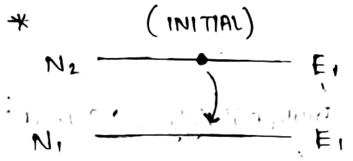
LASERS (Einstein's A, B coefficients):

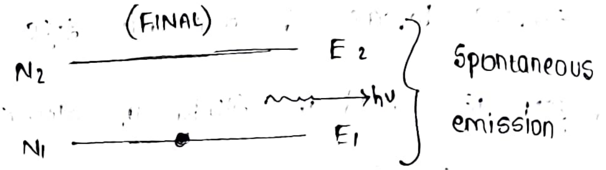
* There are 3 fundamental process that we will discuss.

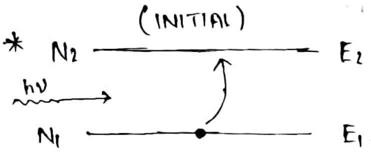
"Stimulated" & "Induced" radiation.



$\Upsilon_{21} \propto N_2$

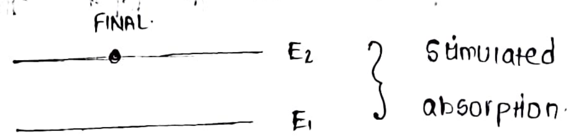
$\boxed{\Upsilon_{21} = A_{21} N_2}$

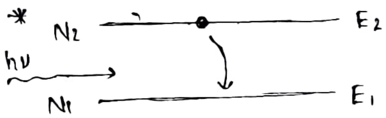


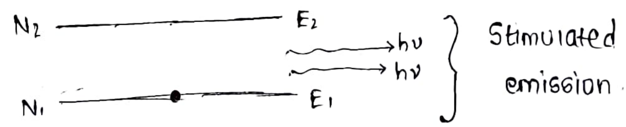


$\Gamma_{12} \propto N_1 u(\nu)$

$\boxed{\Gamma_{12} = B_{12} N_1 u(\nu)}$







$\Gamma_{21} \propto N_2 u(\nu)$

$\boxed{\Gamma_{21} = B_{21} N_2 u(\nu)}$

Υ_{ab} or Γ_{ab} $\longrightarrow$ no. of atoms coming from level a to level b per unit time.

$u(\nu)$ $\longrightarrow$ it is the energy density of incoming $h\nu$.

* By thermodynamical principle (principle of detailed balance)

$$\boxed{\Gamma_{12} = \Gamma_{21} + \Upsilon_{21}}$$

We have to compute $u(\nu)$ from above formula.

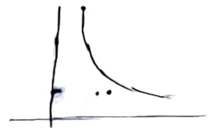
$$\boxed{u(\nu) = \frac{A_{21} N_2}{B_{12} N_1 - B_{21} N_2}}$$

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

$$\frac{N_1}{N_2} = \frac{e^{-E_1/KT}}{e^{-E_2/KT}} = \exp\left(\frac{h\nu}{KT}\right)$$

As energy level $(\uparrow)$, prob of e^- $(\downarrow)$.

i.e, $e^{-E/KT}$



$$u(\nu) = \frac{A_{21}}{B_{12}\left(e^{h\nu/KT} - \frac{B_{21}}{B_{12}}\right)}$$

imp

Significance of A, B coefficient :

A coefficiant is related to rate of spont. emission of light

B coeff. is related to absorption and stimulated emission of light.

* from Black body radiation :

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

$$\therefore \frac{A_{21}}{B_{12}} = \frac{8\pi h\nu^3}{c^3}, \quad \frac{B_{21}}{B_{12}} = 1$$

⇒ Write relation of Einstein's A, B coefficients : (15 M) ↳ FAT.

* Note :

The ratio of Stimulated emission over spontaneous emission is the following :

$$\frac{\Gamma_{21}}{\Gamma_{21}} = \frac{B_{21} N_2 u(\nu)}{A_{21} N_2} = \frac{1}{\left(e^{h\nu/KT} - 1\right)}$$

⇒ For what condition the ratio $\left(\frac{\text{Stimulated em. rate}}{\text{Spontane. em. rate}}\right)$ is 1 ?

Soln

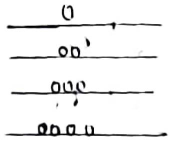
$$e^{\frac{h\nu}{KT}} = 2$$

$$\boxed{\frac{h\nu}{KT} = \ln 2}$$

1) Statement :

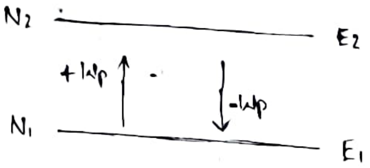
* In a two level system population inversion is not possible.

2) Goal : in a two level system this can't happen.



$N \propto e^{-E/kT}$ → in General

But in this two level system it is opposite.



Sign convention

$1 \longrightarrow 2 \ (+)$

$2 \longrightarrow 1 \ (-)$

* At a normal temp. the population of lower level is greater than upper level.

i.e, $N_1 > N_2$ initially.

* So the (atom/e^-) must be pumped in the upper level by producing energy equal to energy to the energy diff. b/w two level.

* The rate of change in the population in upper level

$$\frac{dN_2}{dt} = (+W_p N_1) + (-W_p N_2) + \left(-\frac{N_2}{\tau}\right)$$

* The total population is $N = N_1 + N_2 \Rightarrow \frac{dN_1}{dt} = -\frac{dN_2}{dt}$

$\frac{dN}{dt} = 0$ → because rate of incoming & outgoing is same

* At steady state : $\frac{dN_2}{dt} = 0$

then

$$\Rightarrow \frac{N_2}{N_1} = \frac{W_p}{W_p + 1/\tau}$$

* If we need population inversion then

$$N_2 > N_1$$

$$\Rightarrow N_2 > N - N_2$$

$$\Rightarrow \boxed{N_2 > \frac{N}{2}}$$

* $N_2 = \frac{W_p}{W_p + 1/\tau} (N_1)$

$$\Rightarrow N_2 = \frac{W_p}{W_p + 1/\tau} (N - N_2)$$

$(\because N_2 > N/2)$

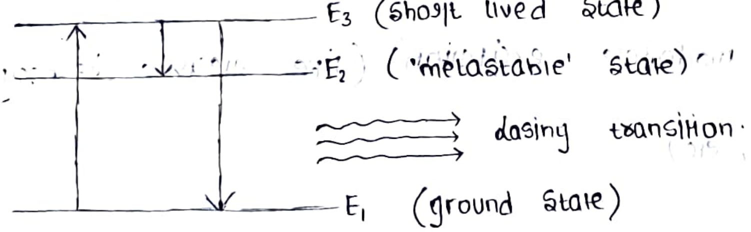
$$\Rightarrow N_2 = \frac{W_p}{2W_p + 1/\tau} N \Rightarrow \frac{W_p}{2W_p + 1/\tau} N > \frac{N}{2}$$

$$\Rightarrow 2W_p \tau > 2W_p \tau + 1$$

$$\Rightarrow 0 > 1 \ (!!!)$$

* Derivations & Conceptual → 80%
  Numerical → 20%
  } FAT.

THREE LEVEL SYSTEM : (LASER)



* In three level pumping scheme the atoms originally in the ground state are pumped into the excited state by some external source of energy (electric discharge, Xe flash lamp)

* The excited atoms decay by spontaneous emission very rapidly into a lower excited state which is known as "Metastable State".

* Atoms stay in metastable state for about 10^{-6} to 10^{-3} s. Therefore it is possible for a large no. of atoms to accumulate in the metastable state.

* In the metastable state population can exceed the population of lower level and it leads to "population inversion".

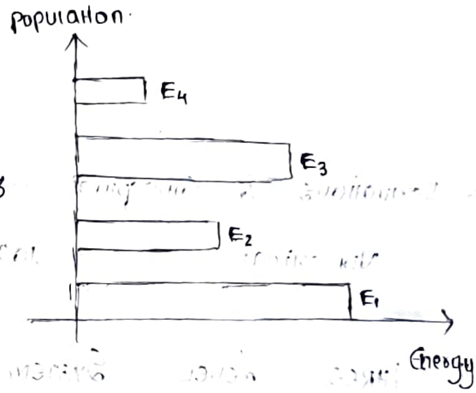
Four - level System :

Laser

* Silfrast
* Ghatak
* Laud

Books

* Atoms are pumped from ground state (E_1) to level four (E_4), From this level, the atoms decay to the "metastable state", and the population in this level grows rapidly.



* If the "lifetime" of level 4 to level 3 (i.e, τ_{43}) is short compared to level 3 to level 2 (i.e, τ_{32}).

* A population inversion from $3 \rightarrow 2$ can be achieved and maintained with moderate excitation (like electric discharge, Xe flash lamp, etc)

Few PUMPING MECHANISM :

* Optical pumping.
* Electrical discharge
* Chemical rx^n
* Injection current.

