LASERS

L - Light
A - Amplification by
S - Stimulated
E - Emission of
R - Radiation.

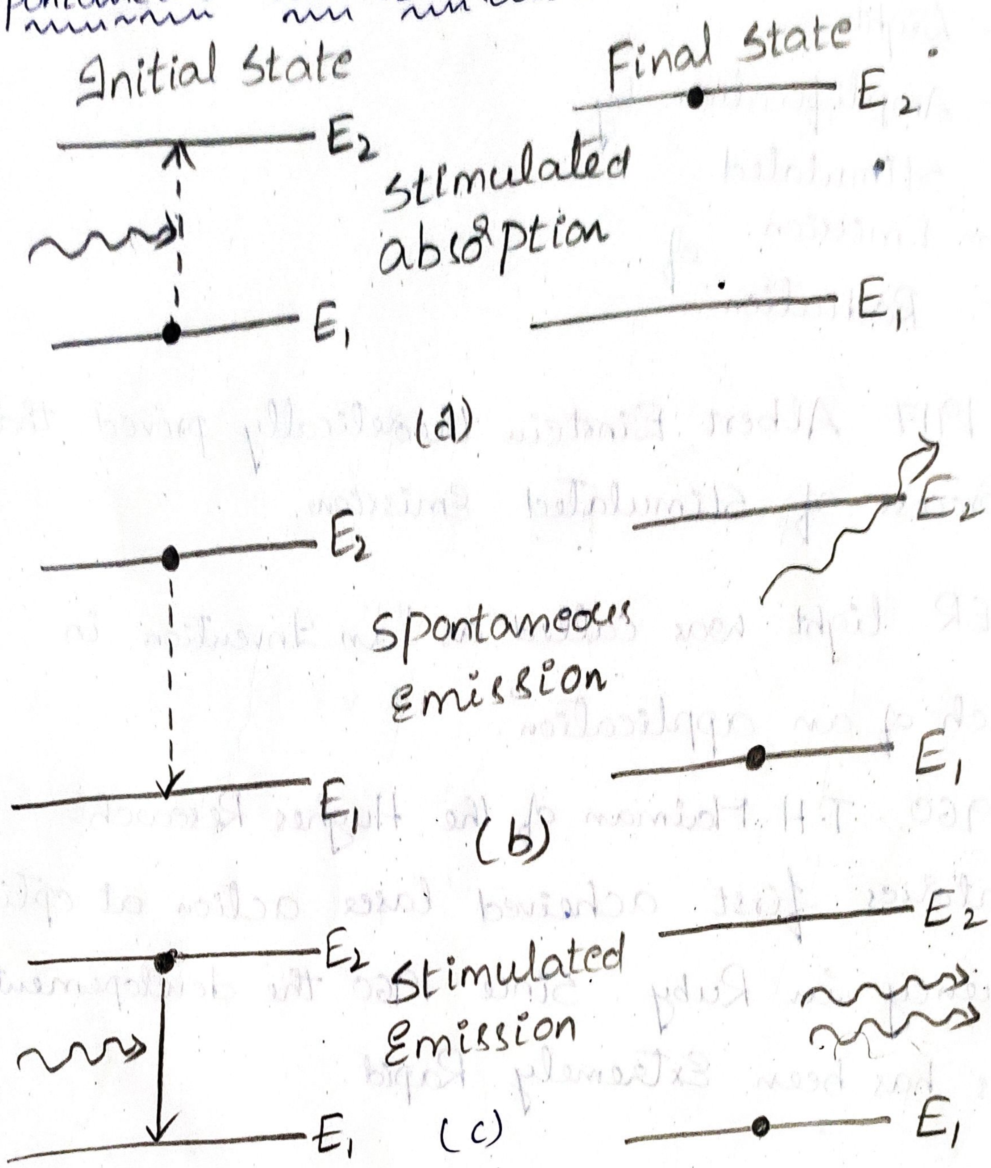
In 1917 Albert Einstein theoretically proved that the process of Stimulated Emission.

LASER light was called as "an Invention in search of an application".

In 1960, T.H. Maiman of the Hughes Research laboratories first acheived laser action at optical frequency in Ruby. Since 1960 the developement of lasers has been Extremely Rapid.

Definition of Lasers:- Laser is a device to produce a powerful monochromatic beam of light in which the waves are coherent. The beam emerges as a narrow beam which can travel over long distances with out much loss of Energy

Spontaneous and Stimulated Emission of Radiation:-



Energy level diagram for (a) Stimulated absorption (b) Spontaneous Emission (c) Stimulated Emission

The black dot indicates the state of atom before and after the transition.

Stimulated absorption:- If the radiation Interacts with atoms in the lower Energy state E_1, the atoms absorbs the Energy and get Excited in to the higher Energy state E_2 by a process called Stimulated absorption as shown in fig (a).

The Energy of the interacting photon $h\nu$ must match with Energy difference b/w the two states

Spontaneous Emission:- The atoms in the Excited state comes to the lower Energy states after they have stayed in a short duration of time called life time.

In this process the photons of Energy $h\nu = E_2 - E_1$ are Emitted as shown in fig (b)

Stimulated Emission:- One photon of Energy $h\nu$ stimulates the atom in the higher Energy state so that the atoms in the Excited state Emits the photon Energy which is Equal to the stimulating photon Energy.

In stimulated Emission two photons are Emitting i.e., (Stimulating photon and Stimulated photon).

Einstein's Coefficients :- In a collection of atoms, all the three transition process- Stimulated absorption, Spontaneous Emission, and Stimulated Emission occur simultaneously.

Let N_1 be the number of atoms per unit volume with Energy E_1 and N_2 be the number of atoms per unit volume with Energy E_2. Let 'n' be the no. of photons per unit volume at frequency ν such that $h\nu = E_2 - E_1$. Then the Energy density of Interacting photons $\rho(\nu)$ is given by

$$\rho(\nu) = nh\nu \qquad \text{— (1)}$$

when these photons interact with atoms, both upward (absorption) and downward (emission) transition occur. At Equilibrium these transition rates must be Equal.

