Introduction

Laser, perhaps one of the most exciting discoveries of the twentieth century, is an acronym for light amplification by stimulated emission of radiation. The first successful operation of a laser was done by Maiman in 1960 using a ruby crystal. Laser light, like light from any other ordinary source, is emitted when atoms make a transition from quantum state of higher energy to a state of lower energy. However, it has unique properties not found in the light from ordinary sources. Let us now discuss its basic principle, working of some laser systems, and its important applications.

Characteristics of LASER Beam:

1. **Highly Monochromatic**: It refers to the single frequency of radiation. The laser light has a single spectral color. That means it has high degree of monochomaticity.

2. **Highly Directional (Small divergence)**: Laser beam is highly directional. The conventional sources emit light in all directions. Lasers emit light only in one direction, as the photons travels along the optical axis of the system.

   Example: a laser beam having 10 cm diameter when beamed at the moon's surface 3,84,000 km, deviation is not more than 5 km wide.

3. **Highly coherent:** Coherence is expressed in terms of ordering of light field. Laser light is characterized by a high degree of ordering of light field than ordinary light.

4. **High Intensity**: The intensity of light from the conventional sources decreases rapidly with distance as it spreads in the form of spherical waves. Laser emits light in the form of a narrow beam which propagates in the form of plane waves. As the energy is concentrated in the narrow its intensity would be very high. It is estimated that 1mw laser is 10,000 times brighter than the light from sun at the earth surface.

3.1 Characteristics of Laser In detailed:

The enormous growth of laser technology has stimulated a broad range of scientific and engineering applications that exploit some of the unique properties of laser light. These properties are derived from the distinctive way laser light is produced in contrast to the generation of ordinary light. Light from a laser differs from light from conventional sources in number of ways. The most striking feature of a laser beam are

i) Monochromaticity

If light from a source has only one frequency of oscillation, the light is said to be monochromatic and the source, a monochromatic source. In practice it is not possible to produce light with only one frequency.

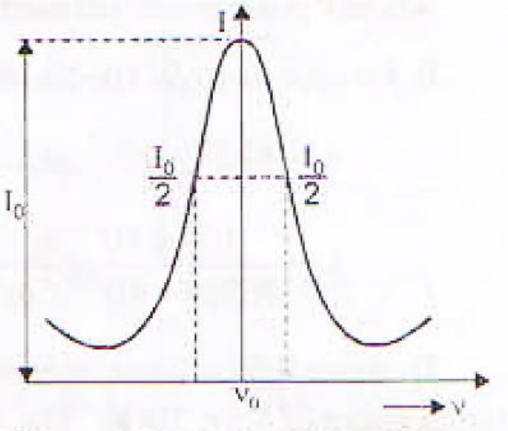


Figure 3.1: (a) Line Width diagram

Light coming out of any source consists of band of frequencies closely spaced around a central frequency $'\nu_0'$. The band of frequencies, $\Delta\nu$, is called the linewidth or bandwidth. The light from conventional sources has large linewidths of the order of 10^{10} Hz or more. On the other hand, light from lasers is more monochromatic having linewidths to 100 Hz.

ii) Higher degree of coherence

Light waves are said to be coherent if they are in phase with each other. For example if they maintain crest-to-crest and trough-to-trough to correspondence. λ

Two things are necessary for light waves to be coherent. First they must start with same phase at the same position. Secondly their wavelengths must be the same or they will drift out of phase because the crusts of the higher frequency will arrive ahead of the crests of the lower frequency wave.

The light that emerges from a conventional light source is a jumble of short waves which combine with each other in a random manner. On the other hand the light from a laser is a resultant of a large number of identical photons which are in phase and therefore exhibits a high degree of coherence.

iii) High Intensity

The power output of a laser may vary from a few milliwatts to a few kilowatts. But this energy is concentrated in a beam of very small cross section. The intensity of a laser beam is approximately given by

$$\boldsymbol{I} = \left(\frac{\mathbf{10}}{\boldsymbol{\lambda}}\right)^{\mathbf{2}} \boldsymbol{P} - - - -(\mathbf{3.1})$$

where *P* is the power radiated by the laser.

In the case of 1m W He-Ne laser

$$\lambda = 6328 \times 10^{-10} m$$

$$I = \frac{100}{(6328 \times 10^{-10})^2 m^2} \times 10^{-3} W = 2.4973 \times 10^{11} W/m^2$$

To obtain light of same intensity from a tungsten bulb, it would have to be raised to a temperature of 4.6×10^6. The normal operating temperature of the bulb is about 2000 K.

iv) Directionality

Conventional light sources emit light in all directions. But light from laser diverges very little. Light beam can travel as a parallel beam upto a distance of d^2/λ where d is the diameter of the aperture through which the light is passing and λ is the wavelength of the light used. After travelling the distance d^2/λ, the light beam spreads radially. In ordinary light beam the angular spread is given by $\Delta\theta = \lambda/d$. For a laser beam the angular spread is 1 mm per 1m, but for an ordinary source of light the angular spread is 1 m per 1 m. This shows the directionality of laser beam. A 10cm wide laser beam has a diameter of only 5 km after reaching the moon which is at an approximate distance of 3,85,000 km.

