# UNIT – VII

# 12. LASERS

## Introduction:

It is a device to produce a powerful monochromatic narrow beam of light in which the waves are convergent. Laser is an acronym for light amplification by stimulated emission of radiation.
Maser is an acronym of microwave amplification by stimulated emission of radiation.
The light emitted from the conventional light source (eg: sodium lamp, candle) is said to be incoherent. Because the radiation emitted from different atom do not have any definite phase relationship with each other. Lasers are much important because the light sources having high monochromaticity, high intensity, high directionality and high coherence.
In the laser the principal of maser is employed in the frequency range of 1014to 1015Hz
and it is termed as optical maser. Laser principle now a day is extended up to γ-rays hence Gamma ray lasers are called Grazers. The first two successful lasers developed during 1960 were Ruby laser and He- Ne lasers. Some lasers emit light is pulses while others emit as a continuous wave.

## Characteristics of laser radiation:

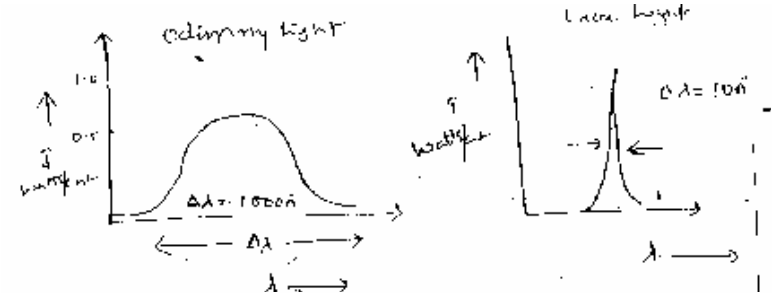
The four characteristics of a laser radiation over conventional light sources are

(1) Laser is highly monochromatic
(2) Laser is highly directional
(3) Laser is highly coherent
(4) The intensity of laser is very high

### HIGHLY MONOCHROMATIC:

The band width of ordinary light is about $1000A^0$ . The band width of laser light is about $10A^0$ . The narrow band width of a laser light is called on high monochromacity.

BAND WIDTH:- The spread of the wavelength (frequency ) about the wavelength of maximum intensity is band width.

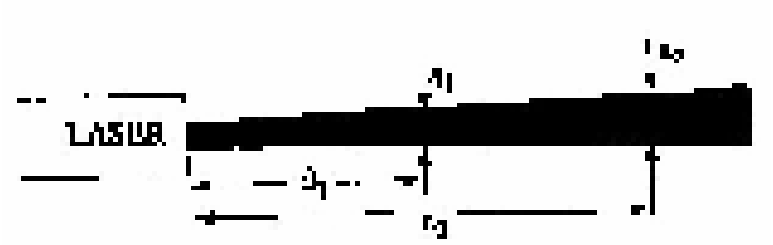


Laser light is more monochromatic than that of a conventional light source. Because of this monochromaticity large energy can be concentrated in to an extremely. Small band width.

For good laser dv=50Hz v=$5\times10^{14}$ Hz. The degree of non-monochromaticity for a conventional sodium light.

**HIGH DIREATIONALITY:**

The conventional light sources like lamp, torch light, sodium lamp emits light in all directions. This is called divergence. Laser in the other hand emits light only in one direction. This is called directionality of laser light.
Light from ordinary light spreads in about few kilometers**.**



Light from laser spreads to a diameter less than 1 cm for many kilometers.

The directionality of laser beam is given by (or) expressed in divergence.

The divergence $\Delta\theta = (r2 - r1) / d2-d1$

Where $r_2$, $r_1$ are the radius of laser beam spots
$d_2$ ,$d_1$ are distances respectively from the laser source. Hence for getting a high directionality then should be low divergence.

**HIGHLY COHERENT:**

When two light rays are having same phase difference then they are said to be coherent.
It is expressed in terms of ordering of light field

Laser has high degree of ordering than other common sources. Due to its coherence only it is possible to create high power($10^{12}$ watts) in space with laser beam of 1μm diameter.
There are two independent concepts of coherence.

