LASER

3.1 INTRODUCTION:

Laser is one of the outstanding inventions of the 20th century. Laser is photonic device, which is actually responsible for the resurgence of interest in optical technology and for the birth of a new field, namely Photonics.

The world 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.

Lasers are essentially coherent optical sources. It was as early as in 1917 that Einstein first predicted the existence of two different kinds of processes by which an atom can emit radiation. These are called **spontaneous and stimulated** emission. The fact that stimulated emission process could be used in the construction of coherent optical sources was first put forward by Townes and Schawlov in the USA and Bosov and Prokhorov in the USSR. Maimam demonstrated the first working Laser in 1960.

Laser differs vastly from the traditional light sources. It is not used for illumination purpose as we use other light sources. Laser produces a highly directional coherent monochromatic light beam. Laser is most sought after tool in metal working, entertainment electronics, optical communications, bloodless surgery, weapon guidance in wars and in a wide variety of other fields.

3.2 BASIC CONCEPTS OF LASER:

Some of the basic concepts associated with the laser are discussed in this section. These include concepts such as spontaneous emission, stimulated emission, absorption, population inversion and pumping.

3.2.1 Spontaneous Emission:

Let us consider two energy levels 1 and 2 of some given atom, its energy being E_1 and E_2 (Fig. 3.1(a)). For convenience level 1 is taken to be the ground level. Let us now assume that the atom is initially in level 2. Since $E_2 > E_1$, the atom will tend to decay on its own to level 1. The corresponding energy difference $(E_2 - E_1)$ must therefore be released by the atom. When this energy is delivered in the form of an electromagnetic wave or photon, the process is called **spontaneous emission.** The frequency υ of the radiated wave is then given by the expression.

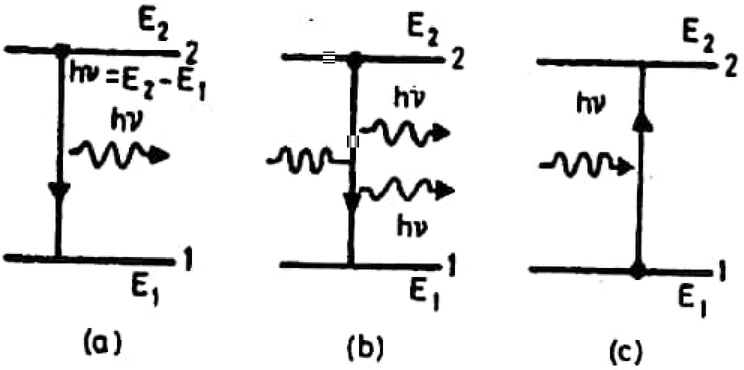

Fig. 3.1(a,b,c)

$$\upsilon = \frac{E_2 - E_1}{h} \quad \text{-----------------(1)}$$

Where h is the Planck's constant. Note that radiative emission is just one of the two possible ways for the atom to decay. The decay can also occur in a non-radiative way for some levels. In this case the energy difference $E_2 - E_1$ is delivered in some form other than electromagnetic radiation (e.g., it may go into kinetic energy of the surrounding molecules).

3.2.2 Stimulated Emission:

Let us again suppose that the atom is found initially in level 2 and that an electromagnetic wave of frequency v given by equation (1) is incident on the atom (Fig. 3.1a). Since this wave has the same frequency as the atomic frequency, there is a finite probability that this wave will force the atom to undergo the transaction 2 → 1. In this case the energy difference $E_2 - E_1$ is delivered in the form of an electromagnetic wave which adds to the incident one. This is the phenomenon of **stimulated emission.**

There is, however, a fundamental distinction between the spontaneous and stimulated emission processes. In the case of spontaneous emission, the atom emits an electromagnetic wave which has no definite phase or directional relation with that emitted by another atom. In the case of stimulated emission, since the process is forced by the incident electromagnetic wave, the emitted light by the atom is in phase with that of the incident electromagnetic wave. The emitted wave is also in the same direction as that of the incident wave. The concept of stimulated emission was first put forward by A. Einstein in 1917.

