and density is 1.977kg/m^3.
Hint: $3.24 \times 10^{-40} Fm^2$

4. A water molecule has a dipole moment of $6.2 \times 10^{-30} Cm$. What is the polarization of a water drop of 0.1cm radius polarized in the same direction.
Hint: $2.64 \times 10^{-9} C/m^2$

Chapter 5

Lasers

Laser is an optical device that amplifies light. The word 'LASER' is the acronym for *Light Amplification by Stimulated Emission of Radiation*. It is an optical device to produce a strong, monochromatic, collimated and highly coherent beam of light.

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. T.H. Maiman built the first laser device using ruby as the active medium in 1960. In 1961, A. Javan and his associates developed the first gas laser, the He-Ne laser. Laser is a high technology device and is the most sought after tool in a wide variety of fields such as metal working, entertainment, communications, surgery in ophthalmology and weapon guidance in wars.

5.1 Characteristics of A Laser Beam

Light from a laser differs from light from conventional sources in a number of ways. The most striking features of a laser beam are:

- *Directionality:* Lasers emit light only in one direction. Because of high directionality, it is possible to focus laser beam to a fine spot.

- *High Intensity:* As laser beam is highly directional, its entire energy is concentrated in a narrow region and therefore its intensity is very high.

- *Highly Monochromatic:* Laser light rays from a laser source have same frequency, same amplitude , same phase and same wavelength and hence has one colour.

- *High Degree of Coherence:* The laser beam is coherent, with the waves of all exactly in phase with one another.
  Two or more light waves with same wavelength, same amplitude, same phase or same phase relationship are said to be coherent.

5.2 Interaction of Radiation With Matter

A material medium is composed of identical atoms or molecules having a set of discrete allowed energy levels. An atom can move from one energy state to another when it receives or release an amount of energy equal to the difference in energy between the two states.

Let us consider two energy states E_1 and E_2 of an atom. Here E_1 is the lower energy state while E_2 is the excited energy state. As the constituent atoms of the medium are identical, majority of them occupy the energy level E_1 and the others the energy level E_2.

The number of atoms per unit volume at an energy level is called the *population density*. Let the populations at the two energy levels E_1 and E_2 be N_1 and N_2 respectively. Under normal conditions, higher the energy, lesser is its population. Hence $N_1 > N_2$

Let a monochromatic radiation of frequency ν be incident on the medium. The radiation may be viewed as a stream of photons, each photon carrying an energy E = $h\nu$ = $E_2 - E_1$, where h is Planck's constant. When photons travel through the medium, they are likely to cause three distinct processes. They are

1. Stimulated absorption

2. Spontaneous emission

3. Stimulated emission

5.2.1 Stimulated Absorption

Suppose an atom is in the lower energy level E_1. If a photon of energy $E_2 - E_1$ is incident on the atom, it imparts its energy to the atom and disappears. Then the atom absorbs this photon of energy and it jumps from its lower energy state E_1 to the excited energy state E_2 as shown in figure 5.1. Here the frequency of the photon is given as

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

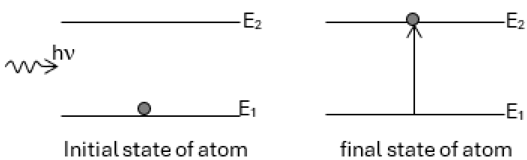

Figure 5.1: Process of Absorption of photons

According to Einstein, induced absorption rate $\frac{dN_1}{dt}$ is proportional to (i) ρ is the density of incident photon, (ii) N_1 is the number of atoms per unit volume in lower energy level E_1. Then

$$\frac{dN_1}{dt} \propto \rho N_1$$

$$\frac{dN_1}{dt} = B_{12} N_1 \rho$$

Here B_{12} is the proportionality constant and is known as *Einstein's coefficients for induced absorption.*

The atoms will be unstable in the excited level. They remain in the excited level for a very short time of the order of 10^{-8}s, after which they will fall back to the ground level. The average time Δt for which an atom remains in an excited level is known as mean life time of that level. With the de-excitation transition, the difference in the energy E = $h\nu$ = $E_2 - E_1$will be given out. There are two distinct ways by which an excited atom can make radiative transitions namely spontaneous emission process and stimulated emission process.