1) Spatial coherence (2) Temporal coherence

***SPATIAL COHERENCE:*** The two light fields at different point in space maintain a constant phase difference over any time (t) they are said to be spatial coherence.

In He- Ne gas laser the coherence length( $l_c$ ) is about 600km.It means over the distance the phase difference is maintained over any time .For sodium light it is about 3cm.
The coherence & monochoremacity is related by

$$\xi = (\Delta\upsilon / \upsilon) \alpha\ 1/ l_c$$

For the higher coherence length $\xi$ is small hence it has high monochromacity

***TEMPORAL COHERENCE:*** The correlation of phase between the light fields at a point over a period of time. For He- Ne laser it is a about $10^{-3}$ second , for sodium it is about $10^{-10}$ second only.

$$\xi = (\Delta\upsilon / \upsilon) \alpha\ 1/ t_c$$

Higher is the $t_c$ higher is the monochromacity.

**HIGH INTENSITY**:

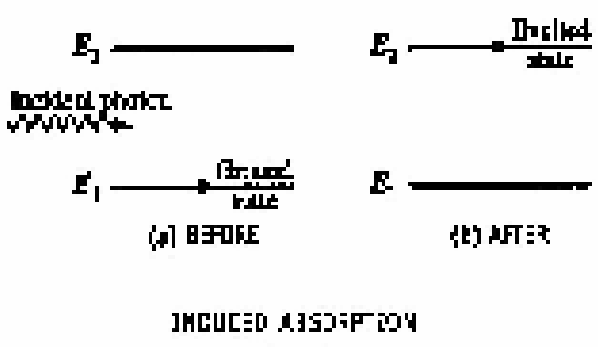
Intensity of a wave is the energy per unit time flowing through a unit area.
The light from an ordinary source spreads out uniformly in all directions and from spherical wave fronts around it.
Ex:- If you look a 100W bulb from a distance of 30cm the power entering the eye is
1 / 1000 of watt.

But in case of a laser light, energy is in small region of space and in a small wavelength and hence is said to be of great intensity.
The power range of laser about $10^{-3}$W for gas laser and $10^{9}$W for solid state laser
The number of photons coming out from a laser per second per unit area is given by

$$N_1 = p / h\upsilon\Pi r^2 \approx 10^{22} \text{ to } 10^{34} \text{ photons/ } m^2 - \text{sec.}$$

**SPONTANEOUS AND STIMULATED (INDUCED) EMISSION:**

Light is emitted or absorbed by particles during their transitions from one energy state to another .the process of transferring a particle from ground state to higher energy state is called excitation. Then the particle is said to be excited.

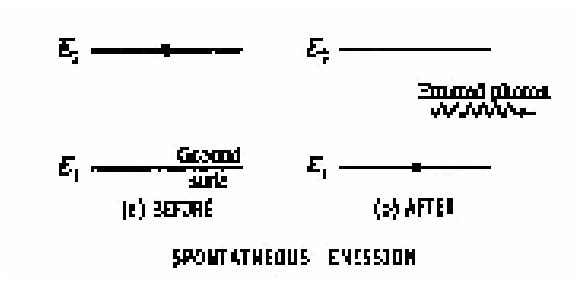


The particle in the excited state can remain for a short interval of time known as life time. The life time is of the order of $10^{-8}$ sec, in the excited states in which the life time is much greater than $10^{-8}$ sec are called meta stable states. The life time of the particle in the Meta stable state is of the order $10^{-3}$ sec

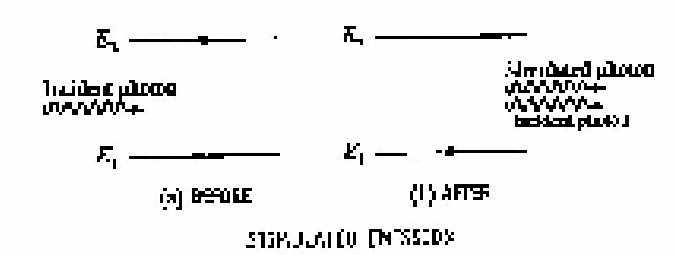
The probability of transition to the ground state with emission of radiation is made up of two factors one is constant and the other variable.

