UNIT 13 PHYSICS OF LASERS

Structure

13.1 INTRODUCTION

In the previous unit, you learnt about coherence and coherent sources of light. It was explained there why conventional thermal sources of light emit radiation which have very low degree of coherence. However, phenomenon like interference which requires coherent light sources, can indeed be observed with conventional light sources. The quest for obtaining a light source with high degree of coherence led to the invention of lasers. As you know, a useful indicator of the degree of coherence is the coherence length. For ordinary light, the coherence length is of the order 10^{-2} m, whereas the coherence length for a laser light can be as long as 10^{5} m! So, you may appreciate the difference in the degree of coherence between an ordinary light and the laser light. In the present unit, we will discuss about this source of highly coherent light beam-the LASER.

The name laser is an acronym for ***L*ight *A*mplification** by Stimulated Emission of Radiation. You must realise that the key words here are amplification and stimulated emission. The existence of stimulated emission of radiation, when radiation interacts with matter, was predicted by Einstein in 1916. His theoretical prediction was realised by *C. H.* Townes and co-workers in 1954 when they developed microwave amplification by stimulated emission of radiation (maser). The principle of maser was adapted for light in visible range by *A.* Schawlow and *C. H.* Townes in 1958 but the first laser device was developed by *T.H.* Maiman in 1960. Once the laser was invented, it has found applications in such diverse fields as basic research, industry, medicine, space, photography, communication, defence, etc.

In Sec. 13.2, you will learn about the quantum mechanical description of the emission and absorption of light. In particular, you will learn about spontaneous emission and stimulated emission of radiation. In Sec. 13.3, the physical principles involved in the operation of lasers viz. excitation (or pumping), the need of an active medium and the feedback mechanism have been explained. Since the invention of laser by Maiman using small ruby rod as active medium, Lasers have come a long way. Presently, lasers are built using solid or liquid or gas as active media. Apart from these, now semi-conductor based lasers are finding wide applications. These different types of lasers have been briefly discussed in Sec. 13.4. The applications of lasers are so many and so varied that their detailed account will take us too far. In Sec. 13.5, we have, however, briefly discussed applications of lasers in industry, medicine, communication and basic research. In the next unit, you will study about holography, which would not have been possible without laser light. And in Unit 15, you will study about optical fibres-a medium of transporting light-which is a very active area of research and development for long distance optical communication purposes.

Objectives

After going through this unit, you should be able to

- explain the concept of stimulated emission of radiation and differentiate it from spontaneous emission
- describe the need and methods of pumping
- list the characteristics of the active medium for lasers
- describe different types of lasers, and
- describe the important applications of lasers.

13.2 LIGHT EMISSION AND ABSORPTION

As you are aware, most of the man-made sources of light are the solids and gases heated to high temperatures. For example, in case of incandesent bulb, the tungsten filament is heated, and in case of murcury tube light, the gas is heated. The energy of the heating source is absorbed by the atoms or molecules of the solid or the gas, which, in turn, emit Light. The basic mechanism of the origin of light from within gas molecules, liquids and solids is similar in many respect to that from an individual atom. And the process of emission and absorption of light from atoms can be understood in terms of Bohr's atomic model. Though you might have studied Bohr's model in your school physics course, we briefly discuss it here for the sake ofcompleteness.

13.2.1 Quantum Theory: A Brief Outline

You may recall from your school physics course that according to Bohr's theory, the energy of an atom or a molecule can take on only definite (discrete) values. These are known as the energy levels of the atom, The transition of an atom from one energy level to another energy level occurs in quantum jump. This was one of the basic assumptions of Bohr's theory. On the basis of this presumption, Bohr postulated that light is not emitted by an electron when it is revolving in one of its allowed orbits (and hence has a fixed value of energy). Light emission takes place when the atom makes a transition from an excited state (of energy E_i) to a state of lower energy E_f. The frequency of the emitted radiation is given by

$$h\nu = E_i - E_f \qquad (13.1)$$

where E_i is the energy of the initial orbit, E_f is the energy of the final orbit, v the frequency of the emitted light and h is the **Planck's** constant. The quantized orbits of the electron and the energy level diagram of the simplest atom-the hydrogen atom-are shown in Fig. 13.1.

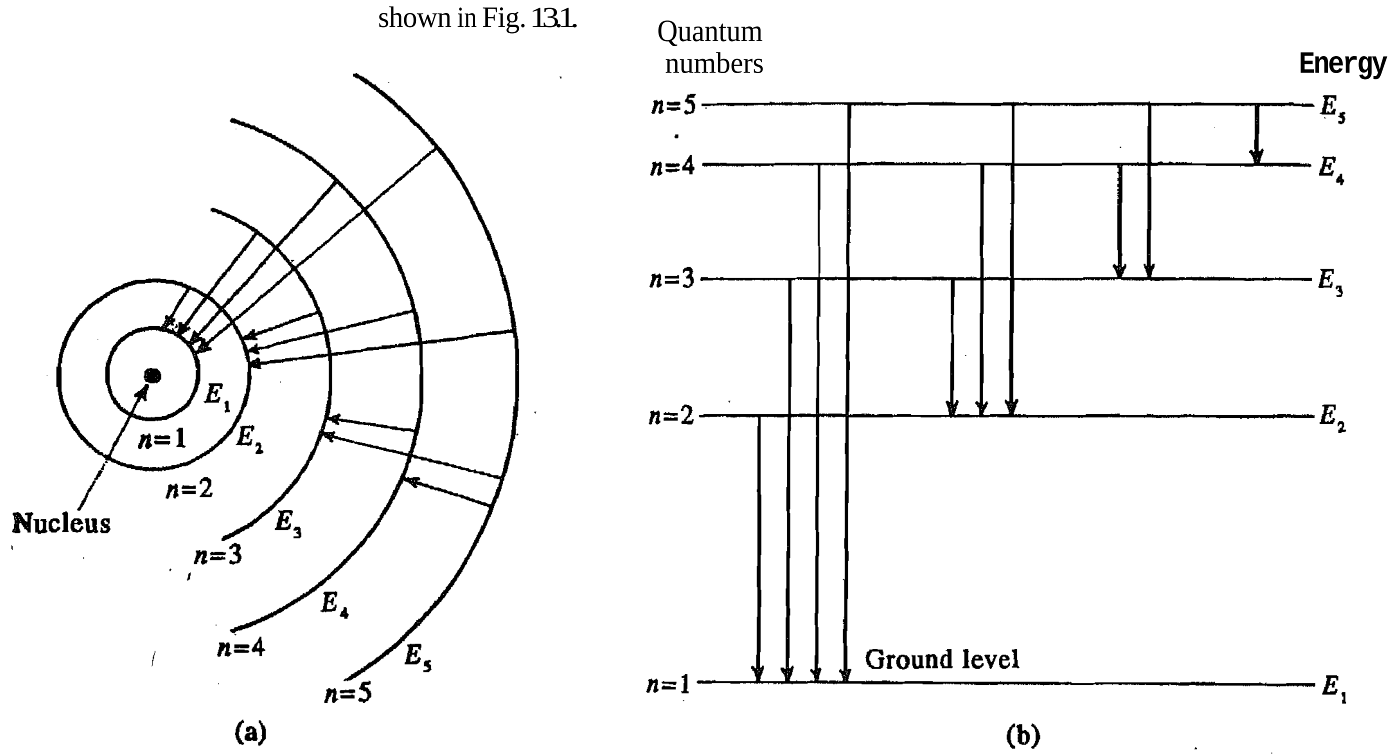


Fig. 13.1: (a) Bohr circular orbits for the revolving electron of hydrogen atom, showing transitions, giving rise to the emitted light waves of different frequencies; (b) Energy level diagram tor the hydrogen atom.

The quantum mechanical explanation about the origin of light, as discussed above, applies to all the known light sources. To focus our attention on the atomic processes involved in the emission and absorption of light, let us consider only two energy levels of an atom. Let the energy of the lower level be E_1 and that of the upper level be E_2. An atom lying in level E_2 will tend to make a transition to level E_1 so that it occupies a state of lower energy. Such emission process is known as spontaneous emission because it occurs in the absence of any external stimulus. The process of spontaneous emission is shown in Fig. **13.2(a).** The photon emitted in spontaneous emission will have the energy (E_2-E_1), **while** its other characteristics such as momentum, polarisation, will be arbitrary. The light emitted by ordinary sources results due to spontaneous **emission.** Absorption of light is the converse process of emission. The atom in a lower energy state can absorb a photon of energy $h\nu\ (= E_2 - E_1)$ and get excited to the upper level E_2. The absorption process is depicted in Fig. 13.2(b).

Now, can you guess what will happen if an atom is in the **higher** energy level, E_2, and a photon of **energy** $h\nu\ (= E_2 - E_1)$ interacts with it? Well, in such a situation, the photon may trigger the atom in the upper level to emit radiation. This emission process is known as stimulated emission. When the atom is already in the higher energy level, the photon, instead of being absorbed, may play the role of a trigger, and induce the transition from E_2 to E_1. As a result, the atom falls into lower energy level and an additional photon **of** energy $h\nu = E_2 - E_1$ is emitted. In this process of stimulated emission, shown in Rg. 13.2(c), both the inducing and **the** induced photons have the same energy. The Light **from** laser is due **to the** stimulated emission of radiation.

