Assignment on LASER

LASER

1. Explain in brief Three and Four level pumping scheme. Why four level pumping scheme is preferred over three level scheme. OR Explain how four level pumping scheme is more efficient than three level pumping scheme. (S- 2012) OR State and explain two important pumping schemes in laser.(S- 2003,2005,2007)
 Distinguish between three level and four level laser pumping schemes.
2. What is an optical resonator cavity? What role does it play in a laser? Or
Write the function of optical resonant cavity. (S- 2012). State Resonance/ Steady state oscillation condition in Optical Cavity Resonator for Light amplification.
3. What is a laser? How it differs from ordinary source of light? OR How is laser light different from an ordinary light?
4.With the help of neat sketches, explain the three quantum processes that may occur when light radiation interacts with matter. Which of these processes is maximized in laser operation? (W-2003,S-2006,2007)
5. Discuss the properties or characteristics of laser beam.(S-2011,2000)
6.Define / Explain the following terms.
(i)Population inversion (ii) Metastable state (iii) Stimulated Emission (iv) Temporal coherence (W-2004)
 (v) Spontaneous emission vi) Pumping vii) Active Medium
7. State and Explain the condition for light amplification
8.Distinguish between (i) Spontaneous and Stimulated emission (ii) Three level and four level lasers. (S 2006)
9. Define / Explain the terms- Temporal and spatial coherence (S-2002, S-2004)
10.What is resonant cavity ? What is its role in laser operation.? (S- 2000,2003,2005,2007)

11.(a)Describe the construction and working of a solid state Ruby laser.
(b) Describe the action of ruby laser using energy level diagram.
 (c)Why the end faces of ruby rod are silvered?
12.With the help of energy level diagram explain how population inversion is achieved in He-Ne laser. OR Explain working of He-Ne laser with the help of suitable energy level diagram. OR Explain the construction and working of He-Ne laser with the help of energy level diagram.(S-2012)_
Explain why increase in diameter of He-Ne tube may reduce lasing frequency? (S-2006)
13.Give two engineering application of laser source. And discuss one of them. OR Mention any three engineering applications of laser.(S-2000,2005,W-2004)

Q.14. In He-Ne Laser, what is the function of He atom? Why is it necessary to use a tube of narrow diameter?
Q.15. Write essential components of a Laser?
Q.16. Write the conditions for light amplification.
Q.17. Explain in brief how four level laser more efficient than three level laser?

LASER

Laser is a photonic device, which is actually responsible for the resurgence of interest in optical technology and for the birth of new field, namely photonics.' The word **LASER** is an acronym for **"Light Amplification by Stimulated Emission of Radiation"**. As the name suggests the amplification is achieved through the process of stimulated emission. The process of stimulated emission can be understood as one of three possibilities arising out of the interaction of matter with radiation.

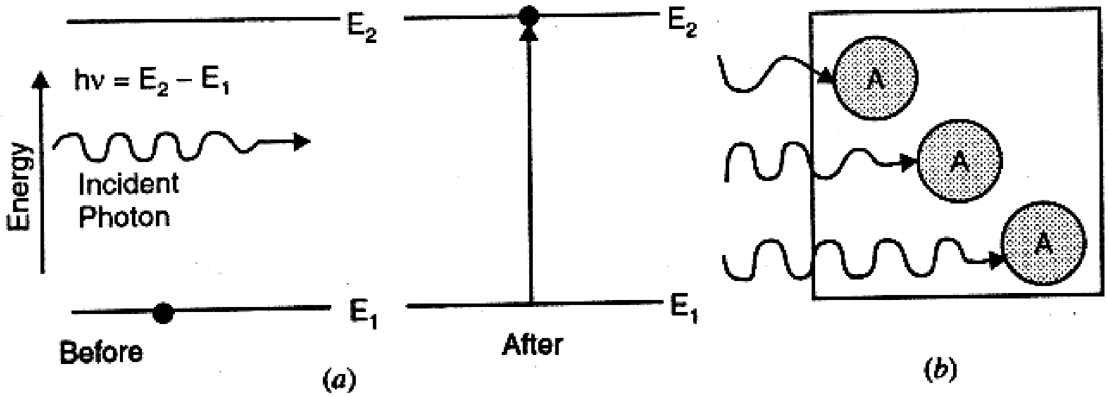
Interaction of light with matter:
A material medium consists of identical atoms or molecules, which are characterized by discrete energy levels. These energy levels are common to all atoms in the medium. According to Einstein's predictions, an atom can move from one energy level to another when it receives or releases an amount of energy equal to energy difference between those two states. This transition is called **quantum transition or quantum jump.**

Principle of working of LASER: LASER is light source which utilizes **quantum processes / quantum transitions for its operation.**

Q.) Explain the terms((i)Coherence (ii) Metastable state (iii) Stimulated emission(S-13/3m)
Q.) Explain the terms (i) Population Inversion (ii) Metastable state (iii) Stimulated emission (S-14/3m)
Q.) What is meant by population inversion and how it is achieved in Ruby laser?(W-15/3m)
Q.) Define the terms: i) Metastable state ii) Temporal Coherence iii) Stimulated emission. (S-16/3m)
Q.) Explain the terms: i) Spontanous emission ii) Stimulated emission iii) Population inversion. (W-16/3m)
Q) Explain the following terms/ quantum processes/ quantum transition?
1) Stimulated or Induced Absorption 2) Spontaneous Emission 3) Stimulated Emission
1) Stimulated or Induced Absorption:-
Let E_1 and E_2 are the ground energy level & excited energy level respectively. An atom residing in lower state E_1 is interacting with the incident photon of energy hν. It absorbs the incident photon and jumps to the excited state E_2. The transition is called **stimulated or induced absorption** and the process is expressed as

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

Where, A - atom in ground state
A* - atom in excited state



Absorption process (*a*) Induced absorption (*b*) Material absorbs photons.

The number of absorption transitions taking place in the material is proportional to the number density of atoms (N_1) in the lower state E_1 and photon density in the incident beam

N_{ab} - No. of atoms excited during time Δt. $\boldsymbol{N_{ab} \propto N_1 \cdot Q \;\therefore N_{ab} = B_{12}\, N_1 \cdot Q \cdot \Delta t}$

$N_{ab} = B_{12}N_1Q\Delta t$ -----------(1)

Where, N_1 is the number of atoms in state E_1 or density of atoms in E_1 state.

Q is the radiation (photon) density in the incident beam.

B_{12} is constant of proportionality **or** Einstein coefficient of Stimulated or Induced Absorption.

Moreover, the number of atoms in the lower state of the material absorbs more incident energy. Therefore, the absorption process leads to attenuation of radiation as light travels through the medium.

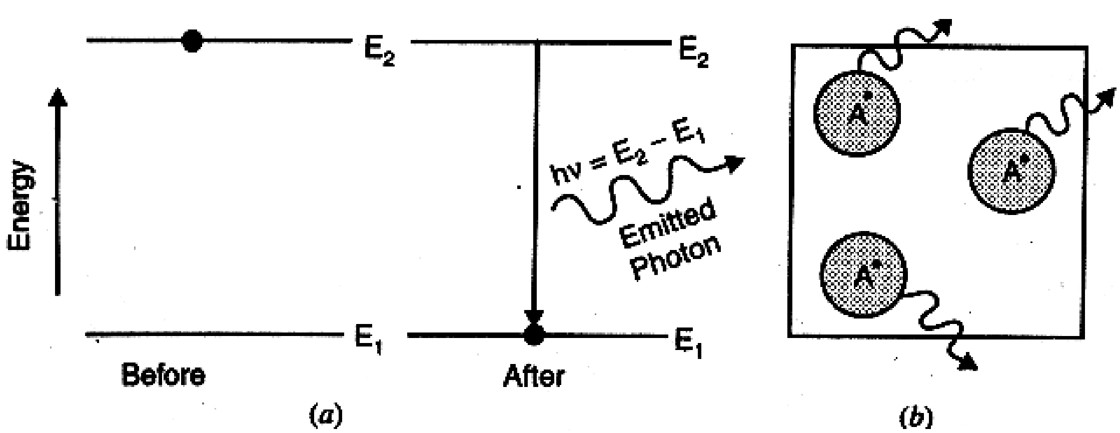
2) Spontaneous Emission:-

Excited state with higher energy is unstable. Due to the natural tendency of atoms to stay in the lower energy state, the excited atoms do not stay in excited state for longer time but tends to return to the lower states by giving up excess energy (E_2-E_1= hν) in the form of photon. The excited atoms in the state E_2 may return to lower state E_1 on its own. This type of process in which photon is emitted without any external impetus is called spontaneous emission.

Definition: The process of photon emission by an excited atom without any external impetus i.e. on its own,is called **Spontaneous Emission.**

Schematically it can be represented as

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



Spontaneous emission process (*a*) emission (*b*) Material emits photons haphazardly.

The number of spontaneous transitions N_{sp} taking place in the material during time Δt depends only on the number of atoms (N2) lying in the excited state E_2.

$$N_{sp} \propto N_2$$

$$N_{sp} = A_{21}N_2\Delta t$$

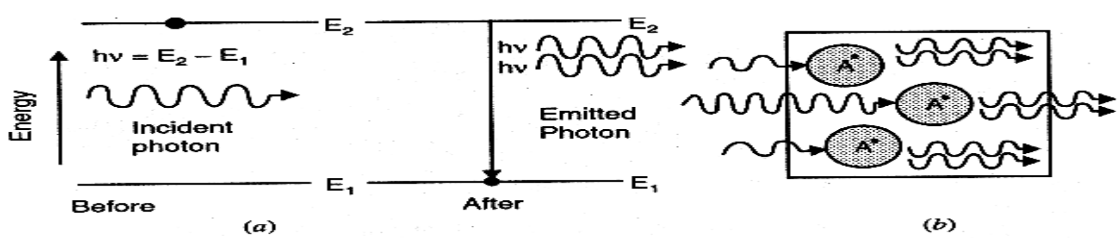
Where, N_2 – density of atoms in E_2 state

A_{21} – Constant of proportionality **or** Einstein's coefficient of **Spontaneous Emission.**

3) Stimulated Emission:-

An atom in the excited state need not wait for spontaneous emission to occur. There exists an alternative mechanism by which an excited atom can make a downward transition and emit light. A photon of energy (hν) can induce the excited atom to make downward transition releasing the energy in the form of photon. Thus, interaction of photon with excited atom triggers the excited atom to drop to lower energy level giving up a photon. **This phenomenon of forced emission of photons is called induced emission or stimulated emission.**

Definition: The process of forced photon emission by an excited atom under the influence of external agent is called **Stimulated Emission.**



Stimulated emission process (*a*) emission. (*b*) Material emits photons in a coordinated manner.

Schematically it can be expressed as

$$A^* + h\nu \rightarrow A + 2\,h\nu$$

The number of stimulated emission transitions taking place in the material is proportional to the number density of atoms (N_2) in the upper state E_2 and photon density Q in the incident beam. The number of stimulated transitions occurring in material in the time Δt is

$$N_{st} = B_{21}N_2Q\,\Delta t$$

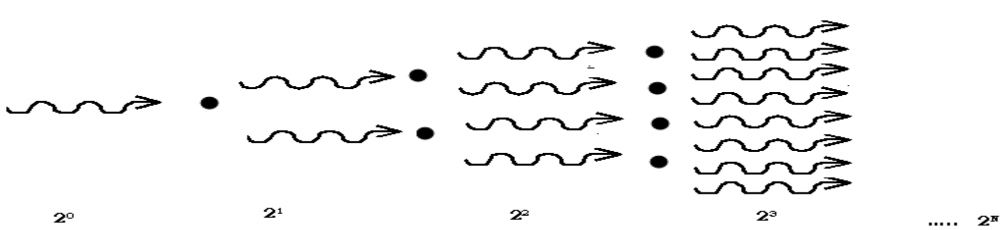
Where B_{21} = constant of proportionality

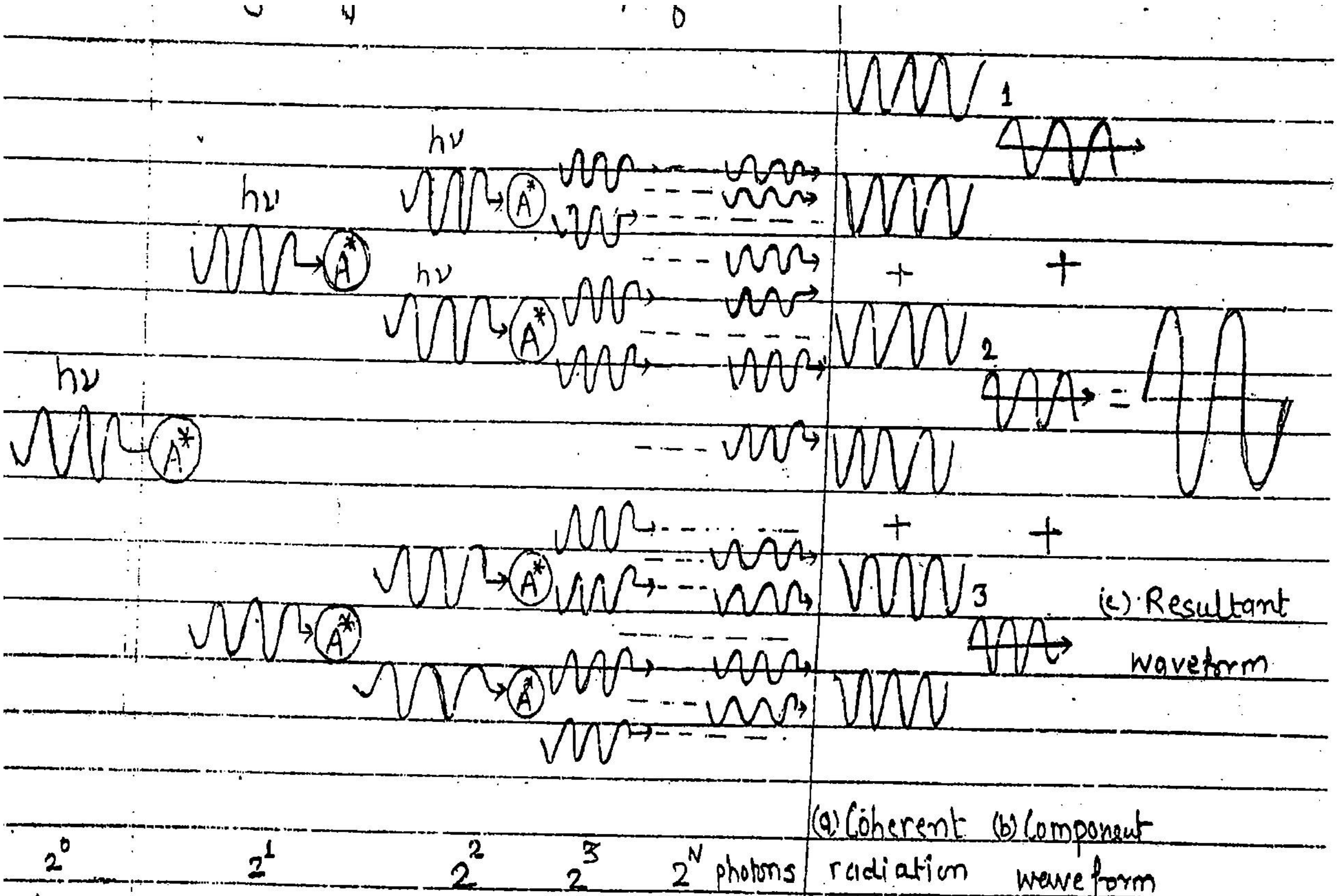
Features/Characteristics of stimulated emission:

1. This process is controllable from outside.
2. Emitted photon propagates in the same direction as that of the stimulating/incident photon.
3. Frequency, phase and plane of polarization of both incident and emitted photon are same.
4. The light produced in this process is unidirectional, coherent and monochromatic.
5. In this process multiplication of photons takes place. One photon induces an excited atom to emit a second photon. These two travelling in same direction, de-excite two atoms in their path producing a total of four photons which in turn stimulate four atoms in avalanche like manner as shown in above figure (b).