5.2.2 Spontaneous Emission

The emission of photons by the natural de-excitation transition of atoms, molecules, ions etc is known as *spontaneous emission* process. This is an uncontrolled and natural phenomenon in which each excited atom emit photons independently in random direction and phase.The emission of photon occurs on its own without any external trigger given to the excited atom and is shown in the figure 5.2. A beam of light made up of billions of such photons will be highly disordered and hence will be incoherent.

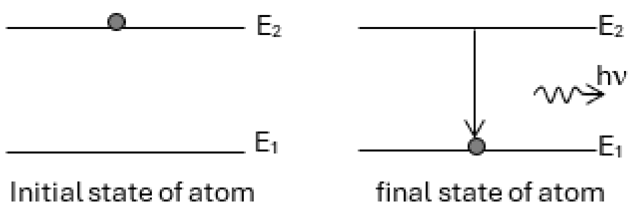

Figure 5.2: Process of Spontaneous emission of photons

According to Einstein, rate of spontaneous emission $\frac{dN_2}{dt}$ is proportional to N_2 - number of atoms in higher energy level E_2.
So,

$$\frac{dN_2}{dt} \propto N_2$$

$$\frac{dN_2}{dt} = A_{21}N_2$$

where A_{21} is the *Einstein's coefficient for Spontaneous emission*.

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

5.2.3 Stimulated Emission

In 1916, Einstein showed the existence of equilibrium between matter and radiation required a new radiation process called stimulated radiation. It requires the presence of external radiation.

If an atom in the excited state interacts with a photon with energy $h\nu = E_2 - E_1$, the photon induces the excited atom to make a downward transition well before the atom can make a spontaneous transition. The atom emits the excess energy in the form of a photon $h\nu = E_2 - E_1$ as it drops to a lower energy state. The passing photon is not affected while the excited atom also emits a photon as shown in figure 5.3.

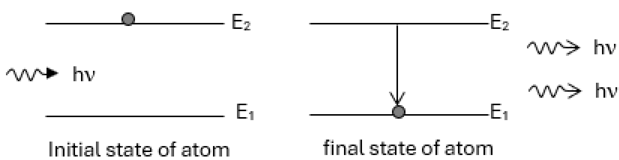

Figure 5.3: Process of Stimulated emission of photons

Hence two photons one original and other emitted move together. This is stimulated emission of radiation. The direction of propagation, phase and energy of the emitted photon is exactly same as that of the incident stimulating photon. So a enhanced beam of coherent light is obtained. This phenomenon of forced photon emission by an excited atom due to the action of an external agency is called *Stimulated emission*.

According to Einstein, rate of stimulated emission $\frac{dN}{dt}$ is proportional to (i) ρ density of incident photon, (ii) N_2 - number of atoms in higher energy level E_2.
So,

$$\frac{dN}{dt} \propto \rho N_2$$

$$\frac{dN}{dt} = B_{21} N_2 \rho$$

where B_{21} is the *Einstein's coefficient for Stimulated emission.*

SL.No	**Spontaneous Emission**	**Stimulated Emission**
1	The atom in the excited state returns to the ground state thereby emitting a photon without any external inducement.	The atom in the excited state returns to the ground state thereby emitting two photons of same frequency and energy.
2	Emitted photons move in all directions and are random.	Emitted photons move in only one direction and are highly directional.
3	Photons are not in phase.	Photons are in phase.
4	Radiation is less intense and incoherent.	Radiation is highly intense and coherent
5	The probability of spontaneous emission depends only on the properties of the two energy levels between which the transition occurs.	The probability of stimulated emission depends on the properties of the two energy levels involved in the transition as well as on the energy density of incident radiation.