Longitudinal/Temporal Coherence:

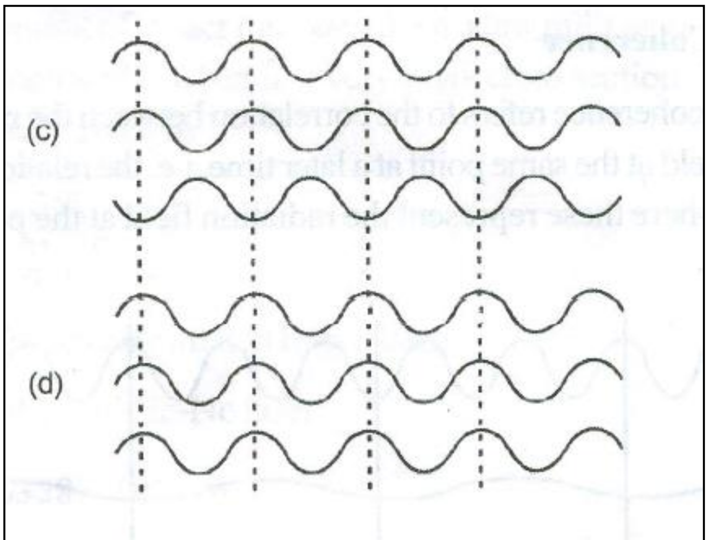
In this case all the optical waves inside the laser cavity are in the same phase, at each and every point in the direction parallel to the laser light. Or it can be said in the other way that is, for all the waves the crust positions will meet crusts of all other waves and similarly for troughs too.

This is said as Longitudinal/Temporal coherence.

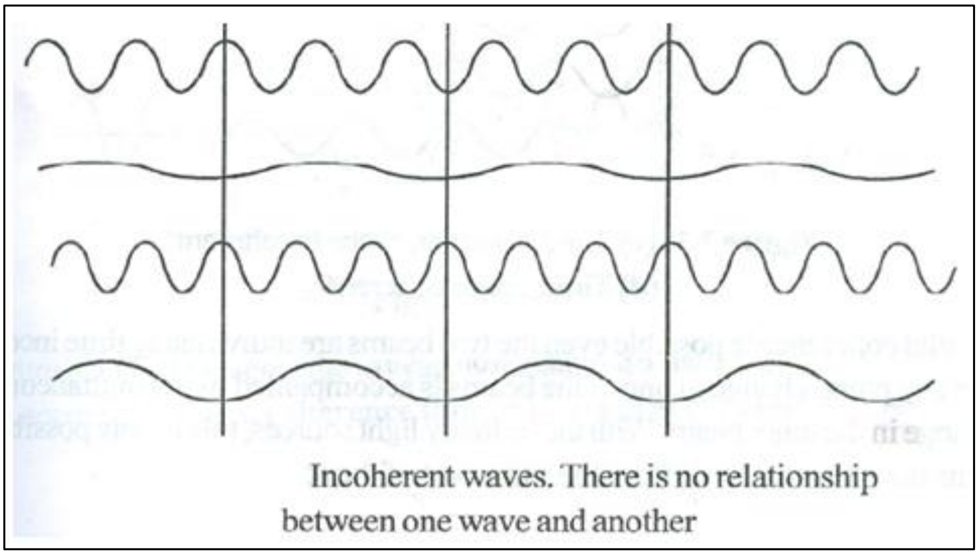
If we check from one of the two mirrors in the cavity, we can find that the longitudinal incoherence will be increasing. So practically this is solved by reducing the distance between the two mirrors. The distance till which the longitudinal incoherence is accepted is called as length of longitudinal coherence.

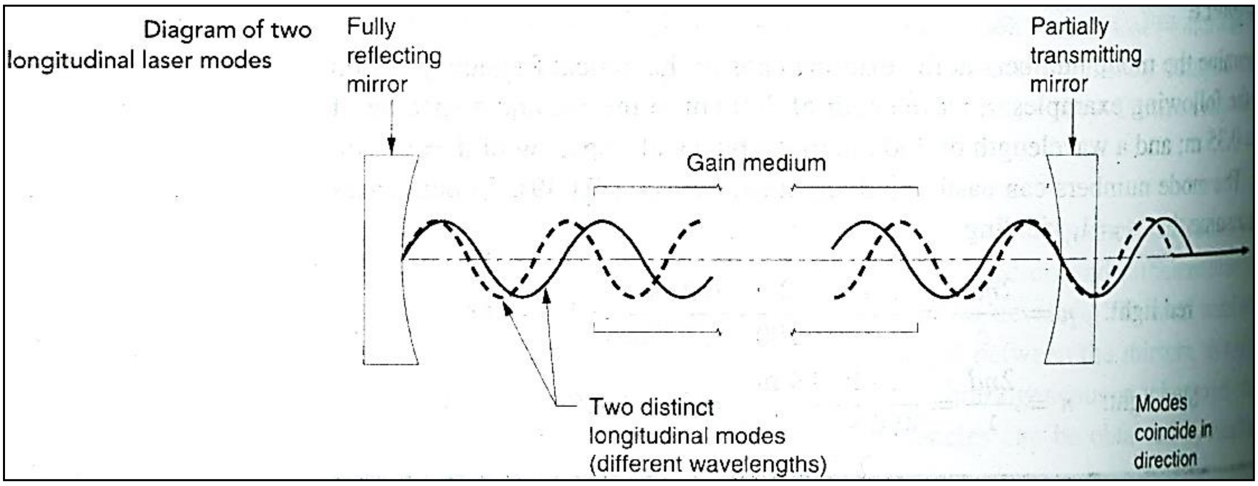
The longitudinal incoherence is introduced because of the emission of light rays from different energy levels that are unwanted.

