 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. Then the rate of absorption transitions is given by

$$R_{abs} = B_{12}\rho(v)N_1 \quad (22.8)$$

Induced absorption involves the excitation of atom to the fixed higher level only. As a result of the absorption, N_1 decreases and N_2 increases. But under normal conditions N_2 cannot be greater than N_1 (see §22.3). Therefore, as light propagates through the medium, it gets absorbed. However, N_2 can be made greater than N_1 using special techniques.

22.4.2 SPONTANEOUS EMISSION



Spontaneous emission (a) emission process (b) Material emits photons haphazardly.

Fig. 22.5

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.22.5). Emission of a photon by an atom *without any external impetus* is called **spontaneous emission**. We may write the process as



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,

$$(P_{21})_{Spont.} = A_{21} \quad (22.9)$$

where A_{21} is a constant and known as the *Einstein coefficient for spontaneous emission*. A_{21} represents the probability of a spontaneous transition from level $2 \rightarrow 1$. 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.

Therefore, the rate of spontaneous transitions is given by

$$R_{sp} = A_{21} N_2 \quad (22.10)$$

It is to be noted that the process of spontaneous emission is independent of the incident light energy.

It follows from quantum mechanical considerations that spontaneous transition takes place from a given state to states lying lower in energy. Thus, spontaneous transition is not possible from level E_1 to level E_2 . Therefore, the probability of spontaneous transition from E_1 to E_2 is zero.

∴

$$A_{12} = 0 \quad (22.11)$$

Let us now look at the salient features of spontaneous emission of light.

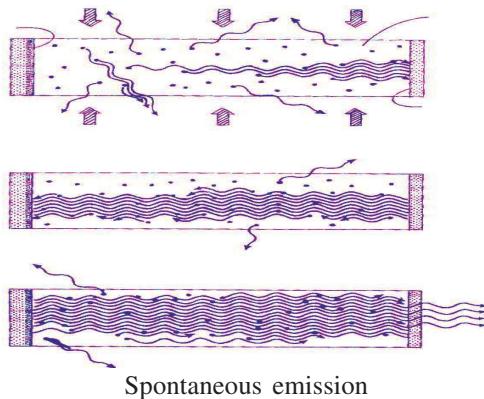
Characteristics of spontaneous emission:

- (i) The process of spontaneous emission is essentially *probabilistic* in nature and is not amenable for control from outside.
- (ii) The instant of transition, direction of propagation, the initial phase and the plane of polarisation of each photon are all *random*.
- (iii) The light resulting through this process is *not monochromatic*.
- (iv) As different atoms in the source emit photons in different directions, light spreads in all directions around the source. The light intensity goes on decreasing rapidly with distance from the source.
- (v) Light emitted through this process is *incoherent*, as it results from a superposition of wave trains of random phases. The net intensity is proportional to the number of radiating atoms. Thus,

$$I_{\text{total}} = N I \quad (22.12)$$

where N is the number of atoms and I is the intensity of light emitted by one atom. It is the process of spontaneous emission that dominates in conventional light sources.

It is seen that the rate of spontaneous transitions is determined only by the population N_2 at the higher energy level whereas the rate of absorption transitions is determined by the population N_1 at the lower energy level and the energy density $\rho(v)$ in the incident light. If absorption and spontaneous emission were the only processes operative, then obviously the number of atoms absorbing radiation per second would be more than the number of atoms emitting light per

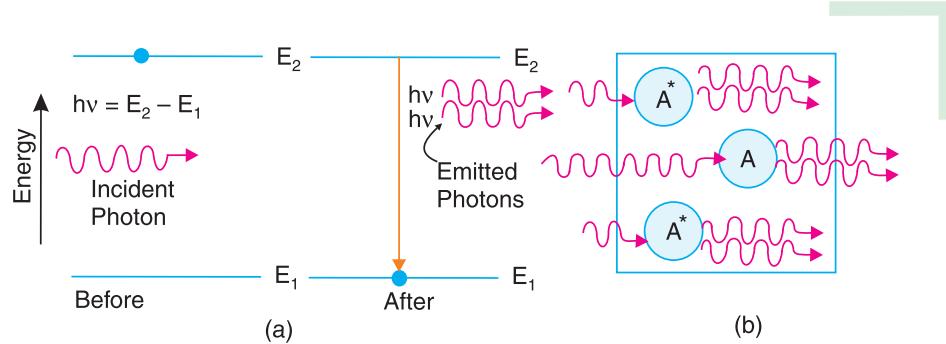


Spontaneous emission



Photoluminescence spectroscopy measures stimulated light emission spectra.

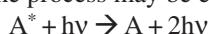
second. Eventually, we may end up with a non-equilibrium situation where all the atoms in the medium are excited. But this condition is not observed in practice. It means that equilibrium is maintained. Therefore, in order to account for the state of equilibrium between light and matter, Einstein pointed out that *if a photon can stimulate an atom to move from a lower energy level E_1 to a higher energy level E_2 by means of absorption transition, then a photon should also be able to stimulate an atom from the same upper level E_2 to the lower level E_1 .* This alternative mechanism of photon emission depends on the photon density present in the medium and is known as **stimulated emission**.



Stimulated emission (a) emission process. (b) Material emits photons in a coordinated manner.

Fig. 22.6

An atom in the excited state need not “wait” for spontaneous emission of photon. Well before the atom can make a spontaneous transition, it may interact with a photon with energy $h\nu = E_2 - E_1$, and make a downward transition. The photon is said to **stimulate** or **induce** the excited atom to emit a photon of energy $h\nu = (E_2 - E_1)$. The passing photon does not disappear and in addition to it there is a *second photon* which is emitted by the excited atom (see Fig. 22.6). The phenomenon of forced photon emission by an excited atom *due to the action of an external agency* is called **stimulated emission** or **induced emission**. The process may be expressed as



The probability that a stimulated transition occurs is given by

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

$$\text{or} \quad (P_{21})_{\text{stimulated}} = B_{21}\rho(v) \quad (22.13)$$

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 . B_{21} represents the probability for induced transition from level 2 → 1. 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 rate of stimulated emission of photons is given by

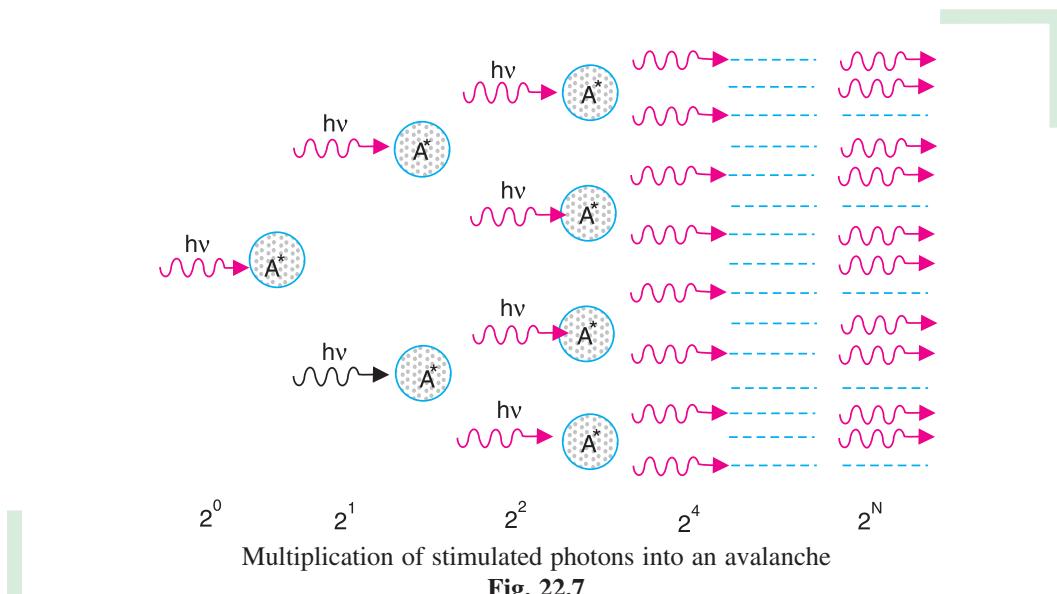
$$R_{st} = B_{21}\rho(v)N_2 \quad (22.14)$$

In stimulated emission each incident photon encounters a previously excited atom, and the optical field of the photon interacts with the electron. The result of the interaction is a kind of resonance effect, which induces each atom to emit a second photon with the same frequency, direction, phase, and polarization as the incident photon.

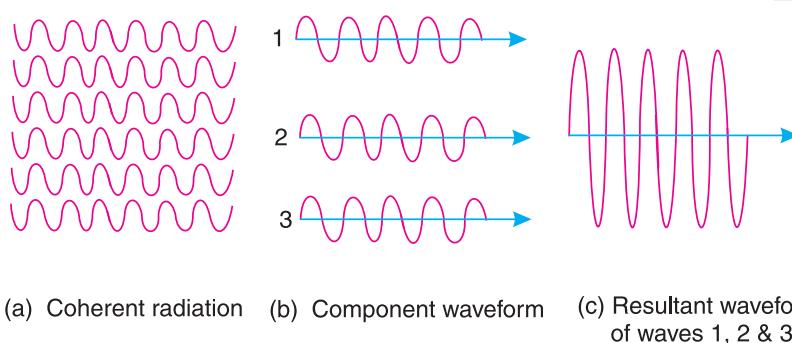
Let us now look at the salient features of the stimulated emission of light.

Characteristics of Stimulated emission:

- (i) The process of stimulated emission is *controllable* from outside.
- (ii) The photon induced in this process propagates in the *same direction* as that of stimulating photon.
- (iii) The induced photon has features identical to that of the inducing photon. It has the *same frequency, phase and plane of polarisation* as that of the stimulating photon.
- (iv) **Multiplication of Photons:** 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. 22.7.



- (v) **Light amplification:** All the light waves generated in the medium are due to one initial wave and all of the waves are in phase. Thus, the waves are coherent and *interfere constructively* (See Fig. 22.8).



Coherent radiation (a) coherent waves (b) component wave form (c) Resultant wave

Fig. 22.8

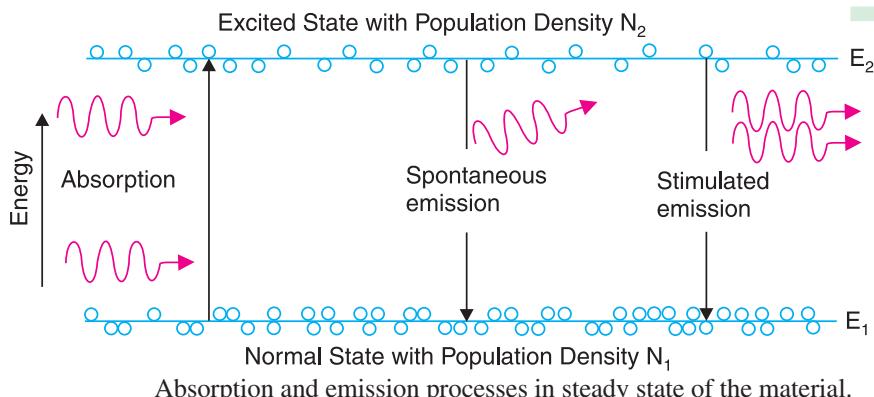
- (vi) The net intensity of light will be proportional to the square of the number of atoms radiating light. Thus,

$$I_{\text{total}} = N^2 I \quad (22.15)$$

The light emitted through the process of stimulated emission is of very high intensity and we say light is *amplified*.