Comparison between Spontaneous Emission and Stimulated Emission

Spontaneous Emission	Stimulated Emission
1. Spontaneous emission is a random and probabilistic process.	1 Not a random process.
2. The process is not controllable from outside	2 Controllable from outside
3. The resultant light is not monochromatic	3 Highly monochromatic
4 Light emitted through this process **is incoherent**. Spontaneously emitted photons have random phases. Hence the emitted beam of light is incoherent.	4 **Highly coherent** All the emitted photons have same phase as that of incident one. Hence the emitted beam of light is highly coherent. Coherent length of source emitting stimulated emission is of few kms
5 Photons are emitted uniformly in all directions. Therefore, the light beam is **non-directional.**	All the photons are emitted in same direction and travel parallel to cavity axis. Therefore, the light beam is **Uni-directional**.
6 No multiplication of photons takes place and hence no amplification of light takes place.	Multiplication of photons leads to amplification of light.
7 The intensity of light decreases with distance.	The stimulated photons travel in same direction and due to negligible divergence their energy is concentrated in very small area of space. Therefore, **the intensity of beam of light is very high and remains constant over a great distance.**
8 The light waves associated with emitted photons travel in form of spherical wavefronts. Hence the emitted beam of light is highly divergent.	The light waves associated with emitted photons travel in form of plane wavefronts. They travel in form of bundle of parallel rays. Hence the emitted beam of light has negligible divergence.
9 The net intensity is proportional to the number of radiating atoms, thus $I_{total} = NI$ Where N – no. of atoms I - Intensity of light emitted by one photon.	5 The net intensity is proportional to the square of number of radiating atoms, thus $I_{total} = N^2 I$ Where N – no. of atoms, I - Intensity of light emitted by one photon





Multiplication of stimulated photons into an avalanche

Fig: Coherent radiation

Population: The number of active atoms in the energy state is called **population** of that state. Thus, N_1 and N_2 are the population of lower energy state E_1 and upper energy state E_2.

OR

The number of atoms per unit volume that occupy a given energy state is called **population of that state.**

Active centers: Atoms which cause light amplification are called as **Active centers.**

Active medium: An active medium is a medium which hosts the active centers.

An active medium is a medium which, when excited, reaches the state of population inversion, and eventually causes for light amplification.

OR

The medium in which light gets amplified is called **active medium**. It may be solid, liquid or gas.

OR

An active medium is a medium in which population inversion can be achieved with the help of a pumping agent.

Thermal Equilibrium:- Let N_1 be the population of E_1 and N_2 is the population of E_2,

$N_1 = \exp(-E_1/kT)$, $N_2 = \exp(-E_2/kT)$

Population ratio $= N_2/N_1 = \exp[-(E_2 - E_1)/kT]$ ----imp. For problems

Thus, in thermal equilibrium population of energy levels E_2 and E_1 are fixed by Boltzmann factor.

The population ratio is also called as relative population. The negative component in eqn. represents that $N_2 << N_1$. i.e. at equilibrium more no. of atoms are in E_1 and this state is called normal state.

When external radiation is incident on medium then under the steady state condition the process takes place simultaneously.

Atoms in the lower energy level E_1 will absorb radiation and make a transition to upper level E_2. Atoms in the upper level will emit radiation and make a transition to lower level.

In order to maintain N_1 and N_2 constant, **the no. of upward transitions must be equal to no. of downward transitions**

$$N_{ab} = N_{sp} + N_{st}$$

$$B_{12}N_1Q\,\Delta t = A_{21}N_2\,\Delta t + B_{21}N_2Q\,\Delta t$$

$$B_{12}N_1Q = A_{21}N_2 + B_{21}N_2Q$$

A_{21}, B_{12}, B_{21} are called Einstein coefficients.

<u>Condition for light amplification</u>:

At thermal equilibrium, the ratio of the stimulated to spontaneous transitions is very small and the stimulated emission is negligible.

Therefore, stimulated emission transition / spontaneous emission transitions = $\frac{B_{21}N_2Q}{A_{21}N_2} = \frac{B_{21}}{A_{21}}Q$ -----(1)

The ratio of stimulated to absorption trasitions

stimulated emission transitions / absorption transitions = $\frac{B_{21}N_2Q}{A_{12}QN_1} = \frac{N_2}{N_1}$ ----------(2)

Since $B_{21} = B_{12}$ as the probability of stimulated emission transition must be equal the probability of stimulated absorption transition.

1) Equation (1) shows that in order to enhance the number of stimulated emission, the radiation density **Q is to be made larger**.
2) Equation (2) shows that stimulated emission will be larger than absorption only when $\mathbf{N_2 > N_1}$

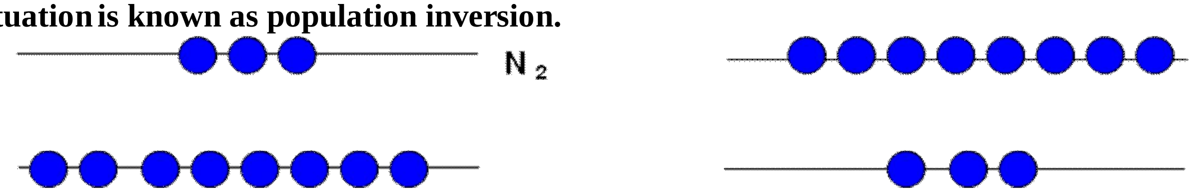
When these two conditions are fulfilled, the medium amplifies light passing through it.

<u>Population inversion/ Non-eqilibrium state/Negative temperature state:</u>

The number of atoms or energy levels decreases as the energy level increases. The ratio of number of atoms or molecules in one or two states is given by,

$$\frac{N_2}{N_1} = \exp\left[\frac{-(E_2 - E_1)}{kT}\right]$$, where k is Boltzmann constant.

Thus, usually number of atoms in higher energy state is less than the number of atoms in lower energy state. i.e., under normal condition $N_2 < N_1$, but **if the number of atoms in upper (higher) energy states is made more than number of atoms in lower energy state, i.e.$N_2 > N_1$, then that state or situation is known as population inversion.**



Normal State $N_2 << N_1$ **Inverted State $N_2 >> N_1$**

Thermal Equilibrium State **Population inversion State**

<u>Metastable state:</u>

An atom in excited state has short life time (10^{-9}s) and atoms do not stay for a longer time in excited state. In order to establish the condition of population inversion, the excited atoms are required to wait

at upper energy level till the large no. of atoms accumulated at that energy level. i.e. it is necessary that the excited state has a longer life time.
A metastable state is (an intermediate state between excited and ground state) a longer lived upper energy level in which a life time of atoms is the order of 10^{-6} to 10^{-3}s. Thus, metastable state allows accumulation of a large no. of excited atoms at that level. It is necessary to achieve Population inversion.

<u>LASER BEAM CHARACTERISTICS</u>
Q) Difference between ordinary and LASER light?

1) Coherence:- A conventional light source/ natural source (sun) produces an incoherent light since they emit random wavelength. Light waves with no common phase relationship.
But waves emitted by Laser source are always in phase and are of same frequency. Light generated by a Laser is highly coherent.

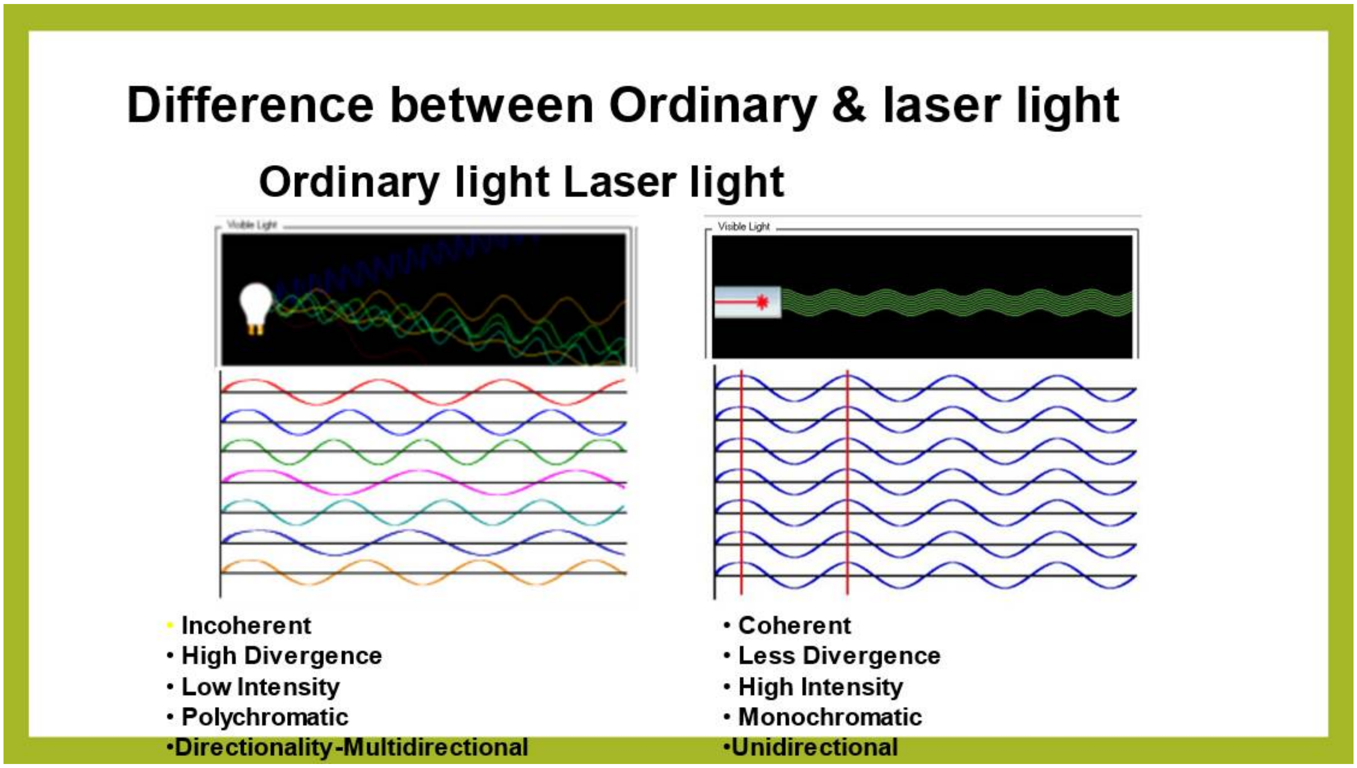
2) Directionality:- Conventional source emits light in all directions whereas Laser emits light only in one direction (because the photons travelling along the optic axis of the system are selected and augmented with the help of optical resonator. Laser is unidirectional.

3) Divergence:- Light from conventional sources spreads out in the form of spherical wavefronts and hence is highly divergent. Divergence of Laser beam is very small (when the light issues out from the front mirror), it undergoes diffraction because semitransparent front mirror acts as a circular aperture. Its angular spread is given by

$$\Delta\theta = \frac{1.22\lambda}{d}$$

4) Intensity:- Intensity of light from a conventional source decreases rapidly with distance, as it spreads in the form of spherical waves.
Laser emits light in the form of a narrow beam. Its intensity is tremendously high. Its energy is concentrated in a narrow region. **Intensity of Laser beam stays constant with distance as light travels in the form of plane waves.**

5) Monochromaticity:- The light from a ordinary source spreads over a wavelength of a range of order of $100A^o$ to $1000A^o$.
Laser light is highly monochromatic. The spread is of the order of few A^o .
Conventional sources emit wave trains of very short duration and length, but Lasers emits continuous waves of very short duration.



Pumping:- For releasing and maintaining the condition of population inversion, the atoms have to be raised continuously to excited state. It requires energy to be supplied to the system.

The process of supplying energy to the medium to transfer it into the state of population inversion is known as **pumping**.

Lasing Transition: The transition between two levels that generates stimulated emission is called a **lasing transition.** The terminal level is called **lower lasing level** and upper level is known as **upper lasing level.** The upper most level is known **as pumping level.**

Three level pumping:-

Three levels pumping have three energy levels E_1(ground state), E_2(metastable state) and E_3(excited state). Initially all atoms are in ground energy state E_1. After supplying external energy $\mathbf{E_3 - E_1 = h\nu_p}$ to the ground state, these atoms will be excited to the higher energy state E_3.

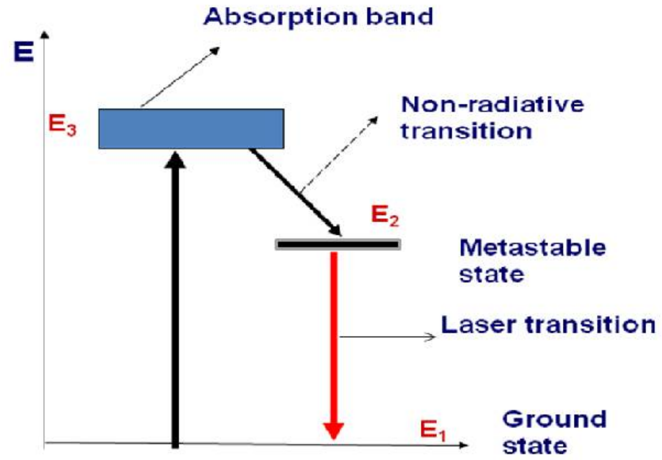
Atoms do not stay at the E_3 level and undergo downward transition either at E_1 or E_2 levels. (i.e., From E_3 some of these atoms make spontaneous transitions to the lowest level E_1 but maximum number of atoms make spontaneous transitions to metastable state E_2 through non-radiative transition). The probability of spontaneous transition from E_3 to E_1 is less as compared to that of E_3 to E_2. As E_2 is metastable state thus the probability of spontaneous transitions from E_2 to E_1 is extremely small and the atoms get trapped in the state E_2.

