# LASERS

1. Characteristics
2. Spontaneous and Stimulated emission of radiation.
3. Population Inversion.
4. Einstein Coefficients & Relation between them
5. Significance of Einstein Coefficients.
6. Pumping schemes
7. Ruby Laser, He-Ne Laser
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# Introduction

→ Laser is an acronym for light Amplification by Stimulated Emission of Radiation.

→ In laser the intensity of light is amplified by a process called stimulated emission. The theory of stimulated emission was introduced by Albert Einstein in 1917.

→ The phenomenon of stimulated emission was first used by Charles Townes in 1954 in the Construction of a Microwave amplifier Called the MASER which is the acronym for Microwave Amplification by Stimulated Emission of Radiation.

→ In 1958, the maser principle was later extended to the optical frequencies by Schawlow and Townes

→ In 1960, T.H. Maiman demonstrated Laser action at optical frequency in ruby Crystal.

→ In 1961, Ali Javan and his associates Constructed the first gas laser, the helium - neon laser.

## CHARACTERISTICS OF LASER

1. Highly Monochromatic
2. Highly coherent
3. Highly directional
4. High Intensity.

## Monochromaticity :

→ If a Source of emits Single colour (or) Single frequency light, then the source is Called monochromatic Source.

→ The light emitted by a Laser is more monochromatic than any Conventional monochromatic Source.

→ The Spectral line emitted by a Conventional monochromatic Source Spreads over a frequency range of the order of thousands of MHz. The light from a Laser Spreads very little.

→ Degree of monochromaticity of light expressed by line width $\Delta\nu$ (Spread in frequency of a line).

→ Degree of Monochromaticity $= \dfrac{\Delta\nu}{\nu_0}$

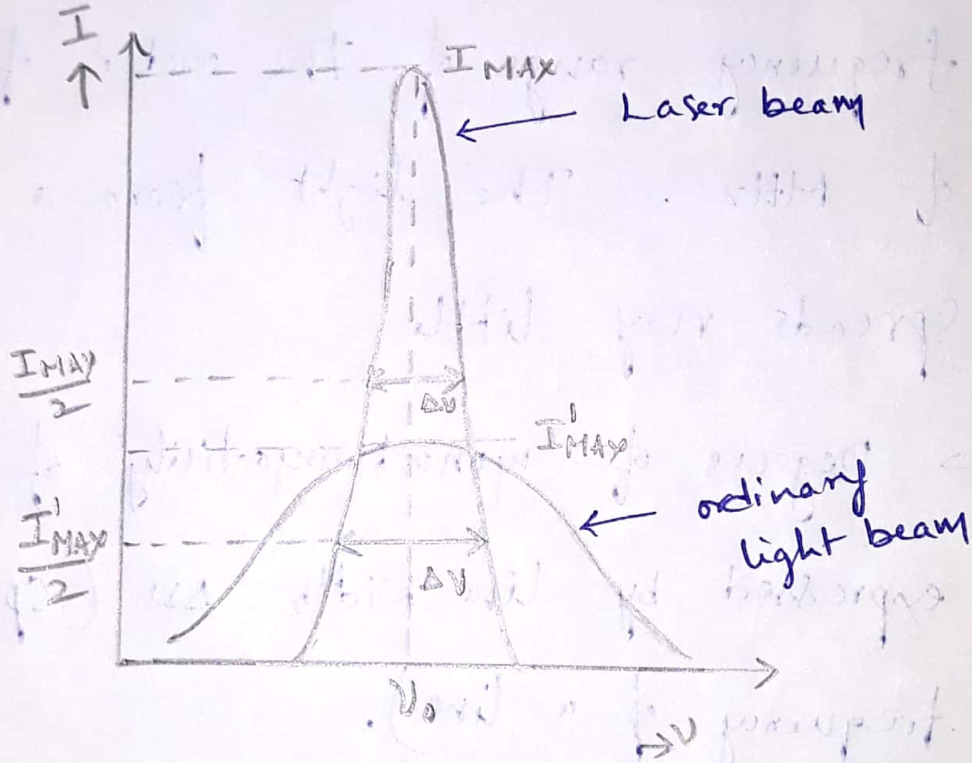
$\nu_0$ = central frequency of the light beam.

Absolute Monochromaticity for which $\Delta\nu = 0$ is an unattainable

→ The output from a high quality gas laser has a bandwidth

$\Delta\nu \sim 500\,Hz$ at $\nu_0 = 5\times10^{14}\,Hz$

$\left(\lambda = \frac{c}{\nu_0} = \frac{3\times10^8}{5\times10^{14}} = 6000\,\mathring{A}\right)$




## Coherence :

→ If a Source of light emits two waves of Same frequency and zero (or) constant phase difference, then the Source is called Coherent Source.

There are two types of Coherence

① Temporal Coherence

② Spatial Coherence.

## Temporal Coherence :

→ Temporal Coherence refers to the relation between phase of the two waves at two separate locations along the propagation direction of the two waves.

→ Temporal Coherence is also called Longitudinal Coherence.

→ Temporal Coherence tells us how monochromatic a source is.

→ If two waves very close to the source are exactly in phase, then the two waves maintain zero (or) near zero phase difference upto a certain distance $l_c$. This distance is called Coherence length.

→ Beyond $l_c$ the waves go completely out of phase.

→ The temporal (or) longitudinal coherence length is given by

$$\boxed{l_c = \frac{\lambda^2}{\Delta\lambda}}$$

where

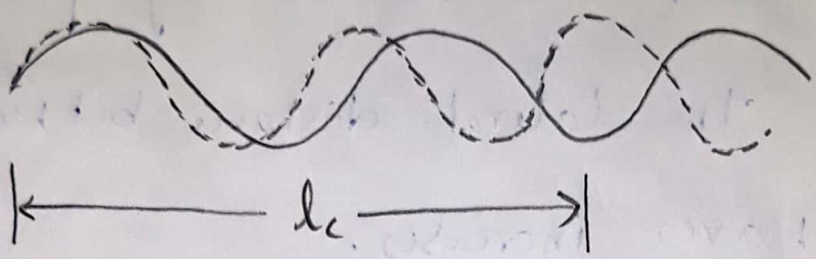
$\Delta\lambda$ = Difference in wavelength of the two waves

$\lambda$ = Average wavelength.

→ A highly monochromatic source will have large temporal coherence

Ex: $l_c$ (Mercury lamp) = 0.5 m

$l_c$ (He-Ne laser) = 301 m




## Spatial Coherence :

→ Spatial Coherence refers to the relation between phase of two waves at two separate locations perpendicular to the direction of propagation of two waves.

→ Spatial Coherence is also called Lateral (or) Transverse Coherence.

→ Consider two waves coming out of the source from the portions P and Q as shown in the fig. Let the Lateral distance between the two portions be "s".

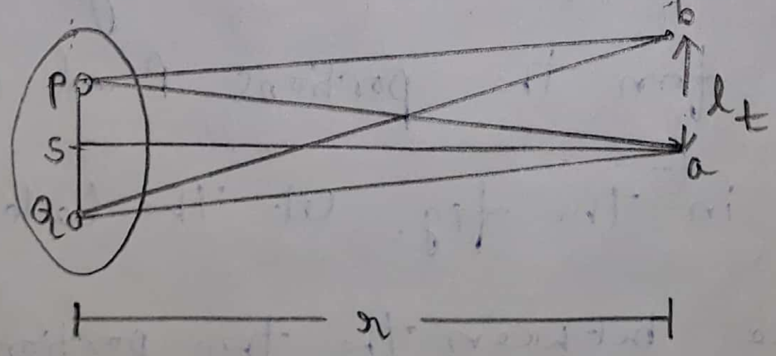
→ The two waves will be in phase as they emanate from the source.