Table 5.1: Difference between Spontaneous Emission and Stimulated Emission

5.3 Conditions For Sustained Lasing

For laser action, the stimulated emission has to dominate over other processes. We know that

$$\frac{\text{Stimulated emission rate}}{\text{Spontaneous emission rate}} = \frac{B_{21}N_2\rho}{A_{21}N_2} = \frac{B_{21}\rho}{A_{21}}$$

Also,

$$\frac{\text{Stimulated emission rate}}{\text{Absorption rate}} = \frac{B_{21}N_2}{B_{12}N_1}\rho$$

Thus, to make stimulated emission dominant requires:

- *Large ratio of B_{21} and A_{21}* - The large value of B_{21}/A_{21} helps stimulated emission to dominate over other processes. To increase the probability of stimulated emissions, the life time of atoms at the excited state should be made larger. This is achieved by choosing the upper level as a metastable level.

- N_2 *should be made larger than* N_1 - Under normal conditions, $N_1 > N_2$.

  The stimulated emission will dominate only when $N_2 > N_1$. It means that there should be more atoms present in the higher energy level than in the lower energy level. The condition $N_2 > N_1$ is termed as population inversion. This is achieved by pumping the atoms of ground state to upper state. The pumping can be done by various methods.

- *Large photon density (ρ)* - Stimulated emission will dominate the spontaneous emission if the radiation density (ρ) is very large. Thus the presence of large number of photons in the active medium is required. This is achieved by enclosing the emitted radiation in a cavity usually between two reflectors. The repeated motion of radiation between reflectors creates large radiation density (ρ).

5.3.1 Population Inversion

Consider an energy state E containing N atoms per unit volume.
This number N is called population and is given by Boltzmann's equation, $N = N_0 e^{-E/kT}$ where N_0 is the population of ground state with E = 0:
k is the Boltzmann's constant and T is the absolute temperature.
We know that the population is maximum in ground state and decreases exponentially as we go to a higher energy state.

If N_1 is population in energy state E_1,

$$\text{then} \qquad N_1 = N_0 e^{-E_1/kT}$$

and N_2 is population in energy state E_2,

$$\text{then} \qquad N_2 = N_0 e^{-E_2/kT}$$

$$\text{We have} \qquad \frac{N_2}{N_1} = \frac{e^{-E_2/kT}}{e^{-E_1/kT}}$$

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

Under thermal equilibrium condition, $N_1 >> N_2$
The stimulated emission dominates over spontaneous emission only when $N_2 > N_1$. If this happens, the state is called the population inversion.

Population inversion is the condition of the material in which population of the upper energy level N_2 is greater than the population of the lower energy level N_1. This state is a non-equilibrium state and it exists only for a short time. Population inversion is obtained by employing pumping techniques, which transfer large number of atoms from lower energy to higher energy level.

5.3.2 Metastable States

A *metastable state* in a laser is an excited energy level of an atom or molecule that has relatively long life-time. This means that the atom or molecule can remain in this state for a longer period of time compared to other excited states before decaying to a lower energy state.
Life time of meta stable state is 10^{-3}seconds. So the excited atoms can remain in a meta stable state for sufficiently long time and population inversion can be achieved. So the presence of meta stable state is essential to achieve population inversion.

5.3.3 Optical Resonant Cavity

High radiation density (ρ) is required to be present in the active medium for the stimulated emission to dominate spontaneous emission. If laser medium is enclosed in between a pair of optically plane parallel mirrors, photon density increases 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*.

5.4 Components of Laser

The essential components of a laser are (i) active medium; (ii) pumping source; (iii) an optical resonator.

Active Medium

Active medium is the medium in which the laser action takes place. In this medium, the atoms which when excited, reaches the state of population inversion and promotes stimulated emissions leading to light amplification.