It is worth mentioning here that of the three processes mentioned above, only the first two, that is, the spontaneous emission and the absorption of light were postulated on the basis of Bohr's theory. It was only when **Einstein** considered the whole idea of emission

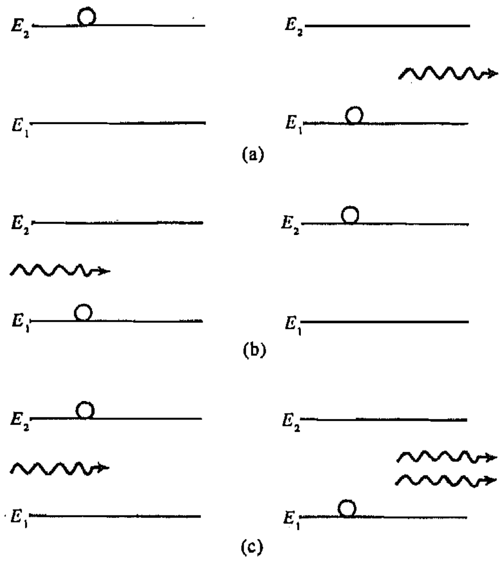


Fig. 13.2: (a) Spontaneous Emission (b) Absorption and (c) Stimulated Emission of light

and absorption of radiation in terms of thermodynamic equilibrium between matter and radiation that stimulated emission of radiation could be predicted. What were Einstein's theoretical arguments for the prediction? Let us learn these now.

13.2.2 Stimulated Emission of Radiation: Einstein's Prediction

Stimulated emission, as mentioned above, is the reverse of the process in which electromagnetic radiation or photons are absorbed by the atomic systems. When a photon is absorbed by an atom, the energy of the photon is converted into the internal energy of the atom. The atom is then raised to an excited (higher energy) state and it may radiate this energy spontaneously, emitting a photon and reverting to the ground (or some lower energy) state. However, during the period the atom is in the excited state, it can be stimulated to emit a photon if it interacts with another photon. This stimulating photon should have precisely the energy of the one that would otherwise be emitted spontaneously. Let us look at the theoretical arguments put forward by Einstein for the existence of stimulated emission.

Refer to Fig. 13.3 which shows a system of two energy levels E_1 and E_2 with population

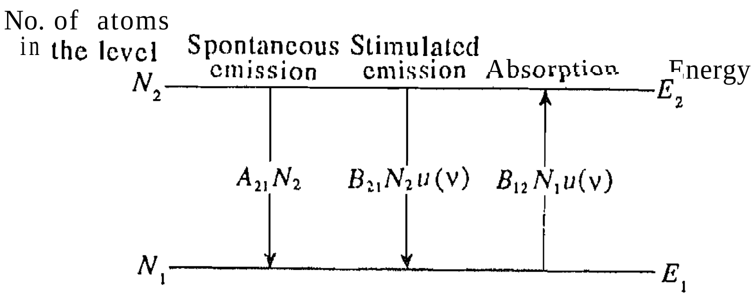


Fig. 13.3: An atomic system of two energy levels showing different emission and absorption processes.

of atoms N_1 and N_2 respectively. Let $E_1 < E_2$. You may recall from Unit 13 of PHE-06 that according to Maxwell-Boltzmann distribution, the ratio of population of atoms in different levels for the system in thermal equilibrium is given as

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

$$\text{or} \quad N_2 = N_1 e^{-h\nu/k_B T} \qquad (13.2)$$

where, k_B is the **Boltzmann** constant and T is the absolute temperature.

Now what **will** be the ratio of the population of the energy levels if radiation of energy hv is introduced into the system? Einstein proposed that if this system of energy levels and the radiations is to remain in thermal equilibrium, the rate of downward transition (due to spontaneous and stimulated emission) must be equal to the rate of upward transition (due to absorption). He, therefore, arrived at the relation (see box below),

$$\frac{N_2}{N_1} = \frac{B_{12}\,u(\nu)}{A_{21} + B_{21}\,u(\nu)} \tag{13.3}$$

where, u (v) is the energy density of radiation at frequency ν and B_{12}, A_{21}, B_{21} are Einstein's co-efficients. A_{21} is associated with spontaneous emission, B_{21} is associated with stimulated emission and B_{12} is associated with absorption.

Following Einstein, let us write down the rates of spontaneous and stimulated emission and **the** rate **of** absorption of radiation. The rate of spontaneous emission will be independent of the energy density of the radiation field because for this process to occur, presence of photon is not required. This emission process will be proportional to the number of atoms, N_2, in the higher energy state, So, we may write the rate of spontaneous emission as

$$P_{21} = N_2 A_{21} \tag{i}$$

where A_{21} is constant of proportionality.

Assume next that the system of atoms is subject to some external radiation field. In that case, as mentioned earlier, one of the two processes, namely, the stimulated emission and absorption, may occur. The probability of their occurrence depends on the energy density of radiation at the particular frequency separating the two levels and the population **of** states from which transition takes place. Therefore, the rate of stimulated emission will be proportional to the energy density of **the radiation** and the population of higher energy state, N_2. Thus, the rate of stimulated emission

$$P_{21} = N_2 B_{21}\,u(\nu) \tag{ii}$$

where B_{21} is another constant of proportionality and u (v) is energy density of radiation at frequency ν.

On the other hand, the rate of absorption will depend on u (v) and **the** population of the lower energy state, N_1. **Thus,** the rate of absorption

$$P_{12} = N_1 B_{12}\,u(\nu) \tag{iii}$$

where B_{12} is the constant of proportionality. The **constants** A_{21}, B_{12} and B_{21} are known as Einstein's **coefficients.**

With the system in thermal equilibrium, the net rate of downward transition must be equal to the net rate of upward transition. Thus, we may write

$$N_2 A_{21} + N_2 B_{21}\,u(\nu) = N_1 B_{12}\,u(\nu) \tag{iv}$$

Dividing both side by N_1, we get

$$\frac{N_2}{N_1}A_{21} + \frac{N_2}{N_1}B_{21}\,u(\nu) = B_{12}\,u(\nu)$$

or

$$\frac{N_2}{N_1}\left(A_{21} + u(\nu)\,B_{21}\right) = B_{12}\,u(\nu)$$

so that,

$$\frac{N_2}{N_1} = \frac{B_{12}\,u(\nu)}{A_{21} + u(\nu)\,B_{21}} \tag{v}$$

Form Eqs. (13.2) and (13.3), we have

$$\frac{B_{12}\,u(\nu)}{A_{21} + u(\nu)\,B_{21}} = e^{-h\nu/k_B T}$$

or

$$u(\nu) = \frac{A_{21}}{B_{12}}\,\frac{1}{e^{h\nu/k_B T} - (B_{21}/B_{12})} \qquad (13.4)$$

Now, you may recall from unit of PHE-06 that the energy density of black body radiation is given by **Planck's** radiation law:

$$u(\nu) = \frac{8\pi h\nu^3}{c^3}\,\frac{1}{e^{h\nu/k_B T} - 1} \qquad (13.5)$$

Equation (13.5) must be same as Eq. (13.4). So we must have

$$B_{21} = B_{12} \qquad (13.6)$$

and

$$A_{21}/B_{21} = \frac{8\pi h\nu^3}{c^3} \qquad (13.7)$$

These are Einstein's relations. On the basis of Einstein's relations, we can conclude the following:

(a) Eq. (13.6) indicates that the probabilities of absorption and stimulated emission are the same. In other words, when an atomic system is in equilibrium, absorption and emission take place side by side. Normally, $N_2 < N_1$, and absorption dominate stimulated emission. An incident photon is more likely to be absorbed than to cause stimulated emission, But, if we could find a material that could be induced to have a majority of atoms in the higher state than in the lower state, i.e. $N_2 > N_1$, the stimulated emission may dominate absorption. This condition of the atomic system (where $N_2 > N_1$) is known as population inversion. And when the stimulated emission dominates over absorption in the atomic system, it is said to lase.

(b) If we substitute $B_{12} = B_{21}$ in equation (13.4), we get the ratio of the number of spontaneous emission to stimulated emission

$$\frac{A_{21}}{B_{21}\,u(\nu)} = e^{h\nu/k_B T} - 1 \qquad (13.8)$$

When the system is in thermal equilibrium at temperature T, for $h\nu << k_B T$, Eq. (13.8) suggests that stimulated emission will dominate spontaneous emission. On the other hand, when $h\nu >> k_B T$, spontaneous emission will dominate stimulated emission. Now which of these two processes will dominate for ordinary thermal sources of light? To know that, you should do the following SAQ.

SAQ 1

Spend 5 min

The absolute temperature, T, for an ordinary source of light is typically of the order of 10^3 K. With the help of Eq. (13.8), show that in such sources, the process of spontaneous emission will dominate over the stimulated emission.

