7.1 INTRODUCTION

We know current can be amplified by vacuum tube or transistor amplifier. Similarly light waves can also be amplified and is termed as 'LASER' which is an acronym for "Light Amplification by Stimulated Emission of Radiation". After the discovery of laser by T.H.Maiman in 1960, a rigorous analysis were made, which lead to many types of lasers got due to the lasing action with atoms, ions, molecules etc., in gases, solids and liquids. The light beam from laser has frequency upto 10^{14} Hz leads to many applications in the scientific world and showed that the function of optics is alive.

7.2 CHARACTERISTICS OF LASER

Directionality : Ordinary light spreads in all directions and its angular spread is 1 metre/metre. But, it is found that laser is **highly directional** and its angular spread its 1 mm/metre. For example the laser beam can be focused to very long distance with a few divergence (or) angular spread.

Divergence (or) Angular spread is given by $(\phi) = \dfrac{r_2 - r_1}{d_2 - d_1}$ degrees.

Where d_1, d_2 are any two distances from the laser source emitted and r_1, r_2 are the radii of the beam spots at a distance d_1 and d_2 respectively as shown in fig.7.1.

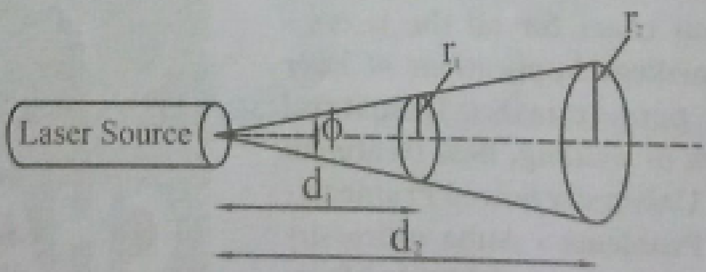


Fig. 7.1

Intensity : Since an ordinary light spreads in all directions, the intensity reaching the target is very less. But in the case of laser, due to high directionality the intensity of laser beam reaching the target is of **high intense beam.** For example, 1 milli watt power of He-Ne laser appears to be brighter than the sunlight.

Monochromatic : Laser beam is **highly monochromatic** (i.e) the wavelength is single, whereas in ordinary light like mercury vapour lamp, many wavelengths of light are emitted.

Coherence : It is an important characteristics of laser beam. In lasers the wave trains of same frequency are in phase (i.e) the radiation given out is in mutual agreement not only inphase but also in the direction of emission and polarization. Thus it is a **coherent beam**. Due to high coherence it results in an extremely high power.

Due to these peculiar properties of laser it has wide engineering and medical applications.

7.3 DIFFERENCES BETWEEN ORDINARY LIGHT AND LASER BEAM

S.No.	Ordinary Light	Laser beam
1.	In ordinary light the angular spread is more	In laser beam the angular spread is less.
2.	They are not directional	They are highly directional
3.	It is less intense	It is highly intense
4.	It is not a coherent beam and is not in phase	It is a coherent beam and is in phase.
5.	The radiations are polychromatic	The radiations are monochromatic
6.	Egs. Sunlight, Mercury vapour lamp etc.	Egs.He-Ne laser, CO_2 laser etc.

7.4 PRINCIPLE OF SPONTANEOUS AND STIMULATED EMISSION - EINSTEIN'S QUANTUM THEORY OF RADIATION

We know that, when light is absorbed by the atoms (or) molecules, then it goes from the lower energy level (E_1) to the higher energy level (E_2) and during the transition from higher energy level (E_2) to lower energy level (E_1), the light is emitted from the atoms (or) molecules.

Let us consider an atom exposed to (light) photons of energy $E_2 - E_1 = h\nu$, three distinct processes takes place.

(i) Absorption

(ii) Spontaneous emission and

(iii) Stimulated emission

Process (i) Absorption

An atom in the lower energy level (or) ground state energy level E_1 absorbs the incident photon radiation of energy ($h\nu$) and goes to the higher energy level (or) excited energy state E_2 as shown in Fig.7.2.

This process is called as absorption.

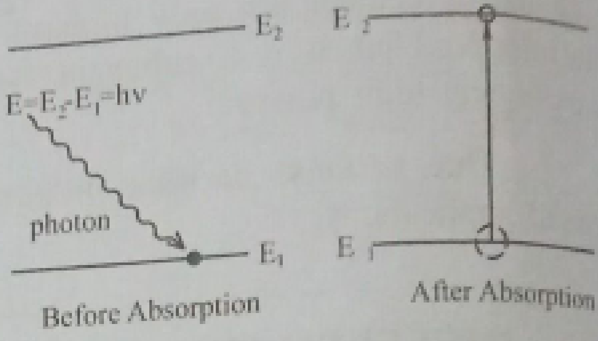


Fig. 7.2 **Absorption**

If there are many number of atoms in the ground state then each atom will absorb the energy from the incident photon and goes to the excited state then,

The **rate of absorption (R_{12})** is proportional to the following factors.

(i.e) $R_{12} \;\alpha$ Energy density of incident radiation (ρ_ν)

α No.of atoms in the ground state (N_1)

(i.e) $R_{12} \;\alpha\; \rho_\nu N_1$

(or) $$\boxed{R_{12} = B_{12}\,\rho_\nu N_1} \quad .....(1)$$

Where B_{12} is a constant which gives the probability of absorption transition per unit time.

> **NOTE:** *The subscript 12 represents the transition is from energy level E_1 to E_2. Similarly 21 represents the transition is from energy E_2 to E_1*

Normally, the atoms in the excited state will not stay there for a long time, rather it comes to ground state by emitting a photon of energy $E=h\nu$. Such an emission takes place by one of the following two methods.

Process (ii) Spontaneous emission

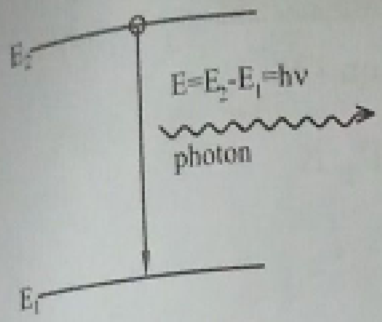


Fig. 7.3 **Spontaneous Emission**

The atom in the excited state returns to the ground state by emitting a photon of energy $E=(E_2-E_1) = h\nu$, spontaneously without any external triggering as shown in fig.7.3. This process is known as spontaneous emission. Such an emission is random and is independent of incident radiation. If N_1 and N_2 are the numbers of atoms in the ground state (E_1) and excited state (E_2) respectively, then

The rate of spontaneous emission is R_{21} (Sp) α N_2

(or) $$\boxed{R_{21}\,(Sp) = A_{21}N_2} \qquad \text{.........(2)}$$

Where A_{21} is a constant which gives the probability of spontaneous emission transitions per unit time.

Process (iii) Stimulated emission

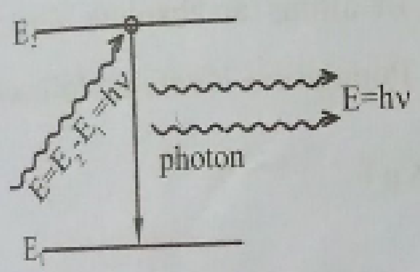


Fig.7.4 **Stimulated Emission**

The atom in the excited state can also return to the ground state by external triggering (or) inducement of photon thereby emitting a photon of energy equal to the energy of the incident photon, known as stimulated emission. Thus results in two photons of same energy, phase difference and of same directionality as shown in fig.7.4.