→ As the waves travel away from the source the lateral distance between the two waves increases.

→ The phase difference will be maintained upto a certain distance "$r$" at which the lateral distance is $l_t$.

→ The distance $l_t$ is called spatial coherence length and is given by

$$\boxed{l_t = \frac{r\lambda}{s} = \frac{\lambda}{\theta}} \quad \left(\theta \approx \frac{s}{r}\right)$$



## Directionality :-

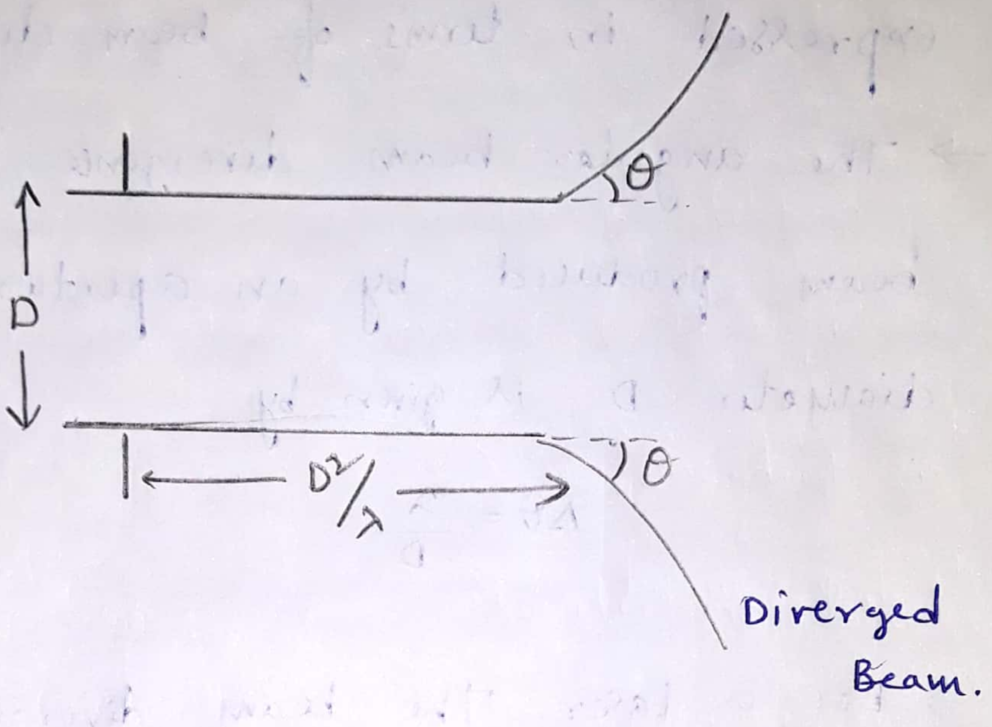
→ The directionality of Laser beam is expressed in terms of beam divergence.

→ The angular beam divergence "$\Delta\theta$" of a beam produced by an aperture of diameter D is given by

$$\boxed{\Delta\theta = \frac{\lambda}{D}}$$

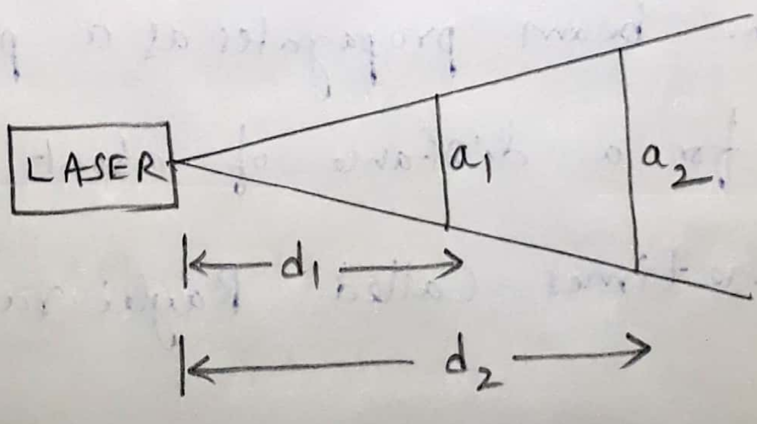
→ For a laser the beam divergence is less than 0.01 milliradian. It means that laser beam spreads less than 0.01mm for every meter travelled by it.

→ When a beam with plane wavefront radiates from an aperture of diameter D, then the beam propagates as a parallel beam for a distance of about $\frac{D^2}{\lambda}$ which is sometimes called Raylei range and then begins to spread linearly with distance due to diffraction.




→ If $a_1$ and $a_2$ are diameters of laser beam at distance $d_1$ and $d_2$ from laser window, then the angle of diverge can be expressed as.

$$\Delta\theta = \frac{a_2 - a_1}{d_2 - d_1}$$



## Intensity:

→ The light from a Conventional Source spreads out uniformly in all the directions.

→ At distance of 30 cm from a 100 watt bulb, power entering the eye is less than $\frac{1}{1000}$ watt. But laser gives out the light into a narrow beam and its energy is concentrated in a small region.

→ Hence even a laser of 1 watt would appear thousand times more intense than 100 watt ordinary bulb.

## Einstein Coefficients and Relations

There are 3 Einstein Coefficients

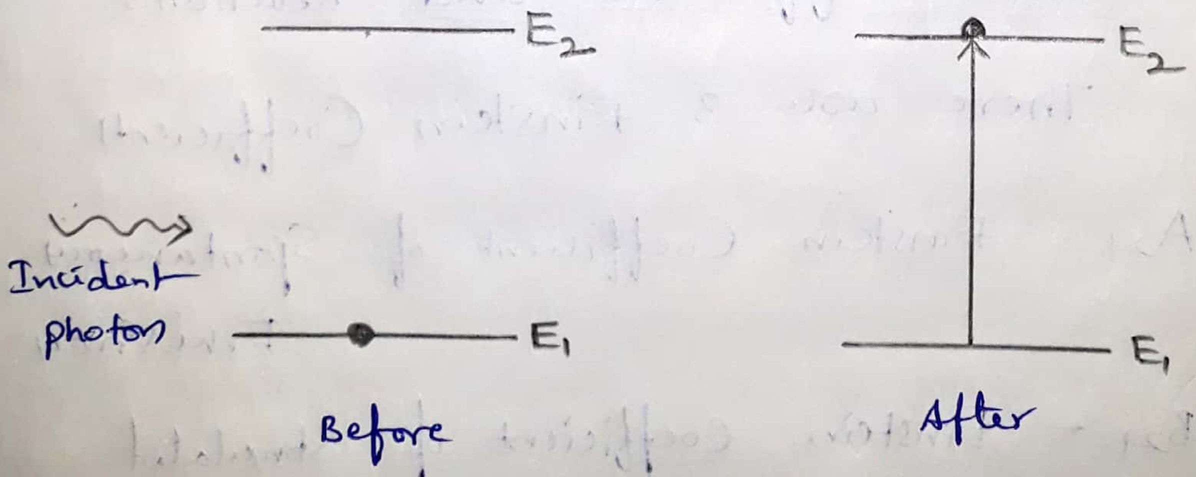
$A_{21}$ – Einstein Coefficient of Spontaneous Emission

$B_{21}$ – Einstein Coefficient of Stimulated Emission

$B_{12}$ — Einstein Coefficient of Stimulated Absorption.

## Stimulated Absorption:

Consider an atom in which electron is in lower energy level $E_1$. If a photon of energy $h\nu \, (= E_2 - E_1)$ is incident on the atom, then the electron absorbs energy from the incident photon and gets excited to the higher energy level $E_2$. This transition is called absorption transition.




$$A + h\nu \longrightarrow A^*$$

where $A$ is ground state atom and

$A^*$ is excited state atom.

