LASERS

2.1 Introduction

LASER stands for light amplification by stimulated emission of radiation. It is different from conventional light (such as tube light or electric bulb), there is no coordination among different atoms emitting radiation. Laser is a device that emits light (electromagnetic radiation) through a process is called stimulated emission.

2.2 Spontaneous and stimulated emission

In lasers, the interaction between matter and light is of three different types. They are: absorption, spontaneous emission and stimulates emission .Let E_1 and E_2 be ground and excited states of an atom. The dot represents an atom. Transition between these states involves absorption and emission of a photon of energy $E_2-E_1=h\nu_{12}$. Where 'h' is Planck's constant.

(a) Absorption: As shown in fig8.1(a), if a photon of energy $h\nu_{12}(E_2-E_1)$ collides with an atom present in the ground state of energy E_1 then the atom completely absorbs the incident photon and makes transition to excited state E_2.

(b) Spontaneous emission: As shown in fig8. 1. (b), an atom initially present in the excited state makes transition voluntarily on its own. Without any aid of external stimulus or an agency to the ground. State and emits a photon of energy $h\nu_{12}(=E_2-E_1)$.this is called spontaneous emission. These are incoherent.

(c) Stimulated emission: As shown in fig8.1.(c), a photon having energy $h\nu_{12}(E_2-E_1)$impinges on an atom present in the excited state and the atom is stimulated to make transition to the ground state and gives off a photon of energy $h\nu_{12}$. The emitted photon is in phase with the incident photon. These are coherent. This type of emission is known as stimulated emission.

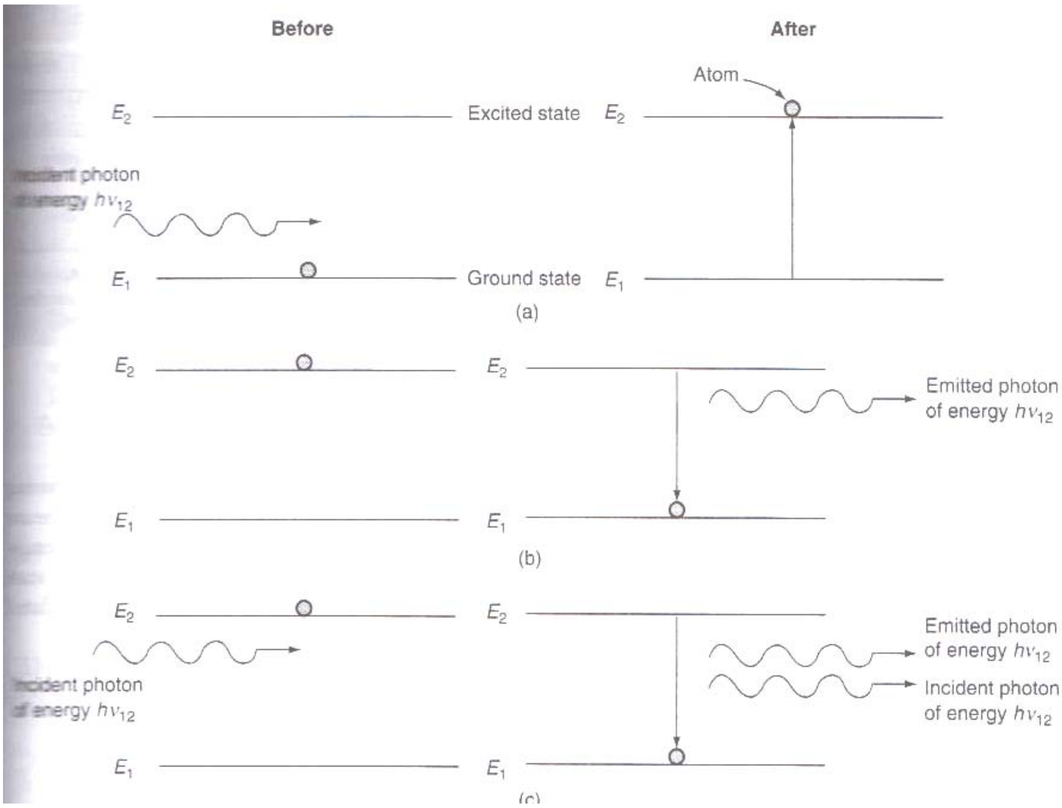


Fig.2.1 (a) Absorption ;(b) Spontaneous emission;(c) Stimulated emission

Differences between Spontaneous emission and stimulated emission of radiation

Spontaneous emission	Stimulated emission
1. Polychromatic radiation	**1.** Monochromatic radiation
2. Less intensity	**2.** High intensity
3. Less directionality, more angular spread during propagation	**3.** High directionality, so less angular spread during propagation.
4. Spatially and temporally in coherent radiation	**4.** Specially and temporally coherent radiation.
5. Spontaneous emission takes place when excited atoms make a transition to lower energy level voluntarily without any external stimulation.	**5.** Stimulated emission takes place when a photon of energy equal to h ν_{12} (=E_2-E_1) stimulates an excited atom to make transition to lower energy level.

