Definition of LASER

- The acronym LASER stands for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.

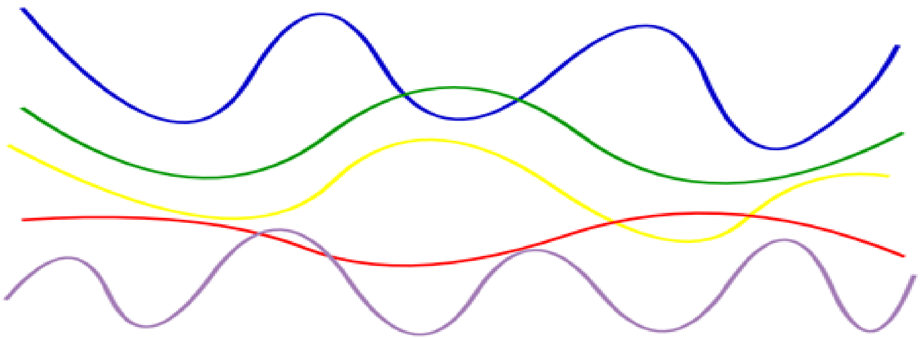
- A laser is a device that generates light by a process called **STIMULATED EMISSION**.

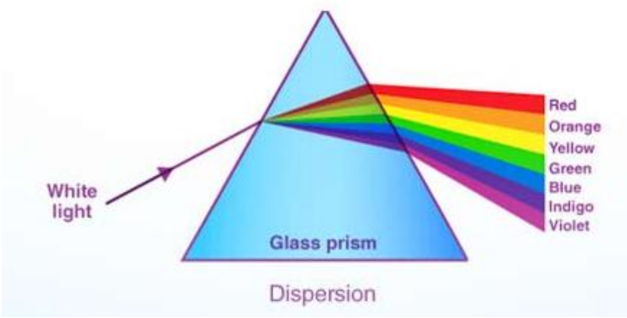
Properties of Laser

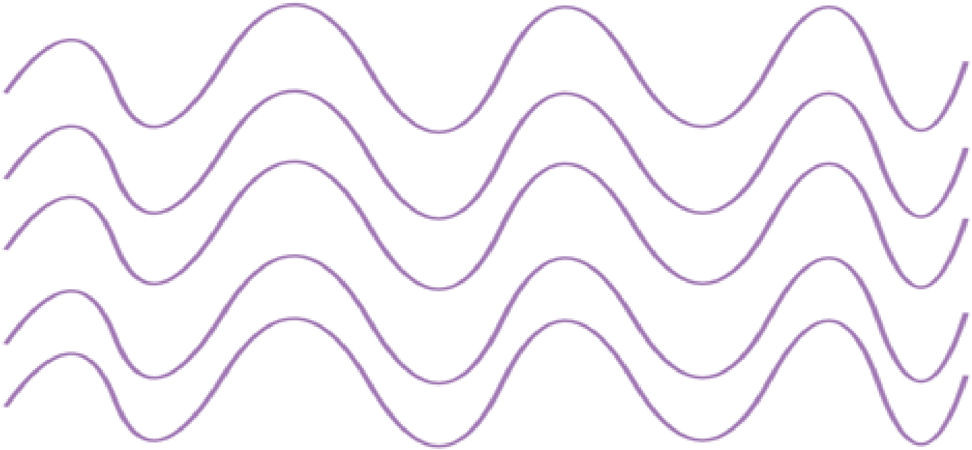
- Monochromatic
- Coherence
- Directionality
- Highly Intensity

Monochromatic

❖ Monochromatic light is a light containing a single colour or wavelength.
❖ The light emitted from ordinary light sources have different energies, frequencies, wavelengths, or colors.
❖ But laser light has a single wavelength or colour.

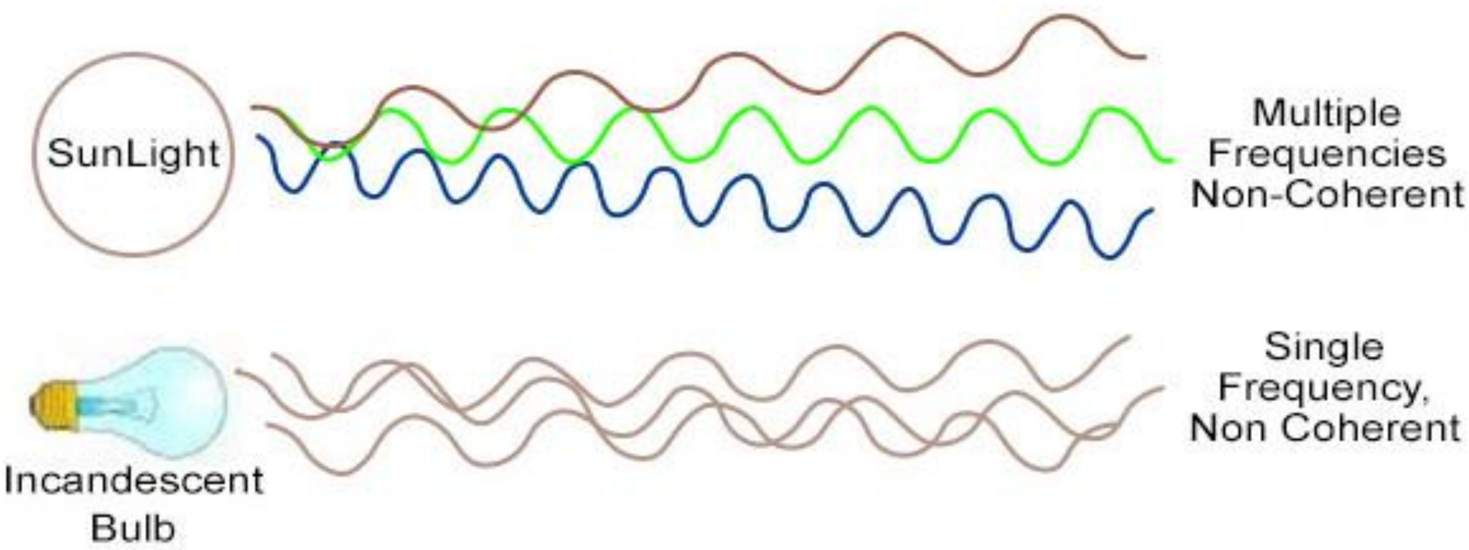






Coherence

- A predictable correlation of the amplitude and phase at any one point with another point is called coherence.
- That means if two or more waves of same frequency are in the same phase or have constant phase difference then these waves are said to be coherent in nature.

