A Presentation on

Lasers

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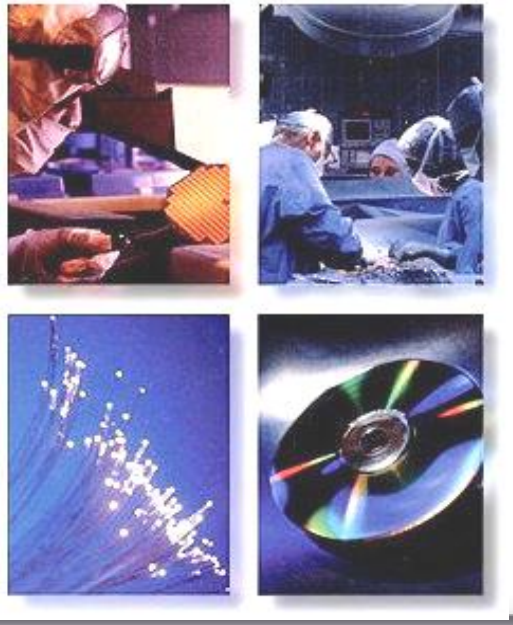
Summary

- What is Laser?
- Classification of light-atom interaction
- Necessary condition for lasing transition
- Properties of Laser
- Types and Use of Laser

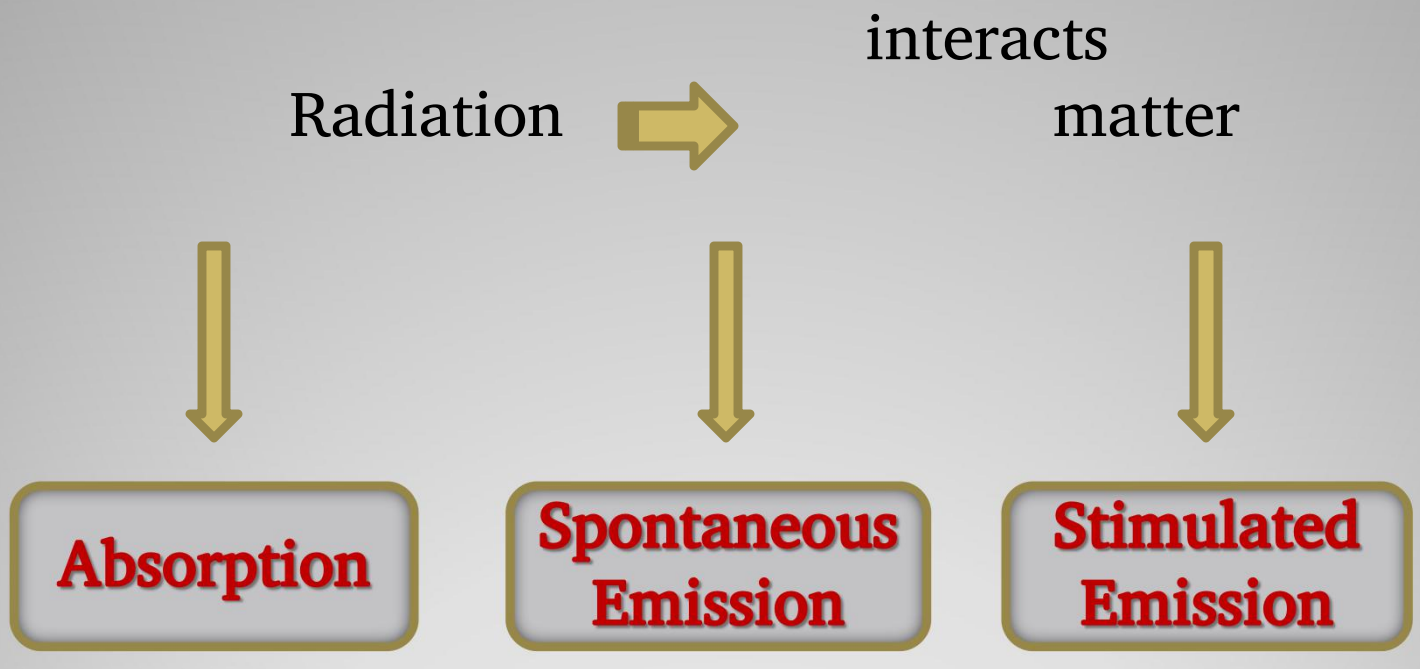
What is Laser?

LASER : Light Amplification by Stimulated Emission of Radiation

Laser is a device which can produce a high intense, highly coherent, more directional and highly monochromatic beam

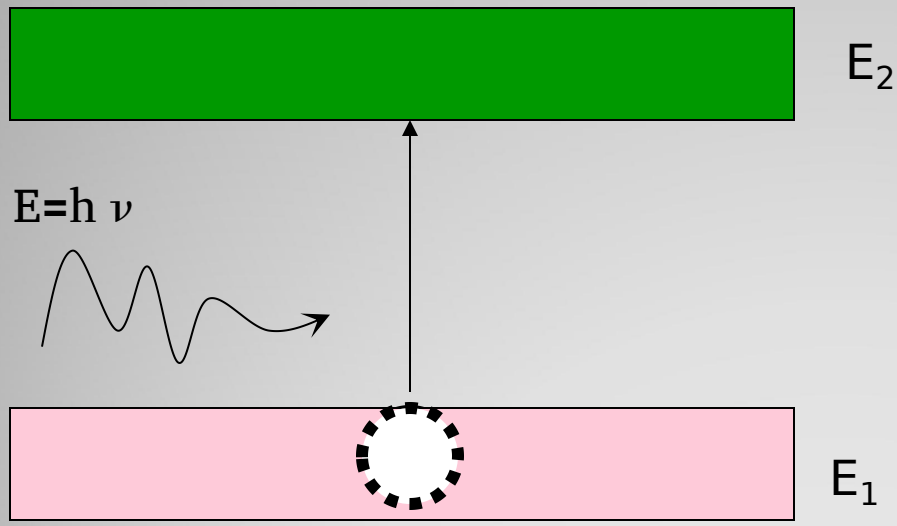


Classification of light-atom interaction



Absorption

Atom be initially in the lower state E_1, If a photon of energy hν is incident on the atom in the lower state, the atom absorbs the incident photon and gets excited to the higher energy state E_2.



$$R_{12} \propto N_1 \rho$$

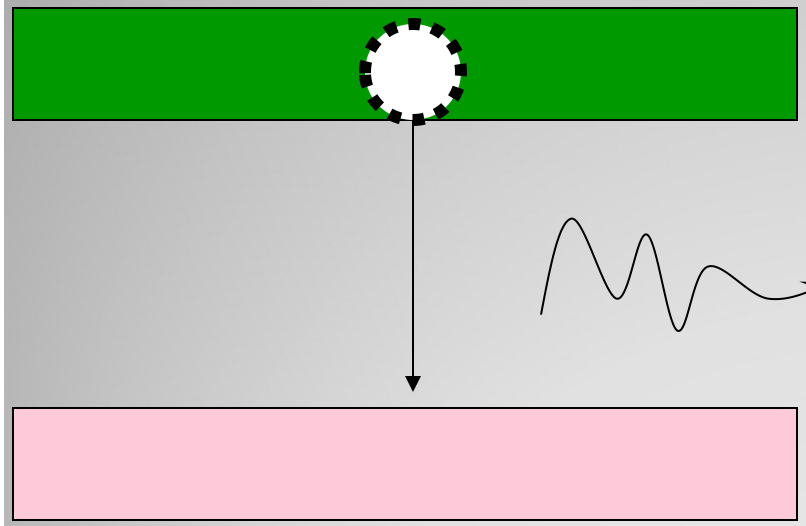
$$R_{12} = B_{12} N_1 \rho$$

Where, B_{12} is the proportionality constant, N_1 is population of the lower energy level, R_{12} is Rate of absorption.