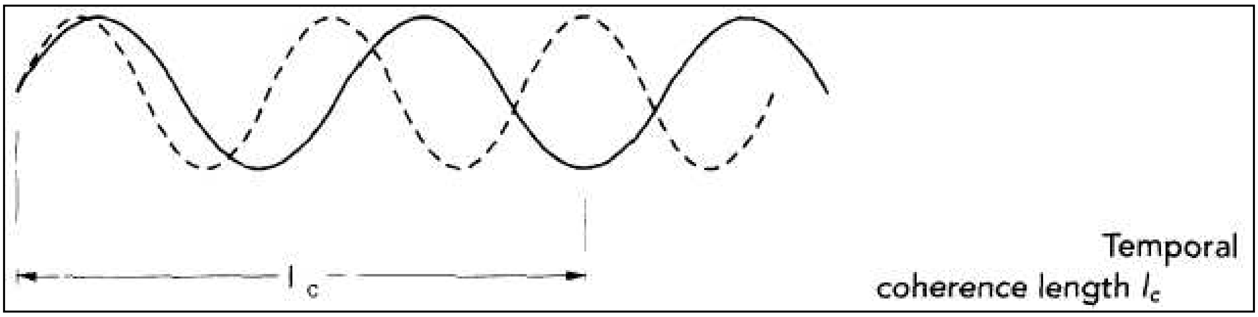
The estimation of longitudinal coherence is important in designing the laser cavity.



(c) Time coherent, space incoherent,
(d) Time, space coherent







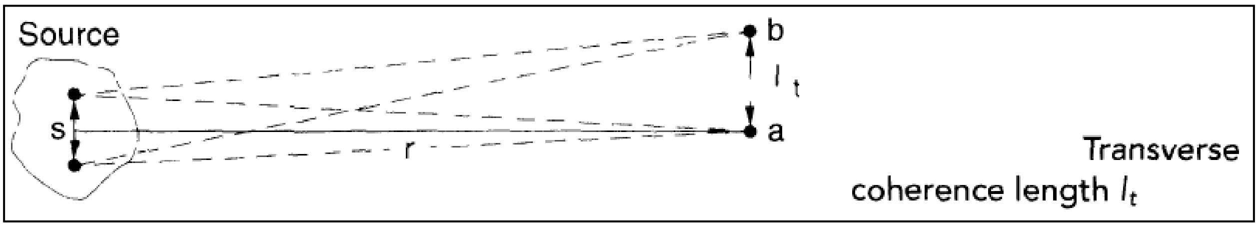
$$\mathbf{l_{longitudinal}} = \frac{\lambda^2}{\Delta\lambda}$$

$$\mathbf{l_{temporal}} = \frac{\lambda^2}{\Delta\lambda}$$

Transverse/Spatial Coherence:

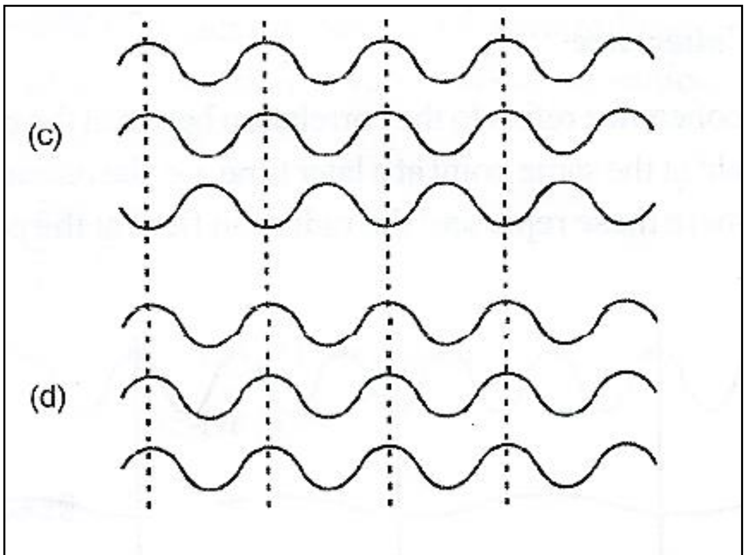
In this case all the optical waves differ in their direction. Still due to diverging characteristics, light those start from sources S_1 and S_2 (as shown in the diagram) will be coherent when they reach points between A and B at a distance r. This is said as Transverse/Spatial Coherence.