$\therefore$ The rate of stimulated emission is given by

$$R_{21}\,(St)\ \alpha\ \rho_V N_2$$

(or) $$\boxed{R_{21}\,(St) = B_{21}\rho_V N_2} \qquad \text{.........(3)}$$

where B_{21} is a constant which gives the probability of stimulated emission transitions per unit time.

Einstein's theory

Einstein's theory of absorption and emission of light by an atom is based on Planck's theory of radiation. Also under thermal equilibrium, the population of energy levels obey the Boltzmann's distribution law.

(i.e) under thermal equilibrium,

The rate of absorption = The rate of emission

(i.e) Eqn.(1) = Eqn.(2) + Eqn.(3)

$$B_{12}\rho_\nu N_1 = A_{21}N_2 + B_{21}\rho_\nu N_2$$

$$\rho_\nu [B_{12}N_1 - B_{21}N_2] = A_{21}N_2$$

$$\therefore \quad \rho_\nu = \frac{A_{21}N_2}{B_{12}N_1 - B_{21}N_2}$$

(or)

$$\rho_\nu = \frac{A_{21}}{B_{12}(N_1/N_2) - B_{21}} \qquad .....(4)$$

We know from Boltzmann distribution law

$$N_1 = N_o e^{-E_1/K_BT}$$

Similarly

$$N_2 = N_o e^{-E_2/K_BT}$$

Where K_B is the Boltzmann constant,
T is the absolute temperature and
N_0 is the number of atoms at absolute zero.

At equilibrium, we can write the ratio of Population levels as follows,

(i.e)

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

Since $E_2-E_1=h\nu$, we have

$$\frac{N_1}{N_2} = e^{h\nu/K_BT} \qquad .....(5)$$

Substituting eqn.(5) in eqn.(4) we have

$$\rho_\nu = \frac{A_{21}}{B_{12}(e^{h\nu/K_BT}) - B_{21}}$$

or

$$\rho_\nu = \frac{A_{21}}{B_{21}} \cdot \frac{1}{[(B_{12}/B_{21})e^{h\nu/K_BT} - 1]} \qquad ..(6)$$

This equation have a very good agreement with Planck's energy distribution radiation law.

(ie.) $$\rho_\nu = \frac{8\pi h\nu^3}{c^3} \cdot \frac{1}{e^{h\nu/K_BT} - 1} \qquad \text{..........(7)}$$

Therefore comparing equations (6) and (7), we can write

$$\boxed{B_{12} = B_{21} = B} \quad \text{and} \quad \boxed{\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}} \qquad \text{..........(8)}$$

Taking $A_{21} = A$

The constants A and B are called as Einstein Coefficients, which accounts for spontaneous and stimulated emission probabilities.

Ratio of magnitudes of stimulated and spontaneous emission rates

From equations (2) and (3) we have

$$\frac{R_{21}(St)}{R_{21}(Sp)} = \frac{B_{21}\,\rho_\nu\,N_2}{A_{21}\,N_2}$$

$$\frac{R_{21}(St)}{R_{21}(Sp)} = \frac{B_{21}}{A_{21}}\rho_\nu \qquad \text{..........(9)}$$

Rearranging eqn.(6), we can write

$$\frac{B_{21}}{A_{21}}\rho_\nu = \frac{1}{(B_{12}/B_{21})e^{h\nu/K_BT} - 1}$$

since $B_{12} = B_{21}$, we have

$$\boxed{\frac{1}{e^{h\nu/K_BT} - 1} = \frac{B_{21}}{A_{21}}\rho_\nu} \qquad \text{..........(10)}$$

Comparing eqn. (9) and eqn. (10) we get

$$\boxed{\frac{R_{21}(St)}{R_{21}(Sp)} = \frac{1}{e^{h\nu/K_BT} - 1} = \frac{B_{21}}{A_{21}}\rho_\nu}$$

In a simpler way the ratio can be written as

$$\boxed{R = \frac{B_{21}}{A_{21}}\rho_\nu}$$

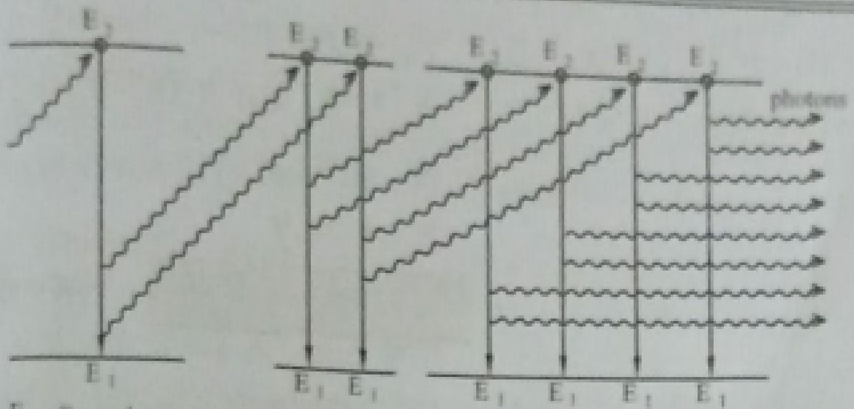
Generally spontaneous emission is more predominant in the optical region (ordinary light). To increase the number of coherent photons stimulated emission should dominate over spontaneous emission. To achieve this, an artificial condition called population inversion is necessary.

7.5 DIFFERENCES BETWEEN STIMULATED AND SPONTANEOUS EMISSION OF RADIATION

S.No.	Stimulated emission	Spontaneous emission
1.	An atom in the excited state is induced to return to ground state, thereby resulting in two photons of same frequency and energy is called stimulated emission.	The atom in the excited state returns to ground state thereby emitting a photon, without any external inducement is called spontaneous emission.
2.	The emitted photons move in same direction and is highly directional.	The emitted photons move in all directions and are random.
3.	The radiation is high intense, monochromatic and coherent.	The radiation is less intense and is incoherent.
4.	The photons are inphase (i.e.) there is a constant phase difference.	The photons are not in phase (ie.) there is no phase relationship between them.
5.	The rate of transition is given by $R_{21}(st) = B_{21} \rho_V N_2$	The rate of transition is given by $R_{21}(sp) = A_{21} N_2$

7.6 PRINCIPLE OF LASER ACTION

Let us consider many number of atoms in the excited state. We know the photons emitted during stimulated emission has same frequency, energy and are in phase as the incident photon. Thus results in 2 photons of similar properties. These two photons induce stimulated emission of 2 atoms in excited state thereby resulting in 4 photons. This 4 photons induce 4 more atoms and give rise to 8 photons etc., as shown in fig.7.5.



E_1 -Ground state energy

E_2 -Excited state energy

Fig. 7.5 Lasing Action

The interactive animation of this concept can be viewed in the CD.

Principle: *Due to stimulated emission the photons multiply in each step giving rise to an intense beam of photons that are coherent and moving in the same direction. Hence the **L**ight is **A**mplified by **S**timulated **E**mission of **R**adiation, termed as **LASER.***

7.7 POPULATION INVERSION

Consider two energy level system E_1 and E_2. Suppose a photon of energy equal to the energy difference between the two energy levels, incident on the system, then there is equal chances for stimulated emission and absorption to occur. At this situation, the chance for emission (or) the absorption depends only on the number of atoms in the ground state and in the excited state.

Let N_1 be the number of atoms in ground state and N_2 be the number of atoms in excited state. Then,

If $N_1 > N_2$ there is more chance for absorption to take place

and If $N_2 > N_1$ there is more chance for stimulated emission to take place.