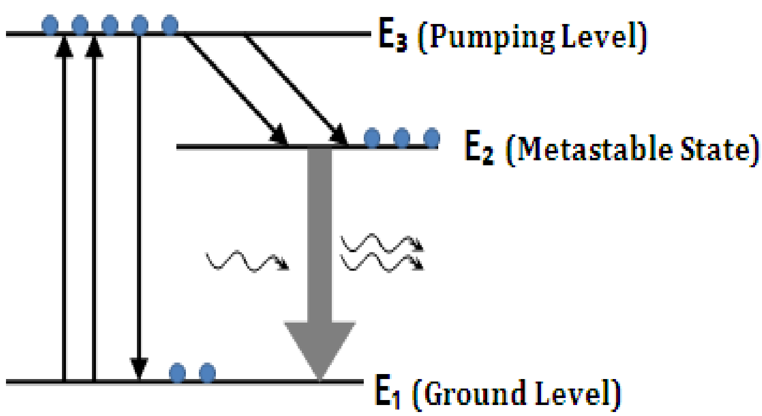
The process continues because of pumping and after a short time there will be accumulation of atoms at E_2. When more than half of the ground state atoms accumulate at E_2, the population inversion condition achieved between the states E_1 and E_2. One of the spontaneously emitted photon of energy $h\nu = E_2 - E_1$ can trigger chain of stimulated emissions of atoms from E_2 and lasing action starts between the excited state E_2 and ground state E_1.

In this scheme, to achieve population inversion more than half of the ground state atoms must be pumped to the upper state. Therefore, **very high power is required.**

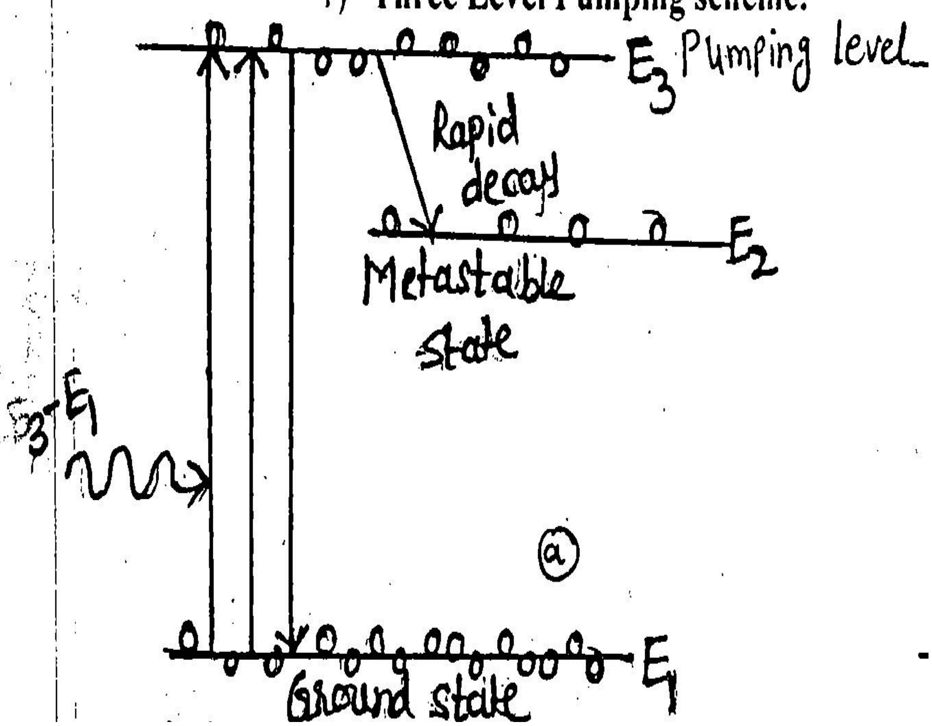
The output of three level laser scheme is **pulsed output and not continuous**, which is one of the most serious **drawbacks** with this scheme.

Ruby laser is based on three level pumping scheme.





I) Three Level Pumping scheme:



Four level Pumping:-

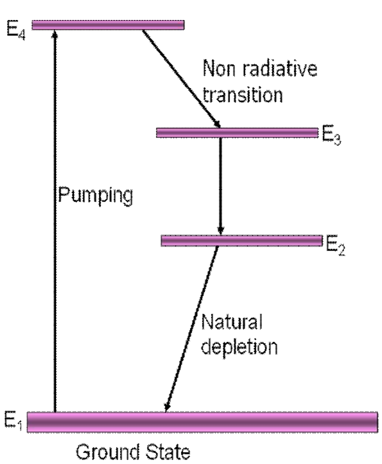
A typical four level pumping scheme is as shown in fig. Let E_1 is the ground state, E_4 is the excited state, E_3 is the metastable state and E_2 is the lower lasing level.

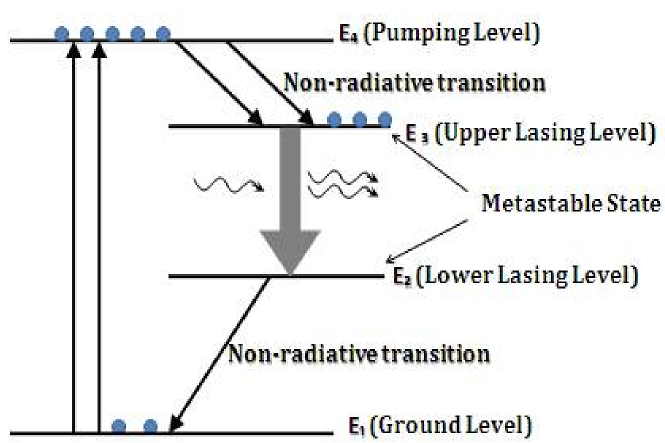
When light of pumping frequency ν_p **($h\nu_p = E_4 - E_1$)** is incident on the ground state energy level E_1, the active centers are readily excited from the ground state to the pumping level E_4. Since E_4 is excited state, these atoms stay for only about 10^{-8} sec, and quickly drop down to the metastable state E_3. E_3 is the metastable state having life time 10^{-6} to 10^{-3} sec which is more than the life time of excited state E_4, spontaneous transition from level E_3 to level E_2, cannot take place and thus atoms get trapped in the state E_3. {The level E_2 is well above the ground state such that $(E_2 - E_1) > kT$. Therefore, at normal temperature atoms cannot jump to level E_2 on the strength of thermal energy}. As a result, the level E_2 is virtually empty.

When atoms accumulate in metastable stable (E_3), population inversion condition arises between E_3 and E_2. The one of the spontaneously emitted photon of energy $h\nu = E_3 - E_2$ can start the stimulated emissions, bringing the atoms to the lower level E_2. From state E_2 the atoms subsequently undergo non-radiative transition to the ground state E_1 and will be once again available for excitation, making it possible for light to be emitted continuously.

The lower laser transition level in this scheme is nearly vacant. Therefore, **less pump power is sufficient to achieve population inversion**. Four level lasers operate in **continuous wave mode**.

1. In a four level pumping scheme, as shown in figure, level E_1 is ground state, E_2 & E_3 are two metastable states and E_4 is excited state.
2. Pumping action lifts the active centers (atoms) from ground level E_1 to pumping level E_4. E_4 is an excited state.
3. As E_4 is highly unstable the atoms make non-radiative transition to E_3.
4. But state E_3 is metastable state, and hence atoms get trapped at E_3.
5. Due to continuous pumping, population of E_3 increases. Since $E_2$is virtually empty, population inversion is easily achieved between E_3 & E_2.
6. Now, a photon of energy $h\upsilon = E_3 - E_2$ can trigger chain of stimulated emissions of atom fromE_3 and atoms come down to E_2 and lasing action starts between two excited states.
7. From E_2 atoms undergo non-radiative transition to ground state E_1.
8. In this scheme, to achieve population inversion more than half of the ground state atoms must be pumped to the upper state. Therefore, very high power is required.
9. The output of three level laser schemes is pulsed output and not continuous, which is one of the most serious drawbacks with this scheme.
10. He–Ne laser is based on four level pumping scheme.





Advantages:-

1) In four level pumping scheme, the terminal level of the laser transition (E_2) is virtually empty and population inversion condition can be easily achieved / established even if less (small) number of atoms arrive at the upper lasing level E_3. Hence **less pumping power is required** to establish population inversion in four level pumping schemes.
2) The condition of population inversion can be held continuously without interruption. Hence light output can be obtained continuously. So, laser operates in **continuous wave mode (CW).**

Q.) Why four level pumping is more efficient than three level pumping scheme? (W-13/3m)

Q.) Explain how four level pumping scheme is more efficient than three level pumping scheme. (S-15/3m)

Q) How four level laser is more efficient than three level laser?

Ans: 1) In three levels pumping scheme, the terminal level of laser transition is ground level. To achieve population inversion more than half of the ground level atoms have to be pumped upto the upper lasing level (i.e. E_2, metastable state), such that $N_2 > N_1$. As the ground level is heavily populated, **high pumping power is required to establish population inversion**.

But in four level pumping scheme, the terminal level of laser transition is virtually empty (i.e. E_2 level) so population inversion can be easily established even if smaller number of atoms arrive at the upper lasing level. Therefore, relatively **less pumping power is required** to establish population inversion, in four level pumping schemes.

2) In case of three level pumping scheme once stimulated emission commences, population inversion condition reverts to the normal population condition ($N_1 > N_2$). So lasing ceases as soon as the excited atoms drop to the ground level during lasing action. Lasing occurs only when population inversion is re-established. Hence the **laser output is in pulses or pulsed mode or pulsed output**.

But in case of four levels pumping scheme, condition of population inversion can be maintained continuously hence **laser output is in continuous wave (CW) mode**.

COMPONENTS OF LASER / BLOCK DIAGRAM OF LASER

The essential components of LASER are,

I] An active medium
II] A pumping agent
III] An optical Resonator

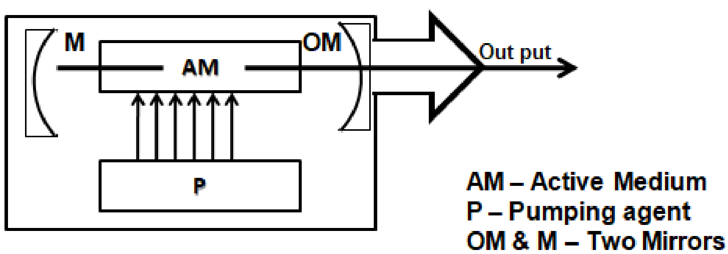


Fig.1.12: Block diagram of LASER

I] ACTIVE MEDIUM

1.An active medium is the material in which the lasing action takes place. The medium may be solid, liquid or gas.
2. Out of different atoms in the medium, only a small fraction of atoms of a particular species are responsible for stimulated emission i.e. for lasing action.
3. Those atoms which cause laser action are called ***active centers*** and the rest of the medium acts as ***host*** and they only support the lasing activity.

II] PUMPING AGENT

1. For achieving and maintaining the state of population inversion, the atoms are required to lift continuously to the excited level.

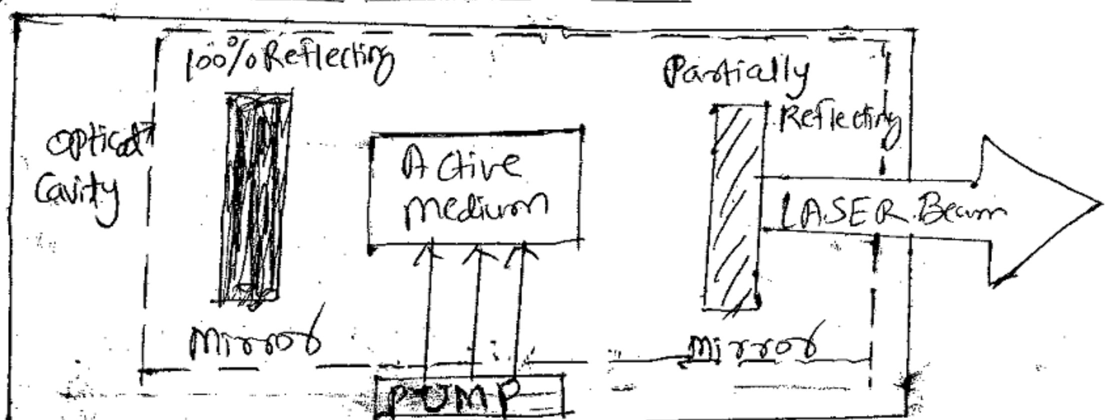
2. The pumping agent is an external source that supplies energy needed to obtain the condition of population inversion.
3. There are different types of pumping agents are available and used according the requirement of medium.
4. Optical pumping, electrical discharge and direct conversion are some of the examples of pumping agent.

III] OPTICAL RESONATOR (RESONATOR CAVITY)

Fig.1.13: Illustration of optical resonator

I] An optical resonator consists of two opposing plane parallel mirrors, with an active material placed in between them. Out of the mirroris partially reflecting (semi-transparent) whole other one is made 100% reflecting mirror. This structure is known as ***Fabry-Perot resonator***.
II] A resonator cavity is a system amplifies the stimulated radiation and intensity of the beam.

Fig:- Components OF LASER:-



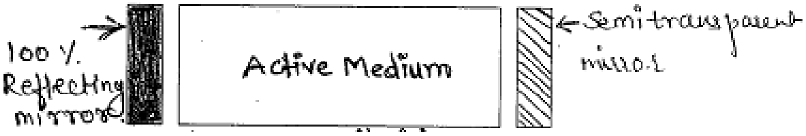
Q) what are the essential components of a laser? Explain their function briefly!

Q.) Explain the lasing action based on cavity resonator. (W-14/3m)
Q.) Explain construction and working of optical resonant cavity. (W-15/3m)

<u>Optical Cavity Resonator (Fabry - Perot resonator)</u>

Light can be amplified when the active medium is taken into the state of population inversion. Laser is very much similar to an electronic oscillator. **Optical cavity resonator converts active medium into an Light oscillator & hence into a light generator.**

Action of optical cavity resonator:- It consists of two opposing plane parallel mirrors with an active medium placed in between them. One of the mirrors is semitransparent which reflects around more than 90% of incident light & other mirror is 100% reflecting which reflects all light falling on it. The mirrors are set normal to the optical axis of the material. This structure is known as Fabry Perot resonator.



