[Laser Systems and Applications]

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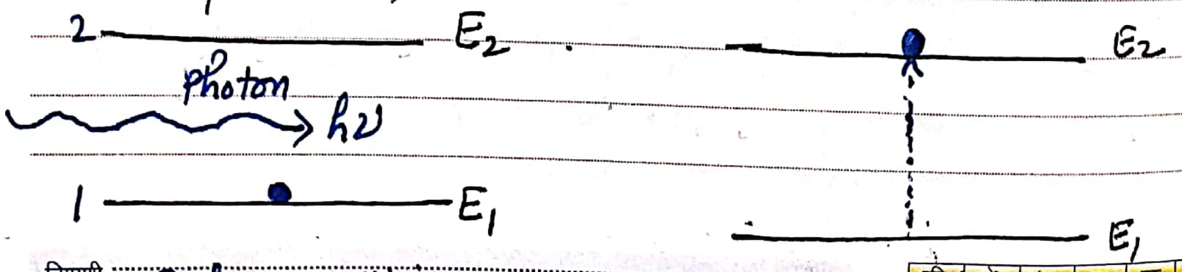
Laser :→ The invention of Laser was done by three scientists " Towner, Basov and Prokhorov" and they awarded a Noval prize in 1964.
Laser is a abbreviation of "Light amplification by stimulated emission of Radiation". It is a device for producing a very intense, almost unidirectional, monochromatic and cohrent visible light beams. Laser is based for its action on the principle of Stimulated emission.
When stimulated emission occurs in the infrared, visible and Ultraviolet region of spectrum then the term Laser is used.

2 शनि

Types of Transition process :→ Basically Three transition processes can take place when photon is incident on a system.

1. Absorption.
2. Spontaneous emission.
3. stimulated emission.

1. Absorption :→



टिप्पणी Before collision After collision

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Consider a two level system having energy of energy levels E_1 and E_2 in an atom such that रवि $E_2 > E_1$ which is shown in a fig. Such an atom can emit or absorb a photon of frequency given by

$$h\nu = E_2 - E_1$$

At ordinary temperatures, most of the atoms are in the ground state E_1. If a photon of frequency (ν) is incident on the system then it will be absorbed by an atom in the ground state E_1 and will therefore rise to excited state E_2. This process is called absorption.

The ~~probl~~ probable rate of absorption of photon 4 सोम of frequency (ν) and due to this the transition of atoms from state 1 to state 2 is proportional to the energy density of incident radiation $u(\nu)$. Hence

$$P_{12} \propto u(\nu)$$

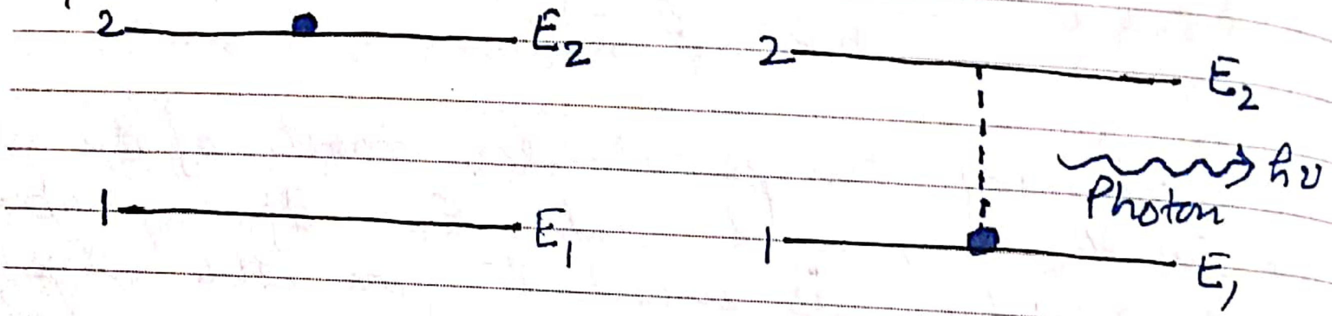
or $$P_{12} = B_{12}\, u(\nu)$$

where B_{12} is a proportionality constant, known as a Einstein's coefficient of absorption of radiation.

Once the atom is in excited state then it can decay (or back to lower energy state) after a short time

5 मंगल approximately 10^{-2} to 10^{-3} sec by two different process :-

(i) Spontaneous emission :→



When an atom in excited state (E_2) falls to the ground state E_1 by spontaneously emitting a photon of frequency $\nu = \frac{E_2 - E_1}{h}$, then this process is known as a spontaneous emission

6 बुध which is shown in a fig.

In spontaneous emission the following factors are takes place :

(i) The emitted photon has energy ($h\nu$) and can move in any random direction.

(ii) The photons emitted from various atoms in a assembly have no phase relationship between them.

