# LASER

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# Syllabus

- **Physics of Materials**: Crystal structure, crystal systems, bonding in solids, P.E curve and Properties of materials, miller indices, Brillouin zones, symmetry, Atomic Packing fraction, imperfections, energy bands in solids,, classification of solids, conductivity in metals and concepts of Fermi level, effective mass and holes, concept of phonons, electron distribution function, Fermi-Dirac distribution function, properties of bulk materials and nanomaterials. Carbon materials.

- **Laser and Fiber Optics**: Principles of lasers, Einstein Coefficients and their relations, Types of Lasers and their applications. Concept of optical fibers and types of optical fibers, modes of propagation, fiber optic communication, optical fiber sensors, connector and couplers.

# LASERS

## History of LASER

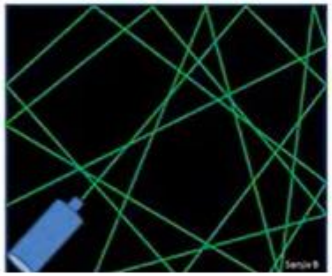
- Invented in 1958 by Charles Townes (Nobel prize in Physics 1964) and Arthur Schawlow of Bell Laboratories

- Was based on Einstein's idea of the ―particlewave duality‖ of light, more than 30 years earlier
- Originally called MASER (m = ―microwave‖)

- **Prerequisites :**

(Absorption, recombination, energy bands of p-n junction)

- **Laser:**
  - spontaneous emission and stimulated emission,
  - metastable state, population inversion, types of pumping, resonant cavity
  - Helium Neon laser, Nd:YAG laser, Semiconductor laser,
  - Einsteins's equations,
  - Applications of laser- Holography



| Year | Name | Development of Laser |
|---|---|---|
| 1917 | Einstein[2] | On the Quantum Mechanics of Radiation |
| 1954 | Townes[3] | Invention of MASER |
| 1958 | Schawlow and Townes[4] | Invention of LASER |
| 1960 | Maiman[5] | Built the first working laser |
| 1963 | Goldman[6] | Introduced laser into medical field |
| 1964 | Goldman[7] | Reported impact of laser beam to dental caries |
| 1964 | Bell Laboratories | Nd:YAG laser and $CO_2$ laser were developed. Extended the application of laser into soft tissue |
| 1980 | Yamamoto and Sato[14] | Nd:YAG laser was first reported to be used in dental caries prevention |
| 1989 | Myers and Myers[15] | Development of a pulsed Nd:YAG laser, made application of laser in general dentistry possible |
| 1990- | Ho:YAG, Er:YAG, Argon, Er:YSGG and other types of laser were invented. Laser has been widely applied in dentistry | |

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Laser: everywhere in your life

Laser printer

Laser pointer

Laser Barcode Scanner

Laser Cutting Machine

Laser Wound Healing

Laser Eye Surgery

# What is Laser?

**Light Amplification by Stimulated Emission of Radiation**

- A device produces a coherent beam of optical radiation by stimulating electronic, ionic, or molecular transitions to higher energy levels
- When they return to lower energy levels by stimulated emission, they emit energy.

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# Properties of Laser

- The light emitted from a laser is **monochromatic**, that is, it is of one color/wavelength. In contrast, ordinary white light is a combination of many colors (or wavelengths) of light.

- Lasers emit light that is highly **directional**, that is, laser light is emitted as a relatively narrow beam in a specific direction. Ordinary light, such as from a light bulb, is emitted in many directions away from the source.

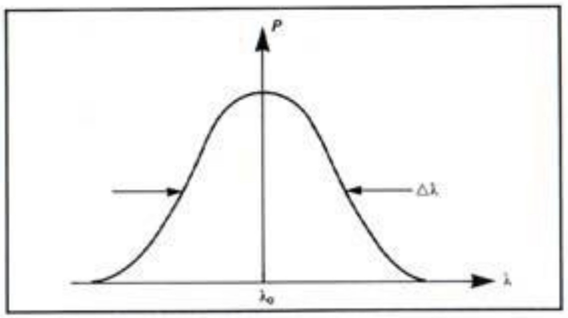
- The light from a laser is said to be **coherent**, which means that the wavelengths of the laser light are in phase in space and time. Ordinary light can be a mixture of many wavelengths.

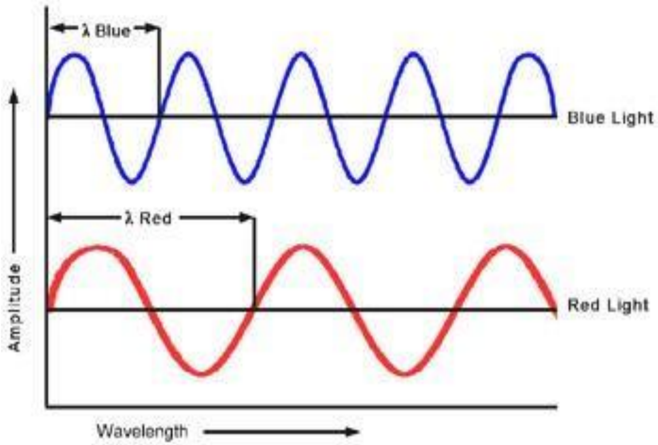
**These three properties of laser light are what can make it more hazardous than ordinary light. Laser light can deposit a lot of energy within a small area.**

LASER is Light Amplification by Stimulated Emission of Radiation.

| Laser as a light source | Non-laser light source |
|---|---|
| 1) Result of stimulated emission. | 1) Result of spontaneous emission |
| 2) Unidirectional, Angular spread is very small | 2) Diverges  |
| 3) Coherent.  | 3) Not coherent.  |
| **4) Highly intense.** | 4) Intensity is comparatively less. |
| 5) Monochromatic  | 5) May not be monochromatic.  |

# Monochromacity




Nearly monochromatic light

**Example:**

He-Ne Laser

λ0 = 632.5 nm

Δλ = 0.2 nm

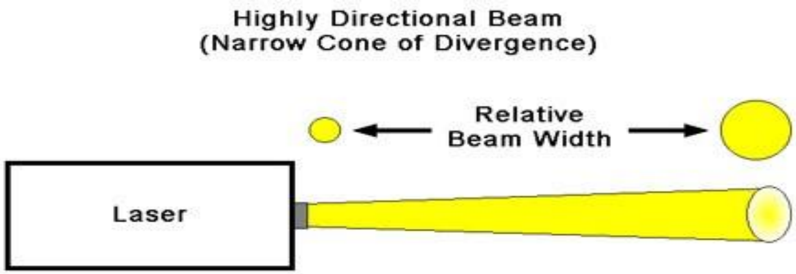
Diode Laser

λ0 = 900 nm

Δλ = 10 nm

Comparison of the wavelengths of red and blue light

# Directionality


Conventional light source Divergence angle ($\theta_d$)

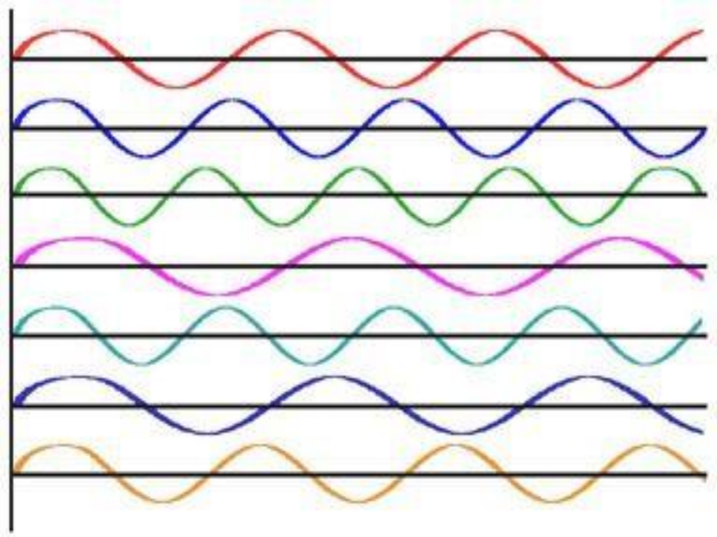
**Beam divergence:** $\theta_d = \beta \lambda / D$

$\beta \sim 1$ = f(type of light amplitude distribution, definition of beam diameter)