13.2.3 Einstein's Prediction Realised

You now know that when matter and radiation are in thermal equilibrium, besides spontaneous emission and absorption of radiation by matter, there must be a third process, called stimulated emission. This prediction did not attract much attention untill

1954, when Townes and coworkers developed a microwave amplifier (MASER) using NH_3. In 1958, Shawlow and Townes showed that the maser principle could be extended into visible region. In 1960, the prediction was realised by Maiman who built the first laser using Ruby as an active medium. Maiman found that a suitable active component for a laser could be made from a single crystal of pink ruby: aluminium oxide (Al_2O_3), coloured pink by addition of about 0.5 percent chromium. For any laser action to take place, a condition of population inversion must be met. By population inversion we mean that the number of atoms in higher energy state is larger than the ground (or some lower energy) state. The energy states of the chromium atom, as shown in Fig. 13.4, are ideal for obtaining population inversion. The chief characteristics of energy levels of a Chromium atom is that the levels labelled as E_1 and E_2 have a life time 10^{-8} s. whereas the state marked M has a life time 3×10^{-3} s. The energy state M with such a long life time (as compared to other excited states) is called a metastable state.

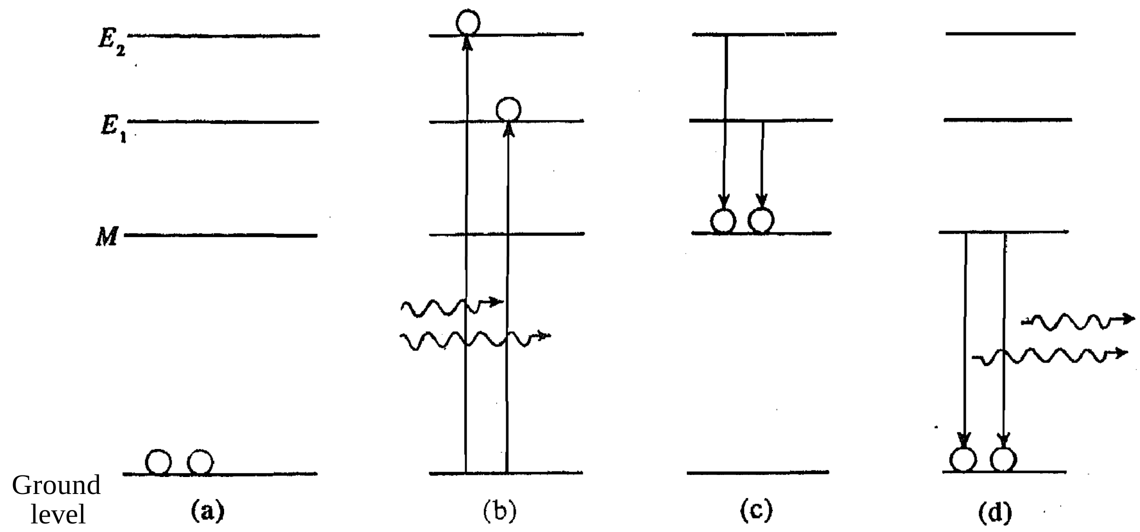
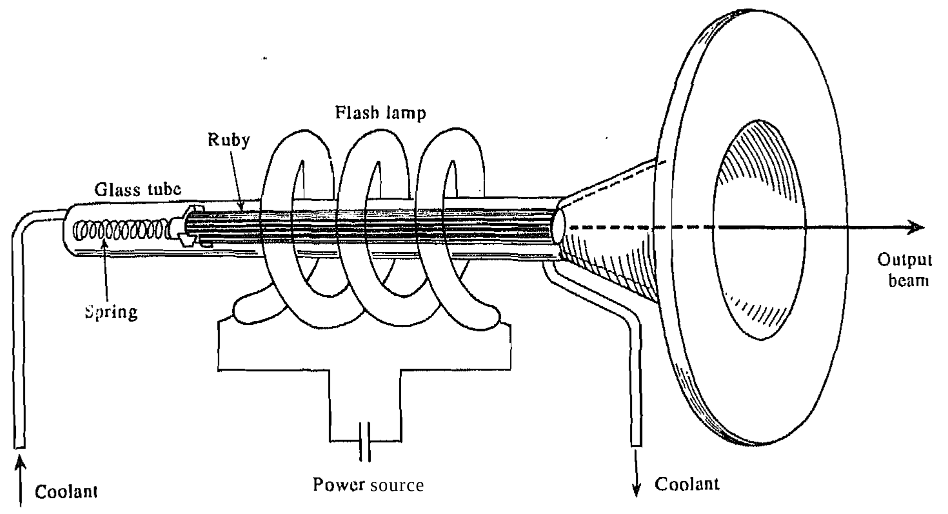


Fig.13.4: Energy levels of chromium atom: (a) atoms in the ground state (b) on absorbing photons, atoms are excited to one of the two energy levels E_1 and E_2, (c) atoms give up some of its energy to the crystal lattice and fall to a metastable level, M, (d) When stimulated by photons, the atoms in metastable level emit photon and fall to ground state.

A chromium atom in its ground state can absorb a photon ($\lambda = 6600$ Å) and make a transition to the level E_1; it could also absorb a photon of λ –4000 Å and make a transition to the level E_2. In either case, it subsequently makes a non-radiative transition, in time 10^{-8} s, to the metastabe state M. Since the state M has a very long life, the number of atoms in this state keeps on increasing and we may achieve a population inversion between the state M and G (the ground state). Thus, we may have larger number of atoms in the level M compared to those in the state G. Once population inversion is achieved, light amplification can take place.

When an atom undergoes a lion-radiative transition the energy is not released in the form of photons; rather, the energy is transferred via atomic collisions, collision with the crystal lattice etc.

In the original set up of Maiman, the pink ruby was machined into a rod of length nearly four centimeter and diameter half a centimeter. Its ends were polished optically flat and parallel and were partially silvered. The rod was placed near an electronic flash tube (filled with xenon gas) that provided intense light for pumping chromium atoms to higher energy states. The set up of ruby laser is shown in Fig. 13.5. When the required population inversion was achieved with the help of electronic flash tube, the first few photons released (at random) by atoms dropping to the ground state stimulated a cascade of photons, all having the same frequency.

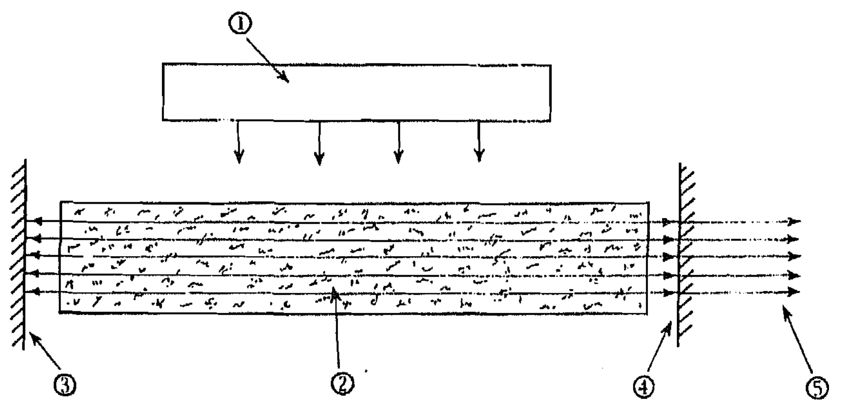


Flg.13.5: The Ruby Laser

You now know how a ruby laser, developed by Maiman, works. You will appreciated that production of laser light demands that certain conclitions must be met beforehand. (We deliberately avoided reference to these in above paragraphs.) Firstly, is it possible to achieve laser light from any medium? If not, what are the chahracteristics of the medium which can produce laser light after proper excitation? (The media capable of producing laser light are called active media.) Secondly, how do we achieve population inversion? Further, for sustained laser light, it is necessary to feed some of the output energy back into the active medium. This is known as feedback and is achieved by resonant cavity. What is the nature of this resonant cavity for lasers? These are some of the important aspects of laser operation and design about which you will learn now.

13.3 PREREQUISITS FOR A LASER

A laser requires three prerequisites for operation. Firstly, there should be an **active medium** which, when excitccl, supports **population inversion** ancl subsequently lases. Secondly, we should ensure **pumping** mechanism, that raises the system to an **excited state.** And lastly, in most cases, there is an **optical cavity** that provides the feedback necessary for laser oscillation. These are shown schematically in Fig. 13.6.



Flg.13.6: Basic components of a laser oscillator: Energy source (1) supplies energy to active medium (2). Medium is contained between two mirrors (3 nnd 4). Mirror 3 is hilly reflective while mirror 4 is partially transparent. Laser radiation (5) emerges through partially transparent mirror.

In a typical laser operation, energy is transferred to the active material, which is raised to the excited state, and ultimately lases in various ways. The medium may be a solid, liquid or gas and it may be one of the thousands of materials that have been found to lase. The process of raising the medium to the excited state is called pumping, in analogy to pumping of water from lower to a higher level of potential energy. Some lasers are built as laser amplifier. They need no optical cavity. Most lasers, however, are laser oscillators. For sustained laser oscillations, some kind of feedback mechanism is needed. The feedback mechanism is provided in the form of optical resonant cavity. In both laser amplifiers and oscillators, the first few quanta of radiation will probably be emitted spontaneously and will trigger stimulated emission.

Let us now discuss the above mentioned three components of a laser.

