Engineering Physics: PHY110

LASER AND APPLICATIONS: UNIT-2

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What is Light?

- Light is a kind of <u>energy</u> released by an <u>atom</u>. Light is made up of very small particles called photons having energy hv.

- Einstein believed that light is a particle or photon and the flow of photons is a wave. Light is obtained from various sources like candles, lamps and sun-rays.

- Candles and lamps are called as the man made light sources and sun-rays is called natural light source.

- The first reliable artificial light source (incandescent light bulb) was invented in 1879 by Thomas Edison.

E1

E2

E3

Nucleus

Electrons
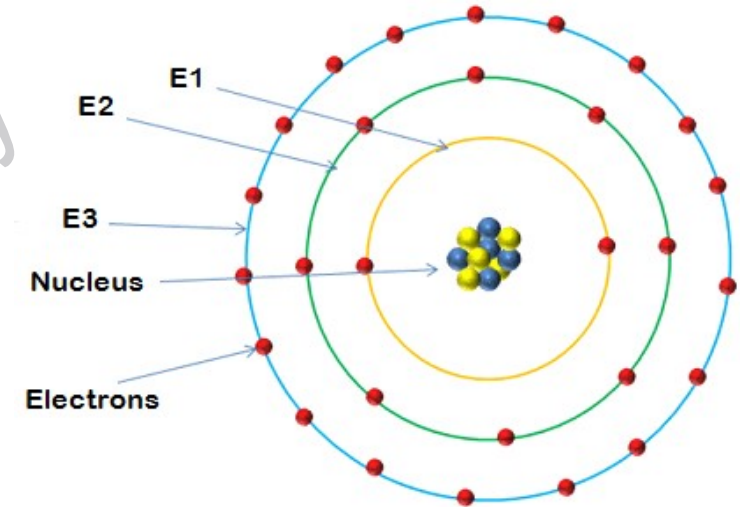
What is LASER ?

- LASER stands for Light Amplification by Stimulated Emission of Radiation. Laser is a device that amplifies or increases the intensity of light and produces highly directional light.

- Laser light is different from the conventional light. Laser light has extra-ordinary properties which are not present in the ordinary light sources like sun and incandescent lamp.

- In 1917, Einstein gave the theoretical basis for the development of laser, when he predicted the possibility of stimulated emission.

- In 1954, using Einstein's idea, C.H. Townes and his co-workers invented a device called MASER (Microwave Amplification by Stimulated Emission of Radiation).