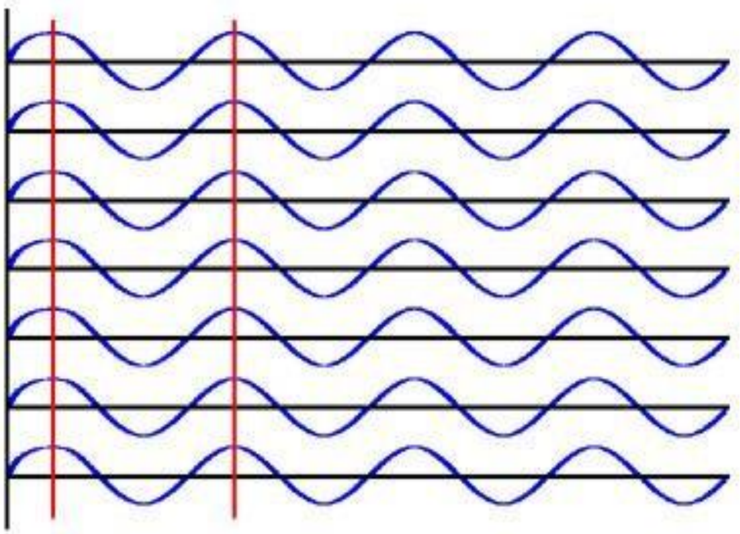
$\lambda$ = wavelength

*D = beam diameter*

# Coherence

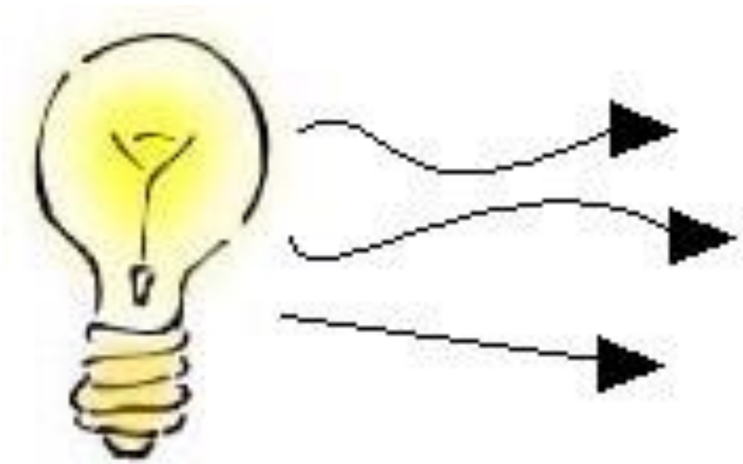


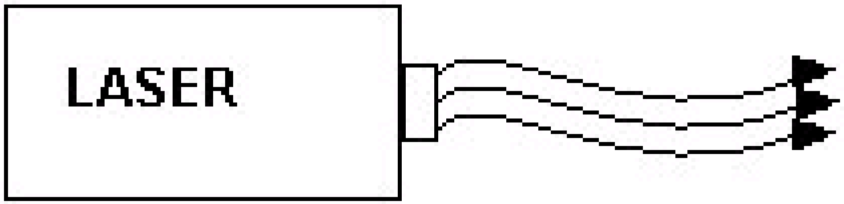
Incoherent light waves



Coherent light waves

# Incandescent vs. Laser Light



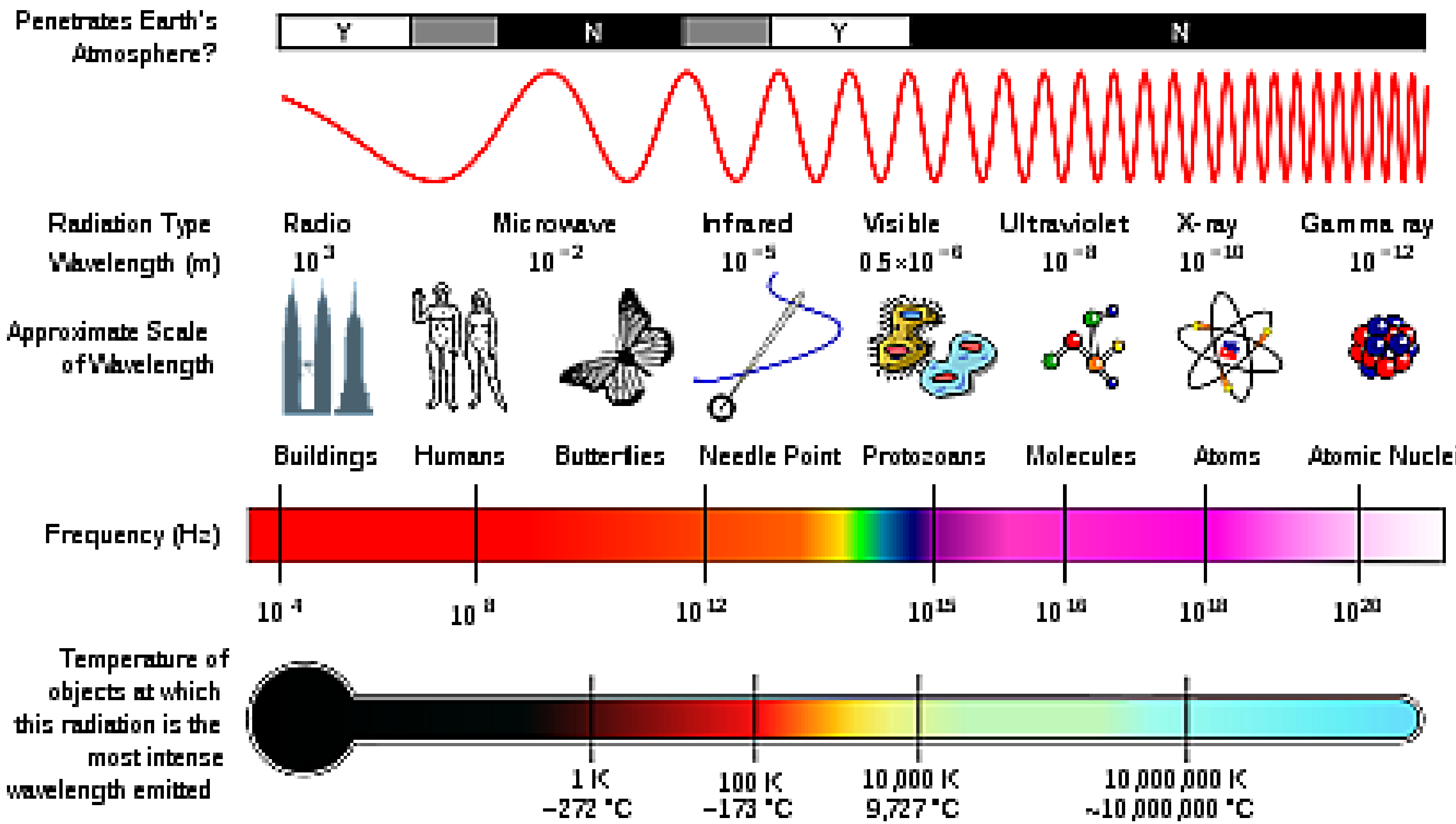



1. Many wavelengths
2. Multidirectional
3. Incoherent

1. Monochromatic
2. Directional
3. Coherent

## How LASERs are different compared to X-rays?

| LASERs | X-rays |
|---|---|
| 1) Wavelength of few thousand angstroms. | 1) Wavelength of few angstroms. |
| 2) LASERs are highly coherent. | 2) X-rays are not highly coherent. |
| 3) LASERs are obtained due to phenomenon called stimulated emission of radiation. | 3) X-rays are given out when high speed electrons strike the target of high atomic number and melting point. |


Penetrates Earth's Atmosphere?
Y
N
Y
N
Radiation Type
Wavelength (m)
Radio
$10^{3}$
Microwave
$10^{-2}$
Infrared
$10^{-5}$
Visible
$0.5\times10^{-6}$
Ultraviolet
$10^{-8}$
X-ray
$10^{-10}$
Gamma ray
$10^{-12}$
Approximate Scale of Wavelength
Buildings
Humans
Butterflies
Needle Point
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
$10^{4}$
$10^{8}$
$10^{12}$
$10^{15}$
$10^{16}$
$10^{18}$
$10^{20}$
Temperature of objects at which this radiation is the most intense wavelength emitted
1 K
−272 °C
100 K
−173 °C
10,000 K
9,727 °C
10,000,000 K
~10,000,000 °C

- Light consists of discrete bundles or chunks (quantum) of energy.
- Energy is emitted or absorbed in distinct units or quanta. Energy of each bundle is "$h\nu$". - Max Planck
- Photon represents minimum energy unit of light.
- While explaining photoelectric effect, Albert Einstein also proposed the existence of such discrete bundles of energy.
- Each photon carries energy '$h\nu$' where '$\nu$' is frequency of light wave.
- Light energy cannot have arbitrary values but must be multiple of '$h\nu$'.

# Basic concepts for a laser

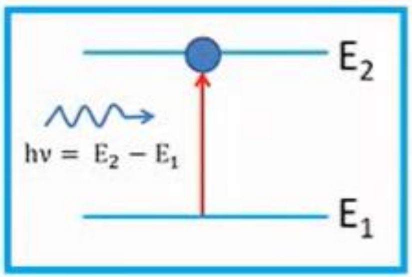
- Absorption
- Spontaneous Emission
- Stimulated Emission
- Population inversion

## Ground State of an atom :

- The lowest stable state of the atom.
- Electrons move in their respective orbits without emitting energy.

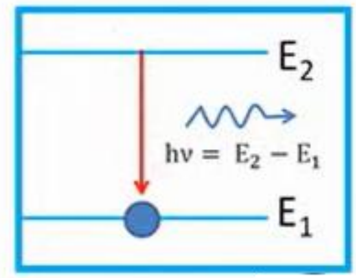
## Excited State of an atom :

- If electrons get sufficient energy, they jump to the higher energy level and the atom is said to be excited state.

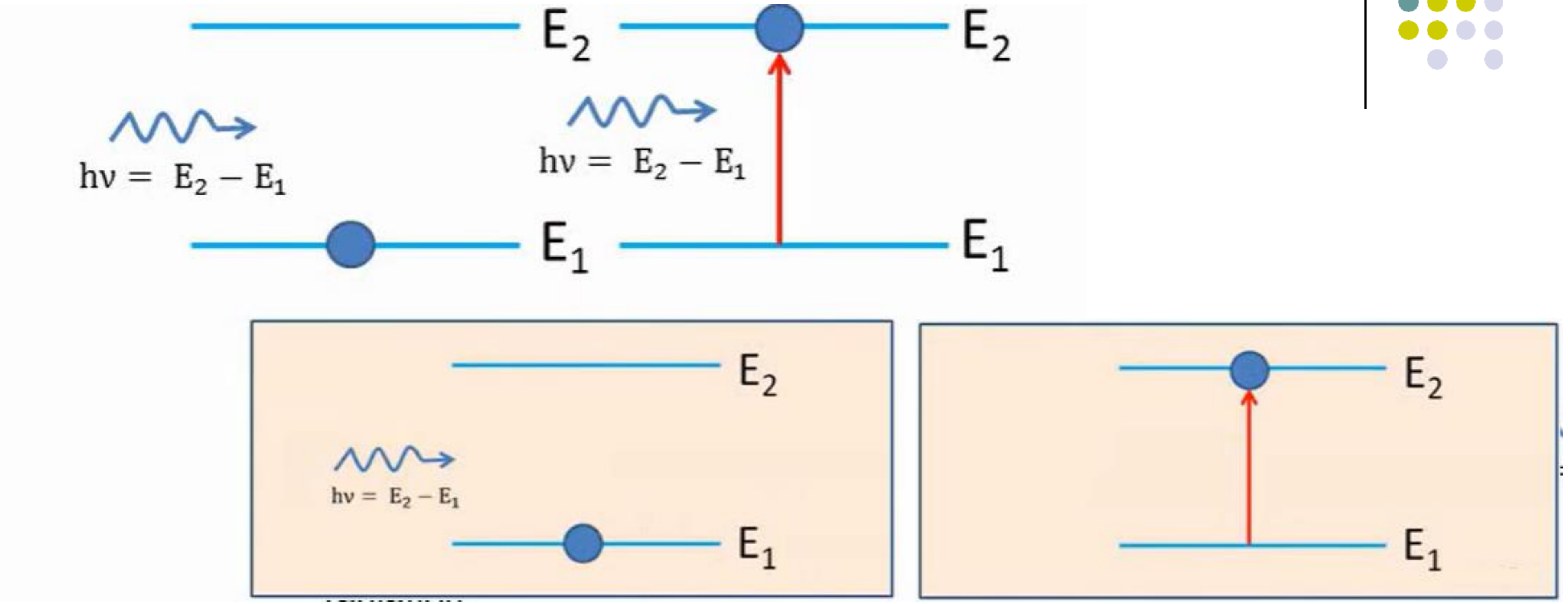



## Quantum Transition :

- Passing of an atom from one energy state to the other state.
- Whenever quantum transition occurs between energy states $E_1$ and $E_2$, energy $E_2 \sim E_1 = h\nu$ is absorbed or released as a radiation.

