Content Outlines

❑ Quantum Nature of light

❑ Photon-Electron Interactions

❑ Thermal Equilibrium & Einstein Prediction

❑ Einstein Relations & Lasing Conditions

❑ Population Inversion & Pumping Methods

❑ Lasing Schemes & Laser Classification

Nature of Light

What is light ? What's its structure ? What does it consist of ?

How to imagine the wave-particle duality.

➤ **Particles** or **Waves** **?**

❖ Stream of minute particles - Corpuscles
- Issac Newton - early 17th Century
- Could explain Reflection, Refraction
- Could not Explain Diffraction, Interference
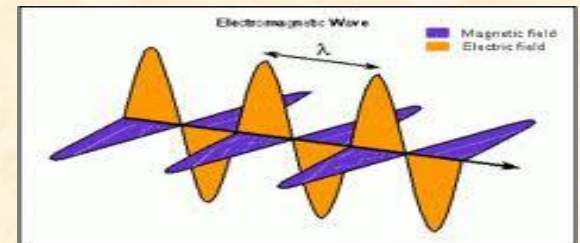
❖ Light as wave motion
- Huygen Principle (1678)
- Could explain diffraction , Interference fringes
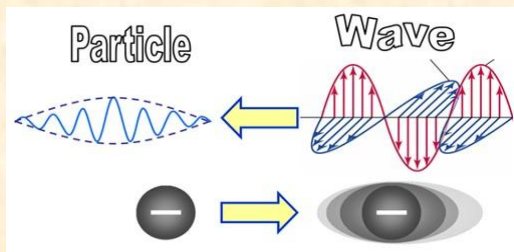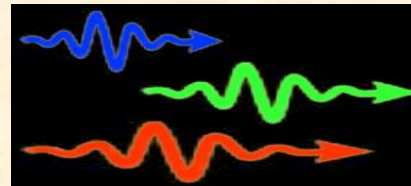- Fresnel (1815) ; Light is a Wave, Polarized
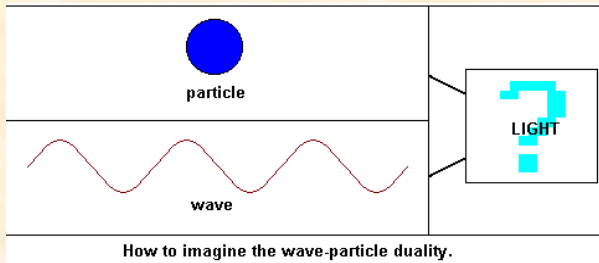
❖ Electromagnetic nature of light (1864)
- Maxwell Equations
- Polarization phenomenon
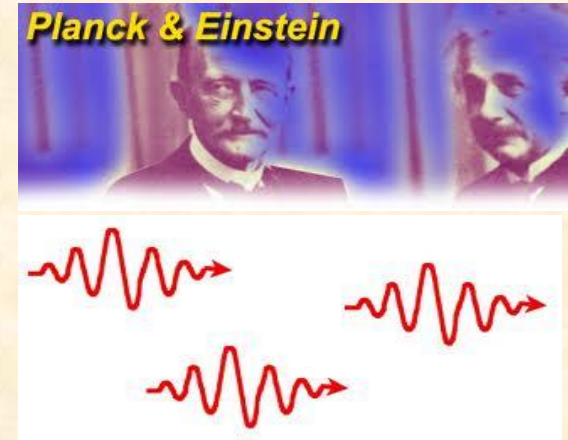- Electromagnetic Spectrum

❖ Quantum Theory of Light
- Albert Einstein (1905)
- Light " Quanta or photons"

❑ **DUAL NATURE OF LIGHT**

☞ **One can imagine a particle, and one can imagine a wave.**

Quantum Nature of Light

Planck & Einstein

❑ 1900, Max Planck; light consists of discrete bundles or chunks each of energy
$$\Rightarrow \text{“\textbf{Quanta}”}$$

❑ 1905 , Einstein refined the Quantum hypothesis and gave the name **"photon"** to the quantum of light energy

▪ Photon represents minimum energy unit of light. It is localized in small volume of space and remains localized as it moves away from the light source.

Energy of photon; $E = h\nu$

▪ Light energy '$\rho(\nu)$' emitted by a source must be integral multiple of photon energy $\Rightarrow$ **Quantization**

$$\rho(\nu) = n\,h\nu \quad ; \quad n = 1, 2, 3, \ldots$$

■ Interaction of radiation with matter is better explained using concept of photon rather than by the wave concept.

➢ *Energy exchange can take place only at certain discrete values for which the photon energy is the minimum energy unit that light can give or accept.*

❖ Wave picture of light is <u>Classical</u> and Photon picture is Quantum Mechanical.
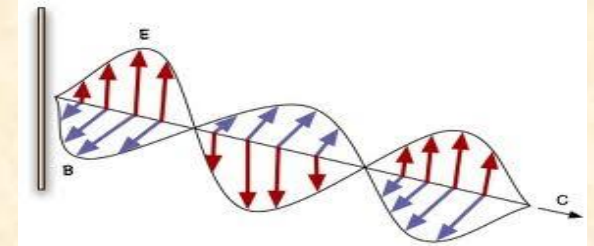
❖ **Laser- inherently a Quantum Mechanical device $\Rightarrow$ its operation depends on the existence of photons.**

Interaction of Light with Matter

❑ **Maxwell**: Light belongs to group of EM waves; propagate with speed 'c' in vacuum.

➢ Frequency and wavelength related through

$$c = \nu \, \lambda$$

❑ Light incident on a substance, may undergo **reflection**, **transmission**, **absorption** and **scattering** to varying degrees depending on nature of substance.

➢ Results in loss of energy and hence decrease in light intensity with distance

⟹ **Absorption** or **Attenuation**
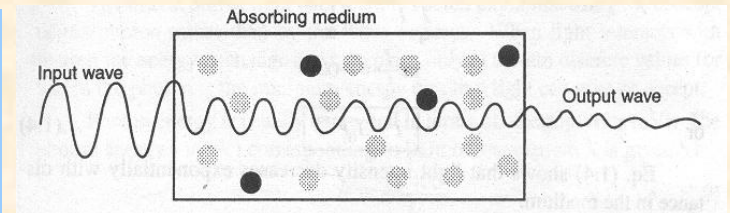
Attenuation of light in an absorbing medium

❖ **Attenuation Coefficient (α)** - A measure of absorption of light in an optical medium.

➢ Is different for different medium and is a function of incident energy.