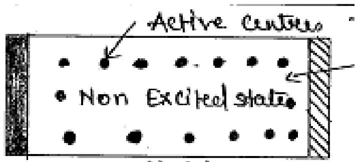


fig (a)

Initially the active centres in the medium are in ground state. fig.(a)

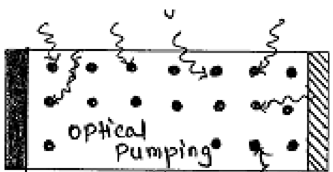
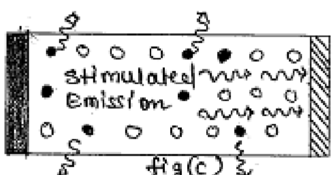


fig (b)

Through suitable pumping mechanism material is taken into a state of population inversion.fig.(b).



fig(c)
Spontaneous emission.

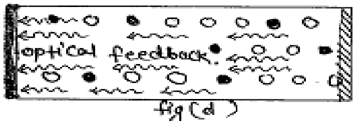
Spontaneous photons are emitted in the initial stage in every direction fig.(c).
There is a possibility that some of the large no. of excited atoms decays spontaneously. They emit photons in various direction .Each spontaneous photons can trigger many stimulated transitions along the direction of propagation.

As the initial spontaneous photons are emitted in different directions, the stimulated photons will also travel in different directions. Many of them leave the medium without reinforcing their strength & are lost.

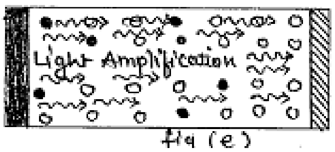
To generate a coherent light output it is necessary that photons with specific directions are to be selected while the others are rejected.

Secondly, to attain the maximum possible amplification of light, the stimulated photons are to be made to pass through the medium a no. of times. The end mirrors constituting the resonator impose the directional selectivity on photons.

These end mirrors impose directional selectivity on photons. Photons propagating along the direction of optical axis of the pair of mirrors are augmented while photons emitted in any other direction other than parallel to the optic axis will pass out of the sides of resonator and are lost as shown in fig (d).On reaching the semitransparent mirror , some of the photons are transmitted out and part of them will be reflected back.

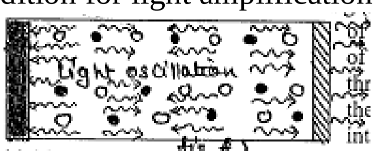


Majority of photons travelling along axis are reflected back on reaching an end i.e. semi transparent mirror. They propagated towards the opposite mirror and on their way they stimulate or de-excite more and more atoms and build up their strength.



At the 100% reflecting mirror some of the photons are absorbed out but major portion will be reflected back. The amplified beam will move along the same path, as the starting photons and undergo some multiple reflections at the mirrors and gains in strength as shown in fig (e).

At each reflection, at the front semitransparent mirror, the beam is partially transmitted through it and partially fed back into the mirror. Thus, the photon density Q in the medium enhanced and satisfies the condition for light amplification.



laser beam

As shown in fig.(f) laser beam oscillations begin when the amount of amplified light becomes equal to the total amount of light lost through the sides of the resonator, through the mirrors and through the absorption by the medium. **As the oscillations build up to enough intensity, it emerges through the front mirror, as the highly collimated intense** beam called **laser beam**.

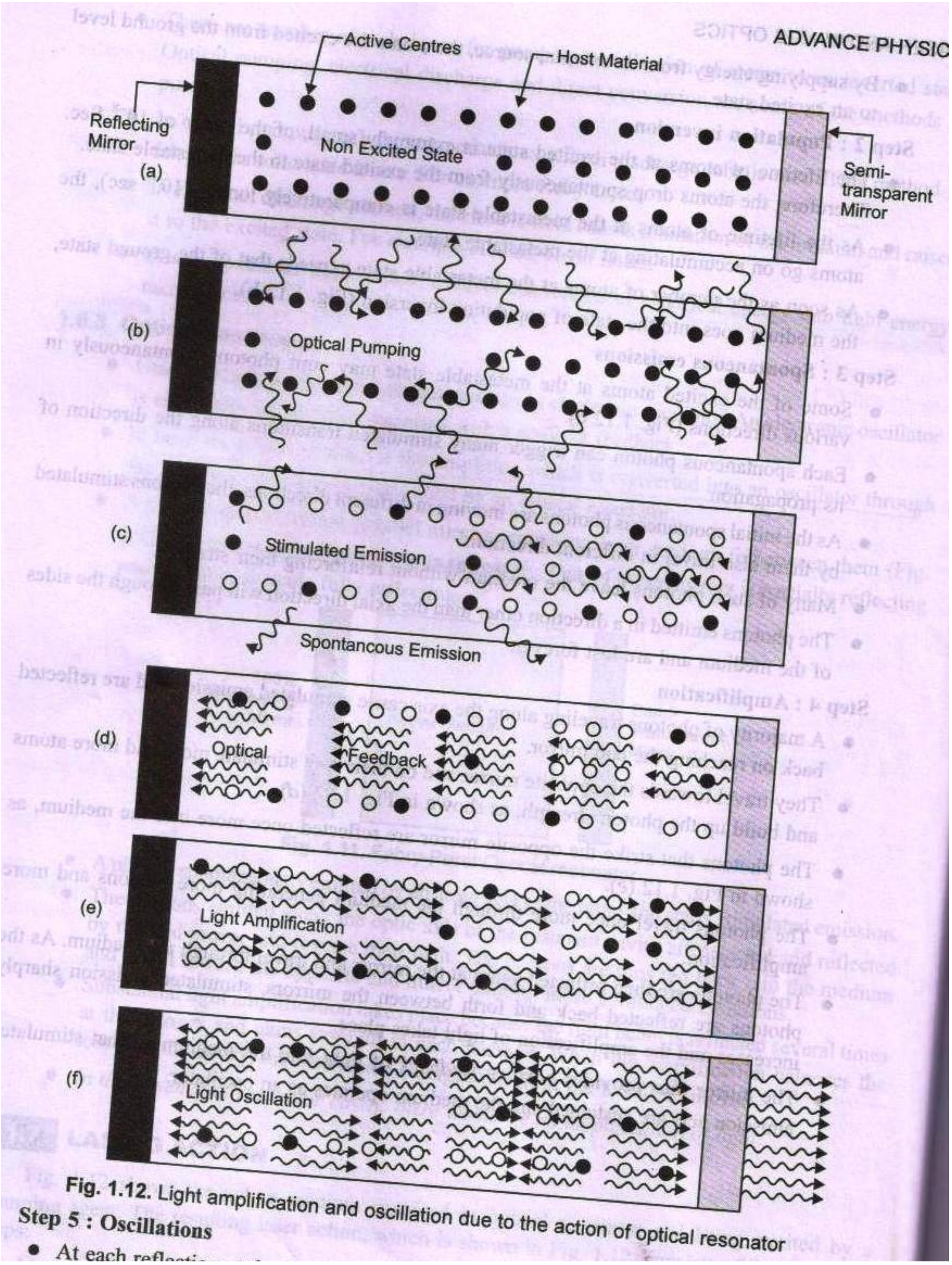


Fig. 1.12. Light amplification and oscillation due to the action of optical resonator

<u>Condition for steady state oscillations or Condition of Standing Wave Pattern OR Condition of Resonance:</u>

For continuous increase in the wave amplitude i.e. for light amplification, light waves propagating within the cavity resonator should take on the standing wave pattern. To get this standing wave pattern, the waves propagating and making a round trip inside a resonator should fulfill phase condition as well as amplitude condition.

To fulfill phase condition, it is necessary that the optical path length (2L) travelled between two consecutive reflections should be an integral multiple of wavelength. So, the condition for forming standing wave pattern is

$$2L = n\lambda \text{----(1)}$$

$L = n\lambda/2$ Where, n = 1, 2, 3……..

λ – Wavelength of photon wave.

L – Length of cavity.

If υ is the frequency of photon wave,

$\lambda = {}^{c}/_{\upsilon}$

$\therefore 2L = n\frac{c}{\upsilon}$

$\rightarrow \ \boldsymbol{\upsilon = \frac{nc}{2L}}$

Eqn. (1) represents the resonance condition, where L is the length of optical cavity resonator and λ is the wavelength of the light wave within the cavity resonator. Eqn. also represents that length of resonator should accommodate an integral number of standing half waves.

Waves whose wavelengths satisfy the condition (1) can only exist inside the cavity in standing wave pattern or steady state whereas the waves whose wavelength does not satisfy the above condition interfere destructively and cancel out.

The waves which form a standing wave pattern and satisfy the resonance condition are called **longitudinal cavity modes**. Each mode has distinct frequency given by

$$\nu_n = \frac{nc}{2L} \qquad \nu_n = c/\lambda$$

Where n is called **mode number**

Q) Explain the role of resonant cavity in laser.

Ans. The primary function of the optical resonator is to provide positive feedback of photons into the medium so that stimulated emission is sustained and the laser acts as a generator of light.

The laser oscillations are initiated by photons spontaneously emitted by some of the excited atoms. Each spontaneous photon can trigger many stimulated transitions along the path of its travel. As the initial spontaneous photons are emitted in different directions, the stimulated photons would travel in different directions. The optical resonator selects the direction in which the light is to be amplified, the direction being the optical axis of the pair of mirrors. Thus, optical cavity makes the laser beam directional. In order to make the stimulated emissions dominate spontaneous emissions, a high radiation density is required to be present in the active medium. The optical cavity builds up the photon density to a very high value through repeated reflections of photons and confines them within the medium. Optical cavity selects and amplifies only certain frequencies causing the laser output to be highly mochromatic.

<u>Types of LASERS</u>:

Lasers are mainly divided into three categories on the basis of material used;

i) Solid state laser for ex. Ruby laser
ii) Gas laser for ex. Helium-Neon laser
iii) Solid state diode laser for ex. Semiconductor diode laser

Most lasers emit light in the red or IR region. Laser can be operated in a continuous wave mode or in pulsed mode with a higher output power.

Solid State laser: Solid state lasers have lasing material distributed in a solid matrix, e.g., the ruby or neodymium-YAG (yttrium aluminum garnet) lasers. The neodymium-YAG laser emits infrared light at 1.064 micrometers.

Q.) Explain construction, working and limitations of Ruby laser with neat energy level diagram. (S-13/5m)

Q.) **Describe the working of Ruby Laser with the help of neat energy level diagram. (S-15/5m)**

Q.)Explain construction and working of Ruby Laser with the help of energy level diagram. (W-16/4m)

RUBY LASER

Ruby belongs to the family of gems. It is a solid state laser built by American physicist, T.H. Maimann in 1960. It is Al_2O_3 crystal doped with about 0.05% of chromium ions. Al^{3+} ions in the crystal lattice are substituted by Cr^{3+} ions. Cr^{3+} ions constitute the active centers whereas the aluminium and oxygen atoms are inert.

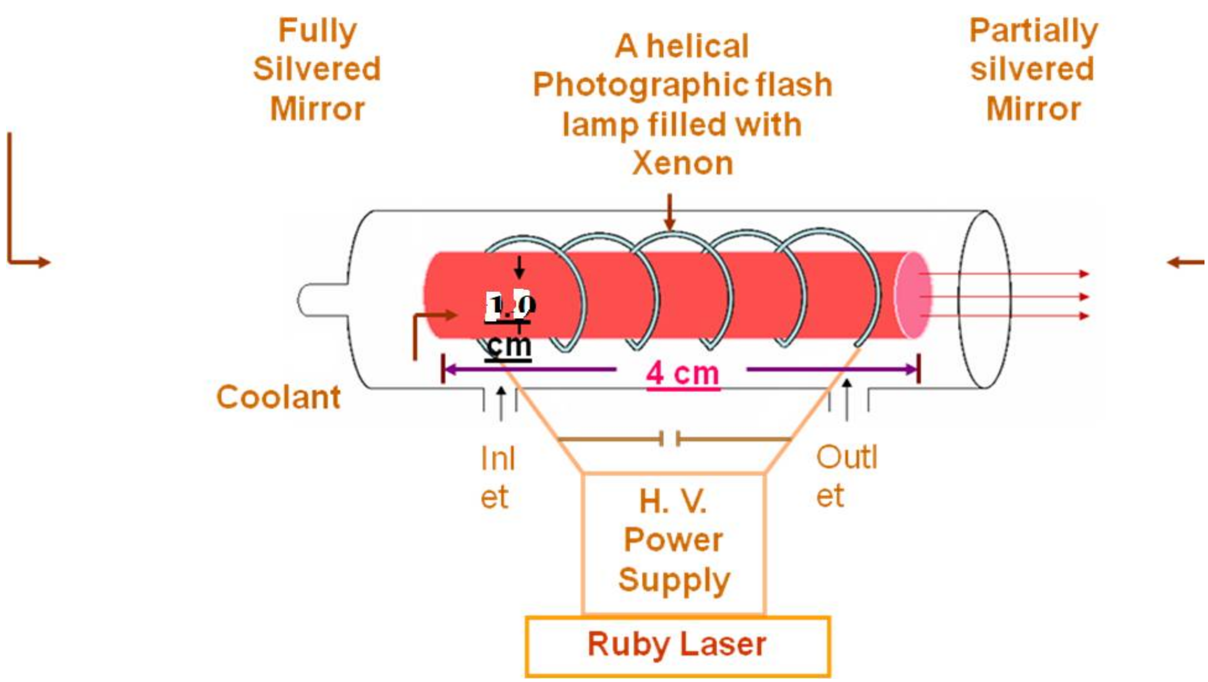
Al_2O_3 crystal is transparent. Cr^{3+} ions give pink colour depending upon the concentration of Cr^{3+}. The Cr^{3+} ions have absorption bands in the blue and green region of the visible spectra and hence the red hue.

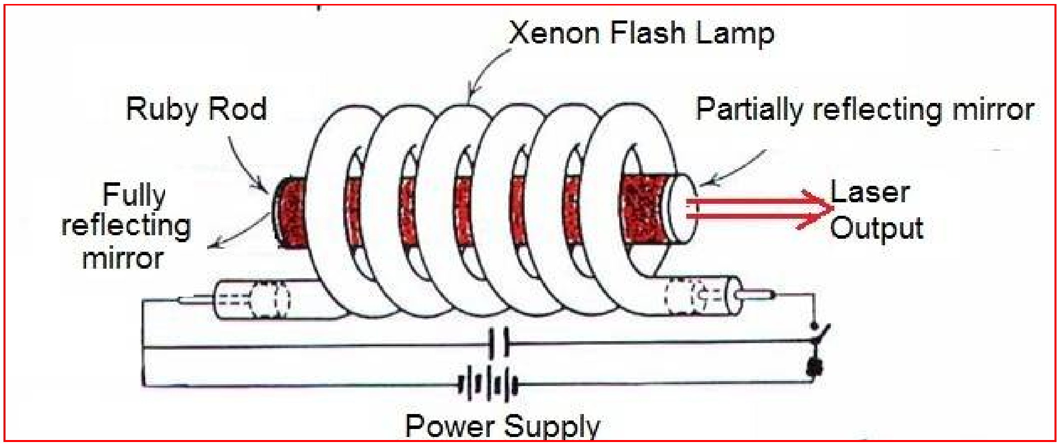
Construction:-

Ruby crystal is taken in the form of cylindrical rod of about **4cm** in length and **1cm** in diameter. Its ends are grounded and polished such that the end faces are exactly parallel and also perpendicular to the axis of the rod. One face of ruby rod is silvered to achieve 100% reflection and opposite face is partially silvered to make it semitransparent (i.e., to achieve 90% reflection). The silvered faces constitute the Fabry-Perot Resonator.