→ The stimulated absorption rate $\propto N_1 \rho(\nu)$

$$= B_{12} N_1 \rho(\nu) \quad \text{—} (1)$$

Where

$N_1$ = Population of lower energy level

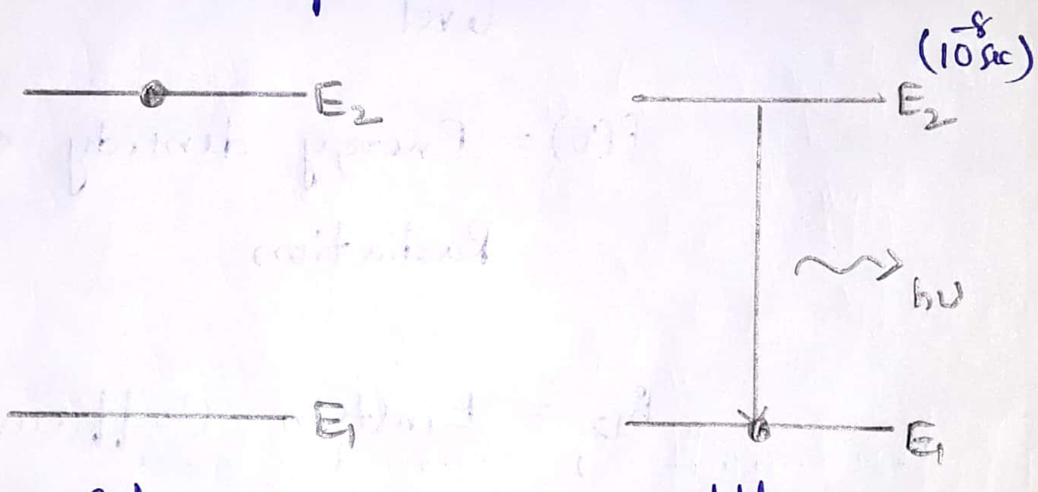
$\rho(\nu)$ = Energy dencidy of incident Radiation

$B_{12}$ = Einstein Coefficient of Stimulated absorption

## Spontaneous Emission :

Suppose an electron is excited from lower energy level to higher energy level. The electron cannot stay in the excited state for a relatively longer time. In a time about $10^{-8}$ s, the electron returns to the lower energy level by releasing a photon of energy $h\nu (= E_2 - E_1)$.

→ The emission of a photon by an atom without any external agency is called Spontaneous emission.




Before After

$$A^* \longrightarrow A + h\nu$$

→ The spontaneous emission rate $\propto N_2$

$$= A_{21} N_2 \quad \text{--- (2)}$$

where
$N_2$ = Population of Higher energy level

$A_{21}$ = Einstein's Coefficient of Spontaneous emission.

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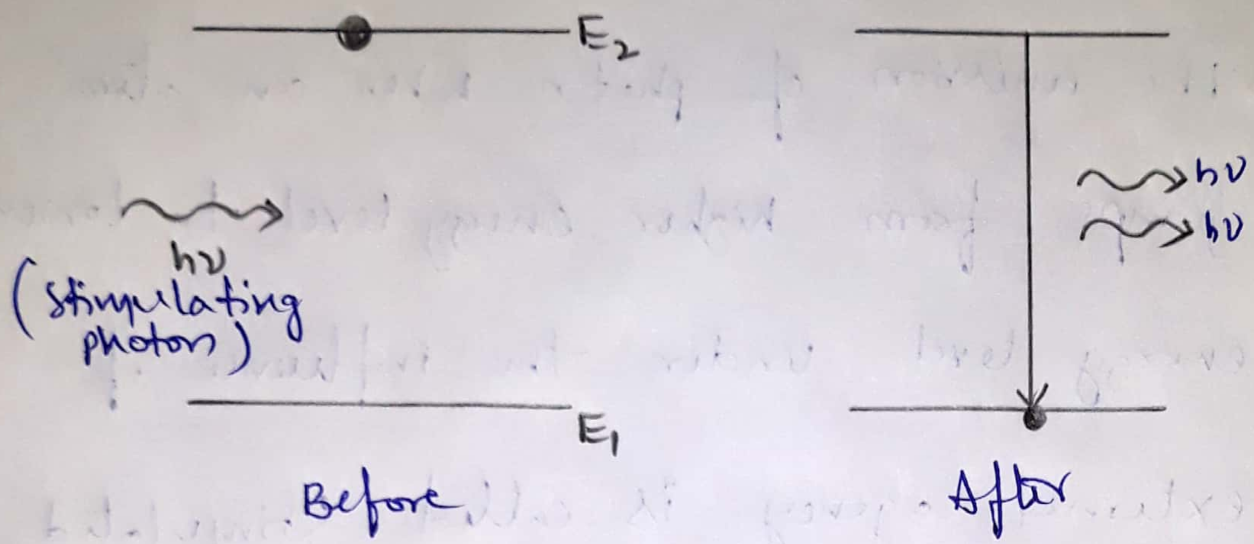
## Stimulated Emission :

→ The emission of photon when an atom jumps form higher energy level to lower energy level under the influence of external agency is called stimulated emission.

→ The photon which stimulate the atom in the excited state to make a transition to the lower energy level is called stimulating photon. (or) inducing photon.

→ Both the inducing photon and the emitted photon will have the same phase, energy and direction of movement.

→ This kind of emission is responsible for laser emission.




$$A^* + h\nu \longrightarrow A + 2h\nu$$

→ Stimulated Emission rate $\propto N_2 \rho(\nu)$

$$= B_{21} N_2 \rho(\nu) \quad \text{—} (3)$$

where

$B_{21}$ = Einstein Coefficient of Stimulated Emission.

→ At thermal equilibrium, the no. of upward transitions is equal to the number of downward transitions.

i.e, Upward transition rate = Downward transition rate.

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

$$\rho(\nu)\left[B_{12}N_1 - B_{21}N_2\right] = A_{21}N_2$$

$$\Rightarrow \rho(\nu) = \frac{A_{21}N_2}{B_{12}N_1 - B_{21}N_2}$$

$$= \frac{\dfrac{A_{21}\cancel{N_2}}{B_{21}\cancel{N_2}}}{\left(\dfrac{B_{12}}{B_{21}}\right)\left(\dfrac{N_1}{N_2}\right) - 1}$$

From Boltzmann distribution law,

$$N_1 = N_0 \, e^{-E_1/k_BT} \quad — (4)$$

$$N_2 = N_0 \, e^{-E_2/k_BT} \quad — (5)$$

Where $N_0$ = Total Number of Atoms

$k_B$ = Boltzman's Constant

$$\therefore \frac{N_1}{N_2} = e^{\frac{-E_1 + E_2}{k_BT}}$$

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

$$= e^{\frac{h\nu}{K_B T}} \quad (\because h\nu = E_2 - E_1)$$

$$\therefore \rho(\nu) = \frac{\frac{A_{21}}{B_{21}}}{\left(\frac{B_{12}}{B_{21}}\right) e^{\frac{h\nu}{K_B T}} - 1} \quad \text{—— (6)}$$

But the Planck's formula for the energy density is given by

$$\rho(\nu) = \frac{8\pi h \nu^3}{c^3} \cdot \frac{1}{e^{\frac{h\nu}{K_B T}} - 1} \quad \text{—— (7)}$$

→ Comparing equations (6) & (7), we get

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h \nu^3}{c^3} \quad \text{—— (8)}$$

$$B_{21} = B_{12} \quad \text{—— (9)}$$

Equations (8) and (9) are called Einstein relations between Einstein

Coefficients.