Therefore, the number of atoms in the excited state should be increased by some means. *Thus the state of achieving more number of atoms in the excited state compared to the ground state atoms is called as population inversion.*

We know from Boltzmann's distribution law $\frac{N_1}{N_2} = e^{(E_2-E_1)/K_BT}$

Case (i) *If T is +ve* $N_1 = N_2 e^{+ve}$

For example, If $N_2 = 5$ and if $(E_2-E_1)/K_BT \approx 2$,

Then, $N_1 = 5 \cdot e^{+2}$

$N_1 = 36.9$

$\boxed{\therefore \quad N_1 > N_2}$ Since $36.9 > 5$

Case (ii) *If T is −ve* $N_1 = N_2\, e^{-ve}$

For example, If $N_2 = 5$ and if $(E_2-E_1)/K_BT \approx 2$,

$\therefore$ $N_1 = 5.e^{-2}$

$N_1 = 0.6766$

$\therefore$ $\boxed{N_2 > N_1}$ Since $5 > 0.6766$

This shows that the number of atoms in excited state can be made more than the number of atoms in the ground state only under negative temperature.

But, the negative temperature is practically not possible. Therefore population inversion can be achieved by some other artificial process known as **pumping process.**

Active medium: *The medium in which the population inversion takes place is called as active medium.*

Active centre: *The material in which the atoms are raised to excited state to achieve population inversion is called as active centre.*

7.8 PUMPING METHODS

Pumping: *The process of raising more number of atoms to excited state by artificial means is called as pumping process.*

There are several methods by which the population inversion (pumping) can be achieved. Some of the most commonly used methods are

(a) Optical pumping
(b) Direct electron excitation (Electric discharge)
(c) Inelastic atom-atom collision.
(d) Direct conversion
(e) Chemical process

(a) Optical pumping: Here the atoms are excited with the help of photons emitted by an external optical source. The atoms absorb energy from the photons and raises to excited state. (e.g) Ruby Laser, Nd-YAG Laser.

(b) Direct electron excitation: The electrons are accelerated to very high velocities by strong electric field and they collide with gas atoms and these atoms are raised to excited state (e.g.) Gaseous ion lasers (argon laser), Helium-Neon (He-Ne) laser, CO_2 Laser etc.

(c) Inelastic atom-atom collision: In this method a combination of two types of gases are used, say A and B, both having same (or) nearly coinciding excited states A* and B*.

During electric discharge 'A' atoms get excited due to collision with electrons. The excited A* atoms now collide with 'B' atoms so that B goes to excited state B* (e.g) Helium-Neon laser, CO_2 laser

$$e^- + A \longrightarrow A^*$$
$$A^* + B \longrightarrow B^* + A$$

(d) Direct conversion: Due to electrical energy applied in direct band gap semiconductor like GaAs etc., the combination of electrons and holes takes place and electrical energy is converted into light energy directly. (e.g) Semiconductor laser.

(e) Chemical method: Due to some chemical reactions, the atoms may be raised to excited state. (e.g) Dye laser.

7.9 OPTICAL RESONATOR

The optical resonator constitutes an active medium kept inbetween a 100% reflecting mirror and a partially reflecting mirror as shown in fig. 7.6.

This optical resonator acts as a feed back system in amplifying the light emitted from the active medium, by making it to undergo multiple reflections between the 100% mirror and the partial mirror. Here the light bounces back and forth between the two mirrors and hence the intensity of the light is increased enormously. Finally the intense, amplified beam called LASER is allowed to come out through the partial mirror as shown in fig.7.6.

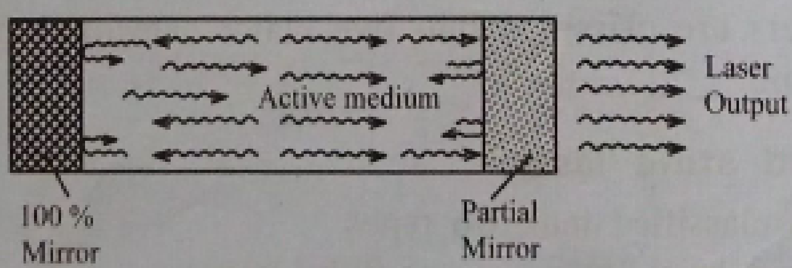


Fig. 7.6

7.10 FLOW CHART FOR LASER ACTION

The flow chart for the laser action is as shown in fig. 7.7. Initially by some means of pumping process atoms in the active medium are allowed to go from ground state to excited state and hence the population inversion is achieved.

At this stage a spontaneously emitted photon, so called stimulating photon incident on the excited atoms in the active medium and initiates the stimulated emission.

The light emitted due to stimulated emission, stimulates more number of atoms in the active medium to come from the excited state to the ground state and hence more number of photons are emitted from the active medium. Thus amplification of light begins.

This amplified light travels back and forth between the 100% mirror and the partial mirror in the optical resonator and hence an intense amplified beam of light, so called LASER is emitted through the partial mirror.

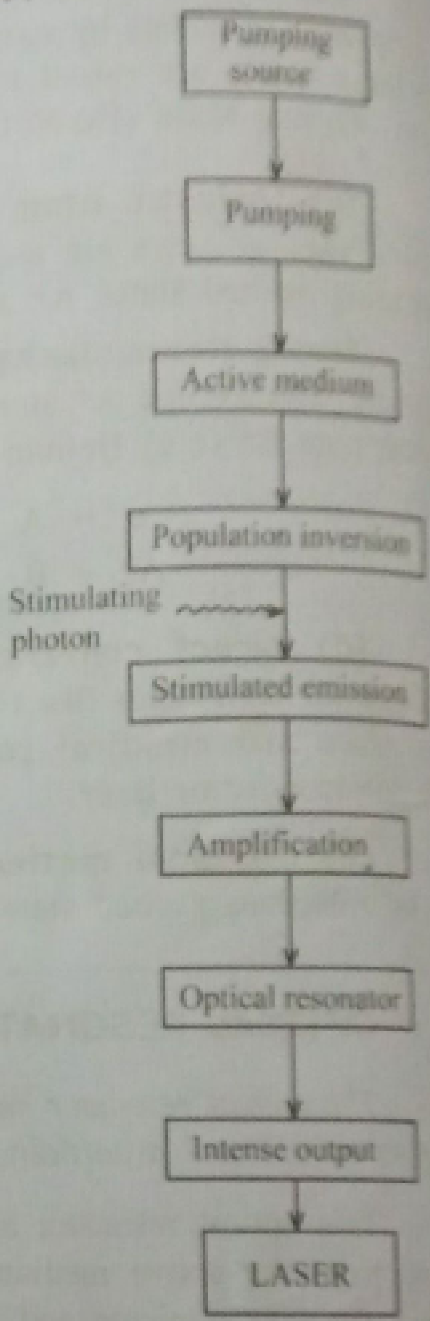


Fig. 7.7

7.11 TYPES OF LASERS

Lasers are classified into five major categories based on the type of active medium.

(i) Solid state laser

It is classified into two types

(a) 3 level laser (e.g) Ruby laser

(b) 4 level laser (e.g) Nd-YAG laser

(ii) **Gas Lasers**

Examples: CO_2 laser, He-Ne laser.

(iii) **Semi conductor laser**

Example: GaAs (Gallium Arsenide laser)

(iv) **Liquid lasers**

Example: Europium benzoyl acetonate dissolved in alcohol.