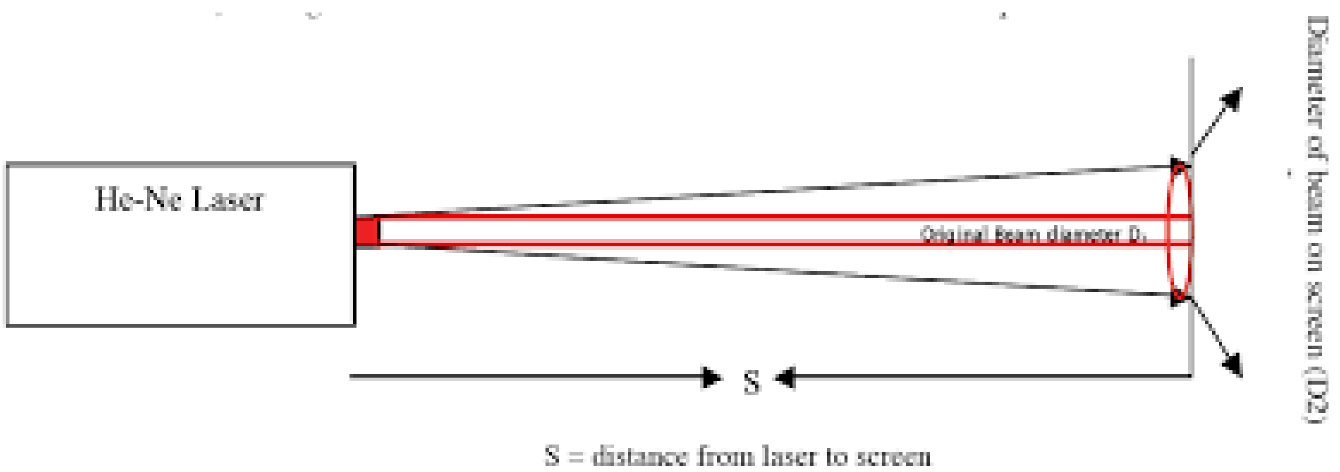


Directionality

❖ The light ray coming from an ordinary light source travels in all directions, but laser light travels in a single direction.

❖ For example, the light emitted from torchlight spreads 1km distance but the laser light spreads a few centimetres distance even it travels lacks kilometre distance.

❖ The directionality of the laser beam is expressed in terms of divergence



Highly Intensity

- Laser light is highly intense than conventional light.

- We know that the intensity of a wave is the energy per unit time flowing through a specific area.

- A one mill watt He-Ne laser is more intense than the sun intensity. This is because of the coherence and directionality of the laser.

Laser beam parameters

- **Beam Intensity**: It is a measure of optical power output from a laser source per unit area.

  It is given by Intensity (I) = Optical Power (P)/ cross-sectional area of laser beam (A) and measured in W/m^2.

- **Coherence**: The narrower the range of wavelengths, the more coherent the beam.

  This is measured by a quantity called coherence length and given by

$$\text{Coherence length} = \frac{\lambda^2}{(\Delta\lambda)}$$

Where λ is the centre of the range of wavelengths emitted and $\Delta\lambda$ is the range of wavelengths emitted

- **Monochromaticity:** It is a measure of linewidth of radiation emitted from a source of light.

- **Directionality:** In a laser, all the photons are emitted with the same energy and in the same direction. Due to this, the width of the laser beam is extremely narrow, and it can travel large distances with almost no losses, known as the directionality of laser.

- **Divergence:** It is a measure of angular spread of the laser beam as it travels away from a laser source.

It is given by $\theta = \dfrac{(d_2 - d_1)}{(z_2 - z_1)}$

where d_1 and d_2 are diameters of laser beam at perpendicular distances z_1 and z_2, respectively.

Basic concepts for a laser

- **Population**
- **Absorption**
- **Spontaneous Emission**
- **Stimulated Emission**
- **Population Inversion**
- **Pumping**
- **Active medium**
- **Metastable state**
- **Resonance Cavity**

Population

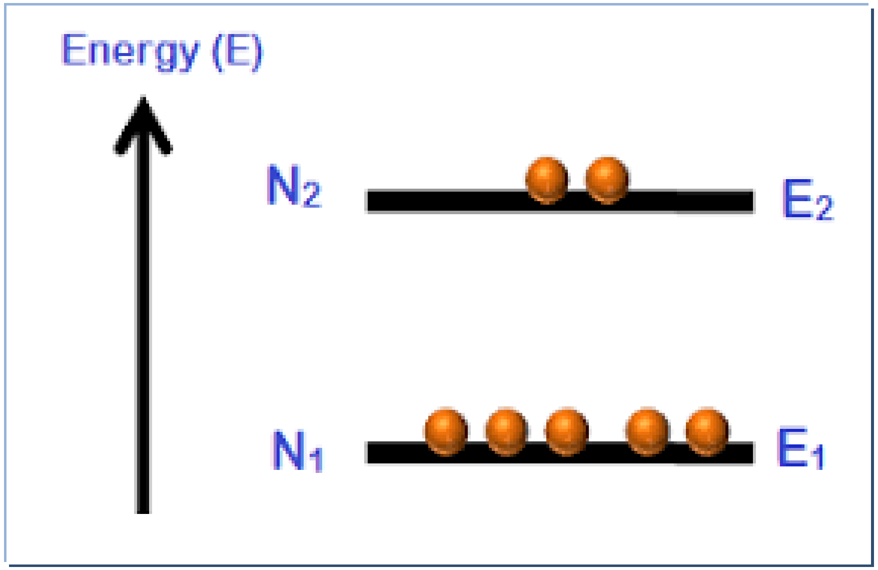
The number of atoms in a particular energy level is called population.