## Conditions to achieve more stimulated Emissions

$$R_1 = \frac{\text{Stimulated transitions}}{\text{Spontaneous transitions}}$$

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

$$= \frac{B_{21}}{A_{21}} \rho(\nu) \quad \text{——} \quad (1)$$

Eq (1) indicates that Stimulated transitions will dominate the Spontaneous transitions if

(1) $\rho(\nu)$ is very large

(2) $\frac{B_{21}}{A_{21}}$ is very large.

→ $$R_2 = \frac{\text{Stimulated transitions}}{\text{Stimulated absorption Transitions}}$$

$$R_2 = \frac{B_{21} N_2 \cancel{\rho(\nu)}}{B_{12} N_1 \cancel{\rho(\nu)}}$$

$$= \frac{N_2}{N_1} \quad (\because B_{12} = B_{21})$$

Hence the stimulated transitions will dominate absorption transitions if $N_2$ is greater than $N_1$.

→ To achieve more stimulated emissions than other transitions the following 3 conditions are to be satisfied.

1. $N_2$ should be greater than $N_1$. This situation is called population inversion.

2. The ratio $\frac{A_{21}}{B_{21}}$ should be large.

A large value of $\frac{A_{21}}{B_{21}}$ is achieved by choosing a metastable energy level as the higher level.

③ $\rho(\nu)$ should be large.

$\rho(\nu)$ is made large by using optical resonant cavity.

## Physical Significance of Einstein Coefficients

spontaneous emission rate = $A_{21} N_2$

$$\frac{dN_2}{dt} = -A_{21} N_2 \quad \text{——} ①$$

(−ve sign indicates that the population in energy level $E_2$ decreases with time)

Rearrange eq ①,

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

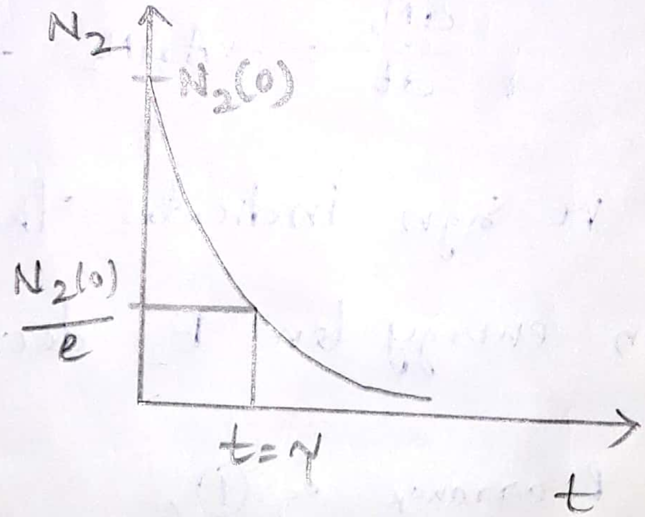
Integrating the above expression, we get

$$\log_e N_2 \Big|_{t=0}^{t=t} = -A_{21}t$$

$$\log_e \frac{N_2(t)}{N_2(0)} = -A_{21}t$$

$$\therefore \boxed{N_2(t) = N_2(0) \cdot e^{-A_{21}t}}$$

This equation indicates that the population in the energy $E_2$ decreases exponentially with time.




Let the population $N_2$ decrease by a factor $e$ at $t=\tau$, where $\tau$ denotes the life time of the excited energy level.

$$\therefore \quad N_2(t=\tau) = N_2(0) \cdot e^{-A_{21}\tau}$$

$$\frac{\cancel{N_2(0)}}{e} = \cancel{N_2(0)} \cdot e^{-A_{21}\tau}$$

$$e^{-1} = e^{-A_{21}\tau}$$

$$\therefore \quad \boxed{A_{21} = \frac{1}{\tau}}$$

Hence $A_{21}$ denotes the reciprocal of the life time of excited state.

→ Rewriting the eq. ①,

$$A_{21} = \frac{\left(\frac{dN_2}{dt}\right)}{N_2}$$

Hence $A_{21}$ denotes the probability of an atom undergoing Spontaneous emission

→ Similarly

$$B_{12} = \frac{\left(\frac{dN_1}{dt}\right)}{N_1\, \rho(\nu)}$$

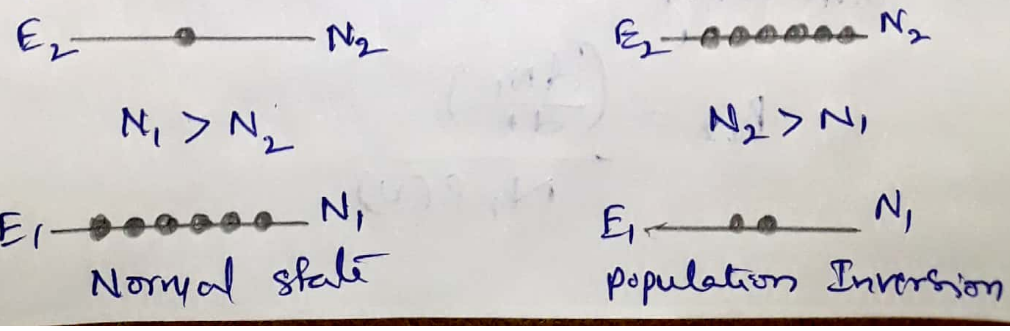
$B_{12}$ denotes the probability of an atom undergoing stimulated emission per unit energy density.

→ From $B_{21} = \dfrac{\left(\frac{dN_2}{dt}\right)}{N_2\,\rho(\nu)}$

∴ $B_{21}$ denotes the probability of an atom undergoing absorption per unit energy density.

## Population Inversion :

"The state in which excited energy level is more populated than Lower energy level is called population inversion."



## Pumping:

The process of raising atoms from the lower energy level to a higher energy level is called pumping.

## Pumping Methods

There are different pumping methods to pump atoms from lower energy level to higher energy level. They are

1. optical pumping
2. Electrical pumping
3. chemical Reaction
4. Direct Conversion.

## optical pumping:

In case of optical pumping an optical source like xenon flash lamp is used to pump the atoms from lower energy level to higher energy level.

Ex: Solid state laser (Ruby laser)

② Electrical pumping:

In electrical pumping an electric discharge is passing through the gas to produce population inversion

Ex: Gas laser (He-Ne laser)

③ Chemical Reaction:

Chemical Reaction may also result in excitation and hence Creation of population inversion in few systems.

Ex: HF, DF and Atomic iodine lasers.

## ④ Direct Conversion :

In this type of pumping, a direct Conversion of electric energy into light takes place.

Ex: Semiconductor laser.