VIBRATIONAL MODES OF CO_2

* Symmetric stretching mode :

$(\nu_1\ 0\ 0)$

* Bending mode :

$(0\ \nu_2\ 0)$

* Assymmetric stretching mode :

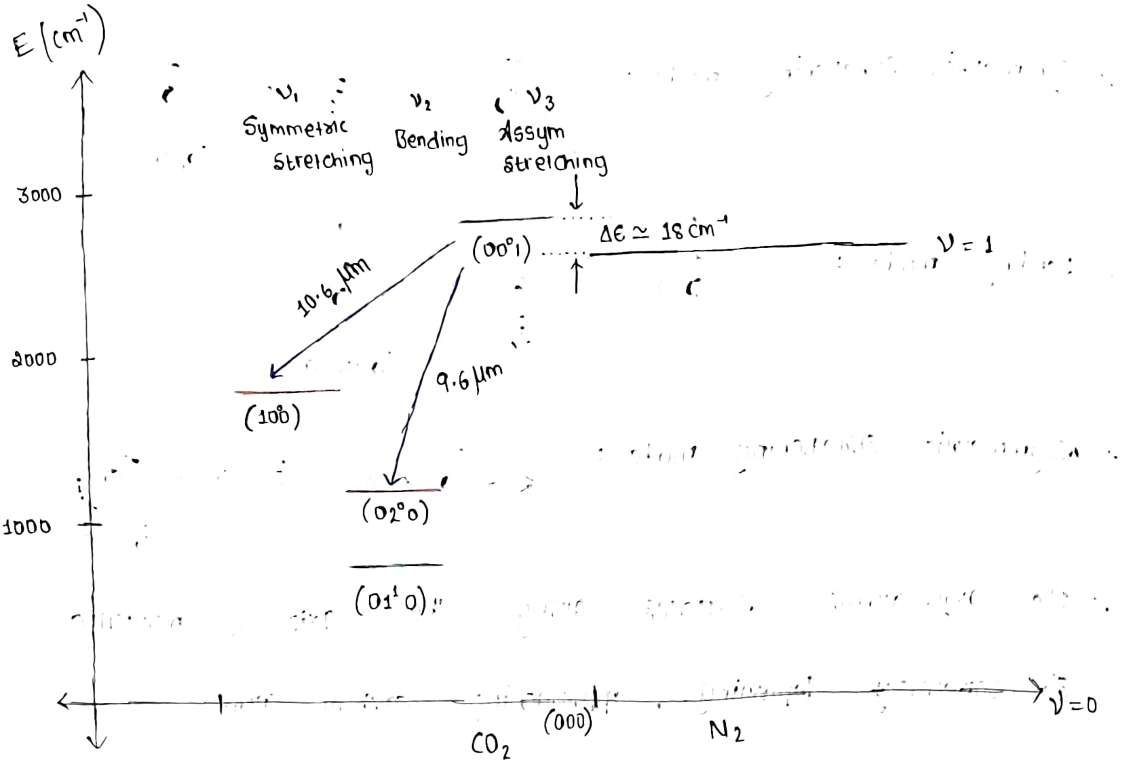
$(0\ 0\ \nu_3)$

* The oxy. atoms oscillates along the axis of molecule simultaneously departing, approaching carbon atom.

* The molecule seizes to be exactly linear as the atoms move $\perp$ to molecular axis.

* All three molecules ossilate ; while both oxygen atoms move in one dir^n carbon atoms move in the opp. dir^n.

CO_2 energy level diagram



* The relevant vibrational energy levels for electronic ground states of CO_2 & N_2 is given in picture.

* N_2 is diatom molecule, so it has only vibrational mode whose lowest two energy levels ($\nu = 0$, $\nu = 1$) are indicated in fig.

* But CO_2 is a triatomic molecule. It has three non degerate modes of vibration (i) Sym. stretching (ii) Bending (iii) Asym stretch.

* The osc. behaviour ~~are~~ at corresponding energy levels are described by three quantum nos., so the energy

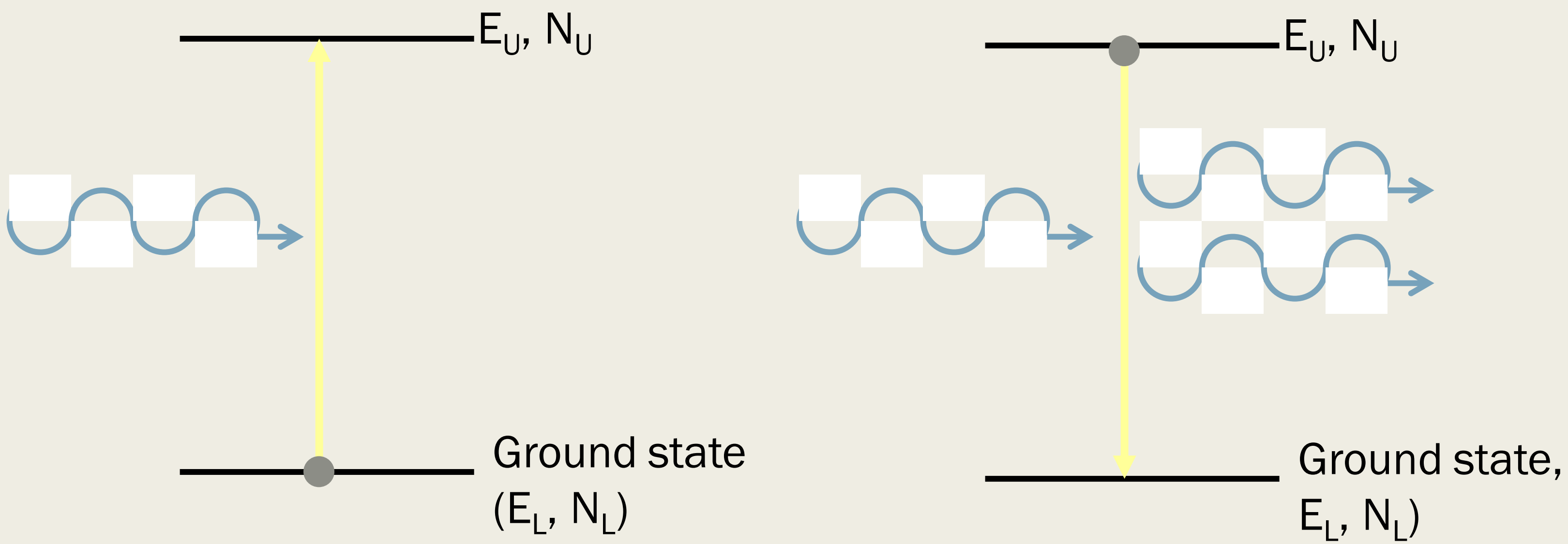
$E = n_1 h\nu_1 + n_2 h\nu_2 + n_3 h\nu_3$ where ν_1, ν_2, ν_3 are freq. of 3 modes.

ex: (01^10) level corresponds (superscript is for angular momentum (l)) to an osc. in which there is one vibrational quantum in mode 2. Similarly (02^00) mode can be described.

* The lasing action takes place b/w $(00^0 1)$ and $(10^0 0)$ level for $\lambda \simeq 10.6\,\mu m$, although it is possible to obtain osc. b/w $(00^0 1)$ and $(02^0 0)$ at $\lambda \simeq 9.6\,\mu m$.

LASERS

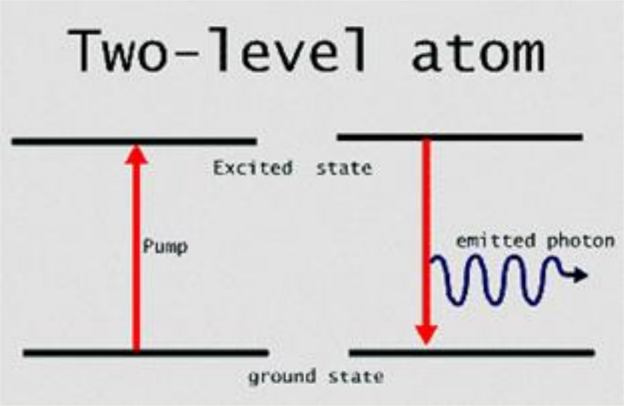
Two-Level System



Even with very a intense pump source, the best one can achieve with a two-level system is

excited state population = ground state population

Two level pumping



$$\boldsymbol{I = I_o e^{\sigma_{UL}(N_U - N_L)L}}$$

I_o - Pumping Intensity
I- Final Intensity of laser output
σ_{UL} -Cross sectional constant
N_u and N_L – Population densities of upper and lower level
L length of cavity

