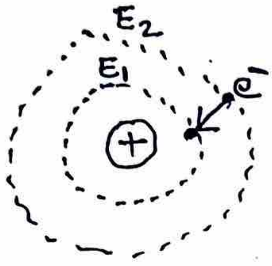
LASER

(Light Amplification by Stimulated Emission of Radiations)

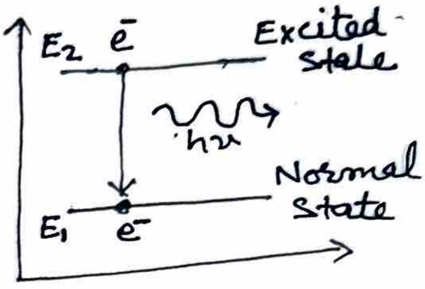
Atomic Emission :-

i Spontaneous Emission ii Stimulated emission



$\rightarrow h\nu = E_2 - E_1$

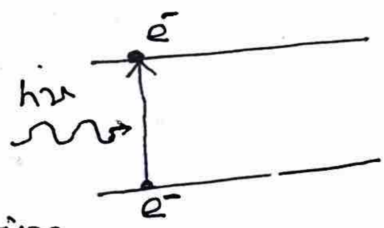
$E_2 > E_1$



$$\boxed{h\nu = E_2 - E_1}$$

(Emission of radiation by transition from one energy state to another)

i Spontaneous Emission :->



With absorption of radiation, the electron in ground state or normal state is transfered to excited state.

The time for which the electron remain in the excited state is called life time τ and is of the order of 10^{-8} sec.

But there are energy levels having energy less than the energy of excited levels, in which the life time is greater than 10^{-8} sec. These levels or states are called metastable levels.

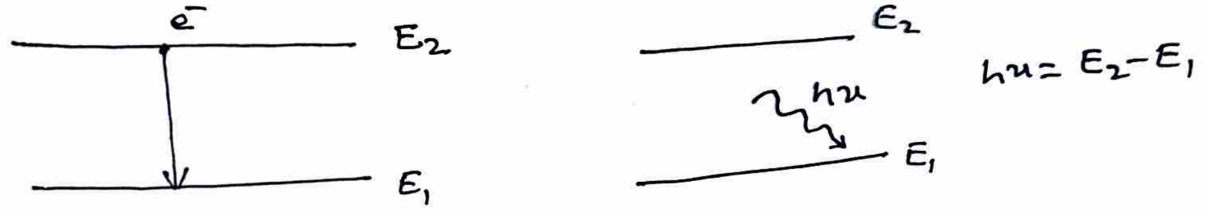
$\tau \sim 10^{-8}$ sec ———— Excited State

$\tau >> 10^{-8}$ sec - - - - - - - - Metastable State

$\tau \rightarrow$ Very Large (unlimited) ———— Ground State

A particle transit from higher energy state to lower energy state by emitting a photon of energy $h\nu = E_{Higher} - E_{lower}$.

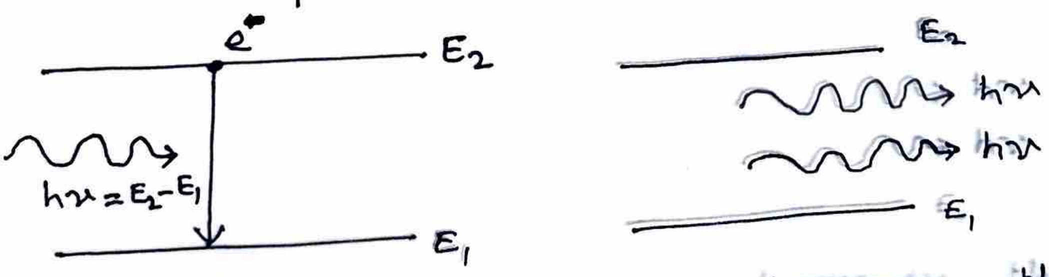
In spontaneous emission, the emission is independent of out-side circumstances. The emitted photon has random phase and direction. So the radiation emitted by spontaneous emission is incoherent and can travel in all direction.



ii <u>Stimulated Emission</u> :→

When a particle is in excited state, it can be forced to transit to ground state by emitting a photon. It is called stimulated emission.