The constant factor of probability is known as spontaneous emission and the variable factor is known as stimulated emission.

*SPONTANEOUS EMISSION:* The emission of particles from higher energy state to lower energy state spontaneously by emitting a photon of energy hυ is known as "spontaneous emission"




*STIMULATED EMISSION:* The emission of a particle from higher state to lower state by stimulating it with another photon having energy equal to the energy difference between transition energy levels called stimulated emission.




| **SPONTANEOUS EMISSION** | **STIMULATED EMISSION** |
|---|---|
| 1) Incoherent radiation | 1) coherent radiation |
| 2) Less Intensity | 2) high intensity |
| 3) Poly chromatic | 3) mono chromatic |
| 4) One photon released | 4) two photons released |
| 5) Less directionality | 5) high directionality |
| 6) More angular spread during propagation | 6) less angular spread during Propagation |
| Ex:-Light from sodium Mercury vapour lamp | ex: - light from a laser source ruby laser, He-He gas laser gas Laser |

## EINSTEINS EQUATIONS (OR) EINSTAINS CO- EFFICIENTS:

Based on Einstein's theory of radiation one can get the expression for probability for stimulated emission of radiation to the probability for spontaneous emission of radiation under thermal equilibrium.

$E_1$, $E_2$ be the energy states
$N_1$, $N_2$ be the no of atoms per unit volume

***ABSORPTION:*** If $\rho(\upsilon)d\upsilon$ is the radiation energy per unit volume between the frequency range of $\upsilon$ and $\upsilon+d\upsilon$

The number of atoms under going absorption per unit volume per second from level

$E_1$ to $E_2 = N_1 \rho(\upsilon) B_{12}$------→ 1

$B_{12}$ represents probability of absorption per unit time

***STIMILATED EMISSION:*** When an atom makes transition $E_2$ to$E_1$ in the presence of external photon whose energy equal to $(E_2-E_1)$ stimulated emission takes place thus the number of stimulated emission per unit volume per second from levels.

$E_2$ to $E_1 = N2\ \rho(\upsilon)\ B_{21}$------→ 2

$B_{21}$ is represents probability of stimulated emission per unit time.

***SPONSTANEOUS EMISSION:*** An atom in the level $E_2$ can also make a spontaneous emission by jumping in to lower energy level $E_1$.

$E_2$ to $E_1 = N_2 A_{21}$---→ 3

$A_{21}$ represents probability of spontaneous emission per unit time.

Under steady state

$$(dN / dt) = 0$$

No of atoms under going absorption per second = no of atoms under going emission per second

$$1 = 2+3$$

$$N_1 \rho(\upsilon) B_{12} = N_2 \rho(\upsilon) B_{21} + N_2 A_{21}$$

$$N_2 A_{21} = N_1 \rho(\upsilon) B_{12} - N_2 \rho(\upsilon) B_{21}$$

$$= \rho(\upsilon)(N_1 B_{12} - N_2 B_{21})$$

$$\rho(\upsilon) = N_2 A_{21} / (N_1 B_{12} - N_2 B_{21})$$

$$= A_{21} / [(N_1 / N_2) B_{12} - B_{21})] \text{ --------→ } \mathbf{4}$$

From distribution law we know that

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

$= e^{h\upsilon / k_B T}$ ----------→ 5

Substituting $N_1 / N_2$ in eqn (4) we get

$\rho(\upsilon) = A_{21} / B_{21} (e^{h\upsilon / k_B T} - 1)$---------→ 6

From Planck's radiation

$\rho(\upsilon) = 8\Pi h n^3 / \lambda^3 \times [1 / (e^{h\upsilon / k_B T} - 1)]$ -------→ 7

n – refractive index of the medium
$\lambda$ - wave length of the light in air.
$\lambda_m = \lambda / n$ wavelength of light in medium --------→ 8