13.3.1 The Active Medium

The heart of the laser is a certain medium – solid, liquid or gaseous – called an active medium. Since Maiman's discovery of ruby, many new laser materials have been discovered. They include crystals other than ruby, glasses, plastics, liquids, gases and even plasma (the state of matter in which some of the atomic electrons are dissociated from the atoms). What should be the characteristics of an active medium? The only general requirement for an active medium is that it provides an upper energy state into which atoms can be pumped and a lower state to which they will return with the spontaneous emission of photons. The medium must also allow a population inversion between the two states. It may happen that the active species or centres, which provide lasing levels, constitute a small fraction of the medium. For example, in case of ruby, which is Al_2O_3 with some of the Al atoms replaced by Cr atoms, only the latter (Cr) is the active centre. Typical number of active species per cubic centimeter in solids and liquids is 10^{19} to 10^{20} and that for gaseous media their number is about 10^{15} to 10^{17}. How the light beam gets amplified when it passes through an active medium? To get the answer we examine the process of population inversion now.

Population Inversion

Why is the condition of population inversion between the lasing level necessary for operation of lasers, i.e. for amplification of light to occur? We can investigate this by calculating the change in intensity of the light beam passing through an active medium. Refer to Fig. 13.7. A collimated beam of light having intensity I_ν, travels along the x-axis through an active medium of thickness dx.

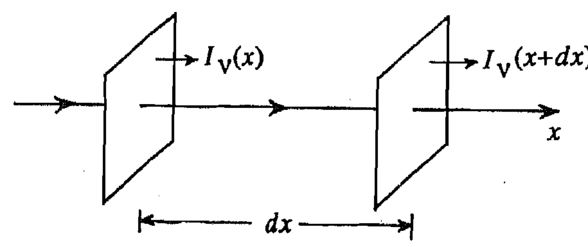


Fig. 13.7: Light beam of intensity I_ν passing through an active medium along the x-axis

If the cross-sectional area of each of the planes is S, volume of the layer will be Sdx. Let $N_1(\nu)\,d\nu$ represent the number of atoms per unit volume which are capable of absorbing radiation whose frequency lies between ν and $\nu + d\nu$. The number of upwardly transmitted ($E_1 \rightarrow E_2$) atoms per unit time in the layer of volume Sdx would be (refer to box on page 26)

$$N_1(\nu)\,d\nu\,B_{12}\,u(\nu)\,Sdx$$

In each transition, a photon of energy $h\nu$ is absorbed. Thus, energy lost per unit time from the incident radiation is

$$h\nu\,[N_1(\nu)\,d\nu\,B_{12}\,u(\nu)]\,Sdx$$

Similarly, let $N_2(\nu)\,d\nu$ represent the number of atoms per unit volume which are capable of undergoing stimulated emission by falling down to level E_1. The frequency of these photons lie between ν and $\nu + d\nu$. Then the number of stimulated photons emitted per unit time in the layer is

$$N_2(\nu)\,d\nu\,B_{21}\,u(\nu)\,Sdx$$

In each transition, photon of energy $h\nu$ is emitted and this reinforces the propagating beam. Thus the energy gain by the incident radiation per unit time is

$$h\nu\,[N_2(\nu)\,d\nu\,B_{21}\,u(\nu)]\,Sdx$$

You may have noticed that we have neglected spontaneous emission. It is so because a photon, emitted via spontaneous process, is in a random direction. And, as such, it does not contribute appreciably to the intensity of the beam.

As a result of above processes, will the intensity of the light beam increase or decrease with time? Since $u(\nu)\,d\nu\,Sdx$ represents the energy in the layer within frequency range ν and $\nu + d\nu$, we can write the rate of change of the energy with time as

$$\frac{\partial}{\partial t}(u(\nu)\,d\nu\,Sdx) = h\nu\,[-N_1(\nu)\,B_{12}\,u(\nu) + N_2(\nu)\,B_{21}\,u(\nu)]\,d\nu\,Sdx$$

or

$$\frac{\partial u(\nu)}{\partial t} = -h\nu\,[B_{12}N_1(\nu) - B_{21}N_2(\nu)]\,u(\nu) \qquad (13.9)$$

If I_ν represents intensity, $I_\nu\,d\nu$ signifies the energy crossing a unit area per unit time whose frequency lies between ν and $\nu + d\nu$. Then

$$[I_\nu(x + dx)\,d\nu - I_\nu(x)\,d\nu]\,S$$

denotes the rate at which the energy flows out of the layer. Since $u(\nu)\,d\nu\,Sdx$ represents radiation energy contained in the layer with frequency in the range ν and $\nu + d\nu$, we will have

$$[I_\nu(x + dx) - I_\nu(x)]\,d\nu\,S = \frac{\partial}{\partial t}[u(\nu)\,d\nu\,Sdx]$$

$$\frac{\partial u(\nu)}{\partial t} = \frac{I_\nu(x + dx) - I_\nu(x)}{dx} = \partial I_\nu/\partial x \qquad (13.10)$$

From Eq. (13.9) and (13.10), we have

$$\frac{\partial I_\nu}{\partial x} = -h\nu\,[B_{12}N_1(\nu) - B_{21}N_2(\nu)]\,u(\nu)$$

But

$$I_\nu = u(\nu)\,v$$

(13.11)

where v = velocity of light in the active medium ($= c/n$; n = refraction index of the medium). Thus, we get

$$\frac{\partial I_\nu}{\partial x} = -\frac{h\nu B}{v}(N_1 - N_2) I_\nu$$

where B $(= B_{12} = B_{21})$ denotes either Einstein's coefficient. Hence

$$\frac{\partial I_\nu}{I_\nu \partial x} = -\frac{h\nu n}{c}(N_1 - N_2) B \qquad (13.12)$$

If the light beam is propagating in absorbing media, the loss of **intensity,** $-dI_\nu$ will be proportional to I_ν and dx;

$$dI_\nu = -\alpha_\nu I_\nu dx$$

where α_ν is absorption coefficient. We can rewrite it as

$$\frac{\partial I_\nu}{\partial x} = -\alpha_\nu I_\nu \qquad (13.13)$$

On integration we find that

$$I_\nu = I_\nu (x = 0) e^{-\alpha_\nu x} \qquad (13.14)$$

If we compare Eqs. (13.12) and **(13.13),** we get the expression for absorption co-efficient:

$$\alpha_\nu = \frac{h\nu n}{c}(N_1 - N_2) B \qquad (13.15)$$

At thermal equilibrium, $N_1 > N_2$, **that** is, the population of ground state is greater than the population of the excited state and as can be seen from Eq. **(13.15),** α_ν is positive. Positive α_ν implies, (from equation **13.14)** that the intensity **of** the beam decreases as it propagates through the material. The lost energy is used up in the excitation of **atoms** to higher energy states.

On the other hand, if we have a situation in which $N_2 > N_1$, α_ν will be **negative** and intensity of the light beam would increase, that is, get amplified as it propagates through the material. This process is light amplification. Since this occurs when there is a higher population in excited state than in the ground (or lower energy) state, the material is said to be in the state of population inversion. Thus, the condition of population inversion is necessary for amplification of intensity of **light** beam.

13.3.2 Excitation (or **Pumping)**

In the previous sub-section, you have learnt about the necessity of population inversion in the active medium for obtaining laser light. The process of obtaining population inversion is known as pumping or excitation. The aim of the pumping is to see that upper energy level is more intensely populated than the lower energy level. Alternatively, we can obtain the population inversion by depopulating lower energy level (other than ground state) faster than the upper energy level. There are several ways of pumping a laser and achieving the population inversion necessary for stimulated emission to occur.

Most commonly used are the following:

1. Optical **Pumping**
2. Electric Discharge
3. Inelastic Atomic Collision
4. Direct Conversion

In Optical Pumping, a source of light is used to supply energy to the activc medium. Most often this energy comes in the form of short flashes of light, a method first used in Maiman's Ruby Laser and widely used even today in Solid-State Lasers. The laser material is placed inside a helical xenon flash lamp of the type customary in photography. The xenon flash lamp for pumping is shown in Fig. 13.5.

Another method of pumping is by direct electron excitation as it occurs in an electric discharge. This method is preferred for pumping Gas lasers of which the argon laser is a good example. The electric field (typically several KV m^{-1}) causes electrons, emitted by the cathode, to be accelerated towards the anode. Some of the electrons will impinge on the atoms of the active mcdium (electron impact), and raise them to the excited statc. As a result, the population inversion is achieved in the active medium.

In the inelastic atomic collision method of pumping, the electric discharge provides the initial excitation which raises one type of atoms to their excited statc or states. These atoms subsequently collide inelastically with another type of atoms. The energy transferred inelastically raises the later typc of atoms to the excited states and these are the atoms which provide the population inversion. An example is Helium-Neon Laser, to be discussed later, in which such a pumping proccss is employed.

A direct conversion of electrical energy into radiation occurs in light emitting diodes. Such light emitting diodes (LED) are used for pumping by direct conversion in semi-conductor lasers.

These are some of the proccsses used for pumping atoms of the active medium to achieve population inversion. Atoms (or molecules) used as active ccntrcs often exhibit rather complex system of energy levels. However, for all the variety of these structures, the actual pumping schemes may be narrowed down to a few rather simple diagrams correctly showing the puinping process. Typically, these pumping schemes involve three to four levels. We think you would like to know about them.