A photon having energy $h\nu$ equal to the energy difference between excited and ground states, ~~indi~~ incidents on excited electron. The incident photon stimulate the electron in excited state to emit a photon of same energy $h\nu$. This forced emitted photon has same phase and direction as of incident photon.

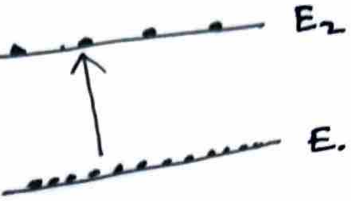


So stimulated photon has same frequency, phase and direction and radiation is coherent.

Einstein's Coefficient :→

Consider two energy levels of an atom having energies E_1 and E_2, such that $E_2 > E_1$. Consider N_1 and N_2 be the no. of atoms per unit volume in energy state E_1 and E_2.

An atom in lower level can absorb radiation and get excited to higher level E_2.



The rate of absorption ~~will~~ would depend upon the density of radiation of energy $E_2 - E_1$ and is called stimulated absorption.

Let $u(\nu)$ → radiation density available.

Now, the probability ~~that a radiation is absorbed~~ of absorption is directly proportion to radiation density.

$$\Rightarrow \quad P_{12} \propto u(\nu) \qquad \text{——— (1)}$$

$$\Rightarrow \quad P_{12} = B_{12}\, u(\nu)$$

The number of absorption per unit time per unit volume is

$$N_1 P_{12} = N_1 B_{12}\, u(\nu) \qquad \text{——— (2)}$$

here B_{12} is called Einstein's co-efficient of Absorption.

~~Now~~, consider the reverse process, emission of radiation. Emission can take place in two different ways –

i Spontaneous ii Stimulated.

In spontaneous emission, the probability per unit time of the atom making a downward transition is independent of density of radiations. But, in the stimulated emission, the probability per unit time of emission depends on the radiation density.

If A_{21} → Einstein's coefficient of spontaneous emission & B_{21} → Einstein's co-efficient of stimulated emission, then rate of total emissions.

$$N_2 P_{21} = N_2 A_{21} + N_2 B_{21} u(\nu) \quad \text{——— (3)}$$

At thermal equilibrium, the number of upward transitions must be equal to no. of downward transitions. So, at thermal equilibrium, we may write from eqns. (2) and (3)

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

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

$$\text{or } u(\nu) = \frac{A_{21}}{\left(\frac{N_1}{N_2}\right) B_{12} - B_{21}} \quad \text{——— (4)}$$

But according Einstein, the probability of stimulated emission must be equal to probability of stimulated absorption.

$$\Rightarrow B_{21} = B_{12}$$

From eqn. (4),

$$u(\nu) = \frac{A_{21}}{\left(\frac{N_1}{N_2} - 1\right) B_{21}} = \frac{A_{21}/B_{21}}{\left(\frac{N_1}{N_2} - 1\right)} \quad \text{——— (5)}$$

At thermal equilibrium, the distribution of atoms among different energy levels is given by Boltzman's Law. According to it,

$$\frac{N_1}{N_2} = \exp\left(\frac{E_2 - E_1}{k_B T}\right) \quad \text{———}$$

$$\Rightarrow \frac{N_1}{N_2} = \exp\left(\frac{h\nu}{k_B T}\right) \quad \text{——— (6)}$$

From (5) and (6),

$$u(\nu) = \frac{A_{21}/B_{21}}{\exp\left(\frac{h\nu}{k_B T}\right) - 1} \quad \text{——— (7)}$$

Equation (7) gives the relation between density of radiation with the atoms in energy levels E_1 and E_2.

Now, According to Planck's radiation law, the energy density of radiation is given as

$$u(\nu) = \frac{8\pi h \nu^3}{c^3} \frac{1}{\exp(h\nu/k_B T) - 1} \quad \text{—— (8)}$$

From (7) and (8), the ratio of the number of spontaneous to stimulated emissions at thermal equilibrium is given as

$$\boxed{\frac{A_{21}}{B_{21}\, u(\nu)} = \exp\left(\frac{h\nu}{k_B T}\right) - 1} \quad \text{—— (9)}$$

Also

$$\boxed{\frac{A_{21}}{B_{21}} = \frac{8\pi h \nu^3}{c^3}} \quad \text{—— (10)}$$

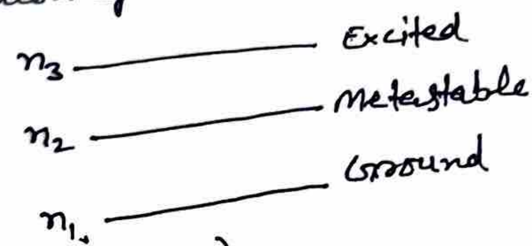
From equ. (9) it is clear that, for $h\nu << k_B T$, the number of stimulated emissions far exceeds the number of spontaneous emission while for $h\nu >> k_B T$, the number of spontaneous emissions far exceeds the number of stimulated emissions.