The estimation of transverse coherence is important in designing the size of active centers inside the laser cavity.



$$\mathbf{l_{transverse}} = \frac{\mathbf{r\lambda}}{\mathbf{s}}$$

$$\mathbf{l_{spatial}} = \frac{\mathbf{r\lambda}}{\mathbf{s}}$$



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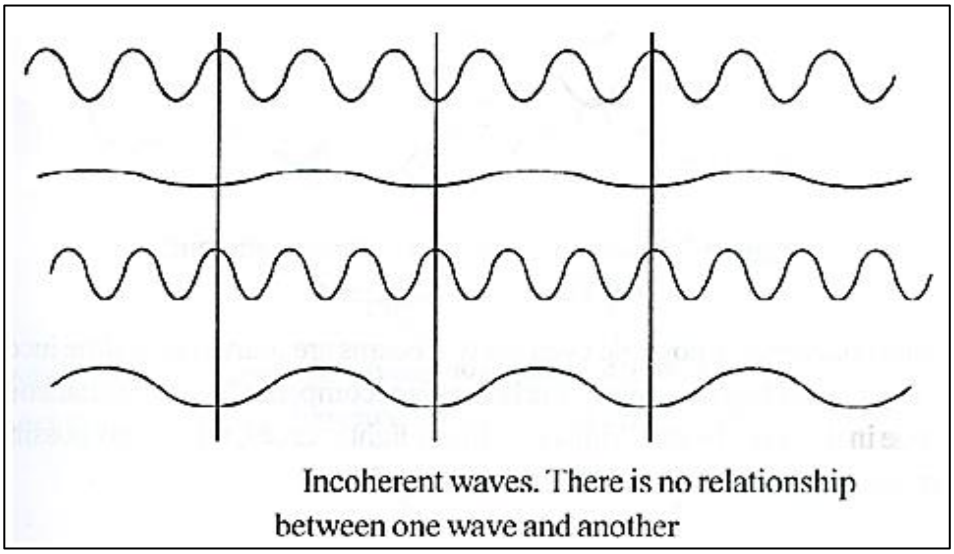
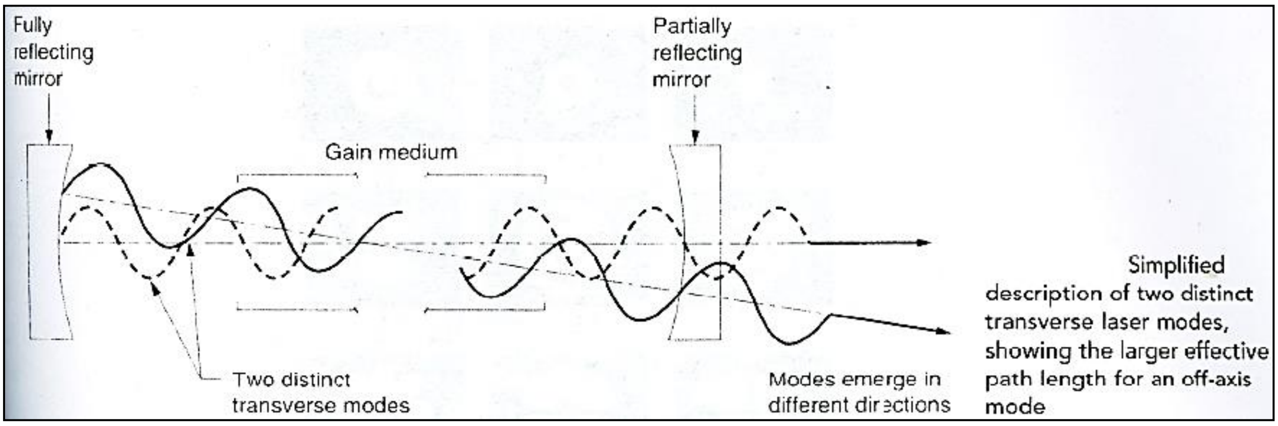
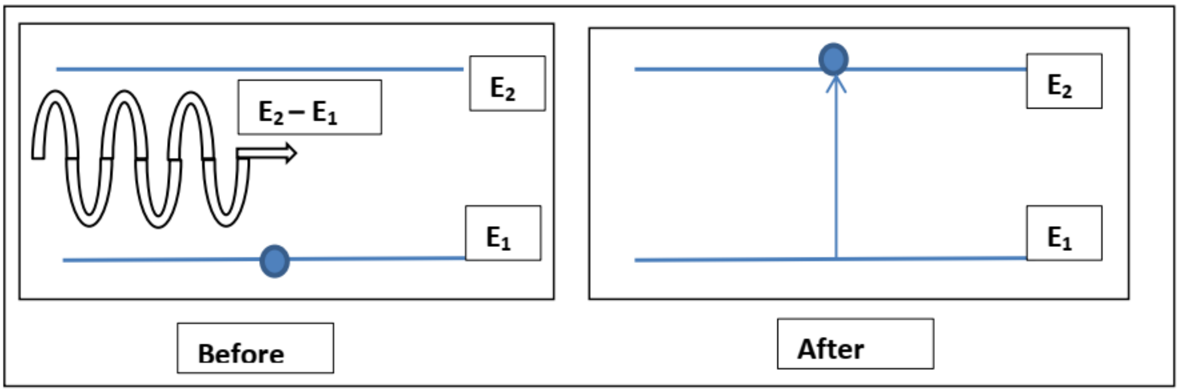