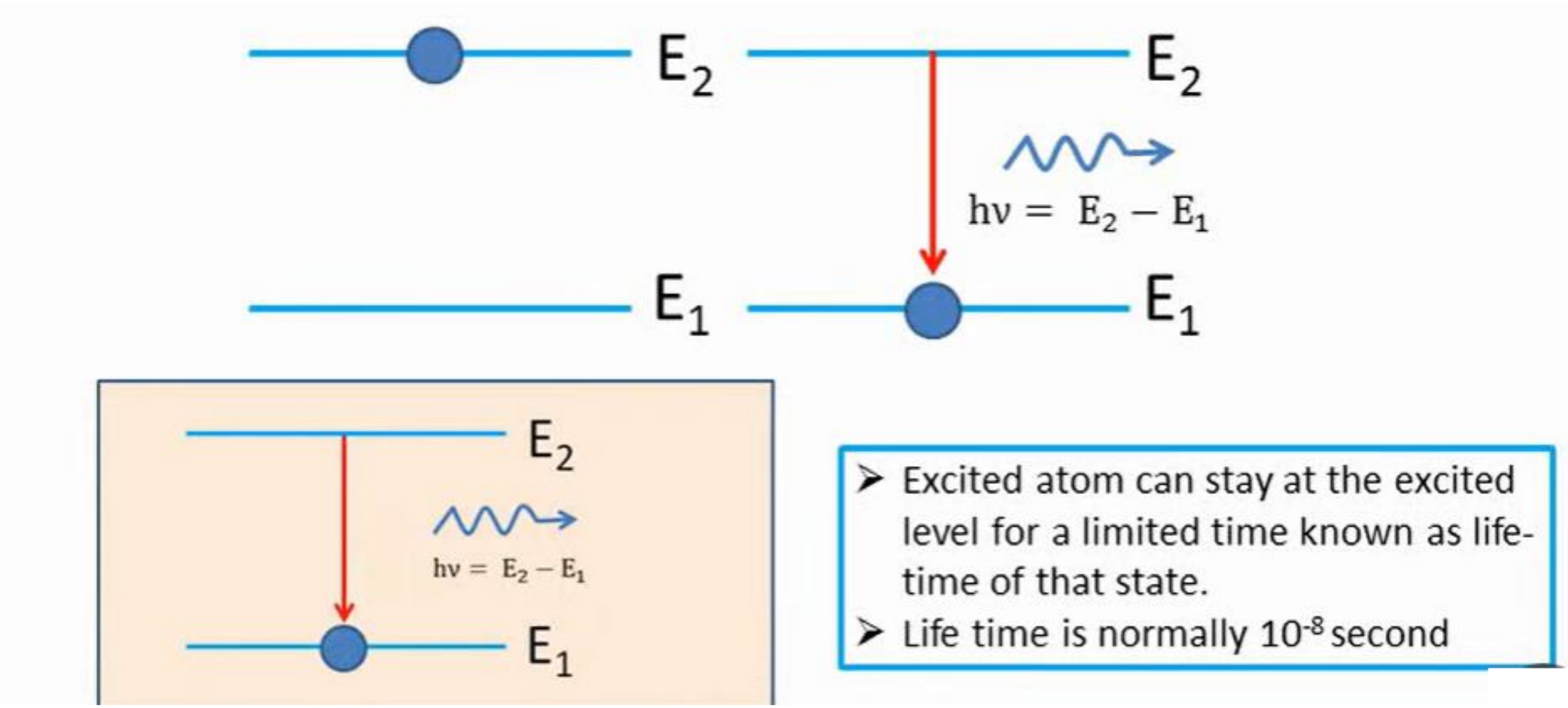


# Absorption



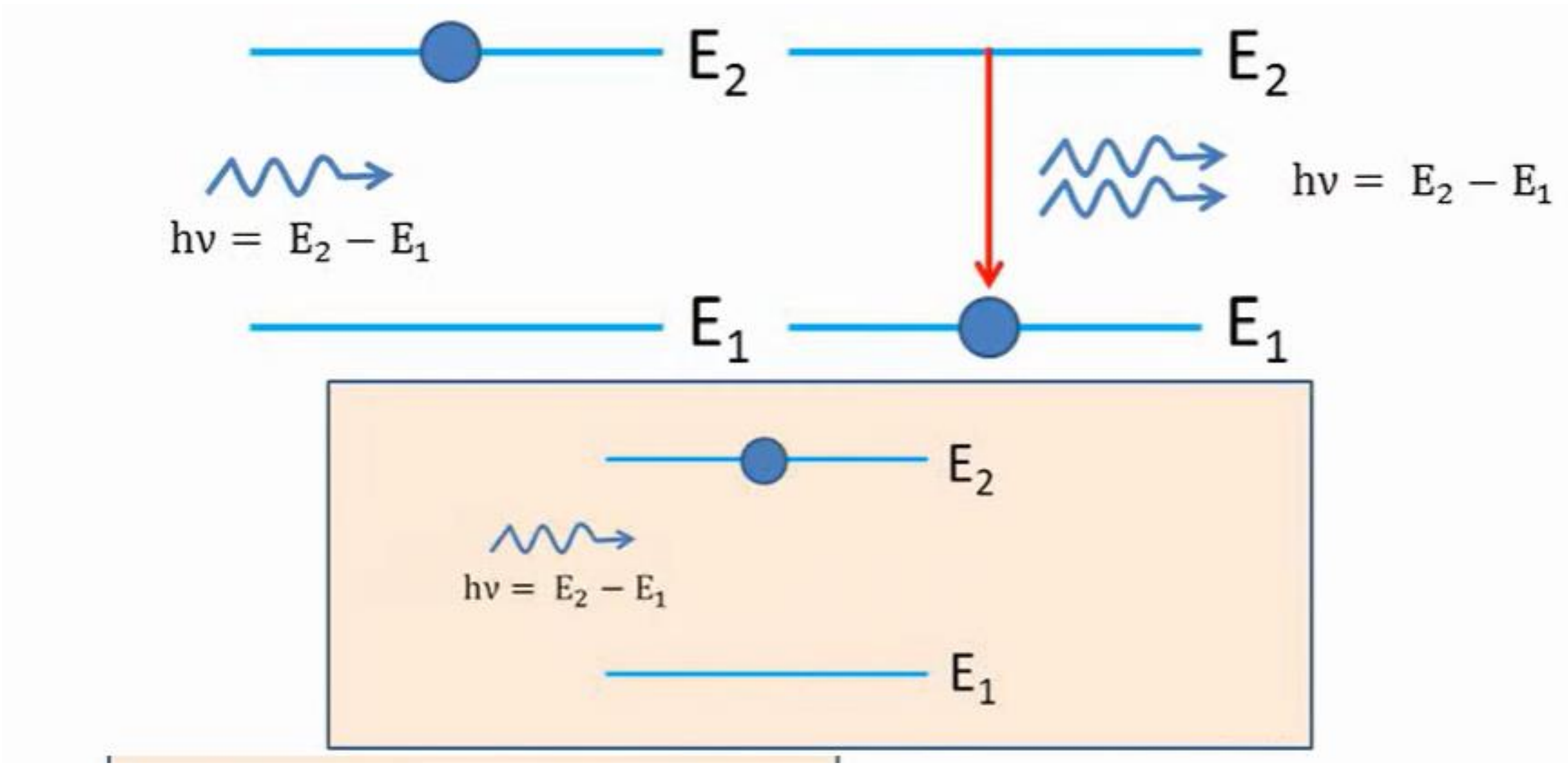

- Energy is absorbed by an atom, the electrons are excited into vacant energy shells.

# Spontaneous Emission




- The atom decays from level 2 to level 1 through the emission of a photon with the energy *hv*. It is a completely random process.

# Stimulated Emission



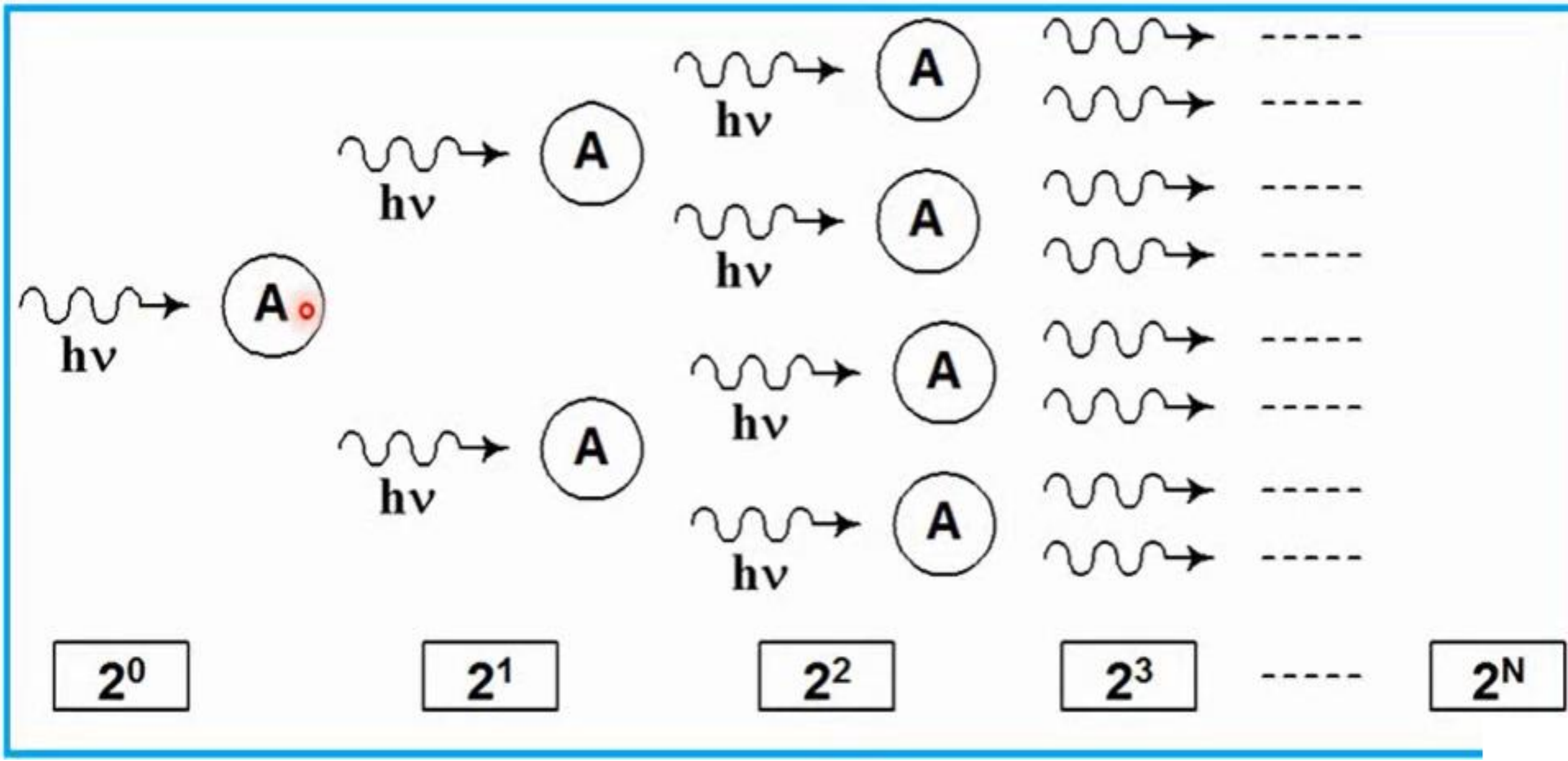

atoms in an upper energy level can be triggered or stimulated in phase by an incoming photon of a specific energy.