Upward transition :- Stimulated absorption depends on the number of atoms available in the lower energy state for absorption of these photons as well as the Energy density of Interacting radiation.

$$\text{Stimulated absorption rate} \propto N_1$$
$$\propto \rho(\nu)$$
$$= N_1 \rho(\nu) B_{12}$$

where the constant of proportionality B_{12} is the Einstein Coefficient of Stimulated absorption.

Downward transition :- Once the atoms are Excited by stimulated absorption, they stay in the Excited state for a short duration of time called the life time of the Excited state. After their life time they move to their lower Energy level spontaneously emitting photons. This spontaneous Emission rate depends on the number of atoms in the Excited Energy state.

$$\text{Spontaneous Emission rate} \propto N_2$$
$$= N_2 A_{21}$$

where constant of proportionality A_{21} is the Einstein coefficient of spontaneous Emission.

Before Excited atoms de excite to their lower Energy states by spontaneous Emission, they may interact with photons resulting in stimulated Emission of photons.

∴ Stimulated Emission rate depends on the number of atoms available in the Excited state aswell as energy density of interacting photons.

$$\text{Stimulated Emission rate} \propto N_2$$
$$\propto \rho(\nu)$$
$$= N_2 \rho(\nu) B_{21}$$

where the constant of proportionality B_{21} is the Einstein coefficient of stimulated Emission.

During stimulated Emission, the interacting photon called the stimulating photon and the photon due to stimulated Emission are in phase with each other.

During stimulated absorption, the photon density decreases whereas during stimulated Emission it increases.

For a system in Equilibrium, the upward and downward transition rates must be Equal.

$$N_1 \rho(\nu) B_{12} = N_2 \rho(\nu) B_{21} + N_2 A_{21} \quad \text{—— (2)}$$

$$\rho(\nu) = \frac{N_2 A_{21}}{N_1 B_{12} - N_2 B_{21}} \quad \text{—— (3)}$$

$$\rho(\nu) = \frac{A_{21}/B_{21}}{\frac{B_{12}}{B_{21}} \cdot \frac{N_1}{N_2} - 1} \quad \text{—— (4)}$$

The population of the various Energy levels of a system in thermal Equilibrium is,

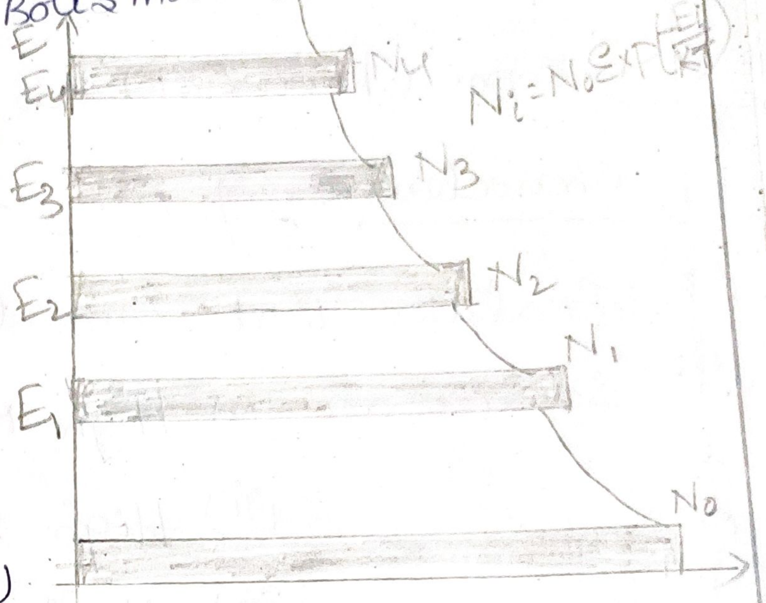
According to Boltzmann distribution law is

$$N_i = g_i N_0 \, \mathrm{Exp}\left(\frac{-E_i}{KT}\right) \quad \text{—— (5)}$$

where N_i is the population density of the Energy level E_i

N_0 is the population density of the ground state at temperature T, g_i is the degeneracy of the ith level

$K = 1.38 \times 10^{-23}$ Joule/K Boltzmann constant



Here $N_1 = g_1 N_0 \exp(-E_1/KT)$

$N_2 = g_2 N_0 \exp(-E_2/KT)$

$$\frac{N_1}{N_2} = \frac{g_1}{g_2} \exp\left(\frac{E_2 - E_1}{KT}\right)$$

$$= \frac{g_1}{g_2} \exp\left(\frac{h\nu}{KT}\right) \quad \text{——} (6)$$

Substituting (6) in Eqn (4)

$$\rho(\nu) = \frac{A_{21}/B_{21}}{\left[\frac{g_1}{g_2}\frac{B_{12}}{B_{21}} \exp\left(\frac{h\nu}{KT}\right) - 1\right]} \quad \text{——} (7)$$

from planck's Law of black body radiation, the radiation density is given by

$$\rho(\nu) = \frac{8\pi h\nu^3}{c^3}\left[\frac{1}{\exp\left(\frac{h\nu}{KT}\right) - 1}\right] \quad \text{——} (8)$$

Comparing Eqns (7) & (8)

$$\frac{g_1 B_{12}}{g_2 B_{21}} = 1$$

So we are able to directly view a glowing 100 watts Electric bulb but we can not see 1mW He-Ne Laser which has 10^5 times lesser power.
A 1 milli watt He-Ne can be 100 times brighter than Sun.

Different Types of Lasers :- (6)

On the basis of active medium the laser system is classified in to several types.

(i) Solid State Laser i.e., Ruby Laser.

(ii) Gaseous Laser i.e., He-Ne Laser, CO_2 Laser.

(iii) Semi Conductor Laser i.e, Ga-As Laser.