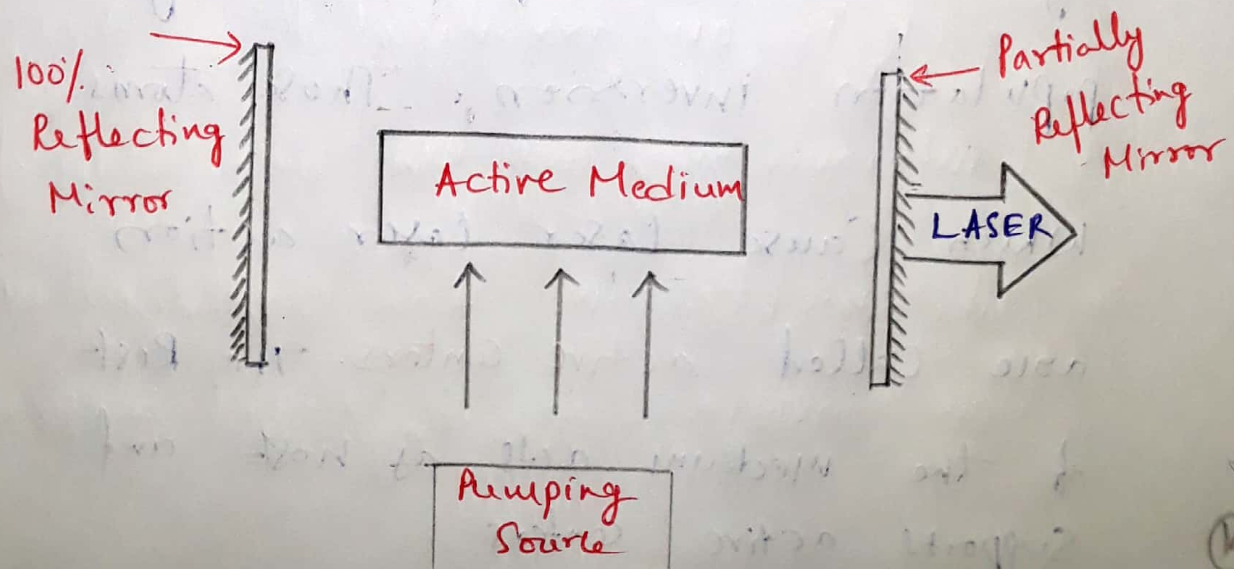
## Components of a LASER :-

A laser system has 3 important components. They are

① Active Medium

② Pumping Source

③ optical Resonator.



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## 1. Active Medium :

"An active medium is a medium which when excited reaches the state of population inversion and promotes stimulated emissions leading to light amplification."

→ If a medium consisting of different types of atoms, then only a small fraction of atoms of a particular type have energy level system suitable for achieving population inversion. Those atoms which cause laser action are called active centers. The Rest of the medium acts as host and supports active centers.

2. Pumping Source :

A pumping Source is required to achieve population inversion.

→ Different pumping methods are used in different lasers.

(a) Solid State Laser (Ruby laser) — optical pumping

(b) Gas Laser (He-Ne laser) — Electric Discharge

(c) Semiconductor laser — Direct Conversion.

3. optical Resonator :

It is an arrangement of two plane mirrors placed on both Sides of the Active medium. one of these mirrors is fully reflecting and reflects all the light that is incident on it. The other mirror is made partially reflecting such that more than 90% of incident light is reflected from it and a small fraction is transmitted through it as the laser beam.

## Pumping Schemes :

Two important pumping schemes are

① 3 level pumping scheme

② 4 level pumping scheme.

## 3 level pumping scheme :

→ In this scheme 3 energy levels are involved in the laser emission.

→ The energy level $E_1$ is the ground state, $E_2$ is a metastable state and $E_3$ is a normal excited state (pumping level).

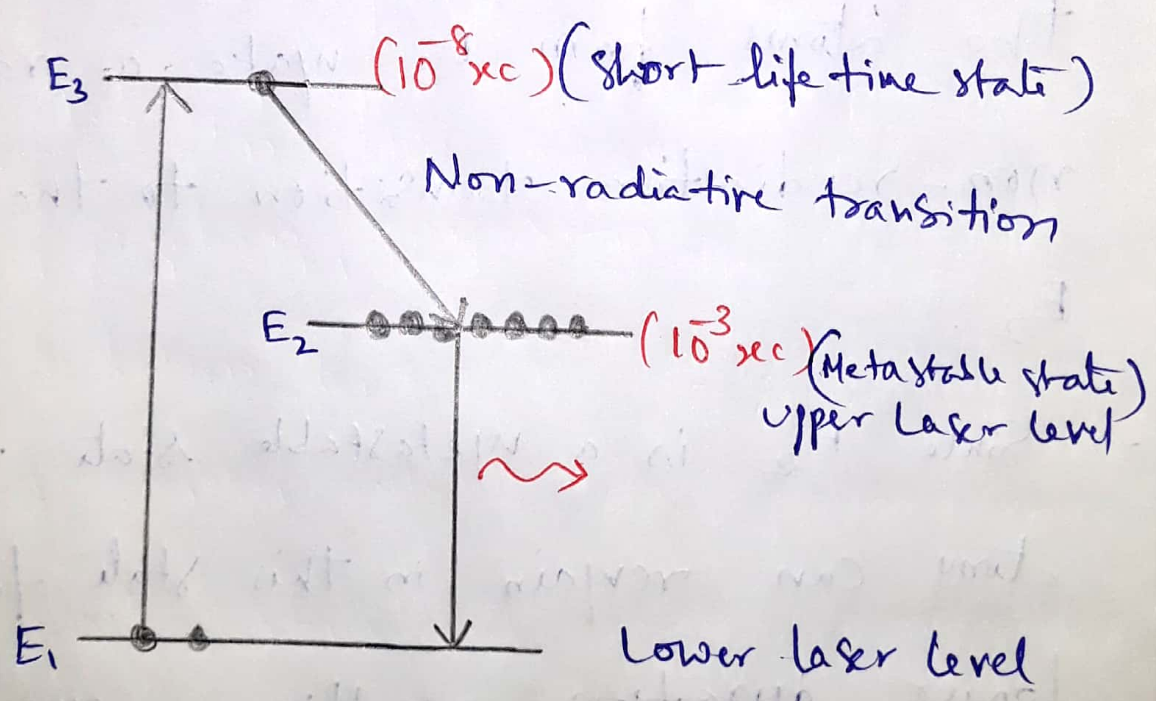
→ When light of energy ($h\nu = E_3 - E_1$) is incident on the medium, atoms from the ground state $E_1$ are excited to the pumping level $E_3$.

→ As $E_3$ has a short life time ($\sim 10^{-8}$ sec), the atoms from $E_3$ make a rapid non-radiative transition to the level $E_2$.

→ Since $E_2$ is a metastable state the atoms can remain in this state for a longer duration resulting in accumulation of atoms in $E_2$.

→ When more than half of the ground state atoms accumulate at $E_2$, the population inversion is achieved between the energy levels $E_1$ and $E_2$.

→ Now Spontaneously emitted photon (chance photon) can trigger stimulated emission from $E_2$ to $E_1$ resulting in LASER.



## Drawback :

Since the lower lasing level is ground state, to achieve population inversion between $E_2$ and $E_1$, more than half of the ground state atoms have to be pumped to the upper lasing level. Hence high pumping power is required.

## 4 level pumping Scheme :

→ In this scheme 4 energy levels are involved in the laser system.

→ The level $E_1$ is the ground state, $E_2$ is a normal excited state, $E_3$ is a metastable state and $E_4$ is the pumping level.