- In 1960, Theodore Harold Maiman built the first laser device.
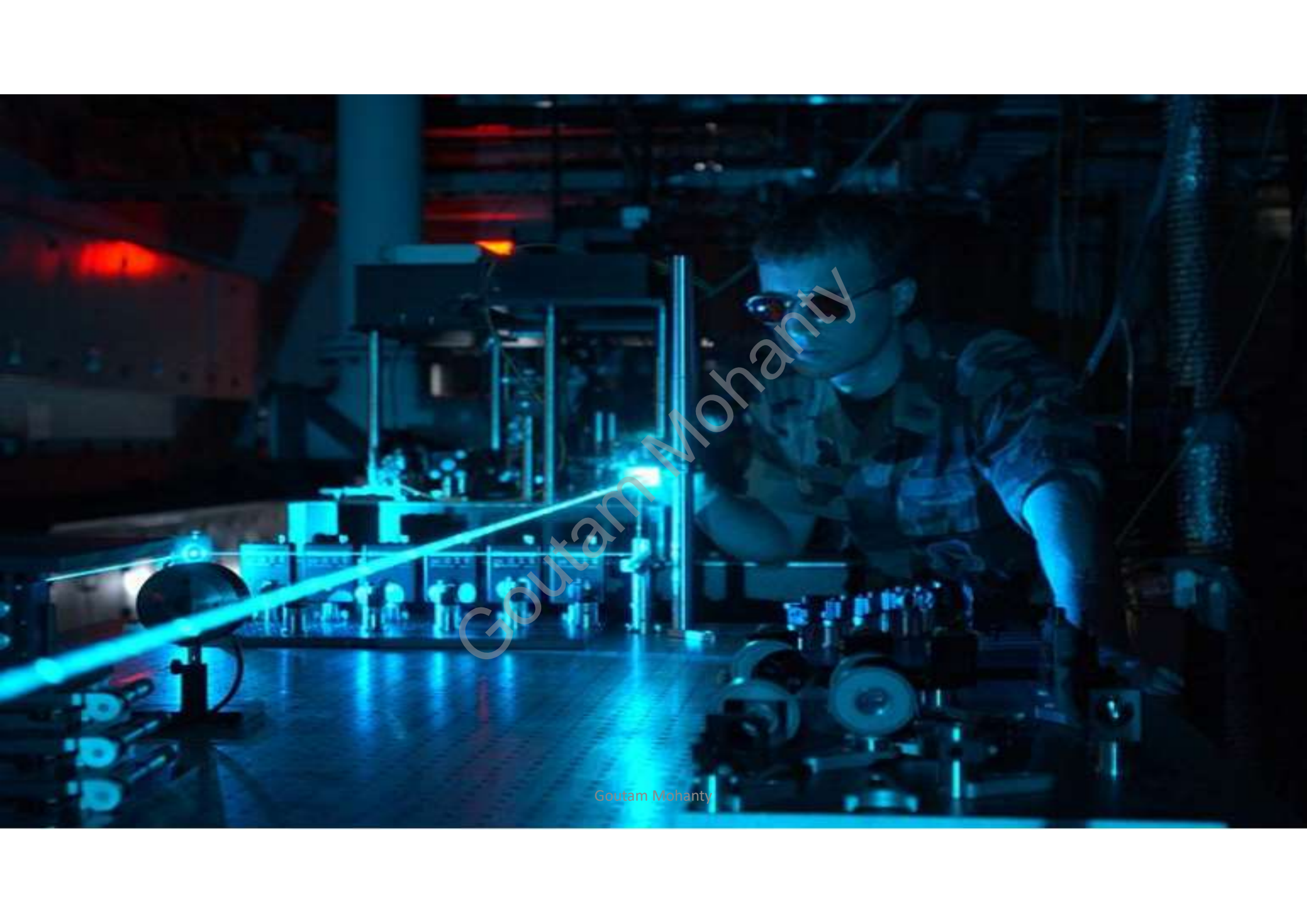
Characteristics of Laser:

Laser light has four unique characteristics that differentiate it from ordinary light: These are

- Coherence
- Directionality
- Monochromatic
- High intensity

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Coherence:

- In Laser, the wavelengths of the laser light are in phase in space & time.

- Light generated by laser is highly coherent.

- Because of this coherence, a large amount of power can be concentrated in a narrow space.

- TWO types:

  ✓ Spatial/ Transverse Coherence

  ✓ Temporal/ Longitudinal Coherence

Incoherent light

Coherent light waves

Coherent light

Incoherent light
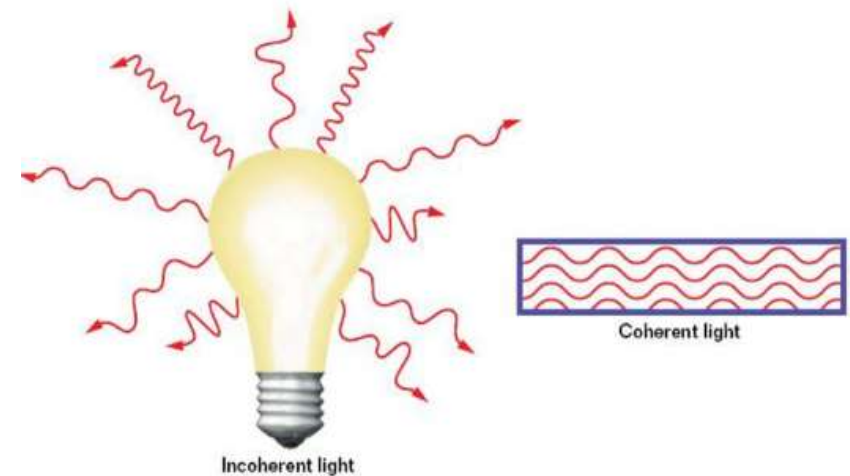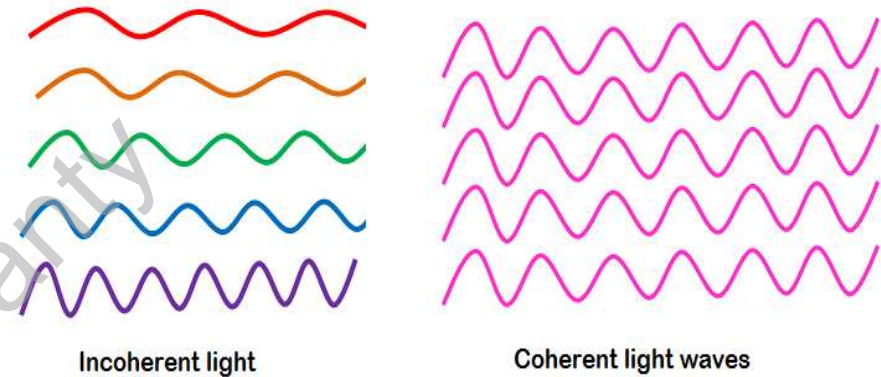
Types of Coherence:

Temporal or Time coherence:

- If the phase difference of waves crossing the two points lying along the direction of propagation of the beam is time dependent, then a beam of light is said to possess temporal or time coherence.

- This coherence is also known as longitudinal coherence.

- Average Length of wave trains is called Coherent Length (L_c). i.e. $L_c = c.T_0$

- Natural line width, $\Delta\lambda = \lambda^2 / L_c$
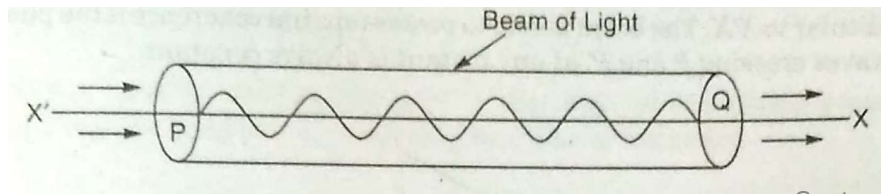
Spatial Coherence:

- A laser beam is said to possess spatial coherence, if the phase difference of the waves crossing the two points lying on a plane perpendicular to the direction of propagation of the beam is time-independent.

- This coherence is also termed as transverse or lateral coherence.

Beam of Light

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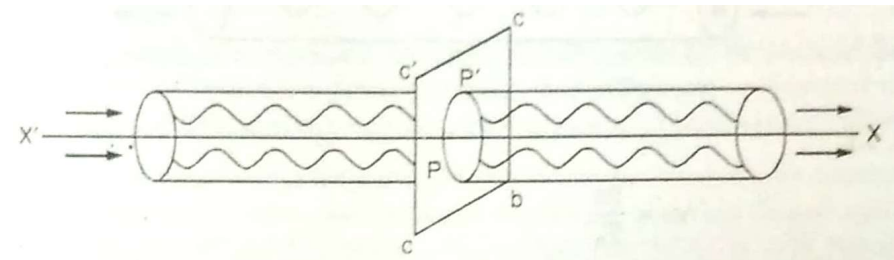
Directionality

- In conventional light sources (lamp, sodium lamp and torchlight), photons will travel in random direction. Therefore, these light sources emit light in all directions.

- On the other hand, in laser, all photons will travel in same direction. Therefore, laser emits light only in one direction. This is called directionality of laser light. The width of a laser beam is extremely narrow. Hence, a laser beam can travel to long distances without spreading.

- If an ordinary light travels a distance of 2 km, it spreads to about 2 km in diameter. On the other hand, if a laser light travels a distance of 2 km, it spreads to a diameter less than 2 cm.