The population of an energy level "E" at temperature "T" is given by

$$\mathrm{N} = N_0\, e^{-\left(\frac{E}{KT}\right)}$$

Consider two energy levels $E_1 \ and E_2$
($E_1 < E_2$) having populations N_1 and N_2 respectively

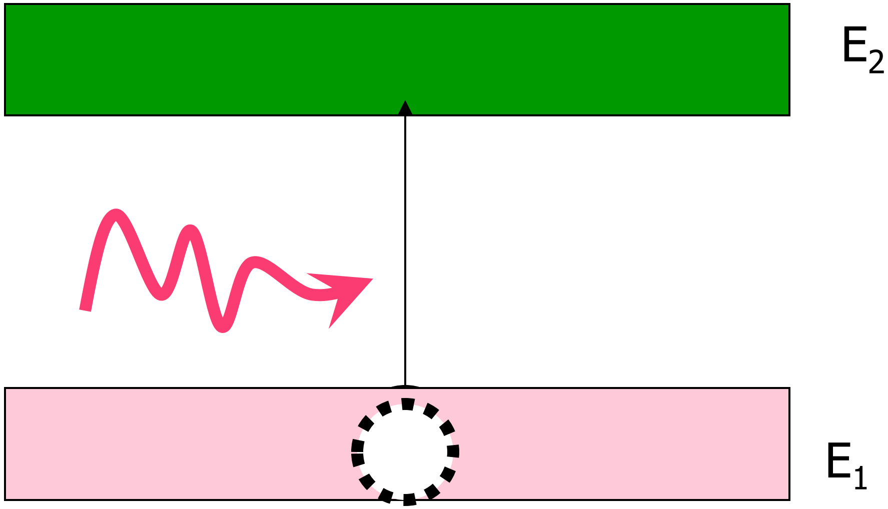
Then what is possible
(a) $N_1 > N_2$
or
(b) $N_1 < N_2$



So the answer is
$N_1 > N_2$
This is also called
Normal Population

Absorption

Consider two energy levels E_1 to E_2 as shown in the figure. Let an atom is present in the energy level E_1 and a quanta or photon of energy $(E_2 - E_1)$ is incident on it



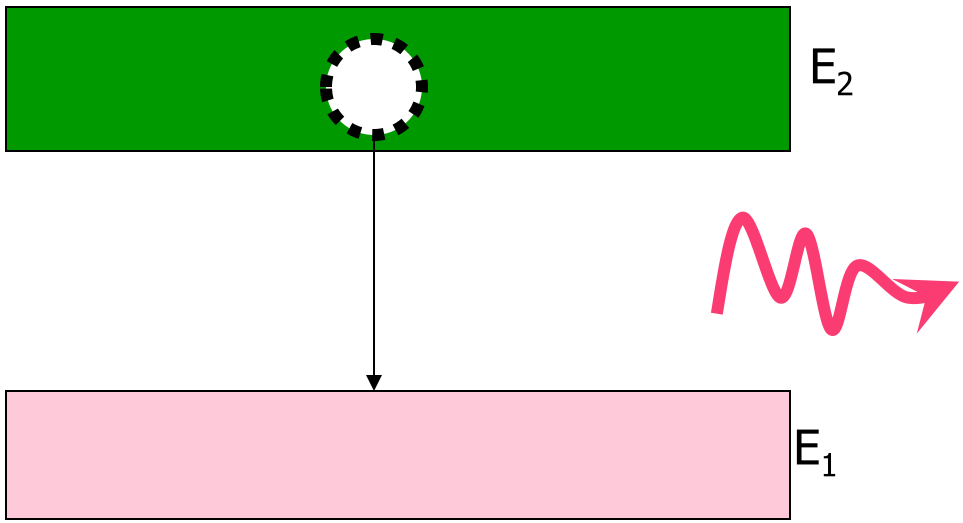
The atom will absorb this photon and make a transition to higher energy level. This is called absorption.

Corresponding to each transition from E_1 to E_2, photon of energy $h\nu = E_2 - E_1$ is absorbed.

The number of atoms excited during time Δt is, $N_{ab} = B_{12}N_1Q\Delta t$

Spontaneous Emission

Consider two energy levels E_1 to E_2 as shown in the figure. Let an atom is present in the energy level E_2 . After its life time atom will make a transition to lower energy state and quanta or photon will be emitted.

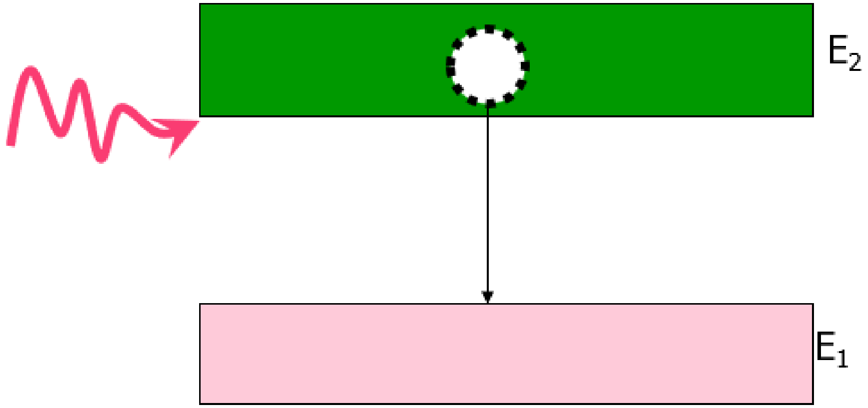


Corresponding to each transition from E_2 to E_1, photon of energy $h\nu = E_2 - E_1$ is emitted. This is called Spontaneous Emission.