$N = N_u + N_L$

Before pumping starts
$Nu \approx 0$; $N = N_L$

$$\boldsymbol{I = I_o e^{\sigma_{UL}(-N_L)L}}$$

Once pumping starts $N_u \neq 0$

$N_u = N - N_L$

$$I = I_o e^{\sigma_{UL}(N - N_L - N_L)L}$$

$$I = I_o e^{\sigma_{UL}(N - 2N_L)L}$$

$$I = I_o e^{\sigma_{UL}\left(1 - \frac{2N_L}{N}\right)NL}$$

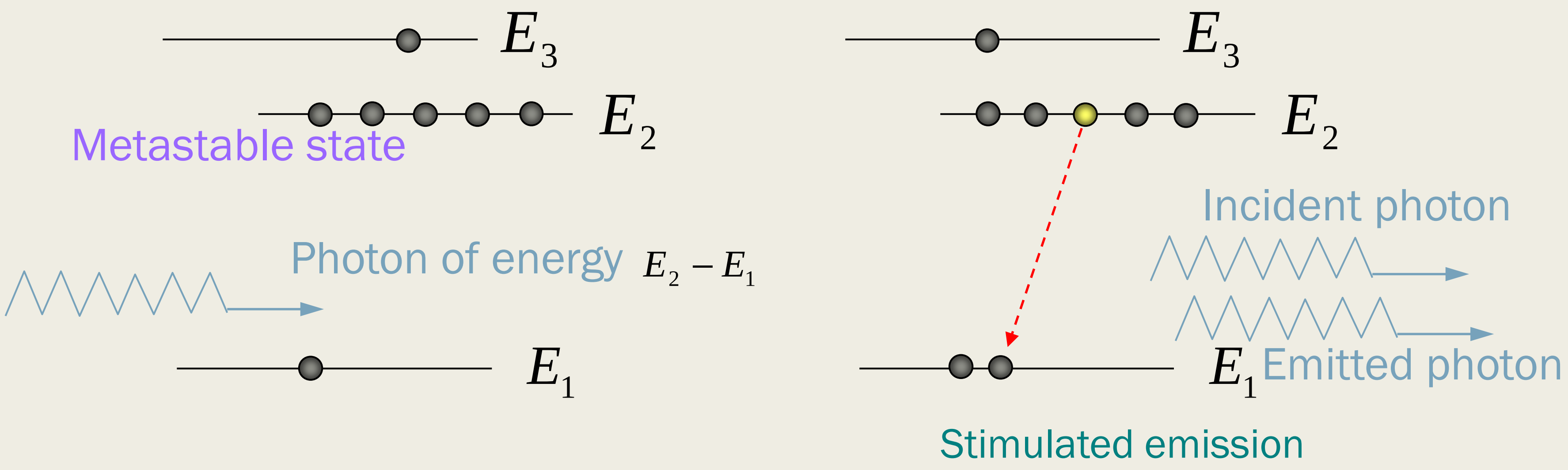
If N=100 electrons N_u =50 ; N_L=50
(i.e) N_L/N=0.5

$$I = I_o$$

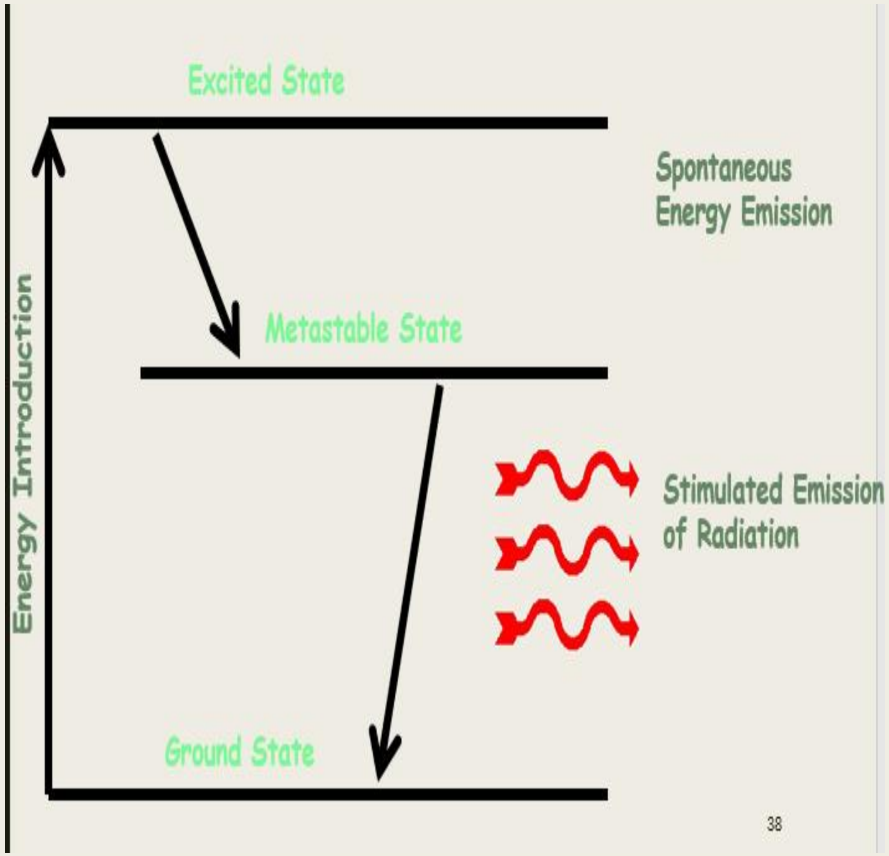
Beyond that its not possible; Population inversion can never happen.

Metastable State

- 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.



Three level system



Eg: Ruby Laser

- **Electrons in the ground state are pumped into the excited state by some external source of energy (an electric pulse or a flash of light).**

- **The excited electrons decay by spontaneous emission very rapidly into a lower excited which is a metastable state. Electrons stay in metastable state for about 10^{-6} to 10^{-3} sec**

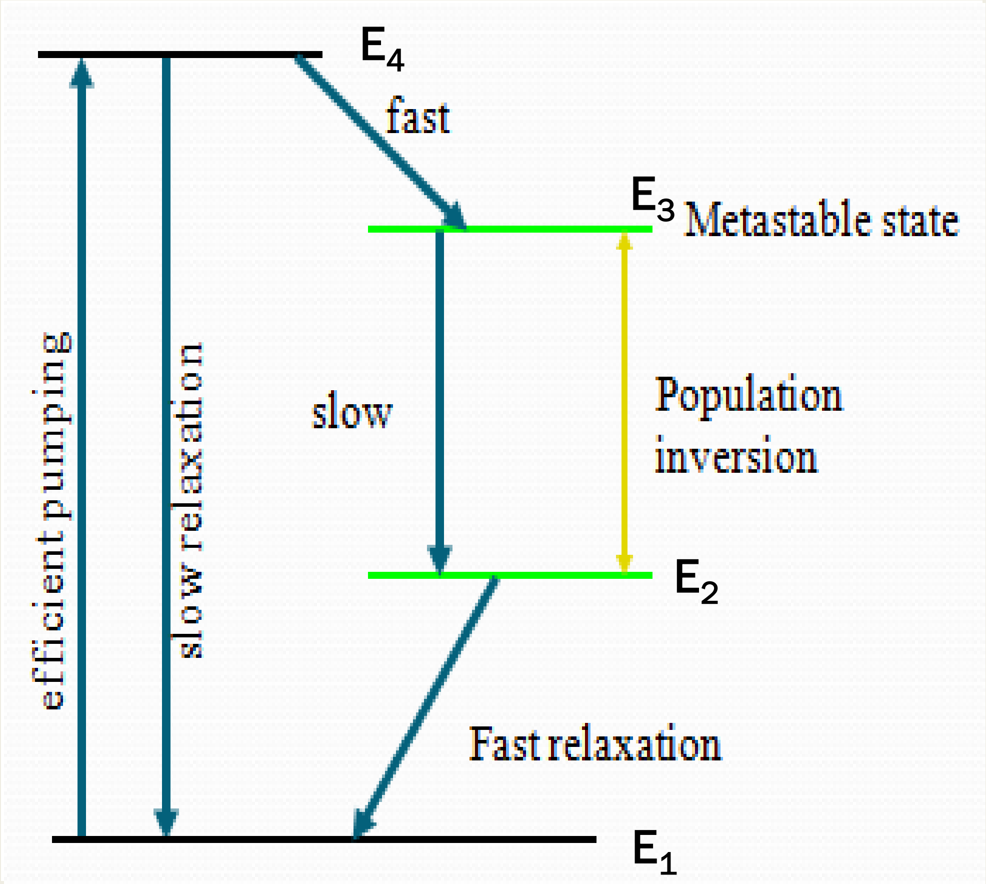
- **Therefore it is possible for a large number of electrons to accumulate at a metastable sate.**

- **In the metastable state, population can exceed the population of a lower level and lead to the state of population inversion.**

Problems with 3-level laser

- ✓ *Any electrons in the ground state will absorb the lasing transition and remove photons from the beam.*
- ✓ *High pumping power is required*
- ✓ *Only pulsed output is possible*

Four Level system



The ground state electrons are pumped to the excited state.

They decay rapidly to the metastable state as in the three level laser.

The lasing transition proceeds from the metastable state (E_3) to E_2 a short lived state.

Electrons from there decay rapidly to the ground state.