2.3 Characteristics of Laser Light

(i). Coherence: Coherence is one of the unique properties of laser light. It arises from the stimulated emission process. Since a common stimulus triggers the emission events which provide the amplified light, the emitted photons are in step and have a definite phase relation to each other. This coherence is described in terms of temporal and spatial coherence.

(ii). Monochromaticity: A laser beam is more or less in single wave length. I.e. the line width of laser beams is extremely narrow. The wavelengths spread of conventional light sources is usually 1 in 10^6, where as in case of laser light it will be 1 in 10^5.I.e. if the frequency of radiation is 10^{15} Hz., then the width of line will be 1 Hz. So, laser radiation is said to be highly monochromatic. The degree of non-monochromaticity has been expressed as

$\xi = (d\lambda/\lambda) = d\nu/\nu$, where $d\lambda$ or $d\nu$ is the variation in wavelength or variation in frequency of radiation.

(iii) Directionality: Laser beam is highly directional because laser emits light only in one direction. It can travel very long distances without divergence. The directionality of a laser beam has been expressed in terms of divergence. Suppose r_1 and r_2 are the radii of laser beam at distances D_1 and D_2 from a laser, and then we have.

Then the divergence, $\Delta\theta = (r_1 - r_2)/ D_2 - D_1$

The divergence for a laser beam is 0.01 mille radian where as incase of search light it is 0.5 radian.

(iv) High intensity: In a laser beam lot of energy is concentrated in a small region. This concentration of energy exists both spatially and spectrally, hence there is enormous intensity for laser beam. The power range of laser is about 10^{-13}w for gas laser and is about 10^9 w for pulsed solid state laser and the diameter of the laser beam is about 1 mm. then the number of photons coming out from a laser per second per unit area is given by

$$N_1 = P/ h\nu\pi r^2 \approx 1022 \text{to} 1034 \text{photons/m}^{-2}\text{-sec}$$

By assuming $h\nu = 10^{-19}$ Joule, Power $P = 10^{-3}$to10^9watt $r = 0.5\times10^{-3}$meter

Based on Planck's black body radiation, the number of photons emitted per second per unit area by a body with temperature T is given by

$$N_{th} = (2h\pi C/ \lambda^4)\,(1/e^{(h\nu/kT)}-1)\, d\lambda \approx 10^{16} \text{photons/m}^2\text{.sec}$$

By assuming T=1000k, λ=6000A^0

This comparison shows that laser is a highly intensive beam.

2.4. Einstein's Coefficients

LetN_1 be the number of atoms per unit volume with energy E_1 and N_2 the number of atoms per unit volume with energy E_2. Let 'n' be the number of photons per unit volume at frequency ν such that $h\nu = E_2 - E_1$. Then the energy density of interacting photons $\rho(\nu)$ is given by

$$\rho(\nu) = n\, h\, \nu \qquad \rightarrow(1)$$

When these photons interact with atoms, both upward (absorption) and downward (emission) transitions occur. At equilibrium these transition rates must be equal.

Upward Transition

Stimulated absorption rate depends on the number of atoms available in the lower energy state for absorption of these photons as well as the energy density of interacting radiation. I.e. stimulated absorption rate $\alpha\ N_1$

$$\alpha\ \rho(\nu)$$
$$= B_{12} N_1\, \rho(\nu) \qquad \rightarrow (2)$$

Where the constant of proportionality B_{12} is the Einstein coefficient of stimulated absorption

Downward transition

Once the atoms are excited by stimulated absorption, they stay in the excited state for a short duration of time called the lifetime of the excited state. After their life time they move to their lower energy level spontaneous by emitting photons. This spontaneous emission rate depends on the number of atoms in the excited energy state.

i.e., spontaneous emission rate α N_2

$$=N_2 A_{21} \rightarrow (3)$$

Where the constant of proportionality A_{21} is the Einstein coefficient of spontaneous emission.