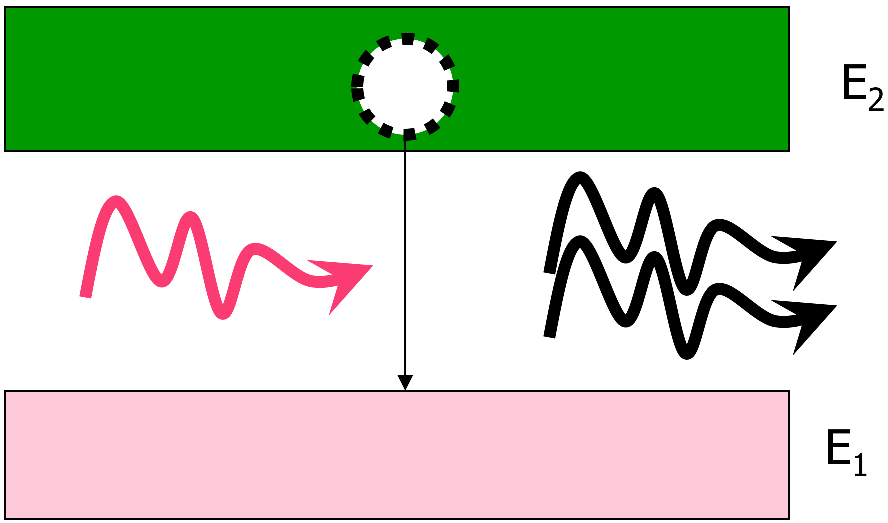
The number of atoms de-excited during time Δt by spontaneous emission is, $N_{sp} = A_{21}N_2\Delta t$

Stimulated Emission

Consider two energy levels E_1 to E_2. Let an atom is present in the energy level E_2 and a quanta or photon of energy $(E_2 - E_1)$ is incident on it before its life time



The photon will force or stimulate the atom in higher energy level to come to lower energy level and a quanta or photon will be emitted without absorbing the incident photon.



Corresponding to every transition from E_2 to E_1 , two identical photons of energy $h\nu = E_2 - E_1$ are emitted. **This is called Stimulated Emission.**

The number of atoms de-excited during time Δt by stimulated emission is, $N_{st} = B_{21}N_2Q\Delta t$.

Advantages of stimulated emission over spontaneous emission

(a) The process is controllable from outside.

(b) The induced radiation is identical to the incident radiation.

(c) By selecting proper active medium and resonance conditions, light amplification can be achieved.

(d) As a result, we get a highly monochromatic, coherent, directional, focused and intense radiation.

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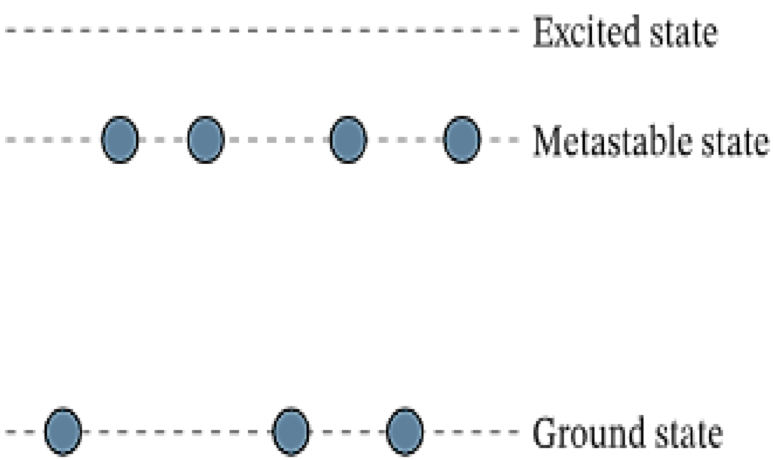
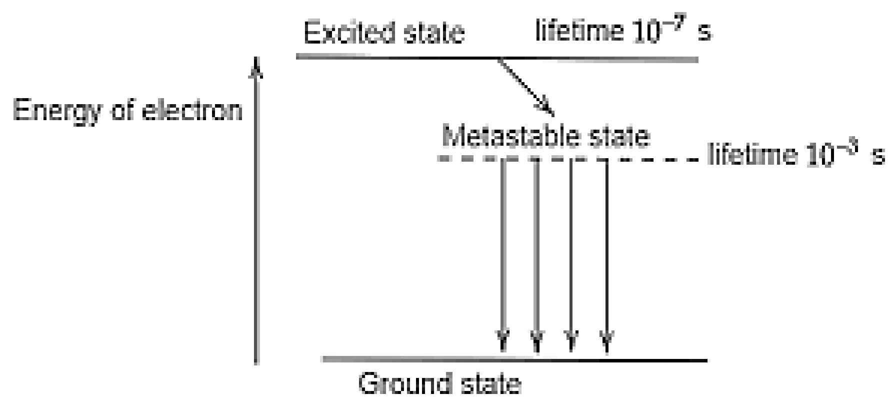
Metastable state

An energy level lying between ground and excited state in which lifetime of an atom is greater than 1 nano second is called Metastable state.

Atoms in the metastable remain excited for a considerable time in order of millisecond.