$\rho(\upsilon) = 8\Pi h / \lambda_m^3 \times [1 / (e^{h\upsilon / k_B T} - 1)]$ ------→ 9

Comparing eqn 6 and 9

**$A_{21} / B_{21} = 8\Pi h / \lambda_m^3$**
Where **$A_{21}$** , **$B_{21}$** are Einstein's co-efficient of spontaneous emission probability per unit time and stimulated emission probability per unit time respectively.

For stimulated emission to be predominant, we have

**$A_{21} / B_{21} << 1$**

## *POPULATION INVERSION:*

The no of atoms in higher energy level is less than the no of atoms in lowest energy level. The process of making of higher population in higher energy level than the population in lower energy level is known as population inversion.

Population inversion is achieved by pumping the atoms from the ground level to the higher energy level through optical (or) electrical pumping. It is easily achieved at the matastable state, where the life time of the atoms is higher than that in other higher energy levels.

The states of system, in which the population of higher energy state is more in comparision with the population of lower energy state, are called "Negative temperature state".

A system in which population inversion is achieved is called as an active system. The method of raising the particles from lower energy state to higher energy state is called "Pumping".

## DIFFERENMT TYPES OF LASES:

1. Solid state laser - Ruby laser, Nd-YAG laser
2. Gas laser - He-Ne laser, CO2 laser
3. Semi conductor laser - GaAs laser

## RUBY LASER:

Ruby laser is a three level solid state laser having very high power of hundreds of mega watt in a single pulse it is a pulsed laser.

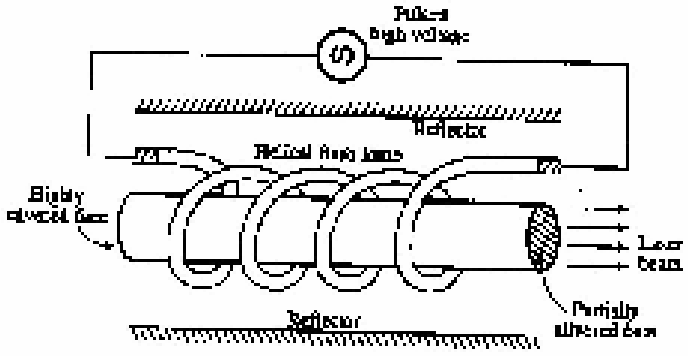
The system consists of mainly two parts

1) ***ACTIVE MATERIAL:*** Ruby crystal in the form of rod.

2) ***RESONANT CAVITY:*** A fully reflecting plate at the left end of the ruby crystal and partially reflecting end at the right side of the ruby crystal both the surfaces are optically flat and exactly parallel to each other.

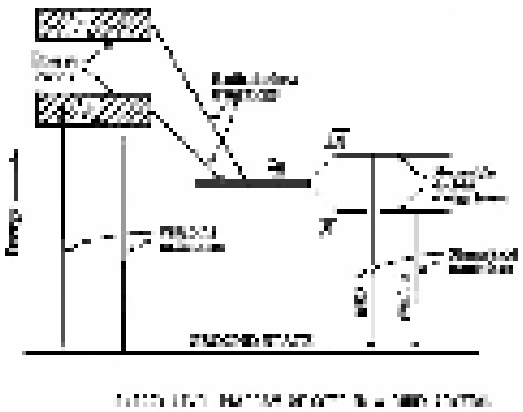
3) ***EXCITING SYSTEM:*** A helical xenon flash tube with power supply source.