Stimulated emission

Before excited atoms de excites to their lower energy states by spontaneous emission they may interact with photons resulting in stimulated emission of photons. Therefore stimulated emission rate depends on the number of atoms available in the excited state as well as energy density of interacting photons

I.e. stimulated emission rate α N_2

$\alpha\ \rho(\nu)$

$$=N_2\rho(\nu) B_{21} \rightarrow (4)$$

Where the constant of proportionality B_{21} is the Einstein coefficient of stimulated emission.

During stimulated emission, the interacting photon called the stimulating photon and the photon due to stimulated emission are in phase with each other. Please note that during stimulated absorption, the photon density decreases where as during stimulated emission it increases.

For a system in equilibrium, the upward and down word transition rates must be equal and hence we have

$$N_1 \rho(\nu) B_{12}= N_2\rho(\nu)B_{21} + N_2A_{21} \rightarrow (5)$$

Hence $$\rho(\nu) = \frac{N_2A_{21}}{N_1B_{12}-N_1B_{21}} \rightarrow (6)$$

$$\rho(\nu) = \frac{A_{21}/B_{21}}{\left({B_{12}}/{B_{21}}\right)\left({N_1}/{N_2}\right)-1}$$

The population of various energy levels in thermal equilibrium is given by Boltzmann distribution law.

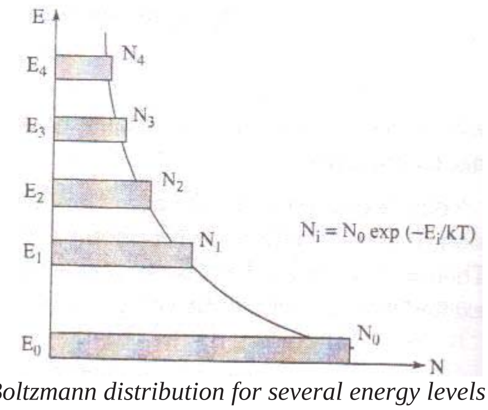


Fig.2.2 Boltzmann distribution for several energy levels

$$N_i = g_i N_o \exp(-E_i/KT)$$

Where N_i is the population density of the energy level E_i, N_0 is the population density of the ground state at temperature T_1, g_i is the degeneracy of the i^{th} level and k is the Boltzmann constant (=1.38x10^{-23}joule/k). The concept of degeneracy occurs since more than one level has the same energy.

Hence $N_1 = g_1 N_o \exp(-E_1/kT)$

$$\frac{N_1}{N_2} = \frac{g_1}{g_2} \exp\left[\frac{(E_2 - E_1)}{kT}\right]$$

$$= \frac{g_1}{g_2} \exp\left[\frac{h\nu}{kT}\right] \qquad \rightarrow (7)$$

Substituting e q (6) in e q (4) $\rho(\nu) = \frac{[A_{21}/B_{21}]}{[\frac{B_{12}}{B_{21}}\frac{g_1}{g_2}\exp[\frac{h\nu}{kT}]}$ $\rightarrow (8)$

From Planck's law of blackbody radiation, the radiation density is given by

$$\rho(\nu) = \frac{8\pi h\nu^3}{C^3} \frac{1}{\exp[\frac{h\nu}{kT}] - 1} \qquad \rightarrow (9)$$

Comparing equations (8) and (9), we get

$$\frac{B_{12}}{B_{21}} \frac{g_1}{g_2} = 1$$

$$g_1 B_{12} = g_2 B_{21} \qquad \rightarrow (10)$$

And $\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{C^3}$ $\rightarrow (11)$

Equation's (10) and (11) are referred to as the Einstein relations.

The ratio of spontaneous emission rate to the stimulated emission rate is given by

$$R = \frac{N_2 A_{21}}{N_2 \rho(\nu) B_{21}} = \frac{A_{21}}{\rho(\nu) B_{21}}$$

From equation (9)

$$R = \frac{A_{21}}{\rho(\nu) B_{21}} = [exp^{[\frac{h\nu}{kT}]} - 1] \qquad \rightarrow (12)$$

In practice, the absorption and emission phase occur simultaneously. Let us calculate the rates of spontaneous emission and stimulating emission for a tungsten filament lamp operating at a temperature of 2000k. Taking the average frequency to be 5x10^{14}Hz, this ratio is

$$R = e^{\frac{(6.6\times10^{-34})\times(5\times10^{14})}{(1.38\times10^{-23}\times2000)}} - 1 \qquad \rightarrow (13)$$

This confirms that under conditions of thermal equilibrium, even for sources operating at higher temperatures and lower frequencies, spontaneous emission predominates.