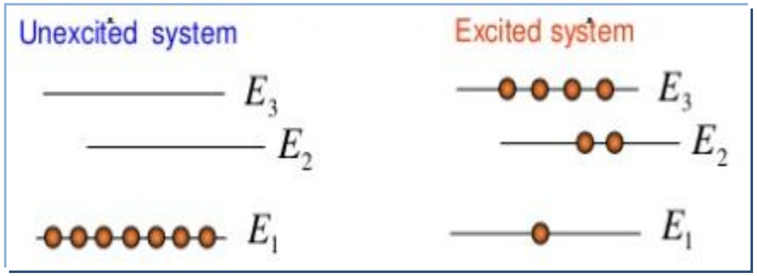


ENERGY LEVEL DIAGRAM

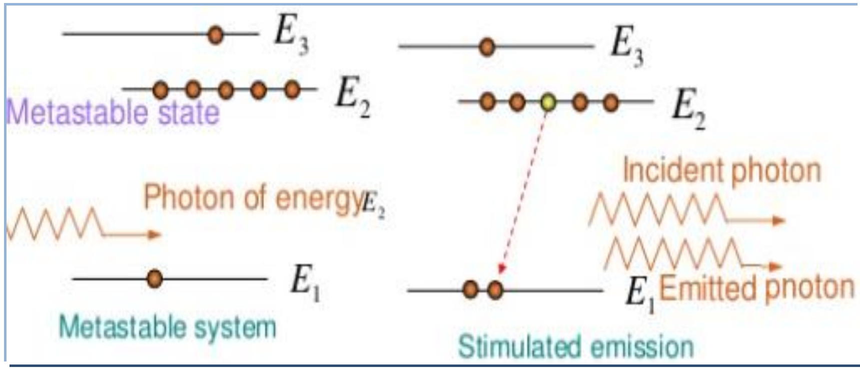
INVERTED POPULATION or POPULATION INVERSION

When a sizable population of electrons resides in upper levels, this condition is called a "population inversion"
In order to obtain the coherent light from stimulated emission, two conditions must be satisfied:

1. The atoms must be excited to the higher state. That is, an inverted population is needed, one in which more atoms are in the upper state than in the lower one, so that emission of photons will dominate over absorption.

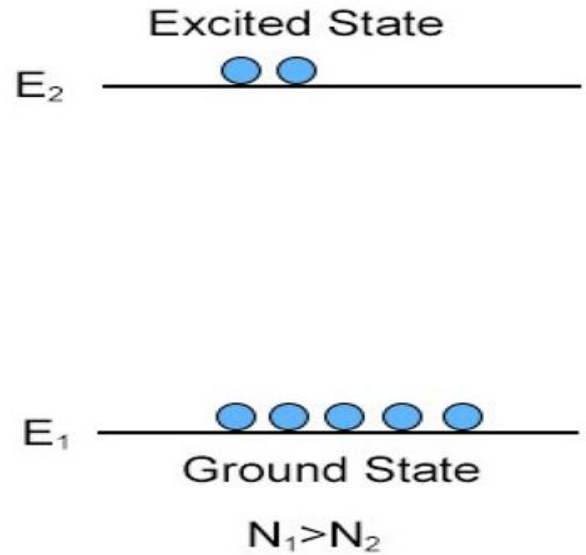


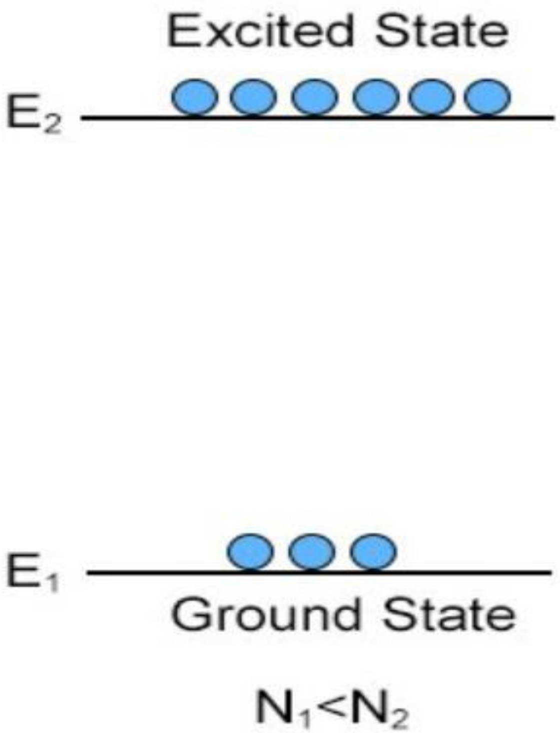
2. The higher state must be a metastable state – a state in which the electrons remain longer than usual so that the transition to the lower state occurs by stimulated emission rather than spontaneously.



Normal Population

$N_1 > N_2$





But for stimulated emission, or LASER operation Population

$N_2 > N_1$

A process of supplying energy to transfer atoms from lower energy state to higher energy state is called pumping.

Pumping

A process of supplying energy to transfer atoms from lower energy state to higher energy state is called pumping.

A process of supplying energy to get population inversion is called pumping.

Pumping can be

Optical: flashlamps and high-energy light sources

Electrical: application of a potential difference across the laser medium etc.