(v) **Dye laser and chemical lasers**

7.12 Nd-YAG [Neodymium-Yttrium Aluminium Garnet] LASER

Characteristics of Nd-YAG laser

Type	-	Doped insulator laser [Solid state laser]
Active medium	-	Yttrium Aluminium Garnet [$Y_3Al_5O_{12}$]
Active centre	-	Neodymium [Nd^{3+} ions]
Pumping method	-	Optical pumping
Pumping source	-	Xenon flash lamp
Optical Resonator	-	Ends of the rods polished with silver and two mirrors, one of them is totally reflecting and the other is partially reflecting.
Power output	-	2×10^4 watts
Nature of output	-	Pulsed
Wavelength emitted	-	1.064 μm.

Introduction: Nd-YAG laser is a doped insulator laser. ***It is a four level system*** in which the active medium is taken in the form of a crystal. Here the crystal is intensionally doped during its growth. Those type of lasers has number of energy levels with same energy. The laser is used to generate high power intensity.

Principle: *The term "Doped Insulator Laser" refers to the active medium, yttrium aluminium garnet doped with neodymium Nd^{3+}. The neodymium ion has many energy levels. Due to optical pumping these ions are raised to excited levels. During the transition from metastable state to E_1 state, the laser beam of wavelength 1.064 μm is emitted.*

Construction: The active medium is made as a rod which has yttrium aluminium garnet [Y_3 Al_5 O_{12}] doped with a rare earth metal ion neodymium Nd^{3+}. The Nd^{3+} ions normally occupies the yttrium ions and provides the energy levels for both the lasing transitions and pumping. This rod is placed inside a highly reflecting elliptical cavity as shown in fig.7.8.

A close optical coupling is made by placing the xenon flash lamp near by the laser rod, in such a way that most of the radiation from the flash tube passes through the laser rod due to the elliptical cavity. The flash tube may be switched ON and controlled with the help of a capacitor. The discharge of capacitor is initiated using a high voltage source.

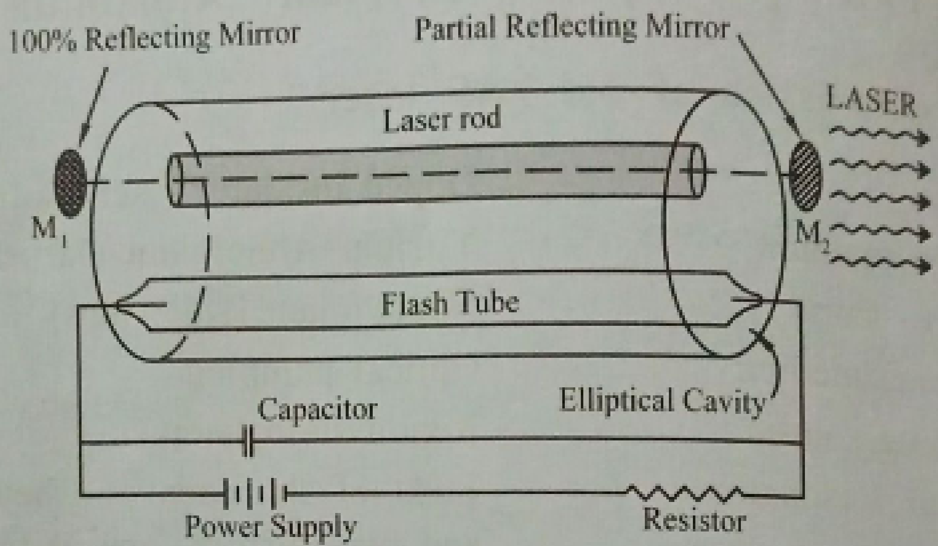


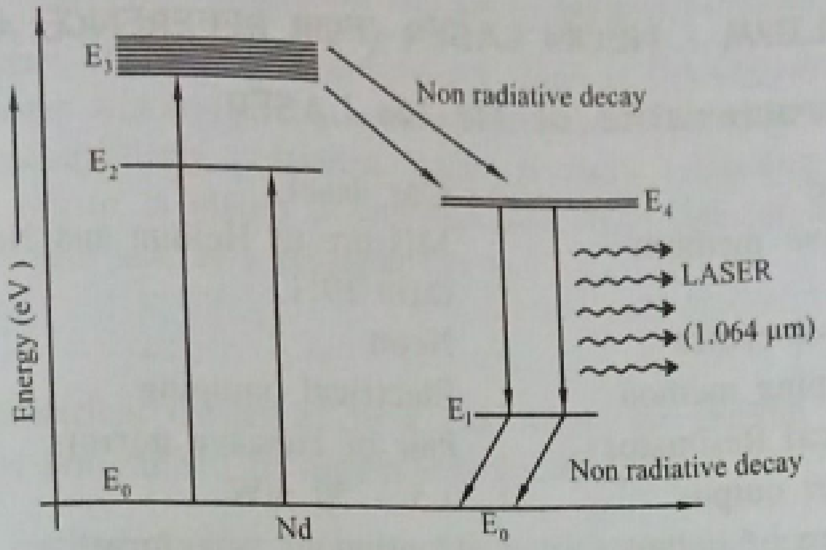
Fig. 7.8

The optical resonator is formed by grinding the ends of the rods and coated with silver accompanied by two mirrors, one is 100% reflecting and the other is partially reflecting which is included to increase the efficiency of the output beam.

Working

1. The xenon flash lamp is switched ON and the light is allowed to fall on the laser rod.

2. The intense white light excites the neodymium (Nd^{3+}) ions from the ground state to various energy levels above E_2. Hence the atoms are raised to group of higher levels in E_3 as illustrated in the energy level diagram fig.7.9.



E_1, E_2, E_3 — Various energy levels of Nd^{3+}
E_4 — Meta stable state
E_0 — Ground state energy level

Fig. 7.9

3. From these energy levels the ions make non-radiative decay and is gathered in a state called as meta stable state, until the population inversion is achieved.
4. Once the population inversion is achieved, the stimulated emission builds up rapidly.
5. Hence, pulsed form of laser beam of wavelength 1.064 μm is emitted during the transition from E_4 to E_1 (lower).
6. A large amount of heat is produced by the flash tube during the working. Hence cooling arrangement is made either by blowing air (or) circulating water over the crystal.

Applications of Nd-YAG Laser

1. It is used in transmitting signals to a longer distances.
2. It is used in long haul communication system.
3. It is also used in the endoscopic applications.
4. It plays a vital role in remote sensing applications.

NOTE: *For continuous laser beam the xenon flash lamp may be replaced with quartz - halogen lamps.*

7.13 HELIUM - NEON LASER (FOR REFERENCE ALONE)

Characteristics of He-Ne LASER

Type	:	Gas laser
Active medium	:	Mixture of Helium and Neon in the ratio 10:1
Active centre	:	Neon
Pumping method	:	Electrical pumping
Optical Resonator	:	Pair of concave mirrors
Power output	:	0.5 - 50 mW
Nature of output	:	Continuous waveform
Wavelength	:	6328Å

Introduction: This laser is discovered by Ali Javan an USA scientist. He-Ne laser is designed for getting a continuous laser beam. Light with high coherence, higher directionality and higher mono-chromacity can be obtained from it. But the output power is generally in the order of few milliwatts.

Principle: *This laser is based on the principle of stimulated emission, produced in the active medium of gas. Here, the population inversion is achieved due to the interaction between the two gases which have closer higher energy levels.*

Construction: It consists of a gas discharge tube, which is made up of quartz and is filled with the mixture of helium under a pressure of 1mm of Hg and Neon under the pressure of 0.1mm of Hg. The ratio of the He-Ne mixture is 10:1 (i.e) the number of He atoms is greater than the number of Ne atoms.

