2 May, 2024 LEC-12 Thursday

LIGHT AMPLIFICATION AND OSCILLATION

Amplification:- occurs when active medium is in inversion state. A photon of appropriate energy can stimulate the emission of cascade (large amount of something which flows) of photons. This process is known as amplification.

- Initial photon → Input signal
- Active medium → Quantum optical amplifier
- Emerging light → Amplified output

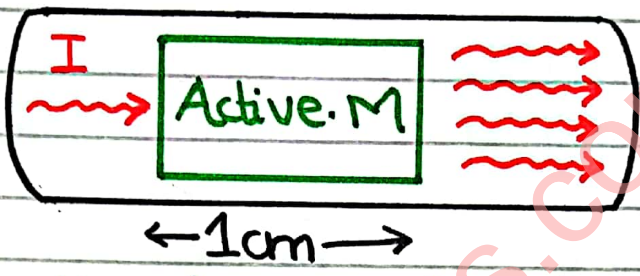
Gain:- is a measure of degree of amplification. It is the increase in the intensity when light beam passes through the active medium.

* It is expressed as:- $G = \frac{1}{I}\left(\frac{dI}{dx}\right)$

where,
- I = initial intensity
- x = distance at which stimulated emission is possible (in cms)

Definition:- Gain is the amount of stimulated emission which a photon can produce in a given distance (x).

example:- If the gain is 4% , it means a single photon produces four photons , per each centimeter it travels in a medium.



$$G = \frac{1}{I}(4I)$$

$$G = 4$$

★ Unfortunately , the laser materials have very low gain . It means that the photon has to travel a large distance for producing large amplification .

For example:- If gain is 0.001% per centimeter and we wish to increase is by 1000 times , it is calculated that the light has to travel about **69m** in the medium. Such a long distance is obviously not practicable . To overcome this problem we will introduce optical resonator .

Optical Resonator

One of the methods of making the light to pass through the long distance of laser material is by keeping mirrors on both sides of a short laser rod or tube .

The light bounces back and forth between the mirrors and make many passes through medium increasingly the affective distance of travel by many times .

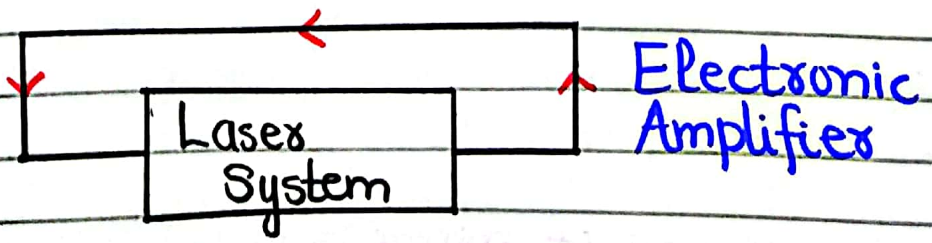
Such an arrangement of mirror is called optical resonator.

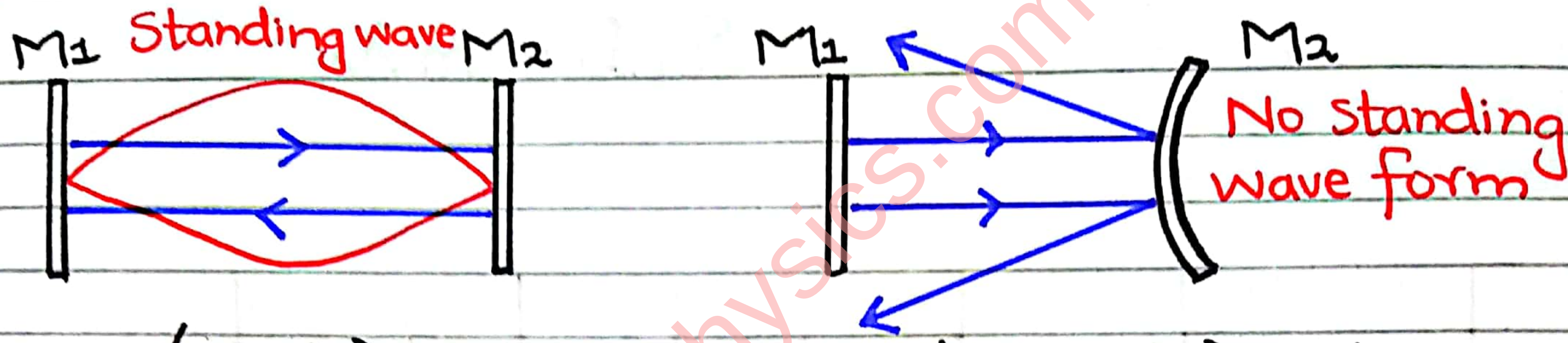
Close Cavity is used as an oscillator in which standing wave may be produced. However at light frequency the close cavity can't sustain the standing wave since the dimensions of cavity should be in order of the wavelength. It is difficult to make such a microcavity.