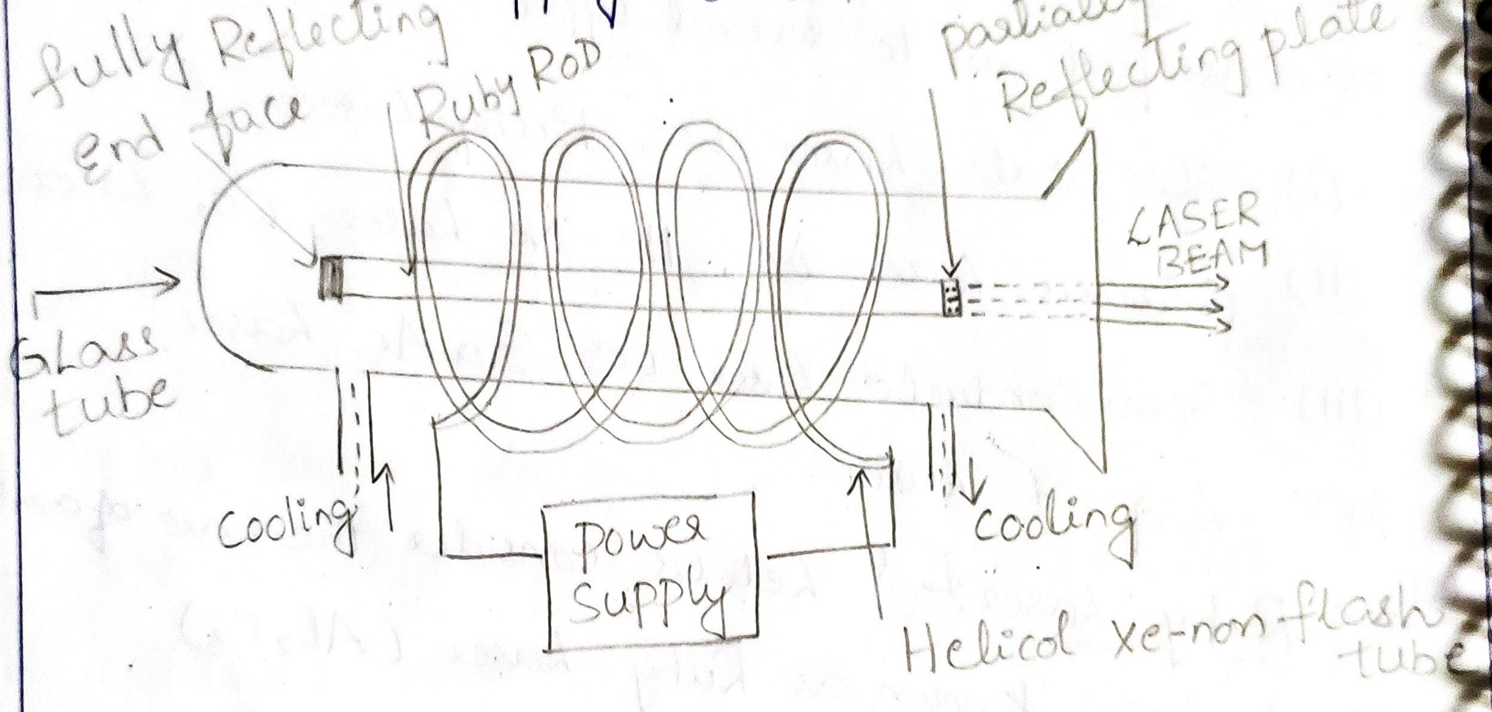
(iv) Liquid Laser.

(1) ⟹ **Ruby Laser** :- Let us consider the case of an actual laser known as Ruby Laser (Al_2O_3).
It uses a crystalline substance as the active material.
The different parts are as shown in fig.
It consists of three main parts :-

(i) An active working material :-
A rod of ruby crystal.

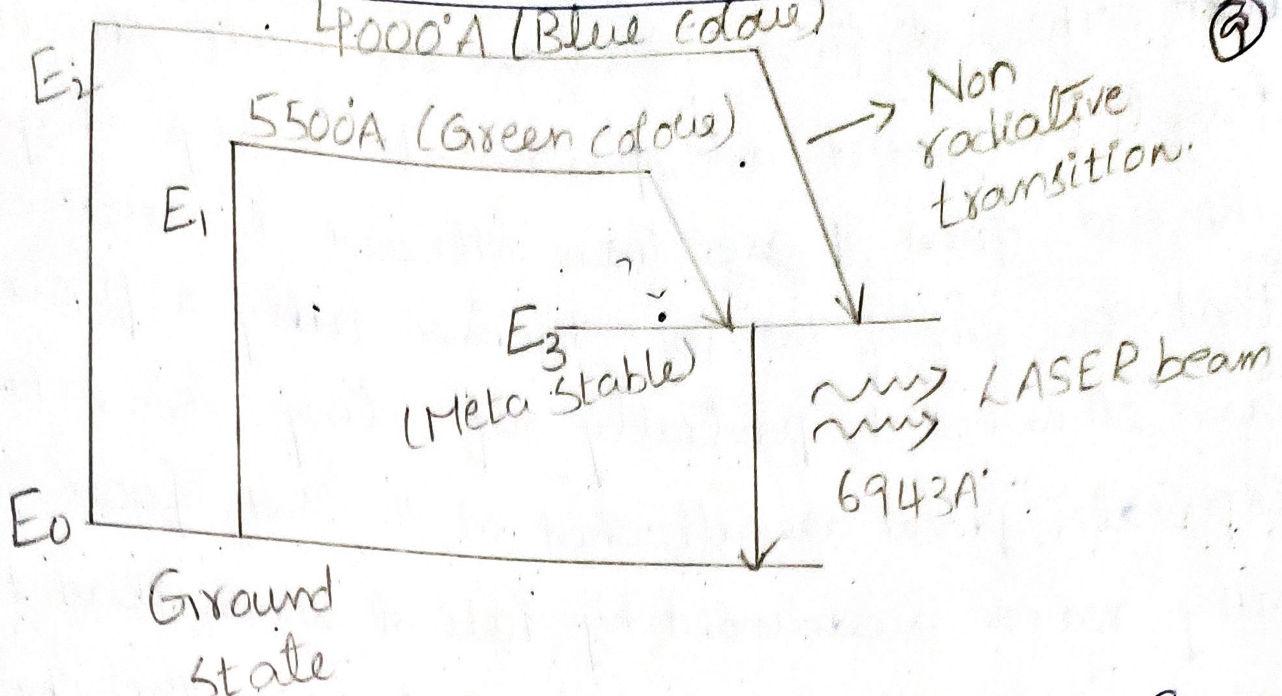
(ii) A resonant Cavity :- made of fully reflecting plate at the left of ruby crystal and a partially reflecting plate at the right of ruby crystal. Both the plates are optically plane and exactly parallel to each other. ⑦