Atom + Photon ⟶ Atom*

Spontaneous Emission

It is a process in which there is an emission of a photon whenever an atom transits from a higher energy state to a lower energy state without the aid of any external agency.



$$R_{21}(sp) \propto N_2$$

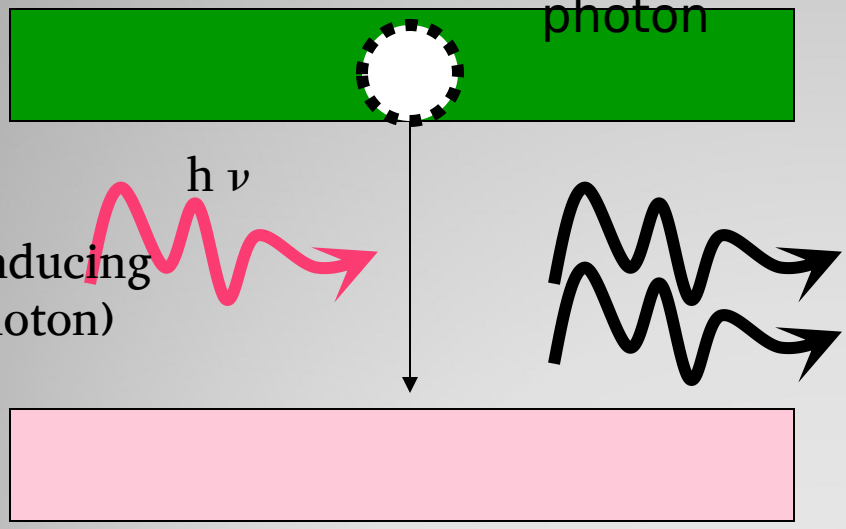
$$R_{21}(sp) = A_{21} N_2$$

Where, A_{21} is the proportionality constant, N_2 is population of the higher energy level, R_{21} is Rate of spontaneous emission.

$$\text{Atom}^* \longrightarrow \text{Atom} + \text{Photon}$$

Stimulated Emission

It is a process in which there is an emission of a photon whenever an atom transits from a higher energy state to a lower energy state under the influence of an external agency. i.e. an inducing photon