⇒ Two American Scientists, **Townes** and **Schawlow** showed that instead of a close cavity, an open cavity may be used at light frequency in the form of two parallel mirrors to serve the purpose. This open cavity for generating light oscillations is called optical resonator.

⇒ In case of laser, **feedback** is produced by placing the active medium between a pair of mirrors facing each other. Chance photons plays the role of input signal which are spontaneously emitted along optical axis of laser rod or tube.

⇒ The photons trigger many stimulated emissions in their path and photons at the end are reflected back into the medium by the mirror.





Closed (stable) cavity Open (Unstable) cavity

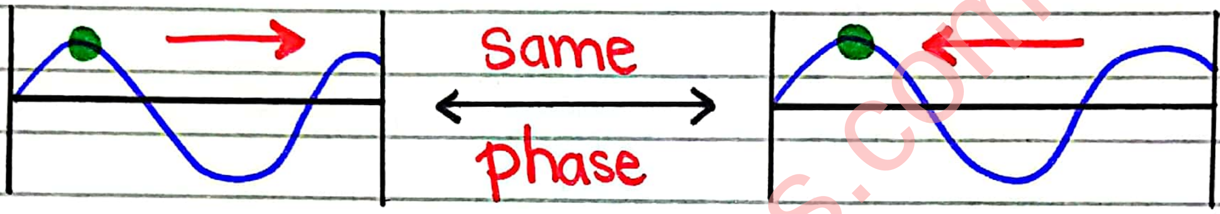
The photons reserve their direction and travel through the medium till they reach the mirror at the other end.

* While forming a cavity, two things must be considered,

(i) Cavity should not change phase of light wave.
(ii) Cavity must be small.

Condition for Steady State Oscillations

The light amplification implies a continuous and marked increase in amplitude of light wave. To achieve **proper amplification**, the wave making round trip should maintain both phase and amplitude conditions.



It is necessary that the wave returning to the same point in the medium must have same phase as that of original wave with any number of reflections within the cavity.

It implies that the phase delay must be some multiple of '2π' i.e:- optical path length travelled by wave between two consecutive reflections at the same end mirror should be integral multiple of wavelength 'λ'.

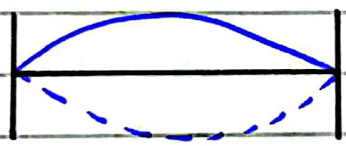
Condition:- This impose a certain condition on the relationship between the wavelength and the length of laser rod given by,

$$2nL = m\lambda \quad \rightarrow (1)$$

n → refractive index of active medium

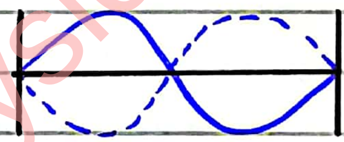
The cavity length therefore, puts restriction that only those light waves which satisfy the above condition **The integral multiple of wavelength within twice the cavity length** are amplified strongly and other wavelengths are all evacuated.

Thus, the cavity length must accomodate integral number of standing waves.