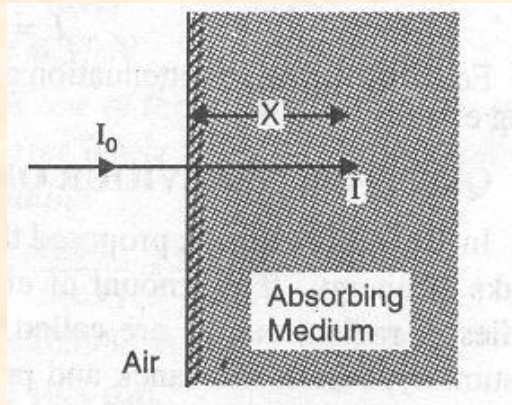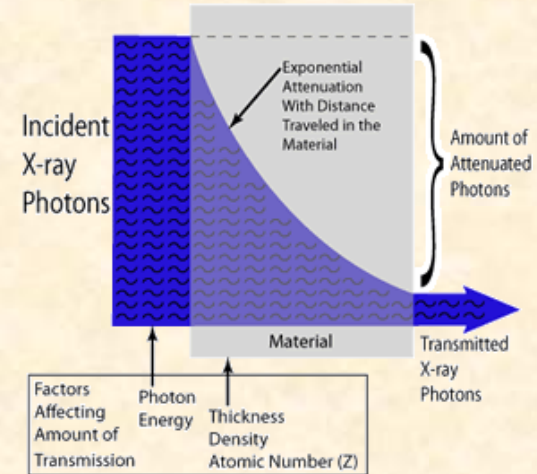# ▪ Intensity of light (I) at any distance 'x' in medium

$$I = I_0\, e^{-\alpha x}$$

➢ **Light intensity decreases exponentially with distance in the medium.**

▪ When a light beam encounters obstacles, which have sizes smaller than a wavelength ($d \ll \lambda$), it is redirected into different direction $\Rightarrow$ **Scattering**

▪ Scattering phenomenon also causes attenuation of energy and is described by exponential law

$$I = I_0\, e^{-\alpha_s x} \qquad ; \alpha_s \text{ is the } \textit{Scattering Coefficient}$$

❖ **Attenuation of light due to both <u>Absorption</u> and <u>Scattering</u> effects is**

$$I = I_0\, e^{-(\alpha_a + \alpha_s) x}$$

Distribution of Atoms

Energy Levels: Permitted orbits with specific amount of energy;

- **Ground State**
- **Excited States**
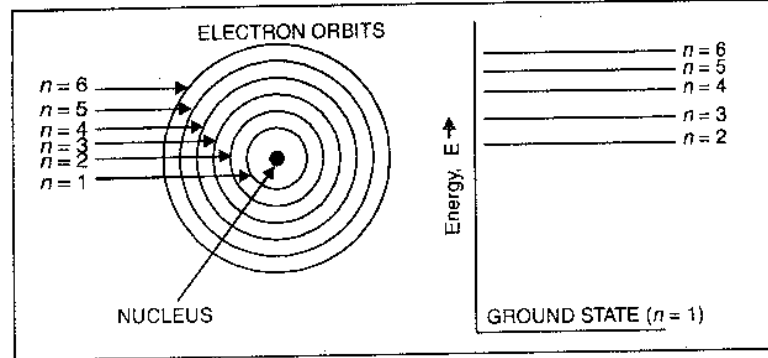
Fig. 1.3. Electron orbits and the corresponding energy levels of the hydrogen atom

- **POPULATION:** Number of atoms per unit volume that occupy a given energy state (N).

Population of an energy state depends on the temperature T, according to Boltzmann's Equation

$$N = e^{-E/KT}$$; where K is the Boltzmann's constant

❑ **Atoms distributed differently in different energy states;**

➢ tends to be at lowest possible energy level.

Thermal Equilibrium

- **At temperature above 0K**,

  - Atoms alway have some thermal energy;

  - Distributed among available energy levels according to their energy.

❖**At Thermal Equilibrium;**

➢ Population at each energy level decreases with increase of energy level,
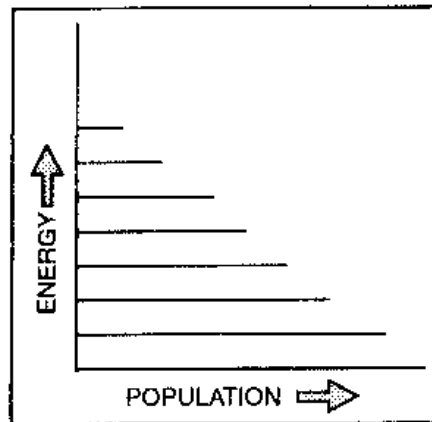
Fig. 1.4. Relative populations of energy levels as a function of energy above the ground state at thermal
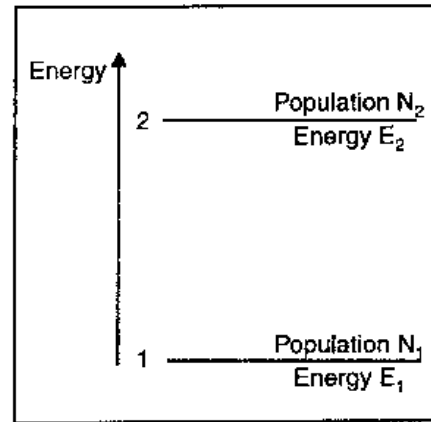
Fig. 1.5. Two energy level system.

For energy levels E_1 and E_2,

- Populations can be computed with Boltzmann's equation

$$N_1 = e^{-E_1/KT} \qquad \& \qquad N_2 = e^{-E_2/KT}$$

- Ratio of populations, N_2/N_1 is called ***Relative Population.***

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

or $\qquad N_2 = N_1 e^{-\Delta E/KT} \qquad ; \; \Delta E = E_2\text{-}E_1$

- **Relative Population** (N_2/N_1); dependent on two factors

  ➤ Energy difference $(E_2\text{-}E_1)$

  ➤ Temperature, T

❖ **At Lower Temperature;** All atoms are in the ground states.

❖ **At higher Temperature;** Atoms move to higher states

- **In a material at thermal equilibrium, more atoms are in the lower energy state than in the higher energy state.**

  - The fraction of excited atoms would be large, if the energy levels are close or temperature is very high.

In limiting case,

- When, $E_2 - E_1 \rightarrow 0$; $N_2 = N_1$

- When, $T \rightarrow \infty$; $N_2 = N_1$

Important Conclusion:

As long as the material is in thermal equilibrium, the population of the higher state cannot exceed the population of lower states.

Excitation and De-excitation

<u>Excitation:</u> *Electron in the ground state receives an amount of energy equal to the difference of energy of ground state and one of the excited states, absorbs energy and jumps to the excited state.*

- Photons of energy **$h\nu = (E_2 - E_1)$** induce electron transitions from energy level E_1 to E_2

  $\Rightarrow$ **Induced or Stimulated Absorption**
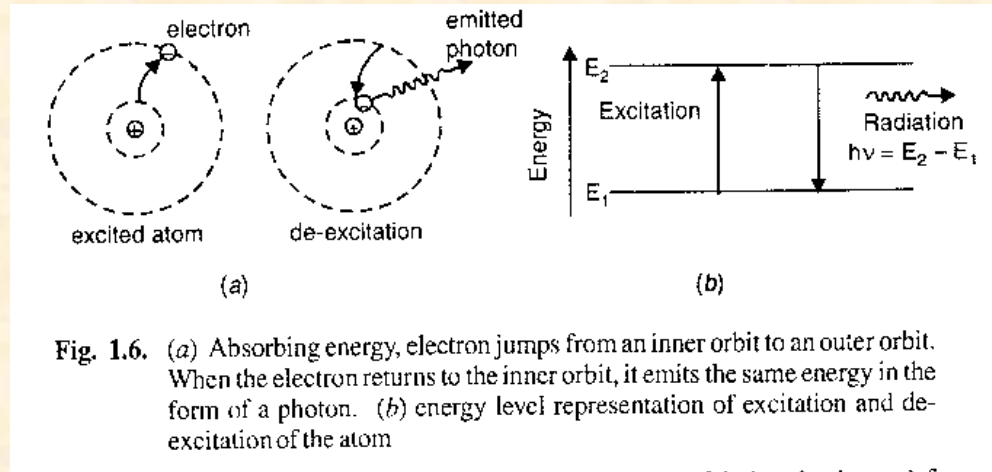
Fig. 1.6. (*a*) Absorbing energy, electron jumps from an inner orbit to an outer orbit. When the electron returns to the inner orbit, it emits the same energy in the form of a photon. (*b*) energy level representation of excitation and de-excitation of the atom

- Electron cannot stay in the excited state for a longer time.