Chemical pumping: Chemical reaction may also result in excitation

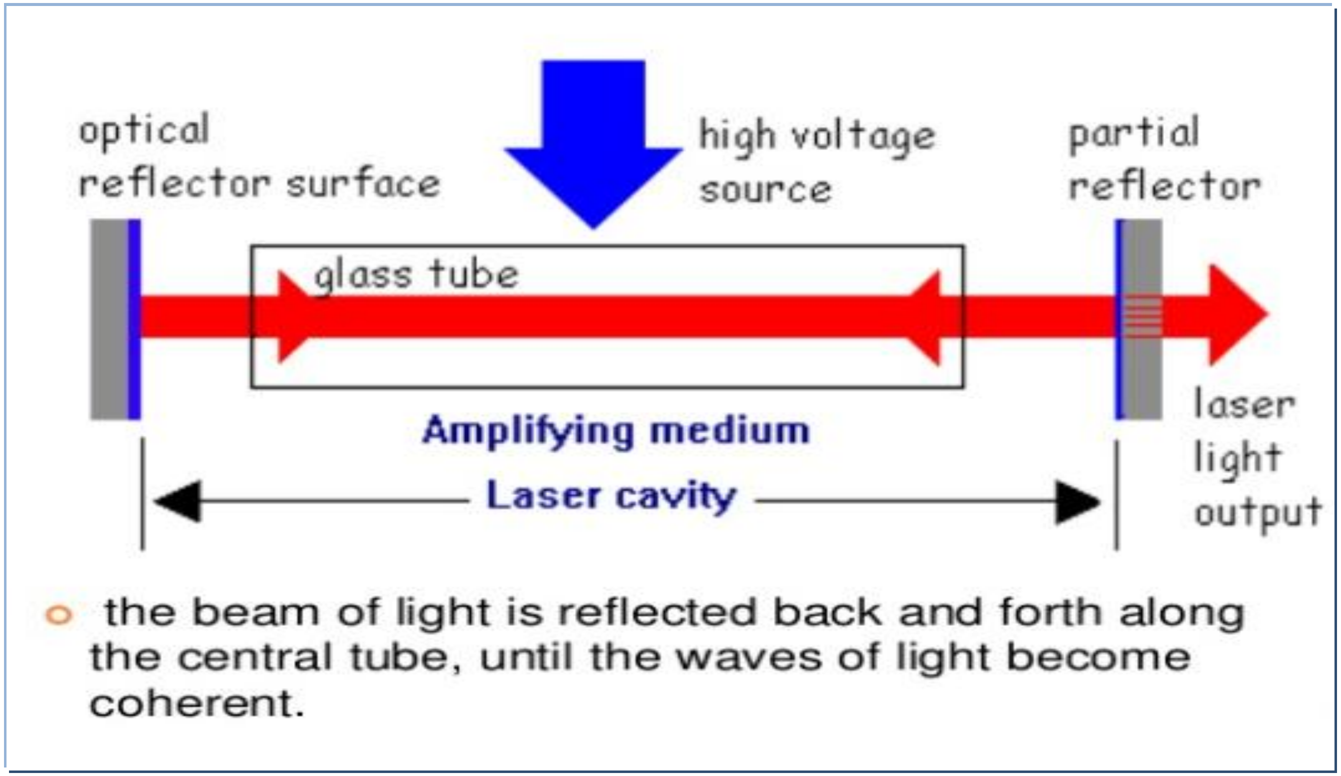
Active medium

The medium in which population inversion is possible is called active medium .

The active medium can be solid, liquid or gas.
The **active medium** is a collection of atoms or molecules, which can be excited into a population inversion situation.

The atoms of active medium are called active atoms or active centers.

Optical Resonator



An optical resonator or optical cavity or , resonating cavity is an arrangement of mirrors that forms a standing wave cavity resonator for light waves.

ACTIVE MEDIUM

Solid (Crystal)
Gas
Semiconductor (Diode)
Liquid (Dye)

The **Active Medium** contains atoms which can emit light by stimulated emission.

EXCITATION MECHANISM
or
PUMPING

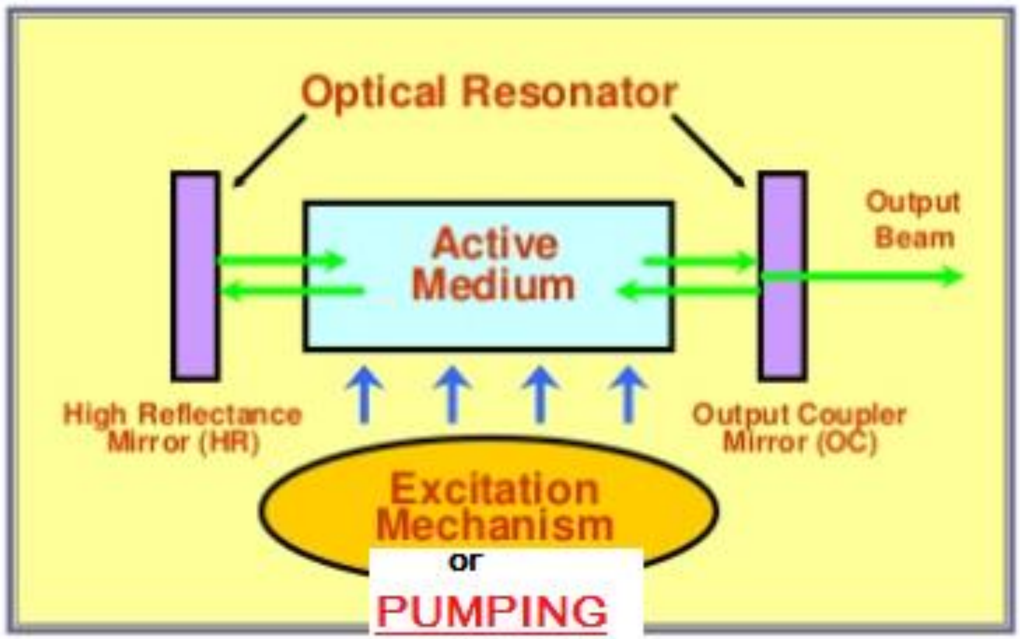
Optical
Electrical
Chemical

The **Excitation Mechanism** is a source of energy to excite the atoms to the proper energy state.