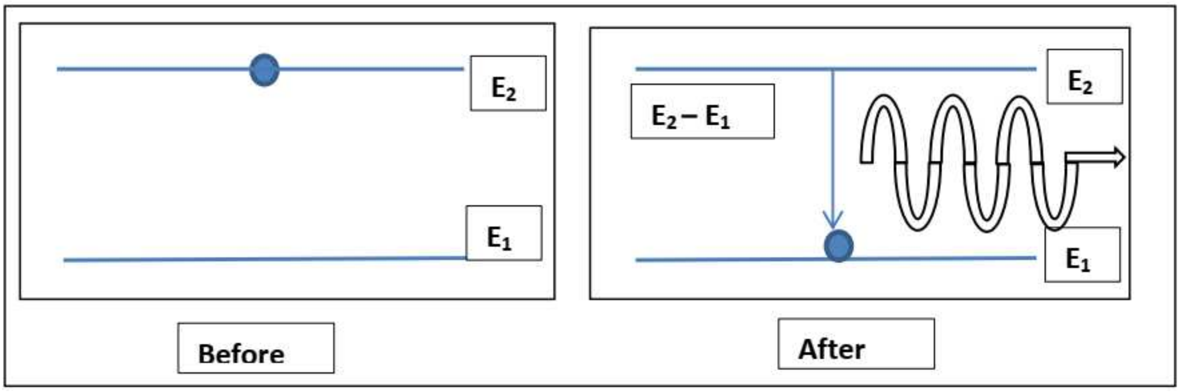


Whole concept of LASER can be understood by looking at the fundamental processes that happens when radiation interacts with matter. Consider a system with two energy levels to which energy corresponding the difference between the levels is supplied externally.

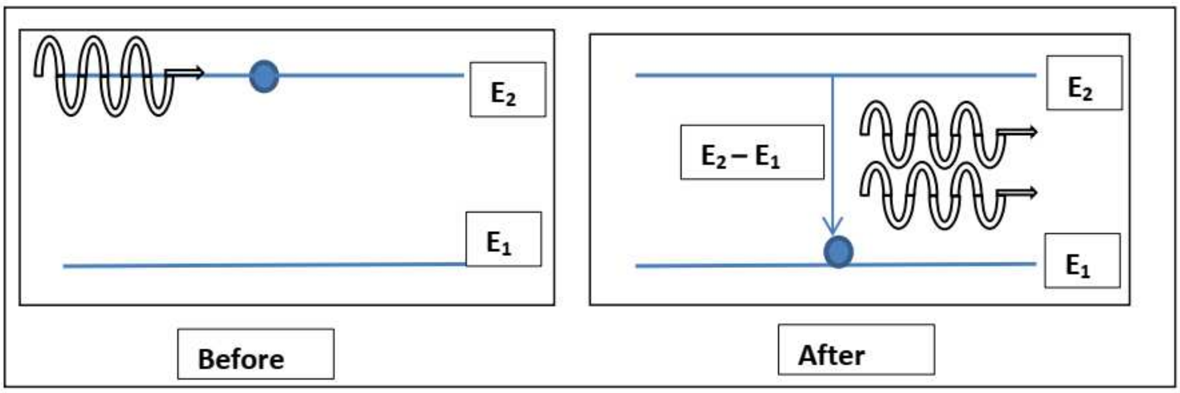


Once energy is supplied, the atoms in the lower energy level will absorb the incident energy and jump to the next possible higher energy level. This process is called Absorption. This depends on the number of atoms available in the lower energy state and the energy density of radiation supplied to the system.

It is known that atoms cannot stay in the higher energy excited state for long. All systems tend to go towards the lower energy state for maintaining their stability. This happens by losing their absorbed energy i.e., excited state atoms emit their excess energy and go to their ground state. This process occurs naturally depending on the lifetime of that excited state and is called the spontaneous emission. It depends only on the number of atoms present in that higher level.



Einstein proposed a modification in this absorption-emission process. Since the process depends on the lifetime of the excited level, He proposed to delay the emission from the excited state so as to make some of the incoming stream of photons to collide with this excited state atom instead of ground state atom. This collision will disturb the excited state atom leading that to drop to the ground state. During this process, it will emit another photon thereby yielding 2 photons at the output.



Here the incoming photon does not undergo absorption, whereas stimulates the excited state atom to emit a photon causing multiplication of output photons of same energy. This process depends on the incident energy and also the number of atoms present in the excited state. Repetition of this process leads to lasing output.