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3.2.3 Absorption:

Let us now assume that the atom is initially lying in level 1 (Fig. 3.1.(c)). If this is the ground level, the atom will remain in this level unless some external stimuli is applied to it. We shall assume then that an electromagnetic wave of frequency ν (given by equation (1)) is incident on the material. The energy difference $E_2 - E_1$ required by the atom to undergo the transition is obtained from the energy of the incident electromagnetic wave. This is called **absorption.**

3.2.4 Population Inversion:

Let us consider the number of atoms N, per unit volume, that exist in a given energy state E. This number, called population N is given by Boltzmann's equation

$$N = N_0 e^{\frac{E}{k_B T}}$$

Here No is the population in the ground state. (E = 0), k_B is the Boltzmann's constant and T the absolute temperature.

It is clear from the above equation that population is maximum in the ground state and decreases exponentially as one goes to higher energy states. If N_1 and N_2 are the populations in two states, a lower state E_1 and a higher state E_2 we have

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

from which it follows that

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

clearly $N_2 < N_1$ since $E_2 > E_1$. Since $N_1 > N_2$, whenever an electromagnetic wave is incident, there is net absorption of the radiation.

For laser action to take place, it is absolutely necessary that stimulated emission predominate over spontaneous emission. This is possible only if $N_2 > N_1$ (i.e., the upper levels are more populated than the lower levels). This situation in which $N_2 > N_1$ is called **population inversion.**

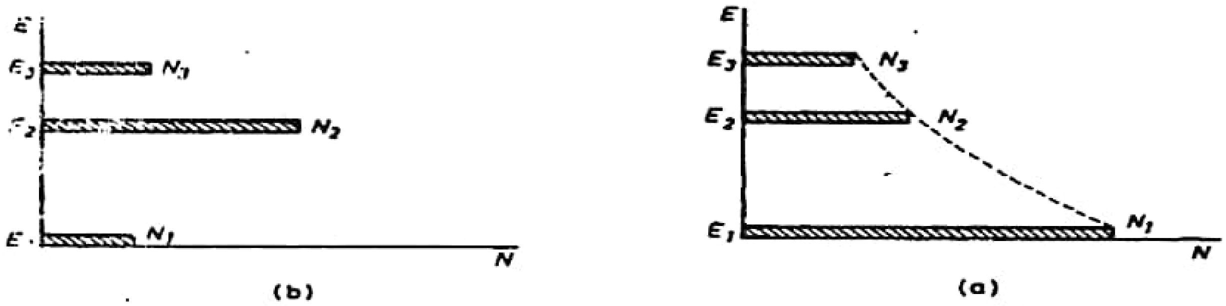


Fig. 3.2

The concept of population inversion can be best illustrated if we consider a system that has three energy states (a-three level system). These states may be designated as E_1, E_2 and E_3. When the system is in equilibrium the upper most state E_3 is populated least and the lowest state E_1 is populated most (Fig. 3.2(a)). the curve shows a Boltzmann distribution. Since the population in the various states is such that $N_3 < N_2 < N_1$, the system is absorptive rather than emissive. But on excitation by outside energy, it is possible that N_2 exceeds N_1 (this is possible if E_2 happens to be a metastable state i.e., an energy state with a long life time and the transition probability between levels 3 and 2 is very high). Thus population inversion is achieved and is shown in Fig. 3.2b.

3.2.5 Pumping:

For achieving and maintaining the condition of population inversion, we have to raise continuously the atoms in the lower energy 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.

These are number of techniques for pumping a collection of atoms to an inverted state. Those are

1. Optical pumping
2. Electrical discharge
3. Direct conversion.

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 laser.

In **Electrical discharge** method, the electric field causes ionization of the medium and raises it to the excited state.

In Semiconductor diode laser, a **direct conversion** of electrical energy in to light energy takes place.

3.3 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.