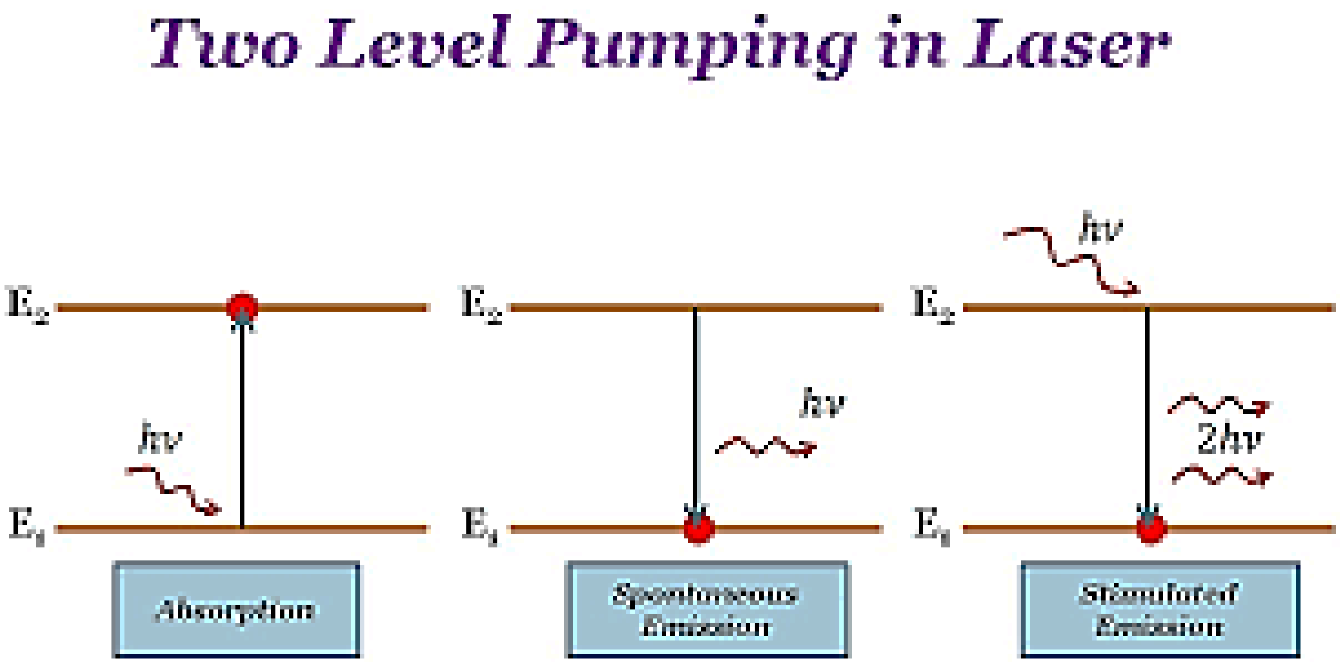
OPTICAL RESONATOR

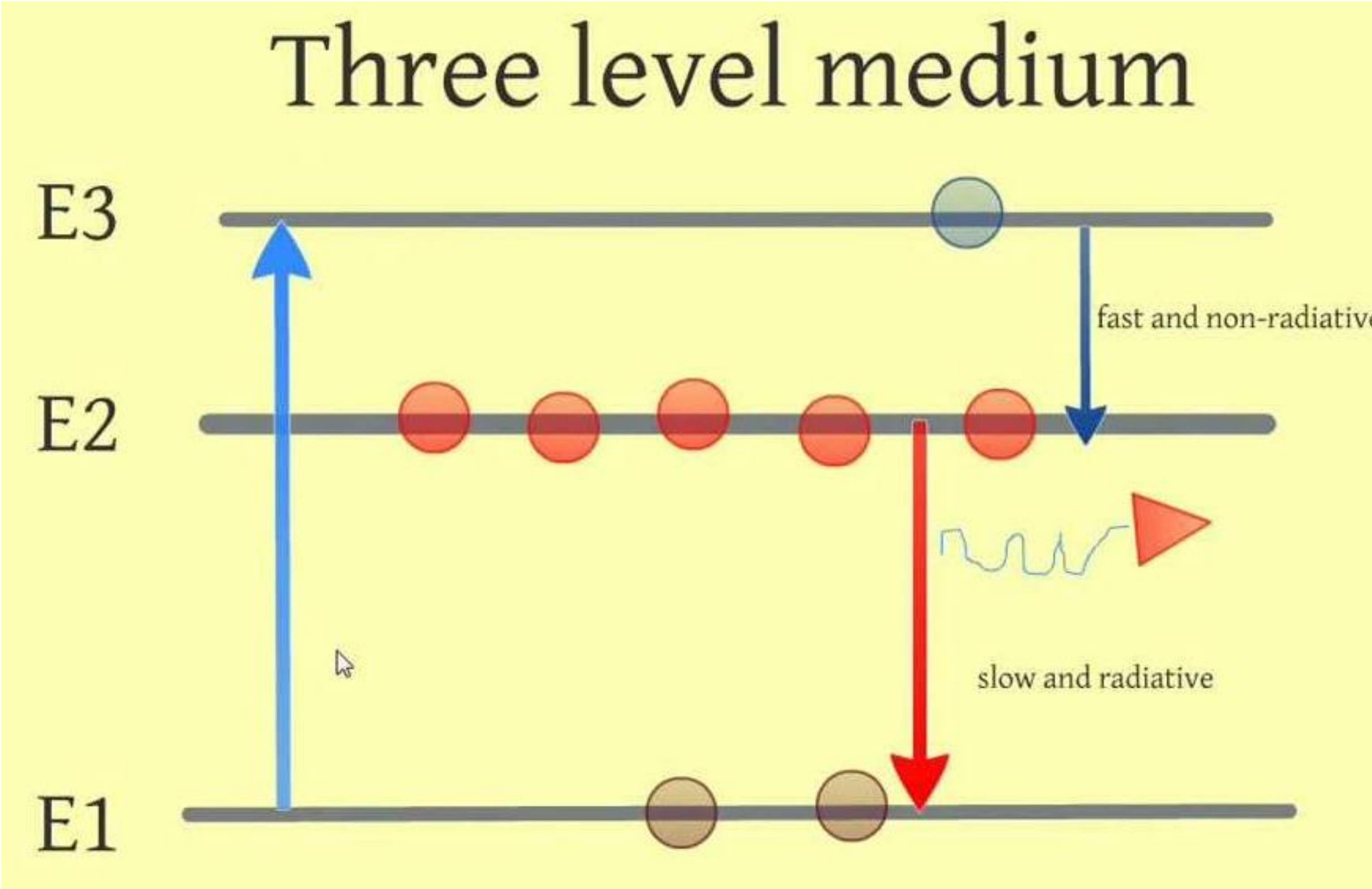
HR Mirror and Output Coupler

The **Optical Resonator** reflects the laser beam through the active medium for amplification.