The electrodes at the ends of the discharge tube are connected to the radio frequency oscillator to produce electrical discharge in the He-Ne mixture as shown in fig.7.10.

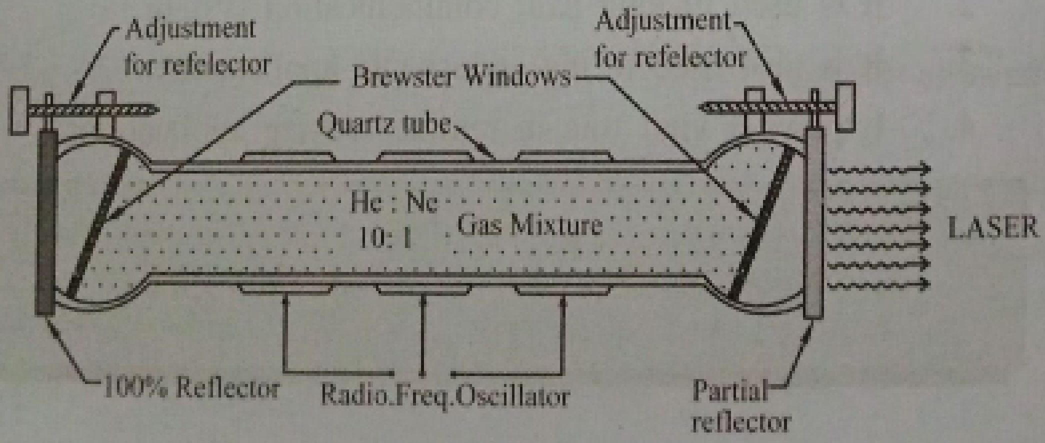


Fig. 7.10 **He-Ne Laser**

The end faces of the discharge tube are tilted at the brewster angle and are called as Brewster windows. It is used to produce plane polarized light by reflecting the perpendicularly polarized light. A fully reflecting and partial reflecting concave mirror is placed at the left and right ends of the discharge tube respectively, which acts as a resonant cavity.

Working

1. By electrical discharge in a gas tube, the ground state helium atoms are excited to higher energy levels.
2. The excitation occurs due to the collision of discharged electrons with helium atoms.
3. The excited helium atoms collide inelastically with the neon atoms which have close energy level as that of the helium energy level.
4. Therefore the Helium atom delivers its energy to Neon atoms by the process known as resonant collision energy transfer.
5. This resonant energy transfer takes place because the corresponding energy levels of helium ($2s^1$ and $2s^2$) are almost closer to the Neon energy levels (2s and 3s).
6. The probability of energy transfer from Neon to He decreases because of high pressure in He than Ne and also because of its density in the mixture.
7. Thus some of the He atoms are de-excited and come back to ground state.
8. The excited states of neon are shown by energy bands.

Designation given	1s	2s	3s	2p	3p
Electronic configuration	$2p^5 3s$	$2p^5 4s$	$2p^5 5s$	$2p^5 3p$	$2p^5 4p$

9. We have two sets of sub levels (3s and 2s) and (2p and 3p) between these levels three predominant laser transition takes place as shown in fig.7.11.

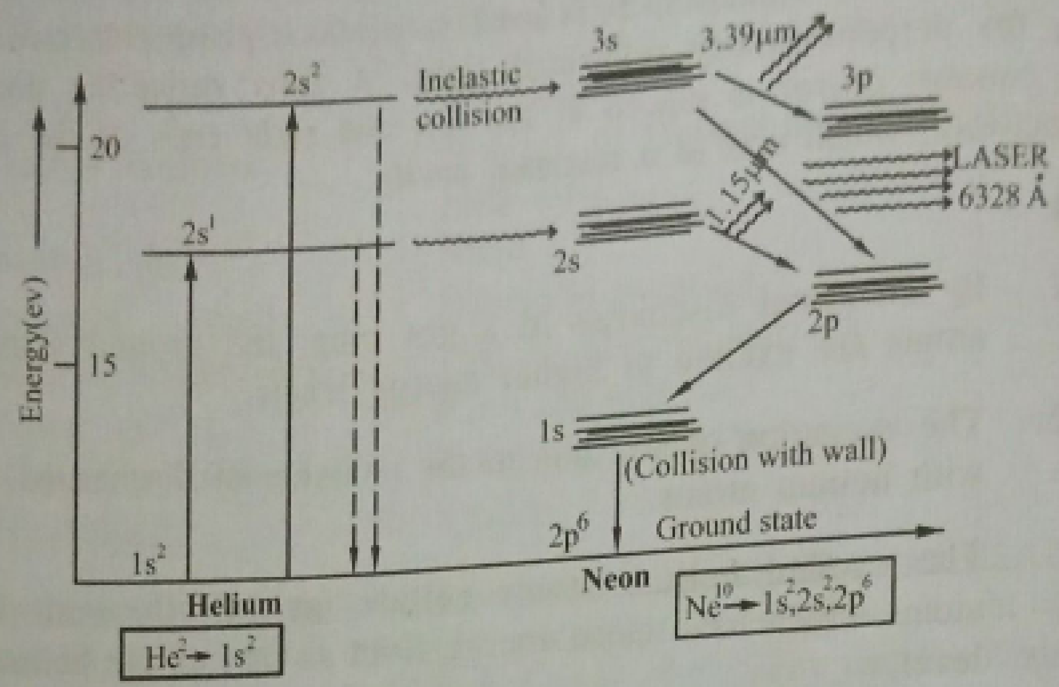


Fig. 7.11 **Energy Level Diagram**

10. First, resonant energy transfer is made from $2s^2$ to 3s and $2s^1$ to 2s. Now, stimulated emission takes place between 3s and 2p, emitting 6328Å wavelength of radiation.

    *(**Note:** Since 3s to 2p has higher energy difference, the laser light emitted is of lower wavelength).*

11. Stimulated emission between 3s to 3p gives 3.39 μm (33912Å which lies in infra red region) of radiation.
12. Stimulated emission between 2s to 2p gives 1.15 μm (11523 Å which also lies in infra red IR region) of radiation.
13. The atoms undergo transition from 2p to 1s giving photons by spontaneous emission.
14. The transition from 1s to ground level takes place by nonradiative process.
15. Since the electron density in 3s and 2s levels of Neon is always greater than the other levels of Neon. We get continuous laser output of wave length 6328Å with few milliwatt power.

Applications of He-Ne Laser

1. Because of its high power it is used in open air communications.
2. It is used to produce holograms (3D photographs).
3. It is used in determining the size of tiny particles.

ALITER - He-Ne Laser energy level diagram

An alternate energy level diagram for He-Ne laser is as shown in fig.7.12.