From equation (12), we understand that to make R smaller $\rho(\nu)$ the energy density of interacting radiation has to be made larger. Let us consider the relation of stimulated emission rate to stimulated absorption rate

Thus at thermal equilibrium stimulated absorption predominates over stimulated emission. Instead if we create a situation that $N_2 > N_1$. Stimulated emission will predominate over stimulated absorption. If stimulated emission predominates the photon density increases and light amplifies the photon density increases and light amplification by stimulated emission of radiation (LASER) occurs. Therefore, in order to achieve more stimulated emission, population of the excited state (N_2) should be made larger than the population of the lower state (N_1) and this condition is called population inversion. Hence if we wish to amplify a beam of light by stimulated emission, then we must create population inversion and increase the energy density of interacting radiation.

2.4.1 Population inversion

Usually in a system the number of atoms (N_1) present in the ground state (E_1) is larger than the number of atoms (N_2) present in the higher energy state. The process of making $N_2 > N_1$ called population inversion. Conditions for population inversion are:

a) The system should posses at least a pair of energy levels ($E_2 > E_1$), separated by an energy of equal to the energy of a photon (hν).
b) There should be a continuous supply of energy to the system such that the atoms must be raised continuously to the excited state.

Population inversion can be achieved by a number of ways. Some of them are (i) optical pumping (ii) electrical discharge (iii) inelastic collision of atoms (iv) chemical reaction and (v) direct conversion

2.5 Helium-Neon gas laser

Helium-Neon gas laser is a continuous four level gas laser. It consists of a long, narrow cylindrical tube made up of fused quartz. The diameter of the tube will vary from 2 to 8 mm and length will vary from 10 to 100 cm. The tube is filled with helium and neon gases in the ratio of 10:1. The partial pressure of helium gas is 1mm of Hg and neon gas is 0.1mm of Hg so that the pressure of the mixture of gases inside the tube is nearly 1 mm of Hg.

Laser action is due to the neon atoms. Helium is used for selective pumping of neon atoms to upper energy levels. Two electrodes are fixed near the ends of the tube to pass electric discharge through the gas. Two optically plane mirrors are fixed at the two ends of the tube at Brewster angle normal to its axis. One of the mirrors is fully silvered so that nearly 100% reflection takes place and the other is partially silvered so that 1%of the light incident on it will be transmitted. Optical resources column is formed between these mirrors.

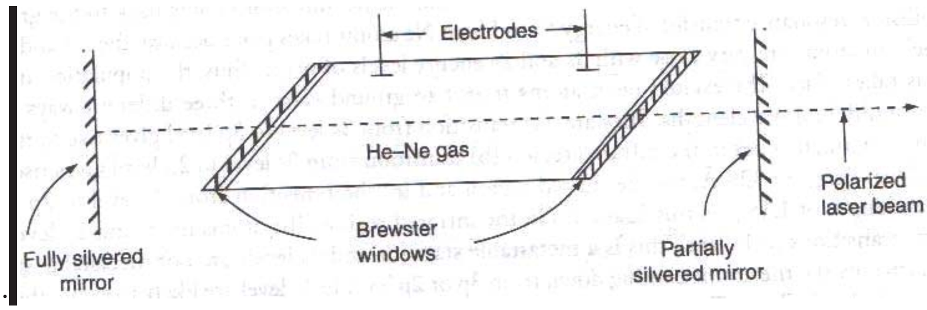


Fig.2.3 Helium-Neon gas laser

Working

When a discharge is passed through the gaseous mixture, electrons are accelerated down the tube. These accelerated electrons collide with the helium atoms and excite them to higher energy levels. The different energy levels of Helium atoms and Neon atoms is shown in fig.2.3 the helium atoms are excited to the levels F_2 and F_3 these levels happen to be meta stable energy states.

Energy levels and hence Helium atoms exited levels spend sufficiently large amount of time before getting de excited. As shown in the fig 2.5(a), some of the excited states of neon can correspond approximately to the same energy of excited levels F_2 and F_3. Thus, when Helium atoms in level F_2 and F_3 collide with Neon atoms in the ground level E_1, an energy exchange takes place. This results in the excitation of Neon atoms to the levels E_4 and E_6 and de excitation of Helium atoms to the ground level (F_1). Because of long life times of the atoms in levels F_2 and F_3, this process of energy transfer has a high probability. Thus the discharge through the gas mixture continuously populates the neon atoms in the excited energy levels E_4 and E_6. This helps to create a state of population inversion between the levels E_4 (E_6) to the lower energy level (E_3 and E_5). The various transitions $E_6 \rightarrow E_5$, E4$\rightarrow E_3$, $E_6 \rightarrow E_3$ leads to the emission of wave lengths 3.39mm, 1.15 um and 6328 A^0. Specific frequency selection may be obtained by employing mirrors