(iii) the rate at which electrons falls from excited state (E_2) to a lower state (E_1), at every time is propotional to the number of electrons

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(iv) The Transition probability depends only upon the two energy states.

7 गुरु

Thus the radiation given out in a spontaneous emission are incoherent.

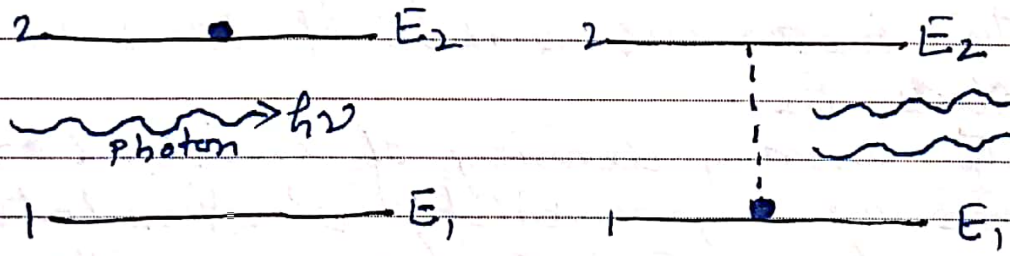
Hence the probability of spontaneous emission from state E_2 to state E_1 is only determined by the properties of state E_2 & E_1. Einstein denoted this probability per unit time by

$$(P_{21})_{spontaneous} = A_{21}$$

where A_{21} is a Einstein's coefficient of spontaneous emission.

8 शुक्र

(ii) Stimulated emission :→



When a photon of frequency exactly equal to $\nu = \frac{E_2 - E_1}{h}$ is incident on the atom in excited state (E_2) then it induces or stimulates the atom to move to ground state (E_1) by emitting a another photon of same frequency (ν). This process is

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(25)

known as stimulated or induced emission

9 शनि which is shown in a fig.

In induced or stimulated emission following factors are takes place:

(i) For every incident photon, we have two outgoing photons going in the same direction with same frequency.

(ii) The emitted photons travels in the direction of incident photon.

Thus the emitted photons have the same frequency and are in the same phase with the incident photon. In this way we can achieve amplified as well as unidirectional cohrent beam.

10 रवि In stimulated emission, the Rate of stimulated emission is proportional to

ⓐ The instaneous number of atoms in excited state E_2.

ⓑ The energy density of incident radiation.

Therefore the probability of stimulated emission from E_2 to E_1 can be written as.

$$(P_{21})_{stimulated} \propto u(\nu)$$

$$(P_{21})_{stimulated} = B_{21}\, u(\nu)$$

where B_{21} is a Einstein's coefficient of

टिप्पणी stimulated emission of Radiation.

11 सोम

Thus the Total probability of emission from state E_2 to state E_1 is the sum of spontaneous and stimulated emission probabilities which is given as

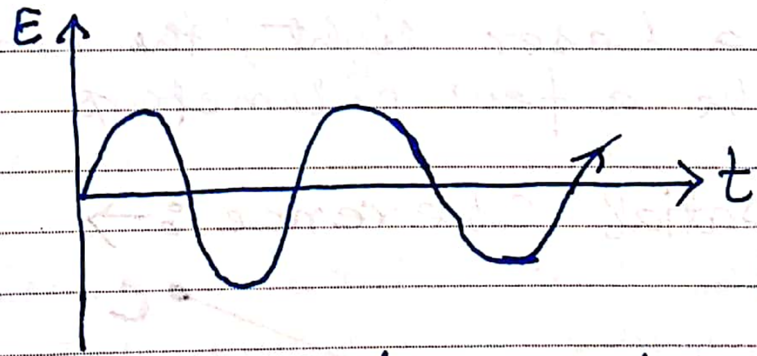
$$P_{21} = A_{21} + B_{21}\, u(\nu)$$

Temporal and Spatial coherence :→ If a wave appears to be a pure sine wave for a infinitely large period of time then it is said to be a perfectly cohrent wave. However no light ~~emi~~ emitted by an actual source is a perfectly coherent wave.

12 मंगल

There are two types of Coherence :

(1) Temporal Coherence :→



If we plot the oscillating electric field (E) of a perfectly cohrent light wave then it will appear as shown in fig.

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It is an ideal sinusoidal function of time. It
 has a constent amplitude of vibration at any point while its phase varies linearly with time.

But no actual light source emits a perfectly sinusoidal wave. Actually a light pulse of short duration (of the order of 10^{-10} sec for sodium atom) is emitted when an excited atom returns to the initial state. Therefore the field remains sinusoidal for only 10^{-10} sec and after it the phase changes abruptly.