At any reasonable temperature there cannot be enough atoms in excited states for any appreciable amount of stimulated emission from these states to occur.

Rather absorption is much more probable.



Absorption and emission processes in steady state of the material.

The three processes, namely, absorption, spontaneous emission and stimulated emission occur simultaneously in a medium. Under steady state condition the absorption and emission processes balance each other. Thus,

$$R_{\text{abs}} = R_{\text{sp}} + R_{\text{st}} \quad (22.16)$$

$$\therefore B_{12} N_1 \rho(v) = A_{21} N_2 + B_{21} N_2 \rho(v) \quad (22.17)$$

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.

22.5 EINSTEIN COEFFICIENTS AND THEIR RELATIONS

22.5.1 EINSTEIN COEFFICIENTS

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

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

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

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

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

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 .

(iv) It follows from quantum mechanical considerations that spontaneous transition is not possible from level E_1 to level E_2 . Therefore, the probability of spontaneous transition from E_1 to E_2 is zero.

∴

$$A_{12} = 0 \quad (22.18)$$

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

- 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).

- 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,

$$A_{12} = 0.$$

22.5.2 EINSTEIN RELATIONS

Under thermal equilibrium, the mean population N_1 and N_2 in the lower and upper energy levels respectively must remain constant. This condition requires 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 (Fig. 22.9). Thus,

$$\begin{array}{lcl} \text{The number of atoms absorbing} & = & \text{The number of atoms emitting} \\ \text{photons per second per unit volume} & & \text{photons per unit volume} \end{array}$$

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

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

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

$$B_{12}\rho(v)N_1 = A_{21}N_2 + B_{21}\rho(v)N_2 \quad (22.19)$$

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

$$\therefore \rho(v) = \frac{A_{21}N_2}{[B_{12}N_1 - B_{21}N_2]} \quad (22.20)$$

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

$$\rho(v) = \frac{A_{21}/B_{12}}{\left[\frac{N_1}{N_2} - \frac{B_{21}}{B_{12}} \right]} \quad (22.21)$$

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

As $E_2 - E_1 = hv$,
 $\frac{N_2}{N_1} = e^{-hv/kT}$ or $\frac{N_1}{N_2} = e^{hv/kT}$

$$\therefore \rho(v) = \frac{A_{21}}{B_{12}} \left[\frac{1}{e^{hv/kT} - B_{21}/B_{12}} \right] \quad (22.22)$$

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

$$\rho(v) = \left(\frac{8\pi hv^3 \mu^3}{c^3} \right) \frac{1}{e^{hv/kT} - 1} \quad (22.23)$$

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

Energy density $\rho(v)$ given by equ.(22.22) will be consistent with Planck's law (22.23), only if

$$\frac{A_{21}}{B_{12}} = \frac{8\pi hv^3 \mu^3}{c^3} \quad (22.24)$$

and $\frac{B_{21}}{B_{12}} = 1$ or $B_{12} = B_{21}$ (22.25)

The above equations are known as the **Einstein relations**. The coefficients B_{12} , B_{21} and A_{21} are known as **Einstein coefficients**. It follows that the coefficients are related through

$$B_{12} = B_{21} = \frac{c^3}{8\pi hv^3 \mu^3} A_{21} \quad (22.26)$$

The relation (22.25) 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.

The relation (22.26) 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.

22.6 LIGHT AMPLIFICATION

If we consider a medium in thermal equilibrium, there would be more atoms in the lower level than at higher level. That is $N_1 \gg N_2$. As the probability for absorption transition is equal to the probability for stimulated transition, a photon travelling 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. Further, the photon density in the incident beam is not sufficient to interact with the excited atoms. Owing to this, the spontaneous emission dominates the stimulated emission.

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.



LASER (Light Amplification by Stimulated Emission of Radiation)

22.6.1 CONDITION FOR STIMULATED EMISSION TO DOMINATE SPONTANEOUS EMISSION

The ratio of equ.(22.14) to equ. (22.10) gives

$$R_I = \frac{\text{Stimulated transitions}}{\text{Spontaneous transitions}} = \frac{B_{21}\rho(v)N_2}{A_{21}N_2} = \frac{B_{21}}{A_{21}}\rho(v) \quad (22.27)$$

Equ.(22.27) indicates that stimulated transitions will dominate the spontaneous transitions if the radiation density $\rho(v)$ is very large and the value of the ratio B_{21}/A_{21} is also large.

(i) Using equ.(22.23) into equ. (22.27), we get

$$\begin{aligned} R_I &= \left(\frac{B_{21}}{A_{21}} \right) \left[\frac{8\pi h\nu^3 \mu^3}{c^3} \cdot \frac{1}{e^{h\nu/kT} - 1} \right] \\ \text{But } \frac{B_{21}}{A_{21}} &= \frac{c^3}{8\pi h\nu^3 \mu^3} \\ \therefore R_I &= \left(\frac{c^3}{8\pi h\nu^3 \mu^3} \right) \left[\frac{8\pi h\nu^3 \mu^3}{c^3} \cdot \frac{1}{e^{h\nu/kT} - 1} \right] \\ \text{or } R_I &= \left[\frac{1}{e^{h\nu/kT} - 1} \right] \end{aligned} \quad (22.28)$$

If we assume $v = 5 \times 10^{14} \text{ Hz}$ and $T=300 \text{ K}$, the value of R_I comes to 10^{-58} .

The above result shows that in the optical region stimulated emission is negligible compared to spontaneous emission.

(ii) Equ.(22.27) indicates that stimulated transitions will dominate the spontaneous transitions if the radiation density $\rho(v)$ 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.

(iii) Requirement of states of larger lifetimes

Equ.(22.27) 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).

22.6.2 CONDITION FOR STIMULATED EMISSION TO DOMINATE ABSORPTION TRANSITIONS

It may be noted that the presence of a large number of photons will lead to more absorption

transitions rather than stimulated emissions. Hence large photon density alone will not guarantee more stimulated emissions.

The ratio of equ.(22.14) to equ. (22.8) yields

$$R_2 = \frac{\text{Stimulated transition}}{\text{Absorption transition}} = \frac{B_{21}\rho(v)N_2}{B_{12}\rho(v)N_1} \quad (22.29)$$

$$\text{As } B_{21} = B_{12}, \quad R_2 = \frac{N_2}{N_1} \quad (22.30)$$

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.

At thermodynamic equilibrium, $N_2 \ll N_1$ and the population at the ground level far exceeds that of the excited level. When light propagates through the medium, a photon may hit an excited atom leading to stimulated emission, or be absorbed on hitting an atom in the ground state. As more number of atoms is there at the ground level, a photon has a much higher probability of being absorbed than of stimulating an atom at the excited level. Therefore, the absorption transitions will be larger than stimulated transitions and the medium will absorb the incident light. If, on the other hand, the number the opposite situation prevails, photons are more likely to cause stimulated transitions than absorption transitions.

Two sum up, three conditions are to be satisfied to make stimulated transitions overwhelm the other transitions: (i) the population at excited level should be greater than that at the lower energy level, (ii) the ratio B_{21}/A_{21} should be large and (iii) a very high radiation density should be present in the medium. A medium amplifies light only when these *three conditions* are fulfilled.

To achieve high percentage of stimulated emissions, (i) an artificial situation known as **population inversion** is to be created in the medium. (ii) A larger value of B_{21}/A_{21} is achieved by choosing a **metastable energy level** as the higher level. As spontaneous transitions are forbidden from a metastable state, the ratio B_{21}/A_{21} will be larger. (iii) $\rho(v)$ is made larger by enclosing the emitted radiation in an **optical resonant cavity** formed by two parallel mirrors. The radiation is reflected many times till the photon density reaches to a very high value and a favourable condition is created for large stimulated emissions.

22.7 MEETING THE THREE REQUIREMENTS

22.7.1 POPULATION INVERSION

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

$$\frac{N_2}{N_1} = e^{-[E_2 - E_1]/kT} \quad (22.31)$$

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 . 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 condition** or **thermal equilibrium** (Fig.22.10a). Thus, under thermal equilibrium, $N_1 \gg N_2$.

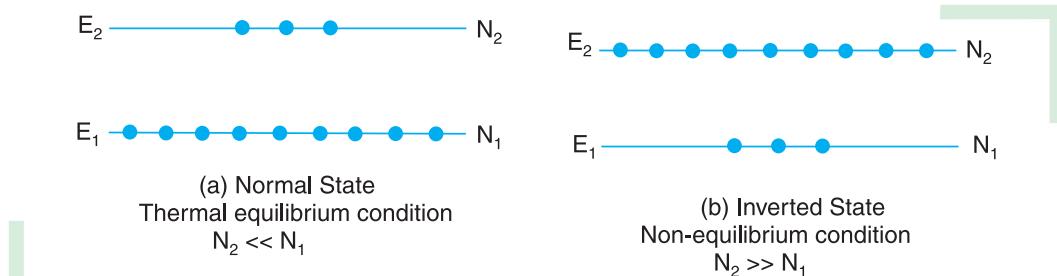


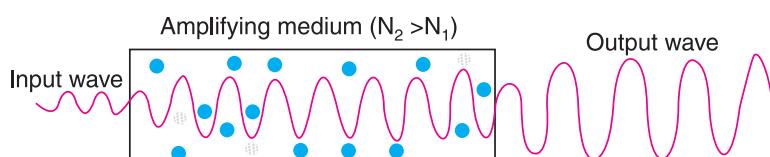
Fig. 22.10

To achieve a high percentage of stimulated emission, a majority of atoms should be at the higher energy level than at the lower level. We may somehow enhance the number of atoms in the excited level, such that the population ratio N_2 / N_1 **momentarily** increases without change in temperature. This is a *non-equilibrium condition* and is known as *inverted population* condition. **Population inversion** is the non-equilibrium condition of the material in which population of the upper energy level N_2 momentarily exceeds the population of the lower energy level N_1 (Fig.22.10 b). That is,

$$N_2 \gg N_1 \quad (22.32)$$

From equ.(22.31) it is seen that N_2 can exceed N_1 only if the temperature were negative. In view of this, the state of population inversion is sometimes referred to as a *negative temperature state*. It does not mean that we can attain temperatures below absolute zero. The terminology underlines the fact that the state of population inversion is a non-equilibrium state. It should be borne in mind that the population inversion is attained at normal temperatures.

The system shown in Fig.22.10(a) has two energy levels. At thermal equilibrium, photon absorption and emission processes take place side by side, but because $N_1 > N_2$, the system absorbs photons rather than emit photons. Now suppose that the system is supplied with energy from an external source till N_2 exceeds N_1 . Then, the system is said to have attained the state of population inversion. The population inversion took place between the levels E_2 and E_1 .



Amplification of a light wave in a medium with population inversion.

Fig. 22.11

When the system is in the population inversion condition, a few randomly emitted photons trigger stimulated emission of photons and those stimulated photons induce more stimulated emissions and so on. Consequently light gets amplified (Fig.22.11) and a cascade of light is produced. However, in this process atoms from E_2 level make downward transitions and as soon as the population at lower level becomes equal or larger than that at the excited level, population inversion comes to an end. Energy is again to be supplied to the system to take it into the state of population inversion.

The non-equilibrium condition is attained by employing pumping techniques to transfer large number of atoms from lower energy level to higher energy level.