The excited Neon atoms drop down from the level E_3 to the E_2 by spontaneously emitting a photon around wavelength 6000A^0. The pressures of the two gases in the mixture are so chosen that there is an effective transfer of energy from the Helium to the Neon atoms. Since the level E_2 is a meta stable state, there is a finite probability of the excitation of Neon, atoms from E_2 to E_3 leading to population inversion, when a narrow tube is used, the neon atoms in the level E_2 collide with the walls of the tube and get excited to the level E_1. The transition from E_5 to E_3 may be non radioactive. The typical power outputs of He-Ne laser lie between 1 and 50 mw of continuous wave for inputs of 5-10W.

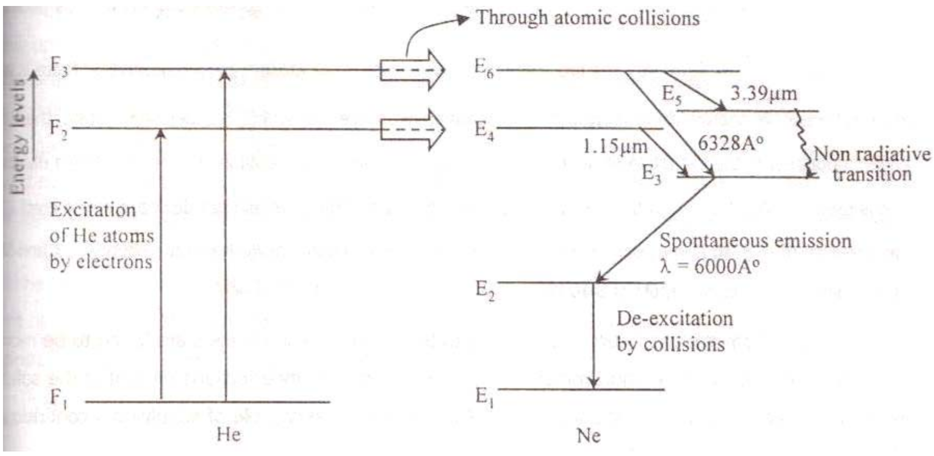


Fig.2.4. Energy level diagram of He-Ne atoms.

2.6 Ruby Laser

Ruby Laser is a solid state pulsed, three level lasers. It consists of a cylindrical shaped ruby crystal rod of length varying from 2 to 20cms and diameter varying 0.1 to 2cms. This end faces of the rod are highly flat and parallel. One of the faces is highly silvered and the other face is partially silvered so that it transmits 10 to 25% of incident light and reflects the rest so as to make the rod-resonant cavity. Basically, ruby crystal is aluminum oxide [Al_2O_3] doped with 0.05 to 0.5% of chromium atom. These chromium atoms serve as activators. Due to presence of 0.05% of chromium, the ruby crystal appears in pink color. The ruby crystal is placed along the axis of a helical xenon or krypton flash lamp of high intensity.