Refer

Population Inversion :- and Pumping :→

For LASER action, the number of particles N_2 in higher energy state should be more than the number of particles N_1 in lower state. It is called population inversion.

In case of system having more than two states and population of higher energy state is more ~~than~~ in comparision of the population of lower energy state are called negative temperature states.



$(n_3 > n_2 > n_1)$

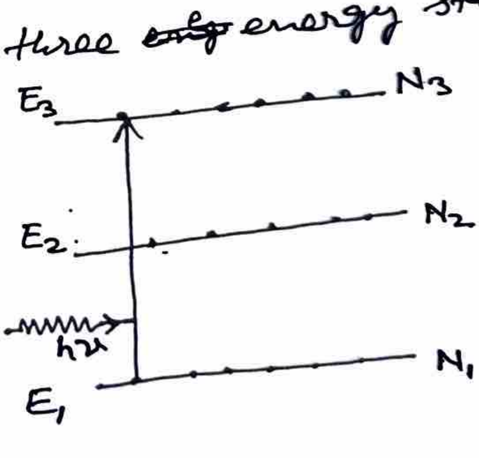
An active system is one in which population inversion is achieved.

Pumping :→ The method of raising the particle from lower energy state to higher energy state is called pumping.

optical pumping, electric pumping, Thermal Pumping

Optical Pumping :→ The process of achieving the population inversion using radiation photons is called optical pumping.

Three-level Laser :→ There are three ~~only~~ energy states.



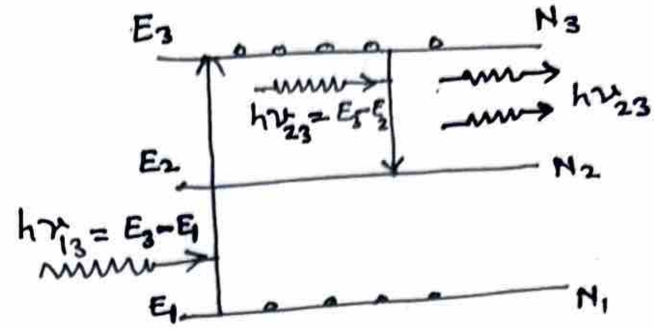
The system is exposed to radiation source (for optical pumping) of energy,

$$h\nu = E_3 - E_1$$

The particles are excited to energy state E_3 and population inversion is achieved between E_3 & E_2

$\Rightarrow N_3 > N_2$

Laser action is achieved between E_3 & E_2

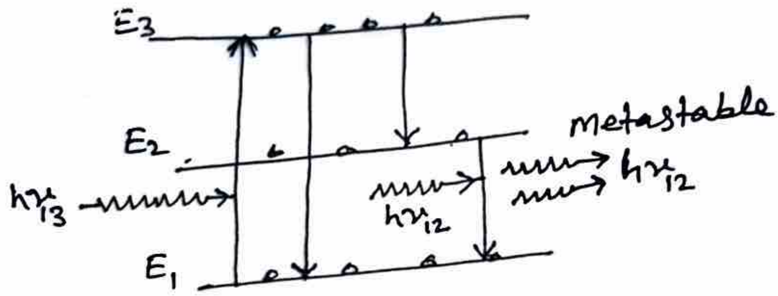


(a)

If E_2 is a metastable state, then population inversion must be achieved between levels E_1 and E_2.