Let us consider some of the pumping schcmcs. To do so, let us identify different energy states necessary to explain the pumping scheme as: the ground state as 0; the lower lasing state as 1; the upper lasing statc as 2; and the puinping state as 3. We shall indicate pumping transition by upward arrow, the lasing transition by downward arrow and non- radiative fast decay by slanted arrows. Now let us consider a three-level pumping scheme shown in Fig. 13.8a. Let us assume that by one of the pumping methods, more than half the number of atoms of active species have been pumped from ground state to pumping statc 3. The pumped atoms in statc 3 decay non-radiatively to upper lasing state 2. This decay is very fast, (life time is typically of the order to 10^{-8} s). The upper lasing state 2 is generally a metastable state i.e. the life time of this statc ($\sim 10^{-3}$ s) is much higher than the pumping state (or the excited state). Therefore, we have a situation of population inversion bctwccn lasing states 2 and 1 and hence lasing may take place. You may note that in this pumping scheme, the ground state (0) and the lower lasing slate (1) are the same state. This feature of the pumping scheme proves too demanding for the pumping process because in normal circumstances, the ground state

Atoms or molecules tend to occupy lowest energy state. Therefore, the population of the ground state (lowest energy state) is high.

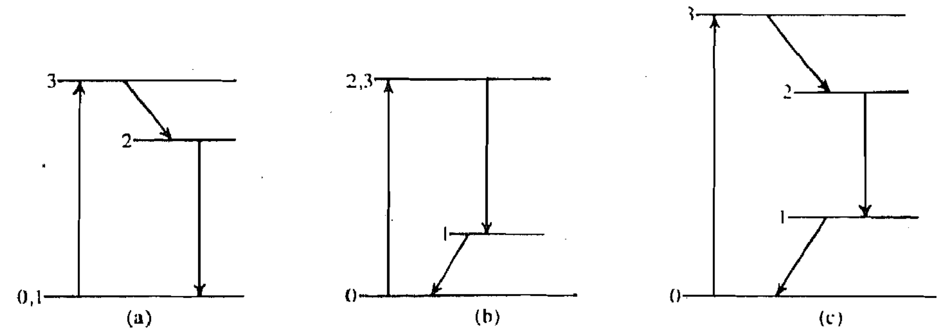


Fig. 13.8: Three level pumping schemes, (a) the ground state (0) and lower lasing state (1) are the same, (b) pumping state (3) and upper lasing state (2) are the same. *(c)* Four level pumping scheme;

is highly populated. And, as you can appreciate, an ideal lower lasing state (1) should be empty or very thinly populated. How to get rid of this problem?

According to the uncertainty principle, about which you will study in the PHE-11 course on Modern Physics, an energy state with longer life time will have narrow frequency band.

This problem can be taken care of if the pumping scheme is as shown in Fig. 13.8 b. As you can see, the atoms in the lower lasing state undergo non-radiative transition to the ground state (0). Since this transition is very fast ($\sim 10^{-8}$ s), the lower lasing level is empty for all practical purposes. You may, however, note that the same energy state acts as pumping state (3) and the upper lasing state (2). This state of affairs has its own shortcoming. If the pumping state has to act as upper lasing state, it must have a longer life time (metastable state) which implies that it must have very narrow frequency width. On the other hand, for proper utilisation of pumping energy, this state must have a wide frequency width so that more and more atoms get accomodated there. So, you see, it is a kind of conflicting requirements put on a single energy slates.

The pumping scheme free from the shortcomings mentioned above with reference to three-level pumping scheme is what we call four-level pumping scheme shown in Fig. 13.8c. In this case, the pumping stale (3) and the upper state (2) are seperate; atoms in the pumping state undergo non-radiative transition to the upper lasing state. The four level pumping scheme, however, has some limitations. Substantial energy is lost during non-radiative transitions between pumping state (3) and the upper lasing state (2) and between the lower lasing state (1) and the ground stale (0).

You may now ask: Which pumping scheme is better and preferred? Each pumping scheme has its own advantages and disadvantages. The choice of the pumping scheme in designing a laser depends upon the active media, the kind of use we want to put the laser light to, etc. We will discuss these aspects in the following sections. You may now like to answer an SAQ

SAQ 2

Spend 2 min

If laser action occurs by the transition from an excited state to the ground state and it produces light of 693nm wavelength, what is the energy of the excited state. Take the energy of the ground state to be zero.

13.3.3 Feedback Mechanism: Optical Resonant Cavity

On the basis of the discussion in the previous sections, you now know that when a state of population inversion exists in an active medium, a light beam of particular frequency passing through it would get amplified. It happens because in such a situation, stimulated emission dominates spontaneous emission. This is the basic principle of optical amplifier. But a laser is much more than a simple optical amplifier. The laser, which produces a highly coherent beam of light, docs not include a coherent light beam to initiate stimulated emission. Instead, it is the spontaneously emitted photon from upper lasing state which stimulates the emission of new photons. Each spontaneous photon can initiate many other stimulated transitions which, in turn, may cause light amplification. Well, in this way, we do get atnplification of light by stimulated emission. But, how is coherence of this amplified light ascertained'? In other words, how can wc ensure that the laser light has a very narrow band width (monochromaticity) and a high degree of phase correlation? As such, the amplificd light from laser is not cohercnt. It is because the spontaneous photons are indcpcndcnt of each other and travel in differcnt directions. Therefore, the corresponding stimulated photons will also travcl in different directions.

Can you suggest as to what should we do for obtaining a highly coherent laser bcam? For obtaining a coherent light beam, we need to have a mcchanism by which a condition is created such that sponlancous emission only in certain selected dircction can dcvelop stumulated emission. This mechanism is known as fccdback mcchanism. The spontaneous photons emitted in othcr directions leave the activc medium without initiating much stimulated emission.

Now, you may ask; how do we actually achieve this favourable condition for spontaneously emitted photons in some preferred direction to further stimulate

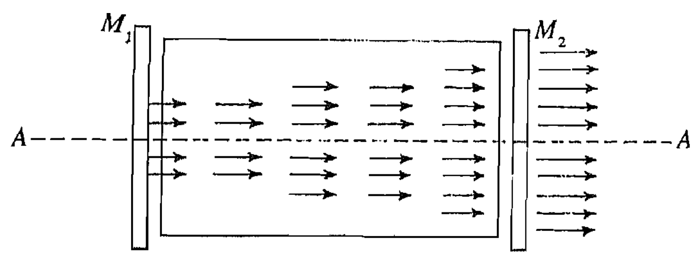


Fig.13.9: Optical resonntor consisting of two mirrors M_1 and M_2; M_1 is totally reflecting whereas M_2 is semitransparent; the axis of the mirrors is aligned with that of the active material.

emission? Well, this is accomplished by means of an optical resonator-an essential component of a laser. Let us undcrstand how an optical resonator works.

Optical cavity resonator can have many conligurations. Thc schematic arrangcmcnt of a simple resonator is shown in Fig. 13.9. It consists of a pair of planc mirrors, M_1 and M_2, set on an optic axis which defincs the dircction of the lascr bcarn. Thc activc material is placed in betwccn these mirrors. The photons emittcd spontancously along the AA direction or sufficiently close to it travcl a relativcly longcr distance within thc active material, It is so because photons travelling along AA will bc reflected back and forth by the mirrors M_1 and M_2. You tnay notice that thc direction of travel of these photons is quite fixcd. Now, as a result of spcnding more timc in the activc material, these spontaneous photons will interact with morc and more atoms in upper lasing level. Thus, the stimulated emission will add identical photons in the samc direction, providing an ever-increasing population of coherent photons that bounce back and forth bctwcen the mirrors. On the other hand, spontaneous photons and thc corresponding stimulated emission in other directions will traverse rclativcly shortcr distances (and hencc spend lesser time) in the activc meclium. Hence thcy will soon dic out. Thus the optical resonant cavity provides the desircd selectivity of propagation clirection and thcreby ensures the spatial coherence of thc lascr bcam.

You may rccall that thc spatial cohcrencc is a measure of the uniformity of thc phasc across the optical wavefront. And thc temporal coherence is a measure of the monochromaticity of thc light.

Now, what about monochromaticity of thc lascr light? Wcll, the laser light is highly monochromatic due to very nature of its origin - thc stimulatcd cmission. It is so bccausc the spontaneously emitted photons whosc frcquency do not match with the frcquency difference betwcen lasing levels will not give risc to stimulated cmission. Thus, thc band of wavelengths emitted during spontaneous emission is narrowed down. The monochromaticity of the laser light can further be enhanced by the optical resonant cavity. Suppose there are more than one upper lasing levels in a particular active medium. In that case, the laser output will consist radiations of more than one frequency. Now, if the mirrors of the resonant cavity are such that their reflectivity is a function of frequency, the radiations due to undesired lasing between levels will be damped out. Therefore, resonant cavity is the most vital component of the laser to obtain highly coherent light beam as output.

In this section, you learnt basic constituents of a laser. Since the invention of ruby laser by Maiman in 1960, the research and development in this field has produced a variety of lasers. It is not possible to discuss all of them in detail here. However, we will discuss some of them now.

13.4 TYPES OF LASERS

As such, lasers can be classified in a variety of ways. One of these is in terms of their active media. As mentioned earlier, materials in all the three states of matter, namely, solid, liquid and gas, have been used as active medium to produce laser beam. Further, lasers have also been constructed using semi- conductors and plasma as active medium. In the following, let us know about some of them with particular reference to the physical properties of the active medium and the pumping methods employed.