22.7.2 METASTABLE STATES

An atom can be excited to a higher level by supplying energy to it. Normally, excited atoms have short lifetimes and release their energy in a matter of nanoseconds (10^{-9} s) through spontaneous emission. It means that atoms do not stay long enough at the excited state to be stimulated. As a result, even though the pumping agent continuously raises the atoms to the excited level, they undergo spontaneous transitions and rapidly return to the lower energy level. Population inversion cannot be established under such circumstances. In order to establish the condition of population inversion, the excited atoms are required to ‘wait’ at the upper energy level till a large number of atoms accumulate at that level. In other words, it is necessary that the excited state has a longer lifetime. A metastable state is such a state. Because of restrictions imposed by conservation of angular momentum, an electron excited to a metastable state cannot return to the ground state by emitting a photon, as it is generally expected to do. Such a state in which single-photon emission is impossible, has an unusually long time and is called a **metastable state**. Atoms excited to the metastable states 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 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.

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

22.7.3 CONFINING RADIATION WITHIN THE MEDIUM

According to equ.(22.27) a high radiation density $\rho(v)$ 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**.

22.8 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. 22.12).



New optical pumping apparatus.

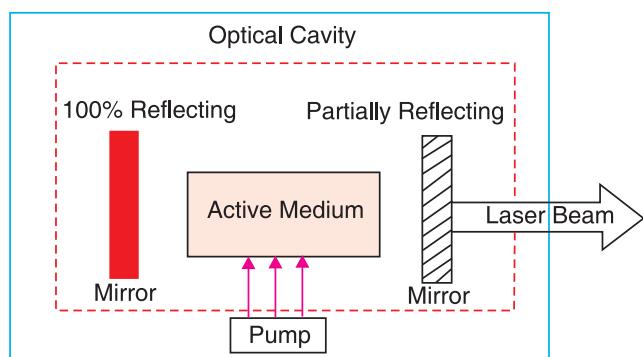


Fig. 22.12. Components of a Laser

22.8.1 ACTIVE MEDIUM

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**. It is also called **laser medium**. *An active medium is a medium which when excited reaches the state of population inversion and promotes stimulated emissions leading to light amplification.*

22.8.2 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 to the laser medium with a view to transfer it into the state of population inversion. Because N_1 is originally very much larger than N_2 , a large amount of input energy is required to momentarily increase N_2 to a value comparable to N_1 . **Pump** is the agency which supplies the energy.

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 to illuminate the active medium. 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.

22.8.3 OPTICAL RESONANT CAVITY

Laser is a light source and it is analogous to an electronic oscillator. An electronic oscillator (Fig. 22.13) 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. When the amplifier is switched on, electrical noise signal of appropriate frequency present at the input will

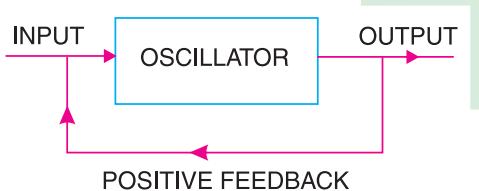


Fig. 22.13

be amplified; the output is fed back to the input and amplified again and so on. A stable output is quickly reached when the oscillator acts as a source of a particular frequency.

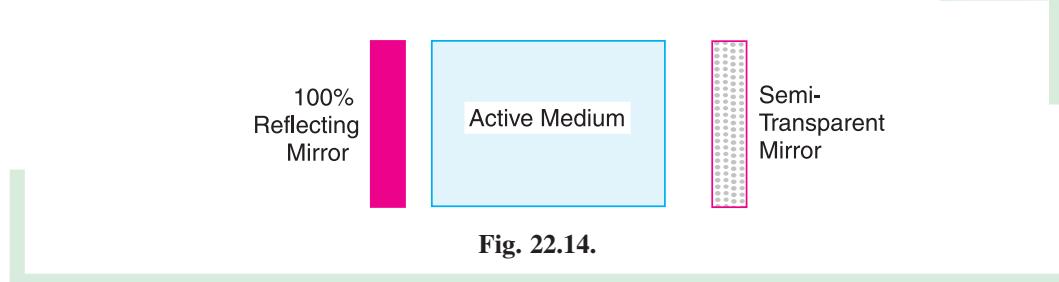


Fig. 22.14.

In laser the active medium is the amplifying medium. It is converted into an oscillator through the feed back mechanism established by an optical resonator. A pair of optically plane parallel mirrors (see Fig. 22.14) constitutes an optical resonant cavity. It is known as a Fabry-Perot resonator. One of these mirrors is fully reflecting and reflects all the light that is incident on it. The other mirror is made partially reflecting such that more than 90% of incident light is reflected from it and a small fraction is transmitted through it as the laser beam.

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.*

22.9 LASING ACTION

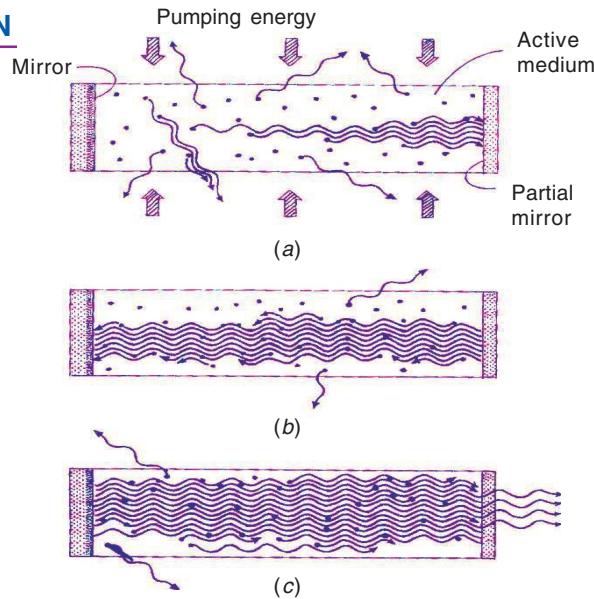


Fig. 22.15

Fig. 22.15 shows the action of an optical resonator. The active centers in the medium are in the ground state initially. Through suitable pumping mechanism, the medium is taken into the state of population inversion.

Some of the excited atoms emit photons spontaneously in various directions (Fig. 22.15a). 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. In the absence of the end mirrors, the net effect would have been the production of incoherent light. Now because of the end mirrors, a specific direction is imposed on photons. Photons travelling along the axis are amplified through stimulated emission while the photons emitted in any other direction will pass through the sides of the medium and are lost forever. Thus, a specific direction is selected for further amplification of light.

A majority of photons travelling along the axis are reflected back on reaching the end mirror. They travel towards the opposite mirror and on their way stimulate more and more atoms and build up the photon strength, as shown in Fig. 22.15 (b). The photons that strike the opposite mirror are reflected once more into the medium, as shown in Fig. 22.15 (b). 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 is augmented. 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.

At each reflection at the front-end mirror, light is partially transmitted through it. The transmitted component constitutes a *loss of energy* from the resonator. When the losses at the mirrors and within the medium balance the gain, the laser oscillations build up. A steady and strong laser beam will emerge from the front-end mirror, as shown in Fig. 22.15 (c).

As the end mirrors reflect light strongly into the laser medium, the light levels are very high within the optical cavity. Consequently, the condition that $p(v)$ should be large within the medium is satisfied.

22.9.1 THRESHOLD FOR OSCILLATION

As the light bounces back and forth in the optical resonator, it undergoes amplification as well as it suffers various losses. The losses occur mainly due to transmission at the output mirror and due to the scattering and diffraction of light within the active medium. For the proper build up of oscillations, it is essential that the amplification between two consecutive reflections of light from rear end mirror can balance the losses. We can determine the threshold gain by considering the change in intensity of a beam of light undergoing a round trip within the resonator.

Fig. 22.16 shows the round trip path of the radiation through the laser cavity. The path is divided into sections numbered by 1-5, while point "5" is the same point as "1".

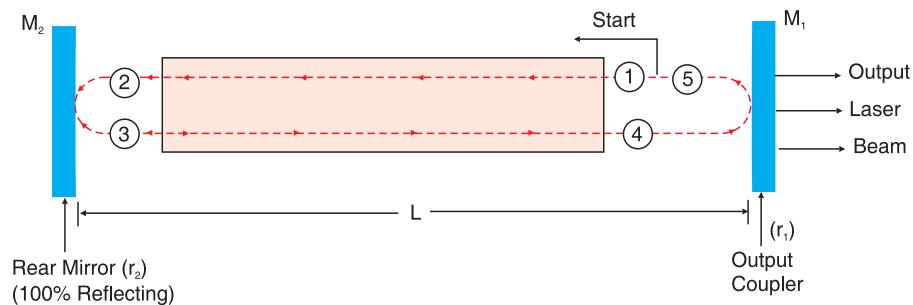


Fig. 22.16. Round trip path of the radiation through the laser cavity

Let us assume that the laser medium fills the space between the mirrors M_1 and M_2 (see Fig.22.16), 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_o at M_1 . Then, in travelling from mirror M_1 to mirror M_2 , the beam intensity increases from I_o to $I(L)$, which is given by

$$I(L) = I_o e^{(\gamma - \alpha_s)L} \quad (22.33)$$

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

$$I(2L) = r_1 r_2 I_o e^{(\gamma - \alpha_s)2L} \quad (22.34)$$

The amplification obtained during the round trip is

$$G = \frac{I(2L)}{I_o} = r_1 r_2 e^{(\gamma - \alpha_s)2L} \quad (22.35)$$

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 $I(2L) = I_o$. It requires that

$$r_1 r_2 e^{2(\gamma - \alpha_s)L} \geq 1 \quad (22.36)$$

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

Taking logarithms on both sides, we get

$$\begin{aligned} 2L(\gamma - \alpha_s) &\geq -\ln r_1 r_2 \\ \gamma - \alpha_s &\geq -\frac{1}{2L} \ln r_1 r_2 \\ \therefore \gamma &\geq \alpha_s - \frac{1}{2L} \ln r_1 r_2 \end{aligned} \quad (22.37)$$

$$\text{or } \gamma \geq \alpha_s + \frac{1}{2L} \ln \frac{1}{r_1 r_2} \quad (22.38)$$

Equ.(22.38) 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 , the **amplification** of the laser 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

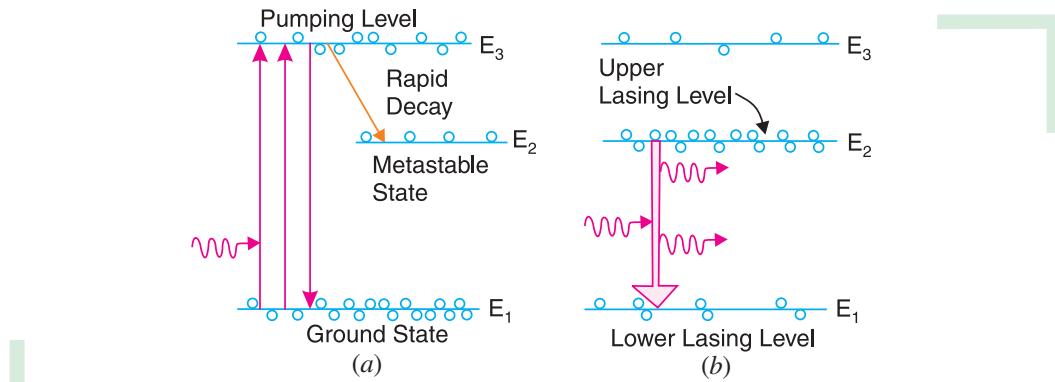
$$\gamma_{th} = \alpha_s + \frac{1}{2L} \ln \frac{1}{r_1 r_2} \quad (22.39)$$

Equ.(22.39) 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.

22.10 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.