$\Rightarrow N_2 > N_1$

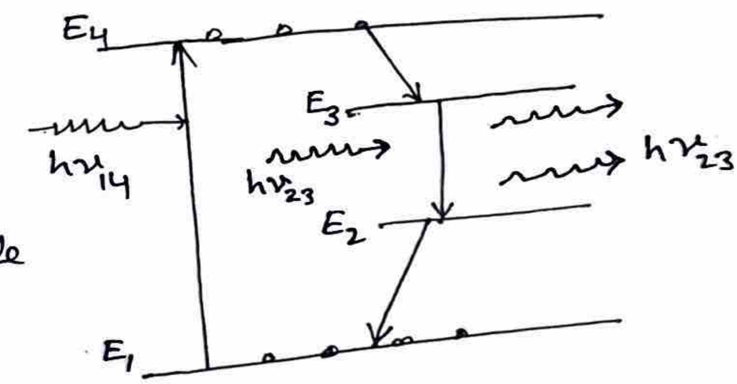
Laser action is achieved between E_2 and E_1



Four Level Lasers :→

Four energy levels (Ground + 3 excited states)

Atoms are excited from E_1 to E_4 by optical pumping.



Level E_3 is metastable level having a long life time.

~~Optical~~ Population inversion is achieved between E_3 and E_2.

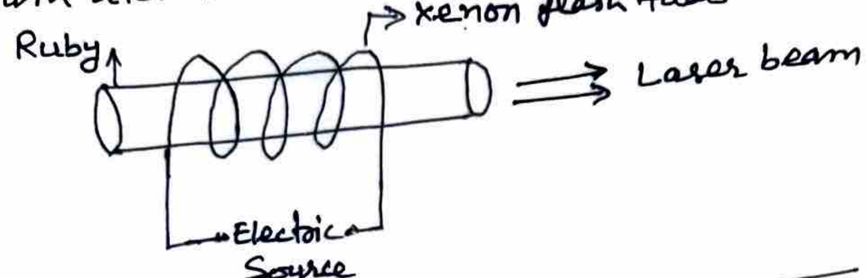
Laser action take place by stimulated emission from energy level E_3 to E_2.

1. Ruby Laser :→

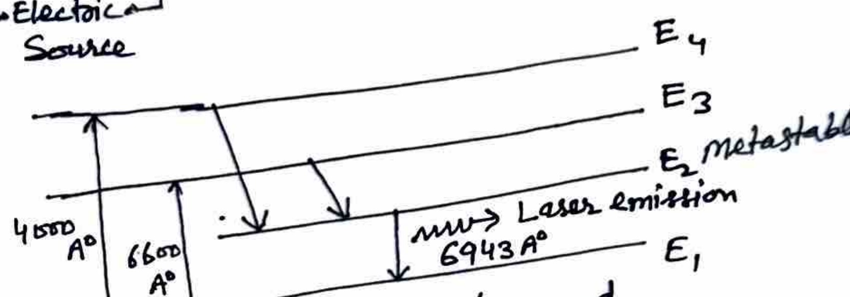
First laser which was practically developed by Maiman 1960.

It is three level laser and consists of single crystal of Ruby (Aluminium oxide Al_2O_3 + 0.05% Chromium oxide Cr_2O_3)

Chromium atoms are responsible for Laser action.



Since metastable state has long life time.



So population inversion is achieved between E_2 and E_1.

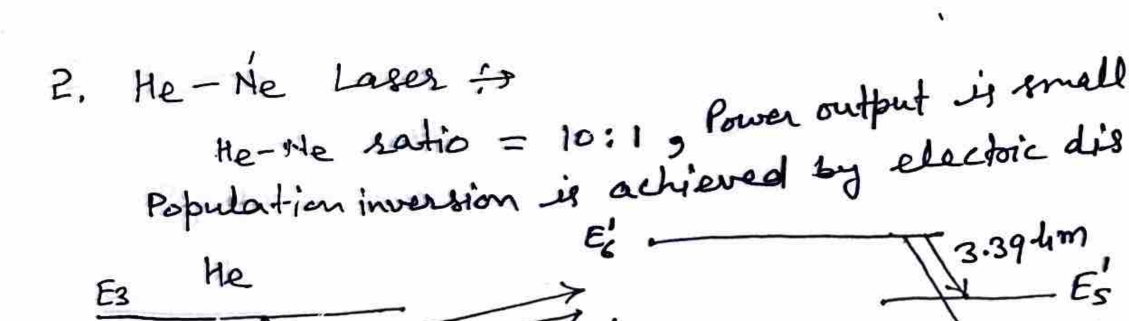
In this way, laser action is triggered between E_2 & E_1

Laser emission has wavelength equ. to 6943 A°

2. He - Ne Laser :→

He-Ne ratio = 10:1, Power output is small ≈ 100 mW

Population inversion is achieved by electric discharge.