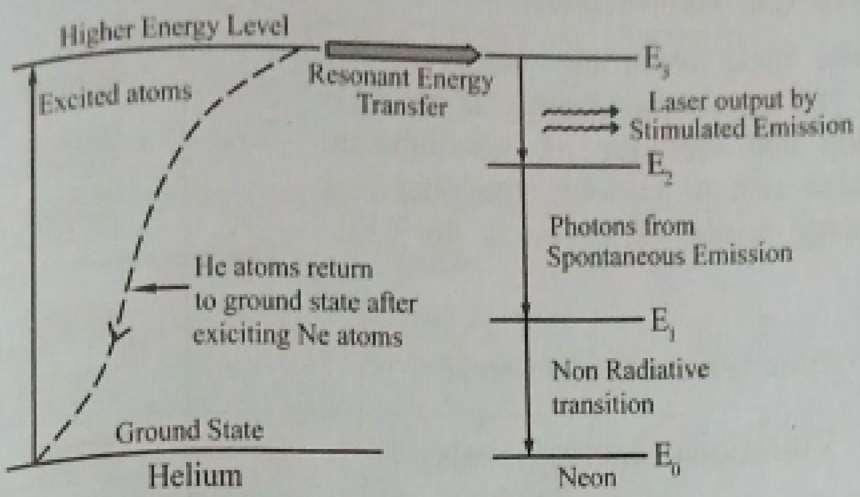


Fig. 7.12 **He-Ne Laser Energy Level Diagram**

Where

G - Ground state of He ($1s^2$)

H - Excited state of He $2s^2$, $2s^1$

E_3 - Sublevel of Ne (3s) [$2p^55s$], 2s[$2p^54s$]

E_2 - Sublevel of Ne (3p) [$2p^54p$], 2p[$2p^53p$]

E_1 - Sublevel of Ne (1s) [$2p^53s$]

E_0 - Ground state of Ne [$2p^6$]

7.14 CARBON-DI-OXIDE [CO_2] LASER

Characteristics of CO_2 Laser

Type	:	Molecular Gas Laser
Active medium	:	Mixture of CO_2, N_2 and Helium (or) Water vapour
Active centre	:	CO_2
Pumping method	:	Electric discharge method
Optical Resonator	:	Metallic mirror of gold (or) silicon mirrors coated with aluminium
Power output	:	10 KW
Nature of output	:	Continuous (or) pulsed
Wavelength of the output	:	9.6 μm & 10.6 μm (96000Å & 106000Å)

7.15 HOMOJUNCTION SEMICONDUCTOR LASER [GA-AS LASER]

Characteristics

Type	:	Homojunction Semiconductor laser
Active medium	:	P-N-junction diode
Active centre	:	Recombination of electrons and holes
Pumping process	:	Direct pumping
Optical Resonator	:	Junction of diodes - polished
Power output	:	1 mW
Nature of output	:	Pulsed (or) Continuous wave form
Wavelength of the output	:	8400 Å – 8600 Å
Band gap	:	1.44 eV

Principle: *The electron in conduction band combines with a hole in the valence band and hence the recombination of electron and hole produces energy in the form of light. This photon, in turn may induce another electron in the conduction band (CB) to valence band (VB) and thereby stimulate the emission of another photon.*

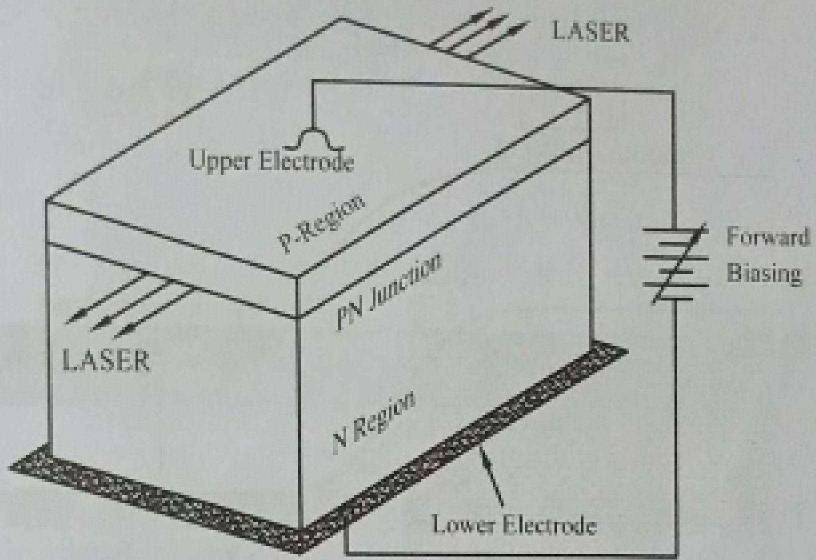


Fig. 7.21 **Semiconductor Laser**

The interactive animation of this concept can be viewed in the CD.

Construction : The active medium is a p-n-junction diode made from a single crystalline material i.e., Gallium Arsenide, in which p-region is doped with germanium and n-region with Tellurium. The thickness of the p-n-junction layer is very narrow so that the emitted laser radiation has large divergence. The junctions of the 'p' and 'n' are well polished and are parallel to each other as shown in fig.7.21.

Since the refractive index of GaAs is high, it acts as optical resonator so that the external mirrors are not needed. The upper and lower electrodes fixed in the 'p' and 'n' region helps for the flow of current to the diode while biasing.

Working

1. The population inversion in a p-n-junction is achieved by heavily doping 'p' and 'n' materials, so that the Fermi level lies within the conduction band of n type and within the valence band of 'p' type as shown fig.7.22.

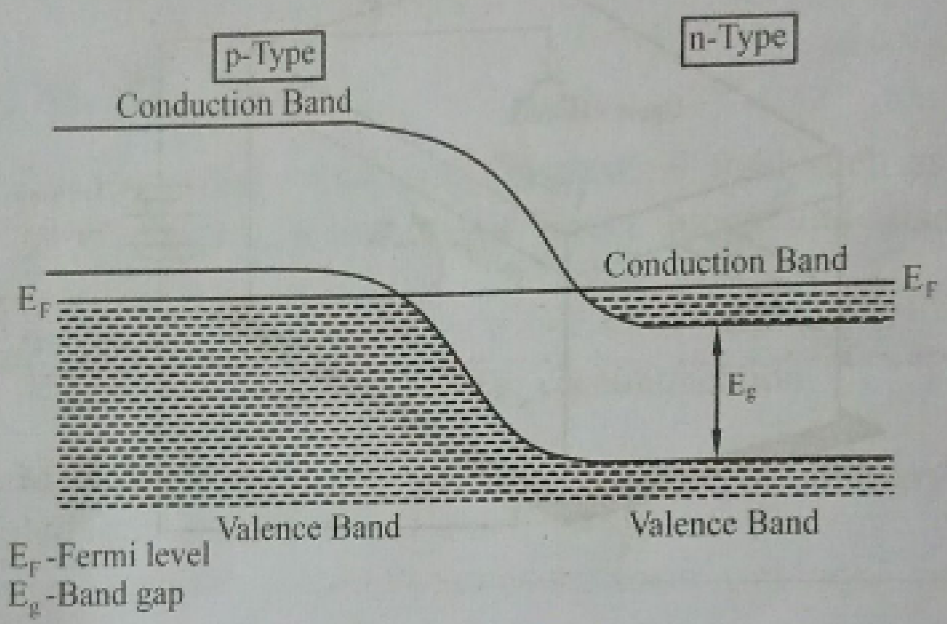


Fig. 7.22

2. If, the junction is forward biased with an applied voltage nearly equal to the band gap voltage, direct conduction takes place. Due to high current density, active region is generated near the depletion region.

3. At this junction, if a radiation having frequency (ν) is made to incident on the p-n-junction then the photon emission is produced as shown in fig.7.23.