Eg: CO_2, He-Ne and Nd-YAG laser

Advantages of 4-level laser

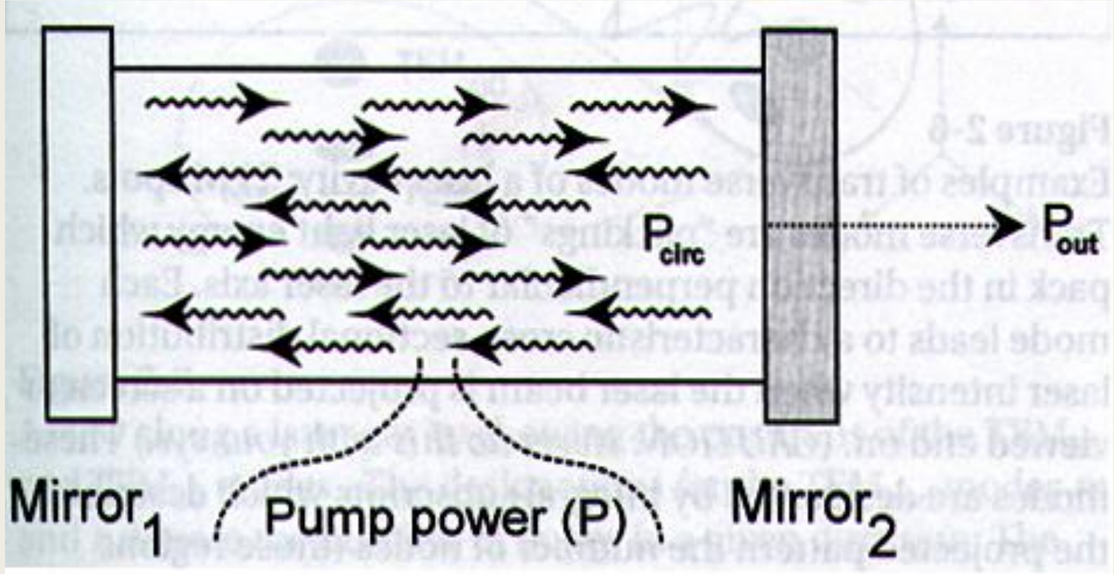
- ❖ The electrons in the ground state cannot absorb at the energy of the lasing transition.
- ❖ Four level laser requires less pumping energy than three level laser
- ❖ They can operate in a continuous mode.

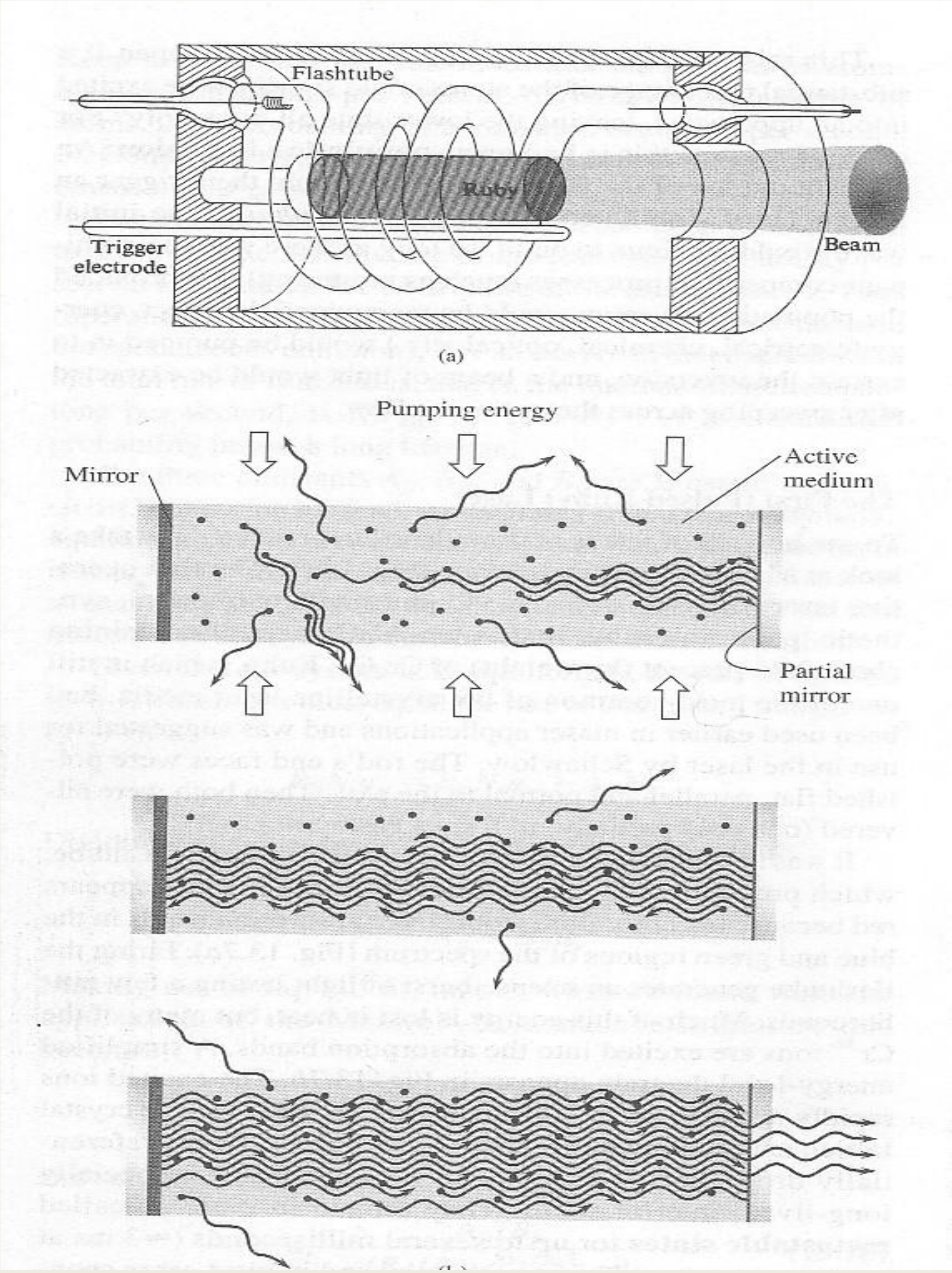
Light Amplification

Create a laser cavity, which consists of the lasing medium and two highly reflective mirrors.

- ❖ When light travels through an absorbing medium, the medium absorbs the light; the amount of light absorbed is determined by Beer's Lamberds Law. $I=I_0\exp(-\alpha L)$; α- absorption coefficient; L is length of travel

- ❖ For a medium to operate as a lasing medium, the transmitted light intensity should be greater than the intensity of light incident on the material.




Flashtube
Ruby
Trigger electrode
Beam
(a)
Pumping energy
Mirror
Active medium
Partial mirror

Active Components of all Lasers

1. **<u>Active Medium</u>**

   The active medium may be solid crystals such as ruby or Nd:YAG, liquid dyes, gases like CO_2 or Helium/Neon, or semiconductors such as GaAs. Active mediums contain atoms whose electrons may be excited to a metastable energy level by an energy source.

2. **<u>Pumping Mechanism</u>**

   Excitation mechanisms pump energy into the active medium by one or more of three basic methods; optical, electrical or chemical.

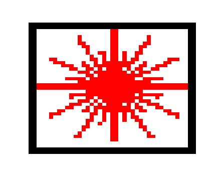
3. **<u>Optical Resonator</u>**

   <u>High Reflectance Mirror</u>

   A mirror which reflects essentially 100% of the laser light.

   <u>Partially Transmissive Mirror</u>

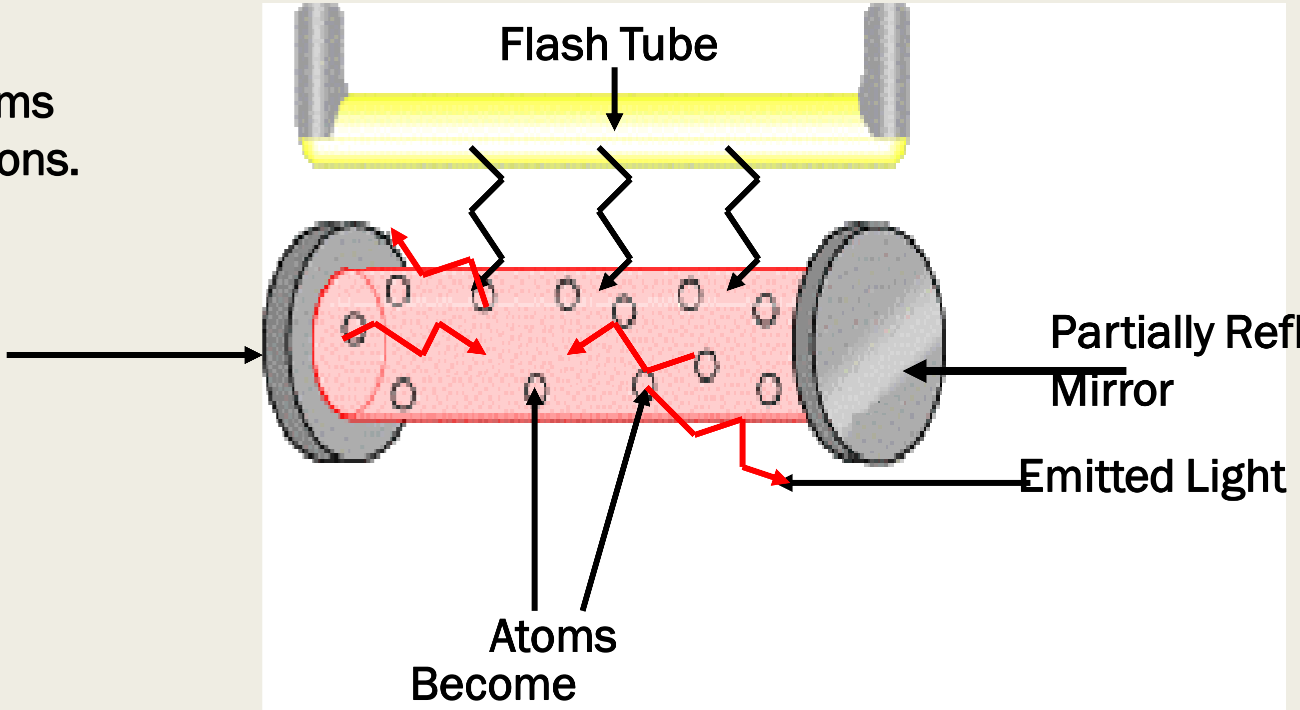
   A mirror which reflects less than 100% of the laser light and transmits the remainder.