***CONSTRUCTION:*** In ruby laser, ruby rod is a mixture of $Al_2O_3$+$Cr_2O_3$. It is a mixture of Aluminum oxide in which some of ions $Al^{+3}$ ions concentration doping of $Cr^{+3}$ is about 0.05% , then the colour of rod becomes pink. The active medium in ruby rod is $Cr^{+3}$ ions. The length of the ruby rod is 4cm and diameter 5mm and both the ends of the ruby rod 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 $Cr^{+3}$ ions to upper energy level.




The chromium atom has been excited to an upper energy level by absorbing photons of wave length $5600A^0$ from the flash lamp. Initially the chromium ions ($Cr^{+3}$) are excited to the energy levels $E_1$ to $E_3$ , the population in $E_3$ increases. Since the life time of $E_3$ level is very less ($10^{-8}$Sec). The $Cr^{+3}$ ions drop to the level $E_2$ which is matastable of life time $10^{-3}$Sec. The transition from $E_3$ to $E_2$ is non-radiative.

Since the life time of metastable state is much longer, the no of ions in this state goes on increasing hence population inversion achieved between the excited metastable 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 emit a photon of wave length $6993A^0$ this photon travel through the ruby rod and if it is moving parallel to the axis of the crystal and it is reflected back and forth by the silver ends until it stimulates an excited ion in $E_2$. The emitted photon and stimulated photon are in phase the process is repeated again and again finally the photon beam becomes intense; it emerges out through partially silvered ends.

Since the emitted photon and stimulating photon in phase, and have same frequency and are traveling in the same direction, the laser beam has directionality along with spatial and temporal coherence.

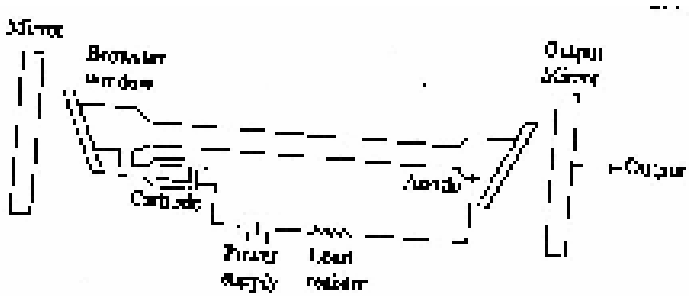
**IMPORTANCE OF RESONATOR CAVITY:** To make the beams parallel to each other curved mirrors are used in the resonator cavity. Resonator mirrors are coated with multi layer dielectric materials to reduce the absorption loss in the mirrors. Resonators act as frequency selectors and also give rise to directionality to the out put beam. The resonator mirror provides partial feedback to the protons.

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## He- Ne Laser

***CONSTRUTION:***

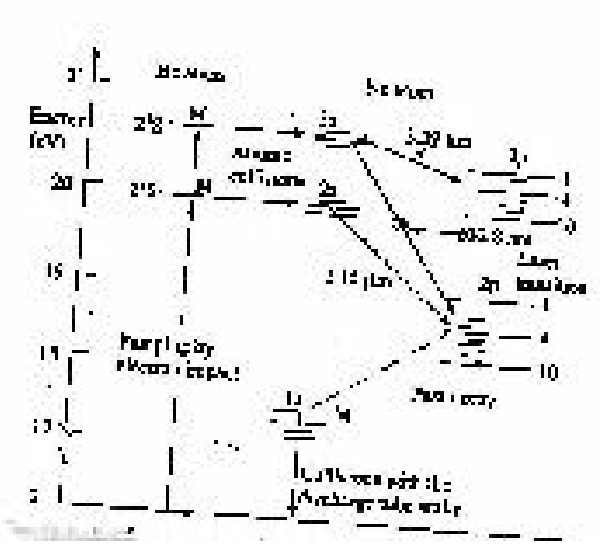
He - Ne gas laser consists of a gas discharge tube of length 80cm and diameter of 1cm. The tube is made up of quartz and is filled with a mixture of Neon under a pressure of 0.1mm of Hg. The Helium under the pressure of 1mm of Hg the ratio of He-Ne mixture of about 10:1, hence the no of helium atoms are greater than neon atoms. The mixtures is enclosed between a set of parallel mirrors forming a resonating



cavity, one of the mirrors is completely reflecting and the other partially reflecting in order to amplify the output laser beam.