22.10.1 THREE-LEVEL PUMPING SCHEME

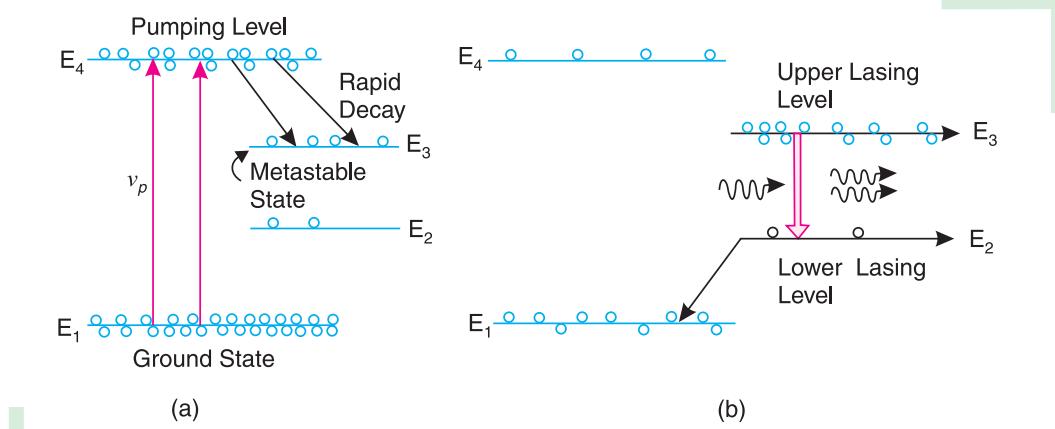


A typical three-level pumping scheme—(a) optical pumping (b) lasing action

Fig. 22.17

A typical three-level pumping scheme is shown in Fig. 22.17. The state E_1 is the ground level; E_3 is the pump level and E_2 is the metastable upper lasing level. 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 level E_2 through non-radiative transitions. The atoms are trapped at this level 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 level atoms accumulate at E_2 , the population inversion condition is achieved between the two levels E_1 and E_2 . Now a chance photon can trigger stimulated emission.

22.10.2 FOUR-LEVEL PUMPING SCHEME



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

Fig. 22.18.

A typical four-level pumping scheme is shown in Fig. 22.18. The level E_1 is the ground level, 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 levels. When light of pump frequency v_p is incident on the lasing medium, the active centers are readily excited from the ground level 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 level E_3 . As spontaneous transitions from the level E_3 to level E_2 cannot take place, the atoms get trapped at the level E_3 . The

population at the level E_3 grows rapidly. The level E_2 is well above the ground level such that $(E_2 - E_1) > kT$. 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 levels E_3 and E_2 . A chance photon of energy $h\nu = (E_3 - E_2)$ emitted spontaneously can start a chain of stimulated emissions, bringing the atoms to the lower laser level E_2 . From the level E_2 , the atoms subsequently undergo non-radiative transitions to the ground level E_1 and will be once again available for excitation.

22.10.3 COMPARISON OF FOUR LEVEL LASER WITH THE THREE LEVEL LASER

1. In the three-level pumping scheme, the terminal level of laser transition is simultaneously the ground level. Therefore, in order to achieve population inversion more than half of the ground level atoms have to be pumped up to the upper lasing level, such that $N_2 > N_1/2$. As the number of atoms in the ground level is very large, high pump power is required in order to promote $N_1/2$ atoms and establish the required population inversion. On the other hand, in the four-level pumping scheme, the terminal level of laser transition is virtually empty and population inversion condition is readily established even if a smaller number of atoms arrive at the upper lasing level. Therefore, relatively small pumping power is required to establish population inversion in four level pumping schemes.
2. In case of three level pumping scheme, once stimulated emission commences, the population inversion condition reverts to normal population condition.. Lasing ceases as soon as the excited atoms drop to the ground level. Lasing occurs again *only* when the population inversion is re-established. The light output therefore is a *pulsed output*.
In case of four level scheme, the condition of population inversion can be held without interruption and light output is obtained continuously. Thus, the laser operates in *continuous wave (cw)* mode.

22.10.4 NECESSITY OF BROAD ABSORPTION BAND AT PUMPING LEVEL

In a laser medium, active centers are excited through absorption of energy from a pumping source. We desire that the energy given through the pumping agent is utilized to the largest possible extent in exciting the ground level atoms. This is denoted by *pumping efficiency*. In case of optical pumping, a flash discharge from a lamp serves as the pumping agent. Normally, light sources such as the flash discharge emit light over a wide frequency range. More number of atoms can be excited to the higher level if large number of the frequency components is utilized instead of a single frequency. That can happen *only* when there is a band of close spaced energy levels at the pumping level.

Thus, for a larger pumping efficiency, the pump level should be a broad band rather than a narrow discrete level.

22.11 ROLE OF RESONANT CAVITY

- (i) The primary function of optical resonator is to provide a positive feedback of light into the lasing medium so that the stimulated emission acts are sustained and the laser acts as a generator of light.
- (ii) A chance photon spontaneously emitted by an excited atom acts as the input and induces stimulated emission. To sustain stimulated emission acts and to increase the light intensity in a cumulative way, a positive feedback of light must be provided. The mirrors by way of reflecting the incident photons provide the feedback.
- (iii) Laser oscillation is initiated by the photons spontaneously radiated 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 various directions, the secondary

stimulated photons will also travel in various directions. The result would be production of incoherent light. In order to build up oscillations, a specific direction has to be defined for photon propagation in the lasing medium.

The optical resonator sets its optic axis as the most favourable direction for build-up of light beam.

- (iv) In order to make the stimulated emissions dominate spontaneous emissions, a high optical energy density Q is necessary to be present in the active medium. The mirrors constituting the cavity confine more than 90% of the emitted photons to be within the laser medium such that a very high optical energy density is always present in the lasing medium.
- (v) The optical cavity is very much similar to a resonating column. Just as standing waves form in a resonating column, standing waves of optical frequencies are formed in the optical cavity. If L is the length of the cavity, the longest wavelength that will produce a standing wave pattern is $\lambda = 2L$. In general the cavity supports the wavelengths

$$\lambda_m = \frac{2nL}{m} \quad (m = 1, 2, 3, 4, \dots) \quad (22.40)$$

where n is the refractive index of the laser medium, and nL is the optical path. Waves of other wavelengths attenuate quickly. Thus, the optical cavity selects and amplifies only certain frequencies. Hence, the value of L should be properly selected.

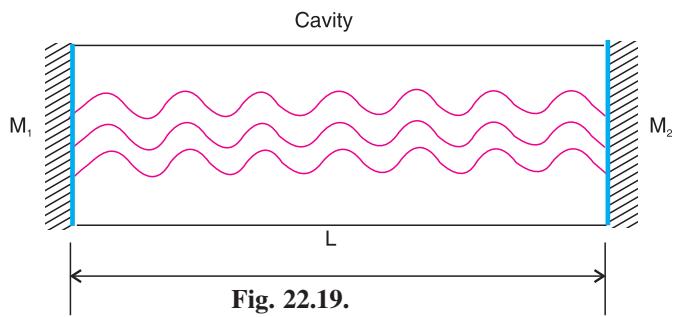
- (vi) Active centers may have a number of lasing transitions instead of only one transition. The mirrors of optical cavity suppress the undesired transitions. The reflectivity of the mirrors is further made less for the undesired photons, which therefore get absorbed at the mirrors.

22.12 MODES OF THE LASER BEAM

We have noted that part of the laser light in the laser cavity emerges through the output mirror. The optical waves within an optical resonant cavity are characterized by their **resonant modes**, which are discrete resonant conditions determined by the **dimensions of the cavity** [equ.(22.40)]. The laser beam radiated from the laser cavity is thus not arbitrary. Only the waves oscillating at modes that match the oscillation modes of the laser cavity can be produced. 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**.

22.12.1 LONGITUDINAL MODES

An electromagnetic wave which moves inside the laser cavity from right to left, is reflected by the left mirror, and move to the right until it is reflected from the right mirror, and so on. Thus, two waves of the same frequency and amplitude are moving in opposite directions, which is the condition for creating a *standing wave*. In order to create a *standing wave*, the wave must start with the same phase at the mirror.



The condition for standing wave pattern is that the path length traveled by a wave between two consecutive reflections at an end mirror should equal an integral multiple of the wavelength. It means that

$$2nL = m\lambda \quad (m = 1, 2, 3, \dots) \quad (22.41)$$

The above equations indicate that only those waves, which satisfy the above condition, can exist inside the cavity in a steady state. Waves of other wavelengths interfere destructively and are quickly attenuated. Because of its length which is very large compared to light wavelength, optical resonator supports simultaneously several standing waves of multiple wavelengths. These wavelengths are called **longitudinal** or **axial modes**. Therefore, m in equ.(22.41) is called the *mode number*. Thus, longitudinal modes are standing waves along the optical axis of the laser.

The frequencies of the longitudinal modes are given by

$$\nu_m = \frac{c}{n\lambda_m} = m \left(\frac{c}{2nL} \right) \quad (22.42)$$

Fig. 22.20 is a graphic representation of allowed frequencies inside a laser cavity.

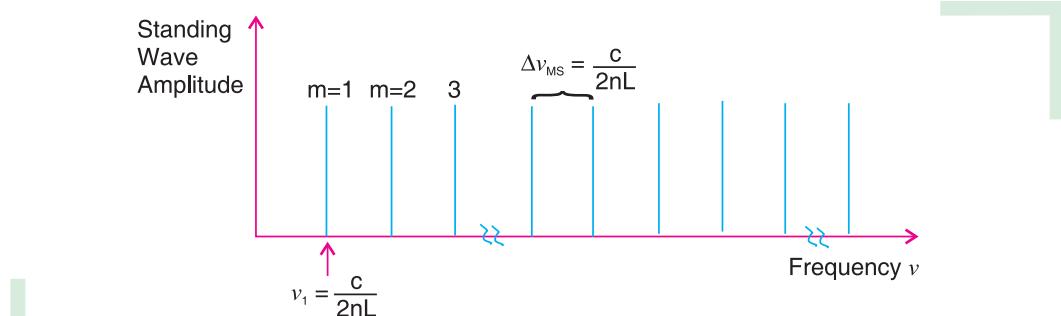


Fig. 22.20. Allowed Longitudinal modes inside a Laser Cavity

Theoretically, the cavity can resonate at a very large number of frequencies (see Fig. 22.20.) that satisfy the equation (22.42). For example, if we take $L = 0.5$ m, and $\lambda = 5000$ Å, we obtain $m = 2 \times 10^6$. It means that the cavity supports 2×10^6 longitudinal modes.

All these allowed frequencies will not be emitted from the laser, since there are more limiting conditions. The modes, which we calculate from (22.42), belong to the *passive cavity* where the active medium is not present. Out of these frequencies, only those frequencies (modes) that have amplification above lasing threshold to overcome absorption, will be emitted out of the laser.

Mode Separation:

The frequency separation between the neighbouring modes is constant and is given by

$$\Delta\nu = \nu_{m+1} - \nu_m = \frac{c}{2nL} \quad (22.43)$$

Equ.(22.43) can be expressed in terms of $\Delta\lambda$ as follows.

$$\Delta\lambda = \lambda^2 \cdot \frac{\Delta\nu}{c}$$

Using the relation (22.43) into the above equation, we find the wavelength separation

$$\Delta\lambda = \frac{\lambda^2}{2nL} \quad (22.44)$$

22.12.2 GAIN CURVE AND LASER OPERATING FREQUENCIES

When the active medium is placed between the two mirrors, the cavity becomes an **active cavity**. Then, the standing waves supported by the cavity are the light waves emitted by the stimulated atoms of the medium. Ideally, the emission should occur at a single frequency, as a group of identical atoms radiate at the same frequency. However, in practice, because of the various line broadening mechanisms, there will be a spread of frequencies about the central frequency of the emission line. Fig. 22.21 shows the shape of a typical emission line. It is also called **gain curve** or **gain profile** because it indicates the range of frequencies over which stimulated emission can provide sufficient gain.