2 Km

2 Km

Ordinary light

Laser light
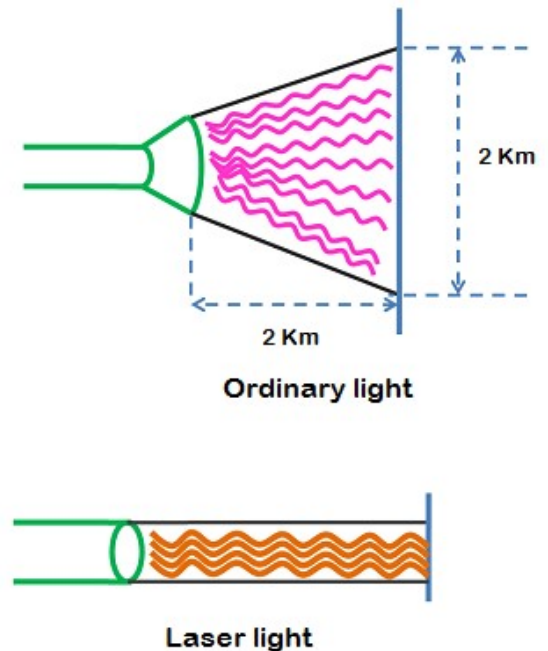
Monochromatic

- Monochromatic light means a light containing a single colour or wavelength.

- In laser, all the emitted photons have the same energy, frequency, or wavelength. Hence, the light waves of laser have single wavelength or colour.

- Therefore, laser light covers a very narrow range of frequencies or wavelengths.

High Intensity

- The intensity of light is the energy per unit time flowing through a unit normal area.

- In laser, the light spreads in small region of space and in a small wavelength range. Hence, laser light has greater intensity when compared to the ordinary light.

- Example, If you look at a 100 Watt lamp filament from a distance of 30 cm, the power entering your eye is less than 1/1000 of a watt. However, in Laser, a 1 Watt laser would appear many thousand times more intense than 100 Watt ordinary lamp.

Interaction of external energy with atomic energy states:

- Different types of radiations:

Absorption · Spontaneous Emission · Stimulated Emission

E1: Lower Energy State, E2: Higher Energy State

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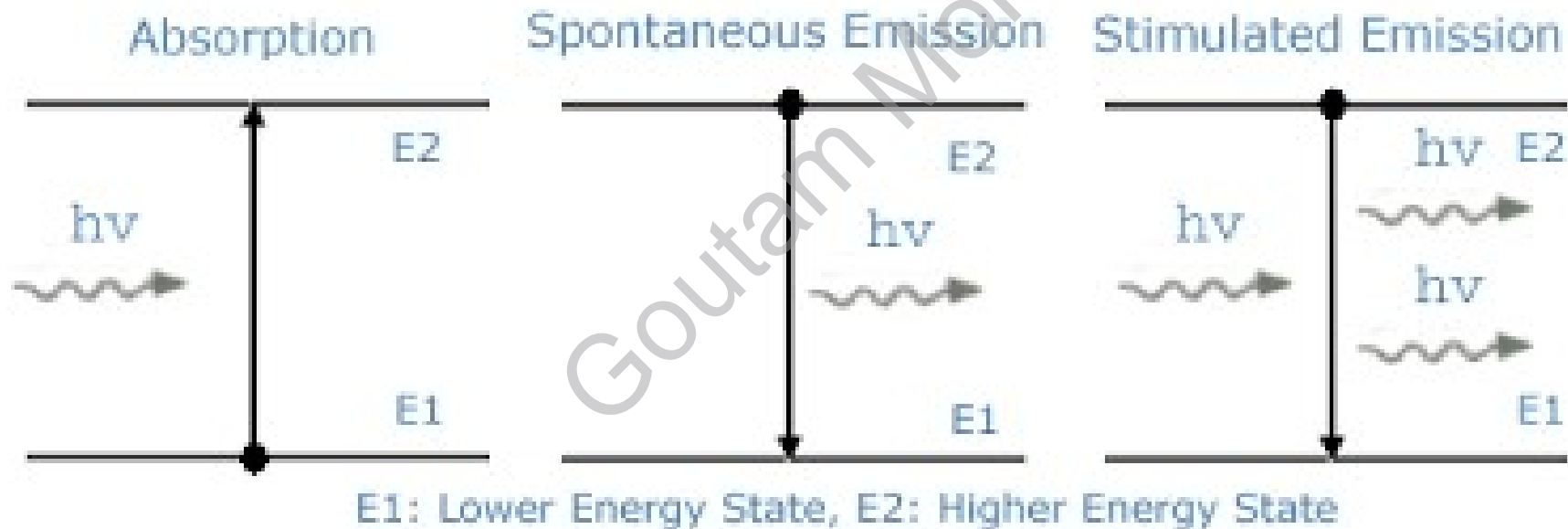
Absorption:

➤ The process of absorbing energy from photons is called absorption of radiation.