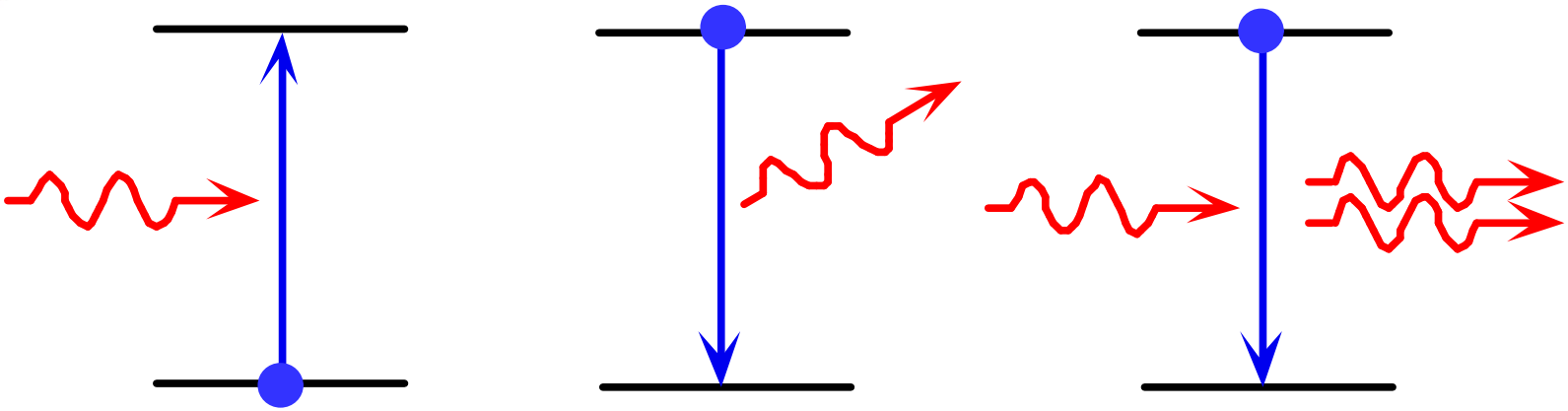


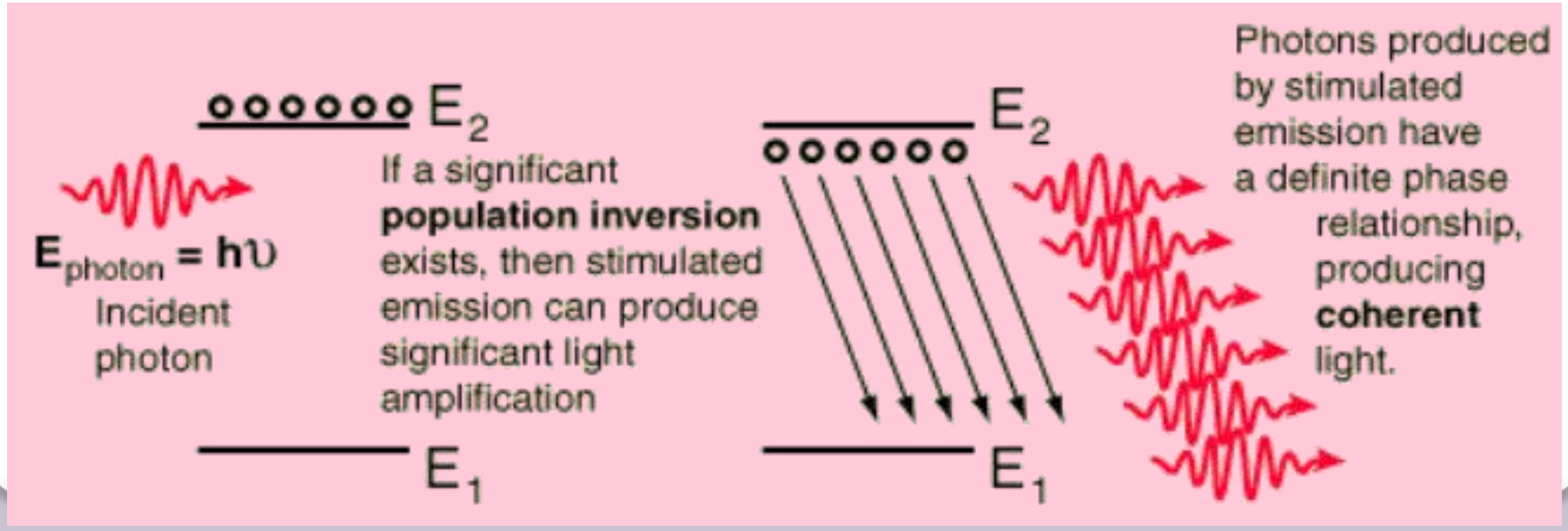
$$R_{21}(st) \propto N_2 \rho$$

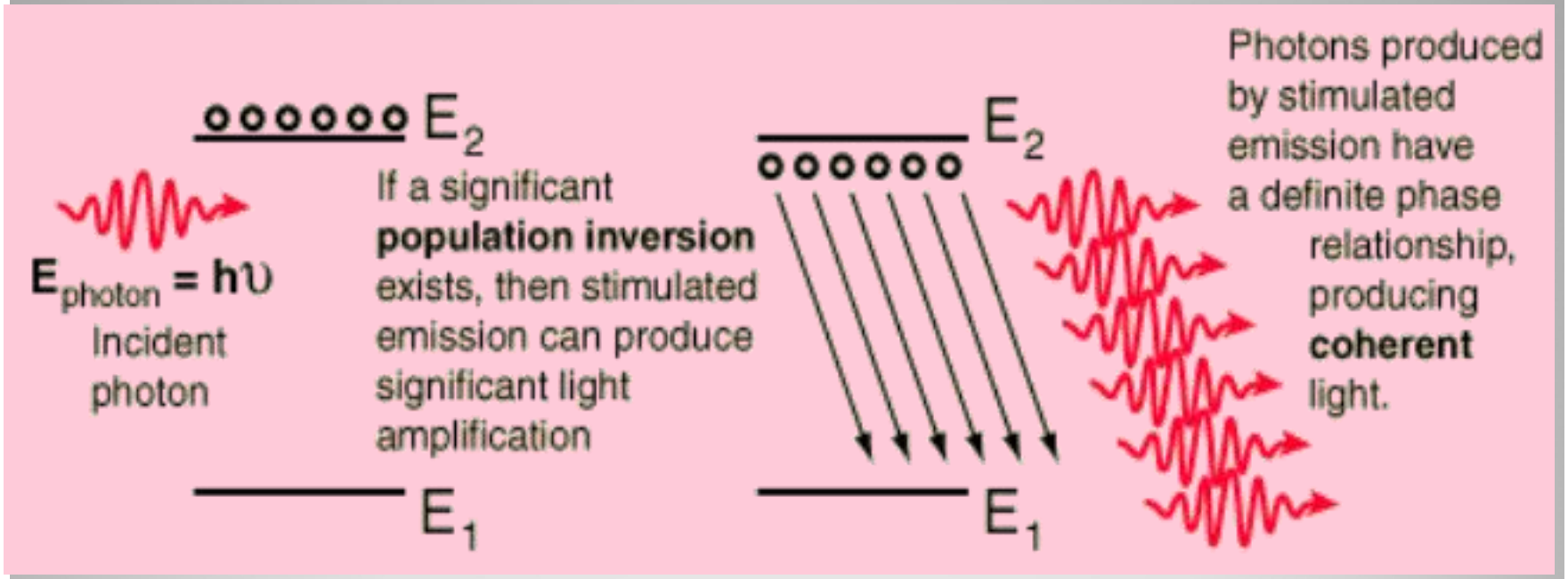
$$R_{21}(st) = B_{21} N_2 \rho$$

Where, B_{21} is the proportionality constant, N_2 is population of the higher energy level, R_{21} is Rate of stimulated emission.

Atom* + Photon $\longrightarrow$ Atom + (Photon + Photon)

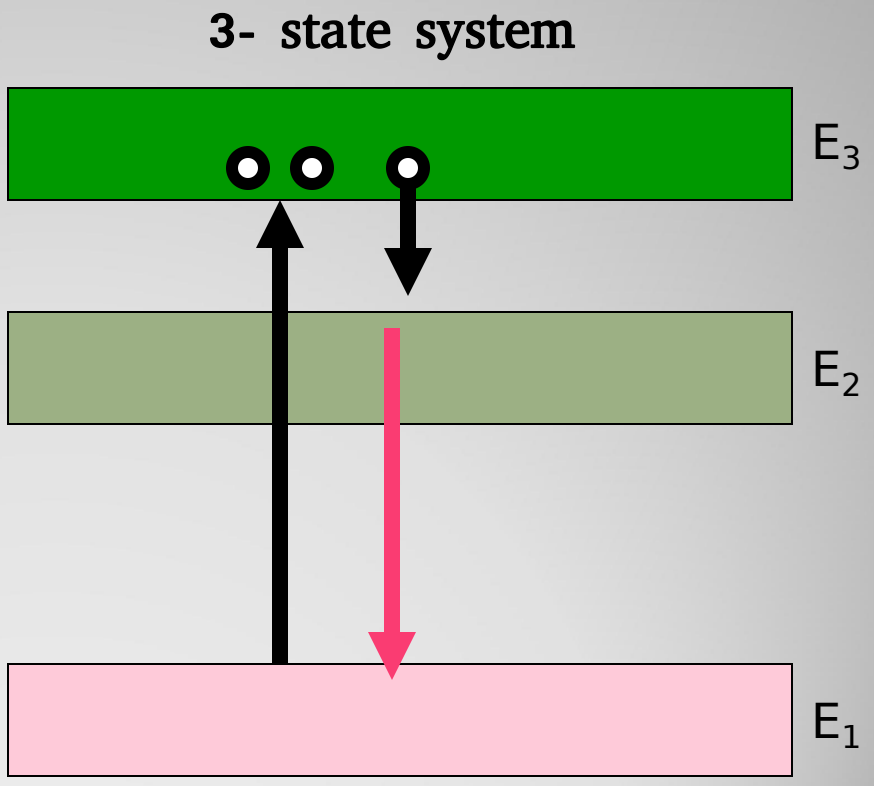



E2
E1
E2
E1
Photons produced by stimulated emission have a definite phase relationship, producing coherent light.
If a significant population inversion exists, then stimulated emission can produce significant light amplification
E photon = hυ
Incident photon


E2
E1
Ephoton = hυ
Incident photon
If a significant population inversion exists, then stimulated emission can produce significant light amplification
E2
E1
Photons produced by stimulated emission have a definite phase relationship, producing coherent light.

Necessary condition for lasing transition

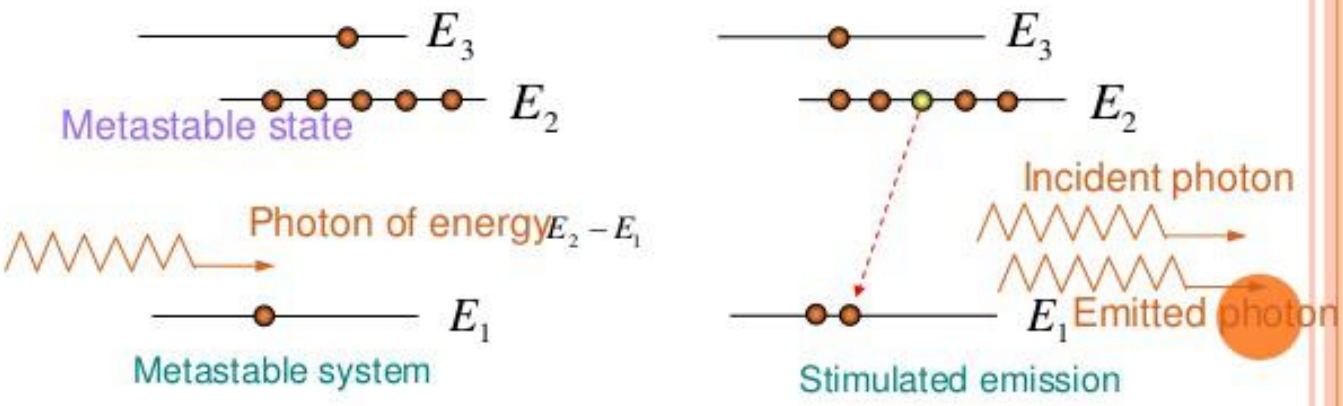
- Ø Stimulated Emission
- Ø Population Inversion
  ($N_2 > N_1$)
- Ø Metastable State