- Has to get rid of the excess energy in order to come to the lower energy level.

  ➢ **Only mechanism is through emission of a photon.**

<u>De-excitation</u>: The excited electron emits a photon of energy, **$h\nu = (E_2 - E_1)$** and jumps from excited state to the ground state $\Rightarrow$ **Spontaneous Emission**

Einstein's Prediction
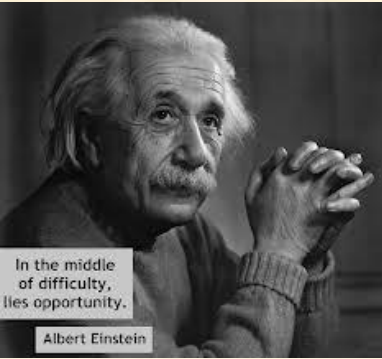
❑ **1917, Einstein predicted that there must be second emission process to establish thermodynamic equilibrium.**

▪ Atoms move to excited state under action of incident light

▪ Excited atoms tend to return randomly to the lower energy state.

▪ It is likely that a stage may be reached when all atoms are excited

➢**Violation of thermal equilibrium condition**

❖ **Einstein suggested ⇒ There could be an additional emission mechanism, by which the excited atoms can make downward transitions.**

➢Predicted that the photons in the light field induce the excited atoms to fall to lower energy state and give up their excess energy in the form of photons.

⟶ **Stimulated Emission**

Three Processes

A medium consisting of identical atoms in thermal equilibrium having;

- **Energy levels E_1 and E_2**
- **Population N_1 and N_2**

(a) Absorption

Atoms in the lower energy level E_1 absorb the incident photon and jumps to the excited state E_2

$$A + h\nu \rightarrow A^*$$

➤ **Induced** or **Stimulated absorption**

Rate of absorption

Fig. 1.7. Absorption process (a) Induced absorption (b) Material absorbs photons.

$$R_{abs} = B_{12}\,\rho(\nu)\,N_1$$

N_1 - population at lower level E_1, $\rho(\nu)$ - energy density of incident light

B_{12} - constant of proportionality ; *Einstein coefficient for induced absorption*.

➤ Indicate the probability of an induced transition from level $1 \rightarrow 2$

(b) Spontaneous Emission

- An excited atom can stay in excited level for an average lifetime τ_{sp}, it is not stimulated by any other agent during this short stay.

- Excited atom undergoes a transition to the lower energy level at its own by giving excess energy in the form of a photon

$$A^* \rightarrow A + h\nu$$
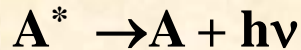
$\Rightarrow$ **Spontaneous Emission**

Rate of Spontaneous transitions

Fig. 1.8. Spontaneous emission process (a) emission (b) Material emits photons haphazardly.

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

A_{21} $-$ *Einstein coefficient for Spontaneous emission* and is a function of frequency and properties of the material.

➤ Probability of a spontaneous transition from level 2 $\rightarrow$ 1

$A_{21} = 1/\tau_{sp}$; τ_{sp} - the lifetime of spontaneous emission
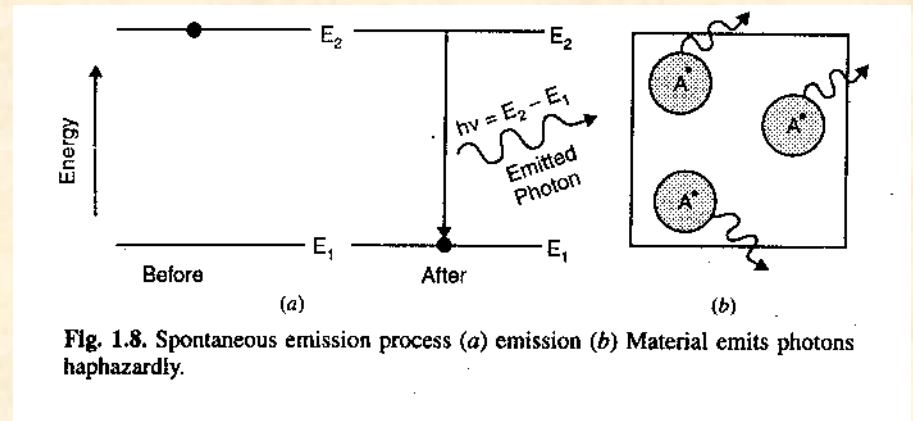
Important Features:

- No outside control

- Probabilistic in nature

- Incoherent Light

- Not monochromatic

- Lack of directionality

Incoherent Radiation:

- Results from superposition of wave trains of random phases.

(a) Chaotic (incoherent)

1
2
3
4

(b) Component waveform

(c) Resultant waveform of waves 1, 2, 3 & 4
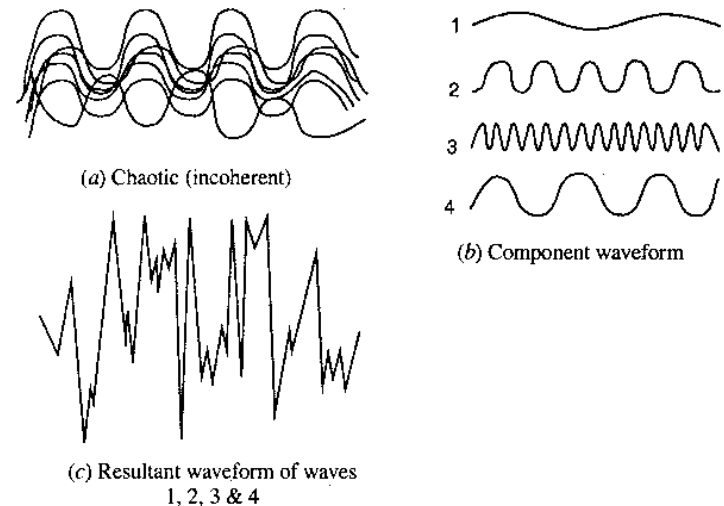
Fig. 1.9. Incoherent radiation (a) Incoherent waves (b) component wave form (c) Resultant wave.

- Net intensity is proportional to the number of radiating atoms

$$I_{Total} = N\,I$$

➤ **Dominates in conventional light sources**.

(c) Stimulated Emission

- An atom in excited state need not to **"wait"** for spontaneous emission to occur.

- If a photon with appropriate energy ($h\nu = E_2 - E_1$) interacts with excited atom, it can trigger the atom to undergo transition to the lower energy level and to emit another photon.