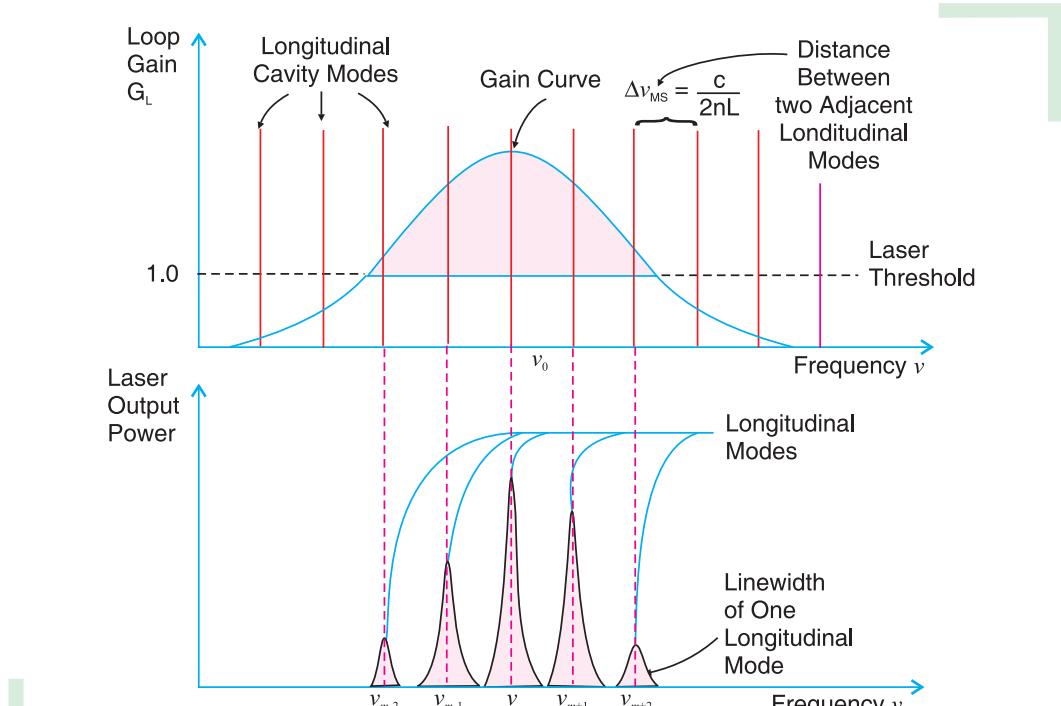


Fig. 22.21.

The laser operating frequencies are determined together by the resonant frequencies of the cavity and by the laser emission line width. If an output has to exist at a particular frequency, the cavity must be resonant at that specific frequency and there must be sufficient gain at that frequency. Laser oscillation can take place only when the gain is large enough to maintain resonance. For example, dashed lines are shown in Fig. 22.21 (a) which corresponds to threshold level. It is seen that frequencies between ν_{m+1} and ν_{m+2} can be amplified, while all other frequencies are cut-off. Thus, there are only a few frequencies that resonate. As a result, the output of a laser consists of a few closely spaced frequencies as shown in Fig. 22.21 (b). Thus, the laser emission line transforms into a series of narrow spectral lines corresponding to cavity modes. If $\delta\lambda$ is the line width of the emission line, then the number of modes that would be ultimately present is given by

$$N = \frac{\delta\lambda}{\Delta\lambda} \quad (22.45)$$

22.13 TRANSVERSE MODES

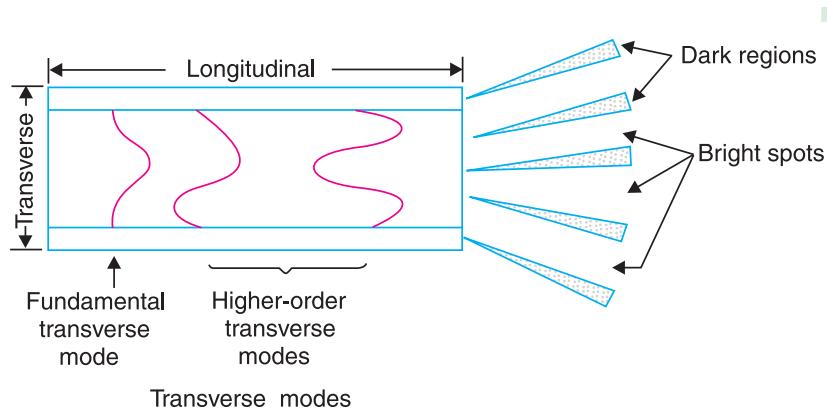


Fig. 22.22.

The longitudinal dimension L of the resonant cavity governs the axial modes. The laser modes (see Fig. 22.22) governed by the cross-sectional dimension of the optical cavity are called **transverse electromagnetic (TEM) modes**. The TEM modes are generally few in numbers and they are easy to see. If the laser beam is spread out by a negative lens and focussed on to a screen, several bright patches are seen on the screen. The patches are separated by intervals called nodal lines. The transverse modes characterize the intensity distribution across the cross-section of the laser beam. In general, the allowed modes are designated as TEM_{mn} , where m and n are integers. The integers m and n represent the number of intensity minima in two orthogonal directions of the laser beam.

BEAM PATTERN

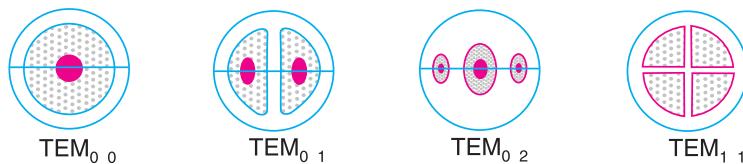


Fig. 22.23.

The lowest order transverse mode is TEM_{00} . It is the simplest mode and has a smooth cross-section profile with a peak in the middle (see Fig. 22.23.). TEM_{01} beam has a single minimum dividing the beam into two bright spots. A TEM_{11} beam has two perpendicular minima dividing the beam into four quadrants, and so on. Operation of a laser in multimode form provides considerably more power than in single mode operation.

22.14 TYPES OF LASERS

There are several ways in which we can classify lasers into different types. We prefer here to classify the lasers on the basis of the material used as active medium. Accordingly, they are broadly divided into four categories, namely solid state lasers, gas lasers, liquid lasers, and semiconductor diode lasers. Most lasers emit light in the red or IR regions. Lasers work in continuous mode or in a pulsed mode.

22.14.1 RUBY LASER

Ruby laser belongs to the class of solid state lasers. The term solid state has different meanings in the field of electronics and lasers. A solid state laser is one in which the active centers are fixed in a crystal or glassy material. Solid state lasers are electrically non-conducting. They are also called **doped insulator lasers**.

Historically, the ruby laser was the first laser. It was invented in 1960 by Theodore Maiman, U.S.A. The ruby laser rod is in fact a synthetic ruby crystal, Al_2O_3 crystal, doped with chromium ions at a concentration of about 0.05% by weight. Cr^{3+} ions are the actual active centers and have a set of three energy levels suitable for realizing lasing action whereas aluminum and oxygen atoms are inert.

Construction: The schematic of a ruby laser is shown in Fig. 22.24. Ruby rod is taken in the form of a cylindrical rod of about 4 cm in length and 0.5 cm in diameter. Its ends are ground and polished such that the end faces are exactly parallel and are also perpendicular to the axis of the rod. One face is silvered to achieve 100% reflection while the other is silvered to give 10% transmission and 90% reflection. The silvered faces constitute the Fabry-Perot resonator. The laser rod is surrounded by a helical photographic flash lamp filled with xenon. Whenever activated by the power supply the lamp produces flashes of white light.

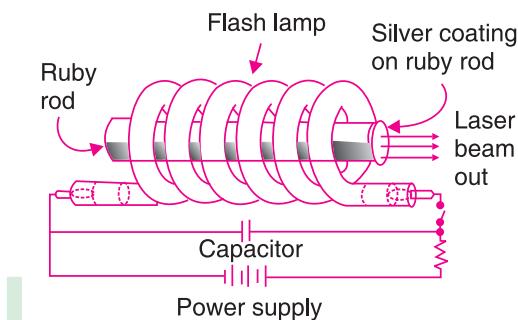
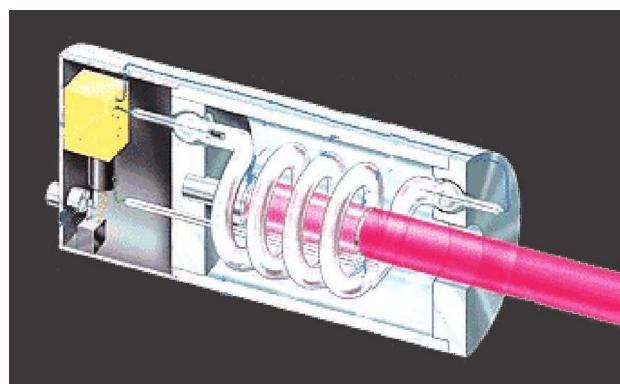


Fig. 22.24



Components of the first ruby laser.

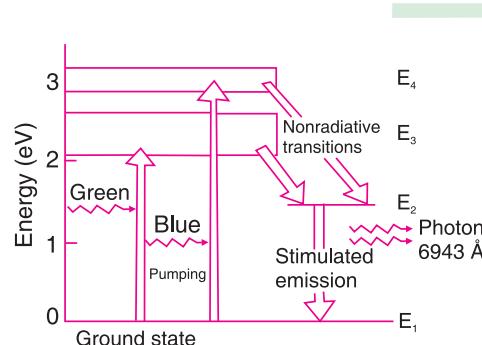


Fig. 22.25

Working: Ruby laser uses a three – level pumping scheme. The energy levels of Cr³⁺ ions in the crystal lattice are shown in Fig. 22.25. There are two wide energy bands E₃ and E_{3'} and a pair of closely spaced levels at E₂. When the flash lamp is activated, the xenon discharge generates an intense burst of white light lasting for a few milliseconds. The Cr³⁺ ions are excited to the energy bands E₃ and E_{3'} by the green and blue components of white light. the energy levels in these bands have a very small lifetime ($\approx 10^{-9}$ s). Hence the excited Cr³⁺ ions rapidly lose some of the energy to the crystal lattice and undergo non-radiative transitions. They quickly drop to the levels E₂. The pair of levels at E₂ are metastable states having a lifetime of approximately 1000 times more than the lifetime of E₃ level. Therefore, Cr³⁺ ions accumulate at E₂ level. When more than half of the Cr³⁺ ion population accumulates at E₂ level, the state of population inversion is established between E₂ and E₁ levels. A chance photon emitted spontaneously by a Cr³⁺ ion initiates a chain of stimulated emissions by other Cr³⁺ ions in the metastable state. 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. A strong intense beam of red light emerges out of the front-end mirror.