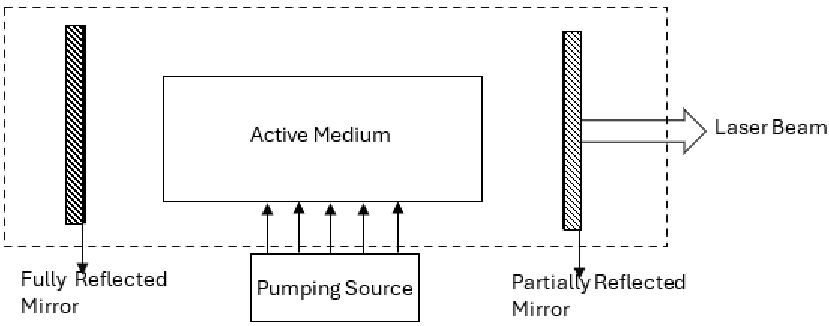

Figure 5.4: Main components of a Laser

Pumping

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 a method or technique of transferring atoms from lower energy level to higher energy level by supplying energy from an external source.

There are a number of pumping techniques like optical pumping, electrical discharge and direct conversion are some of the methods of pumping.

Optical resonator

It consists of two mirrors facing each other. The active medium is enclosed by this cavity. The mirrors could be either plane or curved. One of the mirrors is fully reflective while other mirror is partially transparent. This serves as an output element and let the laser out of the device.

Photons released spontaneously in a direction parallel to the optic axis of the resonator will travel within the active medium. During this travel, each spontaneous photon can trigger many stimulated transition along the direction of its propagation. In the presence of end mirrors, a specific direction is imposed on photons. Photons propagating along the optic axis of the pair of mirrors are retained whereas photons emitted in any other direction will pass out of the sides of the resonator and are lost.

A majority of photons travelling along the optic axis are reflected back on reaching the end mirror. They propagate towards the opposite mirror

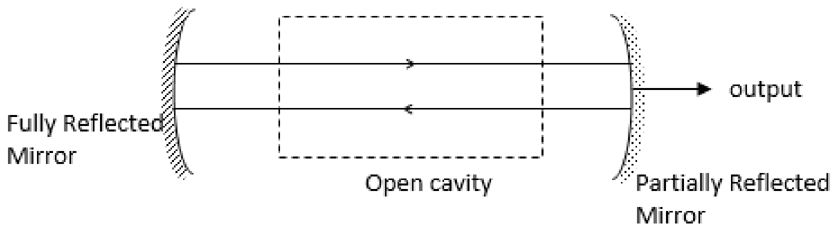

Figure 5.5: Optical Resonator

and on their way they stimulate more and more atoms and build up their strength. Thus by allowing the light beam to travel the same active medium several times, the amplification of light is occurred. At each reflection at the front end mirror, light is partially transmitted through it as laser output.

Thus optical resonator serve the important function of selecting the desired photon state for amplification and guide the radiation parallel to the axis of the resonator.

Thus both the stimulated emission process and the optical resonant cavity action give all the unique features of laser namely high degree of coherence, directionality, monochromaticity and high beam intensity.

5.5 Pumping

It is the method by which population inversion is achieved by supplying energy from an external source is known as pumping. Some of the commonly used methods for pumping are given below.

- *Optical pumping:* The method of achieving population inversion using light energy. In this type of pumping, the light energy usually comes form a light source in the form of short flashes of light. This method is used in solid state lasers like Ruby laser.

- *Electrical pumping:* When a potential difference is applied between cathode and anode in a discharge tube, the electrons emitted from cathode are accelerated towards anode. Some of these electrons collide with atoms of the active medium, ionise the medium and raise it to the higher level. This produces the required population inversion. This method is used in gas lasers.