❖ Process of emission of photons by an excited atom through a forced transition occurring under the influence of an external agent is called **Induced or Stimulated emission.**
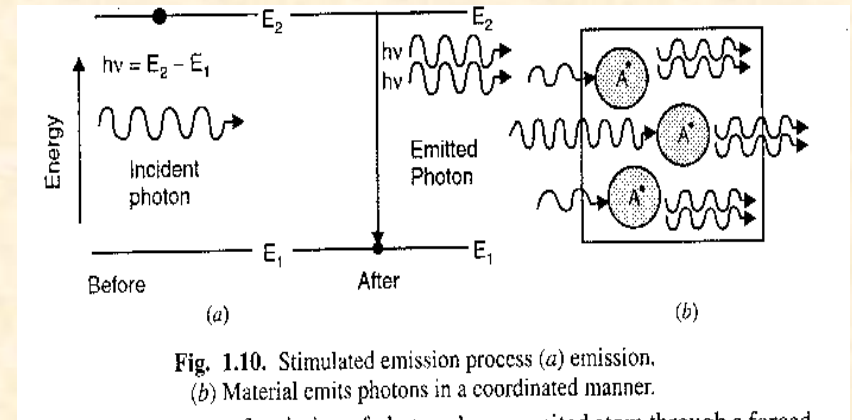
Fig. 1.10. Stimulated emission process (a) emission, (b) Material emits photons in a coordinated manner.

$$A* + h\nu = A = 2\ h\nu$$

- **Rate of stimulated emission**

$$R_{st} = B_{21}\ \rho(\nu)\ N_2 ; \qquad B_{21} - \textit{Einstein coefficient for Stimulated emission}$$

<u>Important Features</u>:

- Controllable from outside

- Emitted photon propagates in same direction as that of stimulating photon.

- Have exactly same frequency, phase and plane of polarization.

- Light produced is directional, coherent and monochromatic.
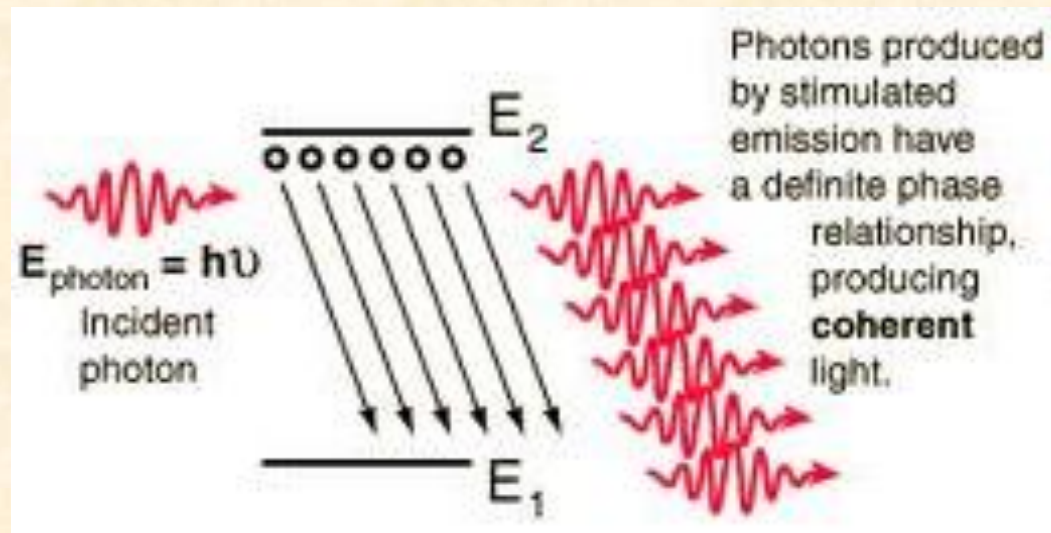
Light Amplification

- Multiplication of photons

- All in phase and travel in same direction

  - All the coherent waves interfere constructively.
  - Resultant amplitude is continuously growing.
  - Result is amplified light.
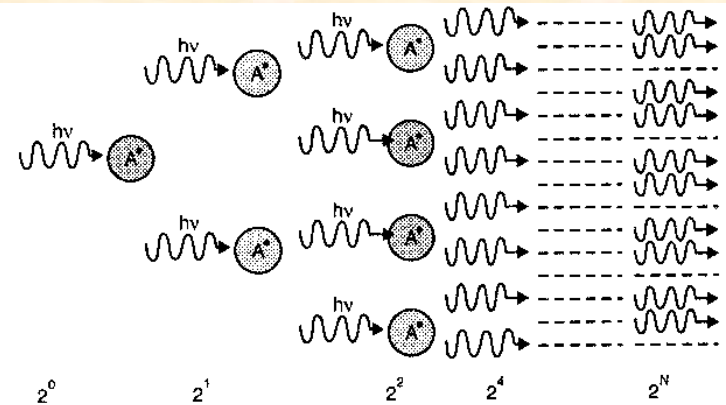
Fig. 1.11. Multiplication of stimulated photons into an avalanche

All the light waves generated in the medium are due to one initial wave and all of them are in phase. Therefore, the waves are *coherent* and

(a) Coherent radiation   (b) Component waveform   (c) Resultant waveform of waves 1, 2, & 3
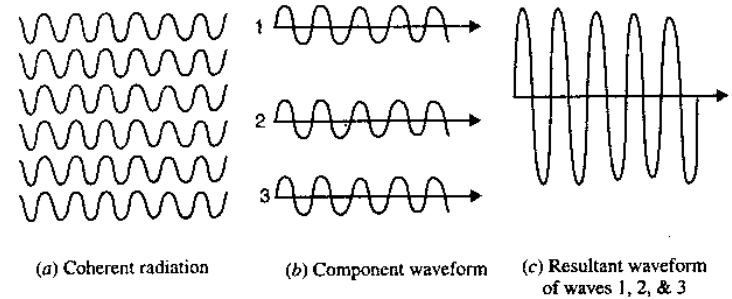
Fig. 1.12. Coherent radiation (a) coherent waves (b) component wave form (c) Resultant wave

High Intensity

- Because of constructive interference of waves, net intensity of the resultant light is proportional to square of the number of atoms emitting light

$$I_{Total} = N^2 I \quad \Rightarrow \quad \textbf{High intensity light}$$

Steady State Condition

❑ **All three processes occur together with a balance between absorption and emission**.

Fig. 1.13. Absorption and emission processes in steady state of the material.
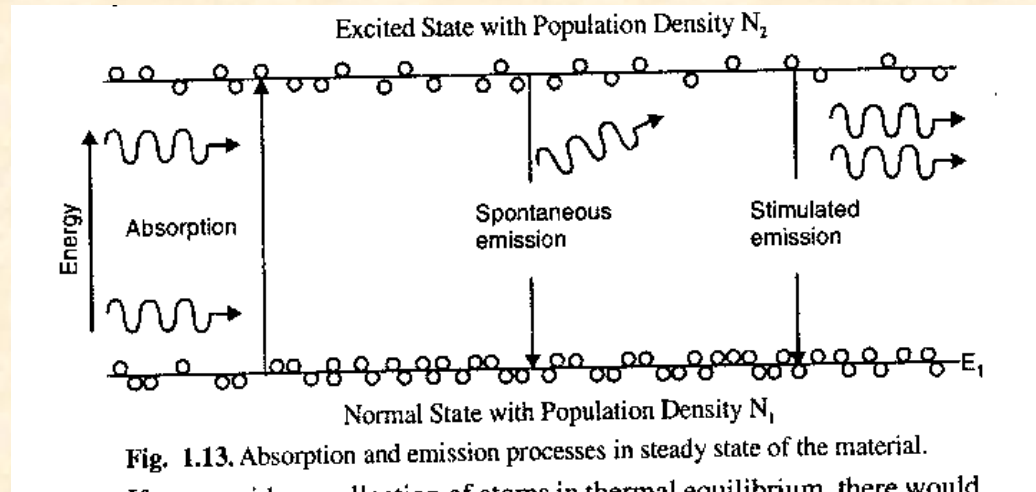
❖ **At Thermal Equilibrium**

- Spontaneously emitted photons can induce stimulated emission from another excited atom

- It is also likely to be absorbed by lower level atoms.