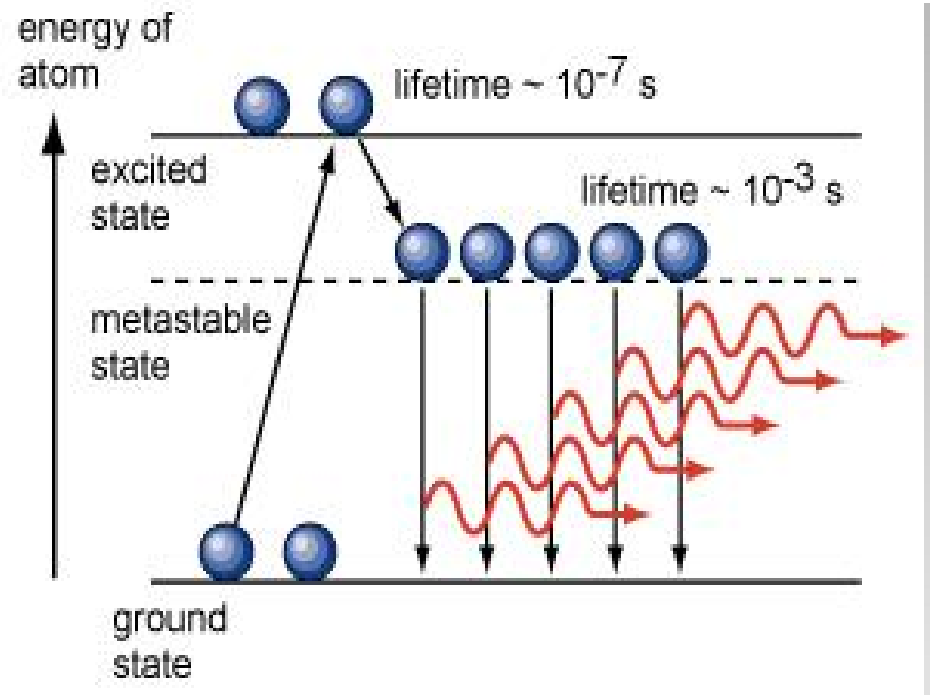


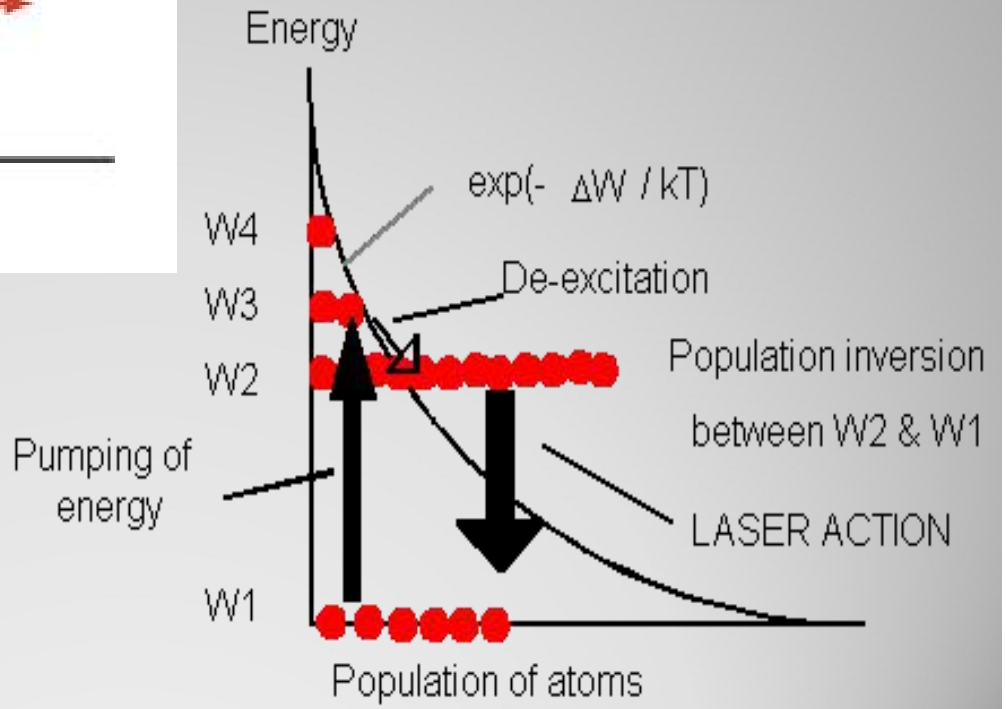
Population inversion: The redistribution of atomic energy levels that takes place in a system so that laser action can occur. Normally, a system of atoms is in temperature equilibrium and there are always more atoms in low energy states than in higher ones. Although absorption and emission of energy is a continuous process, the statistical distribution (population) of atoms in the various energy states is constant. When this distribution is disturbed by pumping energy into the system, a population inversion will take place in which more atoms will exist in the higher energy states than in the lower.

METASTABLE STATE

2. The higher state must be a metastable state – a state in which the electrons remain longer than usual so that the transition to the lower state occurs by stimulated emission rather than spontaneously.




energy of atom
lifetime ~ 10-7 s
excited state
lifetime ~ 10-3 s
metastable state
ground state


Energy
exp(- ΔW / kT)
W4
De-excitation
W3
W2
Population inversion
between W2 & W1
Pumping of energy
LASER ACTION
W1
Population of atoms

Properties/Characteristic of Laser:

Ø High Monochromaticity - It can emit light of single wavelength. The spread is of the order of 1nm for laser.

Ø High Directionality – An ordinary light source emits light in all possible directions. But, laser travels as a parallel beam it can travel over a long distance without spreading

Ø High Intensity - It has a ability to focus over a small area of 10^{-6} cm^2

Ø Coherence - identical in phase and direction. All the constituent photons of laser beam possess the same energy, momentum and propagate in same direction.

Basic concepts:

Population Inversion: It is a state of achieving more number of atoms in the excited state compared to the ground state. i.e., $N_2 > N_1$. It can be achieved by a process called pumping.

Pumping: It is the mechanism of exciting atoms from the lower energy state to a higher energy state by supplying energy from an external source.

Lasing: The process which leads to emission of stimulated photons after establishing the population inversion is referred to as lasing.

Life time: The limited time for which a particle or an atom remains in the excited is known as life time. It is about a nano second.

Metastable State: Metastable states are the energy levels in an atomic system where the life time of atoms is very large (of the order 10-3 to 10-2 second).

Active Medium: A medium in which population inversion is achieved for laser action is called active medium. The medium can be solid, liquid , gas and plasma.

Optical Resonator: It is a pair of reflecting surfaces (mirrors); of which , one is being a perfect reflector and the other being a partial reflector.

DIFFERENT PUMPING MECHANISMS :

i. ***Optical pumping :*** Exposure to electromagnetic radiation obtained from discharge flash tube results in pumping (For solid state lasers)

ii. ***Electrical discharge :*** By inelastic atom-atom collisions, population inversion is established. (For Gas lasers, i.e. CO_2 laser)

iii. ***Chemical pumping :*** By suitable chemical reaction in the active medium, For liquid lasers.

iv. ***Direct Conversions:*** A direct conversion of electric energy into light takes place (for Semiconductor laser).

The Relation between Einstein's Coefficients:

Relation between Einstein's coefficients

Laser action comprises following three processes;

Absorption 2. Spontaneous emission 3. Stimulated emission

In thermal equilibrium, the number of upward transition is equal to the number of downward transition per unit volume per second

In other words;

Rate of absorption = Rate of Spontaneous emission + Rate of stimulated emission

$$R_{12} = R_{21}(\text{sp}) + R_{21}(\text{st})$$

$$B_{12}N_1\rho = A_{21}N_2 + B_{21}N_2\rho \quad \text{.....(1)}$$

Here N_1 = population density of ground state,

N_2 = population density of excited state

ρ is density of incident radiation

By rearranging equation (1), we get

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

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

$\rho = \frac{A_{21}}{B_{12}\frac{N_1}{N_2} - B_{21}}$ .....(2)

According to Boltzmann distribution law

$N_1 = N_O\, e^{-(E_1/K_{BT})}$ .....(3)

$N_2 = N_O\, e^{-(E_2/K_{BT})}$ .....(4)

On dividing equation (3) by equation (4)

$\frac{N_1}{N_2} = \frac{e^{-(E_1/K_{BT})}}{e^{-(E_2/K_{BT})}}$

$\frac{N_1}{N_2} = e^{-\left(\frac{E_1}{K_{BT}}\right)+\left(\frac{E_2}{K_{BT}}\right)} =$

$\frac{N_1}{N_2} = e^{\frac{(E_2-E_1)}{K_{BT}}}$, since $E_2 - E_1 = h\nu$

$\frac{N_1}{N_2} = e^{\frac{h\nu}{K_{BT}}}$ .....(5)

On putting value of $\frac{N_1}{N_2}$ from equation (4) in (2), we get

$$\rho = \frac{A_{21}}{B_{12}e^{\frac{h\nu}{K_{BT}}} - B_{21}}$$

$$\rho = \frac{A_{21}}{B_{21}} \frac{1}{\frac{B_{12}}{B_{21}}e^{\frac{h\nu}{K_{BT}}} - 1]} \quad \text{.....(6)}$$

From plank's black body theory of radiation

$$P = \frac{8\pi h\nu^3}{c^3} \frac{1}{e^{\frac{h\nu}{K_{BT}}} - 1} \quad \text{.....(7)}$$

By comparing equation (6) and equation (7)

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

And $B_{12} = B_{21}$.....(9)

Here A_{21}, B_{12} and B_{21} are proportionality constants which are known as Einstein's constant

Equation (9) show that the probability of absorption is equal to the probability of stimulated emission

Type of Laser

- Solid State Lasers (ND-YAG laser, Ruby laser)
- Liquid Lasers
- Gaseous Lasers (He-Ne laser, CO_2 laser)
- Dye Lasers
- Semiconductor Lasers

Essential components of a laser system :

Active medium or Gain medium : It is the system in which population inversion and hence stimulated emission (laser action) is established.

Pumping mechanism : To achieve Population Inversion i.e., it is the method for raising the atoms from lower energy state to higher energy state to achieve laser transition.