- *Inelastic atom-atom collision:* Here, one type of atoms are raised to their excited state by an electric discharge. They collide inelastically with another type of atoms and achieve the necessary population inversion. Eg: He-Ne laser.
- *Direct Conversion:* In semiconductor lasers, a direct conversion of electrical to light energy takes place.
- *Chemical conversion:* Here pumping energy comes from chemical reactions. Eg: CO2 laser.

5.6 Principle of Laser

The principle of laser is based on three key phenomena: stimulated emission, population inversion, and optical resonance. These processes work together to generate a highly focused, coherent beam of light. The step by step process that takes place in laser action is as follows.

- *Step 1: Pumping:* Atoms in the ground state E_1 are pumped to excited state E_2 by supplying energy from an external source.
- *Step 2: Population inversion:* The life-time of atoms at the excited state is extremely small about (10^{-8}) seconds. Therefore, the atoms drop spontaneously from the excited state to the metastable state. As the life-time of atoms at the metastable state is comparitively longer (10^{-3}sec), the atoms go on accumulating at the metastable state. As soon as the number of atoms at the metastable state exceeds that of ground state, the medium goes into the state of population inversion.
- *Step 3: Spontaneous emission:* Some of the excited atoms at the metastable state may emit photons spontaneously in various directions. Each spontaneous photons can trigger many stimulated transitions along the direction of its propagation. The photons thus emitted also travel in different directions. The photons emitted in a direction other than the axial direction will pass through the sides of the medium and are lost forever.
- *Step 4: Amplification:* A majority of photons travelling along the axis cause stimulated emission and on reaching the end mirror, they are reflected back into the medium. As the photons emitted during stimulated emission are shuttled between these two mirrors, stimulated emission sharply increases and the amplification of light takes place.

- *Step 5: Oscillations:* The photons bounce between the mirrors of the optical resonator, passing through the active medium multiple times to amplify the light further.Ultimately, more coherent laser beam is produced.

5.7 Ruby Laser

Ruby laser belongs to the class of solid state laser. It was first fabricated by T.H. Maimann in 1960. It is a three level laser. Ruby is a transparent pink coloured precious stone of aluminium oxide (Al_2O_3) known as corundum doped with 0.05% of chromium ions (Cr^{3+}). The pink colour of ruby is due to the presence of chromium. Cr^{3+} replace Al^{3+} from corundum to form Cr_2O_3 (ruby), the active material.

Construction

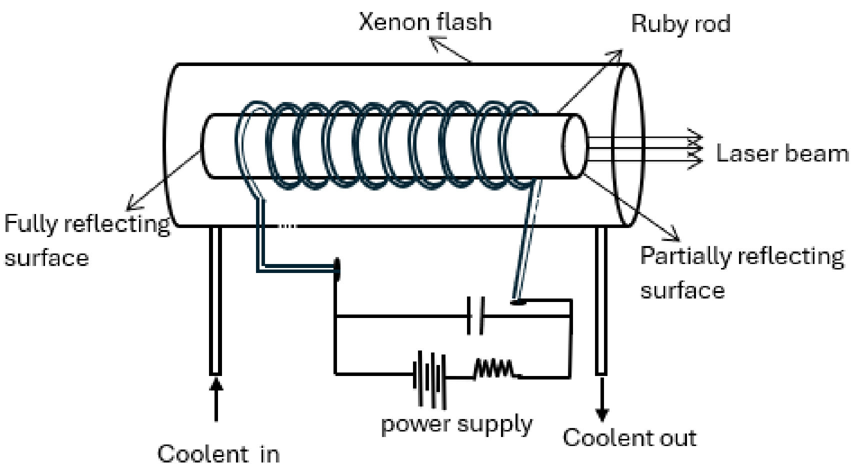

Figure 5.6: Schematic diagram of a Ruby laser

Active Medium: The ruby rod is taken in the form of a cylindrical rod of length about 10cm and diameter about 1cm. Chromium ions (Cr^{3+}) are the actual active centres while (Al_2O_3) act as the host material. Chromium

ions have absorption bands in the blue and green regions. *Optical resonator:* The two end faces of the ruby rod acts as optical resonator. One face is completely silvered and it act as a perfect reflector. The other face is partially silvered and it is a partial reflector.
Pumping Method: Optical pumping method is used here. The ruby rod is surrounded by helical Xenon flash lamp. Whenever activated by the power supply the lamp produces flashes of white light.
Cooling arrangement is provided to keep the Ruby rod cool.