Note that the green and blue components of light play the role of pumping agents and are responsible for causing population inversion. The spontaneous photons of $\lambda = 6943 \text{ \AA}$, corresponding to red colour, act as the input of the oscillator which actually gets amplified. The xenon flash lasts for a few milliseconds. However, the laser does not operate throughout this period. Its output occurs in the form of irregular pulses of microsecond duration. It is because the stimulated transitions occur faster than the rate at which population inversion is maintained in the crystal. Once stimulated transitions commence, the metastable state E_2 gets depopulated very rapidly and at the end of each small pulse, the population at E_2 has fallen below the threshold value required for sustained emission of light. As a result the lasing ceases and laser becomes inactive. The next pulse appears after the population inversion is once again restored. The process repeats.

22.14.2 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, $\text{Y}_3\text{Al}_5\text{O}_{12}$, 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.

Construction: Fig. 22.26 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



YAG Laser.

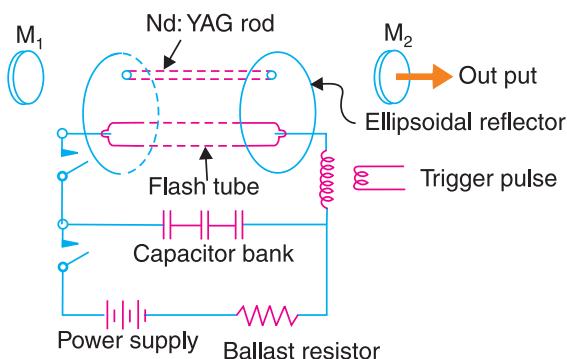


Fig. 22.26

length and 12 mm in diameter. The two ends of the laser rod are polished and silvered and constitute the optical resonator.

Working: A simplified energy level diagram for the neodymium ion in YAG crystal is shown in Fig. 22.27. The energy level structure of the free neodymium atom is preserved to a certain extend because of its relatively low concentration. However, the energy levels are split and the structure is complex. It is essentially a four-level system with the terminal laser level E_2 sufficiently far removed from the ground level. The pumping of the Nd^{3+} ions to upper states is done by a krypton arc lamp. The optical pumping with light of wavelength range to 5000 to 8000 Å excites the ground state Nd^{3+} ions to the multiple energy levels at E_4 . The metastable level E_3 is the upper laser level, while the E_2 forms the lower laser level. 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. 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. Therefore, the population inversion is readily achieved between the E_3 level and E_2 level. The laser emission occurs in infrared (IR) region at a wavelength of about 10,600 Å (1.06 μm). As the laser is a four-level laser, the population inversion can be maintained in the face of continuous laser emission. Thus Nd: YAG laser can be operated in CW mode. An efficiency of better than 1% is achieved. Nd: YAG lasers find many industrial applications such as resistor trimming, machining operations like welding, hole drilling etc. They are also used in surgery.

22.14.3 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

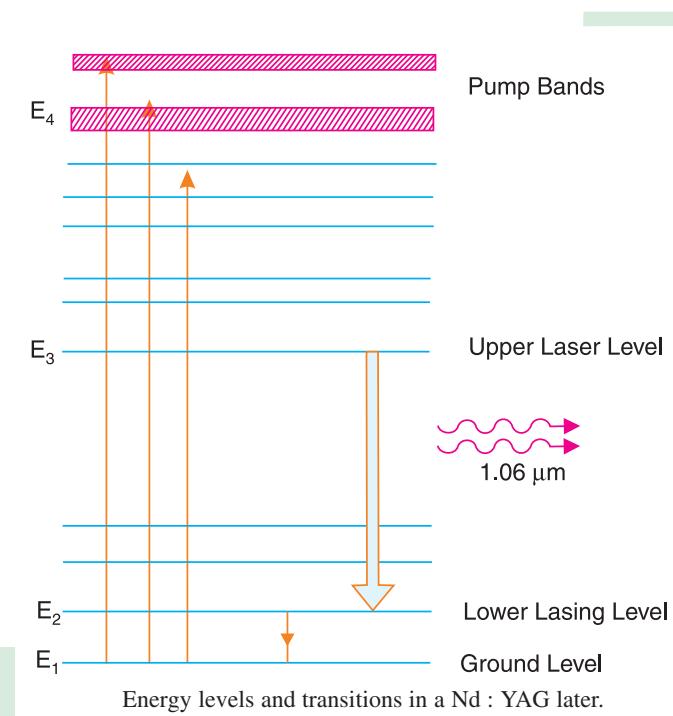


Fig. 22.27

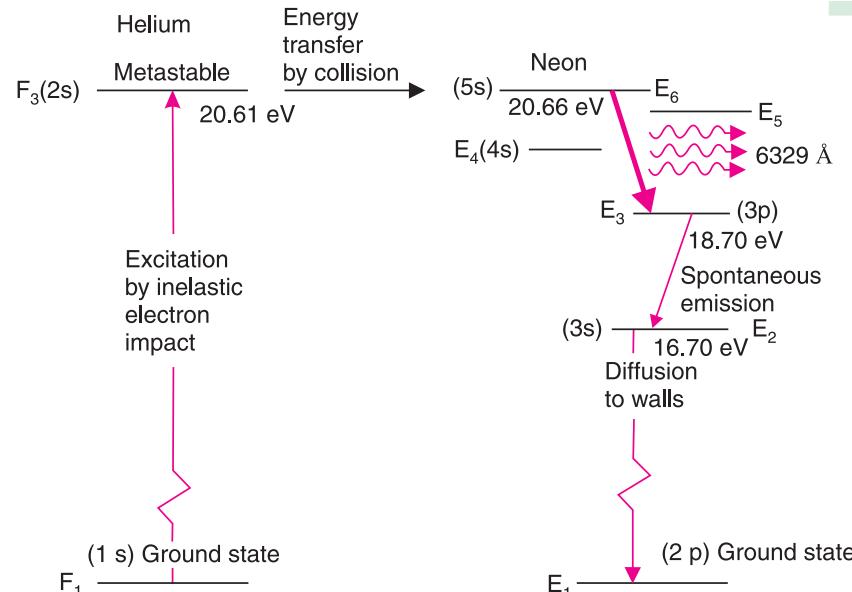


Helium-Neon Laser.

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.

Construction: The schematic of a He-Ne laser is shown in Fig. 22.28. Helium – Neon laser consists 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. 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.



Energy level diagram for a helium-neon laser. Only the relevant energy levels are shown.

Fig. 22.29

Working: Helium – Neon laser employs a four – level pumping scheme. The energy levels of helium and neon are shown in Fig. 22.29. When the power is switched on, a high voltage of about 10 kV is applied across the gas. It is sufficient to ionize the gas. The electrons and ions produced in the process of discharge are accelerated towards the anode and cathode respectively. The energetic electrons excite helium atoms through collisions. One of the excited levels of helium $F_3(2s)$ is at 20.61

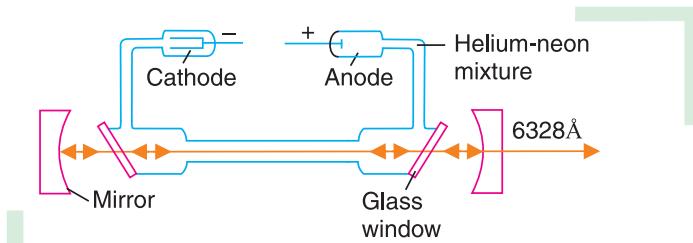


Fig. 22.28.

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. However, it 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**. One of the excited levels of neon E_6 (5s) is at 20.66 eV, which is nearly at the same level as F_3 of helium atom. Therefore, resonant transfer of energy can occur 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. Helium atoms drop to the ground state after exciting neon atoms. This is the pumping mechanism in He-Ne laser. The role of helium atoms 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.

The upper state of neon atom E_6 is a metastable state. Therefore, neon atoms accumulate in this upper state. The E_3 (3p) is sparsely populated at ordinary temperatures, and a state of population inversion is readily established between E_6 and E_3 levels. Random photons emitted spontaneously prompt stimulated emission and lasing occurs. The transition $E_6 \rightarrow E_3$ generates a laser beam of red colour of wavelength 6328 Å. Other possible transitions produce 3.39 μm and 1.15 μm laser beams respectively. These transitions are not shown in Fig. 22.29.

From the level E_3 the neon atoms drop to E_2 (3s) level spontaneously. E_2 level is however a metastable state. Consequently, neon atoms tend to accumulate at E_2 level. It is necessary that these atoms 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. If the discharge tube is made narrow, the probability of atomic collisions with the tube walls increases. Because of frequent collisions with the walls, the neon atoms rapidly drop to the ground level and will be available for excitation once again.

If the diameter of the discharge tube is increased, the probability of collisions of atoms with the walls decreases and the neon atoms tend to accumulate at energy level E_2 . In due course of time, the atoms are no more available at the ground level for further excitation. Therefore, the laser ceases to operate. He-Ne laser operates in cw mode and is widely used in laboratories as a monochromatic source. It is also widely used in laser printing, bar code reading, etc.

22.14.4 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.

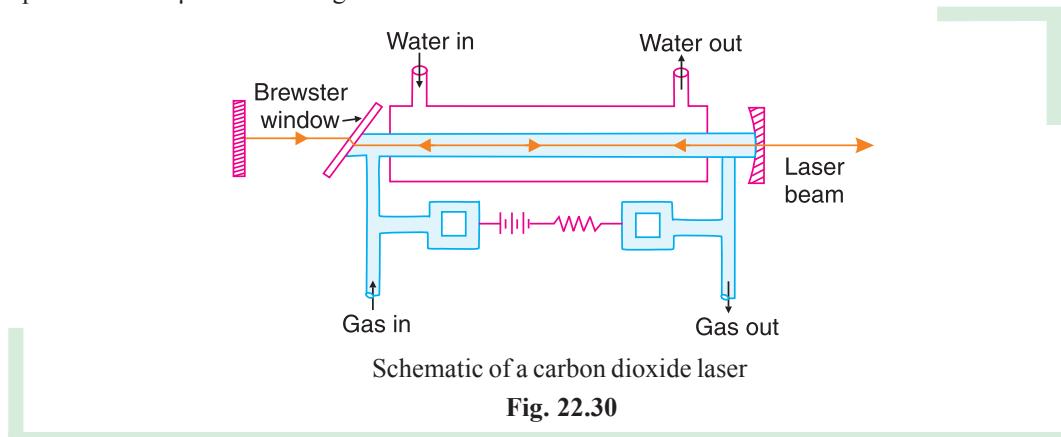


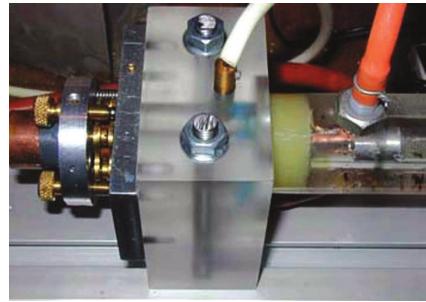
Fig. 22.30

Construction: The schematic of typical CO₂ laser is shown in Fig. 22.30. It is basically a discharge tube having a bore of cross section of about 1.5 mm² 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. Other additives such as water vapour are also added. The active centres are CO₂ molecules lasing on the transitions between the vibrational levels of the electronic ground state.