Active Medium → Pumping Mechanism → Optical resonator

Shedding Some Light

How the Laser Works



The flash tube fires light at the ruby rod. The light excites the atoms.

Lasing Action

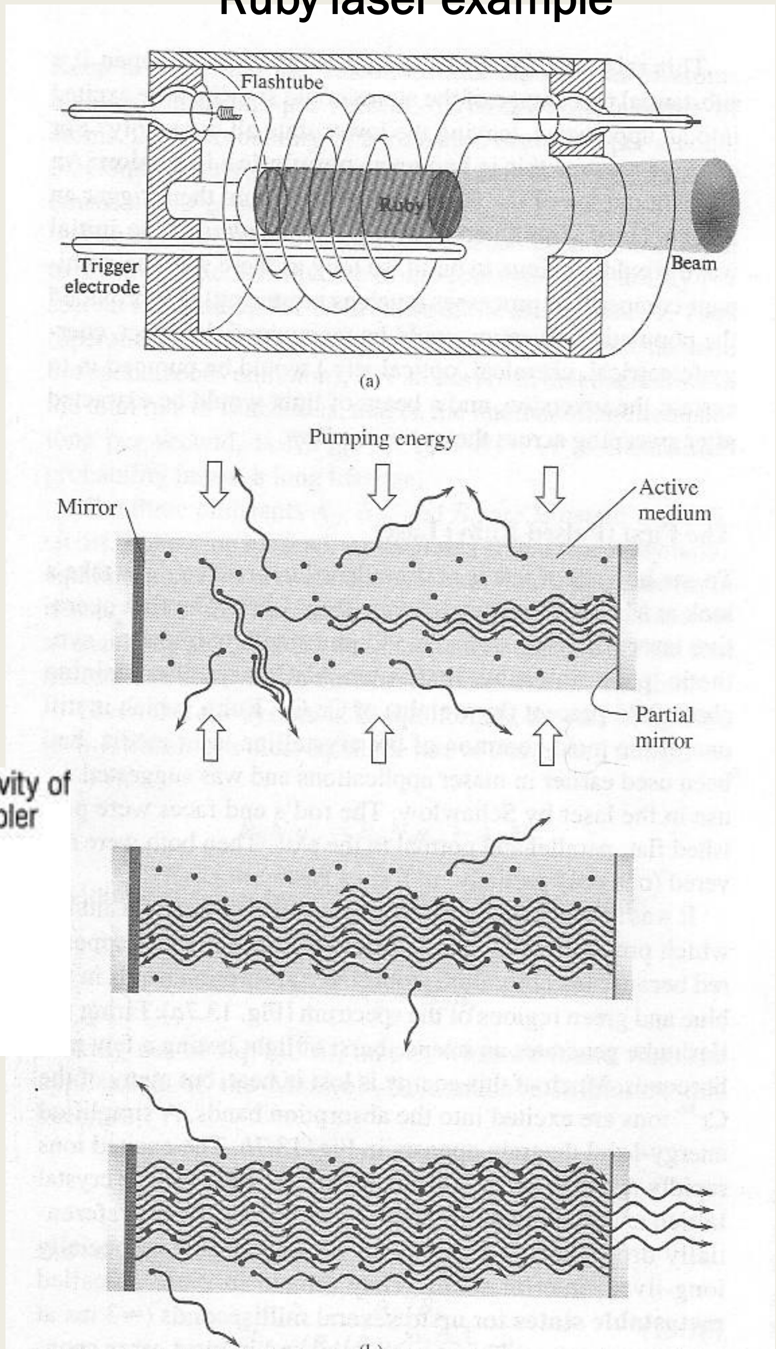
1. Energy is applied to a medium raising electrons to an unstable energy level.
2. These atoms spontaneously decay to a relatively long-lived, lower energy, metastable state.
3. A population inversion is achieved when the majority of atoms have reached this metastable state.
4. Lasing action occurs when an electron spontaneously returns to its ground state and produces a photon.
5. If the energy from this photon is of the precise wavelength, it will stimulate the production of another photon of the same wavelength and resulting in a cascading effect.
6. The highly reflective mirror and partially reflective mirror continue the reaction by directing photons back through the medium along the long axis of the laser.
7. The partially reflective mirror allows the transmission of a small amount of coherent radiation that we observe as the “beam”.
8. Laser radiation will continue as long as energy is applied to the lasing medium.

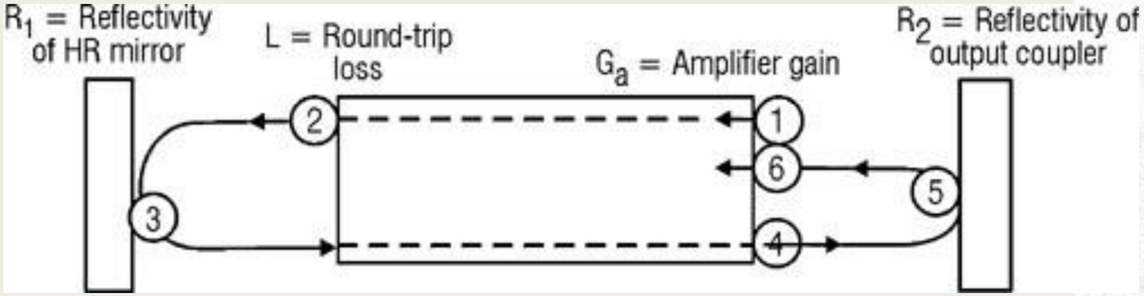
Laser oscillation

Laser is oscillator

- Like servo with positive feedback
- Greater than unity gain
- Threshold gain coefficient $K_{th} = \gamma + \frac{1}{2L}\ln(1/R_1R_2)$
- γ - volume losses
- $\frac{1}{2L}\ln(1/R_1R_2)$ – loss in form of useful output

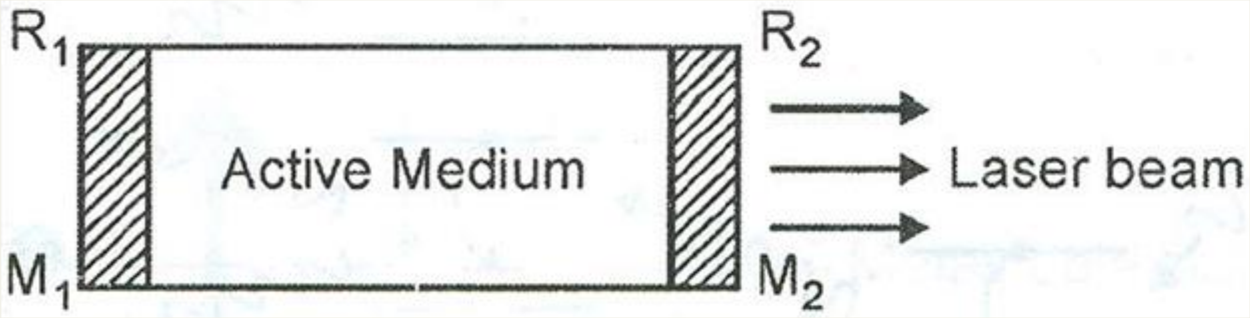
Ruby laser example





Laser gain and losses

Threshold gain coefficient



I_o is the initial intensity of light entering through a light transmitting (e.g glass) solid rod (in the direction of length), then after travelling L distance through it, the final intensity will be I

then **$I=I_0\exp(-\alpha L)$----(1)**

α is the absorption coefficient and it is positive

- In case of laser, where stimulated emission dominates and $N_u > N_L$

$I = I_o \exp(kL)$;—(2) K = small signal gain coefficient = $(-\alpha)$

In the laser system, there can be loss due to

- ✓ Scattering at mirrors
- ✓ Absorption at mirrors,
- ✓ Absorption by the medium
- ✓ Diffraction at the boundaries of mirrors
- ✓ Scattering by inhomogeneities present in the medium

All these losses are taken as a volume loss Υ

Therefore eqn (2) becomes

$I = I_o \exp(k-\Upsilon)L$ ----(3)

After reflecting at mirror M2, $I=I_0R_2\exp[(k-\gamma)L]$

just before reaching M1 again, $I=I_0R_2\exp[2(k-\gamma)L]$

after reflecting from M1, $\mathbf{I=I_0R_1R_2\exp[2(k-\gamma)L]}$ **-----(4)**

To sustain the laser oscillations, the round trip gain must be at least equal to unity

(i.e) Round trip gain (G) = $\dfrac{\text{Final Intensity}}{\text{Initial Intensity}} = \dfrac{I_0R_1R_2\exp[2(k-\gamma)L]}{I_0}$

$\mathbf{G = R_1R_2\exp[2(k-\gamma)L}$ **--------(5)**

G=1 – Sustained Oscillation
G< 1 – Oscillations die out
G > 1 – Oscillations amplify

G=1, Threshold gain coefficient K_{th}

Therefore eqn (5) becomes

$$1 = R_1R_2 \exp\left[2\left(k_{th} - \gamma\right)L\right]$$

$$\ln\ 1 = \ln\ R_1R_2 \exp\left[2\left(k_{th} - \gamma\right)L\right]$$

$$2k_{th}L = 2\gamma L + \ln\left(\frac{1}{R_1R_2}\right)$$

Threshold gain coefficient, $k_{th} = \gamma + \frac{1}{2L}\ln\left(\frac{1}{R_1R_2}\right)$

γ – practical or volume losses

$\left.\frac{1}{2L}\ln\left(\frac{1}{R_1R_2}\right)\right\}$ – useful laser output

Types of Lasers(Based on its pumping action) :

- Optically pumped laser
- Electrically pumped laser
- Basis of the operation mode
- Continuous wave Lasers
- Pulsed Lasers

According to their wavelength :

- Visible Region, Infrared Region, Ultraviolet Region, Microwave Region, X-Ray Region and etc.