Working

The energy level diagram of chromium in ruby crystal is given below.

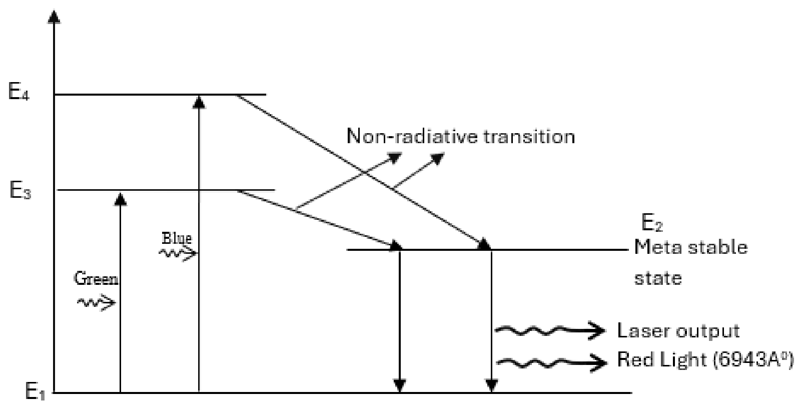

Figure 5.7: Energy level in Ruby laser

When Xenon flash tube is ON, the flash of light falls on the ruby rod, photons are absorbed by chromium ions in ground level. The chromium ions selectively absorb blue and green radiations and are excited to the level E_4 and E_3 respectively. Since the life time of E_4 and E_3 are too small $(10^{-8}$ s), they suddenly jump to meta stable state E_2 by non-radiative transition. The excess energy due to this transition is given out in the form of vibration of lattice atom.

Since the life time of meta stable state is 10^{-3} s, number of chromium ion gets increased and population inversion is achieved. Once population inversion is achieved, spontaneous emission starts.

The spontaneously emitted photons in the system, stimulate the laser action. Large number of photons are emitted by stimulated emission from meta stable state to ground state E_1.

These photons are shuttled between two end faces of the rod which induces further emission of photons. This process is repeated again and again and through the partially reflecting end, a highly coherent, intense, monochromatic and directional red beam of light emerges. This is Ruby laser. Its wavelength is 6943Å.

The moment the Xenon flash tube is OFF, the lasing action stops. The operation starts again when flash tube is again ON.

The light beam from the ruby laser is spiky and irregular. this is primarily due to fast build up of lasing oscillations within the resonance cavity and consequent depletion of population in the upper lasing level. After one set of lasing oscillations, the lasing ceases for a short time, until the flash lamp replenishes the population in the lasing levels.

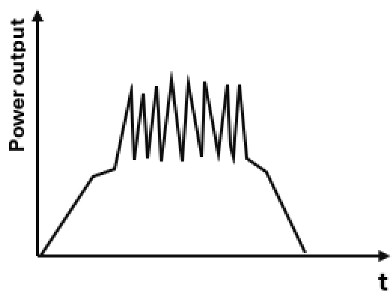

Figure 5.8: Ruby laser pulse

Ruby laser is used for recording holograms. It is used in industry for drilling and cutting materials. It is also used in laser weapons. It is also used in ophthalmic surgeries and for diagnosis.

5.8 Semiconductor Laser

A semiconductor laser is a heavily doped p-n junction device which emits coherent light in forward bias condition.