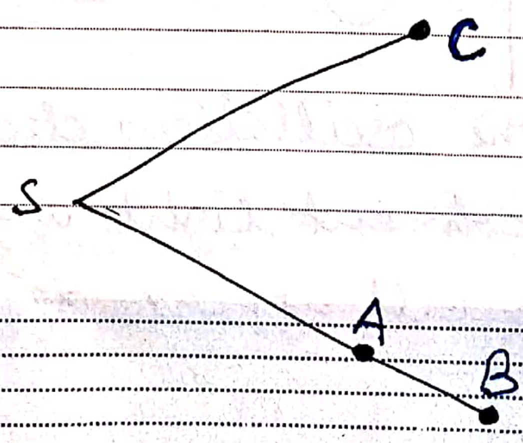
" Thus the average time interval for which the field remains sinusoidal is called Cohrence time or temporal cohrence of light beam and denoted by 'τ'. The distance for which the field is sinusoidal is called cohrence length
 & denoted by L".

Thus

$$L = c\tau$$

For a Laser light, the cohrence length can be a few Kilometers.

(2) Spatial Coherence :→



If there is a definite phase relationship between the radiation fields at different points in space then there will be high coherence between the points which is called "spatial cohrence".

15 शुक्र

Let there is a Source 'S' emitting a waves and two points A and B on a line joining them with 'S'. The phase relationship between these points depends on temporal cohrence and on the distance AB. If AB is less than L i.e.

$$AB << L$$

Then there exists a definite phase relationship between A and B and there is a high cohrence between them.

16 शनि

If however

$$AB >> L$$

Then there is no cohrence between A & B.

If we consider two equidistant points A & C from 'S' then the waves will reach A & C in exactly the same phase. Thus the points 'A' and 'C' have perfect spatial cohrence, if 'S' is a point Source. If 'S' is a extended Source then the point A & C are not be in a perfect spatial Cohrence.

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17 रवि

Population inversion :→ If we have a large number of atoms, say N_0 in thermal Equilibrium then their distribution in different energy states obeys the maxwell-Boltzmann statistics. If we assume that at a Temperature T K, the population in energy state E_1 and E_2 are N_1 and N_2 respectively then

$$N_1 = N_0 e^{-E_1/KT}$$

$$N_2 = N_0 e^{-E_2/KT}$$

Now the relative population

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

18 सोम

The negative exponent in this eqns shows that $N_2 << N_1$ at a equilibrium because $E_2 > E_1$. It means that the number of atoms(N_2) in higher energy states is less than the number of atoms (N_1) in lower energy states.

Under such condition, the probability of stimulated emission is much less than the probability of spontaneous emission. But since in spontaneous emission, the photons emitted from various atoms have random direction and random phase, a

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Source of light emits incoherent radiation.

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On the other hand, in stimulated emission, the radiation is completely cohrent and amplified. Therefore the basic requirement of a Laser is to have predominantly stimulated emission.

For it two conditions must be satisfied:-

(i) The higher energy state should have longer life time i.e. it should be a metastable state.

(ii) The number of atoms in higher energy state (E_2) must be greater than that in (E_1) i.e.

$$E_1 < E_2 \text{ but } n_2 > n_1$$

This condition of $n_2 > n_1$ is quite unnatural, because for any equilibrium state $\frac{n_2}{n_1}$ is less than unity.

If any how by some means, a large number of atoms made available in the higher energy state then stimulated emission takes place.

This situation in which the number of atoms in the higher energy state is greater than that in lower energy state is called <u>population inversion</u>.