  ➢ Higher probability because of larger population of N_1

Einstein Relations

Under thermal equilibrium

- Mean population N_1 and N_2 in the lower and upper energy levels must remain constant

Condition requires that

- Number of transitions from $E_2 \rightarrow E_1$ must be equal to the number of transitions from $E_1 \rightarrow E_2$

$$\left.\begin{array}{l}\text{Number of atoms absorbing}\\ \text{photons per second per unit}\\ \text{volume}\end{array}\right\} = \left\{\begin{array}{l}\text{Number of atoms emitting}\\ \text{photons per second per unit}\\ \text{volume}\end{array}\right.$$

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

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

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

Dividing both the numerator and denominator on R.H.S. with $B_{12}\, N_2$

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

As $\qquad N_1/N_2 = e^{[E_2 - E_1]/KT} = e^{h\nu/KT}$

$$\therefore \qquad \rho(\nu) = \frac{A_{21}}{B_{12}}\left[\frac{1}{e^{h\nu/kT} - B_{21}/B_{12}}\right]$$

❖ To maintain thermal equilibrium, the system must release energy in the form of EM radiations. Must be identical with black body radiation and be consistent with Planck's radiation law for any value of T.

According to Planck's law

$$\rho(\nu) = (8\pi h\nu^3 \frac{\mu^3}{c^3})\frac{1}{e^{h\nu/kT} - 1} \quad ...(2)$$

$\mu \rightarrow$ refractive index of medium, $c \rightarrow$ velocity of light in free space

- Energy density $\rho(\nu)$ derived will be consistent with Planck's law only if

$$B_{21} = B_{12} \qquad \ldots (3a)$$

$$A_{21}/B_{12} = (8\pi h\nu^3 \mu^3/c^3) \qquad \ldots (3b)$$

$$\therefore \qquad B_{12} = B_{21} = \frac{c^3}{8\pi h\upsilon^3\mu^3} A_{21} \qquad \ldots(4)$$

- **Equations (3a) and (3b) are known as Einstein relations and Eqn.(4) gives the relationship between A and B coefficients.**

❖ **EQN.(3a) $\Rightarrow$ Coefficients for absorption and stimulated emission are numerically equal.**

➢ When an atom with two energy levels is placed in the radiation field, the probability for an induced absorption is equal to the probability for a stimulated emission.

❖ **EQN. (3b)** $\Rightarrow$ Ratio of coefficients of spontaneous versus stimulated emission is proportional to the third power of frequency of radiation.

➢ **Difficult to achieve laser action in higher frequency; X-rays.**

Conditions for Large Stimulated Emissions

❑ **Key to Laser Action → Existence of Stimulated Emission**

❖ In practice, absorption and spontaneous emission always occur together with stimulated emission.

❖ **Determine the conditions under which the number of stimulated emissions can be made larger than other two processes?**

A) Ratio of Stimulated transitions to Spontaneous transitions

$$R_1 = \frac{\text{Stimulated transitions}}{\text{Spon tan eous transitions}} = \frac{B_{21}\rho(\nu)N_2}{A_{21}N_2} = \left(\frac{B_{21}}{A_{21}}\right)\rho(\nu)$$

Using value of $\rho(\nu)$ from Planck's law, we get

$$R_1 = \frac{B_{21}}{A_{21}}\left[\frac{8\pi h\upsilon^3\mu^3}{c^3}\frac{1}{e^{h\upsilon/kT}-1}\right]$$

From Einstein relations, $\quad \dfrac{B_{21}}{A_{21}} = \dfrac{B_{12}}{A_{21}} = \dfrac{c^3}{8\pi h\upsilon^3\mu^3}$

$$R_1 = \left(\frac{c^3}{8\pi h\nu^3 \mu^3} \right) \left[\frac{8\pi h\upsilon^3 \mu^3}{c^3} \frac{1}{e^{h\upsilon/kT} - 1} \right] = \frac{1}{e^{h\upsilon/kT} - 1}$$

❖ **If we assume $\nu = 5 \times 10^{14}$ Hz (yellow light) and T=2000K, the value of $h\nu/kT$ is 11.99.**

$$\therefore \qquad R_1 = \frac{1}{e^{11.99} - 1} = 6 \times 10^{-6}$$

➢ **Shows that in the optical region spontaneous emissions dominate over the stimulated emissions.**

☞ **For large number of stimulated emissions, the light field density $\rho(\nu)$ present within the material is required to be enhanced.**

B) Ratio of Stimulated transitions to Absorption transitions

$$R_2 = \frac{\text{Stimulated transitions}}{\text{Absorption transitions}} = \frac{B_{21}\rho(\nu)N_2}{B_{12}\rho(\nu)N_1}$$

As, $B_{21} = B_{12}$ $\qquad \therefore \qquad R_2 = \frac{N_2}{N_1}$

- **At Thermodynamic Equilibrium, $N_2/N_1 <<< 1$**

  - ➤ **Absorption transitions overwhelm Stimulated transitions** $\Rightarrow$ A photon of light field on hitting a medium has a much higher probability of being absorbed in the ground state than of stimulating an excited atom.

- If on the other hand, **$N_2 > N_1$,** photons are more likely to cause stimulated emission than absorption.

  - ➤ To achieve more stimulated emissions, the population N_2 of the excited state should be made larger than the population N_1 of the lower energy state.

- ❑ **Two conditions to be satisfied for Stimulated emissions to overwhelm the Spontaneous emissions are:**

  - ▪ Population of excited level should be greater than that at the lower energy level and

  - ▪ Radiation density in the medium should be very large.

Condition for Light Amplification

❖ **A beam of light propagating through a material medium may absorb or produce more photons.**

➢ Since the probabilities of absorption and stimulated emissions are same, both **attenuation** and **amplification** of the light beam occur simultaneously.

➢ **Amplification can predominate only if there are more atoms in the higher level than in the lower level**.

❖ As the beam travels through the medium, some photons are absorbed due to absorption transitions and some photons are generated due to emission transitions $\Rightarrow$ Difference will decide loss or gain

▪ Let 'α' be the absorption coefficient of the medium, the intensity, I after traveling distance 'x' in medium is

$$I = I_0 \, e^{-\alpha x}$$

$\Rightarrow$ **Light intensity decreases exponentially with distance in the medium**

- **Absorption coefficient, "α"** can be related to the difference in populations; (N_1-N_2) of two energy levels by computing the net loss of photons from the light beam, which is the difference between the net rates of absorption and stimulated emission transitions.

$$\alpha = (N_1 - N_2)\frac{B_{12}h\upsilon}{v} \qquad ; \ v \ (= c/\mu) \text{ is the velocity of light in medium}$$

❖ **For a material in thermal equilibrium, $N_1 > N_2$ and α is always positive.**

❑ **If N_2 is somehow made greater than N_1, then 'α' becomes a negative quantity and the relation takes the form**

$$I \ = \ I_0 \, e^{(-\alpha)x} \ = I_0 e^{\gamma x}$$

where γ is referred as the **gain coefficient** per unit length

➢ **Gain coefficient 'γ'** is a positive quantity ⇒ implies that the intensity grows exponentially as the light beam travels through the medium. This is clearly **Amplification of light**.