Optical Resonator: It is a pair of reflecting surfaces (mirrors) of which one is a perfect reflector and the other one is a partial reflector…….used for amplification of photons.

Nd-YAG Laser

Active medium :

- The host medium for this laser is Yttrium Aluminium Garnet (YAG = Y_3 Al_5 O_{12}) with 1.5% trivalent neodymium ions (Nd^{3+}) present as impurities.

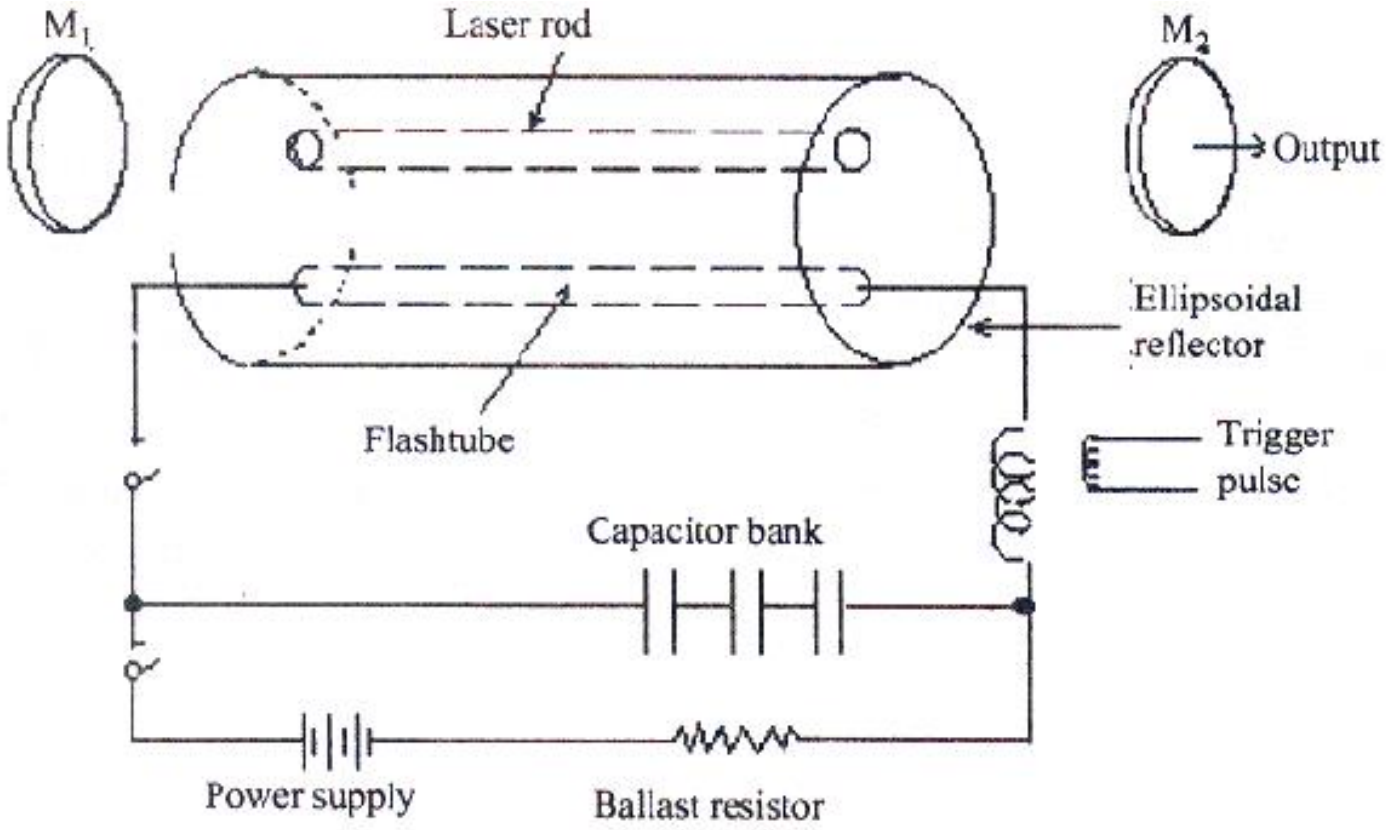
- The (Nd^{3+}) ions occupy the lattice sites of yttrium ions as substitutional impurities and provide the energy levels for both pumping and lasing transitions.

Pumping Source:

-The principle behind Nd-YAG laser is optical pumping. The population inversion is achieved by a flash light either using xenon or krypton flash tube. As a result, Nd ions are transported into the excited levels.

Resonating Cavity:

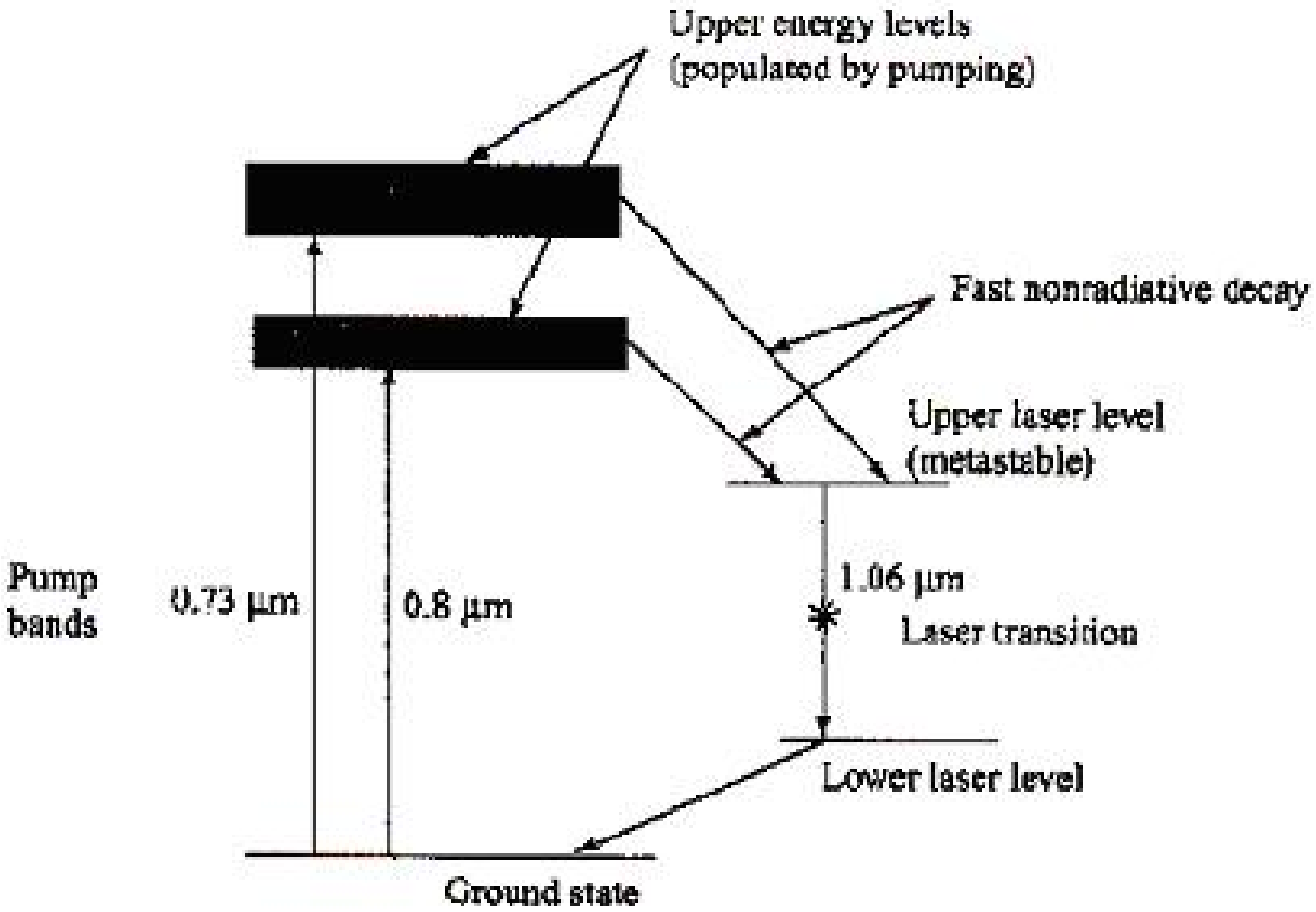
- In the Nd-YAG laser, a rod of 5 to 10 cm length and 6 to 9 mm diameter is used. The ends of the rod are polished and made optically flat and parallel. The optical cavity is formed either by silvering the two ends of the rod or by using two external reflecting mirrors. One mirror is made hundred percent reflecting while the other mirror is left slightly transmitting to draw the output



This laser system has two absorption bands (0.73 m and 0.8 m)

Optical pumping mechanism is employed.