## *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 since the levels are meta stable energy levels he atoms spend sufficiently long time and collide with neon atoms in the ground level $E_1$ . Then neon atoms are excited to the higher energy levels $E_4$ & $E_6$ and helium atoms are de excited to the ground state $E_1$



Since $E_6$ & $E_4$ are meta stable states, population inversion takes place at there levels. The stimulated emission takes place between $E_6$ to $E_3$ gives a laser light of wave length $6328A^0$ and the stimulated emission between $E_6$ and $E_5$ gives a laser light wave length of 3.39µm. Another stimulated emission between $E_4$ to $E_3$ gives a laser light wave length of 1.15µm. The neon atoms undergo spontaneous emission from $E_3$ to$E_2$ and $E_5$ to $E_2$. Finally the neon atoms are returned to the ground state $E_1$ from $E_2$ by non-radeative diffusion and collision process.

After arriving the ground state, once again the neon atoms are raised to $E_6$ & $E_4$ by excited helium atoms thus we can get continuous out put from He-Ne laser.

But some optical elements placed insides the laser system are used to absorb the infrared laser wave lengths 3.39μm and1.15μm. hence the output of He-Ne laser contains only a single wave length of $6328A^0$ and the output power is about few milliwatts .

## $CO_2$ LASER

## Construction and working:

We know that a molecule is made up of two or more atoms bound together. In molecule in addition to electronic motion, the constituent atoms in a molecule can vibrate in relation to each other and the molecule as a whole can rotate. Thus the molecule is not only characterized by electronic levels but also by vibration and rotational levels. The fundamental modes of vibrations of $CO_2$ molecule shown I fig.

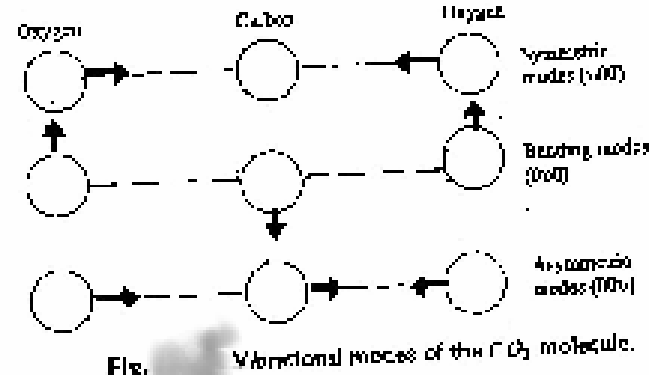


Fig. Vibrational modes of the $CO_2$ molecule.

$CO_2$ Laser is a gas discharge, which is air cooled. The filling gas within the discharge tube consists primarily of, $CO_2$ gas with 10 – 20%, Nitrogen around 10 – 20 %
$H_2$ or Xenon ( Xe ) a few percent usually only in a sealed tube.

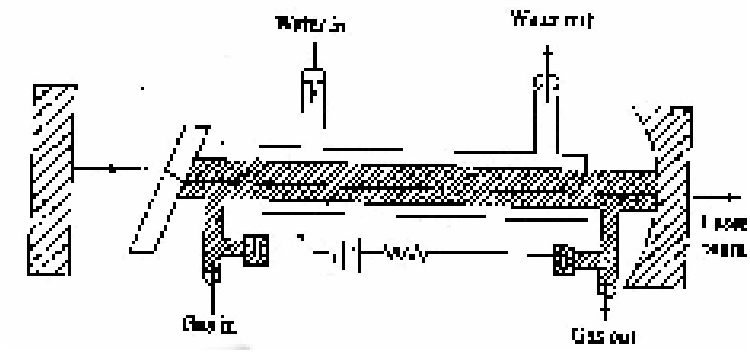
The specific proportions may vary according to the particular application. The population inversion in the laser is achieved by following sequence:

1. Electron impact excites vibration motion of the $N_2$. Because $N_2$ is a homo nuclear molecule, it cannot lose this energy by photon emission and it is excited vibration levels are therefore metestable and live for long time.
2. Collision energy transfer between the $N_2$ and the $CO_2$ molecule causes vibration excitation of the $CO_2$, with sufficient efficiency to lead to the desired population inversion necessary for laser operation.