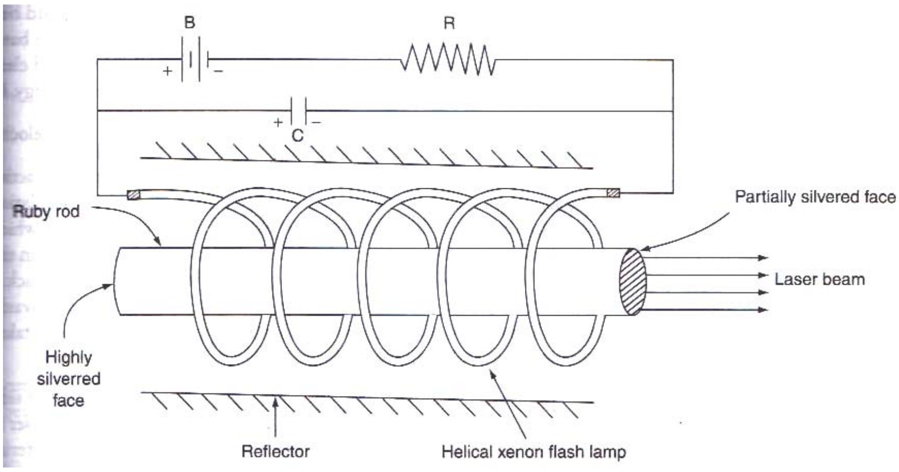


Fig.2.5 Ruby laser

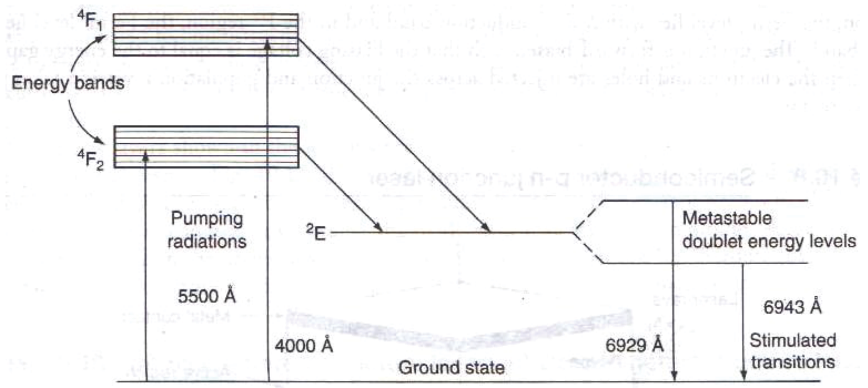


Fig.2.6 Energy level diagram of chromium ions in a ruby crystal

Construction:

Ruby (Al_2O_3+Cr_2O_3) is a crystal of Aluminum oxide in which some of Al^{+3} ions are replaced by Cr^{+3} ions. When the doping concentration of Cr^{+3} is about 0.05%, the color of the rod becomes pink. The active medium in ruby rod is Cr^{+3}ions. In ruby laser a rod of 4cm long and 5mm diameter is used and the ends of the rod are highly polished. Both ends are silvered such that one end is fully reflecting and the other end is partially reflecting.

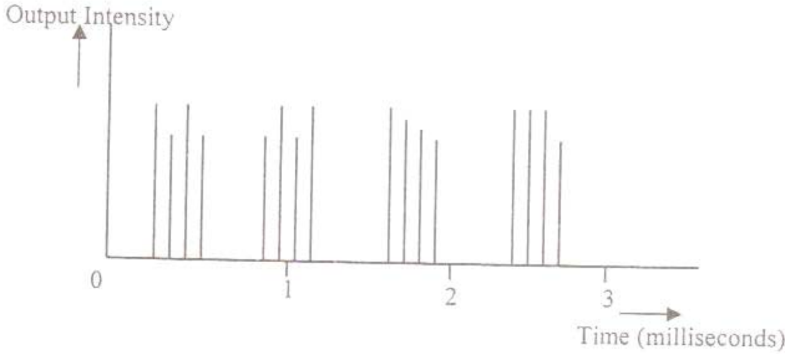
The ruby rod is surrounded by helical xenon flash lamp tube which provides the optical pumping to raise the Chromium ions to upper energy level (rather energy band). The xenon flash lamp tube which emits intense pulses lasts only few milliseconds and the tube consumes several thousands of joules of energy. Only a part of this energy is used in pumping Chromium ions while the rest goes as heat to the apparatus which should be cooled with cooling arrangements as shown in fig.2.5. The energy level diagram of ruby laser is shown in fig.2.6

Working:

Ruby crystal is made up of aluminum oxide as host lattice with small percentage of Chromium ions replacing aluminum ions in the crystal chromium acts as do pant. A do pant actually produces lasing action while the host material sustains this action. The pumping source for ruby material is xenon flash lamp which will be operated by some external power supply. Chromium ions will respond to this flash light having wavelength of $5600A^0$. When the Cr^{+3}ions are excited to energy level E_3 from E_1 the population in E_3 increases. Chromium ions stay here for a very short time of the order of 10-8 seconds then they drop to the level E_2 which is mat stable state of life time 10^{-3}s. Here the level E_3 is rather a band, which helps the pumping to be more effective. The transitions from E_3 to E_2 are non-radioactive in nature. During this process heat is given to crystal lattice. Hence cooling the rod is an essential feature in this method. The life time in mete stable state is 10^{5}times greater than the lifetime in E_3. As the life of the state E_2 is much longer, the number of ions in this state goes on increasing while ions. In this state goes on increasing while in the ground state (E_1) goes on decreasing. By this process population inversion is achieved between the exited Meta stable state E_2 and the ground state E_1. When an excited ion passes spontaneously from the metastable state E_2 to the ground state E_1, it emits a photon of wave length $6943A^0$. This photon travels through the rod and if it is moving parallel to the axis of the crystal, is reflected back and forth by the silvered ends until it stimulates an excited ion in E_2 and causes it to emit fresh photon in phase with the earlier photon. This stimulated transition triggers the laser transition. This process is repeated again and again because the photons repeatedly move along the crystal being reflected from its ends. The photons thus get multiplied. When the photon beam becomes sufficiently intense, such that part of it emerges through the partially silvered end of the crystal.