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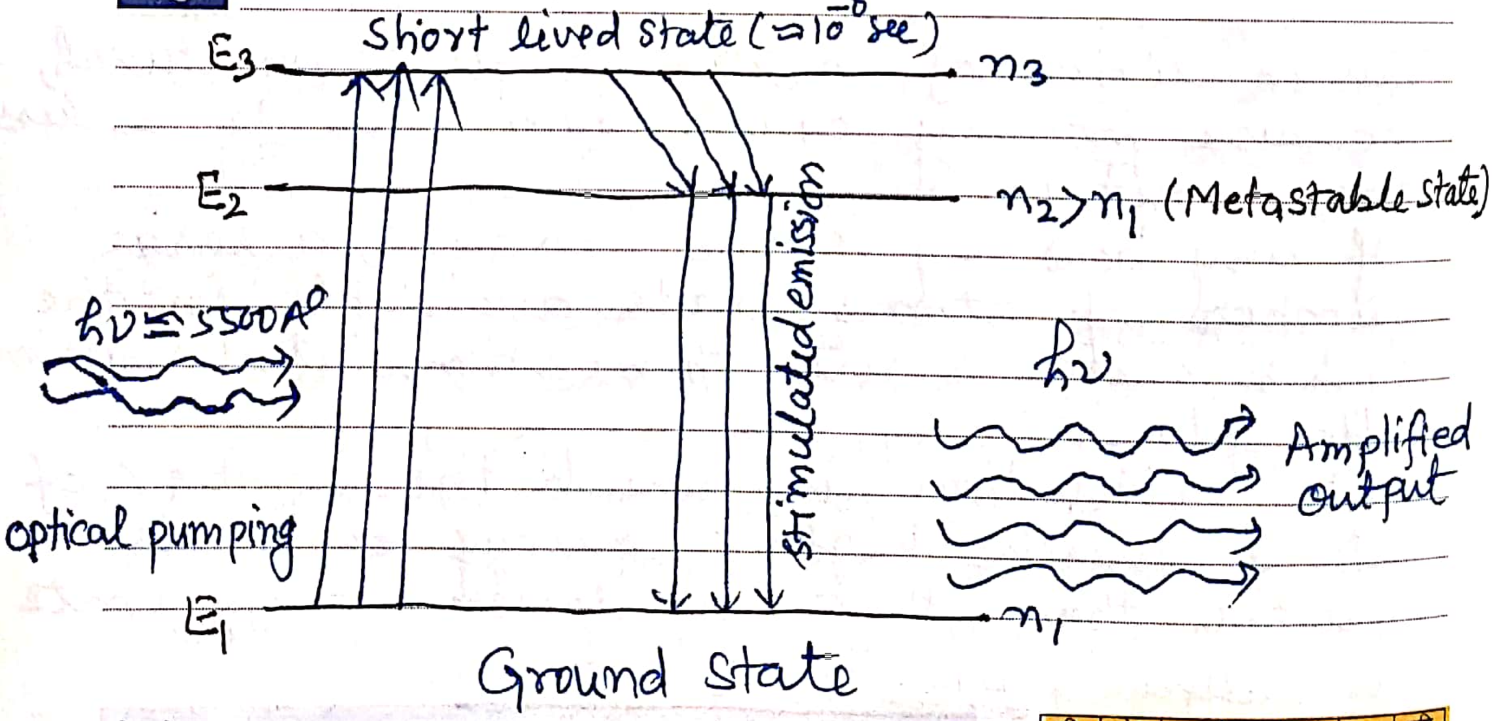
Pumping :→ The process of achieving

population inversion is called pumping. There are several methods of pumping a Laser and producing a population inversion. Some commonly used methods are given as

(i) Optical pumping.
(ii) Electric discharge.
(iii) Direct conversion.
(iv) chemical reactions.

Here we will discuss optical pumping only

Optical pumping :→



In optical pumping, the population inversion is creates by a three level scheme. 23 शनि
To understand this, consider a material whose atoms when raised from the ground state (E_1) to a short lived excited state (E_3) [which has a life time $\simeq 10^{-8}$ sec] do not fall back to state E_1 because transition from E_3 to E_1 is forbidden by a selection Rule. But the transition from E_3 is allowed to a intermediate state (E_2) [which has a longer life time $\simeq 10^{-3}$ sec]. Hence when the frequency of radiation $\nu = E_3 - E_1/h$ is incident on the atoms in state E_1 then the atoms are excited to state E_3 by the process of absorption. Some of the atoms are decay spontaneously to a metastable state (E_2) where they live for a much 24 रवि longer time of 10^{-3} sec as compared to 10^{-8} sec for short lived state E_3. In this situation, the state E_2 has more atoms than state (E_1) which shows that the population inversion is achieved

After achieving a population inversion, if the atoms in metastable state (E_2) are exposed to a photons of frequency $\nu =$ ~~E_3-E_1~~ $E_2 - E_1/h$ then stimulated emission will takes place. In this a single photon produces a very large number of identical photons so that the radiation

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जून 2009

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beam is now highly amplified. Thus an

intense cohrent beam of light, in the direction of incident photons emerges from the Substance.

Principle of a Laser — Conditions of Laser Action :⟹

A laser is a device to produce an intense highly concentrated, monochromatic, unidirectional and highly cohrent beam of light. The operating frequency of laser is 10^{15} Hz in visible region.

A laser is based for its action on the principle

of population inversion and then stimulated emission. Sinse the energy differences between the energy levels are large then the pumping is done by the visible light.

An excited atom emits energy in the form of light when the excited electrons in the atom drop back to lower state. Such an emission of light is known as spontaneous emission in which the radiation is emitted in all directions. If however during the excited state of the atom, it is exposed to a matching photon which has exactly the same frequency as that emitted by the atom in spontaneous emission then it stimulates the atom from excited state to decay by emitting a photon equal in frequency to the one which stimulated it. Such a photon travels in the direction of incident photon and for every incident photon, we have two outgoing photons. Thus a amplified light can take place.