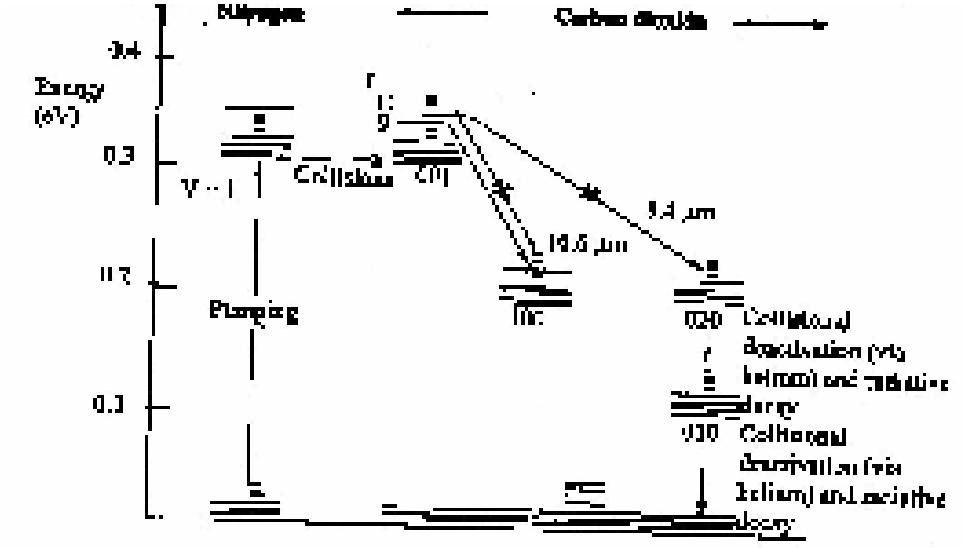
Because $CO_2$ lasers operate in the infrared, special materials are necessary for their construction. Typically the mirrors are made of coated silicon, molybdenum or gold, while windows and lenses are made of either germanium or zinc sulenide. For high power application gold mirrors and zinc selenide windows and lenses are preferred. Usually lenses and windows are made out of salt NaCl or KCl ). While the material is inexpensive, the lenses windows degraded slowly with exposure to atmosphere moisture.

The most basic form of a $CO_2$ laser consist of a gas discharge ( with a mix close to that specified above) with a total reflector at one end and an output coupler ( usually a semi reflective coated zinc selendine mirror ) at the output end. The reflectivity of the out put

coupler is typically around 5 – 15 %. The laser output may be edge coupled in higher power systems to reduce optical heating problems.



$CO_2$ lasers output power is very high compared to Ruby laser or He – Ne lasers. All $CO_2$ lasers are rated in Watts or kilowatts where the output power of Ruby laser or He – Ne laser is rated in mill watts. The $CO_2$ laser can be constructed to have CW powers between mill watts and hundreds of kilowatts.




## SEMICONDIRCTOR LASER (Gallium Arsenide Diode Laser or Homojunction Laser):

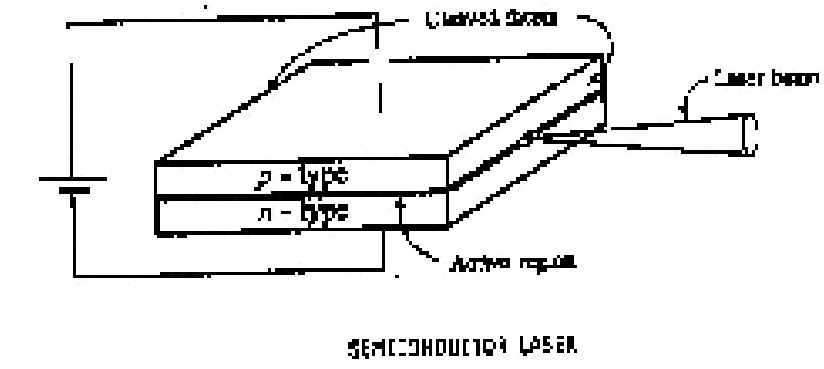
Semiconductor laser is also known as diode laser