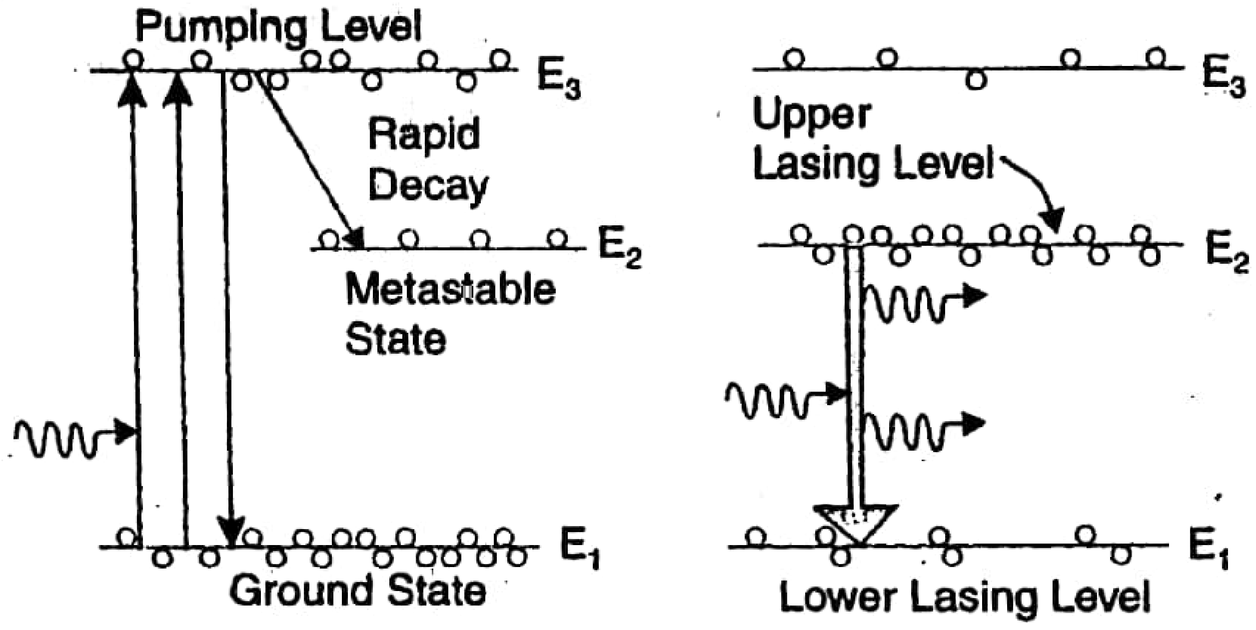
There could be no **population inversion** and hence no laser action, if metastable states do not exists.

3.4 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.

3.4.1 Three LEVEL Pumping Scheme :

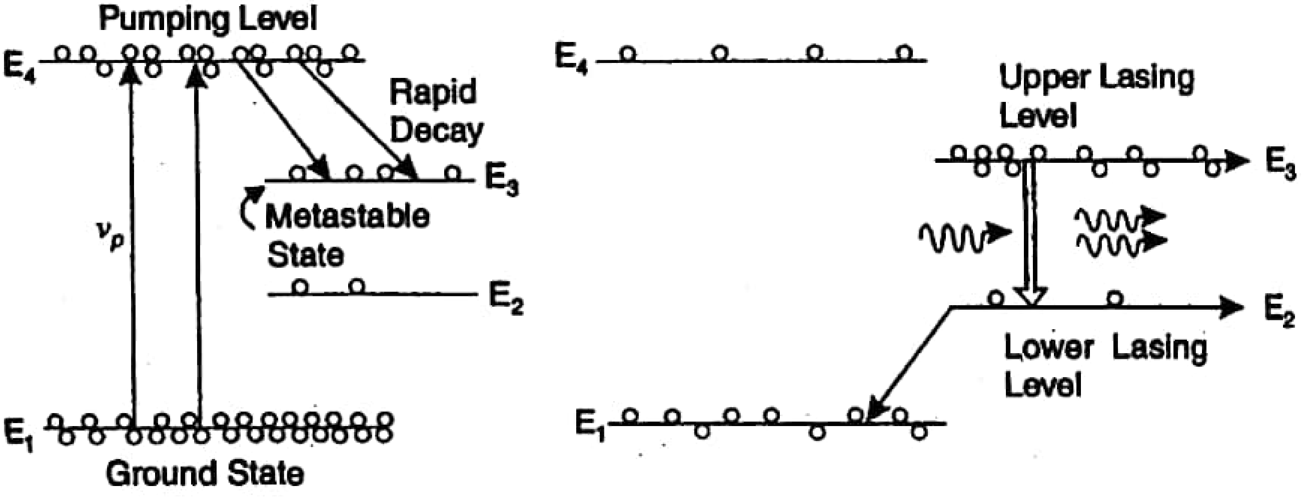
A typical three-level pumping scheme is shown in Fig. 3.3. The state E_1 is the ground level; E_3 is the pump level and E_2 is the metastable upper lasing level. When the medium is exposed to pump frequency radiation, a large number of atoms will be excited to E_3 level. However, they do not stay at 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.



(a) Fig. 3.3 (b)

3.4.2 Four-Level Pumping Scheme :

A typical four-level pumping scheme is shown in Fig. 3.4. 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 ν_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.



(a) Fig. 3.4 (b)

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 from E_1 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 under go non-radiative transitions to the ground level E_1 and will be once again available for excitation.