# Stimulated Emission

The stimulated photons have unique properties:

- In phase with the incident photon
- Same  wavelength as the incident photon
- Travel in same direction as incident photon

| Spontaneous Emission | Stimulated Emission |
| --- | --- |
| 1) Spontaneous emission is a result of the transition of an atom from the excited state to the lower energy state which happens due natural tendency of the atom to attain minimum energy. | 1) Stimulated emission of radiation is the process in which photons are used to stimulate atom in excited state to fall down to lower energy state. |
| 2) No external agent is involved. | 2) Photons need to be incident as stimuli. |
| 3) Results in ordinary light. | 3) Can be utilized to get Laser beam. |
| 4) Light obtained is not coherent. | 4) Coherent light can be obtained. |




Light Amplification continues till the atoms available in excited state

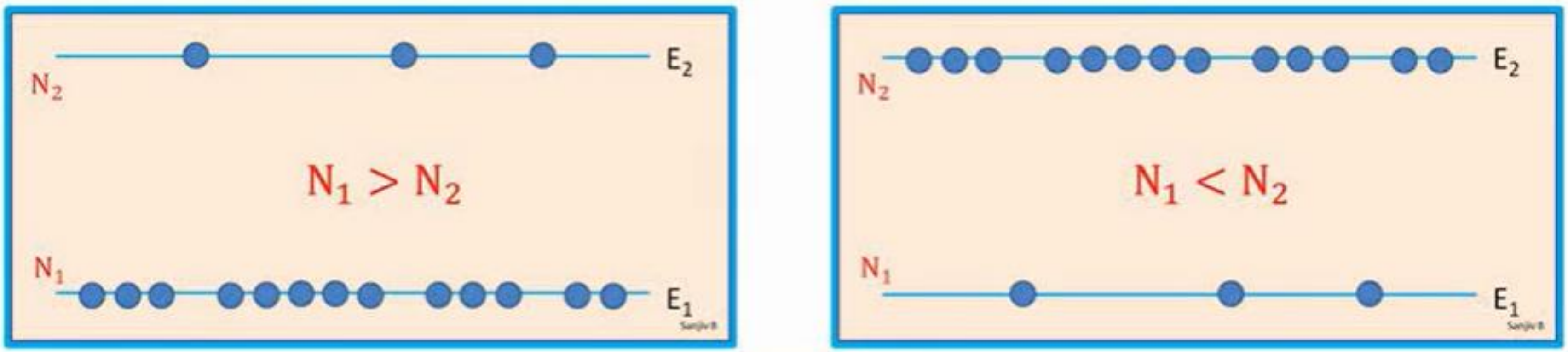
# Population Inversion

- A state in which a substance has been energized, or excited to specific energy levels.
- More atoms or molecules are in a higher excited state.
- The process of producing a population inversion is called pumping.
- Examples:

→by lamps of appropriate intensity

→by electrical discharge

# Population Inversion



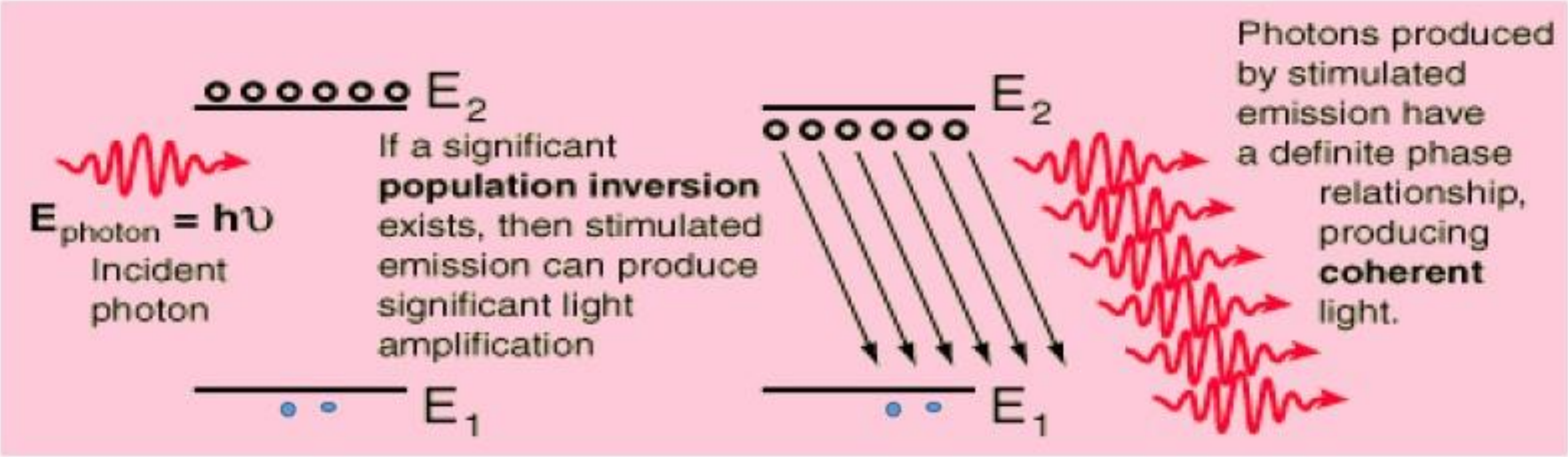

$N_1$ = Number of atoms in the lower energy level.
$N_2$ = Number of atoms in the higher energy level.

In Normal equilibrium, $N_1 > N_2$

Stimulated emission to be effective for light amplification, it should occur at large scale. This is achieved by adjusting $N_2 > N_1$

Getting more number of atoms in higher energy level than the lower energy level ($N_2 > N_1$) is called Population Inversion.

# Condition for Lasing




**Population Inversion**

When no. of atoms per unit volume in higher energy state becomes greater than that of no. of atoms per unit volume in lower energy state, this condition is called "Population inversion". This sets stimulated emission and emits identical photons as of incident photon.

"Threshold Condition For Lasing"

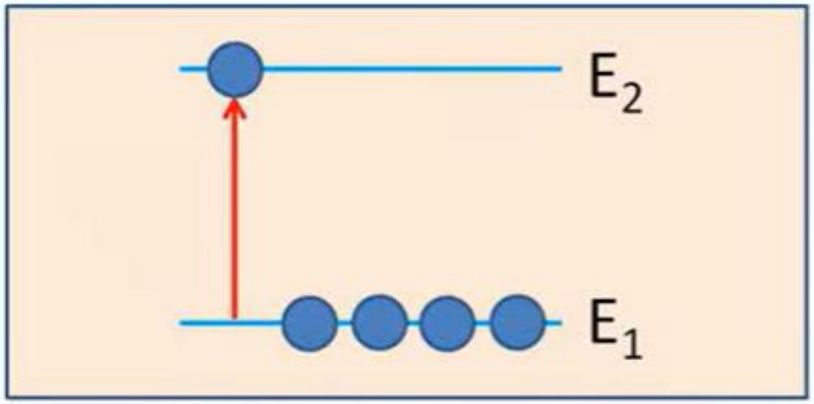
# Pumping

•Optical: flashlamps and high-energy light sources

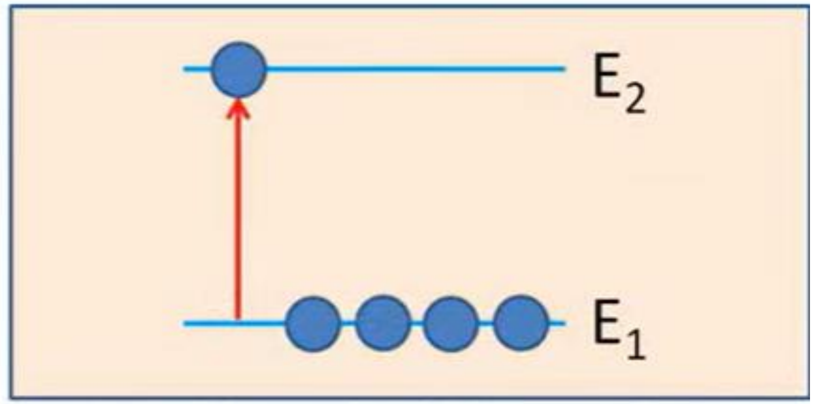
•Electrical: application of a potential difference across the laser medium

•Semiconductor: movement of electrons in ¯junctions,‖ between ¯holes‖

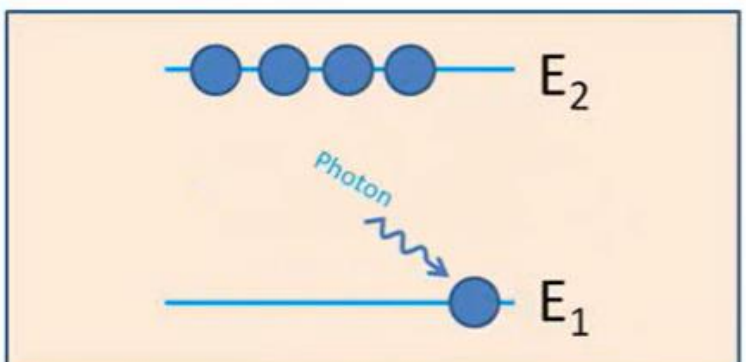
- To achieve population inversion, atoms must be continuously promoted from lower energy level to the higher energy level.
- The process by which atoms are raised from the lower energy level to the higher energy level is called Pumping.