Drawbacks of ruby laser:

1. The laser requires high pumping power to achieve population inversion.
2. It is a pulsed laser.



. *Fig.2.7 the output pulses with time.*

2.7 Semi conductor laser

The semiconductor laser is also called diode laser. Among the different semiconductors there are direct band gap semiconductors and indirect band gap semiconductors. In the case of direct band gap semiconductors, there is a large possibility for direct recombination of holes and electrons which emit photons. But in indirect band gap semi conductors like silicon and germanium, direct recombination of holes and electrons is less possible and hence there is no effective emission of photons. A well know example of a direct band gap semiconductor is GaAs. Let E g be the energy gap of a material, then it emits a photon of wavelength (λ) is given the relation

$$\lambda = \frac{Ch}{E_g} \qquad \rightarrow (1)$$

Where C is the velocity of light and h is the Planck's constant
The equation (1) is reduced to

$$\lambda = \frac{1.24}{E_g}\ \mu m \qquad \rightarrow (2)$$

Where E_g is expressed in eV
As E_g increases, it emits shorter wavelengths. Diode lasers are always operated in forward bias. If p and n type materials are prepared from the same material then the p-n junction, is called as Homo junction semiconductor laser source. If p and n type materials are prepared from different materials then they are called as Hetero junction semi conductor laser source.

Construction of GaAs Semiconductor diode laser

The basic mechanism responsible for light emission from a semi conductor is the recombination of electrons and holes at p-n junction when a current is passed through the diode. The active medium is a p-n junction diode made from crystalline Gallium Arsenide . The p-region and n-region in the diode are obtained by heavily doping with suitable do pants. At the junction the sides through which emitted light is coming out are well polished and parallel to each other. Since the refractive index of GaAs is high, the reflectance at the material air interface is sufficiently large so that the external mirrors are not necessary to produce multiple reflections. When a current is passed through a p-n junction p region being positively biased, holes are injected from p-region into n-region and n-region being negatively biased electrons are injected from n-region into p-region and is shown in fig8.9.

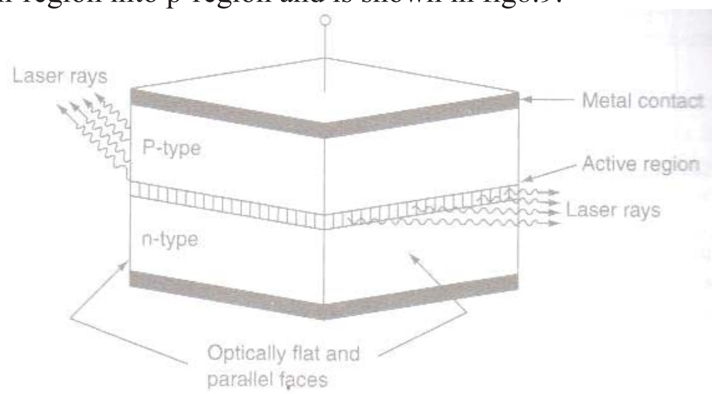
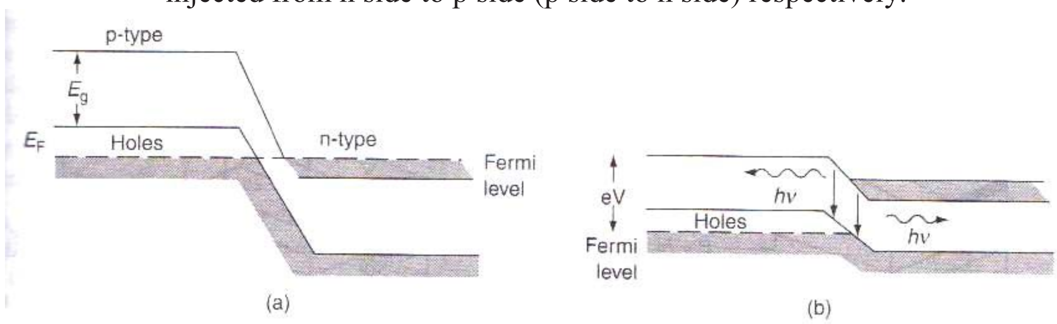


Fig.2.8 GaAs semiconductor diode laser

The connections in this p-n junction circuit are called forward bias. The electrons and holes recombine and release of light energy takes place in or near the junction. In the case of GaAs homo junction which has an energy gap of 1.44ev gives a laser beam of wavelength around 8600A^0 the electron-hole recombination takes place in the active region of the device. When the junction is forward biased, a large amount of the order of 104 amp/cm^2 is passed through the narrow junction. Thus the electrons (holes) are injected from n side to p side (p side to n side) respectively.