Laser transition takes place between two laser levels at 1.06 mm.


Upper energy levels
(populated by pumping)
Fast nonradiative decay
Upper laser level
(metastable)
Pump
bands
0.73 μm
0.8 μm
1.06 μm
Laser transition
Lower laser level
Ground state

Working:

-When flash lamp is switched on, neodymium ions acquire energy from the flash light. The Nd ions are excited to energy levels E3 and E4 by absorbing energy with wavelengths of respectively 0.73µm and 0.80 µm.

- The Nd ions are not stable in the excited state, it makes a non – radiactive transition from E3 and E4 to a metastable state E2 . Ions can stay for a long time in this state until population inversion is achieved. When population inversion is achieved between E2 and E1 state, a stimulated emission takes place from the energy levels E2 to E1 by emitting radiation of the wavelength 1.064 µm.

Nd:YAG applications :

- The important industrial uses of YAG and glass lasers have been in materials processing such as welding, cutting, drilling.
- Since 1.06 m wavelength radiation passes through optical fibre without absorption, fibre optic endoscopes with YAG lasers are used to treat gastrointestinal bleeding.
- Remote sensing applications
- Medicines for endoscopic applications, medical surgery, dental surgery etc.

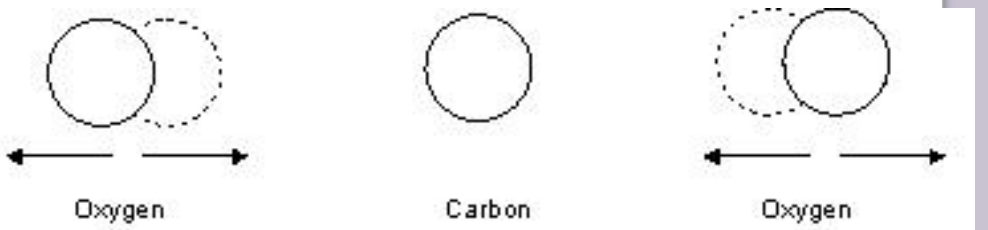
CO_2 LASER

Introduction :

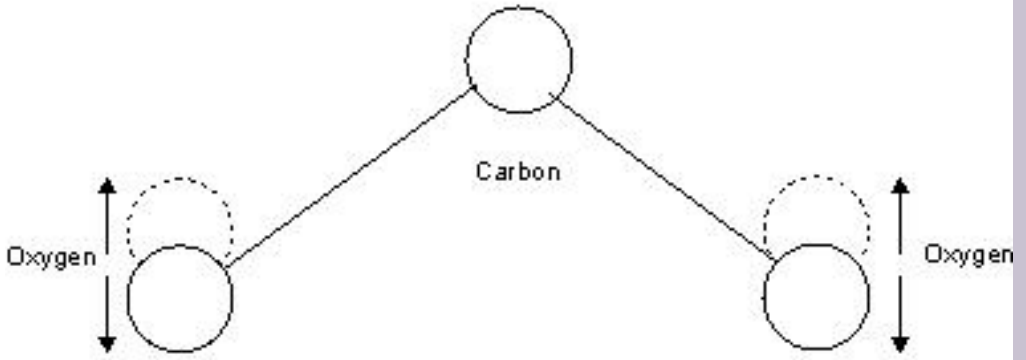
CO_2 lasers belong to the class of molecular gas lasers.

- In the case of atoms, electrons in molecules can be excited to higher energy levels, and the distribution of electrons in the levels define the electronic state of the molecule.
- Besides, these electronic levels, the molecules have other energy levels.

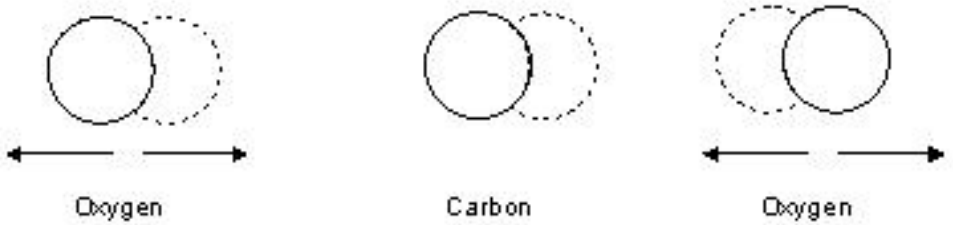
Symmetric stretching mode (m)



Bending mode (n)



Asymmetric stretching mode (q)



INDEPENDENT MODES OF VIBRATION OF CO_2 MOLECULE

Active medium :

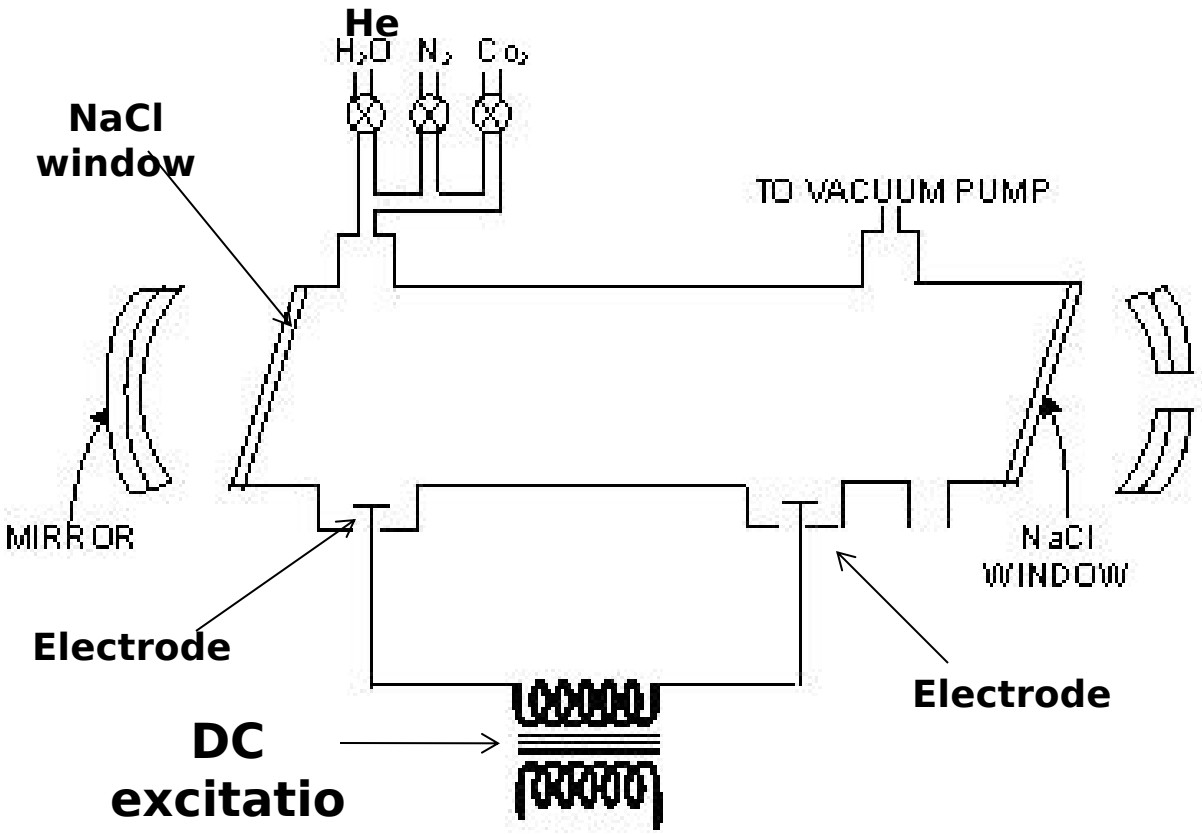
It consists of a mixture of **CO_2, N_2 and He** or water vapour. The active centres are CO_2 molecules lasing on the transition between the rotational levels of vibrational bands of the electronic ground state..