In order to have a unidirectional, coherent beam, we should have more stimulated emission than spontaneous emission. This is achieved by <u>population inversion</u>, so that there are more atoms in the higher energy state (E_2) than in the lower energy state (E_1) i.e

$$E_2 > E_1 \quad \text{and} \quad n_2 > n_1$$

The procedure, to achieve population inversion is called <u>pumping</u>, in which the atoms from excited state first decay spontaneously to a metastable state where they are struck by a ~~mati~~ matching photons resulting a chain of stimulated emission and consequently by giving rise to a coherent, highly intense beam of photons travelling in the direction of incident beam.

~~The Ruby Laser~~ — ~~[illegible]~~ :→

Relation between Spontaneous and stimulated Emission probabilities [i.e. Einstein's 'A' and 'B' Coefficients] :→ Consider an assembly of atoms in thermal Equilibrium at Temprature 'T' and radiation of frequency 'ν' is incident on it then the rate of absorption of radiation and due to this the transition from state $1 \to 2$ is proportional to the energy density of radiation $u(\nu)$. Therefore the transition of atoms per unit time per unit volume from $1 \to 2$ is

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

where N_1 is the number of atoms per unit volume in state 1 and B_{12} is the Einstein's coefficient of absorption.

Now the number of Spontaneous emission per unit time per unit volume will be proportional to N_2, which represents the number of atoms in state '2'. Hence

$$(P_{21})_{\text{Spontaneous}} \propto N_2$$

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or $$(P_{21})_{\text{Spontaneous}} = A_{21} N_2 \quad \text{——— (2)}$$

where, A_{21} is a Einstein's coefficient of Spontaneous emission.

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Now the number of stimulated emission per unit time per unit volume would depend on 'N_2' रवि as well as energy density $u(\nu)$. Hence

$$N_2 (P_{21})_{stimulated} \propto N_2 u(\nu)$$

$$\text{or} \quad N_2 (P_{21})_{stimulated} = B_{21} N_2 u(\nu) \quad \text{--- (3)}$$

Thus the number of atoms in state 2 that drop to state 1 ~~eigt~~ either spontaneously or stimu- -~~tationally~~ latedly will be equal to the sum of these two probabilities. Hence

$$N_2 P_{21} = N_2 [A_{21} + B_{21} u(\nu)] \quad \text{--- (4)}$$

In thermal Equilibrium, the absorption and emission rates must be equal. Hence

$$N_1 P_{12} = N_2 P_{21}$$

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

$$\quad " \quad = N_2 A_{21} + N_2 B_{21} u(\nu)$$

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

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

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जून 2009

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$$= \frac{\cancel{N_2} A_{21}}{\cancel{N_2} B_{21} \left[\frac{N_1}{N_2} \frac{B_{12}}{B_{21}} - 1 \right]}$$

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$$u(\nu) = \frac{A_{21}}{B_{21}} \cdot \frac{1}{\left[\frac{N_1}{N_2}\frac{B_{12}}{B_{21}} - 1\right]} \quad \text{——— (5)}$$

The distribution of atoms in different energy states is given by Boltzmann's Law. According to which the number of atoms N_1 and N_2 in energy states E_1 and E_2 at temprature T is given by

$$N_2 = N_0 e^{-E_2/KT}$$

&

$$N_1 = N_0 e^{-E_1/KT}$$

or

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

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or

$$\frac{N_1}{N_2} = e^{(E_2-E_1)/KT} = e^{h\nu/KT}$$

Now putting this value in equation number (5) then we get

$$u(\nu) = \frac{A_{21}}{B_{21}} \cdot \frac{1}{e^{h\nu/KT} \cdot \frac{B_{12}}{B_{21}} - 1} \quad \text{——— (6)}$$

According to planck's radiation formula,

we Knows the energy density of Radiation

$$u(\nu) = \frac{8\pi h\nu^3}{c^3} \cdot \frac{1}{e^{h\nu/KT}-1} \quad \text{——— (7)}$$