(3) Exciting System :- A Helical xenon flash tube with power supply source.



Ruby ($Al_2O_3 + Cr_2O_3$) is a crystal of aluminium oxide Al_2O_3 in which some aluminium atoms are replaced by chromium atoms (Cr_2O_3). The active material in the ruby are chromium ions Cr^{3+}, when ruby crystal contains about 0.05% of chromium, its colour is pink. In a Ruby Laser, a pink rod of 10cm length and 0.5 cm in diameter is generally used. The End faces of the rod are made strictly parallel ground and polished to a high degree. The End faces of are then silvered in such away that one End of the face becomes fully reflected and other End is partially reflecting. (Some times separate pieces are attached at the End faces). The ruby rod is surrounded by helical xenon flash tube which provides the pumping light to raise the Chromium ions to upper Energy level. The flash of Xenon tube lasts several milliseconds. and the upper part consumes several milliseconds and the tube consumes several thousand Joules of Energy(20kV) only a part of Energy is used in pumping the Cr^{+3} ions while the rest heats up the apparatus. for this purpose, a cooling arrangement is used.

Working :- As the two Ends of the Helical tube is connected to high voltage, the flash of Xenon light is made to fall on the ruby rod. when light fall on the rod, Al^{+3} ions first Excited and made to Excite the Cr^{+3} ions. Now the Cr^{+3} ions moves to the higher Energy state.

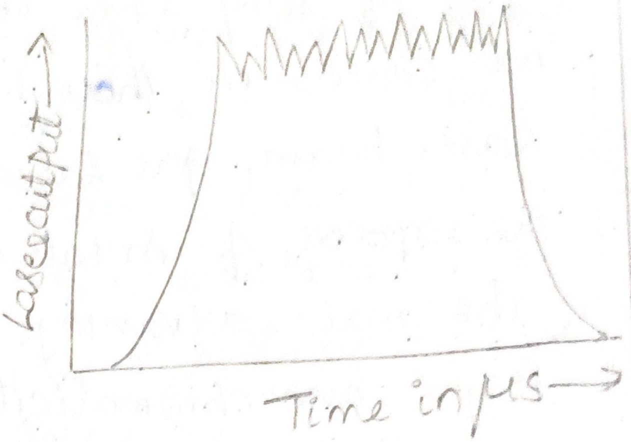


Let E_1 & E_2 be higher Energy states. As the Energy of the states and wave lenghs are inversely propotional to each other. So the atom reaches E_2 state have less wave length (4000A°) then the atom reaches E_1 state (possess 5500A° (Green in colour). As the atom cannot stay more than 10^{-8} sec. So they comes to the stable state called meta stable state where the life time of Meta stable state is 10^{-3} sec. As all the atoms from the higher Energy level comes and accumulate on E_3 state, where the population Inversion takes place. Before reaching the meta stable state E_3 cons present at E_1 & E_2 Under go non-radiative transition. As the population Inversion takes place at E_3 state, stimulated emission starts.

During the transition of atoms/ions from E_3 state to a ground state, it Emits a pair of laser beams having wave lengths 6943A° & 6927A°

beams having wave length 6943Å & 6927Å.

Output beam characteristics :-



The pumping flash lasts for a time duration of around 1ms. once the flash lamp is fired, with in 0.5ms, the population Inversion Exceeds threshold value and hence Stimulated Emission builds up rapidly. Hence the output consists of a large no. of spikes of about 1 μs duration with about 1 μs separation as shown in fig. peak powers with in the spikes are typically of the order of killowatts. when Laser is Q-Switched, it results a single pulse duration of 10-100nsec with a mega-watt range powers. (10)

Applications :-

Ruby Laser is used in variety of Applications.

(i) Distance measurement using "pulse echo" Technique.

2) pulsed Holography.

3) used in Atmospheric ranging, scattering studies and lidar measurements.

4) used for trimming resistors and Integrated circuit masks.