The ruby rod is surrounded by a helical photographic flash lamp filled with xenon. The lamp produces flashes of white light when it is activated by power supply.

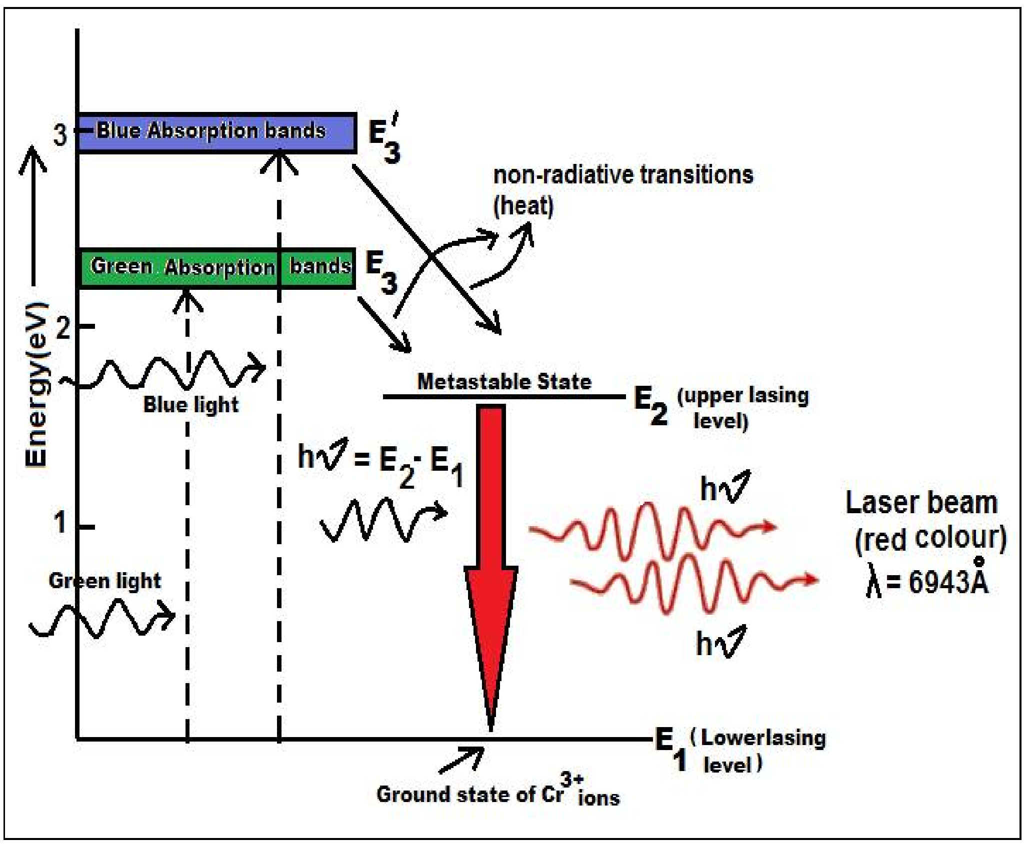
The system is cooled with the help of a coolant around the ruby rod to avoid any damage to ruby crystal.





Working:-

Ruby laser uses a three-level pumping scheme. The energy levels of Cr^{3+} ions in the crystal lattice are as shown in fig. There are two wide energy bands E_3 & E_3' and a metastable state E_2. When the ruby rod is irradiated with an intense burst of white light, for a few milliseconds, the ground state Cr^{3+} ions absorb light in two pump bands (one centered near 5500 Ǻ i.e., green component and the other at about 4000 Ǻ i.e. blue component).



The green component of white light having wavelength centered around 5500 Ǻ is absorbed by Cr^{3+} ions and raised them from ground level E_1 to the excited level E_3. Similarly, the blue component having wavelength centered around 4000Ǻ is absorbed by Cr^{3+} ions and raised them from E_1 to E_3'. The excited levels E_3 and E_3' are highly unstable. Thus, from E_3 and E_3' these Cr^{3+} ions undergo non-radiative transition and quickly drop to the metastable level E_2. The metastable state has life time of atoms of the order of 10^{-6} to 10^{-3} secs.(which is 1000 times more than the life time of E_3 and E_3' level). Therefore Cr^{3+} ions accumulate at E_2 level. When more than half of the ground state Cr^{3+} ions are accumulated at E_2 level, the state of population inversion is established between E_2 and E_1 levels. One of spontaneously emitted photon travelling parallel to the axis of ruby rod initiates the stimulated emission. Photons travelling along the axial directions are repeatedly reflected, amplified and emerge out as a strong laser beam. A laser beam is red in colour and corresponds to the wavelength of 6943Å . Green and blue light components of white light play the role of pumping agent but these components do not get amplified by the active medium. It is a random red photon radiates spontaneously by one of the Cr^{3+} ion that acts as input and gets amplified.

DISADVANTAGES OR LIMITATIONS

1) Xenon flashes last for few milliseconds. Hence laser does not operate through this period. Once stimulated transitions commence the metastable state E_2 gets depopulated very rapidly and lasing cease.
   The laser becomes inactive till the population inversion establishes once again. **The output of laser is not continuous and occurs in the form of pulses of microseconds duration because population inversion cannot be maintained continuously.**
2) The efficiency of the ruby laser is very less because only the green and blue components of white light is utilized while the rest of component of incident light are left unused.
3) Ruby laser **requires high pumping power** as more than half the active centers are to be lifted to the excited state from the ground state to achieve population inversion.

GAS LASER

Gas lasers are made by using gases as the active medium. Neon, Argon, Krypton, Xenon are some of the gases. Optical pumping is not suitable for gases. They are usually excited through electrical pumping. The gas laser radiates in visible and IR region.

Gas lasers (helium and helium-neon, He-Ne , are the most common gas lasers) have a primary output of a visible red light. CO_2 lasers emit energy in the far-infrared, 10.6 micrometers, and are used for cutting hard materials.

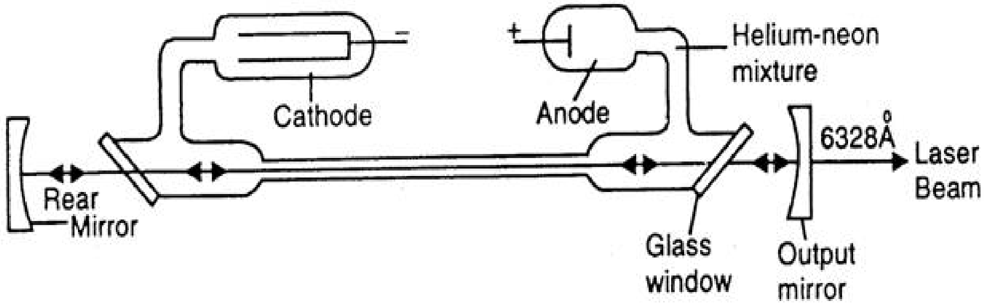
Q.) Explain with suitable energy level diagram the working of He-Ne laser. (W-13/5m)
Q.) Explain the working of He-Ne laser with the help of neat energy level diagram. (S-14/4m)
Q.) Explain in brief construction and working of He:Ne laser with the help of suitable diagram. (W-14/4m)
Q.) Draw well labeled energy level diagram for He-Ne laser. (W-15/2m)
Q.) Describe with the energy level diagram, the construction and working of He-Ne Laser. (S-16/4m)

HELIUM-NEON GAS LASER

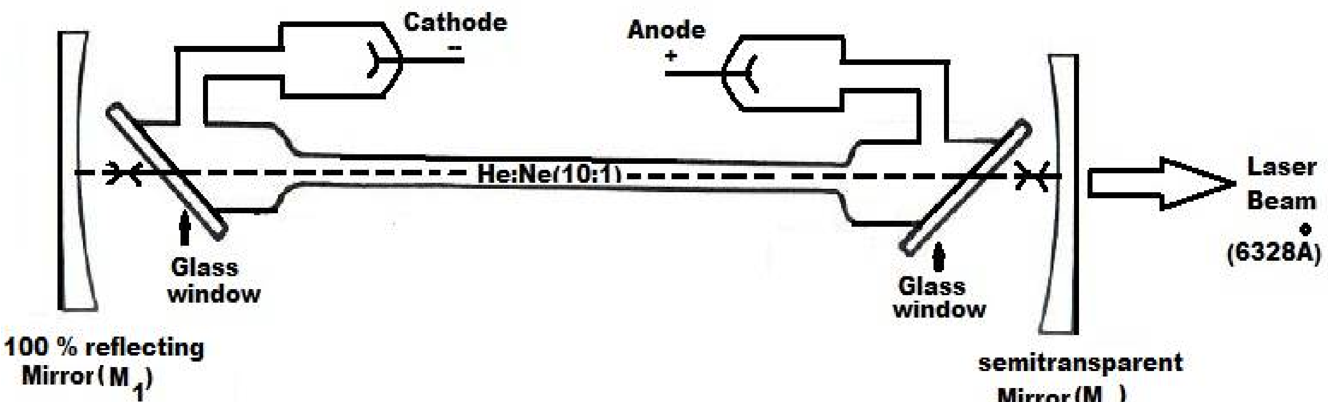
It was the first successful gas laser built by Ali Javan, D. Heriot and W. Benett in 1961.

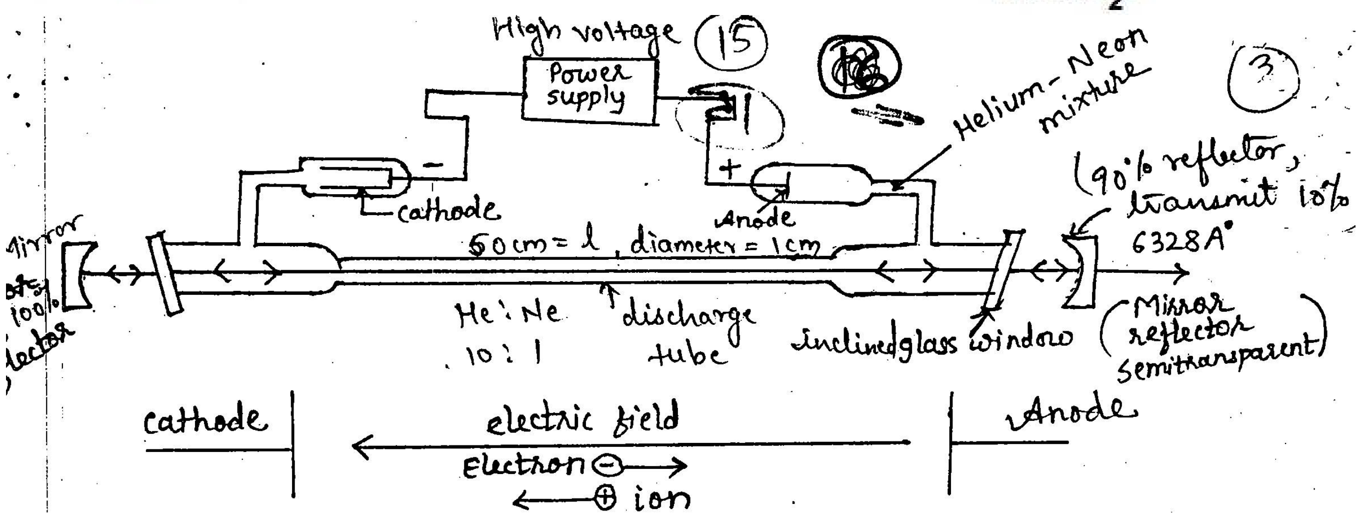
Construction:

Helium-Neon laser consists of a long discharge tube of length 50cm and diameter 1cm. The tube is filled with a mixture of Helium and Neon gases in the ratio 10:1. Neon atoms are the active centres and have energy levels suitable for laser transitions while helium atoms help in exciting neon atoms. Electrodes are provided in the discharge tube to produce discharge in the gas. They are connected to a high voltage power supply. The tube is sealed by inclined window (at brewster's angle with the axis of tube to get linearly polarized laser output) arranged at its two ends. On the axis of the tube, two mirrors (reflectors) are fixed which forms Fabry-perot resonator. The distance between the mirrors is adjusted such that it equals $n\lambda/2 = L$ and supports standing wave pattern.