Semiconductor laser was invented in 1962 by R.N. Hall and his co-workers. Laser diodes are very popular for their compactness and operational efficiency. The fibre communication systems are realized because of the availability of laser diodes.

Construction:

A typical schematic diagram of a semiconductor laser diode is as shown in figure (5.9). The semiconductor laser diodes are made of direct band semiconductors like Gallium Arsenide. A junction is formed between p-type and n-type semiconductors.

The depletion region is the *active medium* in semiconductor laser. The thickness of depletion layer is very small about 1μm. Under the influence of forward biased electric field, conduction electrons will be injected from n-side into the junction area, while holes will enter junction area from p-side. Thus there will be recombination of holes and electrons in depletion region and hence this region becomes thinner. The direct conversion method is used as *pumping method*.

The two faces of semiconductor which are perpendicular to junction are polished which makes a *resonant cavity*.The other two opposite faces are roughened to prevent lasing action in that direction.

The top an bottom faces are metallised and ohmic contacts are provided to pass current through the diode.

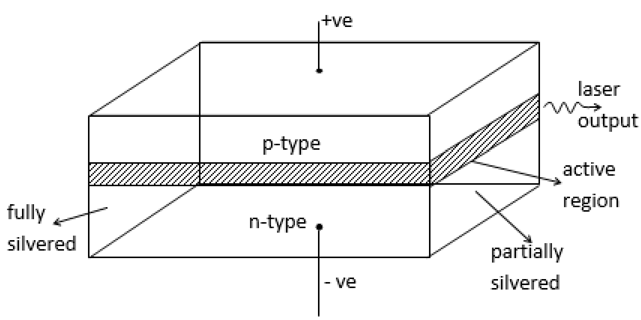

Figure 5.9: Schematic diagram of semiconductor laser

Working:

When no voltage is applied, the Fermi levels of p-type semiconductor and n-type semiconductor lies in the same horizontal line as shown in figure (5.10).

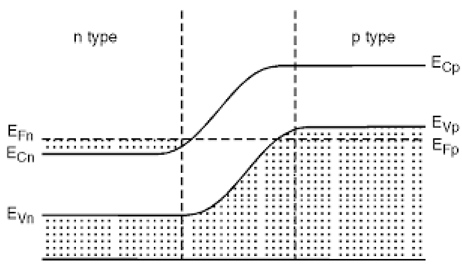

Figure 5.10: Energy level diagram of semiconductor laser with no biasing

When a forward bias voltage V is applied to the diode, the two Fermi levels become separated by an amount given by $\Delta E = eV$. The new distribution is as shown in figure (5.11).

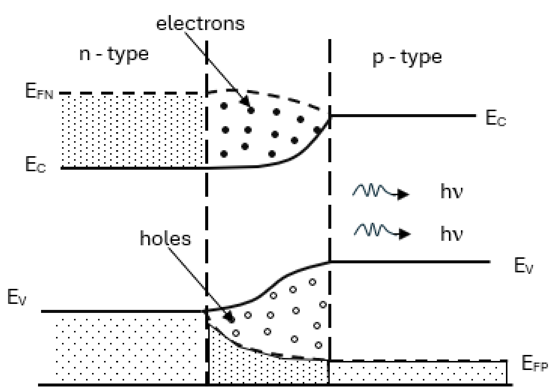

Figure 5.11: Energy level diagram of semiconductor laser with forward biasing

When p-n junction diode is forward biased, there will be injection of electrons into the conduction band along n-side and production of more holes in valence band along p-side into active region of the diode. Thus, there will be more number of electrons in conduction band compared to valence band, and hence population inversion is achieved.
The radiative emission occurs when an electron in the conduction band recombines with the hole in the valence band. The frequency of the emitted radiation has a frequency corresponding to the frequency of the band gap energy. In GaAs laser, the photons emitted have a wavelength 8200Å to 9000Å in IR region.