13.4.1 Solid State Lasers

These lasers use an active material which is essentially an insulator doped with ions of impurity in the host structure. These lasers invariably use optical pumping to obtain the condition of population inversion. The sources for optical pumping may be discharge flashtubes, continuously operating lamps or even an auxiliary laser. The active centres in these lasers are transition element ions doped in the dielectric crystal. The host material for these active centres are generally oxide crystals. The most popular type of solid-state

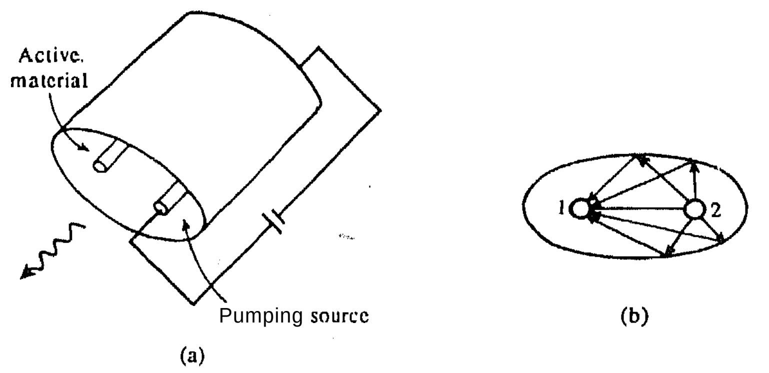


Fig. 13.10: Pumping arrangement for solid-state lasers.

lasers are the ruby laser and Nd:YAG (neodymium: yttrium, aluminium, garnet) laser. Ruby is Al_2O_3 crystal (corundum) doped with triply ionized chromium atom (Cr^{3+}). You have learnt the functioning of this laser in section 13.2.

In solid-state lasers, the optical pumping is done by placing the active material (in the form of rod) at one focus and the pumping source (in the shape of a right cylinder) at another focus of an elliptical reflector as shown in Fig, 13.10a. The advantage of such an arrangement is that any light leaving one focus of the ellipse will pass through the other focus after reflection from the silvered surface of the pump cavity. All of the pump radiation, therefore, is maximally focussed on the active material, as shown in Fig. 13.10b.

The Nd: YAG Laser

This laser, unlike ruby laser, employs four level pumping scheme. The energy levels of the neodymium (the active material) is shown in Fig. 13.11. In order to keep the discussion simple, we have not used the spectroscopic notations for different energy levels in Fig. 13.11. Rather, energy levels have been marked E,, E_1, and so on. The optical pumping raises the Nd atoms in the ground state (E,) to a few excited states (E_7, E_8). The energy levels marked E_4 and E_1 are the lasing levels. The pumped atoms in the excited states undergo non-radiative transition to the upper lasing level, E_4. Out of the group of lower lasing levels, the major portion of energy is emitted in the transition

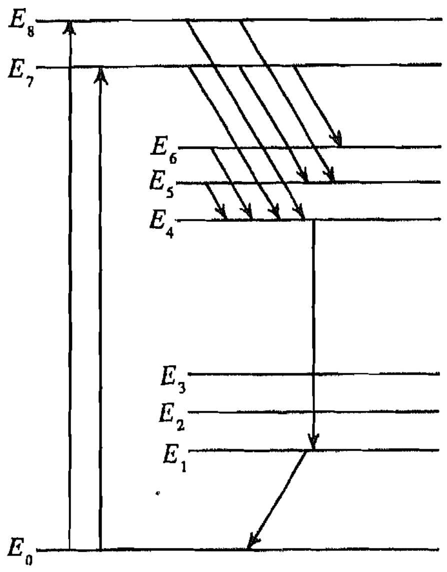


Fig. 13.11: Energy level diugrnm of Nd (neodymium) ion in Nd: YAC.

$E_4 \rightarrow E_1$. The Nd: YAG laser is an example of four-level laser.

This solid-state laser has two advantages: (a) it has a low excitation threshold and (b) has a high thermal conductivity. Due to high thermal conductivity, it can be used for generating light pulses at a high repetition rate or for continuous operation.

13.4.2 Liquid Lasers

In this class of lasers, as the name indicates, the active media are either the liquid solutions of organic dyes or specially prepared liquids doped with rare-earth ions viz Nd^{3+}. However, majority of liquid lasers use a solution of an organic dye as active medium and hence are also called organic **dye lasers.** Solvents used for the purpose are water, methanol, benzen, aceton etc. The liquid lasers are optically pumped. The energy states taking part in the lasing transition are the different vibrational energy states of different electronic energy states of the dye molecule. Since you may not be familiar with the vibrational energy states of molecules, we do not discuss the pumping scheme of this class of lasers.

In contrast to solids, liquid clo not crack or shatter and can be made in sizes almost unlimited. Another advantage of liquid lasers is due to their (that of organic dyes) wide obsorption bands in the visible and near ultravoilet portion of the electromagnetic spectrum. Therefore, liquid lasers are an ideal candidate for **tunable laser i.e.** the frequency and hence energy of the output laser beam can be selected with ease.

13.4.3 Gas Lasers

The attractive feature of gas lasers in which rarified gases are the active media, is that they can be designed to produce output beams over a wide range of wavelengths. Except for the cesium- vapour laser, gas lasers are pumped electrically rather than optically. Can you say **why?** It is because the condition for amplification by stimulated emission, at one wavelength or another, are satisfied by an electrical discharge through almost any gas. Another reason for employing electrical pumping for gas lasers is that, unlike solids and liquids, the absorption lines of active centres in gaseous media exhibit substantially narrow widths. Therefore, optical pumping would prove very inefficient for gas lasers because the pump radiation obtained from optical sources do not have line spectrum of very narrow lines. In other words, the energy of optical pump radiation has a considerable spread in its value and since the gaseous active media will absorb radiation of almost single energy, most of the pump energy will go waste. Hence, optical pumping is not used for gas lasers. Further, gas lasers have advantage over solid state and liquid lasers in that they are free from local irregularities. Most gaseous systems have a high degree of optical perfection simply because the density of the gas is uniform.

We will now briefly describe a typical gas laser-the Helium-Neon gas laser. This was the first gas laser operated successfully.

The Helium-Neon Laser

In the helium-neon laser, a mixture of helium (He) and neon (Ne) gases is used as active medium. **Lasing levels are provided by the exited states of the Ne atoms,** whereas the He atoms play an important role in pumping Ne atoms to the excited states. The He-Nc

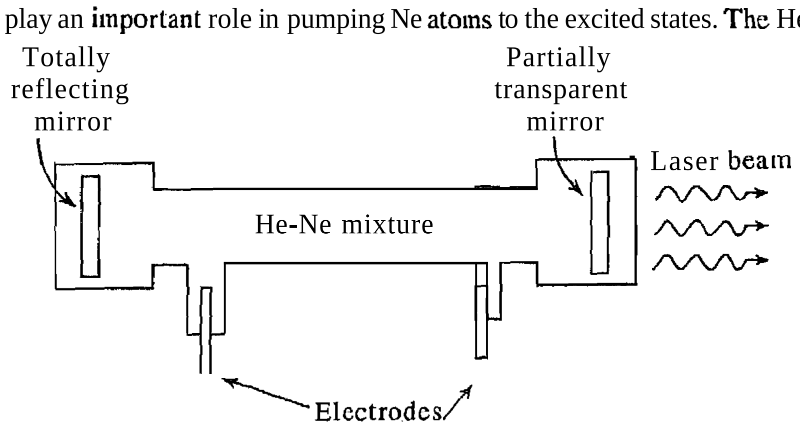


Fig.13.12: The He-Ne Laser

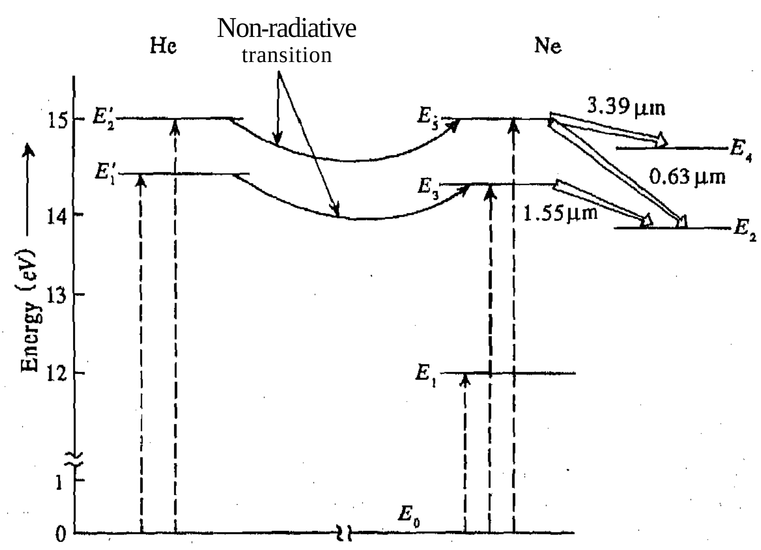


Fig.13.13: Energy level diagram of helium-neon laser. Arrows (⇒) indicate the lasing transition

laser is shown schematically in Fig. 13.12. The pumping is done by a stationary glow discharge fired by a direct current. When thc potential difference between the anode and cathode is about 1000V, a glow discharge is initiated in the working capillary (containing He-Ne mixture) of a few millimcter diameter.