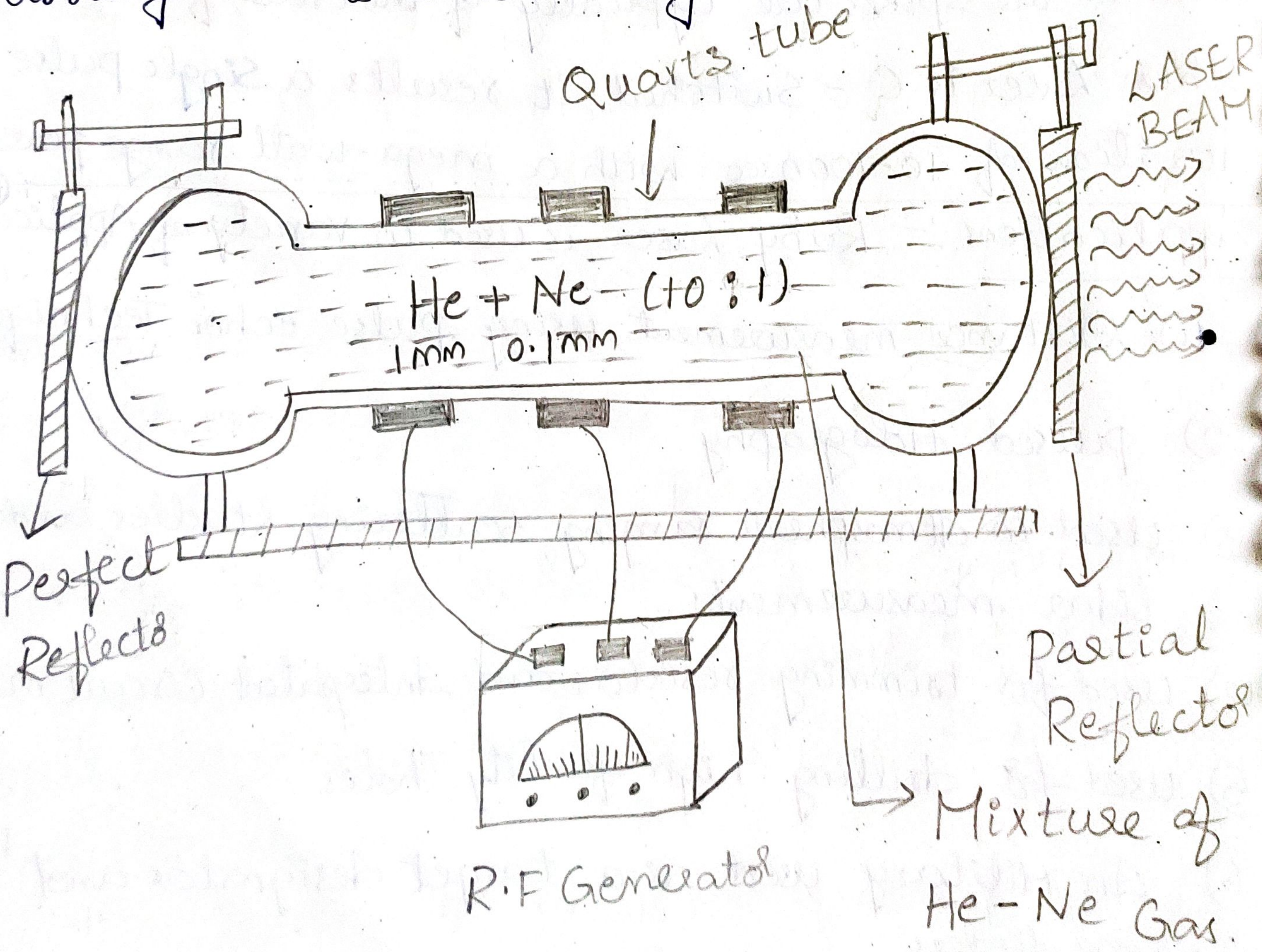
5) used for drilling high quality holes.

6) In Military used as a target designators and range finders.

7) Research applications as plasma production and fluorescence spectroscopy

2) <u>Gas Laser (He-Ne Laser)</u>:- The main draw back of ruby laser is that the output beam is not continuous though very intense. for continuous laser beam, gas lasers are used. (In gas lasers the vapours of metals are employed as active media. The main advantage of gas lasers are exceptionally high monochromaticity, most pure spectrum and high stability of frequency)

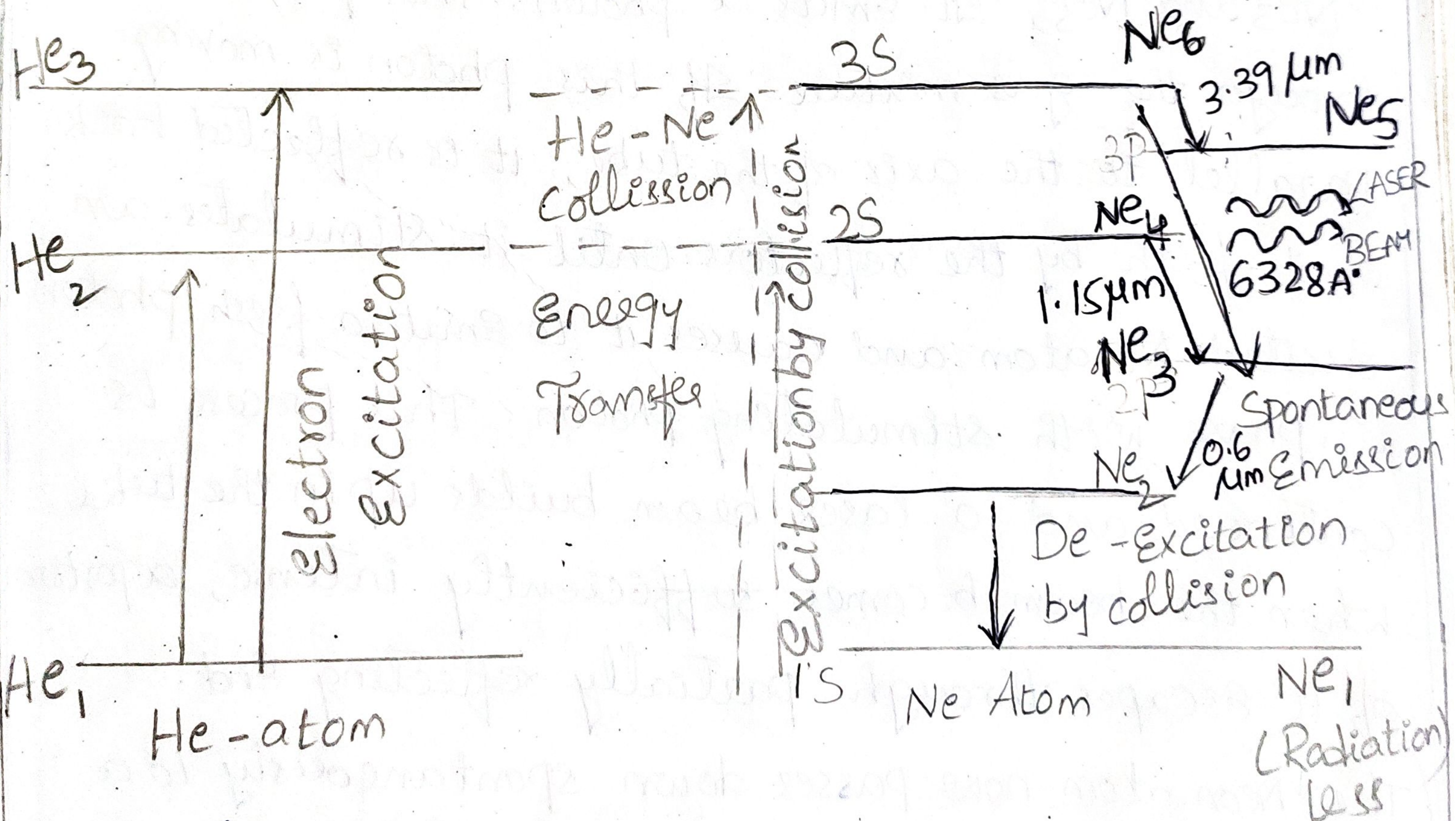
In 1961, A. Javan, W. Benett and D. Herriot reported a continuous gas laser. The experimental arrangement is shown in fig.