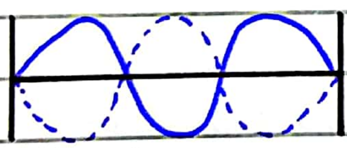
$m=1$

Fundamental Harmonic



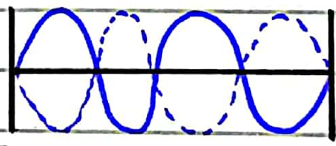
$m=2$

Second Harmonic



$m=3$

Third Harmonic



$m=4$

Forth Harmonic

i) Length of the cavity :- $\left(L = \frac{m\lambda}{2n} \right)$ → (2)

ii) Wavelength of laser :- $\left(\lambda = \frac{2nL}{m} \right)$ → (3)

iii) Cavity resonance frequency :-

$$v = f\lambda \rightarrow f = \frac{v}{\lambda} = \frac{c}{\lambda} = \boxed{\frac{cm}{2nL} = \nu_m}$$ m^{th} mode

↓ (4)

iv) (m+1)th mode frequency :-

$$\nu_{m+1} = \frac{(m+1)c}{2nL} = \frac{mc}{2nL} + \frac{c}{2nL} \rightarrow (5)$$

v) Difference in frequency of modes :-

$$\Delta\nu' = \nu_{m+1} - \nu_m = \frac{mc}{2nL} + \frac{c}{2nL} - \frac{mc}{2nL} = \boxed{\frac{c}{2nL} = \Delta\nu'}$$

↑ (6)

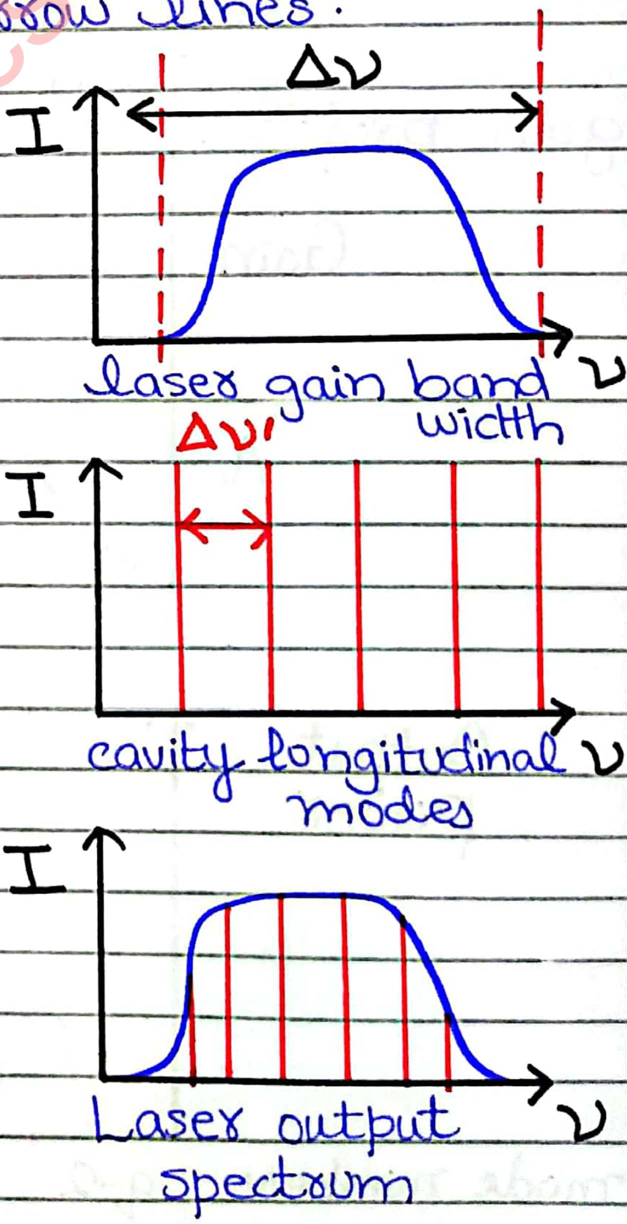
$$\therefore c = \nu\lambda$$

$$\therefore \nu = \frac{c}{\lambda}$$

Number of resonant frequencies within the cavity could be found by bandwidth of the laser

$$N = \frac{\Delta\nu}{\Delta\nu'} = \frac{2nL\Delta\nu}{c} \rightarrow (7)$$

The resonator (cavity) therefore transforms the gain line into a set of narrow lines.