Optical resonators :

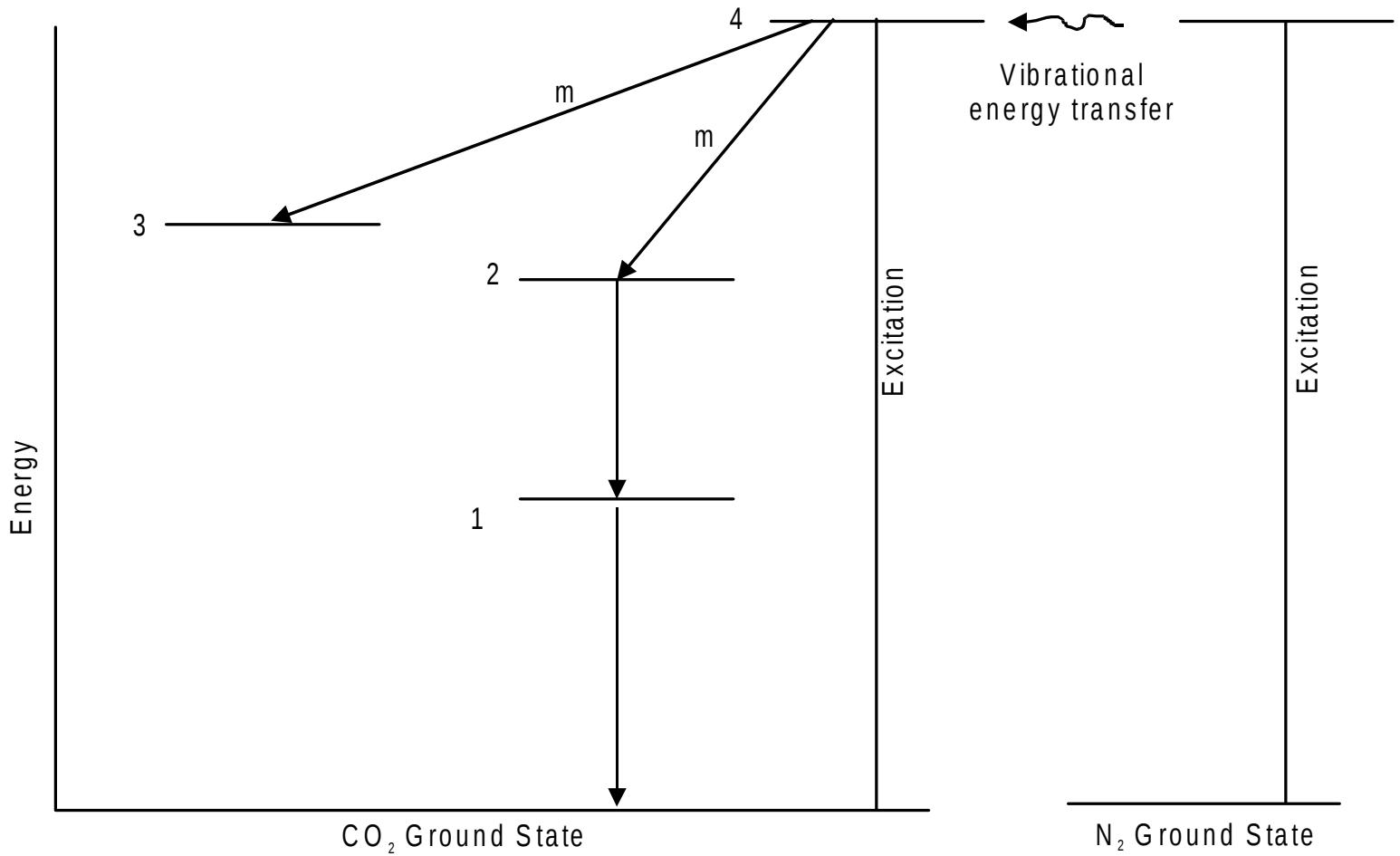
A pair of concave mirrors placed on either side of the discharge tube, one completely polished and the other partially polished.

Pumping :

- Population inversion is created by electric discharge of the mixture.
- When a discharge is passed in a tube containing CO_2, electron impacts excite the molecules to higher electronic and vibrational-rotational levels.
- This level is also populated by radiationless transition from upper excited levels.
- The resonant transfer of energy from other molecules, such as, N_2, added to the gas, increases the pumping efficiency.


He
H2O
N2
Co2
NaCl window
TO VACUUM PUMP
MIRROR
Electrode
NaCl WINDOW
Electrode
DC excitation

CO_2 LASER



ENERGY LEVEL DIAGRAM

- The He molecules increase the population of level 4, and also help in emptying the lower laser levels.

- The molecules that arrive at the levels 3 and 2 decay to the ground state through radiative and collision induced transitions to the lower level 1, which in turn decays to the ground state.

- The power output of a CO_2 laser increases linearly with length. Low power (upto **50W**), longitudinal flow of gases.
- The power o/p – 10kw/m, when flow is perpendicular to the discharge.

Disadvantages:

- The CO_2 molecules dissociate into CO – it may contaminate the active medium.
- It has to be periodically removed away by the vacuum pump.

Advantages:

- In Material Processing: drilling, cutting, etching, welding, melting….
- Open air communication
- Pollution monitoring, remote sensing & LIDAR
- Medical field

The Use of Lasers

- Science and engineering applications
  - precise measurements and spectroscopy
  - Fiber optic communication

- In Medicine
  - for the treatment of detached retinas
  - eye surgery and in cancers treatments

- In Industry
  - cutting, welding, melting
  - To test the quality of the materials
  - for the heat treatment of metallic and non-metallic materials.

Military applications:

- The laser beam can serve as a war weapon, i.e. a powerful laser beam can be used to destroy in a few seconds, the big size objects like aeroplanes, missiles etc. by pointing the laser beam on to them. For this reason, it can be even called as death ray.

- The laser beam can be used to determine precisely the distance, velocity and direction as well as the size and form of distant objects by means of the reflected signal. It is known as LIDAR.

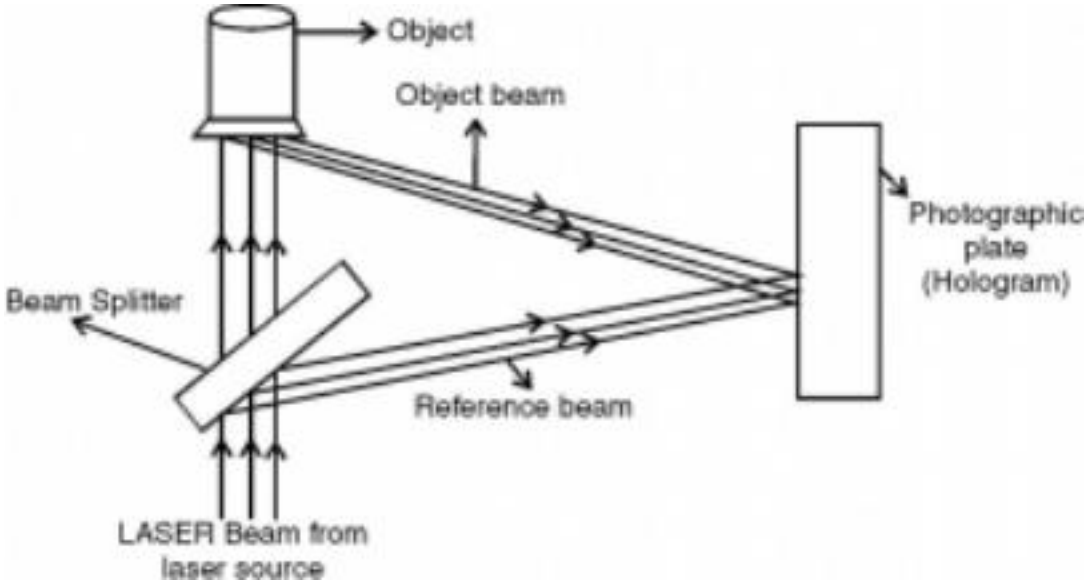
Holography

Holography is a technique of recording the amplitude and phase of the light waves reflected from an object. A three dimensional image of the object can be obtained. The recorded photograph is called a hologram.