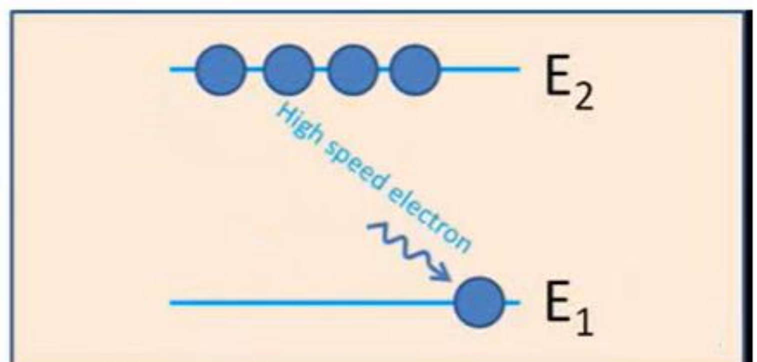

Optical Pumping




Electrical Pumping



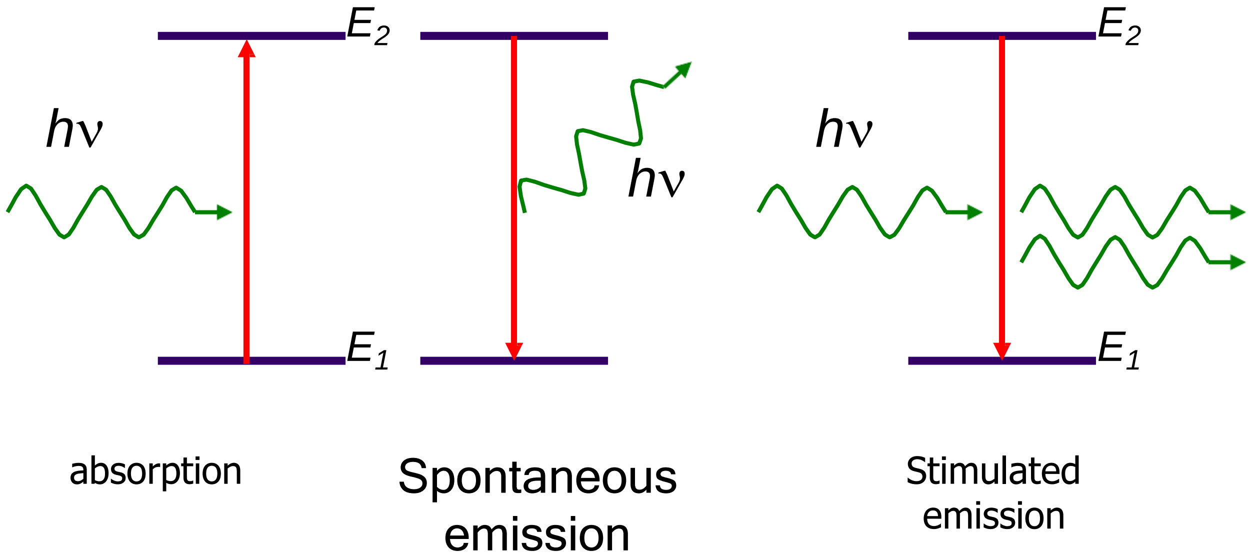

Optical Pumping

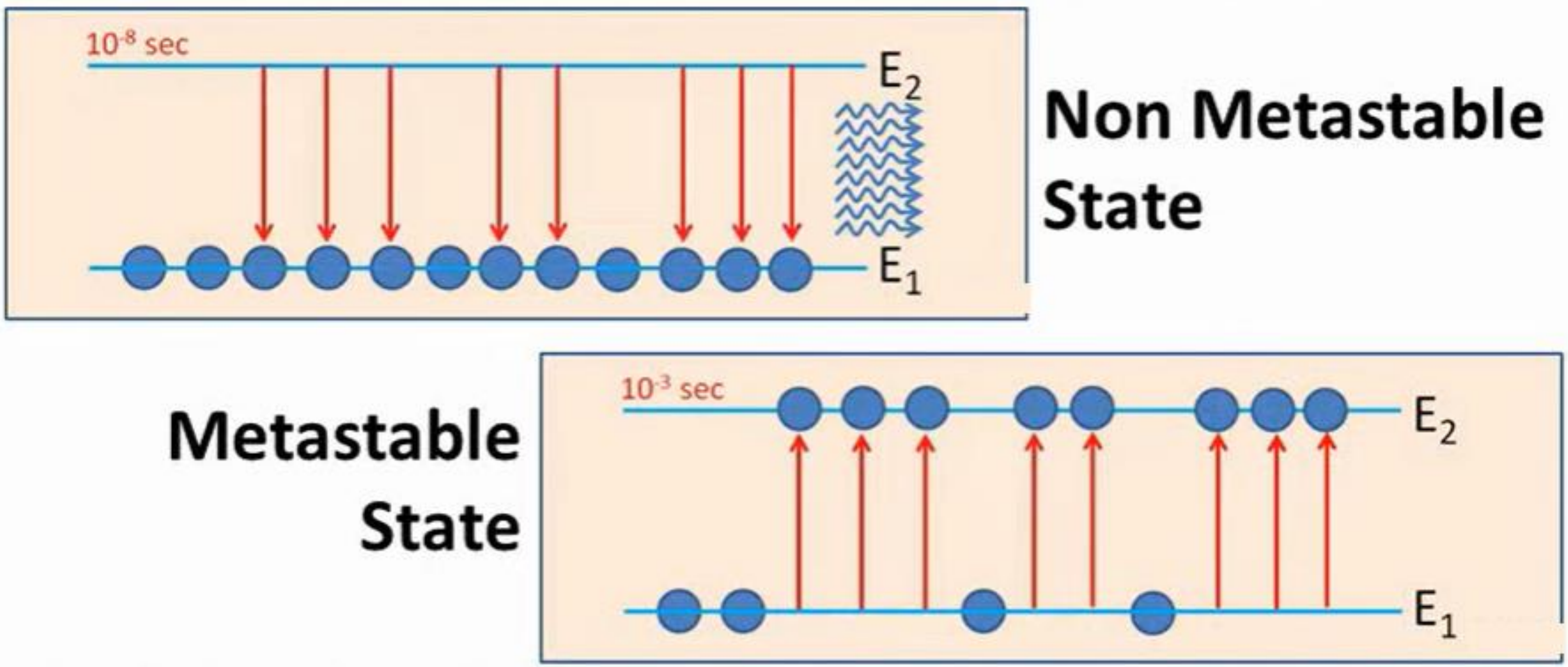



Electrical Pumping

# Two level system

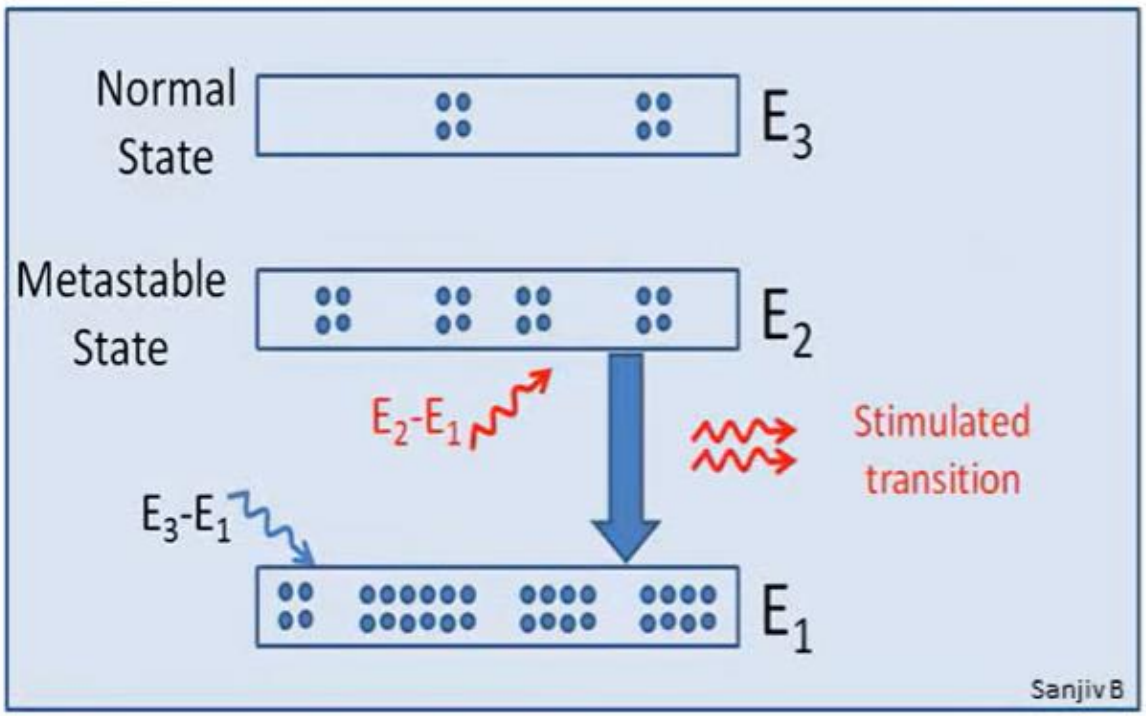
$h\nu = E_2 - E_1$

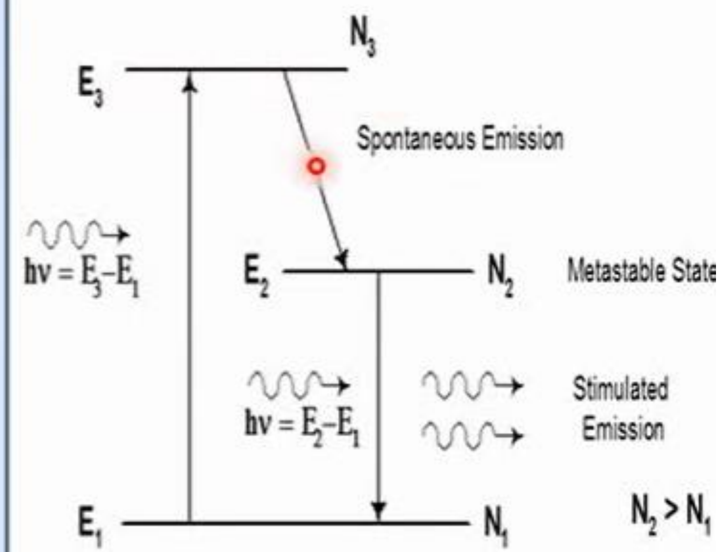




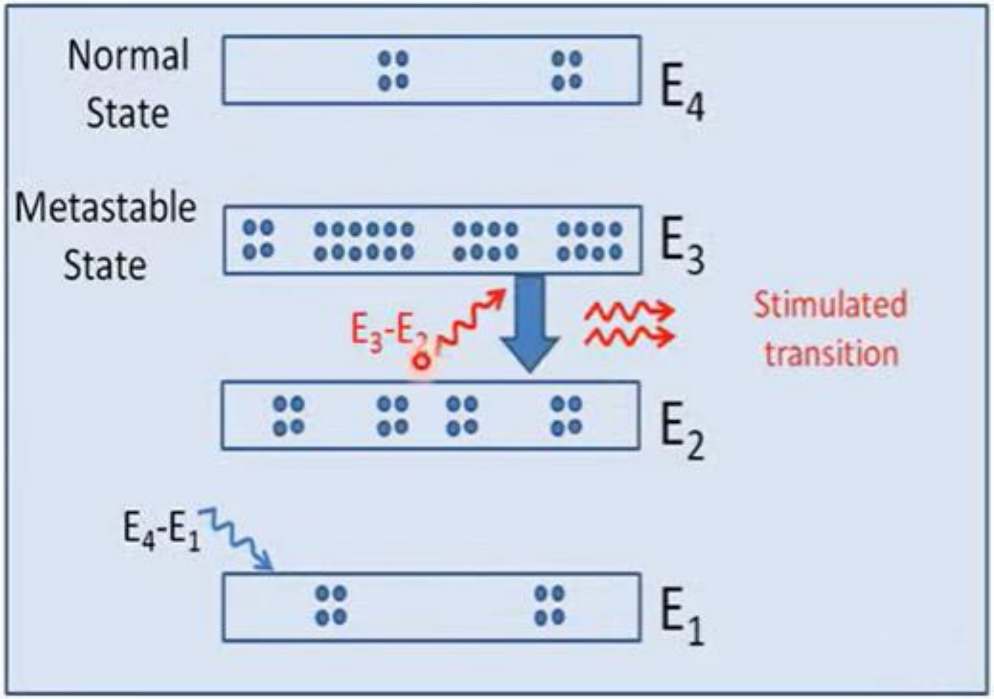

If the metastable state does not exist, there could be no population inversion and hence, no stimulated emission and hence no laser operation.