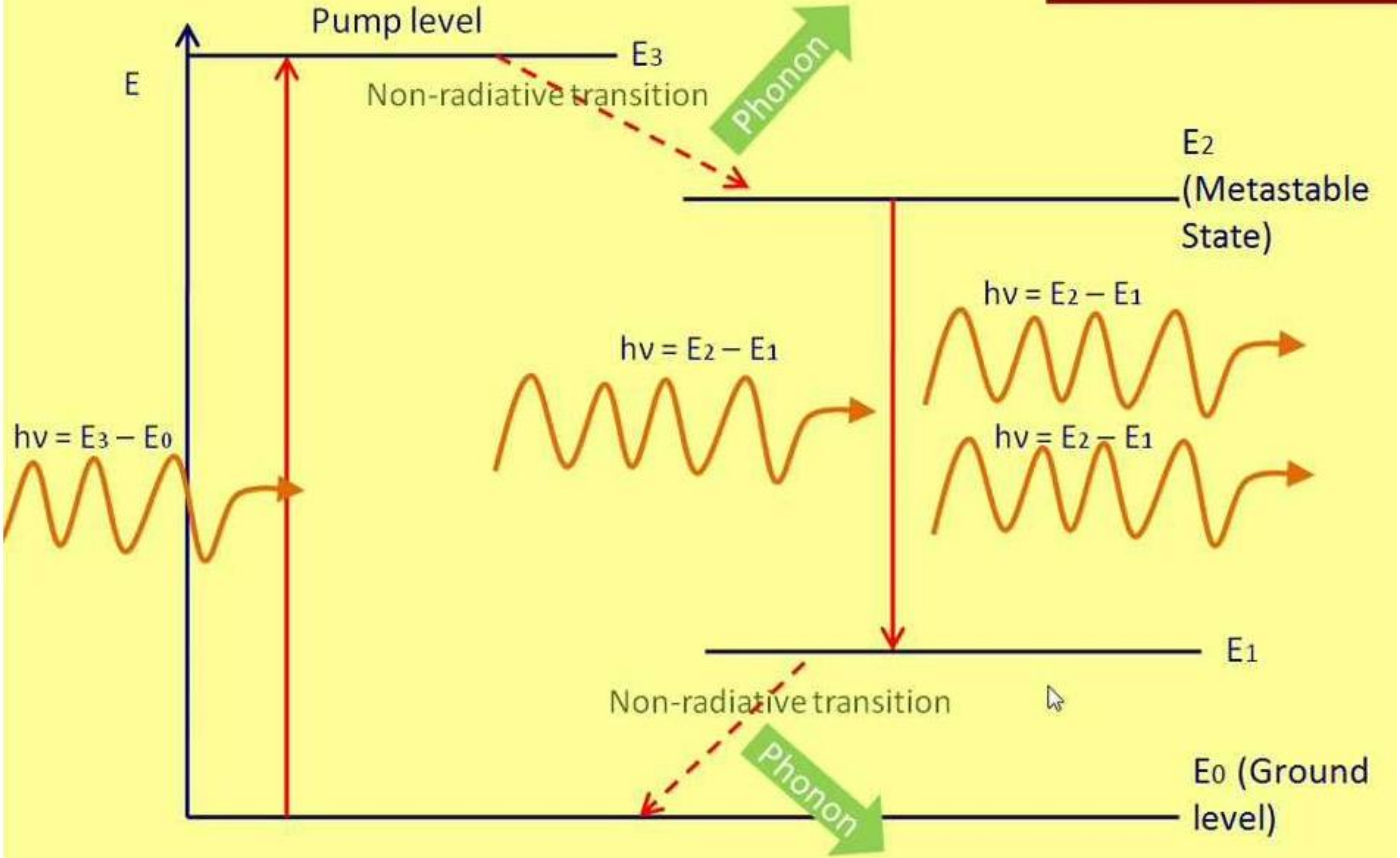


Different Pumping Schemes




Three level medium
E3
fast and non-radiative
E2
slow and radiative
E1

4 Level System



Einstein A and B coefficients

1. Consider a radiation field and a collection of two-level systems.

2. Stimulated emission probability: proportional to the number of atoms in upper state N_2, and to the number of photons

$$N_{st} = (B_{21})\,(N_2)\,(Q)\,(\Delta t)$$

3. Spontaneous emission probability: proportional to N_2, but does not depend on the photon density

$$N_{sp} = (A_{21})\,(N_2)\,(\Delta t)$$

4. Stimulated absorption probability: proportional to the number of atoms in lower state N_1 and to the number of photons

$$N_{ab} = (B_{12})(N_1)(Q)(\Delta t)$$

5. In thermal equilibrium, the upward and downward transition rates must balance

$$N_{ab} = N_{st} + N_{sp}$$

Refer Class notes/discussion for this topic

Threshold condition for LASER

When the small-signal gain just equals the resonator losses then it is called threshold condition of a LASER.

When operation is well above the threshold, then power output is significant, power efficiency is good and stable, noise is low

A low threshold power requires low resonator losses and a high gain efficiency.

It is achieved using a small laser mode area in an efficient gain medium with limited emission bandwidth.

The optimization of the laser output power for a given pump power usually involves a compromise between high slope efficiency and low laser threshold.

Refer Class notes/discussion for this topic