According to the source :

- Solid state Lasers, Liquid lasers, Gas Lasers, Chemical Lasers,Dye lasers, Semi conductor Lasers and other types.

Differences between LED and LASER

All the major differences between LED and LASER are listed in the following table −

Basis of Difference	LED	LASER
Full form	LED stands for Light Emitting Diode.	LASER stands for Light Amplification by Stimulated Emission of Radiation.
Definition	A semiconductor device which produces light when an electric current flows through it is called LED or Light Emitting Diode.	A device which emits light by the optical amplification using stimulated emission of electromagnetic radiation is called LASER.
Working principle	The working of LED is based on the principle of electro-luminance.	The working of the LASER is based on the principle of stimulated emission.
Chromaticity	LED is usually a polychromatic, i.e. it produces a broader band of wavelengths.	LASER is a monochromatic source of light as it generates the light of single wavelength.
Coherence	LED is a non-coherent source of light, i.e. its photons are out of phase,	LASER is a coherent source of light, which means its photons are in phase.
Directionality	LED generates a divergent beam of light. Thus, the light produced by the LED can travel in all directions randomly.	LASER produces a non-divergent beam of light which is highly directional.
Optical spectral width	LED has a broader optical spectrum, usually ranging from 25 nm to 100 nm.	For LASER, the optical spectrum is much narrower, usually 0.01 nm to 5 nm.
Emission	LED involves spontaneous emission.	LASER involves stimulated emission.
Optical power output	LED has comparatively low optical output power.	LASER has high optical output power.
Temperature dependency	The operation of LED is less dependent on the temperature.	The operation of LASER is quite temperature dependent.
Conversion efficiency	LED has very low conversion efficiency, around 10% to 20%.	LASER has comparatively high conversion efficiency, around 30%

		to 70%.
Reliability	LEDs are highly reliable devices.	The reliability of LASER is moderate.
Drive circuit	LED has simple drive circuit.	The drive circuit of LASER is complex.
Impact on eyes	LED is considered for human eyes.	LASER is not safe for naked human eyes. Therefore, there must be rendered eye safe while looking the LASER.
Feedback	There is no need of feedback in LEDs.	A proper feedback is essential in LASER.
Power requirement	LEDs require comparatively less power for operation.	LASER requires more power than LEDs.
Response	LEDs have slow response.	LASER has comparatively faster response.
Cost	The cost of LED is low.	The cost of LASER is more than LED.
Applications	LEDs are used in several applications such as area illumination, communication over moderate distances at low data rate, automobile headlamps, display screens, etc.	LASER is used in optical communication, welding, metal cutting, medical surgery, etc.

Conclusion

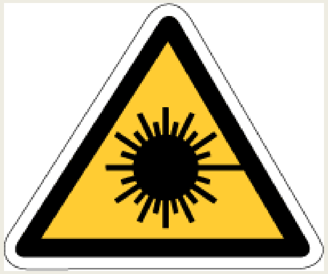
The most significant difference between LED and LASER is that the LED works on the principle of electro-luminance, whereas LASER works on the principle of stimulated emission.

LASERS

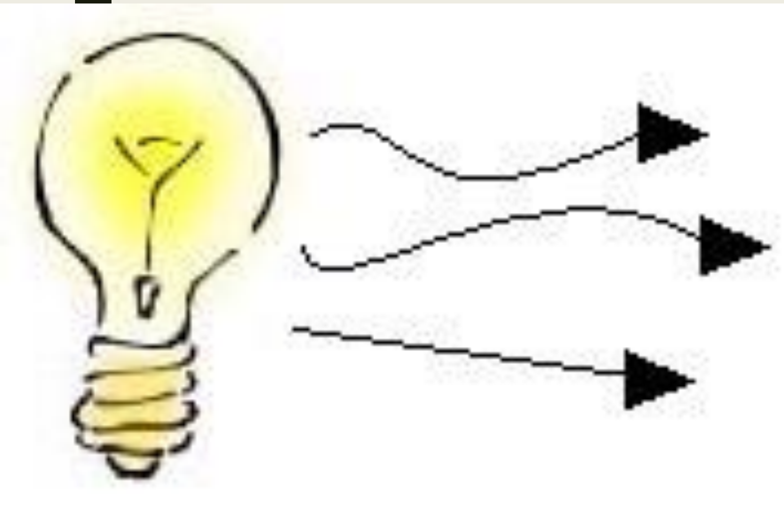
LASER

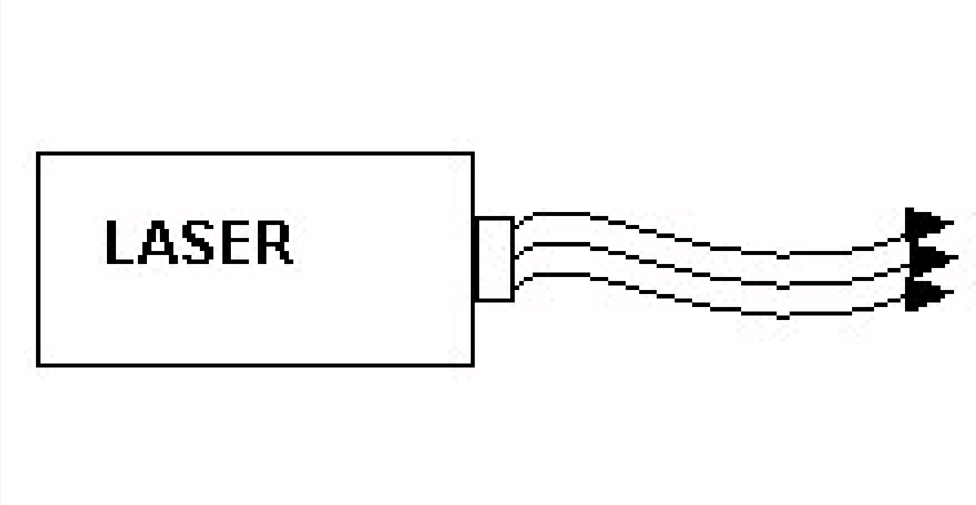
Light Amplification by Stimulated Emission of Radiation

- A laser is a device that can produce a very narrow intense beam of monochromatic coherent light.
- The emitted beam is nearly perfect plane wave.



ncandescent vs. Laser Light





1. Many wavelengths
2. Multidirectional
3. Incoherent
4. Intensity is less

1. Monochromatic
2. Directional
3. Coherent
4. Highly intense

Properties of Laser Light

- **Monochromaticity**
  - ✓ *Laser light is concentrated in a narrow range of wavelengths*
- ✓ Light coming out of any source consists of band of frequencies closely spaced around a central frequency ‘v_0.
- ✓ The band of frequencies, Δv, is called the linewidth or bandwidth.
- ✓ The light from conventional sources has large linewidths of the order of 10^{10}Hz or more.
- ✓ Light from lasers is more monochromatic having linewidths to 100 Hz.

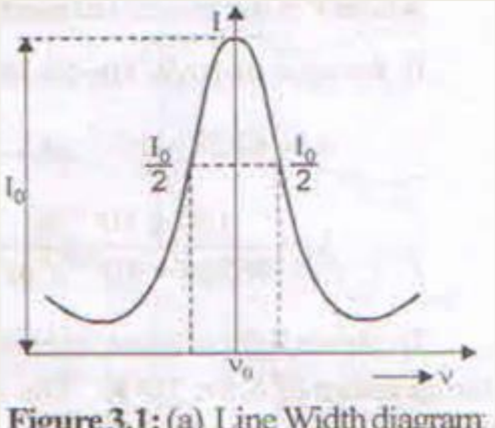


Figure 3.1: (a) Line Width diagram

Directionality

- **Laser beam is highly collimated and can travel long distances without significant spread in the beam cross section.**
- **As the collimated beam propagates, the beam spreads out.**
- **The angular spread is given by**

$$\Delta\theta=\lambda/d.$$

- λ–Wavelength of light; d - diameter of the aperture through which the light is passing
- Radius of the spread (r) for a beam travelling a distance D from source is given by $r = D * \Delta\theta = D\,\lambda/d$

High Intensity

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

$$I = (10/\lambda)^2 * P$$

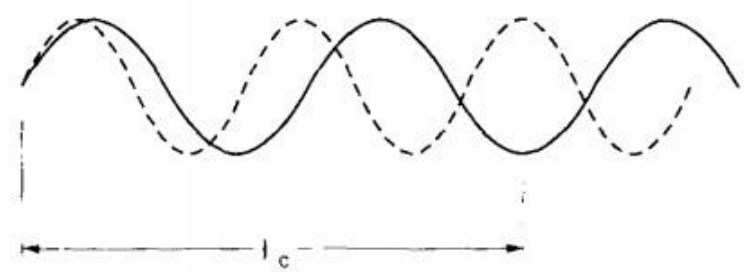
- P is the Power radiated by the laser

Coherence

- Laser beam is highly coherent, i.e, different parts of the beam maintain a phase relationship for a long time. this results in interference effect.
- When a laser beam reflects off a surface, the reflected light can be seen to have bright regions separated by dark regions.