***PRINCIPLE:***

In the case direct band gap semiconductors there is a large possibility for direct recombination of hole and electron emitting a photon. GaAs is a direct band gap semiconductor and hence it is used to make lasers and light emitting diodes. The wave lengths of the emitted light depend on the band hap of the material.

**CONSTRUCTIONS:** The P-region and N-region in the diode are obtained by heavily doping germanium and tellurium respectively in GaAs. The thickness of the P-N junction layer is very narrow at the junction, the sides 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 mirror are not necessary to produce multiple

reflections. The P-N junction is forward biased by connection positive terminal to P-type and negative terminal to N type.




SEMICONDUCTOR LASER

**WORKING:** When the junction is forward biased a large current of order$10^4$ amp/$cm^2$ is passed through the narrow junction to provide excitation. Thus the electrons and holes injected from N side and P side respectively. The continuous injection of charge carries the population inversion of minority carriers in N and P sides respectively.

The excess minority electrons in the conduction band of P – layers recombine with the majority holes in the valence band of P-layer emitting light photons similarly the excess minority holes in the valence band of N- layers recombine with the majority electrons in the conduction band of N- layer emitting light photons.

The emitted photons increase the rate of recombination of injected electrons from the N-region and holes in P- region. Thus more no of photons are produced hence the stimulated emission take place, light is amplified.

The wave length of emitted radiation depends upon the concentration of donor and acceptor atoms in GaAs the efficiency of laser emission increases, when we cool the GaAs diode.

***DRAWBACKS:-***

1. Only pulsed laser output is obtained
2. Laser output has large divergence
3. Poor coherence

**APPLICATION OF LASERS:**

**Lasers in scientific research**

1) Lasers are used to clean delicate pieces of art, develop hidden finger prints
2) Laser are used in the fields of 3D photography called holography
3) Using lasers the internal structure of micro organisms and cells are studied very accurately
4) Lasers are used to produce certain chemical reactions.

**Laser in Medicine:**

1) The heating action of a laser bean used to remove diseased body tissue
2) Lasers are used for elimination of moles and tumours, which are developing in the skin tissue.

3) Argon and $CO_2$ lasers are used in the treatment liver and lungs
4) Laser beam is used to correct the retinal detachment by eye specialist

**Lasers in Communication:**

1) More amount of data can be sent due to the large band with of semiconductor lasers
2) More channels can be simultaneously transmitted
3) Signals cannot tapped
4) Atmospheric pollutants concentration, ozone concentration and water vapour concentration can be measured

**Lasers in Industry:** Lasers are used

1) To blast holes in diamonds and hard steel
2) To cut, drill, welding and remove metal from surfaces
3) To measure distance to making maps by surveyors
4) For cutting and drilling of metals and non metals such a ceramics plastics glass

## Questions:

1. Explain the terms i) Absorption, ii) spontaneous emission, iii) Stimulated emission, iv) pumping mechanism , v) Population inversion, vi) Optical cavity
2. What is population inversion? How it is achieved?.
3. Explain the characteristics of a laser beam.
4. Distinguish between spontaneous and stimulated emission.
5. Derive the Einstein's coefficients.
6. With neat diagrams, describe the construction and action of ruby laser.
7. Explain the working of He – Ne laser
8. Describe the $CO_2$ laser
9. Explain the semiconductor laser.
10. Mentions some applications of laser in different fields.