Fi2.9 (a) Band diagram of heavily doped p-n junction in equilibrium.
(b) Band diagram of heavily doped p-n junction with forward bias

The electrons are minority charge carriers in p-side and holes are the minority charge carriers in n-side. The continuous injection of charge carriers creates the population inversion of minority carriers is n and p side respectively. The excess minority charge carries diffuse away from the region recombining with majority carriers of the n and p type material, resulting in the release of photons. Further, the emitted photons increase the recombination of injected electrons from the n-region and holes in p-region by inducing more recombinations thus the stimulated emission takes place more effectively. The efficiency of a laser emission increases when the device is cooled.

The drawbacks of homojunction lasers

1. Only output is obtained
2. The threshold current density is very large(400amps/mm^2)
3. Electromagnetic confinement is poor.
4. Output has more beam divergence, poor coherence.

To overcome these deficiencies, scientists have developed heterojunction laser sources like GaAs/GaAlAs structures. The advantages of heterojunction laser structures are:

1. Low threshold current density(5-10amp/mm^2)
2. The output is continuous
3. Carrier confinement is more effective there by less beam divergence.
4. High output power.
5. Narrow beam, high coherence, high mono chromaticity is achieved.
6. Long lifetime of the device
7. Very stable. Hence hetero junction laser diode used extensively in optical fiber communication

2.8. Applications of Lasers

Lasers find applications in various fields. They are described below.

a) **In Communications :**

Lasers are used in optical fiber communications. In optical fiber communications, lasers are used as light source to transmit audio, video signals and data to long distances without attention and distortion.

b) The narrow angular spread of laser beam can be used for communication between earth and moon or to satellites.
c) As laser radiation is not absorbed by water, so laser beam can be used in under water (inside sea) communication networks.

2. Industrial Applications

a) Lasers are used in metal cutting, welding, surface treatment and hole drilling. Using lasers cutting can be obtained to any desired shape and the curved surface is very smooth.
b) Welding has been carried by using laser beam.
c) Dissimilar metals can be welded and micro welding is done with great case.
d) Lasers beam is used in selective heat treatment for tempering the desired parts in automobile industry
e) Lasers are widely used in electronic industry in trimming the components of ICs

3. Medical Applications

1. Lasers are used in medicine to improve precision work like surgery. Brain surgery is an example of precision surgery Birthmarks, warts and discoloring of the skin can easily be removed with an unfocussed laser. The operations are quick and heal quickly and, best of all, they are less painful than ordinary surgery performed with a scalpel.
2. Cosmetic surgery (removing tattoos, scars, stretch marks, sun spots, wrinkles, birthmarks and hairs) see lasers hair removal.
3.Laser types used in dermatology include ruby(694nm),alexandrite(755nm),pulsed diode array(810nm), Nd:YAG(1064nm), HO:YAG(2090nm), and Er:YAG(2940nm)
4. Eye surgery and refracting surgery.
5. Soft tissue surgery: Co_2 Er :YAG laser.
6. Laser scalpel (general surgery, gynecological, urology, laparoscopic).
7. Dental procedures.
8. Photo bio modulation (i.e. laser therapy)
9. “No-touch” removal of tumors, especially of the brain and spinal cord.
10. In dentistry for caries removal, endodontic/periodontic, procedures, tooth whitening, and oral surgery.

4. Military Applications

The various military applications are:

a) **Death rays**: By focusing high energetic laser beam for few seconds to aircraft, missile, etc can be destroyed. So, these rays are called death rays or war weapons.
b) **Laser gun:** The vital part of energy body can be evaporated at short range by focusing highly convergent beam from a laser gun.
c) **LIDAR (Light detecting and ranging)**: In place of RADAR, we can use LIDAR to estimate the size and shape of distant objects or war weapons. The differences between RADAR and LIDAR are that, in case of RADAR, Radio waves are used where as incase of LIDAR light is used.

5. In Computers: By using lasers a large amount of information or data can be stored in CD-ROM or their storage capacity can be increased. Lasers are also used in computer printers.