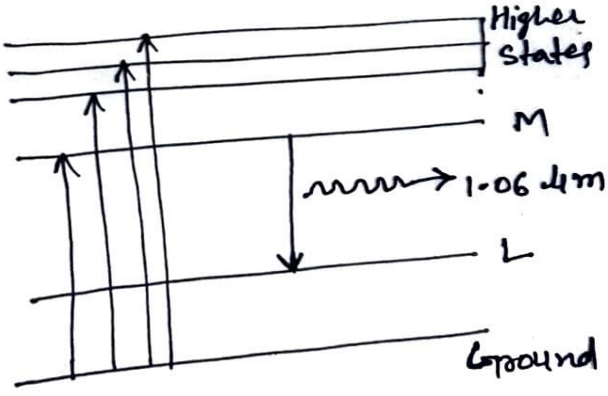


The levels of E_2 and E_3 of Helium have nearly the same energy as the levels E'_4 and E'_6 of Neon.

E_2 and E_3 of He are metastable states.
The He atoms remain in these state for a long time.
These excited Helium atoms collide with unexcited neon atoms and raise them to the levels E_4' and E_6'.
Population inversion occurs with respect to states E_3' & E_5'.
The He-Ne laser produces the radiation of wavelengths 3.39 μm, 6328 A° & 1.15 μm respectively.

3. Nd : YAG Laser :→

It is four level laser.
The active medium for this laser is the Neodymium ion (Nd^{+3}) which is doped in Yattrium Aluminium Garnet (YAG → $Y_3Al_3O_{12}$).
Optical pumping is used to achieve the state of population inversion.
For optical pumping white light of xenon flash tube is used. This excites the Nd^{+3} ions from the ground state to various higher states.

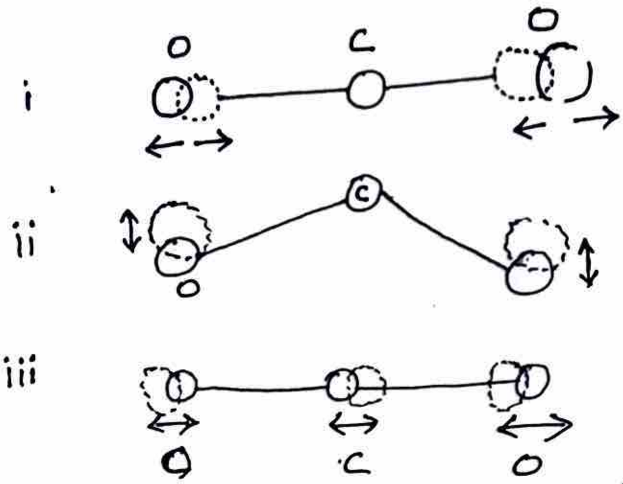


Laser action takes place between M and L levels at a wavelength of about 1.06 μm

It has a large no. of application in industry.

4. CO_2 Laser :— In the molecule, the atoms may vibrate in different modes or rotate about various axis.

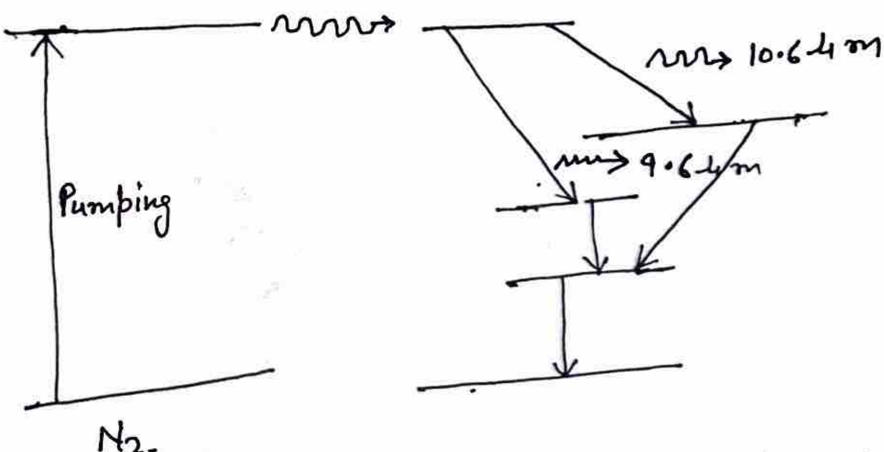
$CO_2 : N_2 : He$
$1 : 4 : 5$



Nitrogen molecules are excited to higher energy level by optical pumping. N_2 molecule transfer the energy to CO_2 molecule ~~through~~ by collision.