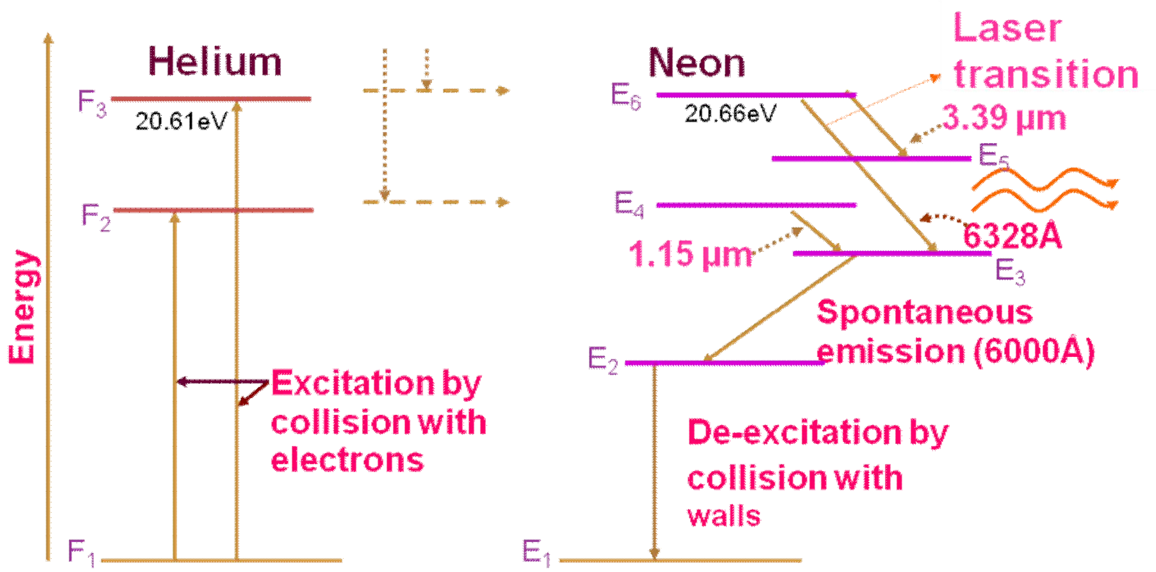
Schematic of a He-Ne laser with external mirrors



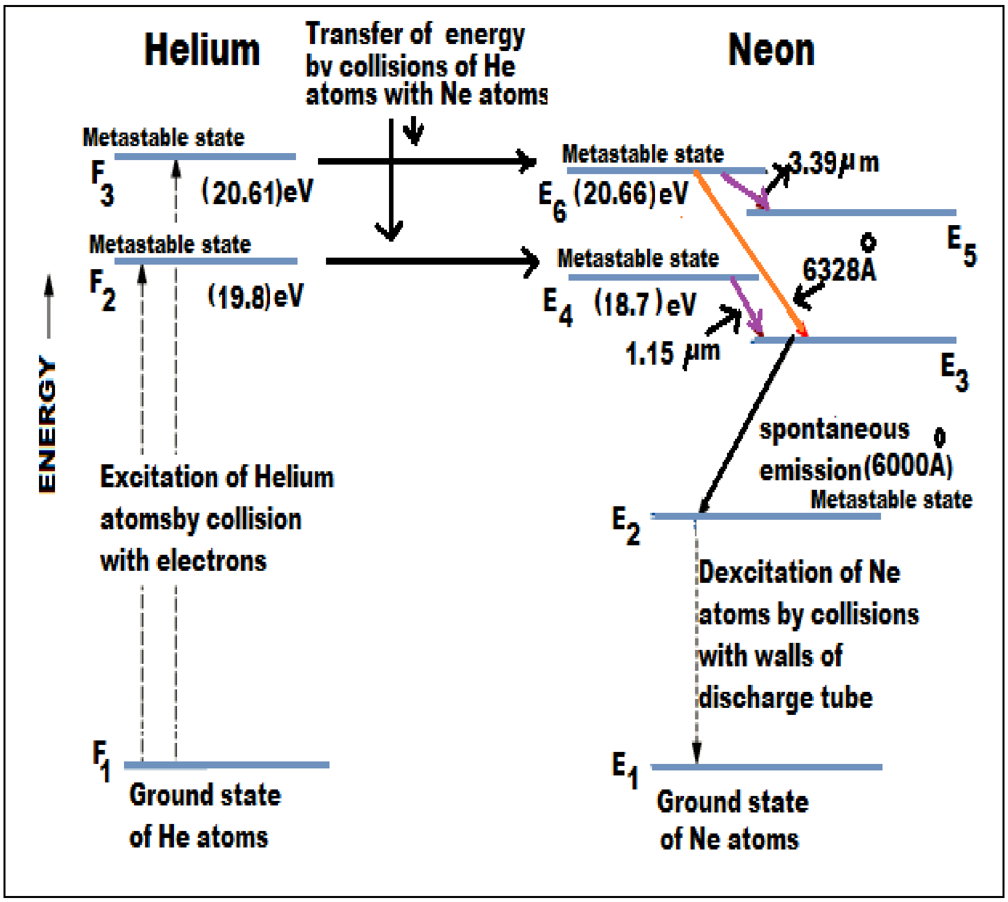


Working:

Helium-Neon laser uses a four level pumping scheme. The energy levels of helium and neon are shown in figure.



Energy levels of Helium and Neon atoms and transitions between the levels.



When power is switched on (a high voltage of about 10KV is applied across the gas), electric field ionizes some of the atoms in the mixture of He & Ne gases. Due to electric field, electrons and ions will be accelerated towards the anode and cathode respectively. Since the electrons have smaller mass they acquire higher velocity. Helium atoms are more rapidly excited than neon atoms by electron impact because they are lighter. Due to excitation, helium atoms are excited to the energy levels F_2 and F_3 which lie at 19.81 eV and 20.61 eV respectively above the ground state. These two states are

metastable states and hence the excited He atoms cannot return to the ground state by spontaneously emitting photons.
With the passage of current through the discharge tube more and more He atoms accumulate in the excited state. These excited He atoms can return to the ground state by transferring their energy to the ground state neon atoms through inelastic atomic collisions. Such energy transfer can take place only when two colliding atoms have identical energy states. It is called as **resonant transfer of energy**. E_6 level is at 20.66eV and E_4 level is at 18.7eV of neon atoms which nearly coincide with energy levels F_3 and F_2 of helium atoms respectively. Therefore, resonant transfer of energy can occur easily between the excited helium atoms and the ground state level neon atoms. The additional 0.05eV energy required is provided by kinetic energy of helium atoms. This is main pumping mechanism in He-Ne system.
When a helium atom in metastable state collides with a neon atom in the ground state, the neon atom is excited to E_4 or E_6 level and the helium atom returns to the ground state after transferring their energy.
Thus, **the neon atoms are active centers and the role of helium atom is to excite the neon atoms and cause population inversion**. {The probability of energy transfer from He atom to Ne atom is more as there are 10 He atoms to 1 Ne atom in the mixture. Therefore, the probability of reversed transfer of energy i.e. from Ne to He atom is negligible.} E_6 and E_4 levels of Ne atoms are metastable. Therefore as the collision increases, more and more Ne atoms accumulate in these two excited states. Successive collision increases the population of E_6 and E_4 levels.
At room temperature E_5 and E_3 levels of Ne are sparsely populated. Hence state of population inversion is achieved between E_6 & E_5, E_6 & E_3 and between E_4 & E_3 levels. So consequently, three lasing transitions can occur. They are $E_6 \rightarrow E_5$, $E_6 \rightarrow E_3$ and $E_4 \rightarrow E_3$ transitions. Since the terminal level of lasing transitions are sparsely populated, population inversion can be achieved by exciting less number of Ne atoms and hence **low pumping power is required for pumping**. Spontaneously emitted photon triggers stimulated emission and coherent laser beam is produced.

i) $E_6 \rightarrow E_3$ transition: This transition generates a laser beam of red colour of wavelength $\lambda = 6328 \acute{A}$ in visible region
ii) $E_4 \rightarrow E_3$ transition: It produces infrared laser at wavelength of 11500 $\acute{A}$.
iii) $E_6 \rightarrow E_5$ transition: A laser beam of wavelength of 33900 $\acute{A}$ (3.39µm) in the far infrared region arises due to this transition.

Q) Why in He-Ne laser discharge tube should be narrow?
Avantages:
As the lower lasing levels i.e. (E_5, E_3) are depopulated faster than the upper metastable state, it is easier to maintain the state of population inversion between the lasing levels throughout the time of laser operation.
E_2 level is metastable state therefore the Ne atoms tends to accumulate at this level once again. When they drift towards the wall of the discharge tube and collide with it. They give up their energy and return to the ground state. These atoms are to be brought to the ground state quickly otherwise the number of atoms available at the ground state will go on diminishing and the laser output will decrease. Hence **to increase the probability of atomic collisions with the wall to maintain population inversion continuously,the discharge tube is made narrow.**

He-Ne laser operates in CW mode. 6328 $\acute{A}$ is the standard wavelength of the He-Ne laser. This laser is simple, practical and less expensive. The laser is highly collimated, coherent and monochromatic. Without Brewster's windows the light output is not Coherent.

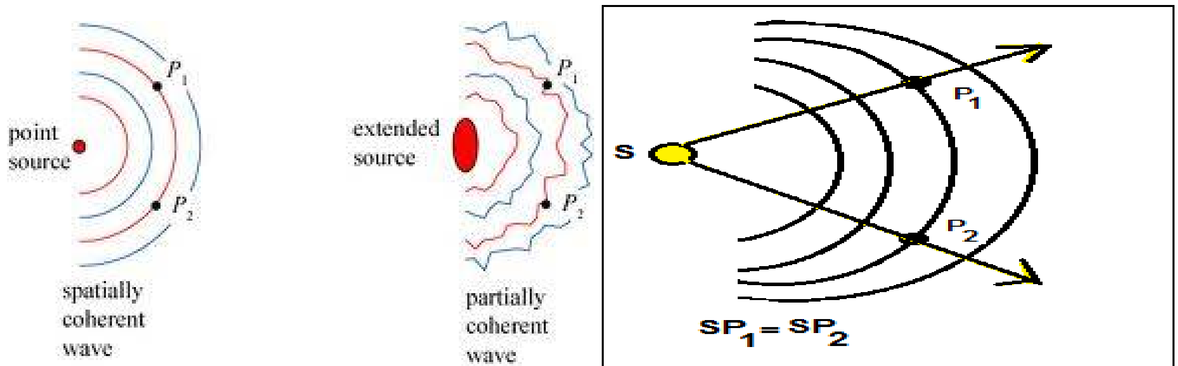
Coherence:

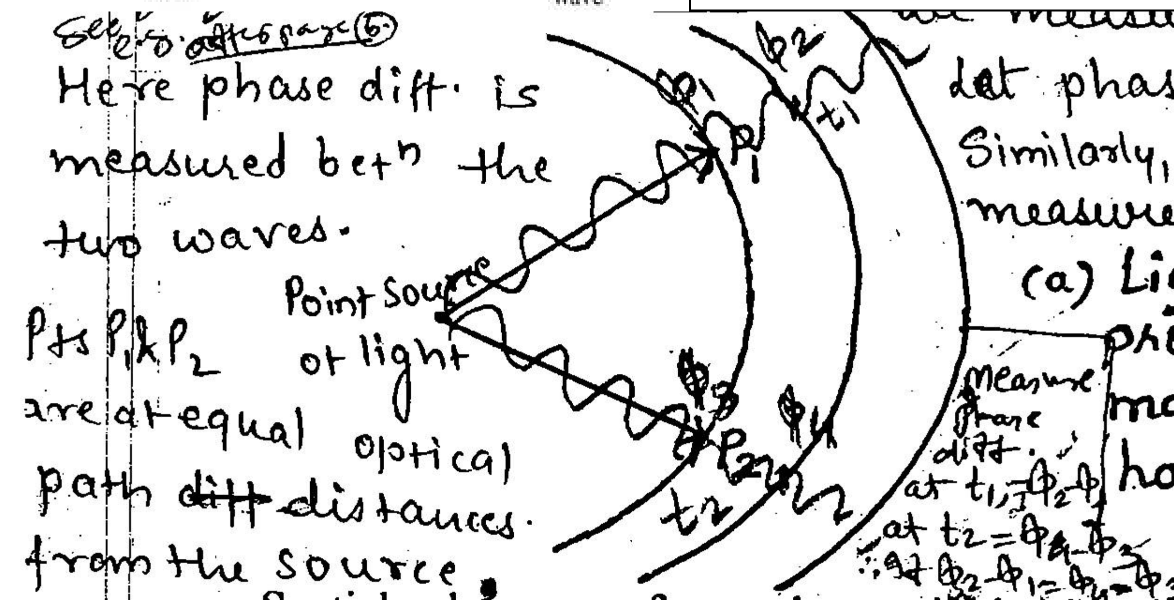
Coherence means the coordinated motion of several waves maintaining a fixed and predictable phase relationship with each other. There are two types of coherence

(i) Spatial coherence (ii) Temporal coherence

__Spatial Coherence__ : Spatial coherence refers to the continuity and uniformity of a wave in a direction perpendicular to the direction of propagation. It is known as **'Lateral' or 'Transverse'** coherence. If the phase difference for any two fixed points in a plane normal to the wave propagation does not vary with time, then the wave is said to exhibit 'Spatial Coherence'.

[Here the phase difference is measured between the two waves. Points P_1 & P_2 are at equal optical path distances from the source. The waves reaching these points will be exactly in the same phase].

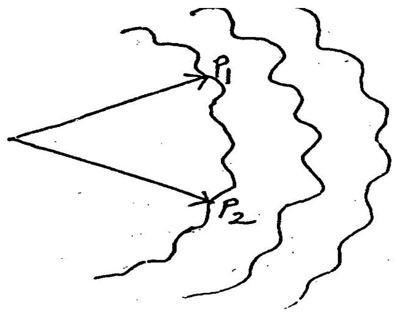




If the source is **point source** the waves will have the same phase at points in space which are equidistant from the sources. All the atoms of the sources produce the same interference pattern and the common pattern looks similar to the pattern produced by an individual atom, but it is much brighter. **The degree of spatial coherence is correspondingly higher.**

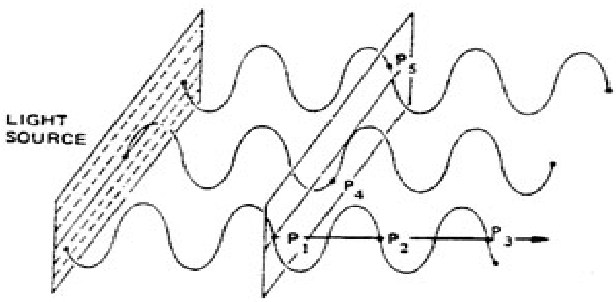
If the source is **an extended source**, it consists of a large number of atoms, each atom acting as point source. The atoms are mutually incoherent point sources. The interference pattern produced by different sets of atoms will be different.

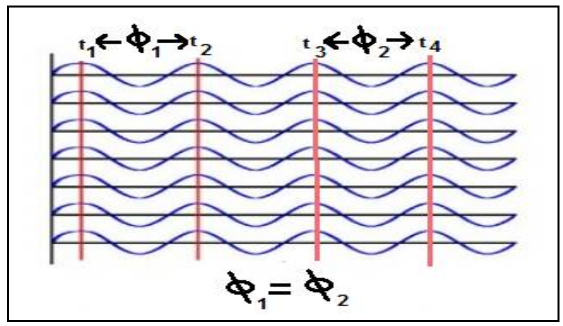
Therefore, the larger the size of the sources, lesser is the spatial coherence. In fact, higher the degree of spatial coherence of a source, the smaller is the divergence of the beam produced by it.



(b) Extended source produces wave fronts far from ideal. Points P_1 and P_2 do not have the same phase, leading to spatial incoherence.

Temporal Coherence: Temporal Coherence refers to the continuity and uniformity of a wave in a direction along the direction of wave propagation. It is known as **'Longitudinal Coherence'**. **If the phase difference for any two fixed points along any ray parallel to the wave propagation, does not vary with time, then the wave is said to be exhibit temporal coherence.**





[If we measure phase of the wave at t_1 and t_2, let the phase difference be Φ_1 for (t_2-t_1). Similarly, if we measure phase of the wave at t_3 and t_4 for the same time interval i.e. $(t_4-t_3) = (t_2-t_1)$. Let the phase difference between the phase at t_3 and t_4 is Φ_2. If $\Phi_1 = \Phi_2$ then the wave is said to exhibit temporal coherence]

Longitudinal (temporal) coherence will be greater if the coherence length of the wave packet will be greater. Also, temporal coherence will greater for the longer coherence time. Thus, temporal coherence depends on the bandwidth and the monochromaticity of a wave.