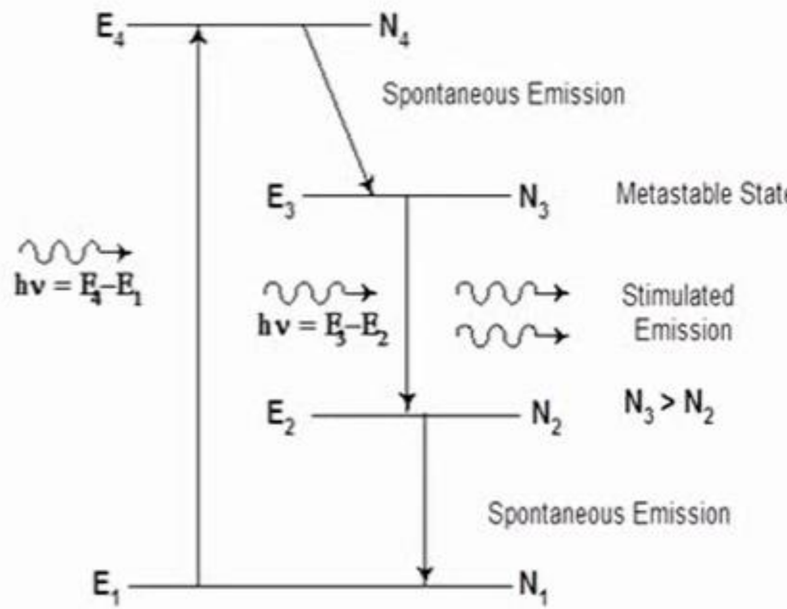
# Three level system



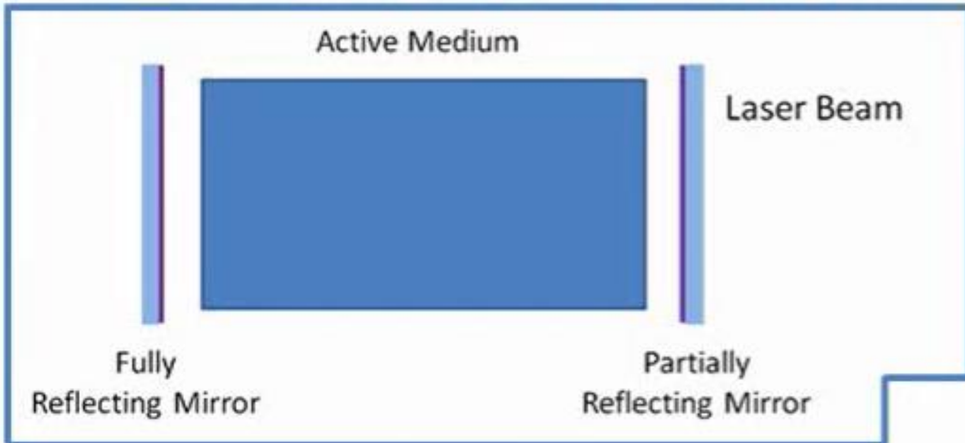



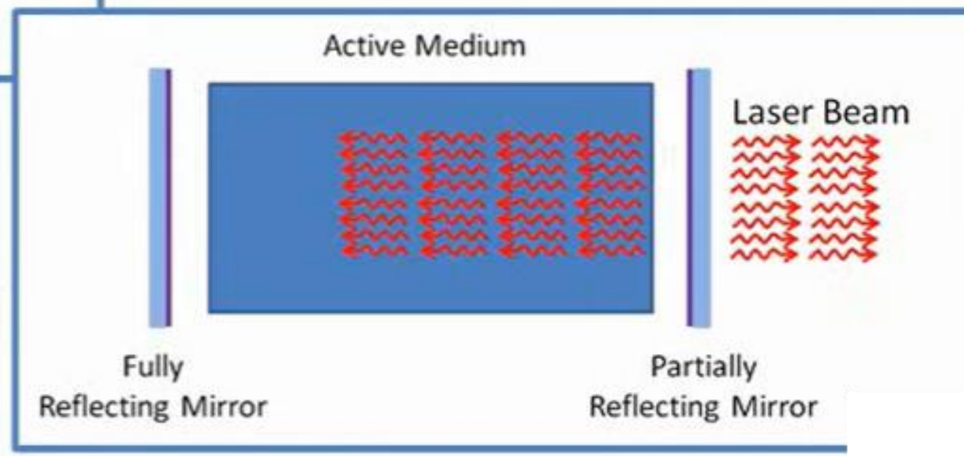
# Four level system



# Resonant Cavity

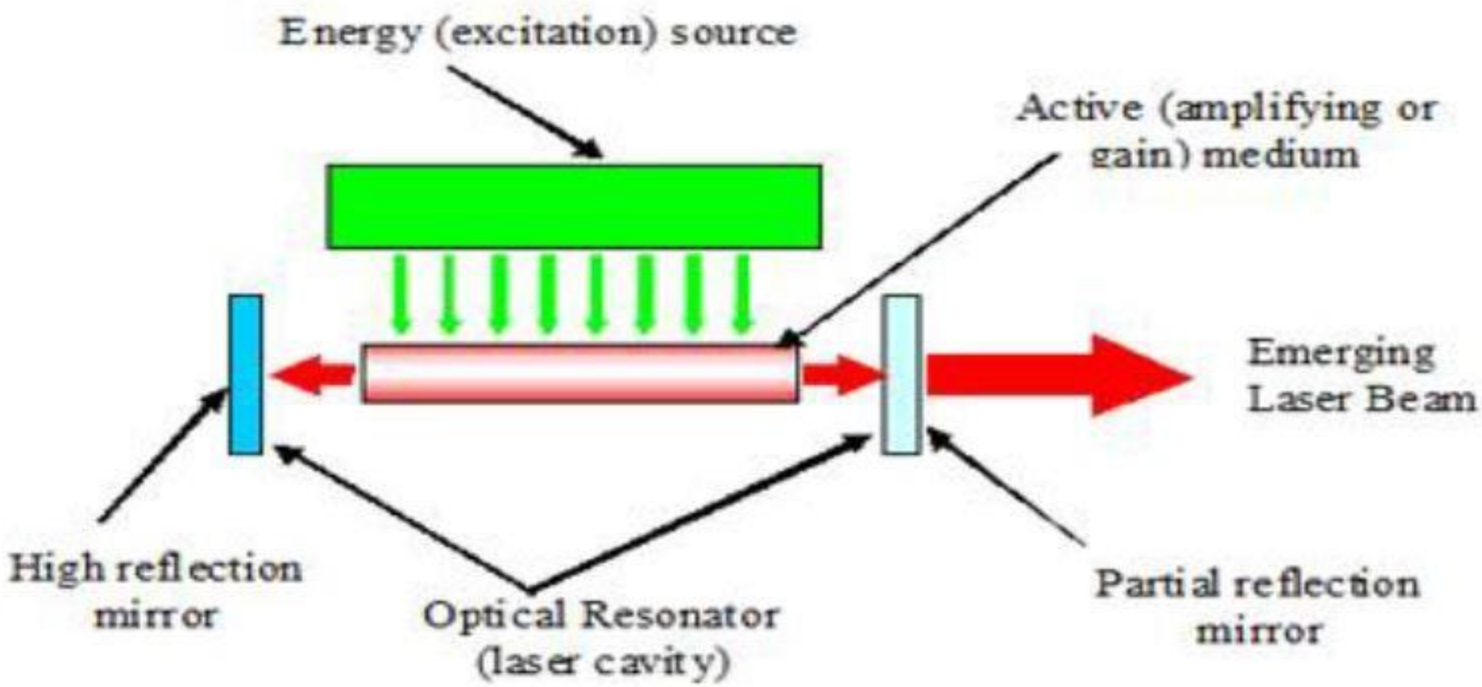



## Role of Resonant Cavity

1. Resonant cavity is useful for enhancing the light amplification.
2. Resonant cavity is used to get a laser beam in one direction.

# Components of LASER



# Planck's law describes the spectral density

- **Planck's radiation law** is a mathematical relationship that describes the **spectral-energy distribution of radiation emitted by a blackbody**. The law was formulated in 1900 by German physicist Max Planck. Planck's law is based on the assumption that the energy of an electrically charged oscillator in a cavity containing black-body radiation can only change in a minimal increment, or quantum of radiation. It is a pioneering result of modern physics and quantum theory.
- Planck's radiation law shows that as the temperature of a body increases, the total radiated energy increases and the peak of the emitted spectrum shifts to shorter wavelengths

- Planck's derivation of the blackbody radiation law is justly lauded as marking the beginning of quantum mechanics. Planck found that, for an oscillator at equilibrium within a cavity, the intensity of radiation at frequency ω would be given by

$$I(\omega)d\omega = \frac{\hbar\omega^3 d\omega}{\pi^2 c^2 (e^{\hbar\omega/kT} - 1)}$$

But Planck's derivation of the above formula used a mixed bag of contradictory assumptions, some of which were later found to be inconsistent with experimental fact.

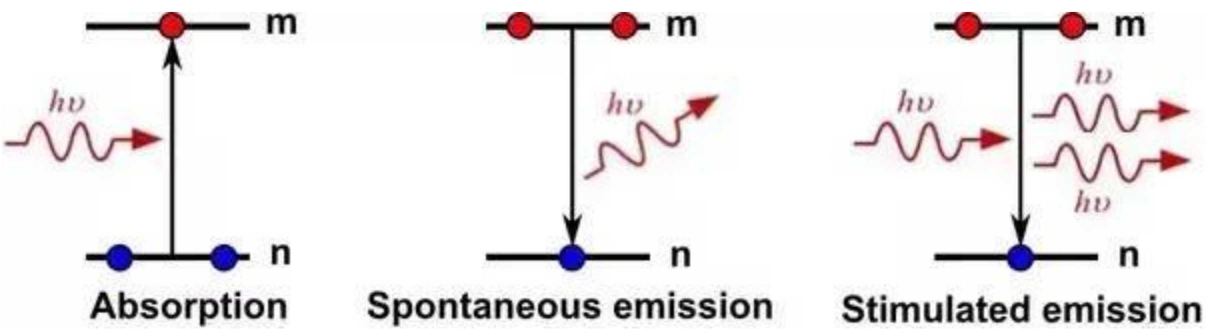
# Einstein Analysis to Planck's work

- His derivation used classical electrodynamics to relate the mean energy of an oscillator to the energy density of the radiation field
- Planck then turned around and assumed that this classical oscillator was split into equally spaced energy levels.
- Planck considered that the oscillators were quantized but not the light. But Einstein had demonstrated in 1905 that light itself displayed quantum behavior.
- Bohr had demonstrated that all systems of atoms had energy levels, but the energy levels were in general **not** equally spaced.