(Mode of vibration of CO_2)

Due to these vibrational motions of atoms in CO_2 molecule, each ~~ene~~ electronic energy levels of atoms in CO_2 get splitted into various vibrational sublevels and each vibrational sublevel is further subdivided into rotational sublevels.



The Laser action produces outputs of 10.6 μm and 9.6 μm.

CO_2 laser has much more efficiency as compared to other lasers.

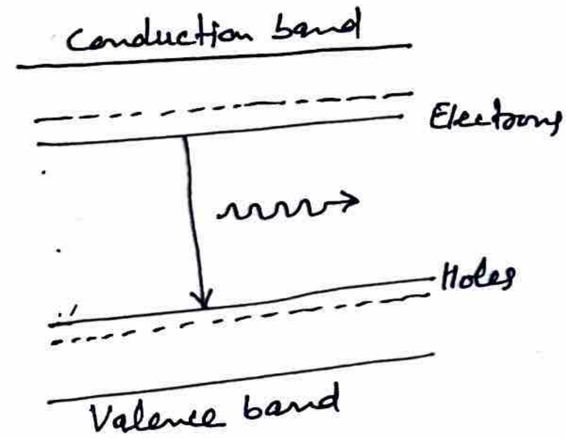
5. Semiconductor Laser :→

Energy is released due to recombination of electrons of holes (in form of heat).

But in case of some semiconductor (GaAs), the energy is released in the form of light.

The photons emitted at the time of recombination of an electron with a hole will stimulate recombination of other carriers of electric charges. The result will be stimulated emission of radiation resulting in laser action.

The active region for laser action is the pn-junction layer which is very thickness of order 0.5 mm.



Holography :→

It is a technique to produe the 3-dimensional picture and lasers are used to record and to reproduce an image of the object.

In ordinary photography, only the amplitude (intensity) is recorded and no phase distribution is recorded.

~~In three dimen~~

In holography, amplitude as well as the phases of the light received from different parts of object is recorded.

(It is based on the phenomenon of interference.)

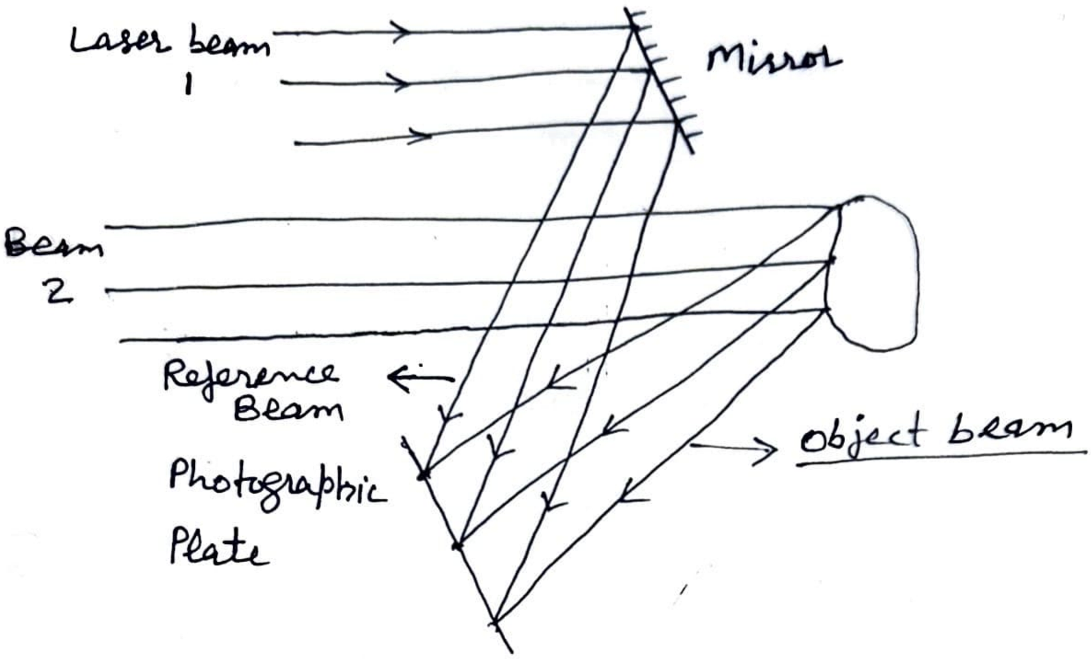
Let there are two point sources. The interference fringes are produced due to interference. ~~The~~ Let I_1 & I_2 are intensities of first and second source respectively and ϕ is the phase difference between ~~two~~ ~~to~~ the waves of two sources at the detection point, then resultant intensity I at the point is