Temporal Coherence (Longitudinal Coherence)

- One can define a coherence time (Δt) after which the phase correlation between two waves which were initially in phase (or between two points in the same wave which had a known phase difference) drops significantly.
- The reason for loss of coherence is than an optical source does not emit a continuous wave for all time to come.



If we assume that the two waves are exactly in phase at the first location, then they will still be at least partially in phase at the second location up to a distance l_c, where l_c is defined as the coherence length

$$l_c = \frac{\lambda^2}{\Delta\lambda}$$

λ = Average wavelength

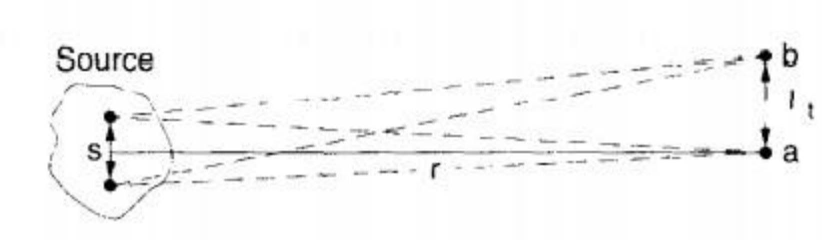
Δλ = Difference in wavelength

Spatial Coherence (Transverse Coherence)

Spatial coherence, also referred to as *transverse* coherence, describes how far apart two sources, or two portions of the same source, can be located in a direction transverse to the direction of observation and still exhibit coherent properties over a range of observation points

Assume that the two sources are separated by a distance s in the transverse direction to the direction of observation and are a distance r from the point of observation. If the two sources exhibit interference effects at point a, then the transverse coherence length l_t is the transverse distance from point a to point b,

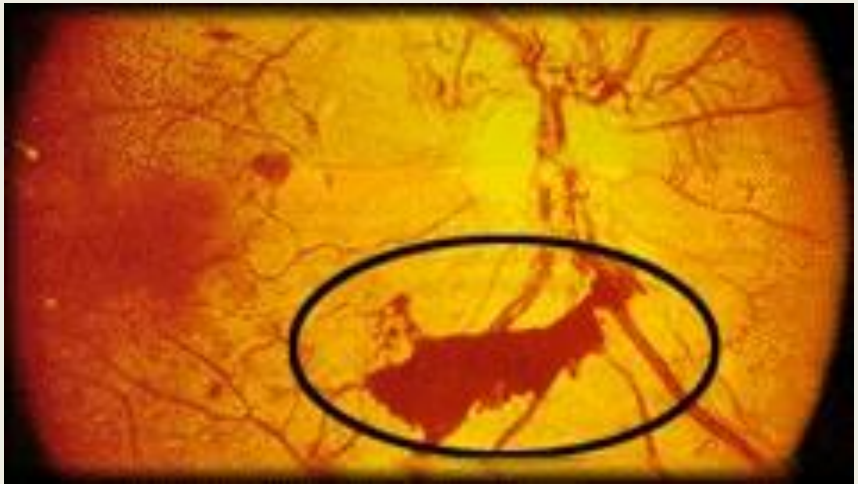
where the two sources cease to show interference effects;



$$l_t = \frac{r\lambda}{s}$$

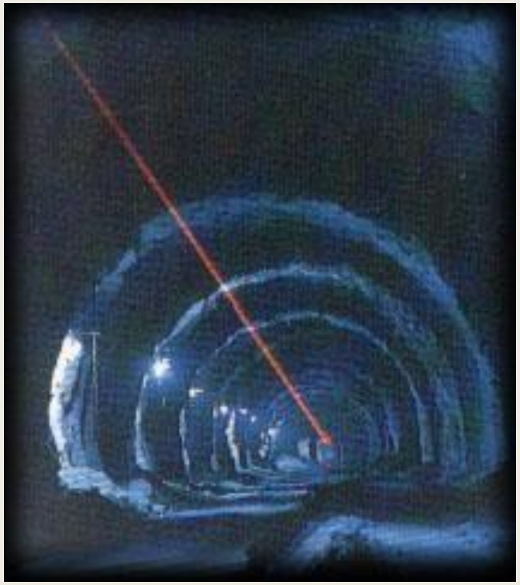
Uses of Laser

- In medicine
  - *to break up gallstones and kidney stones,*
  - *to weld broken tissue (e.g. detached retina)*
  - *to destroy cancerous and precancerous cells; at the same time, the heat seal off capillaries,*
  - *to remove plaque clogging human arteries.*



Uses of Laser

- In Industry
  - *to drill tiny holes in hard materials,*
  - *For welding and machining,*
  - *For lining up equipment precisely, especially in inaccessible places.*



Lasers & Industry

The Cutting Edge

- **The advantages of this system over mechanical processes are substantial:**
  - ***The cuts are more precise and reduce raw material losses***
  - ***Laser welding can be automated for high-precision tasks***
  - ***The process is cleaner***

- **The superior cutting accuracy and precision which have contributed to it's success as a medical tool are also highly desirable for this industry.**

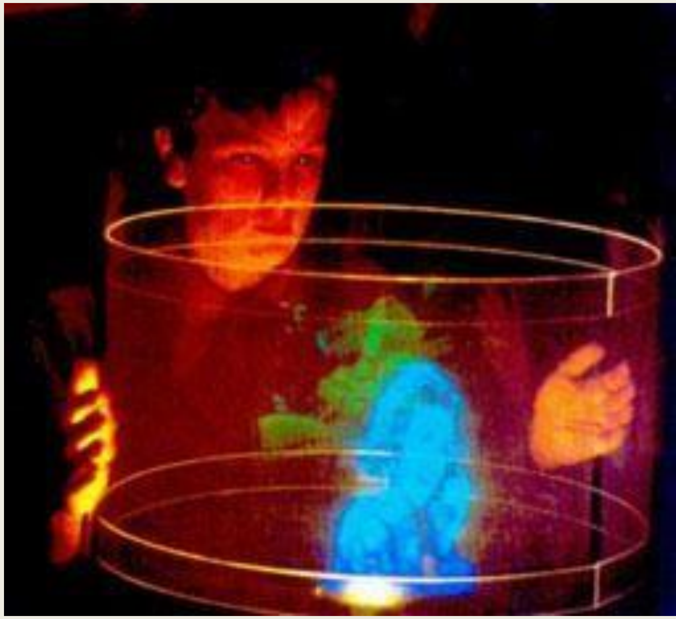
Uses of Laser

- In everyday life
  - *to be used as bar-code readers,*
  - *to be used in compact disc players,*
  - *to produce short pulses of light used in digital communications,*
  - *to produce holograms.*

Uses of Laser

Holography

- Holography is the production of holograms by the use of laser.
- A hologram is a 3D image recorded in a special photographic plate.
- The image appears to float in space and to move when the viewer moves.



Lasers & Military

Ominous lights

High-intensity lasers can be used in omni-directional bombs or flares which can flash-blind personnel as well as degrade sensors and night vision devices.

Low energy lasers can be directed or aimed at specific targets to blind personnel or sensors either temporarily or permanently. The most advanced blinding lasers oscillate between numerous colors to make goggles and other countermeasure ineffective.

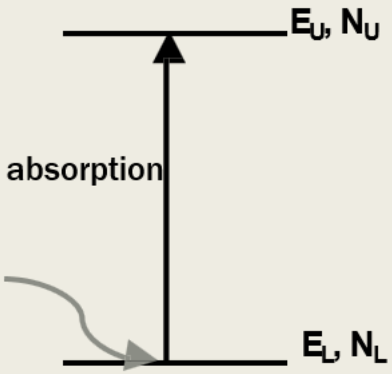
Lasers can also be used to make a gun or other weapon too hot to hold.

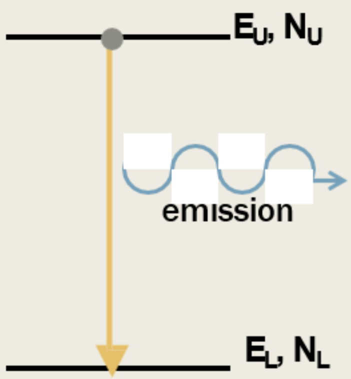
LASERS & ENTERTAINMENT

THE LIGHT AND THE DARK SIDE

One of the most popular applications of laser technology, the Compact Disc Player, marked a revolution in digital video and sound technology.

LASERS





Whenever matter interacts with radiation there is always a process of absorption and emission.