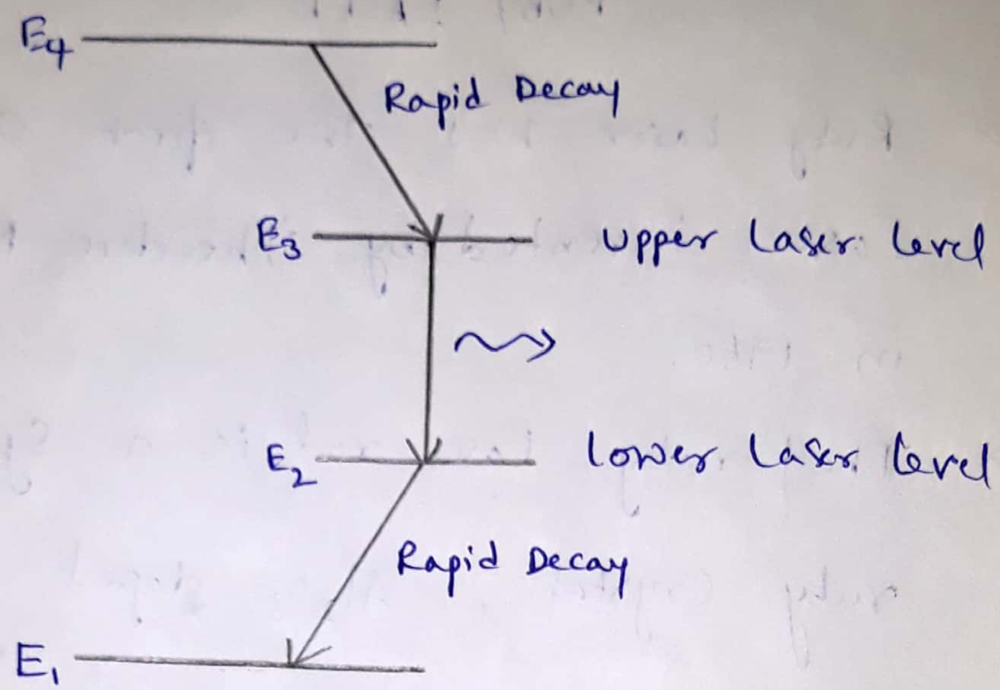
→ When light of pumping energy ($h\nu = E_4 - E_1$) is incident on the material, the atoms are raised from ground state to the pumping level $E_4$.

→ Since $E_4$ is a short life time energy state, the atoms from $E_4$ undergo rapid decay to metastable state $E_3$.

→ Since $E_3$ is metastable state, there is accumulation of atoms in this level.

→ After a short time, the no. of atoms in the level $E_3$ will become more than that in the lower level $E_2$ i.e, population inversion is achieved between the levels $E_3$ and $E_2$.

→ A spontaneously emitted photon can start stimulated emission from $E_3$ to $E_2$ giving rise to LASER.




→ From the level $E_2$ atoms undergo rapid decay to the ground state $E_1$.

Advantage :

As the lower lasing level $E_2$ is not a ground state, the population inversion between $E_3$ and $E_2$ can be achieved at relatively low pumping power.

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# RUBY LASER

→ Ruby Laser was the first Solid state Laser invented by Theodore Maiman in 1960.

→ The ruby laser rod is a Synthetic ruby Crystal, $Al_2O_3$ doped with Chromium ions with the Concentration of about 0.05% by Weight

→ Ruby Laser is an example for 3 level pumping scheme.

## Components of a Laser:

1. Active Medium : Ruby rod ($Al_2O_3 + Cr_2O_3$)

   Active centers : $Cr^{+3}$ ions

2. pumping Source : optical

3. optical Resonator : The Arrangement two plane parallel Mirrors on both Sides of the Active Medium.

Among the two mirrors one mirror is fully reflecting and the other Mirror is partially reflecting.

## Construction :-

→ Ruby rod is taken in the form of a cylindrical rod of length 4cm and diameter 0.5 cm.

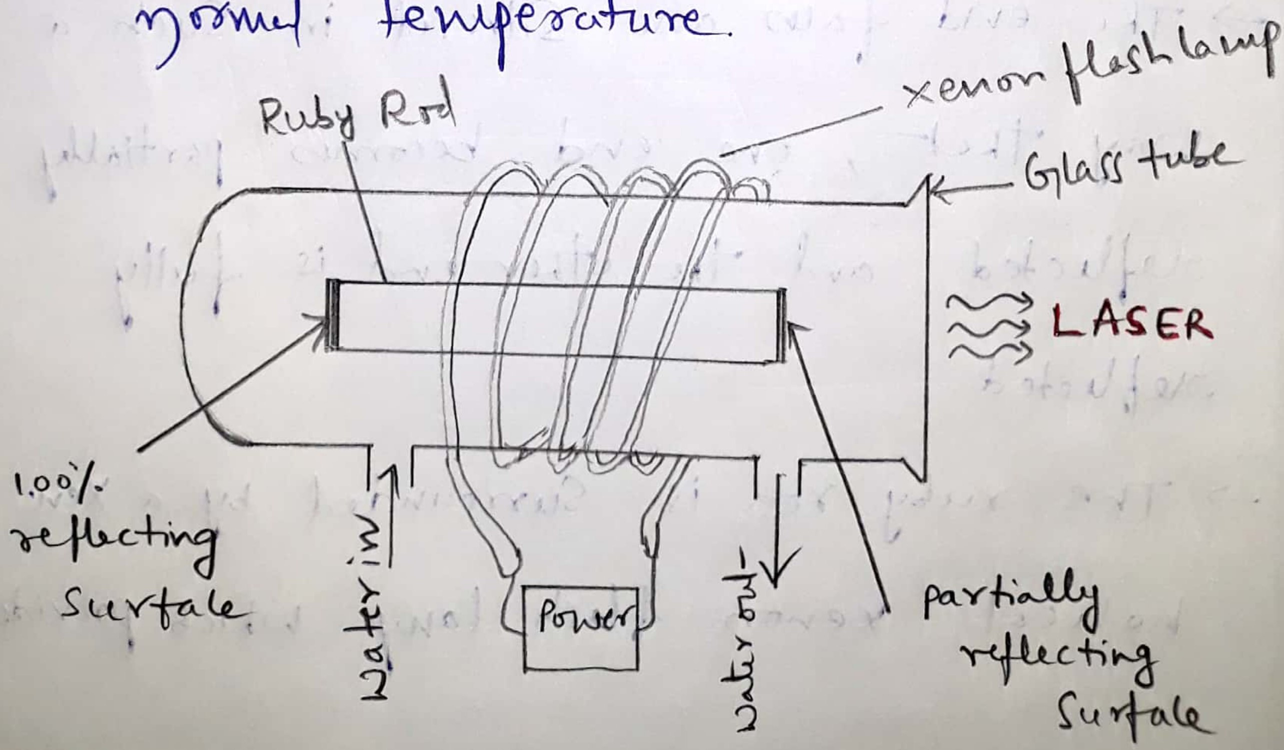
→ The end faces of the ruby rod are polished such that the end faces are exactly parallel to each other and perpendicular to the axis of the rod.

→ The end faces are silvered in such a way that, one end becomes partially reflected and the other end is fully reflected.

→ The ruby rod is Surrounded by a helical xenon flash lamp which provides pumping energy to excite the chromium ions to upper energy levels.

→ Xenon flash lamp produces flashes of white light of short duration. A part of this light energy is ultilised by the chromium ions while the remaining energy heats up the apparatus.

→ A cooling arrangement is provided to keep the experimental setup at normal temperature.



## Working :

→ The energy level diagram of chromium ion is shown in the fig.

→ There are two pump bands $E_3$ and $E_3'$. The level $E_2$ is a metastable state.

→ When the flash lamp is activated, the lamp generates an intense burst of white light lasting for a few milliseconds.

→ The $Cr^{+3}$ ions are excited to the energy bands $E_3$ and $E_3'$ by absorbing blue and green components of white light.

→ As $E_3$ and $E_3'$ have short life time, the chromium ions undergo rapid non-radiative transition to the metastable state $E_2$.

→ Since the lifetime of the metastable state is more, the number of ions in this state goes on increasing due to the continuous pumping.

→ After a short time, the level $E_2$ is more populated than the level $E_1$ and hence the population inversion is achieved between $E_2$ and $E_1$.

→ When the excited chromium ion passes spontaneously from $E_2$ to $E_1$, a photon of wavelength 6943 Å is emitted.