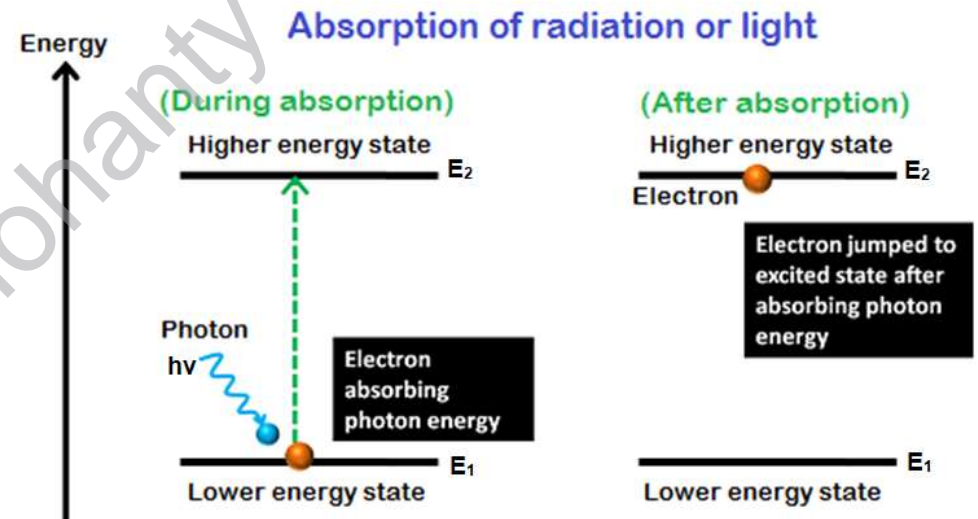➤ If an atom is initially in a lower state 1, it can rise to a higher state 2 by absorbing a quantum of radiation (Photon) of frequency v given by

$$v = \frac{E_2 - E_1}{h}$$

Where E1 and E2 are the energies Of the atom in the states 1 and 2 respectively.

➤ This process is known as absorption of radiation.

Absorption of radiation or light

(During absorption)

Higher energy state ——— E_2

Photon hv

Electron absorbing photon energy

——— E_1
Lower energy state

(After absorption)

Higher energy state ——— E_2
Electron

Electron jumped to excited state after absorbing photon energy

——— E_1
Lower energy state

- The probable rate of occurrence of the absorption transition 1→2 depends on the properties of states 1 and 2 and is proportional to the energy density u(v) of the radiation of frequency v incident on the atom.

- Thus, $P_{12} = B_{12}u(v)$ where B_{12} is proportionality constant and is known as Einstein's coefficient of radiation.

Spontaneous Emission:

➢ The process by which excited electrons emit photons while falling to the ground level or lower energy level is called spontaneous emission.

➢ Consider an atom initially in the higher (excited) state 2. Excited state with higher energy is inherently unstable, hence atom in excited state does not stay for longer time and it jumps to the lower energy state 1 emitting a photon of frequency v. This is spontaneous emission of radiation.

➢ If there is an assembly of atoms, the radiation emitted spontaneously by each atom has a random direction and a random phase and is therefore incoherent from one atom to another.