Gain Coefficient

$$\gamma = (N_2 - N_1)\frac{B_{12}h\upsilon}{v}$$ $\Rightarrow$ **Condition for Amplification**

'γ' will be positive if $(N_2 - N_1) > 0$, i.e. $\boxed{N_2 > N_1}$

➢ **Population Inversion**, because it is the inverse of the normal situation.

☞ **Conditions for γ (Gain Coefficient) $\Rightarrow$ *Population inversion is a necessary condition to be satisfied for causing the amplification of incident light.***

Population Inversion

❑ **Laser operation requires obtaining Stimulated emission exclusively.**

➢ To achieve a high percentage of stimulated emission, a majority of atoms should be at the higher energy level than at the lower level.

❖ *The non-equilibrium state in which the population N_2 of the upper energy level exceeds to a large extent the population N_1 of the lower energy level is known as the **state of population inversion.***

▪ Extending the Boltzmann's distribution, to this non-equilibrium state of P.I.
$\Rightarrow N_2$ *can exceed N_1 only if the temperature be negative.*

▪ The state of P.I. is sometimes referred to as a **negative temperature state**.

➢ *Does not mean that we can attain temperatures below absolute zero,*

➢ *Terminology implies that P.I. is a non-equilibrium state and is attained at normal temperatures.*

❖ For a system with three energy states E_1, E_2 and E_3 in equilibrium, the uppermost level E_3 is populated least and the lowest level E_1 is populated most

➢ *Since the population in the three states is such that $N_3 < N_2 < N_1$, the system absorbs photons rather than emit photons.*

• If the system is supplied with external energy such that N_2 exceeds N_1 ⇒ **System reached Population Inversion**

• P.I. taken place between the levels E_2 and E_1,

(a) Population in equilibrium.

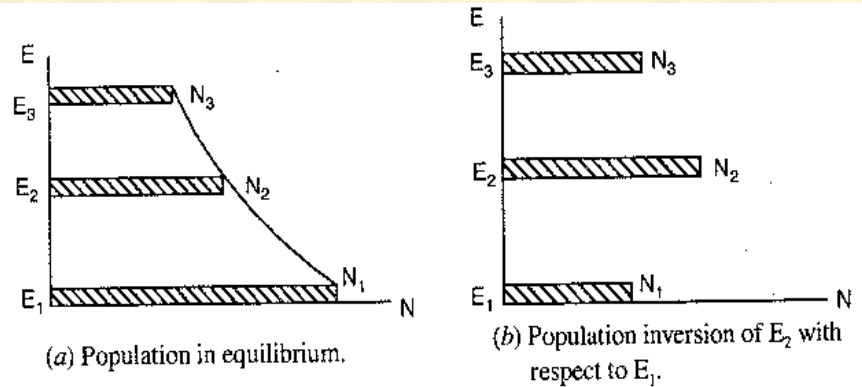(b) Population inversion of E_2 with respect to E_1.

**Fig. 1.16.** Three level system.

❖ **Under P.I. condition, stimulated emission can produce a cascade of light.**

➢ The first few randomly emitted spontaneous photons trigger stimulated emission of more photons and those stimulated photons induce still more stimulated emissions and so on.

➢ As long as $N_2 > N_1$, stimulated emissions are more likely than absorption
⇒ **light gets amplified**.

Fig. 1.17. Amplification of a light wave in a medium with population inversion.
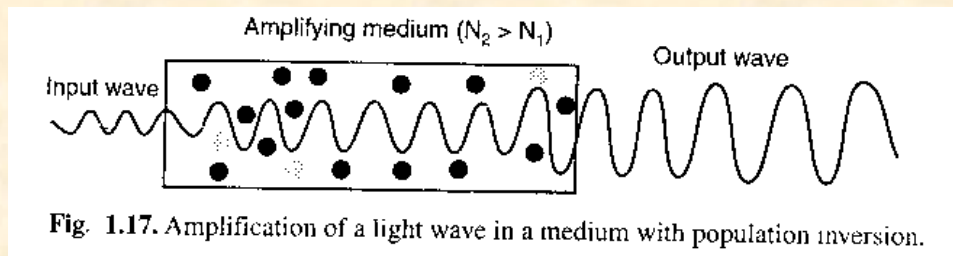
☛ The moment, the population at lower level becomes equal to or larger than at the excited state, *P.I. ends, stimulated emissions diminish and amplification of light ceases.*

How to achieve P.I. ?

▪ **Pumping:** *Process by which atoms are raised from the lower level to the upper level.*

▪ Energy is to be supplied somehow to the laser medium to raise atoms from the lower level to the excited level and for maintaining population at the excited level at a value greater than that of the lower energy.

- Usual method ⟹ **Heat the material**. Will it do the job ?

- Heating the material only increases the average energy of atoms but does not make N_2 greater than N_1.

  ➢ **P.I. cannot be achieved by heating the material.**

Pumping Methods

- **To create the state of P.I.** $\Rightarrow$ *selectively excite the atoms in the material to particular energy levels.*

- Most common methods of pumping make use of **Light** and **Electrons.**

<u>Optical Pumping</u>

- Use of photons to excite the atoms

  - A light source used to illuminate the laser medium

  - Photons of appropriate frequency excite the atoms to upper levels.

  - Atoms drop to the metastable level to create the state of P.I.

❖ **Optical pump sources** : Flash discharge tubes, Continuously operation lamps, Spark gaps or an auxiliary laser.

❖ Optical pumping is suitable for laser medium- <u>transparent to pump light</u>.

❖ Mostly used for solid state crystalline and liquid tunable dye lasers.

Electrical Pumping

- Can be used only in case of laser materials that can conduct electricity without destroying lasing activity.

  ➤ **Limited to gases**.

  - In case of a gas laser, a high voltage pulse initially ionizes the gas so that it conducts electricity.

  - An electric current flowing through the gas excites atoms to the excited level from where they drop to the metastable upper laser level leading to **P.I**.

Direct Conversion

- In semiconductor lasers also electrical pumping is used, but here it is not the atoms that are excited. It is the current carriers; {e- h} pairs which are excited and a population inversion is achieved in the junction region.

- Electrons recombine with holes in the junction regions producing laser light.

  ➤ **A direct conversion of electrical energy into light energy**

Active Centre & Active Medium

- **All types of atoms not suitable for laser operation**.

  - In a medium consisting of different species of atoms, *only a small fraction of atoms of a particular species are suitable for stimulated emission and laser action.*

  - Those atoms which cause light amplification are called **Active Centers**.

  - Rest of the medium acts as host and supports active centers is called an **Active Medium**.

- *An active medium is thus a medium which, when excited, reaches the state of population inversion, and eventually causes light amplification.*

- Active medium may be **a solid, a liquid or a gas**.

Metastable States

- An atom can be excited to a higher level by supplying energy to it. Normally, excited states have *short lifetimes $\approx$ nanoseconds (10^{-9} s)* and release their excess energy by spontaneous emission.