In terms of λ, we get

$$\frac{\Delta\nu}{\nu} = \frac{\Delta\lambda}{\lambda}$$

$$\Delta\lambda = \frac{\Delta\nu}{\nu} \times \lambda$$

$$= \frac{\Delta\nu \times \lambda^2}{c}$$

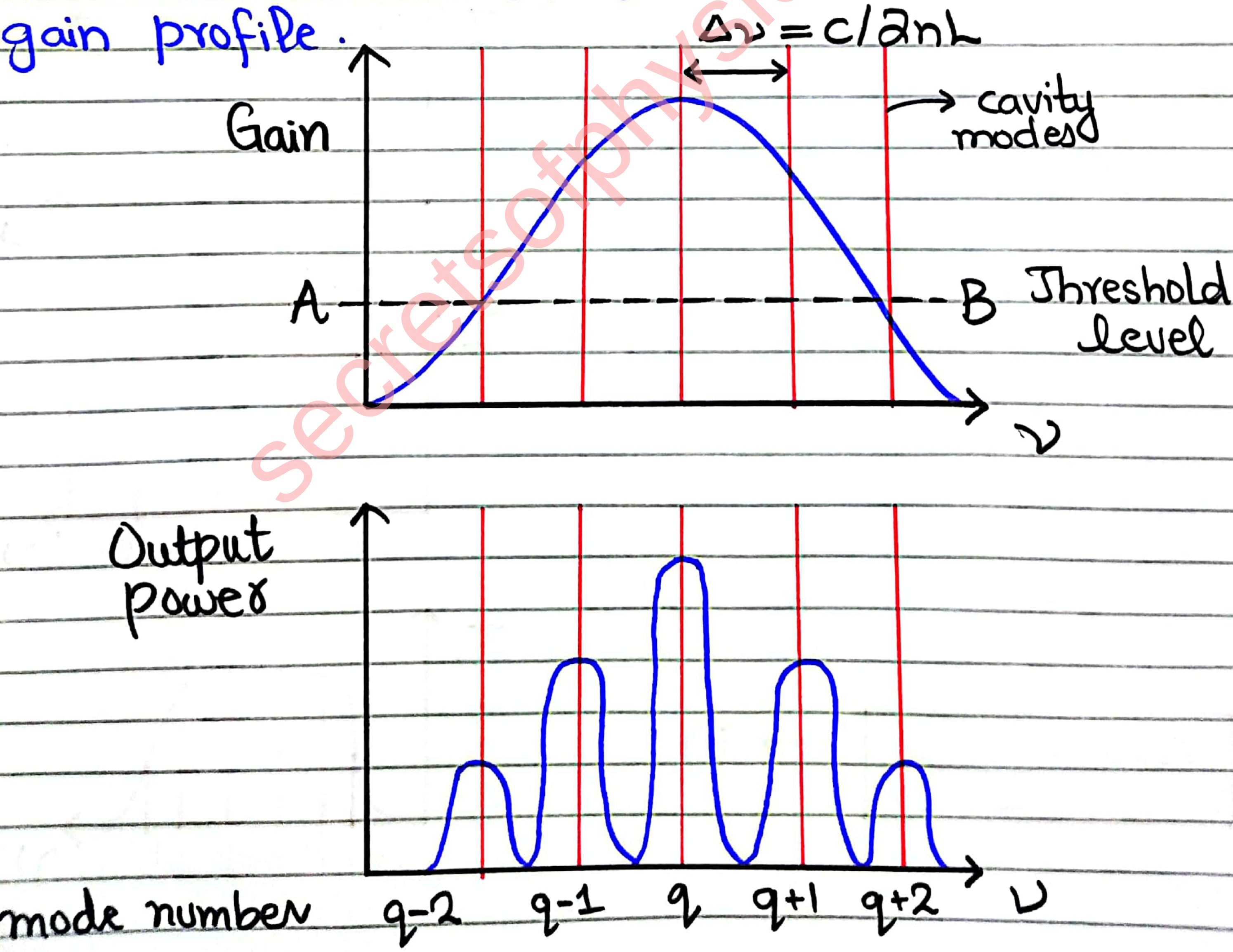
$$= \frac{\lambda^2}{c}\left(\frac{c}{2nL}\right)$$