Principle:

1. Recording of hologram or construction of hologram (based on interference of coherent light waves).
2. Reconstruction of hologram (based on diffraction of light waves).

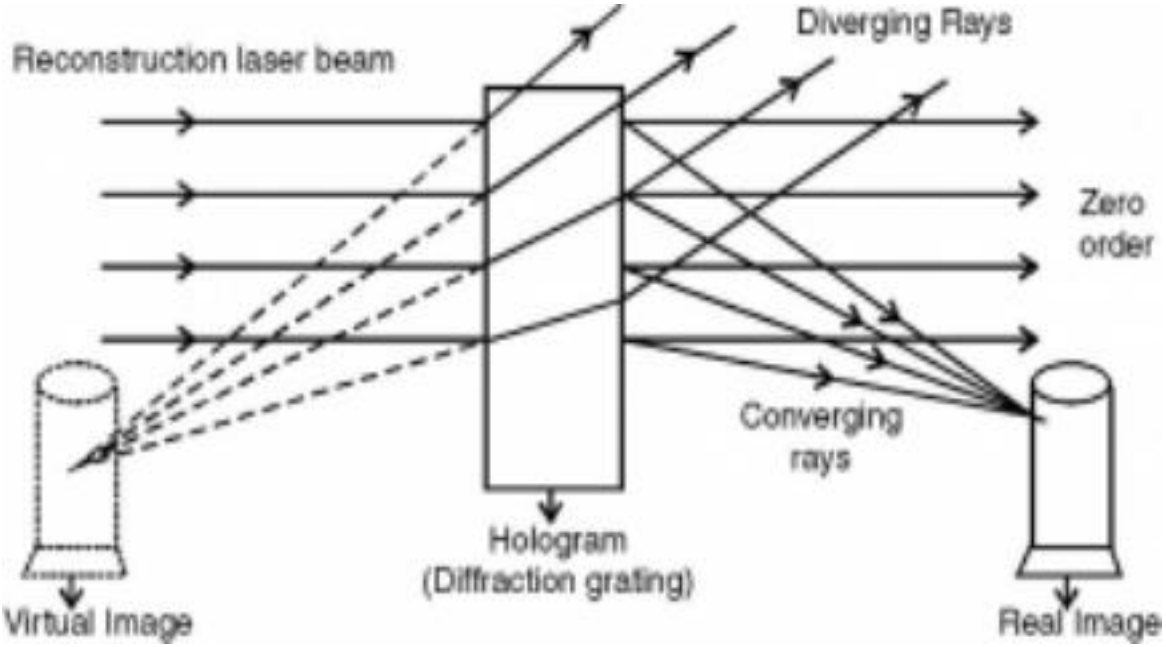
1. Recording of hologram or construction of hologram



The light from a laser source is split into two components – splitter and reference beam. The wave illuminating the object is called the object wave or signal wave and the wave directed towards the photographic plate is called the reference wave.

Thus , the two beams interfere with each other producing interference pattern on the photographic plate. Thus, the record of this interference pattern constitutes a hologram.

2. Reconstruction of hologram



The developed hologram is exposed to a laser beam of the same wavelength. This laser beam interacts with the interference pattern on the hologram and gets diffracted to produced two images of the original object. The virtual image and the real image which is in three dimensional form.

He-Ne Gas Laser

Why Gas Laser?

- Continuous laser beam,
- High Monochromaticity
- Most pure spectrum
- High stability of frequency

Active Medium:

The gas laser requires a mixture of two gases A and B such that some excited level of A falls close enough to an excited level of B. The gas discharge in the mixture excites the gas A. Now collisions transfer the excitation to B. This produces the laser beam. Typical examples are He-Ne and N_2-CO_2 lasers.

Pumping source:

In helium-neon lasers, a high voltage DC power supply is used as the pump source. A high voltage DC supplies electric current through the gas mixture of helium and neon.

Construction:

The gas laser consists of a fused quartz tube with diameter of about 1.5 cm and 80 cm long. This tube is filled with a mixture of neon (Ne) under a pressure of 0.1 mm of mercury and helium (He) under a pressure of 1mm of mercury. There is a majority of helium atoms and minority of neon atoms. At one end of the tube, there is a perfect reflector while on the other end is a partial reflector. The active material is excited by means of a high frequency generator with a frequency of several tens of MHz and an input of about 50 watt.

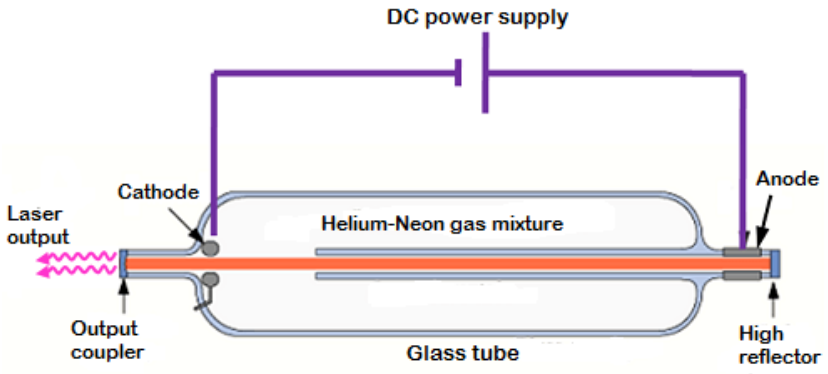


Figure 1 He-Ne Laser

Operation:

The operation of a gas laser is based on the interaction of atoms of two gases that are in close energy levels as shown in fig. 2.

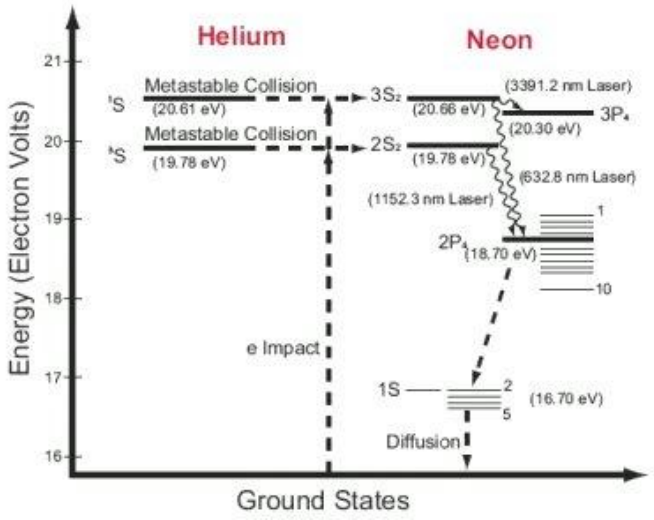


Figure 2 Energy levels of He and Ne

When discharge passes through the gas mixture, helium atoms are excited to higher energy levels (^{3}s and ^{1}s) through collisions with accelerated particles. The excited helium atoms then collide with neon atoms still in ground state and transfer energy to them and so raising it to an excited meta stable states (3s, 2s). Hence, an inversion population between 3s, 2s and 2p results in and lasing takes place between these energy stats by emitting a photon. This photon travels through the gas – mixture. If the photon is moving parallel to the axis of the tube, it is reflected back and forth by the mirror ends until it simulates an excited Ne atom and causes it to emit a fresh photon in phase with stimulating photon. The stimulated transition is a laser transition. This process continued till a beam of coherent radiation builds up in the tube. When the beam becomes sufficiently intense, a portion of it escapes through the partially silvered end. Using tubes with diameters of 6 mm and exactly parallel mirrors at both ends with high reflectivity, a gas laser has emitted a laser radiation of 6328 A^0.

Advantages:

- Very good coherence property
- He-Ne can produce three wavelengths that are 1.152 μm, 3.391 μm and 632.8 nm, in which the 632.8 nm is most common because it is visible usually in red colour.
- Cost is less compare to other laser system.
- Construction is not very complex
- Provide safety due to low power out put.

Disadvantages:

- Relatively out put power is low
- To obtain single wavelength laser light, other two wavelength of laser need suppression. For that high technical skill is required which increases the cost also
- High voltage is required for pumping mechanism.