Now, let us look at the pumping scheme of the He-Nc lascr. Refer to Fig. 13.13 which shows the energy level diagram of Hc-Ne laser. When free clcctrons produced during the gas discharge pass through the Me-Nc mixture, they collide with the He and Ne atoms and excite them by impact energy transfer. Such absorptive transitions due to electron impacts are shown by dashed arrows in Fig. 13.13. These excited states of He (i. e. E_1' and E_2') are metastable. Thus, He-atoms excited to these states stay there for a long time before losing energy by collision. The interesting feature of the Hc-Ne energy diagram is that the excited states of Ne, namely E_3 and E_5 have approximately same energy as that of E_1' and E_2' of He atom. Therefore, wlien Hc-atoms in E_1' and E_2' collide with Ne-atoms in ground state, thc He-atoms transfer their cncrgy to Ne-atoms and raise them to the states E_3 and E_5. Such an exchange of energy is known as **resonant collision energy transfer.** Due to this energy transfer, Hc-atoms fall back to ground state. As a result, tlie excited states E_3 and E_5 of Ne-atoms liavc a sizable population which is much more than that of states E_2 and E_4. Thus a condition of population inversion is achieved between tlic upper lasing levels E_5 (or E_3) and lower lasing levels $E_4(E_2)$. In such a situation, any spontaneously emitted photon can trigger laser action betwccn tliesc lcvels. The Nc atoms then drop clown Gom the lower lasing levels E_2 and E_4, to the level E_1 through spontaneous emission.

The wavelength of transition bctwccn lcvels $E_5 \rightarrow E_4, E_5 \rightarrow E_2, E_3 \rightarrow E_2$ are 3.39 μm, 0.63 μm and 1.55 μm respectively. As you can easily make out, radiations corresponding to 3.39 μm and 1.55 μm fall in tlic infrared rcgion of tlic clectromagnetic spectrum. The radiation corresponding to 0.63 μm, howcver, gives the red liglit - characteristic light of He-Ne laser. Proper selection of different frequcncics may bc made by choosing end mirrors of the resonant cavity wliicli has high reflectivity over only the desired wavelength range.

Before we conclude our discussion about typcs of lasers, you must know that apart Gom those mentioned above, there are many other typcs of gas lasers. Wc may particularly mention **molecular lasers** (carbon Jioxicle lascr), **chemical lasers, plasma lasers, semiconductor lasers,** etc. Wc liavc not discussed these here since for an understanding of their pumping schemes, you need to know molecular spectroscopy, semiconductor physics etc. It is, howcver, worth mentioning here that the essential principles, in so far as laser action is concerned, remain tlie same in all types of lasers.

The importance of lasers in contemporary physics lies in their so many and so varied applications. To give you a glimse of these we now discuss some of the important applications of lasers.

13.5 APPLICATIONS OF LASERS

Applications of any device essentially stern from its unique fcatures. What are the unique features of a lascr? First and the formost, laser light is highly cohcrcnt. This characteristic has cnablcd us to use lasers for data transmission and processing, precision measurements, photography (holography), etc. Secondly, lascr light has unprecedented brightness (cncrgy per unit area). Brightness of lascr light, a by-product of its coherence, can be many orders of magnitude greater than the brightest of the light produced by conventional sources. Further, laser beams arc highly directional.

In a typical laser, this directionality is limited only by the diffraction of the emerging beam by the laser aperture itself. The brightness and directionality of laser beam are exploited to produce targetted effects in materials. These applications include material working (such as heat treatment, welding, cutting, hole burning etc.), isotope seperation, medical diagnostics, etc. In the following, you will learn some of these applications of lasers.

13.5.1 Communication

You may be aware that in a typical communication system, information is communicated (between the transmitter and the receiver) through electromagnetic waves, which are known as carrier wave. These are modulated by the desired signal (the oscillations of the information proper). Normally the signal frequency is appreciably lower than the frequency of the carrier wave. Moreover, higher the carrier frequency, wider frequency range it can modulate. In other words, the capacity of a communication channel is proportional to the frequency of the carrier wave. The frequency in the centre of the visible spectrum is about 100,000 times greater than the frequency of 6 cm waves used in microwave-radio relay systems. Consequently, the theoretical information capacity of a typical light wave is about 100,000 times greater than that of a typical microwave.

Long distance communication systems rely on the principle of multiplexing-the simultaneous transmission of many different messages (information) over the same pathway. The ordinary human voice (conversation) requires a frequency band from 200 to 4000 Hz, a band 3800 Hz wide. A telephone call, therefore, can be transmitted on any band that is 3800 Hz wide. It can be carried by a coaxial cable in the frequency band between 1,000,200 and 1,004,000 Hz, in the MHz range, or a He-Ne laser beam (638.8 nm, 4.738×10^{14} Hz) in the frequency range between 473,800,000,000,200 and 473,800,000,004,000 Hz. You may note here that the telephone message requires about 0.4 percent of the available co-axial carrier frequency. **And,** the same telephone message requires less than one-billionth of 1 percent of the available laser-beam frequency. Thus, the information carrying capacity could be enhanced tremendously if laser beams are employed as carriers. So, wait for some more time till laser trunk lines come into use in a big way and you may be saved from listening ***"All the lines in this route are busy. Please dial after some time"!!***

Now you may ask: Light, as such, was available to us from time immemorial, then why is it that we are using (or planning to use!) it for communication purposes now? Is it related to the discovery of a laser in any way? Yes, it is. As we mentioned earlier, light from conventional sources may not be pure (that is, it may be non-monochromatic) and hence cannot be used for transmitting signals. Radio waves from an electromagnetic oscillator are confined to fairly narrow region of electromagnetic spectrum (i.e. it has a well defined frequency). These radio waves are, therefore, free from "noise" (considerable spread in frequency values) and hence can be used for carrying a signal. In contrast, all conventional light sources are essentially 'noise' generators i.e. they simultaneously emit electromagnetic radiations of different frequencies and hence are not suitable as carrier waves. With the invention of lasers, however, the situation changed. As you know, the light produced by lasers is highly monochromatic and coherent which enable them to act as carrier waves in the communication systems.

Now, what is the medium through which laser beam travels while it carries information'? The signal carrying laser beams can be transmitted through free (unguided) space, and by light guides. Light guides in the form optical fibres have found wide use in optical communication. You will learn about the details of fibre optics in Unit 15 of this course.

13.5.2 Basic Research

The discovery of a laser gave birth Lo an entirely new branch of optics known as **nonlinear** optics. Even at ordinary laser intensities, transparent materials (which are usually nonconductors), respond in an unusual manner. You may recall, for example, that the dielectric constant of malerial depends on its nature as well as on the frequency of the light passing through it. But, it has been observed that when the ordinary light beam is replaced by a lascr beam, the dielectric constant also depends on the instantaneous magnitude of the electric field component of the laser beam. In other words, the response of a matcrial to high electric fields is non-linear. It is just one of the several non linear cffccts that a laser beam produces when it interacts with matter. In fact, almost all the laws of optics are modifiecl to some extent at high intensities produced by pulsed lasers.

Another important application of lasers in basic rcsearch and development is in the field of thermonuclear fusion. As you know, for effective fusion to take place, extremely high temperature ($\sim 10^8$K) must be maintained. In principle, such high temperatures can be achieved by powerful laser beams.

Yet another remarkable application of lasers is in isotope separation. You may recall that one of the basic requirements of harnessing nuclear cncrgy from uranium is to have 2-3% of uranium isotope (^{235}U) in the fuel. In natural uranium, however, the percentage of ^{235}U is only 0.7. (The major constituent of natural uranium is ^{238}U.) Therefore, to have fuel enriched in ^{235}U, we can use laser beams. Each of these isotopes absorbs radiation of different frequency. So when a lascr beam of particular frequency is passed through tlic mixture of ^{235}U and ^{238}U , the atoms of ^{235}U absorb the radiation and get excited. The cxcitcd atoms of the desired isotope arc further excited so that they get ionized. Once ionised, it can easily bc separated by applying a dc electric field. This is one of the several mcthocls of using laser beam for isotope scperation.

13.5.3 Medicine

A properly focussed laser beam, is an excellent tool for surgery. The advantage of lascr surgery is that it is bloodless since the bcam not only cuts, it also "welds" blood vessels. It has a high sterility as no contact of tissues with surgical tools takes place. Also, the laser surgery is painless and operations arc very fast. In fact there is not enough time for the patient to respond to the incision and sense pain. Laser beams are being widely used for performing eye and stone surgcry.

A word of caution. As such, any light can cause damage. Laser, in parlicular, can be highly damaging because it has spatial coherence, i.e., it can be focussed down to a high power densities. The **maximum permissible** exposure (MPE) is 0.0005 mJ cm''. For exposure time from 2×10^{-5} s to 10 s, the limit is MPE $= 1.8t^{3/4}$ mJ cm^{-2}.