$$\boxed{\Delta\lambda = \frac{\lambda^2}{2nL}} \rightarrow (8)$$

Cavity Gain Bandwidth :-

Ideally a group of same frequencies radiate within the cavity by stimulated emission. However due to line broadening mechanism, there is a small spread of frequencies about the central wave-length called **bandwidth**.

The limited range of frequencies over which stimulated emission can provide sufficient gain is called **emission bandwidth** also known as **gain profile**.



Line AB = Cavity Loss Level

The curve above line AB include the area of the net gain for the laser.

The gain bandwidth $\Delta\nu$ is measured at the cavity loss level. Thus, $\Delta\nu$ constitutes of the range of frequencies for which the gain exceeds the cavity losses.

* All the resonators used in the lasers may group into two categories.

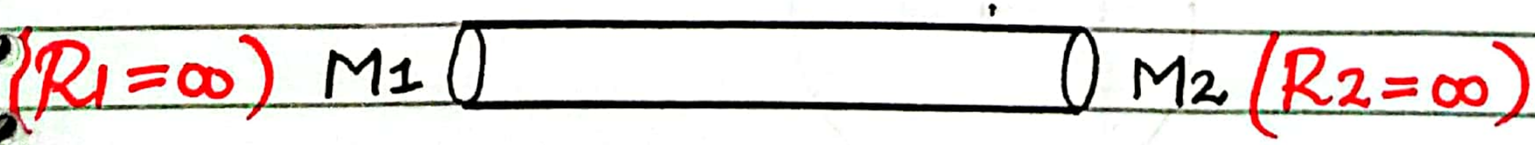
Stable Resonators:- The beam of light strictly remain within the cavity.

Unstable Resonators:- The ray of light after reflecting from the mirror diverges infinitely away from the axis of mirror.

* There are different configurations of resonators which are widely used. Some of the commonly used resonators are:-

(1) Febry-Perot Resonator

Febry-Perot Resonator consists of two plane mirrors alligned parallel to each other as:-



In Febry-Perot Resonator, we have two plane mirrors having radius of curvature ($R_c = \infty$) and active medium is placed between the cavity.

The oscillations take place with two parallel mirrors acting as modes. Thus the optical path length travelled by the wave between the two consecutive reflections at the same end mirror should be integral multiple of wavelength λ :

$$2\mu L = n\lambda$$

* If L is the length of the cavity, $L = \frac{n\lambda}{2\mu}$
* And the frequency difference is, $\Delta\nu = \frac{c}{2\mu L}$

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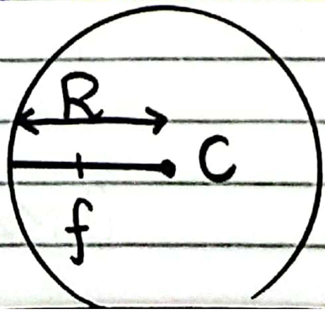
(2) Concentric or Spherical Resonators :-

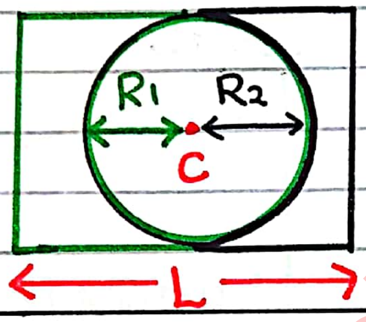
It consists of two spherical mirrors having the same radius of curvature R placed at a distance of length L facing each other, such that the centres of curvature C_1 and C_2 of the mirror coincide.