1.12. LIST OF FORMULAE

- Population ratio $= N_2/N_1 = \exp[-(E_2-E_1)/kT]$ where N_1 be the population of E_1 and N_2 is the population of E_2, $N_1 = \exp(-E_1/kT)$, $N_2 = \exp(-E_2/kT)$
- Coherence length in terms of coherence time: $l_{coh} = c \times t_{coh}$
- Coherence length in terms of half width/ Bandwidth: $l_{coh} = \dfrac{c}{\Delta\nu}$
- Coherence length in terms of line width/ Bandwidth: $l_{coh} = \dfrac{\lambda^2}{\Delta\lambda}$
- Coherence length in terms of number of wave trains: $l_{coh} = N\lambda$
- Frequency spread in terms of coherence time: $\Delta\nu = \dfrac{1}{\Delta t} = \dfrac{1}{t_{coh}}$
- Frequency spread in terms of wavelength: $\Delta\nu = -\dfrac{c}{\lambda^2}\Delta\lambda$

- Number of wave oscillations (N) is given by $N = \frac{\lambda}{\Delta\lambda}$
- Ratio of population between two states $\frac{N_2}{N_1} = e^{\frac{-\Delta E}{KT}}$ *where* $\Delta E = E_2 - E_1 = \frac{hc}{\lambda}$

k = Boltzmann's constant, N_1 and N_2 denote the population of lower and higher energy state

- Number of photons emitted $n = \frac{E}{\varepsilon}$,

Where, E =energy of the pulse = P x t (P = Power of the laser, t = time in second)

ε = energy of photon = $h\nu = \frac{hc}{\lambda}$

$$\Rightarrow n = \frac{E\lambda}{hc}$$

- Intensity of focused beam $I = \frac{Power}{Area} = \frac{P}{A}$
- Length of the laser cavity supporting 'm' modes, given by, $L = \frac{m\lambda}{2}$ (In terms of λ)

$L = \frac{mc}{2\Delta\nu}$ (In terms of half width or frequency spread)

- Number of modes supported by the cavity of length 'L' is given by $m = \frac{2L\Delta\nu}{c}$
- Frequencies of longitudinal cavity are given by $\nu_m = \frac{mc}{2L}$
- Efficiency of power converted is given by $\eta = \frac{P_0}{P_i} \times 100$

Where P_0 is output power, P_i is input power

- Power of laser beam $P = n\,h\nu$

  Where, **n** is the number of photons emitted, **h** is Planck's constant and **v** is the frequency of laser beam

Applications of LASER

Lasers are used in almost every field

1) In Mechanical Industry like cutting, drilling, welding.

a) Cutting:- A wide range of materials like paper, wood, cloth, glass, quartz, steel etc. can be cut by CO_2 LASERS. Advantage of laser cutting is fine and precise. High production rates can be achieved and this process does not introduce~~d~~ any contamination.

b) Drilling:- Holes are drilled by laser beam. It is based on the intense evaporation of material heated by a series of powerful light pulses of short duration 10^{-3} to 10^{-9} sec. Holes are generally made in ceramic materials, diamond etc. CO2 lasers and Nd:YAG lasers are used for drilling.

c) Welding:- It is the process of joining two or more pieces into a single unit. Laser beam heats the edges of two plates to their melting points and causes them to fuse together where they are in contact. Advantage is that this is a contact-less process and hence introduce no impurities into the joint.

2) In medicine:-

a) In eye Surgery, Argon laser is used to weld the detached retina back to the eye ball.

b) Laser is also used to perform microsurgery and bloodless operations to cure cancer and skin tumors in human beings and animals.

c) It is also used in angioplasty and for destroying kidney stone.

3) In Computers:-

a) By using optical fibres as light guides, the entire content of memory can be transmitted from one computer to another computer by laser beam.

b) Laser is used in printers for computer print-outs. e.g. Laser Printers.

4) In Communication:-

a) In communication systems, the laser beams are used to transmit thousands of television programmes and simultaneous conversation at a time.

b) The communication between the planets has been made possible using laser beam.

c) Laser light waves not absorbed by water and hence it can be successfully employed to establish~~ed~~ under water communication between submarines.

5) In Defence:-

a) A powerful laser beam can be used to destroy big size objects like aeroplanes, missiles etc by pointing the laser beams on them and hence it is called death ray.

b) The laser beam can be used to determine the distance, velocity, direction, size and the nature of reflected light in radar.

6) In Holography:- It is the technique by which a three dimensional image of the object can be obtained. He-Ne laser is used for this purpose.

Wave train

Q. Give the concept of wave train in context of ordinary light and obtain corresponding coherence length.

Wave train: The light emitted by an ordinary light source is not an infinitely long, simple harmonic wave but is composed of a jumble of finite wave trains/ wave packets as shown in fig.(2). It is a burst of light waves i.e. superposition of many waves of a slightly different frequencies ranging $\Delta\upsilon$.

Fig.(1)

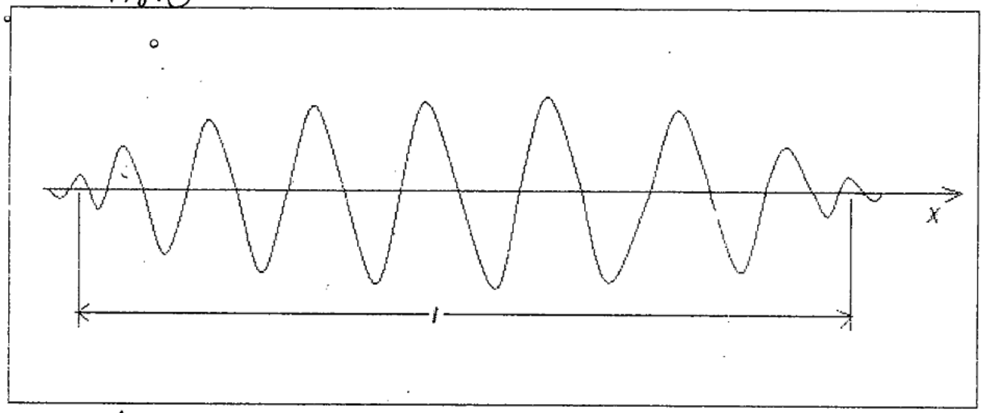
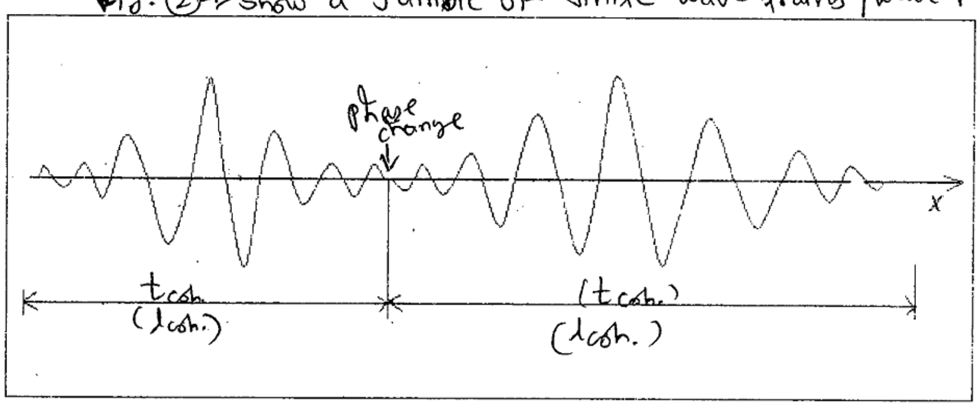


Fig.(1) shows a wave train generated by an atom.

Fig.(2) → show a jumble of finite wave trains | wave packets.



If a wave train lasts for a time interval Δt then the length of the wave train is $l = c\Delta t$, c is the velocity of light in vacuum.

For example if, $\Delta t = 10^{-8}$ sec., $c = 3\times10^{8}$ m / sec,

$l = (3\times10^{8}\text{m /sec}) \times (10^{-8}\text{ sec}) = 3$ m

$l \approx N\lambda$

Let l contains N wave oscillations then $l = N\lambda$.

No. of wave oscillations present in a wave train for $\lambda = 5000\text{A}^\circ = 5\times10^{-7}$ m will be

$$N = \frac{l}{\lambda} = 3\text{m} / 5\times10^{-7}\text{ m} = 6\times10^{6}$$

So a wave train contains millions of wave oscillations.

Introduction : In practice, light is emitted from a light source when excited atoms pass from the upper excited state to a lower energy state. The atom gives the excess energy in the form of a photon. The process of transition from upper state to a lower state lasts for a brief time of about 10^{-8} sec. It means that an atom starts emitting a light wave as it leaves for the lower energy state.

Q. Explain the terms coherence length and coherence time for a light wave. Derive an expression for coherence length ~~of~~ of a wave train that has frequency width $\Delta\nu$. Express the answer in terms of line width $\Delta\lambda$ and mean wavelength λ_0 of the wave train.

Coherence length & coherence time:

Wave packet /Wave train as shown in the above fig.(2) appears sinusoidal fairly for some number of oscillations.

Coherence length: The length of the wave train/ wave packet over which it may be assumed to be fairly sinusoidal (in character) & has predictable phase is called **coherence length.**

It is approximately equal to the length of the wave train $l_{coh.} = c\,\Delta t$ over which its phase is predicted reliably.

Coherence time: The average time or time interval (Δt) during which the wave remains sinusoidal & the phase of the wave can be predicted reliably is called **coherence time.**

$t_{coh.} = \Delta t \rightarrow$ is the time during which the phase of the wave train does not become randomized but undergoes change in a regular systematic way.

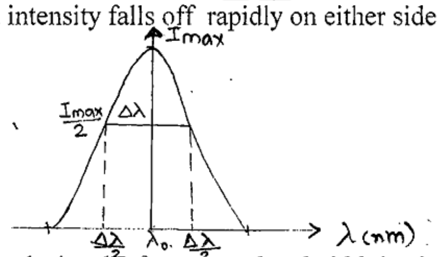
$$l_{coh.} = c.\,\Delta t$$

$$t_{coh} = \Delta t,\quad l_{coh} = c.\,t_{coh}$$

Relation between coherence length and bandwidth:

A wave train consists of group of waves which have a continuous spread of wavelengths over a finite range $\Delta\lambda$, centered on a wavelength λ_o.

The spread of wavelengths is called bandwidth. The maximum intensity of the wave packet occurs at λ_o and intensity falls off rapidly on either side of λ_o as shown in fig.



According to Fourier analysis, the frequency bandwidth is given by,

$$\Delta\upsilon = \frac{1}{\Delta t} \qquad \left(\nu = \frac{1}{T}\right)$$

Where, $\Delta t \rightarrow$ average life time of an excited state of the atom. It is the time during which a wave train is radiated by the atom and corresponds to the coherence time t_{coh}, of the wave train.

$$\Delta\upsilon = \frac{1}{\Delta t} = \frac{1}{t_{coh.}}$$

$$\Delta\upsilon = \frac{c}{l_{coh}} \qquad \left(\because t_{coh} = \frac{l_{coh}}{c}\right)$$

The frequency & wavelength of a light wave are related through the eq^{n}.

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Lasers:

Problems On Coherence Length & Time.

W-97 P/188

1) A sodium atom radiates for 4×10^{-12} s. What is the coherence length of light from a sodium lamp? Ans → 1.2 mm

2) If light of 6600Å wavelength has wavetrains 20λ long; what are its coherence length and coherence time? Ans → 1.32×10^{-5} m $t = 4.4 \times 10^{-4}$ s

3) A He-Ne laser giving light at 6330Å has a coherence length of 20 Km. Determine
a) its coherence time and
b) the number of waves per wavetrain.
Ans → $t = 6.7 \times 10^{-5}$ sec. $N = 3.2 \times 10^{10}$ waves

4) A mercury lamp has a bandwidth $\Delta\nu = 1000$ MHz. Calculate the coherence length and coherence time of its light. Ans → $l = 30$ cm.

S-94
5) Calculate the coherence length for CO_2 laser whose line width is 1×10^{-5} nm at IR emission wavelength of 10.6 μm. Ans:- $l = 11.2$ Km

S-96
6) White light has frequency range from 0.4×10^{15} Hz to 0.7×10^{15} Hz. Find the coherence time and coherence length. Ans: $t = 3.33 \times 10^{-15}$ sec $l = 1$ μm.

S-00
7) A ruby laser emits light of wavelength 694.4 nm. If the laser pulse is emitted for 1.2×10^{-11} sec and the energy release per pulse is 0.15 J
① what is the length of the pulse and
② How many photons are there in each pulse?

(Ans: $l = 3.6 \times 10^{3}$ m $E = 2.86 \times 10^{-19}$ J No. of photons $= 5.24 \times 10^{17}$)

S-01
8) Light of certain wavelength has wave train of width 13.2×10^{-2} m. Calculate Coherence time.
(Ans : $t = 4.4 \times 10^{-10}$ sec)

S-02
9) Compute the coherence length of yellow light with 5893 Å in 10^{-12} sec pulse duration. Find also the bandwidth. (Ans: $l = 3 \times 10^{-4}$ m, $\Delta\lambda = 1.1576 \times 10^{-9}$ m ~~Hz~~)

10) Calculate the coherence length for CO_2 laser whose line width is 1×10^{-5} nm at IR emission wavelength of 10.6 μm. (Ans: $l = 112.36 \times 10^{2}$ m)

Problems on LASERS

11) Find the relative populations of the two states in a ruby laser that produces a light beam of wavelength 6943 Å at 300 K and 500 K (Ans: $a = \cancel{8 \times 10^{-32}}$ $b = \cancel{8.75 \times 10^{-19}}$)
$= 9.77 \times 10^{-31}$ 9.86×10^{-19}

12) Find the ratio of populations of the two states in a He-Ne laser that produce light of wavelength 6328 Å at 27°C. (Ans: 1.1×10^{-33})

13) A typical helium - neon laser emits radiation of $\lambda = 6328$ Å. How many photons per second would be emitted by a one milliwatt He-Ne laser? (Ans: 3.18×10^{15} s^{-1})

Summer 2007
14) If the half-width of the He - Ne laser operating at wavelength 6328 Å ~~what~~ is 1500 MHz, what must be the length of the laser cavity to ensure that only one longitudinal mode

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oscillates? (Ans: $L = 0.1$ m)

15) If the half width of the $10.6\ \mu m$ transition of a CO_2 laser is 60 MHz, calculate the coherence length of the laser. If the cavity length is 2 m, show that not more than one mode will oscillate.
(Ans: $l = 5$ m, $m = 0.8 \approx 1$)

16) Imagine that we chop a continuous laser beam (assumed to be perfectly monochromatic $\lambda = 623.8$ nm) into 0.1 ns pulses using some sort of shutter. Compute the resultant line width $\Delta\lambda$, bandwidth and coherence length. Find the bandwidth and line width that would result if we could chop at 10^{15} Hz. (Ans: $\Delta\nu = 10^{10}$ Hz; $\Delta\lambda = 0.13$ Å)
$l_{coh} = 3 \times 10^{-2}$ m

17) In a helium-neon laser the two plane mirrors forming the resonant cavity are at a distance d of 0.5 m. What is mode separation of longitudinal cavity in terms of frequency?
(Ans: $\Delta\nu = 300$ MHz) (Assume $m = 1$, $n = 1$)

18) A three-level laser emits laser light at a wavelength of 5500 Å.
i) In the absence of optical pumping, what will be the equilibrium ratio of the population of the upper level to that of the lower level. Assume $T = 300$ K.
ii) At what temperature for the conditions of i) above would be the ratio be 1/2?
iii) What conclusion can be drawn on of the results obtained by you in relation to choice of pumping mechanism?
(Ans: $\frac{N_2}{N_1} = 1.406 \times 10^{-38}$, $T = 37222.298$ K)

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WORKED-OUT PROBLEMS

Example 7.1: *Compute the coherence length of yellow light with 5893Å in 10^{-12} second pulse duration. Find also the bandwidth.*

Solution: Coherence length is given by $l_{coh} = ct_{coh}$.

$$\therefore l_{coh} = (3\times10^8 \text{ m/s})(10^{-12}\text{s}) = \mathbf{0.3\ mm}$$

Bandwidth is given by $\Delta\lambda = \dfrac{\lambda^2}{l_{coh}} = \dfrac{(5893\times10^{-10}\,m)^2}{3\times10^{-4}\,m} = \mathbf{11.6Å}$

Example 7.2: *If light of 6600 Å wavelength has wave trains 20 λ long, what are its coherence length and coherence time?*

Solution: Coherence length is $l_{coh} = wavetrain\ \ length\ l = 20\times6600\times10^{-10}$ m $= \mathbf{1.32\times10^{-5}\ m}$.