➢ The probability of spontaneous emission 2➔ 1 is determined only by the properties of states 2 and 1. This is denoted by
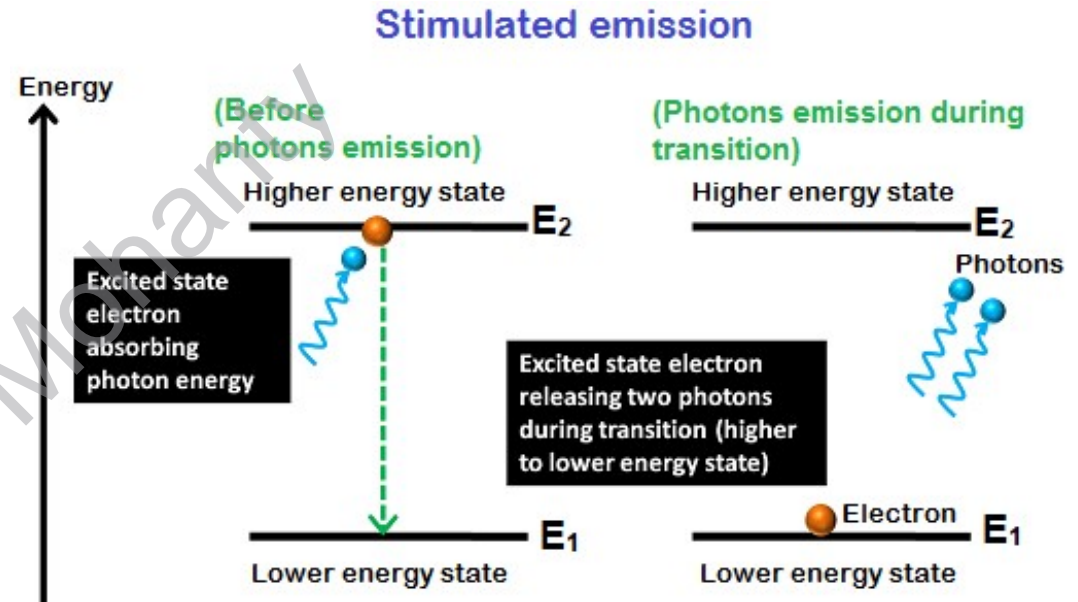
$$P_{21}=A_{21}$$

Where A_{21} is known as 'Einstein's coefficient of spontaneous emission of radiation'. In this case the probability of spontaneous emissions is independent of it.

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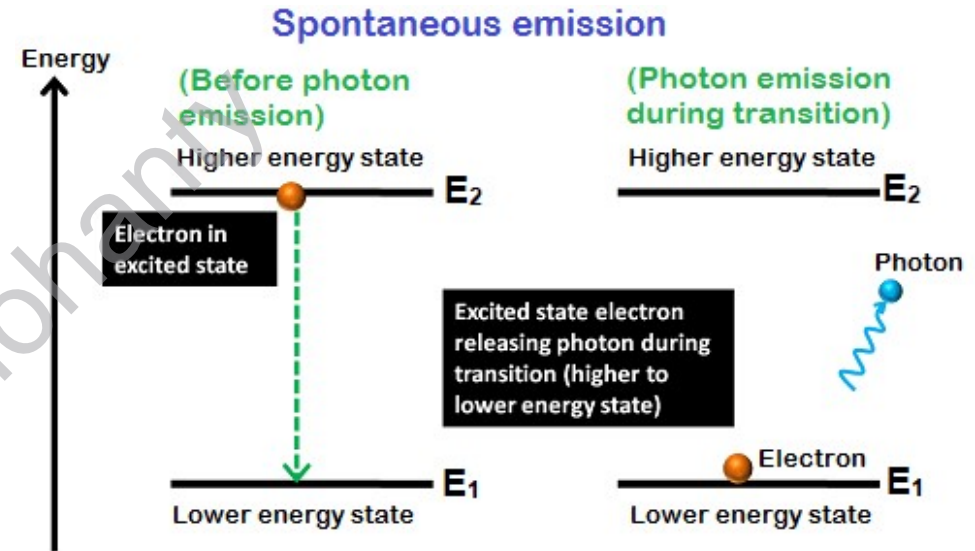
Stimulated (Induced)emission:

- The process by which electrons in the excited state are stimulated to emit photons while falling to the ground state or lower energy state is called stimulated emission.

- According to Einstein, an atom in an excited energy state may, under the influence of the electromagnetic field of a photon of frequency v incident upon it, jumps to a lower energy state, emitting an additional photon of same frequency (v). Hence two photons, one original and the other emitted, move together. This is stimulated (or induced) emission of radiation.

- The direction of propagation, phase, energy and state of polarisation of the emitted photon is exactly same as that of the incident stimulating photon, so the result is an enhanced beam of coherent light.