4. Thus the frequency of the incident radiation should be in the range

$$\frac{E_g}{h} < \nu < \frac{(E_{F_c} - E_{F_v})}{h}$$

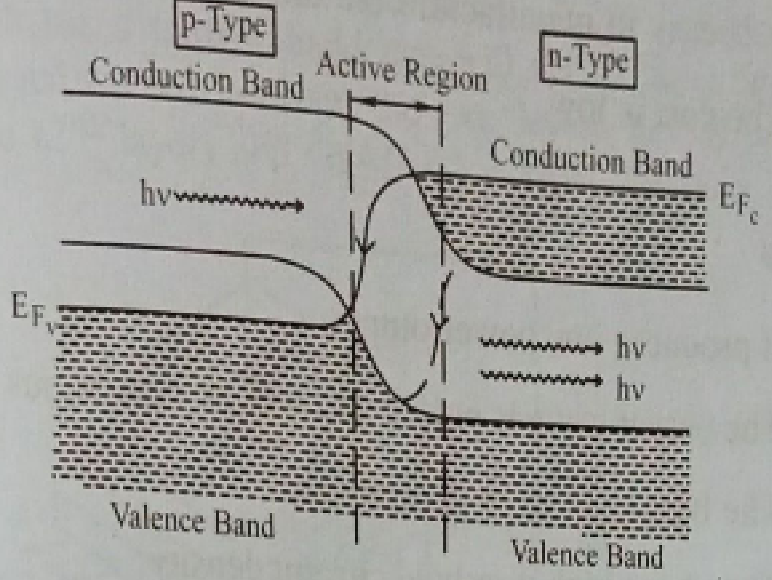


Fig. 7.23

The interactive animation of this concept can be viewed in the CD.

5. Further, the emitted photons increases the rate of recombination of injected electrons from the n region and holes in p region by inducing more recombinations.

6. Hence the emitted photons have the same phase and frequency as that of original inducing photons and will be amplified to get intense beam of LASER.

7. The wavelength of the emitted radiation depends on (i) the band gap and (ii) the concentration of donar and acceptor atoms in GaAs.

8. ***Calculation of wavelength***

Band gap of GaAs = 1.44 eV

$$E_g = h\nu = \frac{hc}{\lambda}$$

$$\lambda = \frac{hc}{E_g} = \frac{6.625 \times 10^{-34} \times 3 \times 10^{8}}{1.44 \times 1.6 \times 10^{-19}}$$

$$\lambda = 8626 \text{ Å}$$

The wavelength is near *IR Region.*

Advantages

(i) It is easy to manufacture the diode.

(ii) The cost is low.

Disadvantages

(i) It produces low power output.

(ii) The output wave is pulsed and will be continuous only for sometime.

(iii) The beam has large divergence.

(iv) They have high threshold current density.

7.16 HETEROJUNCTION SEMICONDUCTOR LASER (GaAlAs-Laser)

Characteristics

Type	:	Heterojunction semiconductor laser
Active medium	:	p-n- junctions (with various layers)
Active Centre	:	Recombination of electrons and holes
Pumping Process	:	Direct pumping
Optical resonator	:	Polished junctions of diode
Power Output	:	10mw
Nature of output	:	Continuous wave form
Wavelength of output	:	8000 Å
Band Gap	:	1.55 eV

Principle: *The electron in conduction band combines with a hole in the valence band and hence the recombination of electron and hole produces energy in the form of light. This photon, in turn may induce another electron in the conduction band (CB) to valence band (VB) and thereby stimulate the emission of another photon.*

Construction

It consists of five layers as shown in fig. 7.24. A layer of GaAs– p-type (3^{rd} layer) which has a narrow band gap will act as the active region. This layer (3^{rd} layer) is sandwitched between the two layers having wider band gap i.e. GaAlAs – p-type (2^{nd} layer) and GaAlAs – n-type (4^{th} layer).

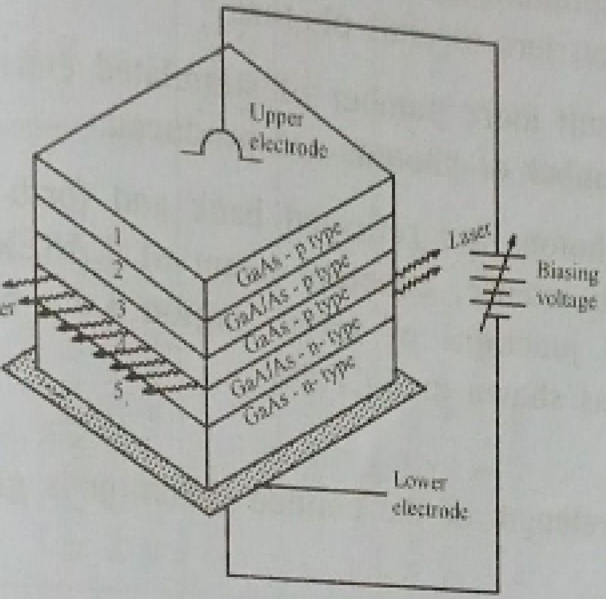


Fig. 7.24

A contact layer made of GaAs – p-type (1^{st} layer) is made to form at the top of the 2^{nd} layer for necessary biasing. All these four layers are grown over the substrate (5^{th} layer) made of GaAs-n-type.

The junctions of GaAs - p-type (3^{rd} layer) and GaAlAs - n-type (4^{th} layer) are well polished and hence it act as an optical resonator. The upper and lower electrodes helps in forward biasing the diode.

Working

The working of a heterojunction laser is similar to that of the working of a homojunction laser.

1) The diode is forward biased with the help of upper and lower electrodes.

2) Due to forward biasing the charge carriers are produced in the wide band gap layers (2 and 4).

3) These charge carriers are injected into the active region (layer 3).

4) The charge carriers are continuously injected from 2nd and 4th layer to the 3rd layer, until the population inversion is achieved.

5) At this state some of the injected charge carriers recombines and produces spontaneously emitted photons.

6) These spontaneously emitted photons stimulates the injected charge carriers to emit photons.

7) As a result more number of stimulated emission arises and thus large number of photons are produced.

8) These photons are reflected back and forth at the junction and hence an intense, coherent beam of LASER emerges out from the P-N junctions of active region i.e., between layer-3 and layer-4 as shown in fig.7.24.

9) The wavelength of the emitted radiation is given by $\lambda = \frac{hc}{E_g}$

$$\text{(or) } \lambda = \frac{6.625 \times 10^{-34} \times 3 \times 10^{8}}{1.55 \times 1.6 \times 10^{-19}}$$

$$\therefore \lambda = \mathbf{8014\text{Å}}$$

This wavelength lies in IR region.

Advantages

(i) Power output is very high.

(ii) It produces continuous wave output.

(iii) It has high directionality and high coherence.

(iv) It has low threshold current density compared to homojunction laser.

(v) These diodes are highly stable and has longer life time.

Disadvantages

(i) Cost is higher than homojunction laser.

(ii) Practical difficulties arises while growing the different layers of *p-n* junction.

7.17 COMPARISON CHART

Characteristics	Nd-YAG LASER	He-Ne LASER	CO_2 LASER	SEMICONDUCTOR (Ga-As) LASER
Type	Doped Insulator Laser (Solid state laser)	Gas laser	Molecular Gas Laser	Semiconductor laser
Active medium	Yttrium Aluminium Garnet ($Y_3Al_5O_{12}$)	Mixture of Helium and Neon in the ratio 10:1	Mixture of CO_2, N_2 and Helium (or) Water vapour	P-N junction diode
Active centre	Neodymium (Nd^{3+} ions)	Neon	CO_2	Recombination of electrons and holes
Pumping method	Optical pumping	Electrical pumping	Electric discharge method	Direct pumping
Optical Resonator	Ends of the rods polished with silver and two mirrors, one of them is totally reflecting and the other is partially reflecting	Pair of concave mirrors	Metallic mirror of gold (or) silicon mirrors coated with aluminium	Junction of diodes-polished
Power Output	2×10^4 watts	0.5 – 50 mW	10 kW	1 mW
Nature of Output	Pulsed	Continuous waveform	Continuous (or) pulsed	Pulsed (or) Continuous wave form
Wavelength	1.064 μm	6328 Å	9.6 μm & 10.6 μm	8400 Å - 8600 Å

7.18 ENGINEERING AND MEDICAL APPLICATIONS OF LASER (BASED ON THEIR PROPERTIES)

1. Property: It has Narrow band width and angular spread

Due to this property it is used in communications, to transmit thousands of programs, transmitting signals from longer distances called as long haul communication system.