3.4.3 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 reestablished. 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.

3.5 TYPES OF LASERS:

There are several ways in which we can classify lasers in to 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 and few subcategories as mentioned below

1. Solid State Laser
    - Ruby laser
    - Nd : YAG laser
2. Gas Laser
    - He-Ne laser
    - CO2 laser
3. Liquid Dye Lasers
4. Solid State Diode Laser or Semiconductor Diode Laser.

Among all the various types of lasers, few out of them are discussed below of our interest.

3.5.1 RUBY LASER:

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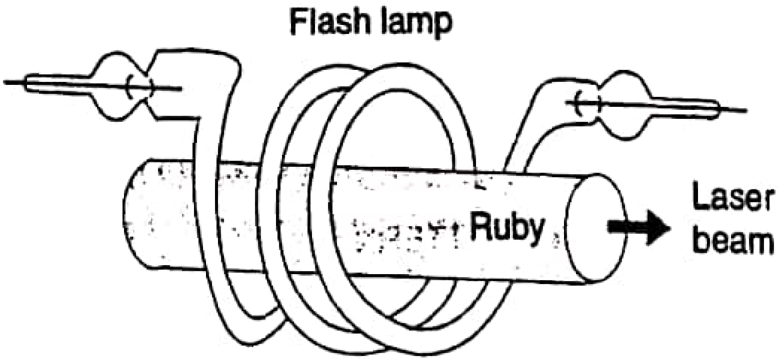
3.5.1.1 Introduction:

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.**



Schematic of a ruby laser.

Fig. 3.5

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.

3.5.1.2 Construction:

The schematic of a ruby laser is shown in Fig. 3.5. 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 grounded and polished such that the end faces are exactly parallel and are also perpendicular 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.

3.5.1.3 Working:

Ruby laser uses a three-level pumping scheme. The energy levels of Cr^{3+} ions in the crystal lattice are shown in Fig. 3.6. There are two wide energy bands E_3 and E'_3 and a pair of closely spaced levels at E_2. When the flash lamp is activated, the xenon discharge generates an intense burst of white light lasting for a few milliseconds. The

Cr^{3+} ions are excited to the energy bands E_3 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 Cr^{3+} ions rapidly lose some of the energy to the crystal lattice and undergo non-radiative transitions. They quickly drop to the levels E_2. The pair of levels at E_2 are metastable states having a lifetime of approximately 1000 times more than the lifetime of E_3 level. Therefore, Cr^{3+} ions accumulate at E_2 level. When more than half of the Cr^{3+} ion population accumulates at E_2 level, the state of population inversion is established between E_2 and E_1 levels. A chance photon emitted spontaneously by a Cr^{3+} ion initiates a chain of stimulated emissions by other Cr^{3+} ions in the metastable state. Red photons of wavelength 6943 Å traveling 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.

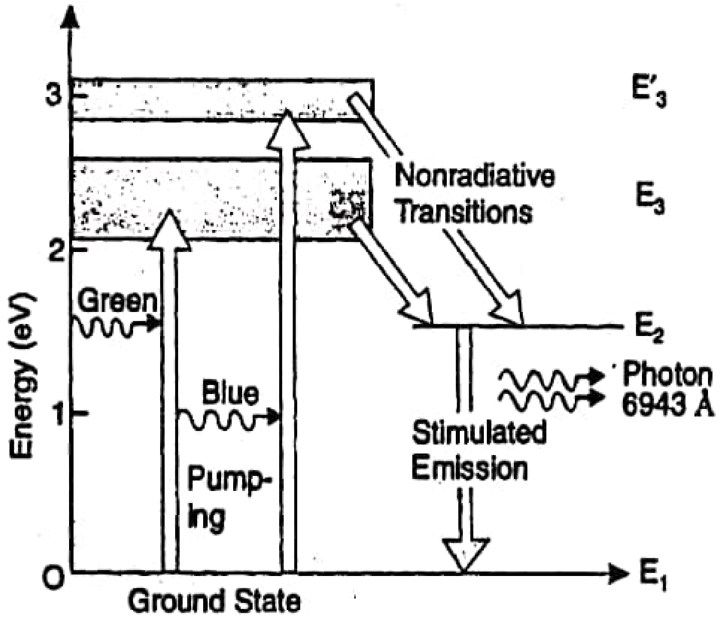


Fig. 3.6

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 $\lambda = 6943$ Å, 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.