Now comparing Equation (6) and (7) then we get

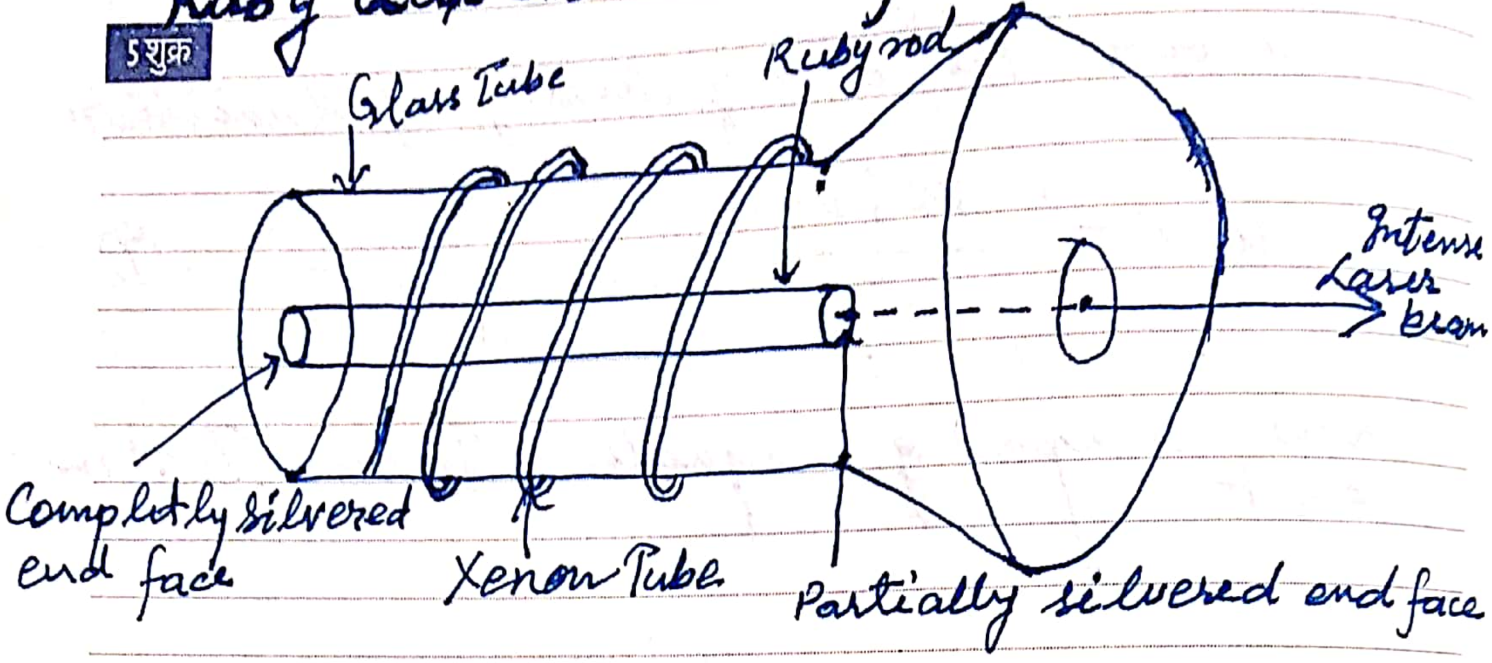
$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}$$

$$\& \quad \frac{B_{12}}{B_{21}} = 1 \quad \text{or} \quad B_{12} = B_{21}$$

i.e the probability of stimulated emission is equal to the probability of induced absorption.

Also, we knows that the ~~probability~~ Ratio of Spontaneous emission and stimulated emission is proportional to ν^3. It means that the probability of spontaneous emission increases rapidly with the energy difference between the two states.

Ruby Laser — A pulsed laser :→



It is a solid state laser and makes use of the three level scheme of population

inversion. It consists of three main parts :-

① **The working Material :→** The working material is a ruby crystal.
Actually it is aluminium oxide (Al_2O_3) doped with 0.05% chromium oxide (Cr_2O_3). Thus some of the aluminium atoms in the crystal lattice are replaced by Cr^{++} ions which gives ruby a pink colour.

② **The Resonant Cavity :→** It is a specially prepared ruby cylinder in which light intensity can be build up by multiple

reflections. For this purpose a ruby rod 2.0 to 3.0 cm long and 0.5 to 2 cm in a diameter. The crystal is cut and polished so that one of its end is completely silvered so that fully reflecting while the other is only partially silvered so that an intense beam can emerge out of it.

7 रवि

③ **The Optical pumping System** :→ The optical pumping is done by an external source. In general, a helical xenon flash tube acts as a pump. It is bound around the glass envelope surrounding the ruby rod through which liquid nitrogen is circulated to keep the rod cool.

8 सोम

Operation :→ The active material in ruby laser is Cr^{++} ions. The optical pumping takes place when a flash of light about a millisecond from Xe flash tube falls upon the ruby rod. Due to this the green yellow radiations of wavelength ($\lambda = 5500\,Å$) are absorbed by Cr^{++} ions, which are excited from state E_1 to energy state E_3.

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जुलाई 2009

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The Cr^{++} ions excited to state E_3, Jumps to

9 मंगल

metastable state E_2 by losing 0.47eV of energy in the first step. These are non-radiative transitions then the excess energy is absorbed by the lattice and does not appear in the form of electromagnetic radiations. Sinse the metastable state E_2 has a very long life ($\sim 3\times10^{-3}$ sec) as compared to 10^{-8} sec of E_3 then the number of atoms in this state keep on increasing and ultimately exceeds the ground state E_1. Thus the level E_2 becomes more populated than the level E_1 and hence the population inversion is created between the metastable state E_2 and ground state E_1.