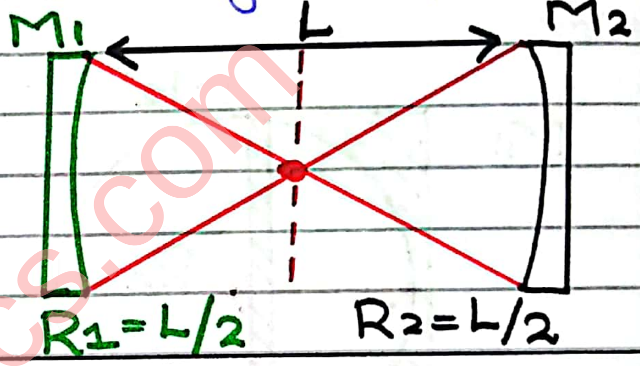


Thus the distance between end mirrors is 2R. This configuration of the resonator can be used for oscillation of the wave of wavelength $L/2$.

$R_1 = \frac{L}{2}$

$R_2 = \frac{L}{2}$

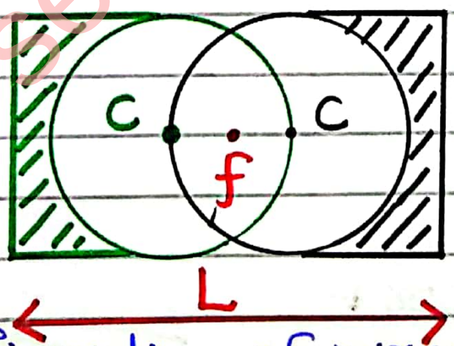


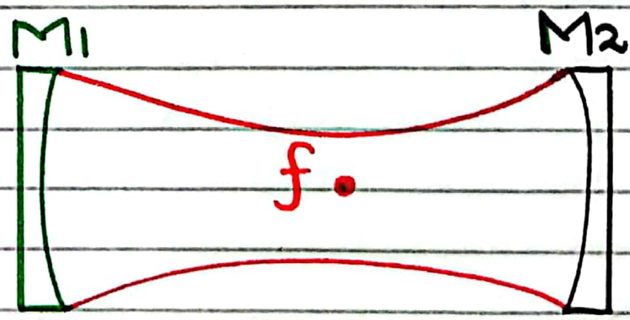


3) Confocal Resonator :- consists of two spherical mirrors M_1 and M_2 of same radius of curvature R placed at a distance L such that the foci of two mirrors coincide. Hence the centre of curvature of M_1 lies on the surface of mirror M_2 and vice versa. Thus the distance between end mirrors is $L = R$.