Applications:

Laser diodes are very popular for their compactness and operational efficiency. The fibre communication systems are realized because of the availability of laser diodes. Some of the applications of semiconductor lasers are given below.

- Used in CD players, laser discs etc.
- Used for laser printing, laser type setting, laser pointers.
- Used in fibre optic communications.
- Used in barcode scanners.
- Used in laser welding and laser cutting.
- Used in laser ranging systems to measure distances accurately.
- Used in lidar systems for remote sensing and mapping.
- Semiconductor lasers can be used for various surgical procedures, such as eye surgery and laser skin resurfacing. They are also used in diagnostic tools like flow cytometry and laser Doppler velocimetry.

5.9 Applications of Laser

Lasers find applications in almost every field like material processing, communication, medical diagnosis and treatment etc. The large intensity, its high directionality and coherence make laser an extremely useful tool for these variety of applications.

- *Medical Applications:* Laser is used in eye surgery, used to treat patients suffering from myopia. Laser is used to breakup gallstones and kidney stones.Lasers can be used to destroy cancerous cells.Laser is used for bloodless surgery. Laser is also used in endoscopy.

- *In Industry:* The energetic and highly collimated and intense beam of laser can be used for welding and cutting. Laser is used for drilling.

- *In Communication field:* Laser is used in fibre optic communication. They are used to transmit radio and television programs. Lasers can be used for establishing underwater communication between submarines.

- *In Computers:* Laser is used in computer printer, compact discs, optical memory cards etc.

- *In Defence:* Laser is used to find distance of targets.Laser is used to guide missiles. They can be used to destroy war planes.

- *In Holography:* Laser is used in 3D photography called holography.

5.10 Solved Numerical Problems

Example 5.10.1 Find how many photons are required per second to produce laser beam 3mW, when wavelength of laser light is 6943Å?
Solution

Power = $\frac{Nh\nu}{time}$ where N is the number of photons

$P = \frac{Nhc}{\lambda t}$ or $N = \frac{P\lambda}{hct}$

$$N = \frac{3 \times 10^{-3} \times 6943 \times 10^{-10}}{6.625 \times 10^{-34} \times 3 \times 10^{8} \times 1} = 1.048 \times 10^{16}$$

Example 5.10.2 Calculate the ratio of transition rates of spontaneous emission for length of wavelength 10^{-6}m and cavity temperature T = 100K and hence determine which type of emission will dominate?
Solution

The required ratio is

$$\frac{A_{21}}{B_{21}\rho} = [e^{h\nu/kT} - 1] = exp\left[\frac{hc}{\lambda kT}\right] - 1$$
$$= exp\left[\frac{6.625 \times 10^{-34} \times 3 \times 10^{8}}{10^{-6} \times 1.38 \times 10^{-23} \times 100}\right] - 1 = 13.40$$

Hence A_{21} » $B_{21}\rho$. Therefore, the spontaneous emission is more predominant in this case.

Example 5.10.3 The ratio of population of two energy states out of which upper one corresponds to a metastable state is 1.059×10^{-30}. Find the wavelength of light emitted at 330K.

Solution

Given $\frac{N_2}{N_1} = e^{-\Delta E/kT}$

We have $\frac{N_2}{N_1} = 1.059 \times 10^{-30}$ = $e^{-\Delta E/(1.38\times10^{-23}\times300)}$

$$ln(1.059 \times 10^{-30}) = \frac{-\Delta E}{1.38 \times 10^{-25} \times 300}$$
$$\Delta E = ln(1.059 \times 10^{-30}) \times 1.38 \times 10^{-25} \times 300$$
$$= 2.8427 \times 10^{-19}$$

We know $\Delta E = \frac{hc}{\lambda}$

$$\lambda = \frac{hc}{\Delta E}$$
$$\lambda = \frac{6.625 \times 10^{-34} \times 3 \times 10^{8}}{3.147 \times 10^{-19}}$$
$$= 632 \times 10^{-9}$$