- Atoms do not stay at such excited states long enough to be stimulated to emit their energy. Though, the pumping agent continuously raises the atoms to the excited level, many of them rapidly undergo spontaneous transitions to the lower energy level $\Rightarrow$ *Population inversion cannot be established*.

- For establishing population inversion, the excited atoms are required to **"wait"** at the upper lasing level till a large number of atoms accumulate at that level.

- **What is needed is an excited state with a longer lifetime ?**

  ☞ *Such longer-lived upper levels from where an excited atom does not return to lower level at once, but remains excited for an appreciable time, are known as **Metastable States.***

- Atoms stay in metastable states for about **10^{-6} to 10^{-3}s**. This is **10^3 to 10^6 times longer** than the time of stay at excited levels.

  - Possible for a large number of atoms to accumulate at a metastable level. The metastable state population can exceed the population of a lower level and lead to the state of population inversion.

- **If the metastable states do not exist, there could be no population inversion, no stimulated emission and hence no laser operation.**

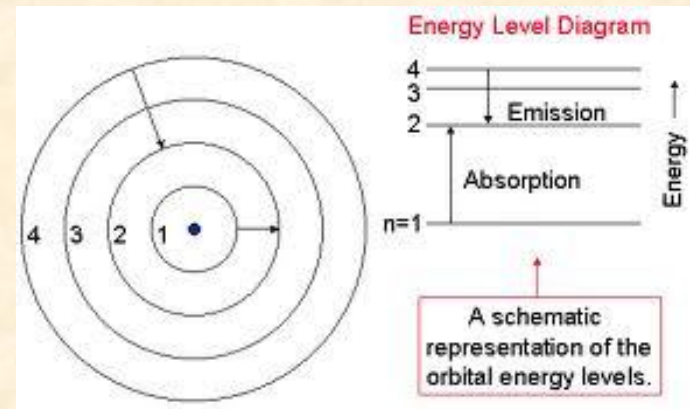- ❖ **Foundation to the laser operation is the existence of metastable states.**

Pumping Schemes

❖ **Atoms characterized by a large number of energy levels.**

➢ Only two, three or four levels are pertinent to the pumping process.

❑ **Classified as**

▪ Two-level,

▪ Three-level and

▪ Four –level schemes.

Energy Level Diagram

A schematic representation of the orbital energy levels.

❖ Two-level scheme will not lead to laser action.

❖ Three-level and four-level schemes are important and are widely employed.

Two Level Pumping Scheme

- Appears to be most simple and straight-forward method to establish population inversion;

  ➢ Pumping an excess of atoms into the higher energy state by applying intense radiation.

- A two-level pumping scheme is not suitable for attaining P.I.

- P.I. requires the lifetime Δt of upper level E_2 must be longer.

- **Heisenberg's Uncertainty principle,**

$$\Delta E_2 . \Delta t \geq h/2\pi$$

$\Rightarrow$ Smaller ΔE_2 ; the upper energy level must be narrow
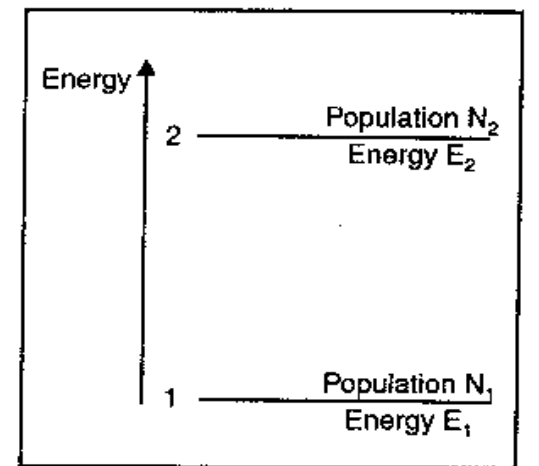
Two Energy level system

- **For such system, to excite atoms, pump source should be highly monochromatic.**

  ➢ In practice, monochromatic source of required frequency may not exist.

  ➢ Even if it exists, the pumping efficiency would be very low $\Rightarrow$ enough population cannot be excited to level E_2.

- Further, pumping radiation on one hand excites the ground state atoms and on the other hand induces transitions from the upper level to the lower level.

  ➢ **means that pumping operation simultaneously populates and depopulates the upper level.**

☞ **Hence, P.I. cannot be attained in a two-level scheme. All that it may achieve at best is a system of equally populated levels.**
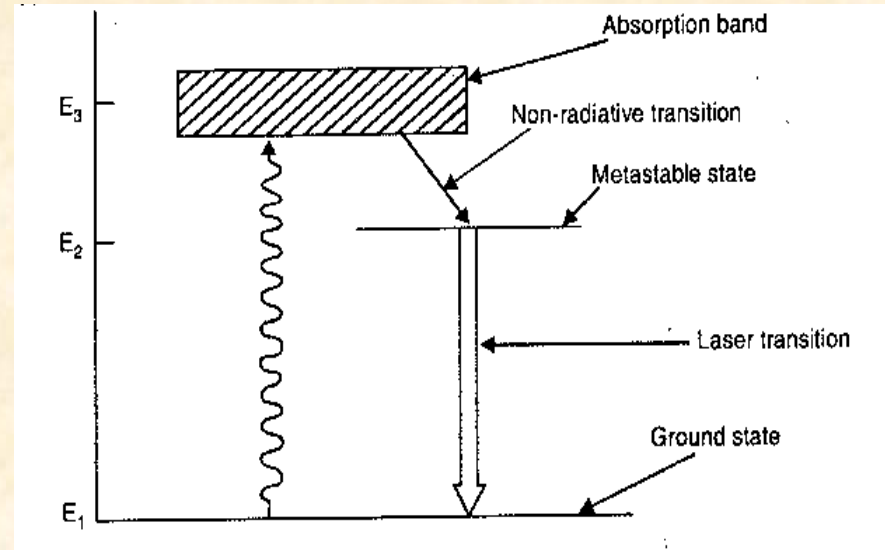
Three Level Pumping Scheme

- **A three level scheme**; Lower level is either the ground state or a level whose separation from the ground state is small compared to kT.

E_2 – A metastable level

- Atoms accumulate at level E_2

- Build-up of atoms at E_2 continues because of pumping process.

- Population N_2 at E_2 exceeds the population N_1 at E_1 and

  ➢ **P.I. is attained**.

Three level Energy diagram

❖ **A photon of $h\nu(=E_2-E_1)$ can induce stimulated emission and laser action.**

❖ **Major disadvantage of a three level scheme ⟹ it requires very high pump powers.**

- Terminal level of the laser transition is the ground state.

- As the ground state is heavily populated, large pumping power is to be used to depopulate the ground level to the required extent ($N_2 > N_1$)

- **Three level scheme can produce light only in Pulses.**

➢ Once stimulated emission commences, the metastable state E_2 gets depopulated very rapidly and the population of the ground state increases quickly. As a result the population inversion ends. One has to wait till the population inversion is again established.

➢ **Three level lasers operate in Pulsed Mode.**

Four Level Pumping Scheme

- **In Four level scheme, the terminal laser level E_2 is well above the ground level such that $(E_2 - E_1) \gg kT$.**

  - ➤ It guarantees that the thermal equilibrium population of E_2 level is negligible.