3.2 Einstein's Prediction

When we see light from any source, we actually see electrons jumping from excited states to lower states. This type of emission of light which occurs on its own is known as spontaneous emission and is represented for the light coming from candles, electric bulbs, fire, sun etc.

Einstein predicted in 1917, there must be a second emission process to establish thermal equilibrium. For example, if we illuminate a material with light of suitable frequency, the atoms in it absorb light and go to higher energy state.

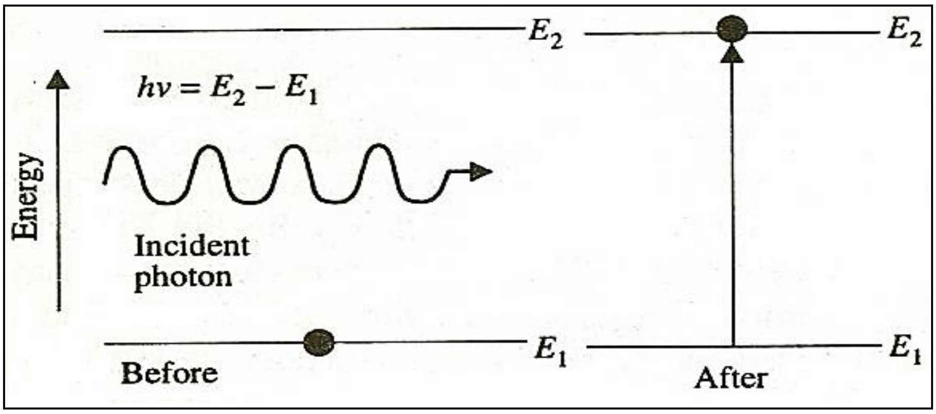
The excited atoms tend to return randomly to the lower energy state. As the ground state population is very large, more and more atoms are excited under the action of incident light and it is likely that a stage may reached where all atoms are excited. This violates thermal equilibrium condition. Therefore Einstein suggested that there could be an additional emission mechanism, by which the excited atoms can make downward transitions. He predicted that the photos in the light field induce the excited atoms to fall to lower energy state and give up their excess energy in the form of photos. He called this type of second emission as stimulated emission.

The Three Fundamental Processes

Let us consider a medium consisting of identical atoms capable of being excited from the energy level 1 to the energy level 2 by absorption of photons. Let the levels be denoted by E_1 and E_2 and their populations be N_1 and N_2 respectively. Let the atoms be in thermal equilibrium. In the equilibrium condition the number of atomic-upward transitions must be equal to the number of downward transitions. Thus no net photos are generated or lost. However, when the atoms are subjected to an external light of frequency, 'v', the following three processes occur in the medium.

i) Absorption

An atom in the ground state E absorbs an incident photon and makes a transition to the excited state E_2. This transition is known as induced or stimulated absorption or simply absorption.



Corresponding to each absorption transition, one photon disappears from the incident field and one atom adds to the population at the excited energy level E_2. This process may be represented as

$$\text{atom} + \text{photon} \rightarrow atom^*$$

$$* \rightarrow \text{atom is in the excited state}$$

The number of absorption transitions occurring in the material at any instant will be proportional to the population in the lower level and the number of photons per unit volume in the incident beam. The rate of absorption may be expressed as

$$\mathrm{R_{abs}} = \mathrm{B_{12}}\rho(\vartheta)\mathrm{N_1}$$

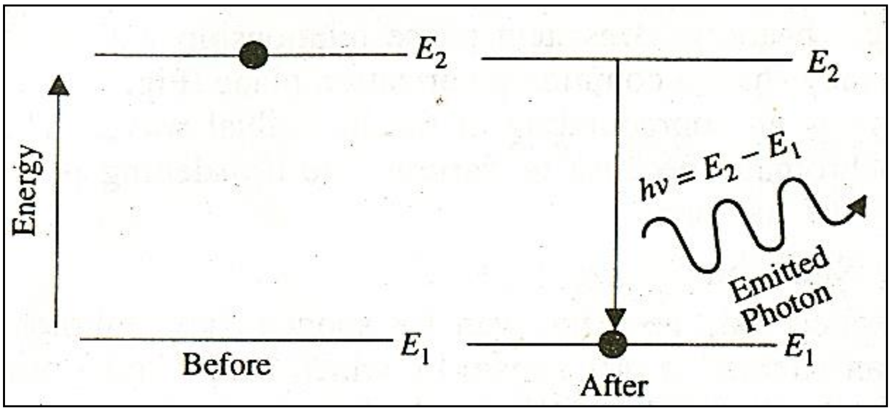
$$\rho(\vartheta) - \text{ energy density of incident light}$$

$$\mathrm{B_{12}} - \text{Einstein coefficient for absorption}$$

At thermal equilibrium, the population in the lower energy state is far larger than that in the higher energy state. Therefore as light propagates through the medium, it gets absorbed.

ii) Spontaneous emission

An excited atom can stay at the excited level for an average life time (10^{-8} Sec). If this atom is not stimulated by any other agent during its short lifetime, the excited atom undergoes a transition to the lower level on its own. During the transition it gives up the excess energy in the form of photon. This process in which an excited atom emits a photon without any external agent is known as spontaneous emission.