$R_1 = L$

$R_2 = L$

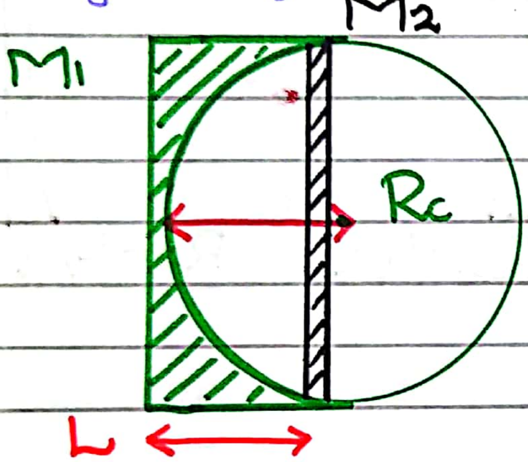


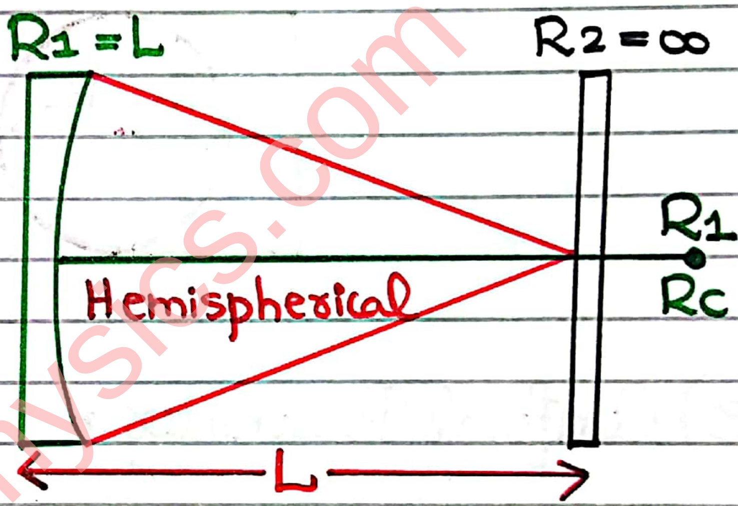


This configuration of mirror is an excellent choice where frequence allignments are required. However it is very difficult to obtain configuration of modes and resonant frequency in this configuration.

(4) Combination of Plane and Spherical Resonator :-

The radius of curvature of the spherical mirror in this configuration is usually larger than the cavity length.

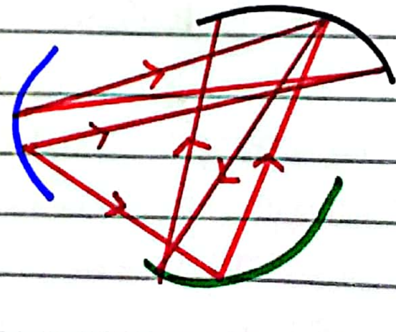




If the radius of curvature of the spherical mirror is equal to the length of the cavity, the beam takes conical shape inside the active medium.

Gain :- The gain is unequal between two sides of cavity if $R_c = L$. The gain may be equal inside the cavity, if a gain medium placed near to spherical mirror.

5) Multiple Spherical Mirror :-



"PUMPING PROCESS"

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

⇒ The process of supplying energy to the medium with a view of transferring it into the state of population inversion is known as **pumping**.

Q) Can population inversion achieved by heating?

Heating the material will not bring population inversion. Thermal energy will only heat up the collection of atoms and all of them maintaining the same population ratio will just gain more heat energy.

Types of Lasers

The pumping process in lasers involves a number of energy levels with complicated excitation mechanisms.

1) Atomic Lasers include:-
- Helium Neon laser (He-Ne).
- Helium Cadmium laser (He-Cd).
- Copper Vapour laser.

2) Molecular Lasers include:-
- Carbon dioxide laser (CO_2).
- Nitrogen laser (N_2).
- ArF and KrF excimer laser.

3) Liquid Lasers include:-
- Organic dye lasers have molecules dilutely dissolved in various solvent solutions.

4) Dielectric Solid Lasers include:-
- Nd:YAG laser
- Nd: Glass lasers

Neodymium atoms doped in YAG or glass to make crystalline Nd:YAG or Nd:Glass lasers.

5) SemiConductor Lasers include:-
- Gallium Arsenide laser.
- Indium Phosphide Crystal laser.

Active Medium:- The medium in which light gets amplified is called active medium. The medium may be solid, liquid or gas.

Out of the different atoms in the medium, only a small fraction of atoms of particular species are responsible for stimulated emission and consequent light amplification. They are called **active centres**.

The remaining bulk of material plays the role of a host and supports active centres.

The population inversion happens only in the active centres of the medium and pumping process should be such that the maximum input energy should be targetted to the active centres.

Because of the consequences of the **Einstein's theory**, radiation grows in intensity as it passes through the active medium.

PUMPING METHODS

According to requirement, diverse methods of pumping are used. Given below are some types of lasers and pumping mechanisms used in them.

Types of Lasers	Pumping Mechanism
1) Gas Laser (He-Ne) (Argon Ion)	AC or DC Electrical discharge through gas medium.
2) Solid State (Ruby) (Nd : YAG)	Optical Pumping High energy Xenon Flash lamp.
3) Liquid Laser (Dye laser)	Optical pumping
4) Free electron	Particle accelerators

1) OPTICAL PUMPING :-

In this method, photons are used to excite the atoms. A light source such as flash discharge tube is used to illuminate the laser medium and the photon of appropriate frequency excite the atoms to an uppermost level.