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\phi \qquad (1)$$

From eqn. (1), it is clear that the resultant intensity contains the information about amplitude as well as phase between the two sources.

For ~~inf~~ interference, one needs the coherent light and lasers are used for this purpose.

To construct the hologram, one needs two beams i Reference beam ii Object beam

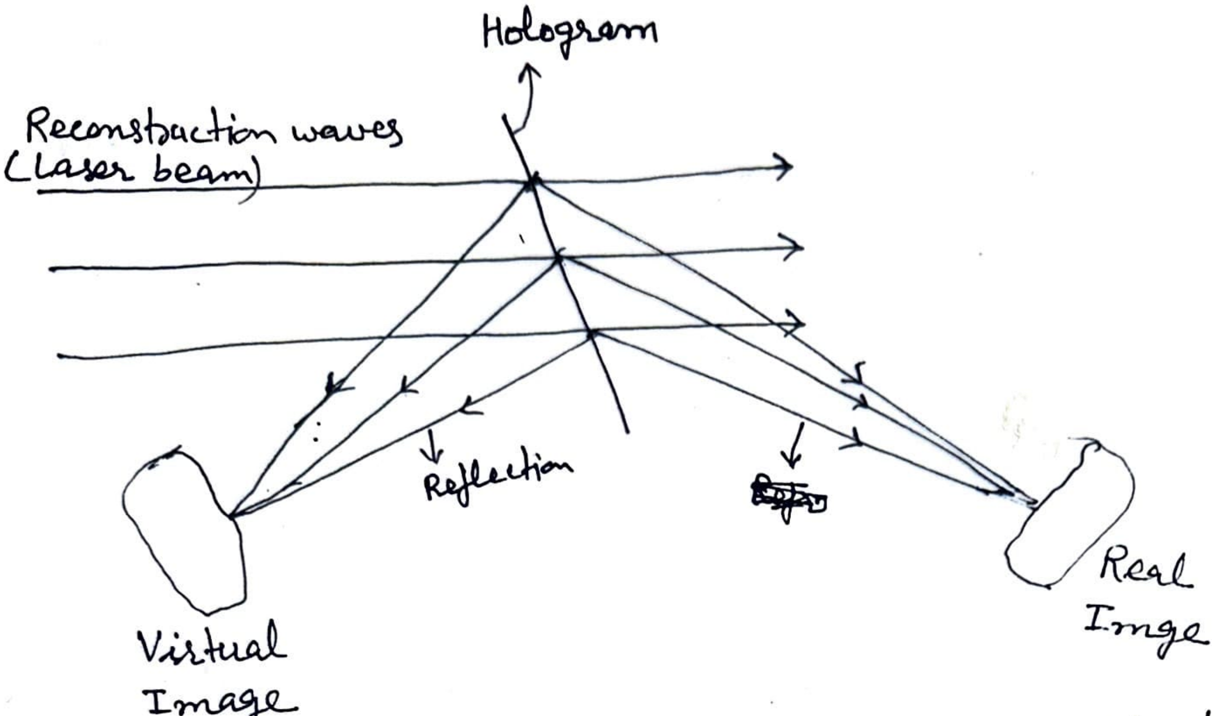


These two beams, reference beam and object beam interfere on the photographic plate. The interference pattern is obtained on the photographic plat. This film is called a hologram.

The hologram contains the information about amplitude as well as the phase of the object wave.

To produce image from Hologram :→

To illuminate the hologram single laser beam is used and it is called reconstruction wave. The reconstruction wave is identical to the reference wave used to produce hologram. There emerges various components of wave, one of the which is the object wave itself.



In this way, we get the wave which is identical to the wave that was inmating from the object at the time of construction of hologram.

We have two types of image.

i Virtual ~~conf~~ image, which can be seen by eye

ii Real image, which can be recorded on the light sensitive material (like photographic plate)