The gas laser consists of a fused Quartz tube with a diameter of about 1.5cm and 80cm long. This tube is filled with a mixture of neon (Ne) under a pressure of 0.1mm of mercury and helium (He) under a pressure of 1mm of mercury. There is a majority of Helium atom 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 high frequency generator with a frequency of several tens of MHz and an input of about 50 watts.

The Energy levels of two gases are shown in figure.



When a Discharge is passed through the gas, the electrons are accelerated towards the positive Electrode.

During their passage they collide with helium atoms and excite them in to the upper states labelled He_2 and He_3. These are metastable states. Thus the atoms remains in these levels sufficiently long time. Now these atoms interact with neon atoms to their metastable states Ne_4 and Ne_6 (i.e., 1S to 2S and 3S energy levels). While the He atoms return to their ground states. As the energy exchanges continuously, the population of Ne atoms in the excited states increases more and more. When an excited Neon atoms passes spontaneously from meta stable states {Ne_4 & Ne_6 (i.e 2S and 3S to 3P and 2P) to Ne_3 and Ne_5; It emits a photon. This photon travels through the gas mixture. If this photon is moving parallel to the axis of the tube, it is reflected back and forth by the reflectors until it stimulates an excited Ne atom and causes it to emit a fresh photon in phase with stimulating photon. This process is continued and a laser beam builds up in the tube. When the beam becomes sufficiently intense, a portion of it escapes through partially reflecting end.

(The Neon atom now passes down spontaneously to a lower state Ne_2 by emitting non-radiative transition. Finally Ne atom comes to ground state through collision with the tube wall.)

The He-Ne Lasers are very compact. The output power varies from 0.5mW to a maximum of about 100mW. The cost varies from Rs 10,000 to Rs 5 Lakhs.

Although 632.8 nm is the standard wave length, other wave length 543 nm (green),

594 nm (Yellow - orange),

612 nm (red - orange).

Applications:- (i) very widely used in Laboratories for all Interferometric Experiments.

2) used widely in metrology in surveying, alignment etc

3) The tightly focussed beam from a He-Ne laser can be scanned across a surface to read barcodes, special characters or other symbols. He-Ne laser scanners have also been used for optical character recognition.

4) used in three dimensional recording of objects called holography.

⟹ Semi Conductor Lasers:-

(i) Homojunction Laser :- It is similar to the principle from the Light Emitting diodes.

A p-n junction provides the active medium. This can be acheived by forming a homojunction from very heavily doped n and p materials. In such n+ type material, the fermi level lies with in the conduction

Applications of Lasers:- Due to high intensity, high mono-chromaticity and high directionality of lasers, they are widely used in various fields like

(i) Communication
(2) Computers
(3) Chemistry
(4) Photography
(5) Industry
(6) Medicine
(7) Military
(8) Scientific research.

(1) Communication:-

* In case of optical Communication, Semiconductors laser diodes are used as optical sources.
* More Channels can be sent simultaneously signal can not be tapped as the bandwidth is large, more data can be sent.
* A laser is highly directional and less divergence, hence it has greater

Potential use in space crafts and submarines.

2) Computers :-

(i) In LAN (local area network), data can be transferred from memory storage of one computer to the other computer using laser for short time.

2) Lasers are used in CD-ROMS during recording and reading the data.

3) Chemistry :-

* Lasers are used in molecular structure identification.
* Lasers are also used to accelerate some chemical reactions.
* using lasers, new chemical compound can be created by breaking bonds b/w atoms (or) molecules.

4) Photography :-

* Lasers can be used to get 3-D lens less photography.
* Lasers are also used in the construction of holograms.

5) Industry :-

* Lasers can be used to blast holes in diamonds and hard steel.
* Lasers are also used as a source of Intense-heat.

* Carbondioxide laser is used for drilling of metals and nonmetals, such as ceramics, plastics, glass etc. (25)
* High power lasers are used to weld (or) melt any material.
* Lasers are also used to cut teeth in saws and test the quality of fabric.

6) Medicine:-

* pulsed neodymium laser is employed in the treatment of liver cancer.
* Argon and Carbondioxide lasers are used in the treatment of liver and lungs.
* Lasers are used in the treatment of Glucoma.

7) Military:-

* Lasers can be used as a war weapon.
* High energy lasers are used to destroy the enemy air-crafts and missiles.
* Lasers can be used in the detection and ranging like RADAR.

8) Scientific research:-

(1) Lasers are used in the field of 3D-photography.
(2) Lasers are used in Recording and reconstruction of hologram.
(3) Lasers are employed to create plasma.
(4) Lasers are used to produce certain chemical reactions.
(5) Lasers are used in Raman spectroscopy to identify the structure of the molecule.