The optical pumping source can be any one of the various types of flash discharge tubes such as continuously operated lamps, spark gaps or auxiliary laser etc.

*Optical pumping is used for :-

(i) Solid State Crystalline Lasers.
(ii) Liquid Tunable Dye Lasers.

The pumping level of the atom must not be of narrow level. It should be sufficiently large/wide, spaning a range of energies.

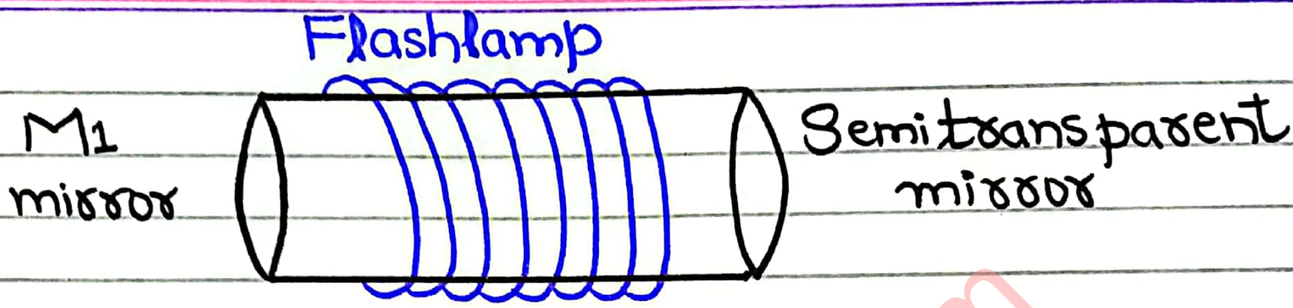
If it is narrow, one can use pump photon of only specific frequency such a situation severly restricts the choice of source and a large portion of source power will go wasted.

However, in majority of cases, the upper levels are wide bands and atoms can be excited to many of the upper levels. Therefore light sources emitting a broad range of wavelengths like flash-lamps can be used to execute the atoms.

RUBY LASER :-

First successful optical laser constructed by Maiman in 1960 consisted of ruby crystals surrounded by a hellical/helicolidal flash lamp/tube enclosed within a polished aluminium cylindrical cavity cooled by forced air.

Note :- Cooling system is a must in Lasers because the heat will hijack the whole system. Water circulates all time in the cavity.



The most common configuration is the gain medium is in the form of rod at one of the focus of a mirrored cavity, consisting of an elliptical cross-section perpendicular to the rods axis. The flash lamp is tube located at other focus of the ellipse.

2) ELECTRIC PUMPING (Direct Discharge) :-

If laser medium is placed in an electron beam, the electrons create a population inversion by transferring their energy to atom when they collide.

Consequently, the atoms are ionized and excitation is produced. Several types of high power lasers (gas lasers) are pumped this way.

Examples :- Argon gas laser, Nitrogen laser.

P-N Junction Laser

Another variation of electric pumping creates a population inversion in semiconductor diode lasers.

When a current passes through the interface between two different types of semiconductors, it creates mobile charge carriers. If enough of these are created, they can produce a population inversion.

The p-n junction lasers are called **injection lasers.**

Inelastic atom-atom collisions :-

The atoms excited by electrical discharge method collide inelastically with other atoms, transferring their energy in the process. Population inversion is produced in the other atoms.

Examples:- He-Ne lasers and CO_2 lasers.

3) CHEMICAL PUMPING :-

In chemical pumping, the energy for pumping is obtained from a chemical reaction.

As an example, when hydrogen combines with fluorine to form hydrogen fluoride, enough heat is generated

$$H_2 + F_2 \longrightarrow 2HF + \text{heat}$$

exothermic reaction

This reaction is employed for pumping in HF lasers and HCl lasers.