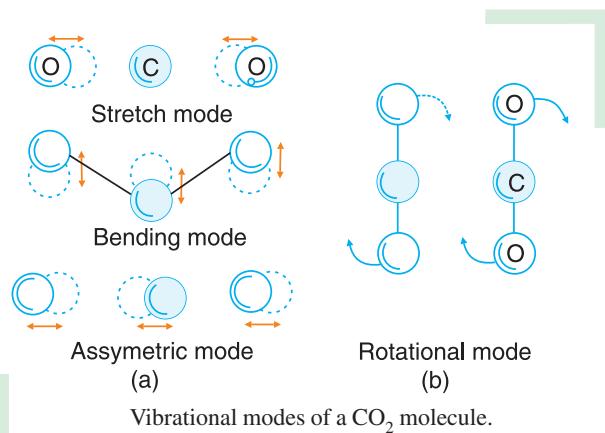
Energy levels of CO₂ molecule

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

CO₂ molecule is a linear molecule consisting of a central carbon atom with two oxygen atoms attached one on either side. It undergoes three independent vibrational oscillations known as the **vibrational modes**. These vibrational degrees of freedom are quantized. At any one time, a CO₂ molecule can vibrate in a linear combination of three fundamental modes. The energy states of the molecule are then represented by three quantum numbers (m n q). These numbers represent the amount of energy associated with each mode. For example, the number (020) indicates that the molecule in this energy state is in the pure bending mode with two units of energy. Each vibrational state is associated with rotational states corresponding to the rotation of CO₂ molecule about its centre of mass. The separations between vibrational – rotational states are much smaller on the energy scale compared to the separations between electron energy levels. The nitrogen molecule N₂ is also characterized by similar vibrational levels. Fig. 22.31 shows the vibrational modes and rotations of CO₂ molecule.



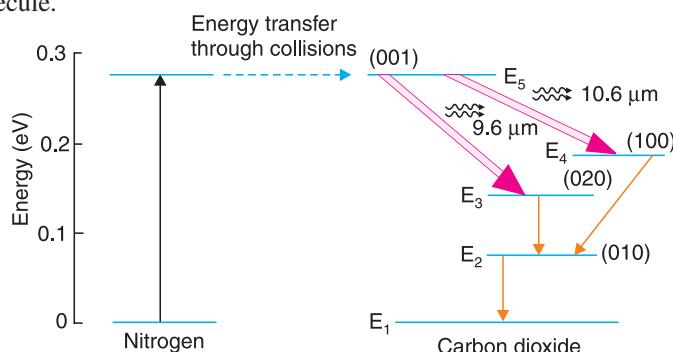
Carbon Dioxide Laser.



Vibrational modes of a CO₂ molecule.

Fig. 22.31

Energy transfer through collisions



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

Fig. 22.32.

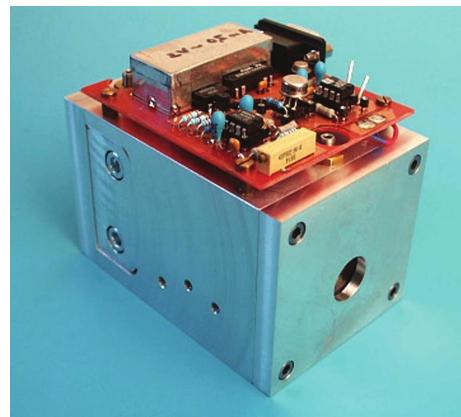
Working: Fig.22.32 shows the lowest vibrational levels of the ground electron energy state of CO_2 molecule and an N_2 molecule. The excited state of an N_2 molecule is metastable and it is identical in energy to (001) vibrational level of CO_2 molecule, indicated as E_5 in Fig. 22.32. As current passes through the mixture of gases, the N_2 molecules get excited to the metastable state. The excited N_2 molecules cannot spontaneously lose their energy and consequently, the number of N_2 molecules at the level keeps on increasing. The N_2 molecules return to ground state through inelastic collisions with ground state CO_2 molecules. Thereby the CO_2 molecules are excited to E_5 level. Some of the CO_2 molecules are also excited to the upper level E_5 through collisions with electrons. The excitation of CO_2 molecules through collisions with excited N_2 molecules is similar to that of helium atoms by neon atoms in helium-neon laser. 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. 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 . The laser transition between $E_5 \rightarrow E_4$ levels produces far IR radiation at the wavelength $10.6 \mu\text{m}$ ($1,06,000\text{\AA}$). The lasing transition between $E_5 \rightarrow E_3$ levels produces far IR radiation at $9.6 \mu\text{m}$ ($96,000\text{\AA}$) wavelength. 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. This process leads to accumulation of population at E_2 level. And also, as the gaseous mixture heats up, the E_2 level, which is close to the ground state, E_1 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. The presence of helium along with CO_2 helps to decrease the population density at E_2 level. It de-excites CO_2 molecules through inelastic collisions and aids cooling the gaseous mixture through heat conduction.

The CO_2 laser operates in CW mode and is capable of generating high powers of the order of several kilowatts at a relatively high efficiency of about 40%. Therefore, it is the most widely used laser. Its applications include use in communications, weaponry and laser fusion.

22.15 SEMICONDUCTOR LASER

A **semiconductor diode laser** is a specially fabricated pn junction device, which emits coherent light when it is forward biased. R. N. Hall and his coworkers made the first semiconductor laser in 1962. It is made from Gallium arsenide (GaAs) which operated at low temperatures and emitted light in the near IR region. Semiconductor lasers working at room temperature and in continuous wave mode are produced by 1970. Now pn-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, high speed laser printing etc wide variety of applications.

A **semiconductor** is a material with electrical properties intermediate to those of a conductor and an insulator. The allowed energy values of the valence electrons in semiconductors occur within two



Semiconductor Laser.

well-defined energy bands separated by an energy gap known as **band gap**. A pure semiconductor crystal has exactly enough electrons to fill all the states in the lower band, namely **valence band**. However, when a covalent bond is just broken, an electron is just set free. Then we say that the electron jumped into the upper band, namely **conduction band**. The electron jumping to the conduction band leaves behind a vacancy in the valence band. The vacancy is called a **hole** and is assigned a positive charge and a mass equivalent to that of an electron. In a pure semiconductor, for each covalent bond broken an electron and a hole are generated. Therefore, the number of electrons in the conduction band and the number of holes in the valence band are equal. When a conduction electron falls into the valence band, it recombines with a hole there. The electron rejoins the broken covalent bond and therefore both the electron and hole disappear. The recombination energy is released in the form of heat in silicon and germanium crystals. In some crystals it is released in the form of light.

Doping with small amounts of impurities can drastically increase the electrical conductivity of a pure semiconductor. When the dopant is a pentavalent element, each dopant atom contributes an electron to the conduction band without creating a hole simultaneously in the valence band. Hence the addition of the pentavalent element increases the number of conduction electrons which become the **majority carriers** in the silicon crystal. As negatively charged electrons are current carriers in this crystal, it is called a **n-type semiconductor**. On the other hand, a trivalent dopant atom produces a hole in the valence band without the simultaneous generation of electron in the conduction band. Hence the addition of the trivalent element increases the number of holes which become the *majority carriers* in the silicon crystal. As positively charged holes are current carriers in this crystal, it is called a **p-type semiconductor**.

There is a reference level in the energy band diagram of each type of semiconductor. The reference level is called the **Fermi level**. The Fermi level E_{Fp} is nearer to the top of the valence band in the p-type material and the Fermi level E_{Fn} is nearer to the bottom of the conduction band in the n-type material. When the p-type and n-type materials are joined at the atomic level to form a pn-junction device, equilibrium is attained only when equalization of Fermi levels takes place. The energy levels in p-region move up and those in n-region move down till the Fermi levels (E_{Fp} and E_{Fn}) in both the regions come to the same level. The mutual displacement of the energy levels on both sides of the junction causes a bending of the energy bands around the junction.

Achieving population inversion in a semiconductor:

Population inversion is required for producing stimulated emission. The way in which population inversion is achieved in semiconductors is very different from the way it is established in other types of lasers. A semiconductor cannot be regarded as two-level atomic system. It consists of electrons and holes distributed in the respective energy bands. Therefore, laser action in semiconductors involves energy bands rather than discrete levels. Secondly, in other types of lasers, population inversion is obtained by exciting electrons in spatially isolated atoms. In semiconductors, electrons are not associated with specific atoms but are injected into the conduction band from the external circuit. Therefore, the conduction band plays the role of excited level while the valence band plays the role of ground level. Population inversion requires the presence of a large concentration of electrons in the conduction band and a large concentration of holes in the valence band. A simple way to achieve population inversion is to use a semiconductor in the form of a pn-junction diode formed from heavily doped p- and n-type semiconductors.

22.15.1 PN-JUNCTION LASER

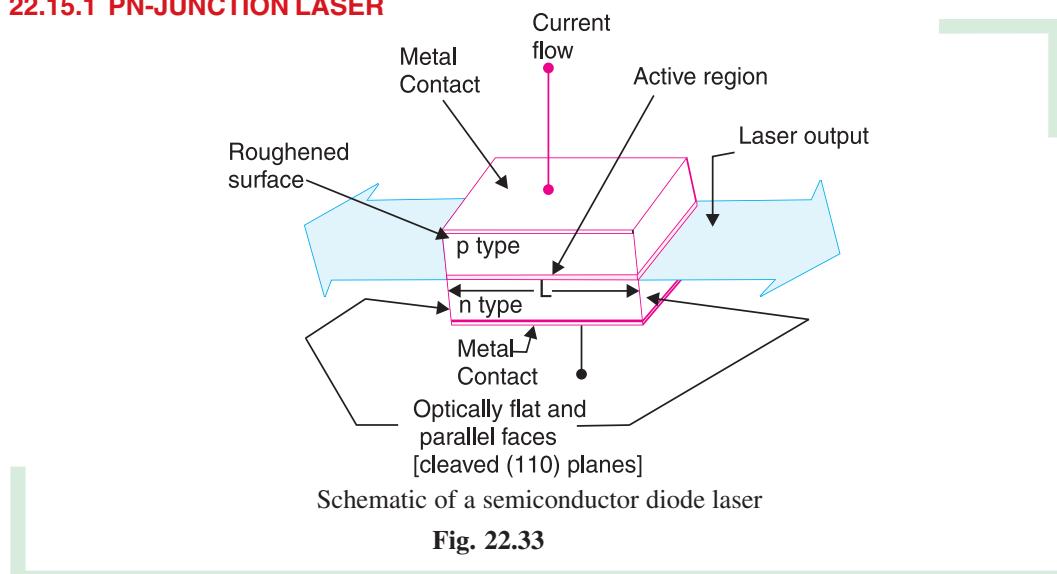
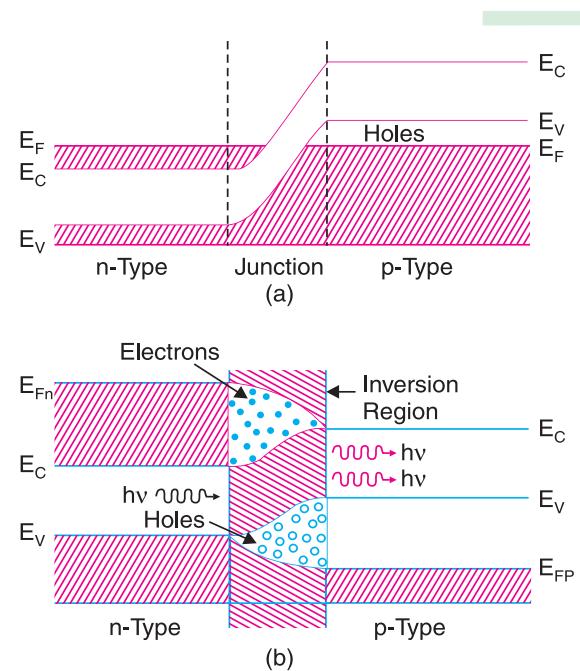


Fig. 22.33

Construction : Fig. 22.33 shows the schematic of a semiconductor laser. A simple diode makes use of the same semiconductor material, say, GaAs on both sides of the junction. 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 $500 \mu\text{m}$ long and about $100 \mu\text{m}$ 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.