Stimulated emission

(Before photons emission)

(Photons emission during transition)

Higher energy state E_2

Excited state electron absorbing photon energy

Higher energy state E_2

Photons

Excited state electron releasing two photons during transition (higher to lower energy state)

Electron E_1

Lower energy state E_1

Lower energy state

Energy

- The probability of stimulated emission transition 2→1 is proportional to the energy density u(v) of the stimulating radiation and is given by

$$P_{21}=B_{21}\,u(v)$$, Where B_{21} is the 'Einstein's coefficient of stimulated emission of radiation'

- The total probability for an atom in state 2 to drop to the lower state 1 is therefore

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

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Relation bet^n Einstein's co-efficient:

- Let us consider an assembly of atoms in thermal equilibrium at temperature T with radiation of frequency v and energy density u(v). Let N_1 and N_2 be the number of atoms in states 1 and 2 respectively at any instant. The number of atoms in state 1 that absorb a photon and rise to state 2 per unit time is

$$N_1 P_{12} = N_1 B_{12}\, u(v)$$

- The number of atoms in state 2 that drop to state 1, either spontaneously or under stimulation, emitting a photon per unit time is

$$N_2 P_{21} = N_2 [A_{21} + B_{21}\, u(v)]$$

- For equilibrium, the absorption and emission must occur equally.

$$\text{i.e. } N_1 P_{12} = N_2 P_{21}$$

- Relation bet. Einstein's co-efficient

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

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

$$u(v) = \frac{A_{21}}{B_{21}} \frac{1}{\dfrac{N_1}{N_2}\left(\dfrac{B_{12}}{B_{21}}\right) - 1}$$

- Einstein proved thermodynamically that the probability of (stimulated) absorption is equal to the probability of stimulated emission i.e.

$$B12 = B21$$

- Then, we have

$$u(\nu) = \frac{A_{21}}{B_{21}} \frac{1}{\left(\dfrac{N_1}{N_2} - 1\right)}$$

- The equilibrium distribution of atoms among different energy states is given by using Boltzmann's Distribution Law according to which

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

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

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- Consequently, $$u(\nu) = \frac{A_{21}}{B_{21}} \frac{1}{e^{\frac{h\nu}{KT}} - 1}$$

- This is the energy density of photon of frequency v in equilibrium with atoms in energy states 1 and 2, at temperature T. Comparing it with the Planck's radiation formula (according to which the energy density of the black body radiation of frequency v at temperature T is given as:

$$u(\nu) = \frac{8\pi h\nu^3}{c^3} \frac{1}{e^{\frac{h\nu}{KT}} - 1}$$

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

- This shows that the ratio of Einstein's coefficient of spontaneous emission to the Einstein's coefficient of absorption of radiation is proportional to cube of the frequency (v3). This means that the probability of spontaneous emission increases rapidly with the energy difference between two states.
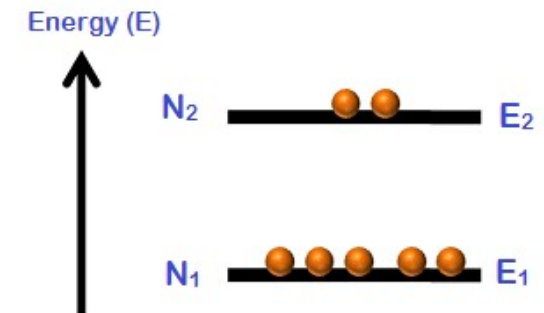
Population Inversion

- Population inversion is the process of achieving greater population of higher energy state as compared to the lower energy state. Population inversion technique is mainly used for light amplification. The population inversion is required for laser operation.

- Consider a group of electrons with two energy levels E_1 and E_2.

- The number of electrons per unit volume in an energy state is the population of that energy state.

- Population inversion cannot be achieved in a two energy level system. Under normal conditions, the number of electrons (N_1) in the lower energy state (E_1) is always greater as compared to the number of electrons (N_2) in the higher energy state (E_2).

$$\text{i.e. } N_1 > N_2$$

- When temperature increases, the population of higher energy state (N_2) also increases. However, the population of higher energy state (N_2) will never exceeds the population of lower energy state (N_1).