13.5.4 Industry

Invention of lasers has made it possible to develop sophisticated tools of material working (such as drilling, welding, etc) processes used in industry. With appropriate choice of lasers, a laser beam can be focusscd into a light spot of diameter 10-100μm! Can you imagine this dimension-it will be smaller than the dot you mark with your pen on a piece of paper! Due lo this sharp focussing, a very high concentration of energy is available within a small spot on the surface of the material. For example, when a 1kW output of a continuous wave (cw) laser is focusscd a spot of 100μ m diameter, the resultant **irradiance** (intensity) will be 10 W cm . This makes laser an effective tool for drilling **very** fine hole through the materials.

Laser cutting, as compared to other cutting processes, offers several advantages **e.g.** possibility of fine and precise cuts, minimal amount of mechanical distortion and thermal damage introduced in the material being cut, chemical purity of the cutting process, etc. Laser cutting is extensively used in industry. For example, in high-tech garment factories, CO_2 laser capable of 100W of continuous output is used for cutting cloth. The laser cuts 1 m cloth in a second! And, laser cutting is also employed in the fabrication of spacecraft to cut the sheets of titanium, steel and aluminium. In cutting and most of the industrial applications, carbon-dioxide (CO_2) laser is **used.**

13.5.5 Environmental Measurements

You may be aware of the conventional technique of determining the concentration of various atmospheric pollutants such as gases (carbon monoxide, sulphur dioxide, oxides of nitrogen, etc) and a variety of material particles (dust, smoke, **flyash** etc). In this method, the nature and concentration of pollutants is determined by chemical analysis. The major deficiency of this method is that it does not provide real-time data. The technique developed with lasers for measuring the concentration of pollutants is essentially the 'remote-sensing' technique which does not require sample to be analysed in laboratory. Since it provides information about the change in atmospheric composition with time, it can serve well for monitoring the environmental pollution.

For determination of pollutants in the form of material particles, the technique is based on the scattering of light. The technique is known as LIDAR (light detection andranging) and its operations are similar to those of a radar. In brief, a pulsed laser is passed through the location under investigation and the back scattered light in detected by a photodetector. The time taken by the back scattered light to be detected gives information about the concentration of pollutant matter.

For the determination of gaseous pollutants, the basic principle involved is the, absorption of tight by the gaseous atoms or molecules. As different gas absorbs at different wavelengths, passing laser beams of different wavelengths provides information about the gaseous constituents of the environment.

13.5.6 Photography: Holography

The conventional photographic process, as you know, consists of recording an illuminated three-dimensional object or scene as a two-dimensional image on a photosensitive surface. The light reflected from the object is focussed on the photo sensitive surface by some kind of image forming device, **which** can be a complex series of lenses or simply a pin-hole in an opaque screen.

The coherent nature of the laser beam has brought **about** a **qualitatively** new method of photography without lens system, This new method, called holography, allows three-dimensional (tbat is, complete), pictures of a given object or a scene to be taken. Holography (also known as photography by wave-front reconstruction) does not, as such, record an image of the object being photographed; rather, it records the reflected light waves themselves. The photographic record so obtained is called hologram. The hologram bears no resemblence to the original object. It, however, contains - in a kind of optical code - all the information about the object that would be contained in an ordinary photograph. In addition, the hologram also contains **information** about the object that cannot be recorded by any other photographic process. Holography is the subject matter of the next unit (i.e. Unit 14).

13.6 SUMMARY

According to the Bohr's theory, if an atom makes a transition from an excited state (of energy E_i) to a state of lower energy E_f, emission of electromagnetic radiation (photons) take place. The energy of the emitted photon is

$$h\nu = E_i - E_f$$

When electromagnelic radiation interacts with matter, three type of processes may occur

(i) Spontaneous Emission

(ii) Absorption

(iii) Stimulated Emission

- Light emitted by ordinary sources is due to spontaneous emission,

  The existence of stimulated emission of radiation was predicted by Einstein on the basis of thermodynamic considerations. If the population of the energy level E_1 be N_1 and that of E_2 be N_2 $(E_1 < E_2)$, then, the ratio of the population of the two states is given as

$$\frac{N_2}{N_1} = \frac{B_{12}\,u(\nu)}{A_{21} + B_{21}\,u(\nu)}$$

  where, u (v) is energy density of radiation at frequency ν and B_{12}, B_{21} and A_{21} are Einstein co-efficients.

- Einstein coefficients are related to each other through the relations

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

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

- Einstein's relation clearly indicates that stimulated emission may dominate spontaneous emission provided the condition of population inversion exists. And in a atomic system where a condition of population inversion exists, one may have amplification of light, that is, laser light.
- Einstein's prediction was first realised in the optical frequency range by Maiman who developed a laser using a ruby rod.
- There are three prerequisits for laser operation:

(i) Active medium

(ii) Pumping

(iii) Optical resonant: cavity

- The change in intensity of a light beam passing through an active medium is given by

$$\frac{\partial I_\nu}{\partial x} = - I_\nu \frac{h\nu n}{c}(N_1 - N_2)B$$

where n is refractive index

B is Einstein's coefficient.

This relation clearly indicates that for enhancement in the intensity of the light beam as it traverses the active medium, $N_2 > N_1$, **i.e.** a condition of population inversion must exist.

There are variety of methods for pumping, such as, optical pumping, electronic discharge, inelastic atomic collisions etc, The choice of pumping process mainly depends upon the nature of the active medium.

- There are two types of pumping **schemes:three** level and four-level.

Optical resonant cavity helps in obtaining sustained laser light.

13.7 TERMINAL QUESTIONS

1. Assume that an atom has two energy levels seperated by an energy corresponding to a frequency 4.7×10^{14} Hz, as in the He-Ne laser. Let us assume that all the atoms are located in one or the other of these two states. Calculate the fraction of atoms in the upper state at room temperature T = 300K.

2. A pulsed laser used for welding produces **100** W of power during 10 m. Calculate the energy delivered to the weld.

13.8 SOLUTIONS AND ANSWERS

SAQs

1. The ratio of the number of spontaneous to stimulated **emission** is given as

$$\frac{A_{21}}{B_{21}\,u(\nu)} = e^{h\nu/k_B T} - 1$$

The absolute temperature of an ordinary source of light has been given as

$$T = 10^3 K$$

Let us take the wavelength of **light,** λ = **6000** Å. Hence the corresponding frequency,

$$\nu = \frac{c}{\lambda} = \frac{3 \times 10^8 \text{ ms}^{-1}}{6000 \times 10^{-10} \text{ m}} = 0.5 \times 10^{15} \text{ Hz}$$

Planck's constant $h = 6.6 \times 10^{-34}$ J s

Boltzmann constant $k_B = 1.38 \times 10^{-23}$ JK^{-1}

Hence,

$$\frac{A_{21}}{B_{21}\,u(\nu)} = \left[\frac{6.6 \times 10^{-34} (\text{J.s}) \times 0.5 \times 10^{15} (\text{s}^{-1})}{1.38 \times 10^{-23} (\text{JK}^{-1}) \times 10^3 (\text{K})}\right] - 1$$

$$= \exp[23] - 1$$

$$= 10^{10}$$

Thus, for ordinary sources of light, the number of spontaneous emission is much, **much** greater than the number of stimulated emission.

2. Let the energy of the excited state (upper lasing state) be E_2 and that of the ground state (lower lasing state) be E_1. The laser light is due to the atomic transitions from E_2 to E_1. Thus, the frequency of the laser light will be

$$\nu = \frac{E_2 - E_1}{h}$$

Now, as per the given problem,

$$E_2 = ?\ E_1 = 0 \text{ and } \lambda = 693\text{nm} = 693 \times 10^{-9}\text{m}$$

Hence,

$$\nu = \frac{c}{\lambda} = \frac{3 \times 10^8 (\text{m/s})}{693 \times 10^{-9} (\text{m})} = 3.1 \times 10^{14} \text{s}^{-1}$$

$$E_2 - E_1 = h\nu$$

$$E_2 = 6.6 \times 10^{-34} (\text{J.s}) \times 3.1 \times 10^{14} (\text{s}^{-1})$$

$$= 20.46 \times 10^{-20}\text{J}$$

$$= 12.77 \text{ eV}$$

TQs

1. Let the two energy levels bc E_1 and E_2 (such that $E_1 < E_2$) and their population be N_1 and N_2 respectively. According to the Boltzmann distribution

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

.We know that

$$(E_2 - E_1) = h\nu$$

$$= 6.62 \times 10^{-34} (\text{J.s}) \times 4.7 \times 10^{14} (\text{s}^{-1})$$

$$= 31{,}114 \times 10^{-20}\text{J}$$

and

$$k_B T = 1.38 \times 10^{-23} (\text{J/K}) \times 300 (\text{K})$$

$$= 4.14 \times 10^{-21}\text{J}$$

Hence,

$$\frac{N_2}{N_1} = e^{-h\nu/k_B T}$$

$$= e^{-\left[\frac{31.114 \times 10^{-20}}{4.14 \times 10^{-21}}\right]}$$

$$= e^{-(75.1)}$$

$$= 2.29$$

2. Power = Energy per unit time

$$= \frac{\text{Energy}}{\text{Time}}$$

Given, Power = 100W = 100 (J/s)

Time = 10ms = 10 x 10^{-3} (s)

$\therefore$ Energy = Power × Time

= 100 (J/s) x 10 x 10^{-3} (s)

= 1J.

$\therefore$ Energy delivered to the weld is 1 joule.