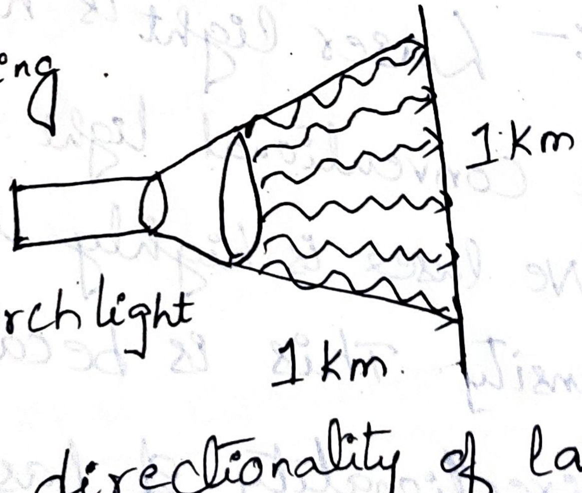
Characteristic of LASER Radiation :-

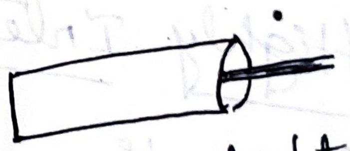
The Laser beam has the properties given below which distinguish it from an ordinary beam of light. Those are

(i) Highly directional
(2) Highly monochromatic
(3) Highly intense.
(4) Highly coherence.

1) Highly directional :-

Any conventional light source Emits light in all directions. On the other hand, Laser Emits light only in one direction. The width of Laser beam is Extremely narrow and hence a laser beam can travel to long distances with out Spreading.





The directionality of laser beam is Expressed in terms of divergence.

$$\Delta\theta = \frac{r_2 - r_1}{d_2 - d_1}$$

where r_1 and r_2 are the radii of laser beam spots at distances of d_1 and d_2 respectively from laser source.

2) Highly monochromatic :-

A monochromatic source is a single frequency (or) single wavelength source of light. The laser light is more monochromatic than that of a conventional light source. This may be due to stimulated characteristic of laser light. The band width of the conventional mono-chromatic light source is 1000Å. But the band width of ordinary light source is 10Å for high sensitive laser source is 10^{-8}Å.

3) Highly Intense :- Laser light is highly intense than the conventional light. A one milli-watt He-Ne laser is highly intense than the sun intensity. This is because of coherence and directionality of laser.

Suppose when two photons of each amplitude A are in phase with each other, then young's principle of superposition, the resultant amplitude of two photons is 2A and the Intensity is $4A^2$. Since in laser many numbers of photons are in phase with each other, the amplitude of the resulting wave becomes nA and hence the intensity of laser is proportional to n^2A^2. So 1mW He-Ne laser is highly intense than the sun. (17)

4) <u>Highly Coherence</u>:- A predictable correlation of the amplitude and phase at any one point with other point is called Coherence. In case of conventional light, the property of coherence exhibits b/w a source and its virtual source where as in case of laser the property coherence exists between any two sources of same phase. There are two types of Coherence

(i) Temporal Coherence.

(2) Spatial Coherence.

<u>Temporal Coherence (or longitudinal Coherence)</u>:-

The predictable correlation of phase and amplitude at one point on the wave

Suppose when two photons of each amplitude A are in phase with each other, then young's principle of superposition, the resultant amplitude of two photons is 2A and the Intensity is $4a^2$. Since in laser many numbers of photons are in phase with each other, the amplitude of the resulting wave becomes nA and hence the intensity of laser is proportional to n^2A^2. So 1mW He-Ne laser is highly intense than the Sun (17)

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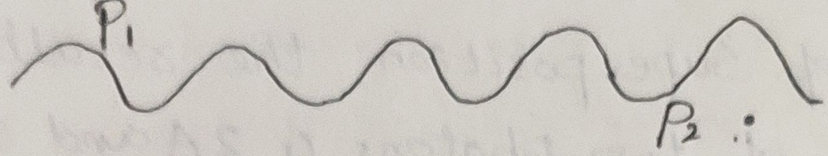
There are two types of coherence

(i) Temporal Coherence.

(2) Spatial Coherence.

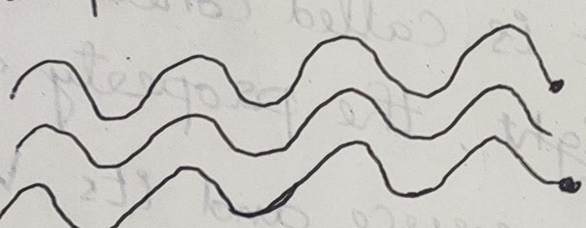
<u>Temporal Coherence (or longitudinal coherence)</u>:-

The predictable correlation of phase and amplitude at one point on the wave train, then the wave is said to be temporal Coherence. (18)



Spatial Coherence (or) (transverse coherence):-

The predictable correlation of amplitude and phase at one point on the wave train w.r.to another point on a second wave, then the waves are said to be spatial coherence (or) transverse coherence. Two waves are said to be coherent when the waves must have same amplitude & phase.



Comparison b/w Spontaneous and Stimulated Emission:-

Spontaneous Emission	Stimulated Emission
(i) The Spontaneous Emission was postulated by Bohr.	(i) The Stimulated Emission was postulated by Einstein.
2) Additional photons are not required in Spontaneous Emission	2) Additional photons are required in Stimulated Emission

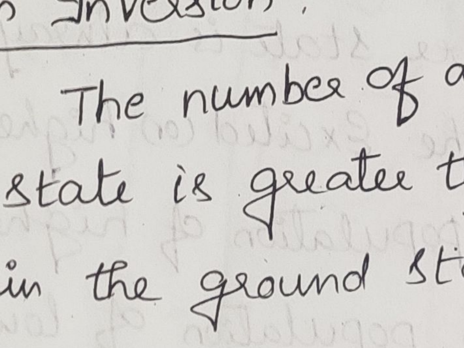
* Lasers are used in Michelson - Morley Experiment.
* A laser beam is used to Confirm Doppler shifts in frequency for moving objects.