This process is represented as

$$atom^* \rightarrow \text{atom} + \text{photon}$$

The number of photons generated will be proportional to the population of the excited level only. The rate of spontaneous emission may be expressed as

$$\mathrm{R_{sp}} = \mathrm{A_{21}N_2}$$

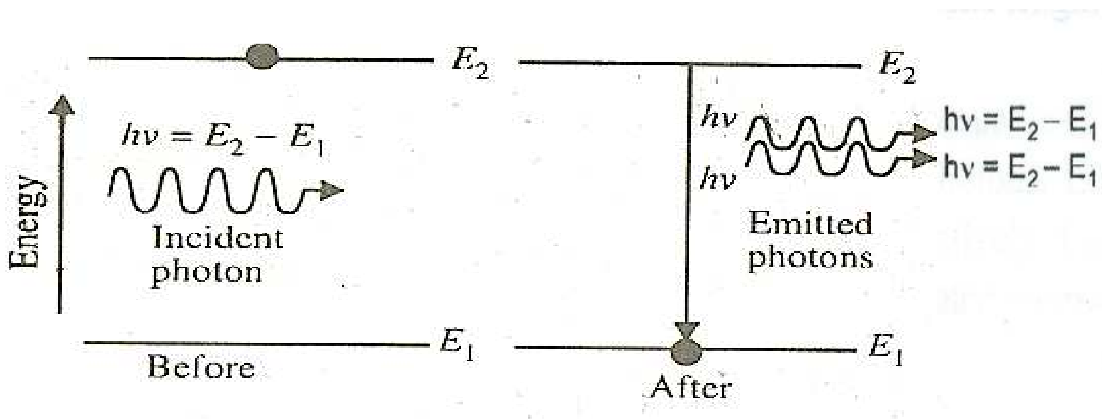
$$\mathrm{A_{21}} - \text{Einstein coefficient for spontaneous emission}$$

Thus the process of spontaneous emission is independent of energy density.

iii) Stimulated emission

An atom in the excited state need not wait for spontaneous emission to occur. If a photon with appropriate energy ($h\vartheta = \mathrm{E_2} - \mathrm{E_1}$) interacts with the excited atom, it can trigger the atom to undergo transition to the lower level and to emit another photon.

The process of emission of photons by an excited atom through a force transition occurring under the influence of an external agent is called induced or stimulated emission.



The process may be represented as

$$atom^* + \text{ photon} \rightarrow \text{atom } + \text{ 2 photons}$$

The rate of stimulated emission of photons is given by

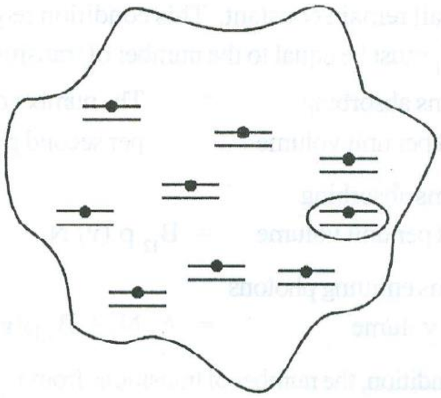
$$\mathrm{R_{st}} = \mathrm{B_{21}}\rho(\vartheta)\mathrm{N_2}$$

$$\mathrm{B_{21}} - \text{Einstein coefficient for stimulated emission}$$

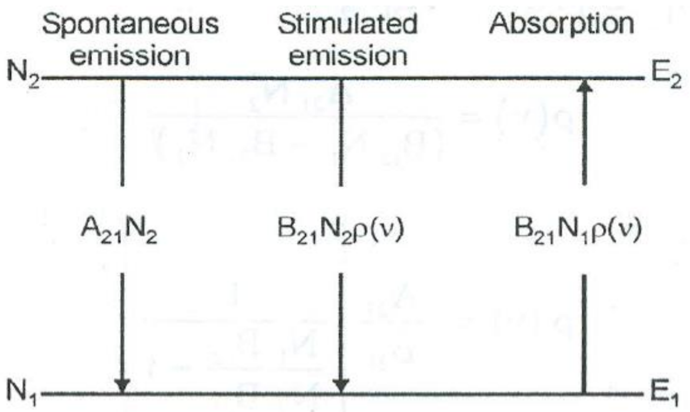
Differences between spontaneous and stimulated emission:

Spontaneous Emission	Stimulated Emission
1. In this process transition occurs from higher energy level to lower energy level	1. In this process transition occurs from higher energy level to lower energy level
2. No incident photon is required for transition.	2. Photon whose energy is difference in two energy levels is required
3. Single photon is emitted.	3. In this process two photons of equal energy are emitted.
4. In this process emitted light is less amplified.	4. More amplified.
5. Direction of the emitted photons is random	5. Direction of the emitted photons is in thedirection of incident photon
6. Emitted light is incoherent.	6. Coherent radiation is emitted.
7. This process was postulated by Bohr.	7. This process was postulated by Einstein.