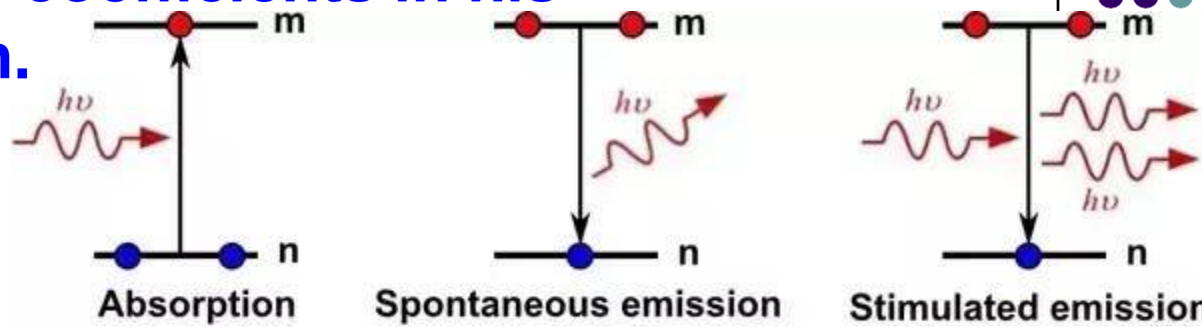
Therefore, although Einstein praised Planck's courage in making the quantum leap – ―his derivation was of unparalleled boldness‖ – he noted that Planck's analysis ―remains unsatisfactory that the electromagnetic-mechanical analysis [that Planck used] is incompatible with quantum theory … . Since Bohr's theory of spectra has achieved its great successes, it seems no longer doubtful that the basic idea of quantum theory must be maintained.‖

# Einstein Analysis to Planck's work

Going further, Einstein stated that the classical elements in Planck's derivation must be replaced by quantum-theoretical contemplations on the interaction between matter and radiation.‖



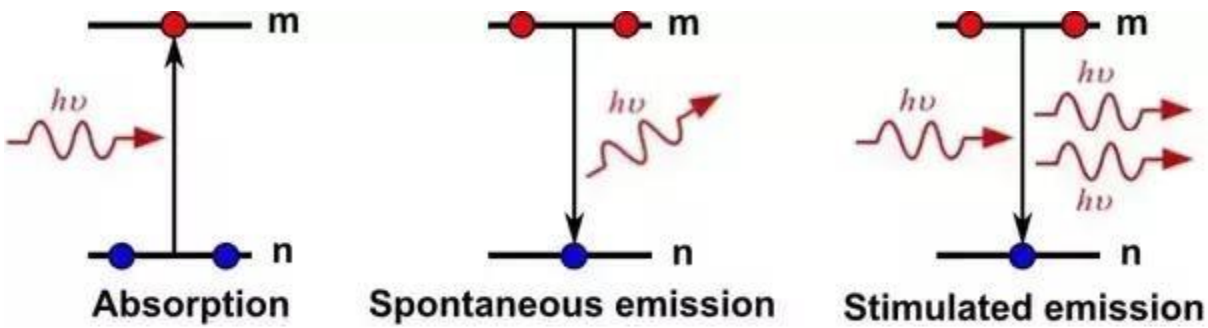
# Einstein's A and B coefficients in his theory of radiation.




Consider a pair of energy levels of an atom (or molecule), *m* and *n*.
When light of the right frequency shines on the atom, it can absorb a photon and make a transition from state *n* to state *m* with a probability that is proportional to the intensity of the light.
Einstein designated the proportionality constant for this transition $B_{nm}$.

According to Einstein, a finite probability exists for an excited atom to undergo *spontaneous emission* of a photon.

He designated this probability $A_{mn}$, a number which is independent of whether light is shining on the atom or not.




Besides spontaneous emission, Einstein also considered *stimulated emission* events.
The probability of stimulated emission was proportional to the intensity of the incoming radiation with a proportionality constant of $B_{mn}$.

Einstein was able to demonstrate that $B_{nm}=B_{mn}$.
In other words, the induced emission probability and the absorption probability must be equal.

Let $N_n$ be the number of atoms in state $n$ and $N_m$ be the number of atoms in state $m$. Then the rate at which atoms go from state $n$ to state $m$ is given by

$$R_{n\to m} = N_n B_{nm} I(\omega)$$

while the rate at which atoms go from state $m$ to state $n$ is given by

$$R_{m\to n} = N_m [A_{mn} + B_{mn} I(\omega)].$$

At equilibrium, $R_{n\to m} = R_{m\to n}$

**Einstein pointed out that this equilibrium condition must hold between any pair of states, as well as balancing out overall.** Unlike Planck's derivation, where it was necessary for the energy levels to be equally spaced before a sum could be taken of the contributions of an infinite series of harmonic oscillators, Einstein's energy levels had no restrictions on their spacing.

From the Boltzmann distribution, we know the ratio of $N_m$ to $N_n$ at equilibrium:

$$N_m = N_n e^{-(E_m - E_n)/kT}$$

Einstein assumed that only light with a frequency corresponding to the energy difference would be effective in driving the transition from $n$ to $m$, so that $E_m - E_n = \hbar\omega$. Hence,

$$N_m = N_n e^{-\hbar\omega/kT}$$

We can thus write

- $N_n B_{nm} I(\omega) = N_m [A_{mn} + B_{mn} I(\omega)]$
- $B_{nm} I(\omega) e^{\hbar\omega/kT} = A_{mn} + B_{mn} I(\omega)$
- $I(\omega) = \frac{A_{mn}}{B_{nm} e^{\hbar\omega/kT} - B_{mn}}$
- Since $I(\omega)$ goes to infinity as temperature goes to infinity, $B_{nm} = B_{mn}$. In other words, the induced emission probability and the absorption probability must be equal.
- $I(\omega) = \frac{A_{mn}/B_{mn}}{e^{\hbar\omega/kT} - 1}$
- Einstein argued that he could use Wien's distribution law (also called Wien's radiation law) in the numerator to deduce $A_{mn}/B_{mn} = \hbar\omega^3/\pi^2 c^2$



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# Einstein's Relation

Under thermal equilibrium, the mean population $N_1$ and $N_2$ in the lower energy level ($E_1$) and upper energy level ($E_2$) respectively must remain constant

Number of atoms absorbing photons per second per unit volume = Number of atoms emitting photons per second per unit volume

Number of atoms absorbing photons per second per unit volume $= B_{12}\ \rho(v)\ N_1$ (1)

Number of atoms emitting photons per second per unit volume $= A_{21} N_2 + B_{21}\ \rho(v)\ N_2$ (2)

In Equilibrium,

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

$$\therefore \quad \rho(v)\left[B_{12}\ N_1 - B_{21}\ N_2\right] = A_{21}\ N_2$$

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

Dividing numerator and denominator by $B_{12}\ N_2$,

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

**$\rho(v)$ is the energy density of incident light**

**$B_{12}$, $A_{21}$ and $B_{21}$ are Einstein coefficients of absorption, spontaneous emission and stimulated emission respectively**

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

From Boltzmann equation, population N of energy level E at temperature T is given by -

$$N = e^{\frac{-E}{kT}}$$

$$\text{Therefore, } N_1 = e^{\frac{-E_1}{kT}} \quad (4)$$

$$N_2 = e^{\frac{-E_2}{kT}} \quad (5)$$

Divide (4) by (5)

$$\therefore \frac{N_1}{N_2} = e^{-(E_1-E_2)/kT} = e^{(E_2-E_1)/kT} = e^{h\nu/kT} \quad (6)$$

Substituting in (3)

$$\rho(v) = \frac{A_{21}}{B_{12}}\left[\frac{1}{e^{h\upsilon/kT} - \frac{B_{21}}{B_{12}}}\right] \quad (7)$$

$$\rho(v) = \frac{A_{21}}{B_{12}} \left[ \frac{1}{e^{h\upsilon/kT} - \frac{B_{21}}{B_{12}}} \right] \quad (7)$$

This radiation must be identical to the radiation formula given by Planck which gives density of photons as -

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

Comparing (7) and (8)

$$\therefore B_{21} = B_{12} \quad (9)$$

*and* $\frac{A_{21}}{B_{12}} = \frac{8\pi h \upsilon^3}{c^3}$

$$\text{i.e.} \quad A_{21} = \frac{8\pi h \upsilon^3}{c^3} B_{12} \quad (10)$$

| Einstein Relation | Physical Significance |
| --- | --- |
| $\therefore B_{21} = B_{12}$ (9) | Thus probability of upward transition is equal to probability of downward transition. |
| $A_{21} = \frac{8\pi h \upsilon^3}{c^3} B_{12}$ (10)<br>$A_{21} = \frac{8\pi h \upsilon^3}{c^3} B_{21}$ | Spontaneous emission dominates over the stimulated emission if the energy difference (E2-E1 = hν) between the two levels is high.<br>So it is difficult to achieve lasing action in higher frequency ranges and low wavelengths. |

**Find the ratio of population of higher energy state to lower energy state when the optical pumping is used at $27^0C$ and photons of wavelength $6982 \times 10^{-8}m$ are emitted.**

Given : $E_2 - E_1 = h\nu = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{6982 \times 10^{-8}} = 2.848 \times 10^{-21}J$

$T = 27^0C = 300^0K, \quad k = 1.38 \times 10^{-23}J/^0K$

We know, population of energy level $E = N = e^{\frac{-E}{kT}}$

$N_2$ = population of atoms in higher energy state and

$N_1$ = population of atoms in lower energy state

$$\frac{N_2}{N_1} = e^{\frac{-(E_2-E_1)}{kT}} = e^{\frac{-(2.848\times10^{-21})}{1.38\times10^{-23}\times300}} = 0.503$$

विश्वतीर्थनामृतं ज्ञानम्

## If wavelength of the laser beam is 6550 $A^0$, calculate the energy and momentum of photon.

Given : $\lambda = 6550\ A^0 = 6550 \times 10^{-10}$m

$$E = h\nu = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{6550 \times 10^{-10}} = 3.0366 \times 10^{-19} J$$

According to De Broglie hypothesis,

$$\lambda = \frac{h}{p}$$

$$\therefore p = \frac{h}{\lambda} = \frac{6.63 \times 10^{-34}}{6550 \times 10^{-10}} = 1.012 \times 10^{-27}\ kg\frac{m}{s}$$

विश्वशीलनामृतं ज्ञानम्

# Types of LASER

Lasers are classified into 6 types based on the types of medium used in them, and they are:

- Solid-state lasers (Ruby, Nd: YAG)
- Gas lasers (CO2 and He-Ne, Ar-ion)
- Liquid lasers (Dyes: ethylene glycol, ethyl, or methyl, as the laser medium)
- Semiconductor lasers (GaAs based PN Jun Diode)
- Chemical lasers( HF and Deuterium Fluoride)
- Metal-vapour lasers (He-Cd and Cu Vapour)

**Semiconductor and solid-state lasers are both lasers with a solid lasing medium, but they have several differences:**

- **Solid-state lasers are optically pumped, meaning they receive energy in the form of light. Semiconductor lasers are excited by an electric current passing through them.**
- **Solid-state lasers are typically made of an optically transparent crystal or glass doped with activated ions or other substances. Semiconductor lasers are made of materials like gallium arsenide (GaAs), cadmium sulfide (CdS), indium phosphide (InP), and zinc sulfide (ZnS).**

# Types of LASER

## Types of Industrial Laser:

Depending on the followings:

1. The state of Lasing Material

   (Solid OR Gas)

2. The range of the laser wavelength

   (Short OR Large Wavelength)

3. The mode of operation

   (CW-Laser OR PW-Laser)