2. Property: It is not absorbed by water

Hence they are used in underwater communication between the submarines, which is very useful for military.

3. Property: It has high penetrating power

(a) It is useful to (a) blast holes in diamonds and hard steels.

(b) It is used in drilling minute holes in cellwalls of human body.

(c) Using lasers, Cancer treatment can also be done.

(d) It is used to destroy tumors.

4. Property: Directionality

(a) It is useful in the production of laser gun and laser torches.

(b) It is used to do micro surgery and blood less operations.

(c) It is further used in laser printing and in computer storage devices.

5. Property: Highly intense

Because of its high intensity and directionality they are very useful in endoscopic applications in the medical field.

6. Apart from these applications they are used in recent engineering applications like

(i) Material processing, (ii) CD-ROM, (iii) Holography etc.

Let us discuss these applications in detail.

7.19 INDUSTRIAL APPLICATIONS [LASERS IN WELDING, HEAT TREATMENT AND CUTTING]

Laser Heat Treatment

We know laser is a light beam of very high intensity, directionality and coherence. So, when laser light is focused on a particular area, even of micrometer size, for a very longer time, then that particular area alone will be heated and the other area will remain as such. **This is called thermal effect (or) Laser heat treatment.** *In this process the light energy is converted into heat energy.*

Instrumentation technique

Principle

*The technique of **laser heat treatment** is used in Engineering applications like surface hardening, coating, glazing, alloying, cutting, welding, drilling and perforating holes in the materials and hence this process is called **material processing**. In general ruby laser, Nd-YAG Laser and CO_2 laser are used for this purpose.*

Instrumentation

The instrumentation for materials processing consists of a laser source to produce laser beam, shutter to control the intensity of the laser beam and an assembly of lenses to effectively focus the laser onto the specimen as shown in fig. 7.25.

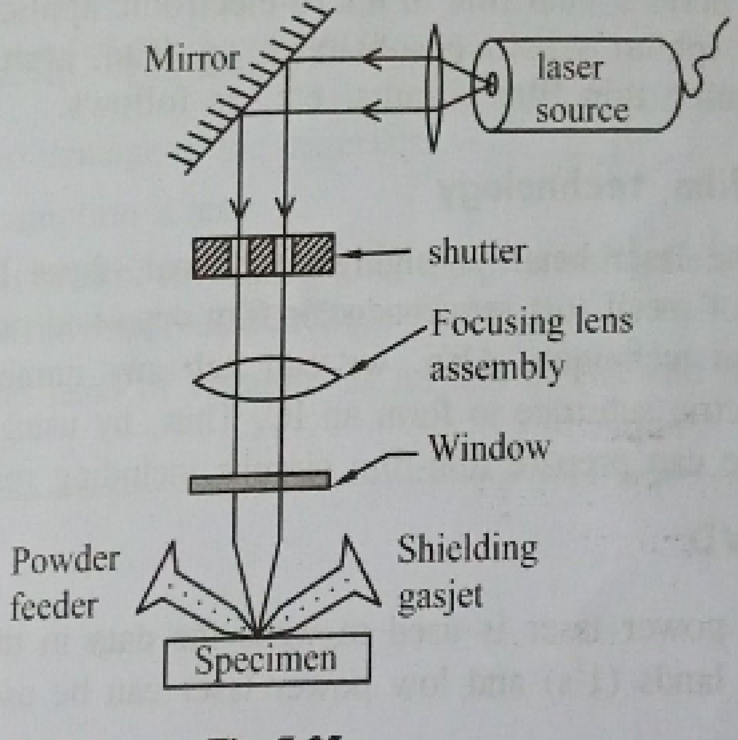


Fig. 7.25

Apart from these instrumentation, separate control arrangements are made for removing the molten materials, smokes, fumes etc., with the help of a shielding gas jet, which consist of the assisting gases such as air, N_2, O_2, Ar etc. The powder feeder is used to feed the metal powder, wherever necessary.

Processing

Laser source is switched ON. The light reflected by the plane mirror is made to pass through the shutter. The intensity of the laser beam is controlled by the shutter and the controlled laser beam is allowed to fall on the focussing lens assembly. This lens assembly focusses the light effectively onto the window and is made to incident on the specimen.

Now the specimen gets heated, giving rise to smokes, fumes and molten materials. These smokes, fumes and the molten materials are removed immediately by blowing the assisting gas from the shielding gas jet and this inturn makes the laser beam to continuously fall on the specimen, thereby increasing the cutting rate. Thus the materials can be drilled, cut, put holes etc. using this technique, effectively and easily.

In case of alloying, cladding, molding, welding etc. the power feeder will be used to spray the metal power over the specimen, during the focussing of laser beam onto the specimen.

Applications

Laser in Microelectronics

Laser plays a vital role in micro-electronic applications, such as making photo masks (photo sensitive substrates on ICs), writing/ reading CDs and DVDs, designing thin film circuits, etc. as follows.

(i) Thin film technology

As the laser beam is highly directional, these beams are used to trim off a portion of metal (or) semiconductor film deposited on the dielectric substrate, by evaporation technique. Also, we can itch any number of microcomponents over the dielectric substrate to form an IC. Thus, by using as accurately controlled laser beam we can prepare thin-film circuits including resistors, capacitors, etc.

(ii) CD/DVD

High power laser is used to write the data in the CD/DVD by creating pits (0's) and lands (1's) and low power laser can be used to read the data.

Laser Cutting

Laser is used as a tool to cut thin metal sheets by properly focusing the laser onto any particular area to be cut, for a longer time. Thus due to thermal effect the sheet is cut as shown in fig. 7.26.

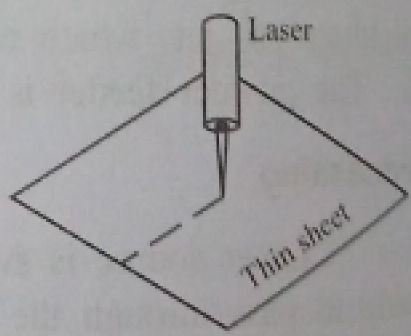


Fig. 7.26

Laser Drilling and perforating holes

The same technique as used for cutting will be adopted for drilling and perforating holes, even upto 0.2 to 0.5 μm of thickness.

Thus, using thermal effect, with extremely high precision we can drill or perforate holes in any desired position.

Laser Welding

We know in ordinary welding process heat will be made to fall on the area to be welded, so that the material in that area will go to molten state. This on cooling will join the material. In this process the heat will spread all over the surroundings and will affect the other areas of the material and hence the material gets damaged.

To avoid this difficulty, laser is used for welding. Due to its high directionality, it is focused onto that particular area alone, even of very small size and the other area remains unaffected. Thus due to thermal effect the parts can be welded. This process is also called ***Micro-Welding.***

Advantages of Material Processing

1) There is no damage to the materials.
2) Time consumption is less
3) There is no need of machining after the processing i.e., after welding we can use the materials directly.
4) There is no need of vacuum, as needed in electron beam material processing.