Coherence time, $$t_{coh} = \frac{l_{coh}}{c} = \frac{1.32\times10^{-5}\,m}{3\times10^{8}\,m/s} = \mathbf{4.4\times10^{14}\ s.}$$

Example 7.3: *Calculate the coherence length for CO_2 laser whose line-width is 1×10^{-5} nm at IR emission wavelength of 10.6 μm.*

Solution: $$l_{coh} = \frac{\lambda^2}{\Delta\lambda} = \frac{\left(10.6\times10^{-6}\,m\right)^2}{1\times10^{-5}\times10^{-9}\,m} = \mathbf{11.2\ km.}$$

Example 7.4: *With a He-Ne laser, interference fringes remain clearly visible, till the path difference is increased up to 8 m. If the wavelength of the light is 6328 Å, determine (i) coherence time and (ii) spectral half-width.*

Solution: (*i*) $$t_{coh} = \frac{l_{coh}}{c} = \frac{8\,m}{3\times10^{8}\,m/s} = \mathbf{2.67\times10^{8}s}$$

(*ii*) $$\Delta\lambda = \frac{\lambda^2}{l_{coh}} = \frac{\left(6328\times10^{-10}\,m\right)^2}{8\,m} = \mathbf{5\times10^{-4}\ Å.}$$

Example 7.5: *Find the ratio of populations of the two states in a He-Ne laser that produces light of wavelength 6328Å at 27°C.*

Solution:

The ratio of population is given by $\dfrac{N_2}{N_1} = e^{-(E_2-E_1)/kT}$

$$E_2 - E_1 = \frac{12400}{6328}eV = 1.96eV$$

$$\therefore \frac{N_2}{N_1} = \exp\left[\frac{-1.96\text{ eV}}{(8.61\times10^{-5}\,eV)(300K)}\right] = e^{-75.88} = 1.1\times10^{-33}$$

Example 7.6: *A 10 mW He-Ne laser has efficiency of 1%. Assume that all input energy is utilized in pumping the atoms from the ground state to the excited state, which is 20 eV above the ground state. Find how many atoms are promoted to the excited state in one second.*

Solution: Efficiency of laser = 1% = 0.01

$$Power\ input = \frac{Power\ output}{Efficiency} = \frac{10\,mw}{0.01} = \mathbf{1\ W.}$$

Therefore, energy input in one second = 1 J.

Number of atoms excited in one second = $\frac{1\,\text{J}}{20\,\text{eV}} = \frac{1\,\text{J}}{20\times1.602\times10^{-19}\,J} = \mathbf{3.12\times10^{17}}$.

Example 7.7: *A 10 mw laser has a beam diameter of 1.6 mm. What is the intensity of the light assuming that it is uniform across the beam?*

Solution:

Intensity of light is given by

$$\frac{\text{Power of the laser}}{\text{Area of cross section of the beam}} = \frac{P}{A} = \frac{10\times10^{-3}W}{3.143(0.8\times10^{-3}m)^2}$$

$$\therefore\ \mathbf{I = 4.97\ kW/m^2}$$

Example 7.8: *If the half-width of the He-Ne laser operating at wavelength 6328Å is 1500 MHz, what must be the length of the laser cavity to ensure that only one longitudinal mode oscillates?*

Solution:

The length of cavity is given by $L = \frac{mc}{2\Delta\nu} = \frac{1\times3\times10^8\,m/s}{2\times1.5\times10^9\,/s}$

$$\therefore\ \mathbf{L = 0.1\ m.}$$

1.13. SOLVED NUMERICAL

1. **Compute the coherence length of yellow light with 5893 A^0 in 10^{-12} sec pulse duration. Also find the band width. (2M) [W-15] (3M) [W-16][W-17]**

Solution: λ = 5893 A^0

$t_{coh} = 10^{-12}$ sec

l_{coh}=?

$\Delta\lambda$=?

$$\ell_{coh} = c\times t_{Coh} = 3\times10^8\times10^{-12} = 3\times10^{-4}\,\text{m}$$

$$\Delta\lambda = \frac{\lambda^2}{\ell_{coh}} = \frac{(5893\times10^{-10})^2}{3\times10^{-4}} = 11.57A^0$$

2. **If light of 6600A^0 wavelength has wave train 20 λ long, what are its coherence length and coherence time?**

Solution: λ=6600A^0 = 6600 x10^{-10} m

l_{coh}= 20λ

l_{coh}= ?

t_{coh}= ?

$$l_{coh} = 20\times\lambda = 20\times6600\times10^{-10} = 1.32\times10^{-5}\,m$$

$$t_{coh} = \frac{l_{coh}}{c} = \frac{1.32\times10^{-5}}{3\times10^8} = 4.4\times10^{-14}\,s$$

3.White light has frequency range from 0.4 x 10^{15} Hz to 0.7 x 10^{15} Hz. Find the coherence time and coherence length. (3M) [S-15] [S-17]; (2M) [W-13]

Solution: Bandwidth $\Delta v = (0.7 - 0.4) \times 10^{15} = 0.3 \times 10^{15}$ Hz

$t_{coh} = ?$

$l_{coh} = ?$

$$t_{coh} = \frac{1}{\Delta \nu} = \frac{1}{0.3 \times 10^{15}} = 3.33 \times 10^{-15} \text{ sec}$$

$$l_{coh} = c \times t_{Coh} = 3 \times 10^{8} \times 3.33 \times 10^{-15} = 9.99 \times 10^{-7}\, m$$

4.If coherence length of sodium light is 2.9x10^{-2} m and its wavelength is 5890A^0, then calculate (i) the number of oscillations corresponding to coherence length (ii) coherence time.

Solution: $l_{coh} = 2.9 \times 10^{-2}$ m $= N\lambda$

$\lambda = 5890 A^0 = 5890 \times 10^{-10}$ m

$N = ?$

$t_{coh} = ?$

$$N = \frac{l_{coh}}{\lambda} = \frac{2.9 \times 10^{-2}}{5890 \times 10^{-10}} = 4.92 \times 10^{4}$$

$$t_{coh} = \frac{l_{coh}}{c} = \frac{2.9 \times 10^{-2}}{3 \times 10^{8}} = 9.667 \times 10^{-11}\, s$$

5.He-Ne system is capable of emitting laser at different wavelengths, the prominent one being 3.3919µm. Determine the energy difference (in eV) between the upper and lower levels for this particular wavelength.

Solution: $\lambda = 3.3919 \mu m$

$E = ?$

$$E = \frac{hc}{\lambda} = \frac{12400}{33913 A^{0}} = 0.365 eV$$

6. A typical He-Ne Laser emits radiation of wavelength 6328 A^0. How many photons per second would be emitted by one milli Watt He-Ne Laser?

Solution: $\lambda = 6328$ Å $= 6328 \times 10^{-10}$ m

$p = 1mW = 1 \times 10^{-3}$ W, $E = p \times t$, $t = 1$ sec.

$n = ?$ $E = 1 \times 10^{-3}$ J

$$E = p = nh\nu = \frac{nhc}{\lambda} \Rightarrow n = \frac{p\lambda}{hc}$$

$$\therefore n = \frac{1 \times 10^{-3} \times 6328 \times 10^{-10}}{6.626 \times 10^{-34} \times 3 \times 10^{8}} = 3.18 \times 10^{15} / \text{sec}$$

7.A ruby laser emits light of wavelength 694.4nm. If a laser pulse is emitted for 1.2 x10^{-11}sec and the energy released per pulse is 0.15 J (i) what is the length of the pulse? (ii) Calculate the number of photons in each pulse.

(3M) [W-14]

Solution: $\lambda = 694.4$ nm $= 694.4 \times 10^{-9}$ m

$t_{coh} = 1.2 \times 10^{-11}$ sec

$E = 0.15$ J

$l_{coh} = ?$

$n = ?$ $E = nh\nu = nhc/\lambda$, $n = E\lambda/hc$ ($\nu = c/\lambda$)

$$l_{coh} = c \times t_{coh} = 3 \times 10^{8} \times 1.2 \times 10^{-11} = 3.6 \times 10^{-3}\, m$$

$$n = \frac{E\lambda}{hc} = \frac{0.15 \times 694.4 \times 10^{-9}}{6.626 \times 10^{-34} \times 3 \times 10^{8}} = 5.239 \times 10^{17} / \text{sec}$$

8.Calculate the population ratio of two states in a laser that produces light of wavelength 7000A^{0}at 27^{0}C.

Solution: $\lambda = 7000 A^0$

$t = 27^0 C \Rightarrow T = 273 + 27 = 300^0 K$

$$\frac{N_2}{N_1} = \exp\left(\frac{-\Delta E}{KT}\right) \qquad \text{Where, } \Delta E = E_2 - E_1 = h\nu = \frac{hc}{\lambda}$$

$$\therefore \Delta E = \frac{12400}{7000A^0} = 1.77eV$$

$$\Rightarrow \frac{N_2}{N_1} = \exp\left(\frac{-1.77}{8.6\times10^{-5}\times300}\right) = 1.6046\times10^{-30}$$

9.A He-Ne laser of wavelength 11.5x10^{-7} m produces coherent light for 8m distance. Calculate (a) Coherence time (b) Spectral half width.

Solution: λ=11.5 x 10^{-7} m

l_{coh}= 8 m

t_{coh}= ?

$\Delta\lambda$ = ? λ^2/ l_{coh}

$$t_{coh} = \frac{l_{coh}}{c} = \frac{8}{3\times10^8} = 2.66\times10^{-8}\text{sec}$$

$$\Delta\nu = \frac{1}{t_{coh}} = \frac{1}{2.66\times10^{-8}} = 0.375\times10^8 Hz$$

$$\Delta\lambda == \frac{\lambda^2}{c}\times\Delta\nu = \frac{\left(11.5\times10^{-7}\right)^2}{3\times10^8}\times0.375\times10^8 = 1.65\times10^{-13} m$$

10. If the half-width of a CO_2 laser is 60 MHz, calculate the coherence length of the laser. If the cavity length is 2m, show that not more than one mode will oscillate.

Solution: $\Delta\nu$ = 60MHz=6x10^7 Hz

L = 2m

l_{coh}= ?

m=?

$$l_{coh} = \frac{c}{\Delta\nu} = \frac{3\times10^8}{6\times10^7} = 5m$$

$$m = \frac{2L\Delta\nu}{c} = \frac{2\times2\times6\times10^7}{3\times10^8} = 0.8\approx1$$

11. The half-width of the gain profile of He-Ne laser is 2x10^{-3} nm, what should be the maximum length of the cavity in order to have a single longitudinal mode oscillation. Wavelength of He-Ne laser is 6328A^0.

Solution: λ = 6328A^0 = 6328x10^{-10}m

$\Delta\lambda$ = 2x10^{-3} nm = 2x10^{-12} m

m=1

L=?

$$\Delta\lambda = \frac{\lambda^2}{2mL} \Rightarrow L = \frac{\lambda^2}{2m\Delta\lambda} = \frac{(6328\times10^{-10})^2}{2\times1\times2\times10^{-12}} = 0.1m$$

12.Find the relative populations of the two states in a ruby laser that produce the light beam of wavelength 6943Å at 300K. (3M) [S-16]

Solution: Wavelength 'λ' = 6943 Å =6943×10^{-10}m.

temp. 'T'=300K.

Boltzmann's constant 'K'=1.38×10^{-23}J/K

Planck's constant 'h'=6.63×10^{-34}J/s

$$\frac{N_2}{N_1} = \exp\left(-\frac{hc}{\lambda KT}\right) = \exp\left(-\frac{6.63\times10^{-34}\times3\times10^8}{6943\times10^{-10}\times1.38\times10^{-23}\times300}\right) = 8.8\times10^{\ \ 31}$$

13.Calculate number of photons emitted per second by a 3mW laser emitting radiation of wavelength 6943Å. (3)[S-18]

Solution: Wavelength 'λ' = 6943Å=6943×10^{-10}m.

Power P= 3mW= $3x10^{-3}$W = 3×10^{-3}Joules/sec , P=E/t, E=P.t

Time t= 1sec

Planck's constant 'h'= 6.63×10^{-34}Js,

No. of photons emitted per second = ? E=nhν =nhc/λ, n=E λ/hc , n= P.t.λ/hc (ν =c/λ)

$$n = \frac{Pt\lambda}{hc} = \frac{3\times10^{-3} \times 1\times 6943\times10^{-10}}{6.63\times10^{-34} \times 3\times10^{8}} = 1.047 \times 10^{16}$$

14. Compute the coherence length of light with 6328 Å in 10^{-9} second pulse duration. (2M) [W-18]

Solution: speed of light 'c'=3×10^{8}m/s,

coherence time = t_{coh}=10^{-12}s

wavelength 'λ' = 6328 Å =6328×10^{-10}m,

coherence length l_{coh} =?

$$l_{coh} = c\ X\ t_{coh} = 3\times10^{8}\times10^{-9}\text{m} = 0.3\text{m}.$$