E_3 - a metastable level

- ➤ Laser transition takes the atoms to the level E_2

- ➤ Atoms lose the rest of their excess energy & finally reach the ground state E_1.

- ➤ Atoms are once again available for excitation.
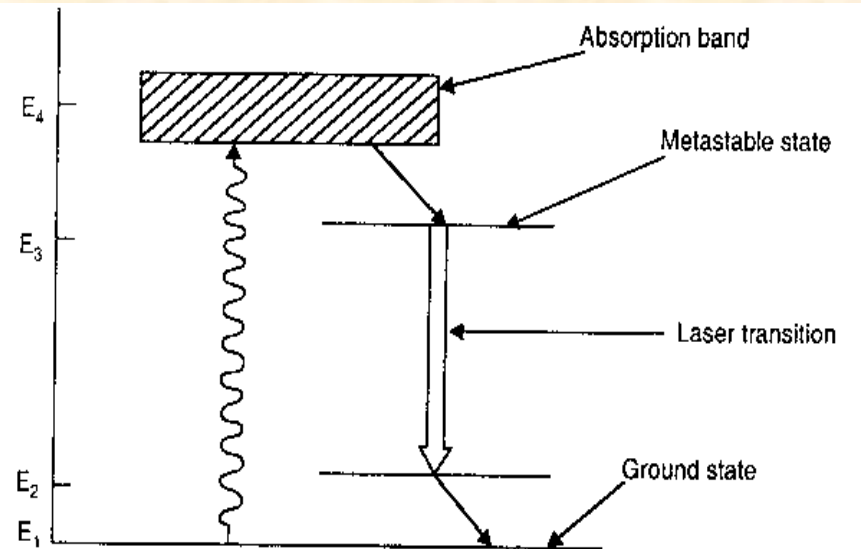
Four level Energy diagram

- *In contrast to three level scheme, the lower laser transition level in four level scheme is not the ground state and is virtually vacant.*

  - It requires less pumping energy than does a three level laser. This is the major advantage of this scheme.

- *Further, the lifetime of the lower laser transition level E_2 is much shorter, hence atoms in level E_2 quickly drop to the ground state.*

  - This steady depletion of E_2 level helps sustain the population inversion by avoiding an accumulation of atoms in the lower lasing level.

- Four level lasers can operate in **Continuous Wave mode.**

❑ **Most of the working lasers are based on Four Level Scheme**

Laser Block Components
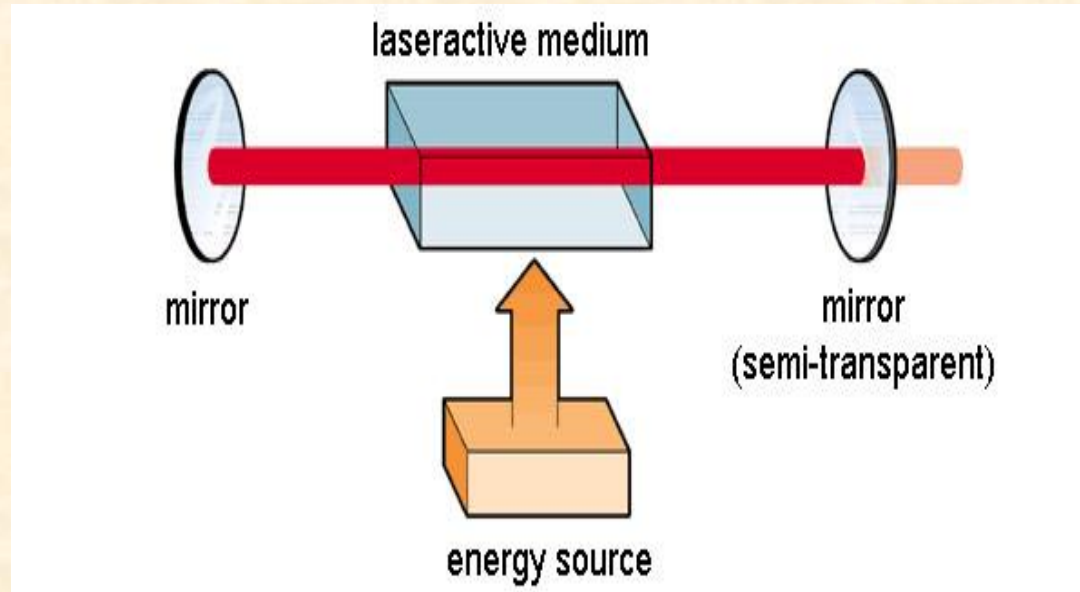
Major Components:

- **Active medium**
- **Pumping Source**
- **Mirrors**

Classification of Lasers

❑ **Several ways to classify the different types of lasers**

- What material or element is used as active medium

- Mode of operation : CW or Pulsed

❑ **Classification may be done on basis of other parameters**

- Gain of the laser medium

- Power delivered by laser

- Efficiency or

- Applications

❖ **Preference to classify the lasers on the basis of material used as Active Medium.**
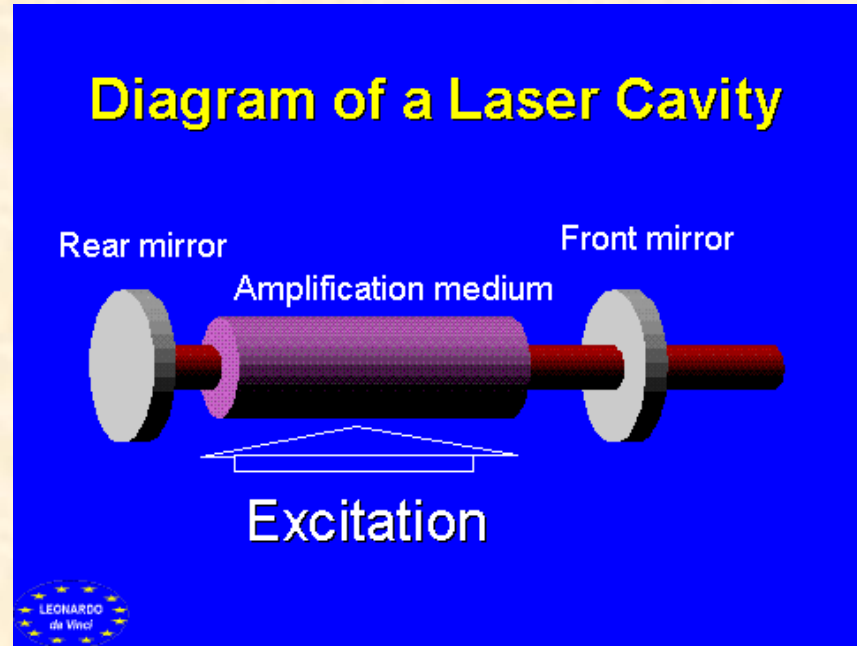
▪ **Broadly divided into four categories;**

- Solid lasers

- Gas lasers

- Liquid lasers

- Semiconductor lasers

☞ **Will discuss some of the important and practical lasers ?**

Laser Cavity

❑ **All the lasers comprise of three basic components**

- **Active medium,**

- **Excitation source and**

- **Reflecting mirrors**

Diagram of a Laser Cavity

- Whether Solid State, Liquid or Gas laser, the basic mechanism is same i.e. *Laser Action*

- They differ only in terms of Active medium or Excitation process.

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