- At best an equal population of the two states can be achieved which results in no optical gain. $$\text{i.e. } N_1 = N_2$$

Energy (E)

N_2 ——————— E_2

N_1 ——————— E_1

- Therefore, we need 3 or more energy states to achieve population inversion. The greater is the number of energy states the greater is the optical gain.

- There are certain substances in which the electrons once excited; they remain in the higher energy level or excited state for longer period. Such systems are called active systems or active media which are generally mixture of different elements.

- When such mixtures are formed, their electronic energy levels are modified and some of them acquire special properties. Such types of materials are used to form 3-level laser or 4-level laser.

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3-level laser:

- Consider a system consisting of three energy levels E_1, E_2, E_3 with N number of electrons. Let N_1 be the number of electrons in the energy state E_1, N_2 be the number of electrons in the energy state E_2 and N_3 be the number of electrons in the energy state E_3.

- We assume that $E_1 < E_2 < E_3$.

- The energy level E_1 is known as the ground state or lower energy state and the energy levels E_2 and E_3 are known as excited states. The energy level E_2 is sometimes referred to as Meta stable state. The energy level E_3 is sometimes referred to as pump state or pump level.

- Under normal conditions, $N_1 > N_2 > N_3$. But to get laser emission or population inversion, N_2 should be greater than N_1.

- Under certain conditions, $N_2 > N_1$ is achieved. Such an arrangement is called population inversion.

- Let us assume that initially the majority of electrons will be in the lower energy state or ground state (E_1) and only a small number of electrons will be in excited states (E_2 and E_3).

- When we supply light energy which is equal to the energy difference of E_3 and E_1, the electrons in the lower energy state (E_1) gains sufficient energy and jumps into the higher energy state (E_3). This process of supplying energy is called pumping.

- The lifetime of electrons in the energy state E_3 is very small as compared to the lifetime of electrons in the energy state E_2. Therefore, electrons in the energy level E_3 does not stay for long period. After a short period, they quickly fall to the Meta stable state or energy state E_2 and releases radiation less energy instead of photons. Because of the shorter lifetime(10^{-8} sec), only a small number of electrons accumulate in the energy state E_3.

- The electrons in the Meta stable state E_2 will remain there for longer period because of its longer lifetime(10^{-3} sec). As result, a large number of electrons accumulate in Meta stable state. Thus, we can get $N_2 > N_1 > N_3$. So we can achieve population inversion between energy levels E_1 and E_2.

- After completion of lifetime of electrons in the Meta stable state, they fall back to the lower energy state or ground state E_1 by releasing energy in the form of photons. This process of emission of photons is called spontaneous emission.

- When this emitted photon interacts with the electron in the Meta stable state E_2, it forces that electron to fall back to the ground state. As a result, two photons are emitted. This process of emission of photons is called stimulated emission.

- When these photons again interacted with the electrons in the Meta stable state, they forces two Meta stable state electrons to fall back to the ground state. As a result, four photons are emitted. Likewise, a large number of photons are emitted.

- As a result, millions of photons are emitted by using small number of photons. Thus, light amplification is achieved by using population inversion method. The system which uses three energy levels is known as 3-level laser.

- Drawbacks: In a 3-level laser, at least half the population of electrons must be excited to the higher energy state to achieve population inversion. Therefore, the laser medium must be very strongly pumped. This makes 3-level lasers inefficient to produce photons or light.

Population inversion in 3-level laser

① Normal distribution of electrons

E₃

E₂

E₁

Absorption

$N_1 > N_2 > N_3$
$E_1 < E_2 < E_3$

② E₃

E₂

E₁

③ Population inversion

E₃

Non-radiative emission

E₂

E₁

④ E₃

E₂

Spontaneous emission

E₁

⑤ E₃

E₂

E₁

⑥ E₃

E₂

Stimulated emission

E₁

Electron ●
Photon ●

$N_2 > N_1 > N_3$
$E_1 < E_2 < E_3$

Level 3, E_3, N_3

R (fast, radiationless transition)

Level 2, E_2, N_2

P (pump transition)

L (slow, laser transition)

Level 1 (ground state), E_1, N_1

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