10 बुध

Such a system with population inversion is very unstable. when an atom decays spontaneously from metastable state E_2 to the ground state then a photon correspo-nds to red light of $\lambda = 6943A^\circ$ is produced. This photon travels through the ruby rod and if it moves parallel to the axis of the Crystal then it reflected back and forth between the two ends of the Crystals, one of which is fully and other is partially silvered to act as resonator. It stimulates

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an excited atom to emit a fresh photon in phase with the stimulating photon. This process 11 गुरु is repeated again and again. Thus a chain reaction is produced till the beam becomes sufficiently intense to emerge out of the partially silvered end of the crystal. Thus highly intense, coherent, monochromatic and unidirectional beam is obtained.

Helium - Neon (He-Ne) Gas Laser: A Continuous wave Laser :→

The Two main disadvantages of Ruby Laser are :-

(i) Output beam is not continuous.

(ii) It requires a large amount of a optical energy to create population inversion.

Many Laser applications however requires a continuous wave. Javan, Bennett and Herriott in 1961 invented a gas laser which emits a light continously 12 शुक्र rather than pulses. It uses a mixture of He-Ne gases. It differs in operation from ruby laser because four energy levels are involved in it - one in He & three in Ne. The excitation of He-Ne atoms is obtained by high frequency Electromagnetic field. The energy is transferred to the atoms of the gas by impact of electron and collision between atoms.

Construction :→ He-Ne Laser consists of :-

(i) A nearly 1 metre narrow quartz tube containing He-Ne in the ratio of 7:1 at a pressure of 1 mm of Hg.

(ii) An excitation source for creating a discharge in the gas. It is generally high voltage, high frequency potential difference.

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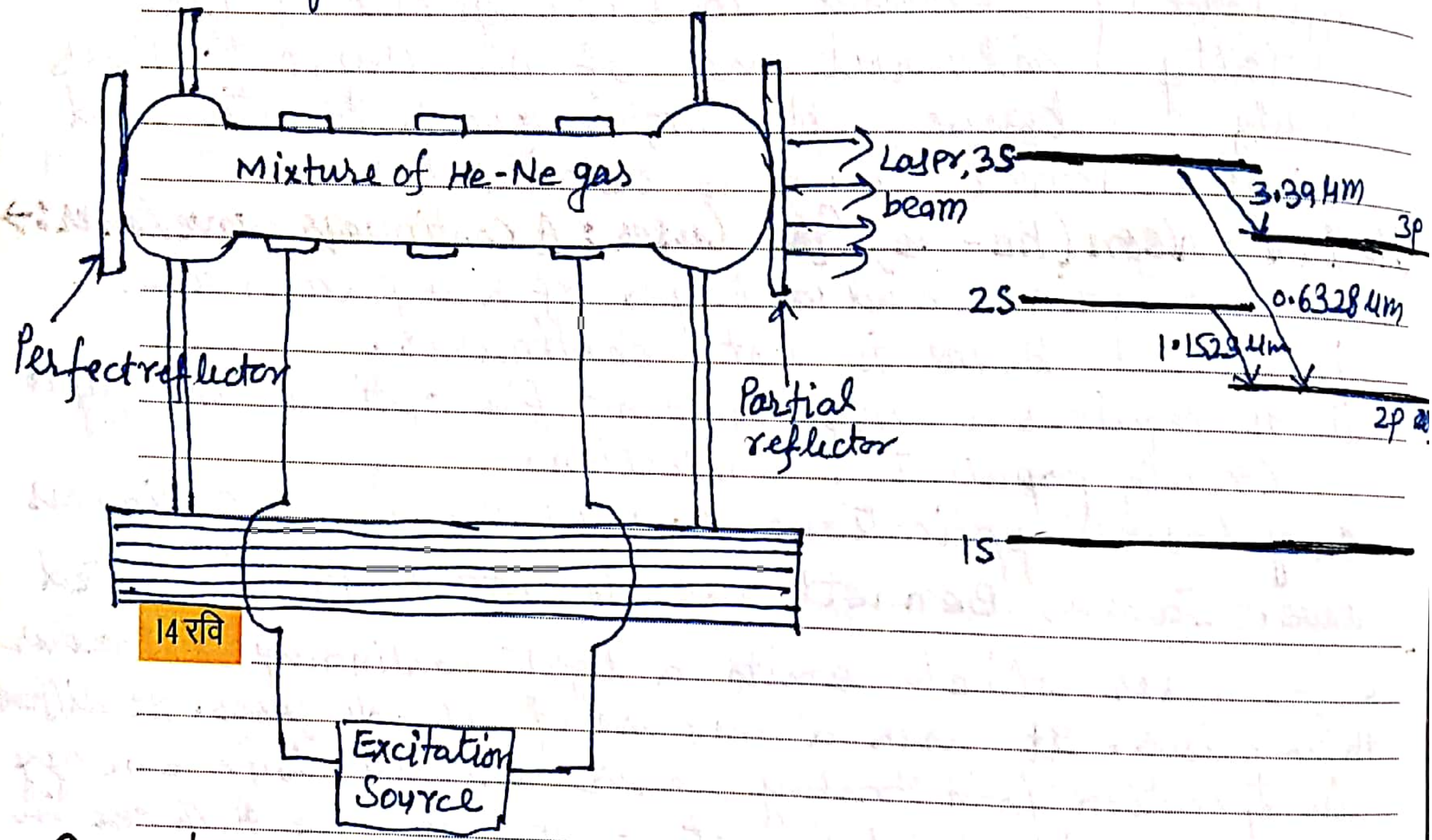
(iii) End mirrors for forming the resonant cavity. At one end of the tube, the mirror is fully silvered (Perfect reflector) while the other end is partially silvered (Partial reflector).