Metastable State :-

In general the number of Excited in a system is smaller than the non Excited particles. The time during which a particle Can Exist in the ground state is unlimited. On the other hand, the particle can remain in the Excited state for a limited time known as life time. The life time of the Excited hydrogen atom is of the order of 10^{-8} sec. How ever there exist such Excited states in which the life time is greater than 10^{-8} sec. These states are called as Meta stable states.

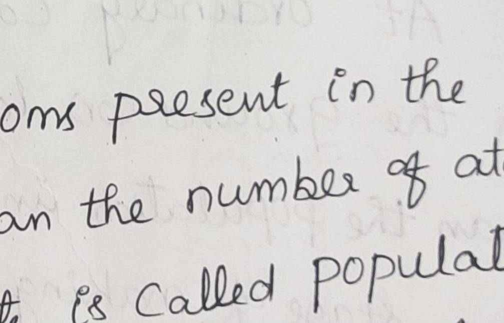
Population Inversion :-

The number of atoms present in the Excited state is greater than the number of atoms present in the ground state is Called population Inversion.



At thermal Equilibrium $N_1 > N_2$

Population Inversion.



$N_2 > N_1$

Let us consider two level Energy systems of Energies E_1 and E_2 as shown in figure (21)

Let N_1 and N_2 be the population (means no. of atoms per unit volume) of E_1 and E_2 respectively.

According to Boltzmann's distribution the population of an energy level E_i at temperature T is given by

$$N_i = N_0 e^{\left(\frac{-E_i}{K_B T}\right)} \quad \text{where } i = 1, 2, 3 \ldots N_i$$

where N_0 is the number of atoms in the ground (or) lower Energy states & K is the Boltzmann Constant.

from the above Equation, the population of Energy levels E_1 & E_2 are given by

$$N_1 = N_0 \, Exp\left(\frac{-E_1}{K_B T}\right)$$

$$N_2 = N_0 \, Exp\left(\frac{-E_2}{K_B T}\right)$$

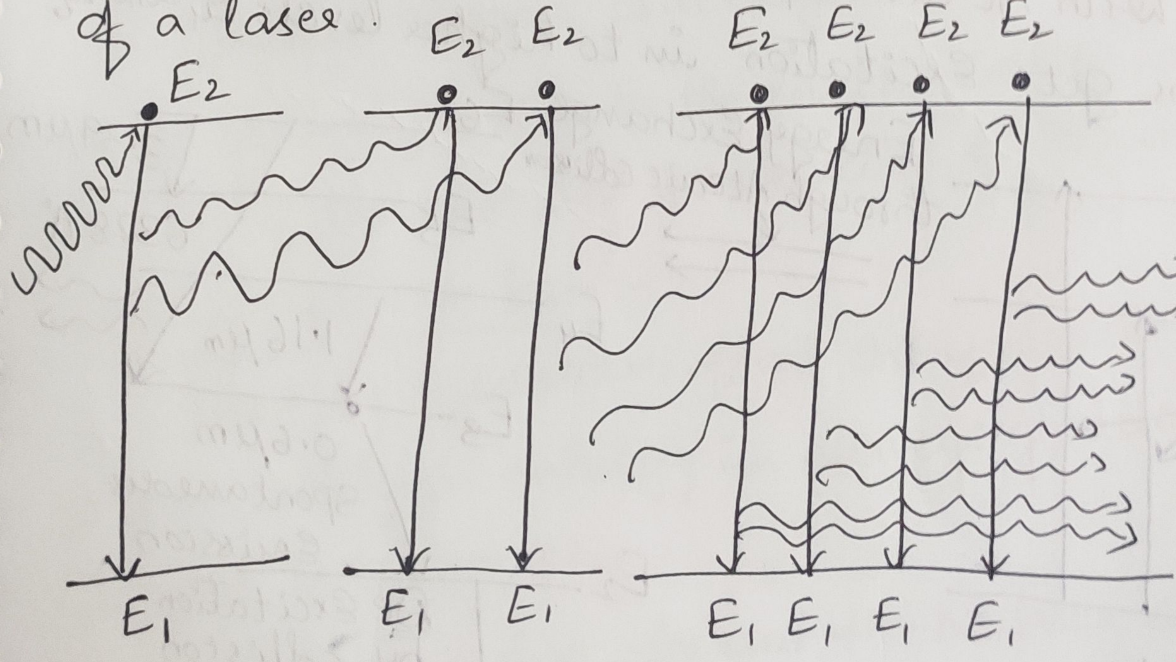
At ordinary conditions $N_1 > N_2$ i.e., the population in the ground (or) lower state is always greater than the population in the Excited (or) higher states.

The stage of making, population of higher Energy level greater than the population of lower Energy level is called population Inversion

i.e, $N_2 > N_1$.

Principle of LASER / LASING ACTION

Let us Consider many no. of atoms in the Excited State. Now the Stimulating photon Interacts with any one of the atoms in the Excited State, the stimulated Emission will occur. It Emits two photons, having same Energy and same frequency. The two photons will move in the same direction. The two photons will Interact with another two atoms in Excited State & Emit 4-photons. In a similar way Chain reaction is produced, this phenomenon is called "principle of lasing action". We get a monochromatic, coherent, directional & Intense beam is obtained. This is Called laser beam. This is the principle of working of a laser.



$$\Rightarrow g_1 B_{12} = g_2 B_{21} \quad \text{——— (9)}$$

(5)

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

Eqns (9) and (10) are referred as Einstein relations.

Charecteristics of Laser :- The most striking features that laser light differ from conventional sources are (i) High Monochromaticity

(ii) High Degree of coherence.

(iii) High Directionality

(iv) High Brightness.