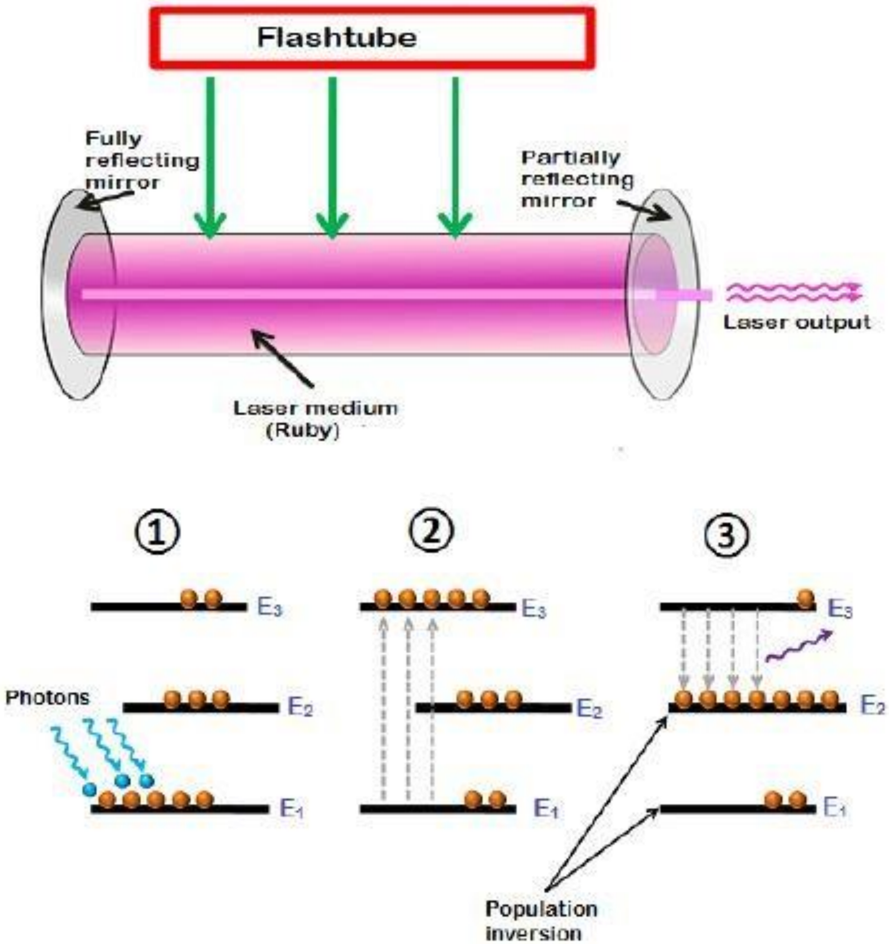
4. The pumping method

   (Optical Pumped OR Discharge Pumped)

# Applications:

- In CD, Blue-Ray, DVD, and HD-DVD players,
- Bar code readers;
- Laser pointers
- welding metal and other materials;
- "marking"—producing visible patterns such as letters;
- Military applications: range-finding, target designation, and illumination, weapons;
- Medicine: laser surgery (i,.e., correction of cornea in the eye), diagnostics, and therapeutic applications;
- Holography;
- Laser microscopy;

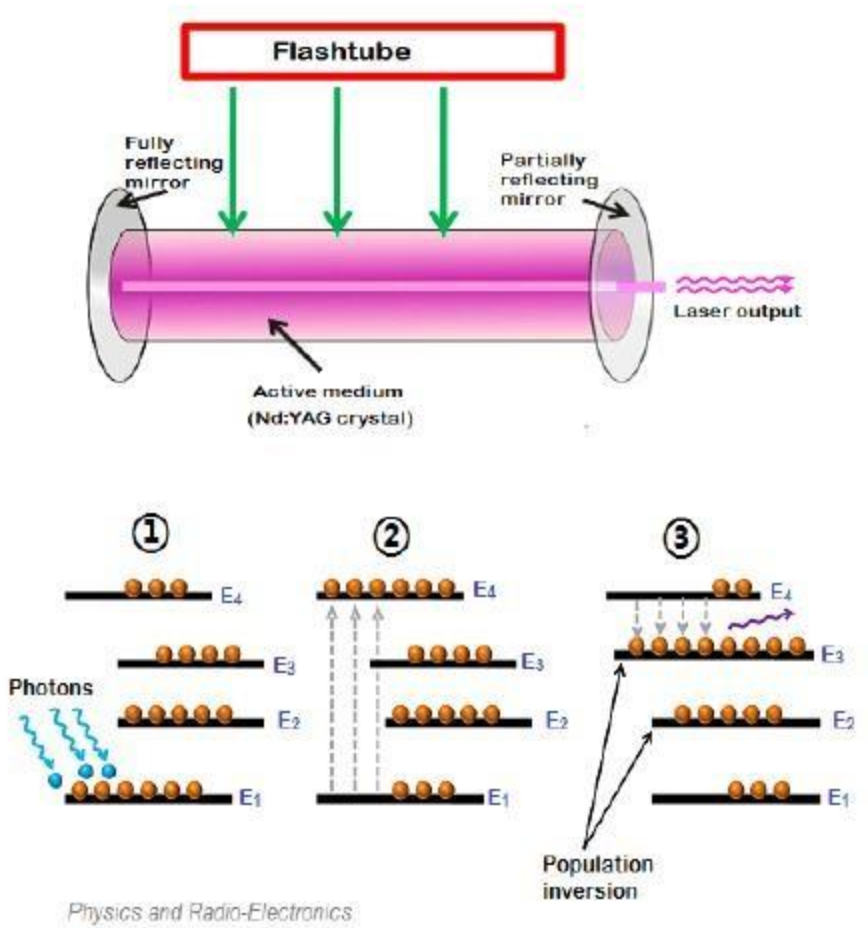
# Ruby Laser




$Cr - AlO_3$
Similar to Neodimium-YAG

Solid laser
pulsed
Pumping: Flashlamp
Excited atom: $Cr^{3+}$
Laser levels: $Cr^{3+}$
P = 100 MW
D = 0.5 … 5 mm
Divergence = 0.5 - 1 mrad
$\lambda$ = 694 nm
Cooling: water / air
Pulse width: 10 ns

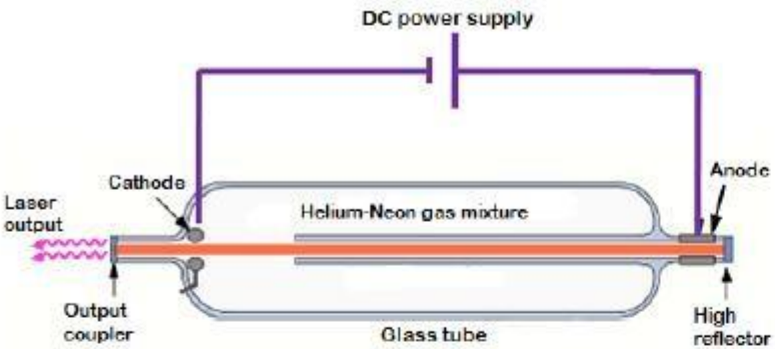
# Nd:YAG Laser

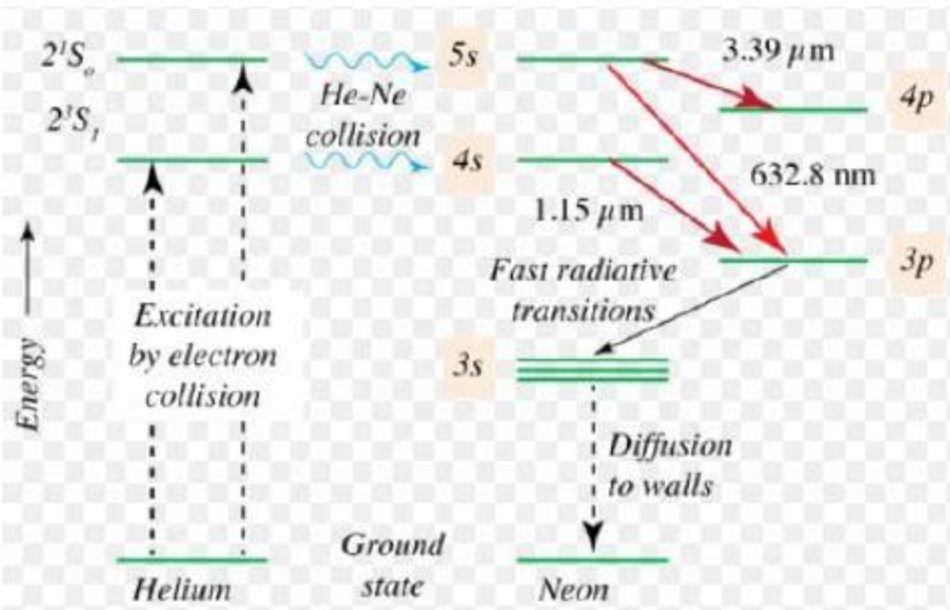



Neodimium - $Y_3Al_5O_{12}$ granite

- Solid laser
- Pulsed or C.W.
- Pumping: flashlamp
- Excited atom: $Nd^{3+}$
- Laser levels: $Nd^{3+}$
- P = 60 W (c.w.) … 1 MW
- D = 0.5 … 5 mm
- Divergence = 0.5 - 1 mrad
- λ = 1065 nm
- Cooling: water
- Pulse width: 10 ns (Q-switched)
- Similar: ruby, Er-YAG, Tm-YAG
- Non-linear optics: 532, 355, 266 nm

# He-Ne Laser



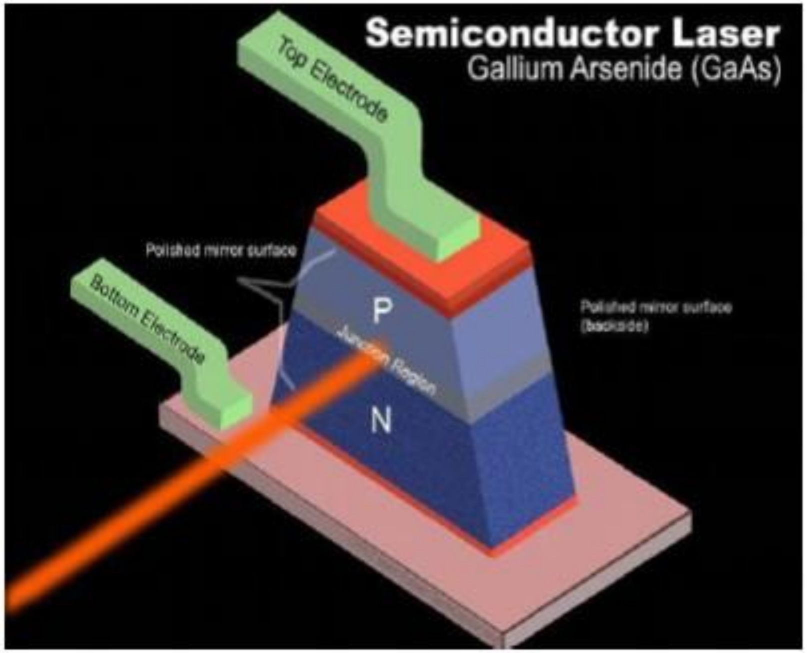

Gas (atomic) laser
continous wave (c.w.)
Pumping: electric pulse (
Excited atom: He
Laser levels: Ne
He:Ne = 10:1
p = 1 torr
Exit mirror: T = 2 %
P = 1 … 100 mW
D = 1 mm
Divergence = 1 mrad
λ = 632.8 nm
λ= 543 nm

# Semiconductor laser-Construction

**Active Medium**: Heavily doped Semiconductor material such as GaAs, InP, etc.

**Optical Resonator**:

- By cleaving two ends (110) optical resonator is obtained
- Due to refractive indices difference between material and air ideally R=33%.
- It is increased by coating both end with suitable materials such as $Al_2O_3$, $TiO_2$ etc.




**Excitation Source** : Current is pumping source.

# Working

- When p-n junction is forward bias, depletion region is reduced and hence causing diffusion of electrons and holes further and recombination of these majority carrier takes place which leads to emission of light.