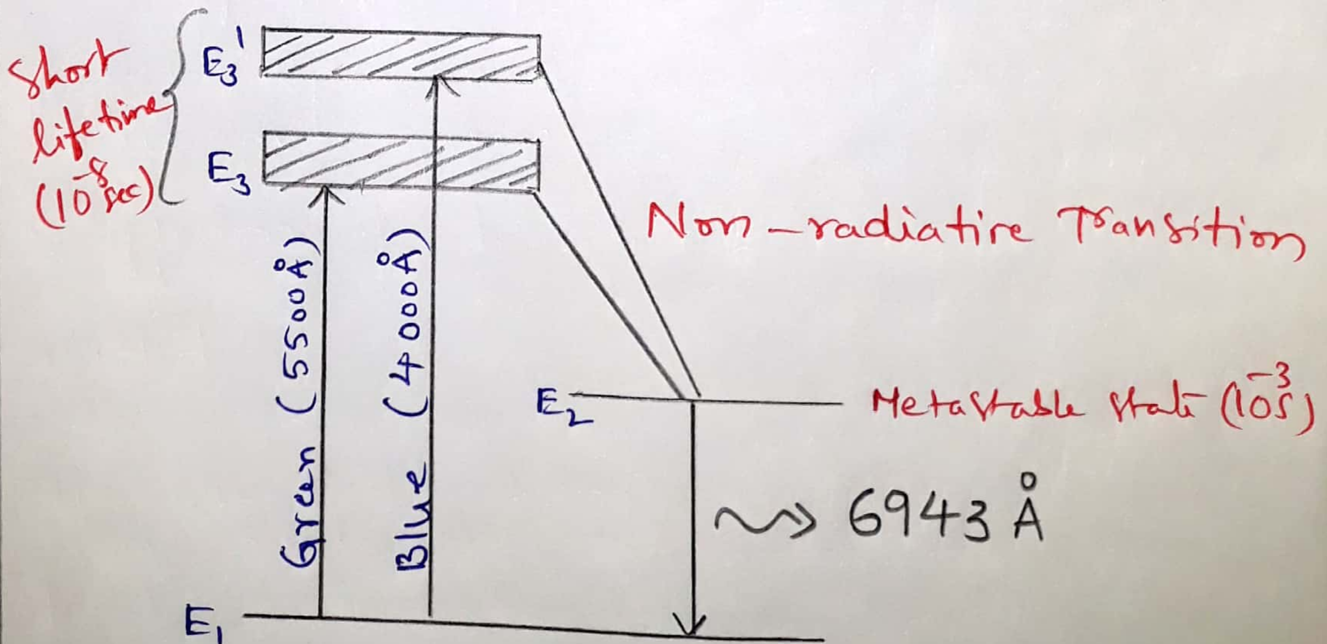
→ The emitted photon reflected back and forth by the silvered

Surfaces and produces more stimulated emissions.

→ The process is repeated again and again until the Laser beam has sufficient intensity.

→ When the beam gets sufficient intensity, it emerges from the partially silvered end of the rod.

→ The wavelength of the Laser beam is 6943 Å.



Drawbacks :

1. The Laser requires high pumping power

2. The efficiency of ruby laser is very small.

3. It is a pulsed Laser.

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# He-Ne Laser

→ The He-Ne Laser was the first gas Laser invented by Ali Javan and his coworkers in 1961.

→ The He-Ne Laser is an example of 4 level pumping scheme.

## Components of a Laser:

1. Active Medium : Gas Mixture (He and Ne)

   He : Ne = 10 : 1

   Active Centers : Ne atoms.

2. Pumping Source : Electrical Discharge

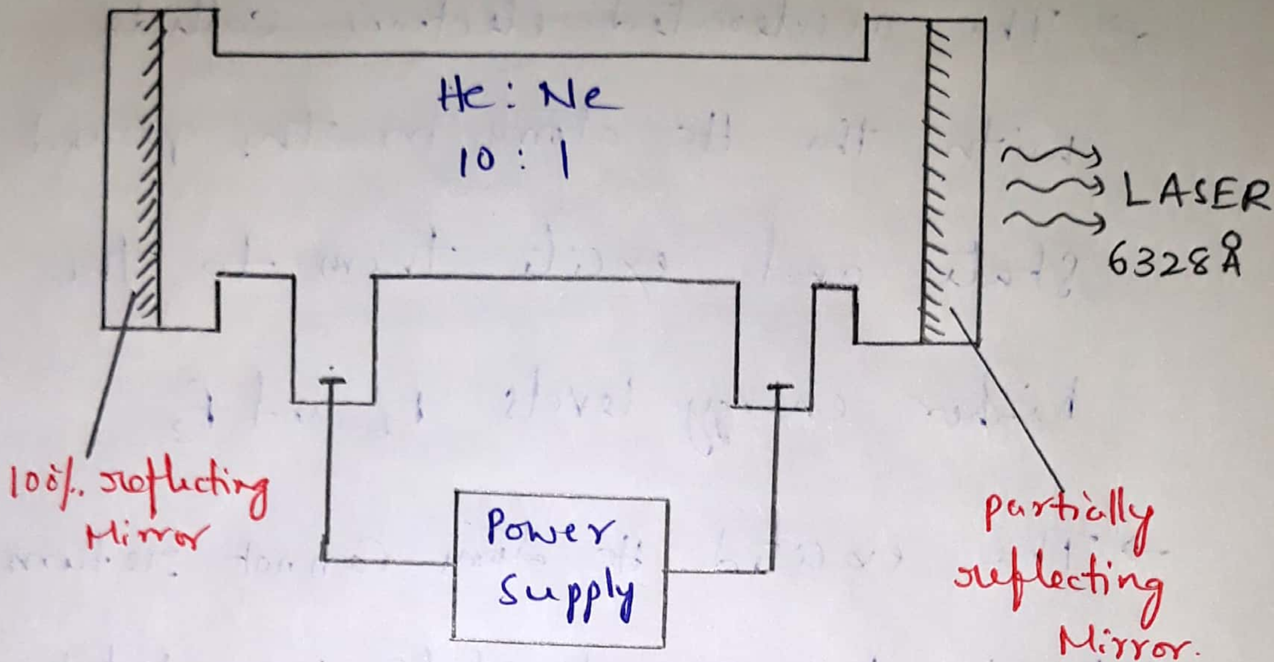
3. optical Resonator : The arrangement of two plane parallel Mirrors, one of the Mirrors is fully reflecting and the other Mirror is partially reflecting.

## Construction :

→ He-Ne Laser Consists of a long narrow discharge tube filled with a mixture of helium and neon gases in the ratio 10:1

→ Electrodes are provided in the discharge tube to produce discharge in the gas. They are connected to high voltage power supply.

→ At both ends of the tube, there are optically plane and parallel mirrors. one of the Mirror is fully silvered and the other is partially silvered.




## Working :

→ The energy levels of He and Ne atoms are shown in the fig.

→ If a high voltage of about 10kV is applied to the electrodes, then an electric discharge is passing through the gas mixture.