Operation:→ When E.M. energy is injected into the Tube through metal bands then He-atoms are excited to metastable states by collision with the electrons in tube. The excited He-atoms collide with unexcited neon atoms. Since He has metastable levels at almost the same energies as 2S and 3S levels of Ne, it allows a resonant exchange of energy and a resultant increase in Population of the Corresponding Ne-levels. The Laser action takes place in Neon atoms.

Helium in the mixture serves only purpose to enhance the excitation process.

The Ne levels important for 2S laser action. The strongest emission line occurs between 2S and 2P levels with wavelength 11523A° which lies in the infrared region. Another important transition takes place between 3S and 2P levels giving of photon of wavelength 6328 A° which lies in the red part of visible spectrum. A Third transition takes place between 3S and 3P levels gives photon of wavelength 339 um.

The light waves emitted parallel to the tube axis bounce back and forth between silvered ends and stimulates emission of same frequency from other excited neon atoms. Thus the photons get multiplied

and the initial beam is built up into a powerful, cohrent, parallel beam and emerges through the partially silvered end of the Tube.

Applications of Lasers :→

Laser is a

very intense, highly unidirectional, monochromatic and Cohrent visible light. Hence, it has got some special properties like Narrow band width (which is the same thing as high monochromaticity) and Narrow angular spread (which is the same thing as high directionality) not available in light from the ordinary sources. Consequently, it has got very wide applications in different branches of science, technology and in surgery etc. Some of its importent applications are given below :-

(1) In Surgery :→ Intense and powerful laser

beam has been used to remove eye tumour. Preliminary success has also been obtained in treatment of both human and animal Cancer by laser beam. As the beam is very intense, it has been used for painless drilling and welding of a surface of a tooth to prevent further decay. It acts as a sharp knife and its localized heating seals the blood vessels.

(2) In Industry :→ Lasers have got wide

7 मंगल

industrial and chemical applications. A laser beam when focussed, produces a very high temperature. It can therefore be used in melting and vaporizing metals and drilling holes in diamonds and hard steels. Laser beam is also used in separating uranium from the Uranium ore. Laser beam can also initiate certain chemical reactions.

(3) For Military purposes :→ Laser beam is being used for effective and automatic control and guidance of rockets and satellites.

8 बुध

When used in radars, it can be used to destroy aeroplanes and missiles. Focussed laser beams would become the legendary "death ray" of science fictions that would burn everything standing in the way of the beam.

(4) In Scientific Research :→ Laser beam provides a new source of exploring the molecular structure and nature of chemical reactions. It is very important

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in study the Raman Spectroscopy, measurement of length and accurate determination of velocity of light.

(5) In Radio communication and Space Explorations:

Laser light being a highly cohrent can be modulated to transmit hundreds of messages at a time on radio and television. It can accommodate in a single frequency band, greater number of channels of carrier wave with enough band width. It has also proved very usefull for underwater communication, because it is not easily absorbed by water.

Narrow angular spread of the laser beam is being used for communications with earth satellites and rockets to the moon and other planets. By measuring the time interval for receiving the reflected beam, the earth moon distance has been measured accurately with the use of laser.

(6) Miscellaneous Uses :→ The use of lasers in Computers is under solid investigations. It is being tried to transmit an entire memory bank

टिप्पणी from one Computer to another by use of Laser beam. Laser have

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been used for obtaining very sharp images of a

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moving objects. Thus the use of lasers has made holography possible (three dimensional photography).

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