Einstein's A and B Coefficients



A blackbody at a temperature 'T' emits radiation that interacts with the atoms in the blackbody



Radiative processes that affect the number of atoms at energy E_1 and E_2. The two emission processes remove atoms from level E_2 add them to level E_1. The absorption process involves transition from E_1 to E_2.

Einstein's proof for the existence of stimulated emission grew out of this desire to understand the basic mechanism in the interaction between electromagnetic radiation and matter. Let us assume matter (a collection of atoms) is in thermodynamic equilibrium with black body radiation field. The atoms and the resonant radiation are contained in an enclosure at some temperature T and interact with one another. The figure shows a simplified picture of two level atoms and radiation bound inside of an arbitrary unit volume. If thermodynamic equilibrium exists, the number of atoms N_2 at energy level E_2, the number of atoms N_1 at energy level E_1, and the number of photons in the radiation field will all remain constant. This condition requires that the number of transitions from E_2 to E_1 must be equal to the number of transitions from E_1 to E_2. Thus

The number of atoms absorbing photons per second per unit volume = The number of atoms emitting photons per second per unit volume

The number of atoms absorbing photons per second per unit volume = $B_{12}\rho(\vartheta)N_1$

The number of atoms emitting photons per second per unit volume = $A_{21}N_2 + B_{21}\rho(\vartheta)N_2$

In equilibrium condition, the number of transitions from
E_2 to E_1 must be equal to the number of transitions from E_1 to E_2.

Thus

$$B_{12}\rho(\vartheta)N_1 = A_{21}N_2 + B_{21}\rho(\vartheta)N_2$$

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

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

$$\rho(\vartheta) = \frac{A_{21}}{B_{21}}\left[\frac{1}{\frac{N_1}{N_2}\frac{B_{12}}{B_{21}} - 1}\right]$$

Einstein proved thermodynamically that the probability of absorption is equal to the probability of stimulated emission.

i.e $B_{12} = B_{21}$

Then we have

$$\rho(\vartheta) = \frac{A_{21}}{B_{21}}\left[\frac{1}{\frac{N_1}{N_2} - 1}\right]$$

The equilibrium distribution of atoms among different energy states is given by Boltzmann's law according to which

$$\frac{N_2}{N_1} = \frac{e^{-E_2/kT}}{e^{-E_1/kT}}$$

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

$$= e^{-(h\vartheta)/kT}$$

$$\rho(\vartheta) = \frac{A_{21}}{B_{21}}\left[\frac{1}{e^{h\vartheta/kT} - 1}\right]$$

This is the formula for the energy density of photon of frequency ϑ in equilibrium with atoms in energy states 1 and 2, at temperature T.

Comparing it with Planck's radiation formula

$$\rho(\vartheta) = \frac{8\pi h\vartheta^3}{c^3}\left[\frac{1}{e^{h\vartheta/kT} - 1}\right]$$

thus we get,

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

This gives the relationship between Einstein's A and B coefficients.

Significance of Einstein's A and B Coefficients

1. Einstein coefficients A_{21}, B_{21} and B_{12} are all interrelated. If one is known, by measurement or calculation, all are known.

2. The stimulated emission coefficient B_{21} and the absorption coefficient B_{21}, are equal, at least for the case of non degenerate energy states.

The rates $R_{st} = B_{21}\rho(\vartheta)N_2$ and $R_{abs} = B_{12}\rho(\vartheta)N_1$ differ depending upon the population densities N_2 and N_1. If N_2 is greater than N_1 and a radiation field interacts with the atoms, stimulated emission exceeds absorption and photos will be added to the field.

If N_1 is greater than N_2, absorption exceeds stimulated emission and photons will be removed from the field.

$N_2 > N_1$ leads to increase in $\rho(\vartheta)$ and hence, amplification.

$N_1 > N_2$ leads to decrease in $\rho(\vartheta)$ and hence, attenuation.

For laser to operate, it is necessary that $N_2 > N_1$. This is the condition of population inversion. Without population inversion laser action cannot occur.

3. Since $\frac{B_{21}}{A_{21}}$ is proportional to the reciprocal of the cube of the frequency ϑ, the higher the frequency (shorter the wavelength) the smaller B_{21} becomes in comparison with A_{21}. Since B_{21} is related to stimulated emission and A_{21} is related to spontaneous emission it would seem that lasers of short wavelength radiation would be more difficult to build and operate.

4. Although the relations A_{21}, B_{21} and B_{12} were derived based on the condition of thermal equilibrium, they are valid and hold under any condition. The laser while operating is hardly an enclosure in thermodynamic equilibrium. Yet A and B coefficient relationships hold good because they are characteristic of the atom, are equally valid whether the atom is on the intense radiation field of a laser cavity or in a hot furnace that can be treated as a blackbody in thermodynamic equilibrium.

So, two important ideas emerge from a review of Einstein's study of the interaction of electromagnetic radiation with matter which is useful for the successful operation of laser.

i) Stimulated emission that leads to light amplification.

ii) Population inversion of atoms in energy levels must be achieved if the stimulated emission process producing coherent photons is to outrival the absorption process removing photons.