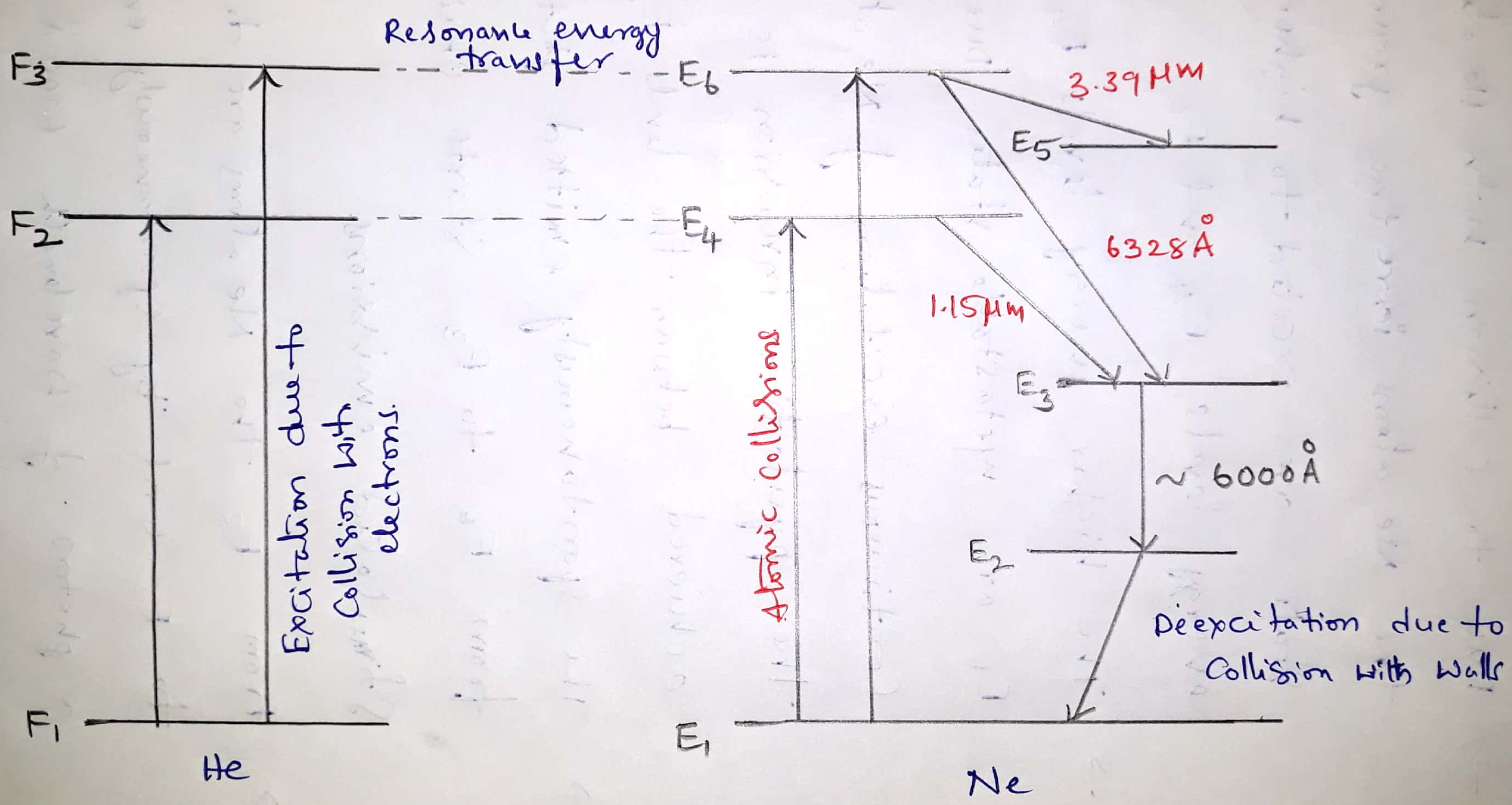
→ The electrons and ions produced in the process of discharge are accelerated towards anode and Cathode respectively.

→ The accelerated electrons collide with the He atoms in the ground state and excite them to the higher energy levels $F_2$ and $F_3$.

→ The excited He atoms cannot return back to ground state immediately as $F_2$ and $F_3$ levels are metastable states.

→ The excited He atoms return back to ground state $F_1$ by giving their energy to the ground state Ne atoms through atomic collisions. Such an energy transfer is called "resonance energy transfer" which is possible only if two colliding atoms have identical energy levels.

# ENERGY LEVEL DIAGRAM



→ Due to Collision with He atoms, the Ne atoms in the ground State are excited to higher energy levels $E_4$ and $E_6$.

→ The higher energy levels $E_4$ and $E_6$ are metastable states. Due to Continuous excitation of Ne atoms, the population inversion is achieved between the levels $E_6$ and $E_3$.

→ The spontaneously emitted photon from $E_6$ to $E_3$ starts chain of stimulated emissions.

→ From $E_3$ the Ne atoms are de-excited to $E_2$ level by spontaneously emitting a photon of wavelength 6000 Å.

→ If a narrow discharge tube is used, the Ne atoms in the level $E_2$ are rapidly drop to the ground level by colliding with the walls of the tube. Now the atoms available in the ground state for excitation once again.

→

| Transition | Wavelength of the Laser |
|---|---|
| $E_6 - E_5$ | 3.39 μm |
| $E_6 - E_3$ | 6328 Å |
| $E_4 - E_3$ | 1.15 μm |

→ The laser transitions corresponding to 3.39 μm and 1.15 μm are not in the visible region.

→ only the transition corresponding to 6328 Å lies in the visible region.



Scanned with CamScanner

Advantages:

1. Low pumping power is required
2. High Efficiency
3. output is continuous.

-x-

# Applications of LASER :

1) **Industry :**

   (a) cutting
   (b) welding
   (c) Drilling
   (d) Marking

2). **Medical :**

   (a) Cosmetic Surgery
   (b) Eye Surgery
   (c) Dentistry
   (d) Removal of kidney and Gall Stones.
   (e) Cancer diagnosis and theraphy
   (f) Bloodless Surgery

3) **Scientific :**

   (a) Isotopes separation
   (b) Nuclear Fusion
   (c) Spectroscopy

(d) Holography

(e) optical fiber Communication.

(f) LIDAR (Light Detection and ranging)

4) DEFENCE :

(a) Laser Designator

(b) Guiding Missile

(c) Range finders

5) Commercial :

(a) Laser printer

(b) pointers

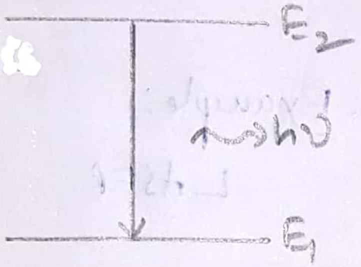
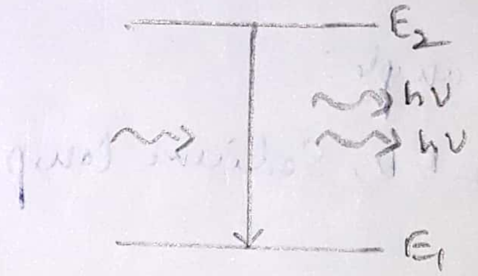
(c) CD & DVD player

(d) Laser show

(e) Barcode Scanner

(f) Laser spean gun

# Differences between Spontaneous and Stimulated Emissions.

| Spontaneous Emission | Stimulated Emission |
|---|---|
| 1. The emission of a photon when atom drop to the ground state from excited state without any external agency. | 1. The emission of a photon when atom drop to the ground state from excited state with the help of external agency. |
|   |   |
| 2. One photon is emitted | 2. Two photons emitted |
| 3. It is an uncontrollable process | 3. It is a controllable process |
| 4. Less Intensity | 4. More Intensity |
| 5. polychromatic radiation | 5. Monochromatic radiation |
| 6. It was postulated by Bohr | 6. It was postulated by Einstein. |

| | |
|---|---|
| 7. Incoherent radiation | 7. Coherent radiation. |
| 8. The emitted photons move in the random direction. | 8. The emitted photons move in the same direction. |
| 9. Less Directionality | 9. High directionality |
| 10. Emission rate $= A_{21} N_2$ | 10. Emission rate $= B_{21} N_2 \rho(\nu)$ |
| 11. Example: LED, Sodium Lamp | 11. Example: LASER |