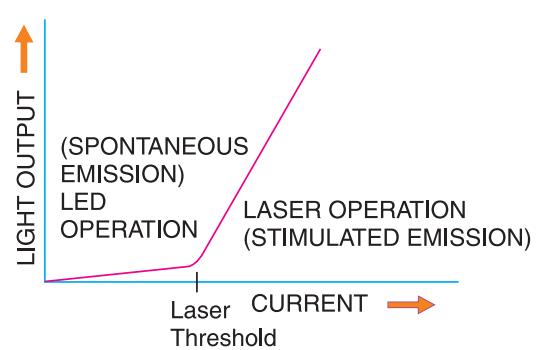


Energy band structure of a semiconductor diode
 (a) Heavily doped pn-junction without bias. (b) Heavily doped pn-junction forward biased above threshold value

Fig. 22.34

Working : The energy band diagram of a heavily doped pn junction is shown in Fig.22.34 (a). 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. Electrons occupy the portion of the conduction band lying below the Fermi level. 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. At thermal equilibrium, the Fermi level is uniform across the junction.

When the junction is forward-biased, electrons and holes are injected into the junction region in high concentrations. In other words, carriers are *pumped* by the dc voltage source. At low forward current level, the electron-hole recombination causes spontaneous emission of photons and the junction acts as an LED. As the forward current through the junction is increased the intensity of the light increases linearly. However, when the current reaches a threshold value (see Fig.22.35), the carrier concentrations in the junction region will rise to a very high value. As a result, the region (region'd' in Fig.22.34 b) contains a large concentration of electrons within the conduction band and *simultaneously* a large number of holes within the valence band. Holes represent absence of electrons. 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. 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**. Chance recombination acts of electron and hole pairs lead to emission of spontaneous photons. The spontaneous photons propagating in the junction plane stimulate the conduction electrons to jump into the vacant states of valence band. This stimulated electron-hole recombination produces coherent radiation. GaAs laser emits light at a wavelength of 9000 Å in IR region.



Light output-current characteristic of an ideal diode laser.

Fig. 22.35

22.16 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.

(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 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.

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

$$\phi = \frac{d_2 - d_1}{l_2 - l_1} \quad (22.46)$$

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

(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

$$I = \left[\frac{10}{\lambda} \right]^2 P \quad (22.47)$$

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.

(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).

22.19. 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.

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.

Welding: Welding is the joining of two or more pieces into a single unit. If we consider welding of two metal plates, the metal plates are held in contact at their edges and a laser beam is made to move along the line of contact of the plates. The laser beam heats the edges of the two plates to their melting points and causes them to fuse together where they are in contact. The main advantage of

the laser welding is that it is a contact-less process and hence there is no possibility of introduction of impurities into the joint. In the process, the work-pieces do not get distorted, as the total amount of input is very small compared to conventional welding processes. The heat-affected zone is relatively small because of rapid cooling. Laser welding can be done even at difficult to reach place. CO₂ lasers are used in welding thin sheets and foils.

Drilling: The principle underlying drilling is the vaporization of the material at the focus of the beam. With lasers, one can drill holes as small as 10 μm in diameter. For drilling, the energy must be supplied in such a way that rapid evaporation of material takes place without significant radial diffusion of heat into the work piece. The vaporized material is removed with the help of a gas jet. Pulsed ruby and neodymium lasers are commonly used for drilling holes of small l/D ratio, where l is the thickness of the work and D is the hole diameter.

Hardening: Heat treatment is the process, which is done for sometime 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 CO₂ lasers of about 1 kW output power operating in cw 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 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.

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.

Measurement of atmospheric pollutants: Laser is a very useful tool for the measurement of the concentrations of various atmospheric pollutants such as N₂, CO, SO₂ etc gases and particulate matter such as dust, smoke and flyash. 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.

In one of the laser techniques, the light scattered by pollutants is studied. A pulsed laser is used as the source of light and the light scattered back is detected by a photodetector. The distance to particulate matter and the concentrations of particulate matter is obtained in this method. The distance is inferred from the time that light takes to travel up to the pollutant region and to return back. This technique is known as LIDAR which stands for light detection and ranging. The principle is very much similar to that of RADAR. The method helps in determining the concentration of particulate matter as a function of distance. However, this method cannot provide any information regarding the nature of the scattering particles. It is mainly useful in knowing the distribution of atmospheric pollutants in different vertical sections and in monitoring their variations. Environmental agencies measure concentrations of harmful gases such as SO₂ and NO₂ using this method.

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.

WORKED-OUT EXAMPLES

Example 22.1: 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 $\frac{N_2}{N_1} = e^{-(E_2 - E_1)/kT}$

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

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

Example 22.2: The wavelength of emission is 6000Å and the coefficient of spontaneous emission is $10^6/\text{s}$. Determine the coefficient for the stimulated emission.

Solution: The coefficient for stimulated emission is given by

$$B_{21} = \frac{c^3}{8\pi h\nu^3 \mu^3} A_{21} = \frac{\lambda^3}{8\pi h} A_{21} \quad (\text{Taking } \mu = 1)$$

$$\therefore B_{21} = \frac{(6000 \times 10^{-10})^3 m^3 (10^6 / s)}{8\pi \times 6.626 \times 10^{-34} Js} = 1.3 \times 10^{19} \text{ m/kg.}$$

Example 22.3: At what temperature are the rates of spontaneous and stimulated emission equal? Assume $\lambda = 5000\text{\AA}$.

Solution: If the rates of spontaneous and stimulated emission are equal, then

$$R_1 = \left[\frac{1}{e^{h\nu/kT} - 1} \right] = 1 \quad \text{or} \quad e^{h\nu/kT} = 2$$

As $\lambda = 5000\text{\AA}$, $v = c/\lambda = 6 \times 10^{14} \text{ Hz}$ and

$$\frac{h\nu}{kT} = \frac{6.626 \times 10^{-34} Js (6 \times 10^{14} / s)}{(1.38 \times 10^{-23} J/K)T} = \frac{28.8 \times 10^3}{T} K$$

$$e^{h\nu/kT} = \exp\left[\frac{28.8 \times 10^3}{T} K\right] = 2$$

$$\text{or} \quad \frac{28.8 \times 10^3}{T} K = \ln 2 = 0.693$$

$$\therefore T = \frac{28.8 \times 10^3}{0.693} K = 41,558 \text{ K.}$$

Example 22.4: The length of a laser tube is 150 mm and the gain factor of the laser material is 0.0005/cm. If one of the cavity mirrors reflects 100% light that is incident on it, what is the required reflectance of the other cavity mirror?

Solution:

$$\gamma_{th} = \frac{1}{2L} \ln \frac{1}{r_1 r_2}$$

$$\therefore r_2 = \frac{1}{r_1 e^{2L\gamma}} = \frac{1}{1 \times e^{2 \times 15 \times 0.0005}} = 0.985$$

It means that the second mirror should have a reflectance of 98.5%.

Example 22.5: The half-width of the gain profile of a He-Ne laser material is 2×10^{-3} nm. If the length of the cavity is 30 cm, how many longitudinal modes can be excited? The emission wavelength of He-Ne laser is 6328 Å.

Solution: The separation between successive longitudinal modes is given by

$$\Delta\lambda = \frac{\lambda^2}{2L} = \frac{(6328 \times 10^{-10} m)^2}{2(30 \times 10^{-2} m)} = 0.66 \times 10^{-3} \text{ nm}$$

$$\text{Number of modes } N = \frac{\delta\lambda}{\Delta\lambda} = \frac{2 \times 10^{-3} \text{ nm}}{0.66 \times 10^{-3} \text{ nm}} = 3.$$

QUESTIONS

1. Explain with neat diagram absorption, spontaneous emission and stimulated emission of radiation.
2. What is population inversion? Explain why laser action cannot occur without population inversion between atomic levels?
3. What do you understand by a negative temperature state? How can it be achieved?
4. Discuss the four-level (pumping) scheme for laser action.
5. What do you understand by an optical resonant cavity? Explain.
6. Why is the optical resonator required in lasers? Illustrate your answer with neat sketches.
7. What are the essential components of a laser? Explain their functions briefly.
8. Describe the working of solid state ruby laser.
9. Explain the principle and working of a He-Ne laser.
10. In helium – neon laser lasing is through neon gas. What is then the role of helium gas?
11. In helium – neon laser why is it necessary to use narrow tubes?
12. What is the reason for monochromaticity of laser beam?
13. With the help of energy band diagram discuss the working of a semiconductor laser.
14. Explain in brief the characteristics of a laser beam.
15. What is population inversion? Describe the construction and working of He-Ne laser. (GNDU, Amritsar, 2010)
16. What do you mean by non-radiative decay? (GNDU, Amritsar, 2010)
17. What is the role of He in He-Ne Laser ? (GNDU, Amritsar, 2010)
18. Write the rate equation for three level laser system. (GNDU, Amritsar, 2010)
19. Why heterojunction semiconductor lasers are preferred? (GNDU, Amritsar, 2010)
20. Discuss the absorption and amplification of a parallel beam light passing through a medium. (GNDU, Amritsar, 2010)
21. Explain the concept of the Longitudinal and Transverse modes. (GNDU, Amritsar, 2010)

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22. Explain the terms Doppler and line broadening. (GNDU, Amritsar, 2010)
23. Discuss the working, construction and applications of CO₂ Laser with neat labeled diagrams. (GNDU, Amritsar, 2010)
24. Write the requirements for producing high inversion density for Q-Switching. (GNDU, Amritsar, 2010)
25. Draw the electronic energy levels diagrams showing the output wavelength / frequency of Ruby and Nd:YAG Lasers ? (GNDU, Amritsar, 2010)

PROBLEMS FOR PRACTICE

1. A pulsed laser is constructed with a ruby crystal as the active element. The ruby rod contains typically a total of 3×10^{19} Cr³⁺ions. If the laser emits light at 6943 Å wavelength, find
 - a. the energy of emitted photon (in eV)
 - b. the total energy available per laser pulse(assuming total population inversion)
[Ans : (a)E = 1.79 eV; (b) 8.6 J]
2. Find the relative populations of the two states in a ruby laser that produces a light beam of wavelength 6943Å at 300K. [Ans : 8×10^{-31}]
3. Find the ratio of populations of the two states in a He-Ne laser that produces light of wavelength 6328Å at 27°C. [Ans : 1.1×10^{-33}]
4. The He-Ne system is capable of lasing at several different IR wavelengths, the prominent one being 3.3913μ m. Determine the energy difference (in eV) between the upper and lower levels for this wavelength. [Ans : E = 0.37 eV]
5. The CO₂ laser is one of the most powerful lasers. The energy difference between the two laser levels is 0.117 eV. Determine the frequency and wavelength of the radiation.
[Ans : $\lambda = 10.5\mu$ m. $v = 2.9 \times 10^{13}$ Hz]
6. A laser beam can be focused on an area equal to the square of its wavelength. For a He-Ne laser, the wavelength of emitted light is 6328Å. If the laser radiates energy at the rate of 1 mW, find out the intensity of the focused beam. [Ans : $I = 2.5 \times 10^{15}$ W/m²]
7. Compute the Doppler broadening for the 6328A laser transition in the He-Ne Laser, assuming a single isotope of Ne²⁰ and that the laser operate at a discharge-bore temperature of 373 K. (GNDU, Amritsar, 2010)