As a result, electrons in the lower level are pushed to upper level or vice – versa.

The population in the two levels, can be found by the relation given by Maxwell- Boltzmann distribution

Population of electrons (atoms) in upper level with energy E_u be given as

$$N_u = \mathrm{e}\frac{-E_u}{kT}$$

Similarly population at lower level be

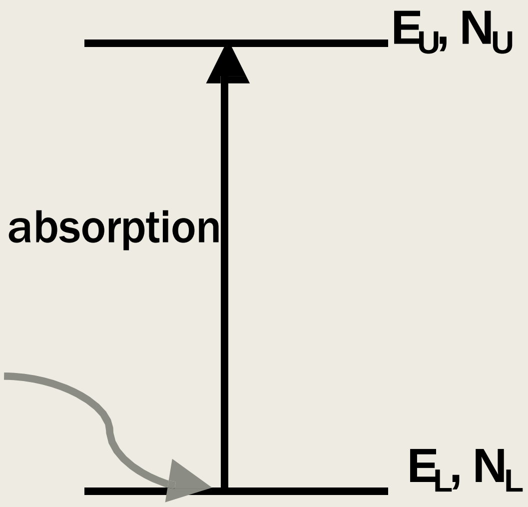
$$N_L = \mathrm{e}\frac{-E_L}{kT}$$

Where K is the Boltzmann constant and T is the temperature in Kelvin.
Ratio of population in two energy levels

$$\frac{N_u}{N_L} = \mathrm{e}^{-\frac{(E_u - E_L)}{KT}} = e^{-(h\gamma)/kT}$$

Stimulated Absorption

Consider a two-level system



An electron in a lower level absorbs a photon of frequency hv and moves to an upper level.

$h\Upsilon = E_u - E_L$

Rate of population of upper energy level as a result of absorption

$$\frac{dN_u}{dt} \,\alpha\, N_L\,\rho(\gamma)$$

$$\frac{dN_u}{dt} = B_{LU} N_L\,\rho(\gamma)$$

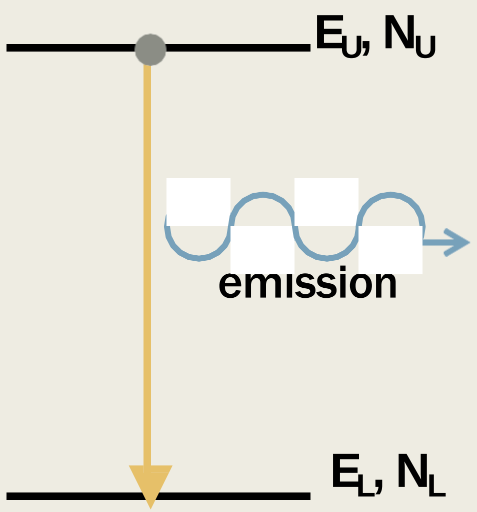
B_{LU} - **Einstein Stimulated absorption coefficient**

E_u and E_L -upper and lower energy levels

N_u and N_L - population density of electrons in the upper and lower level

$\rho(\gamma)\ -\ energy\ density\ of\ incident\ photon$

Spontaneous Emission



Light from bulbs are due to spontaneous emission

- An atom/electron in an upper level can decay spontaneously to the lower level and emit a photon of frequency hv if the transition between EU and EL is radiative.
- This photon has a random direction and phase.

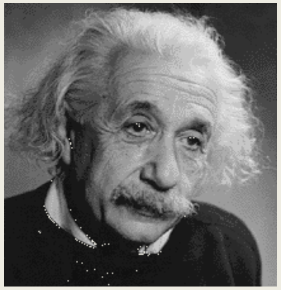
- Rate of population of upper energy level as a result of stimulated emission

$$\frac{dN_u}{dt} \propto -N_U$$

$$\frac{dN_u}{dt} = -A_{UL} N_u$$

- A_{UL} - Einstein spontaneous emission coefficient
- It is inversely proportional to the life time of the electrons in excited state.

Stimulated Emission

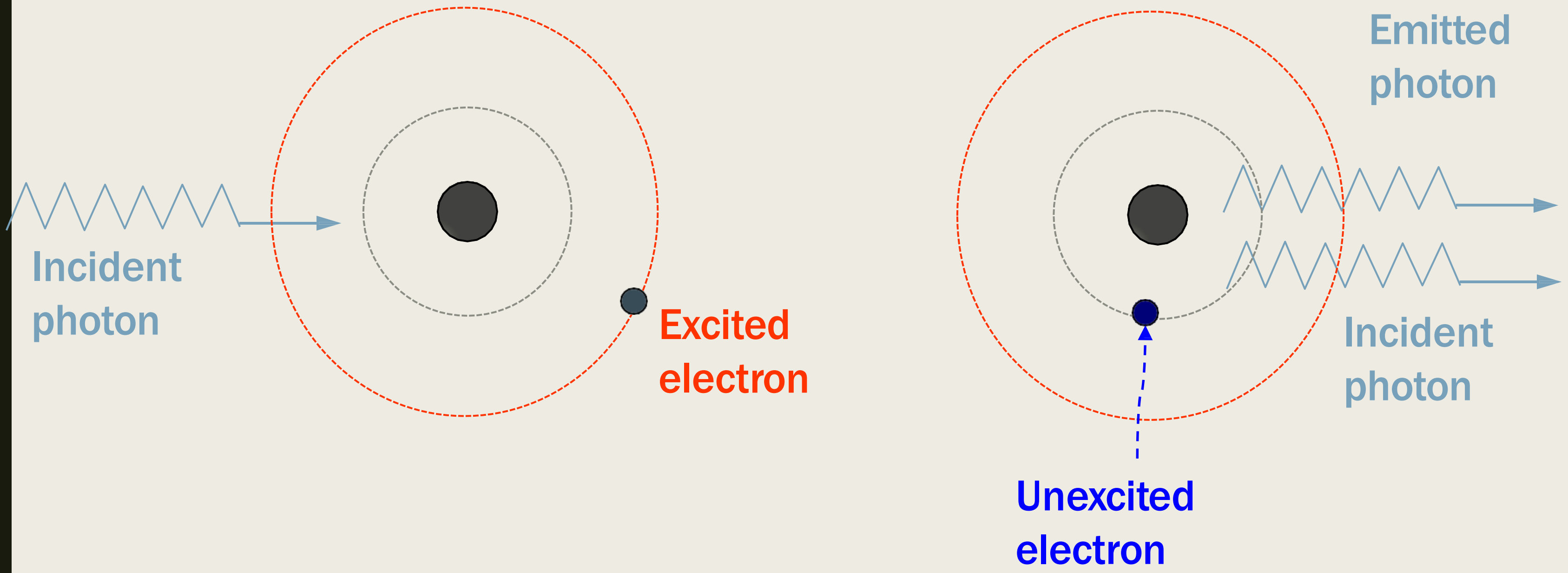


- It is pointed out by Einstein that:

  Atoms in an excited state can be stimulated to jump to a lower energy level when they are struck by a photon of incident light whose energy is the same as the energy-level difference involved in the jump. The electron thus emits a photon of the same wavelength as the incident photon. The incident and emitted photons travel away from the atom in phase.

- This process is called stimulated emission.

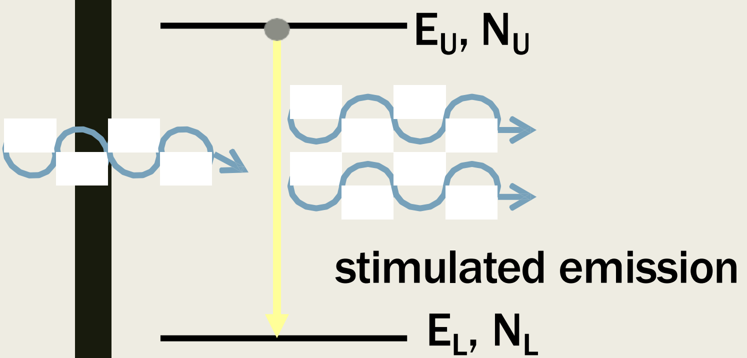
Stimulated Emission



Before emission

After emission

Stimulated Emission



Laser light results from stimulated emission

Rate of population of upper energy level as a result of stimulated emission

$$\frac{dN_u}{dt} \alpha -N_U \rho(\gamma)$$

$$\frac{dN_u}{dt} = -B_{UL} N_U \rho(\gamma)$$

B_{UL} **Einstein Stimulated emission coefficient**

- ❖ An incident photon causes an upper level atom to decay, emitting a "stimulated" photon whose properties are identical to those of the incident photon.
- ❖ The term "stimulated" underlines the fact that this kind of radiation only occurs if an incident photon is present.
- ❖ The amplification arises due to the similarities between the incident and emitted photons.

Stimulated vs Spontaneous Emission

- Stimulated emission requires the presence of a photon. An “incoming” photon stimulates a molecule in an excited state to decay to the ground state by emitting a photon. The stimulated photons travel in the same direction as the incoming photon. They also are in phase with each other. Because energy and momentum has to be conserved.

- Spontaneous emission does not require the presence of a photon. Instead a molecule in the excited state can relax to the ground state by spontaneously emitting a photon. Spontaneously emitted photons are emitted in all directions.

Einstein A and B Co-efficients

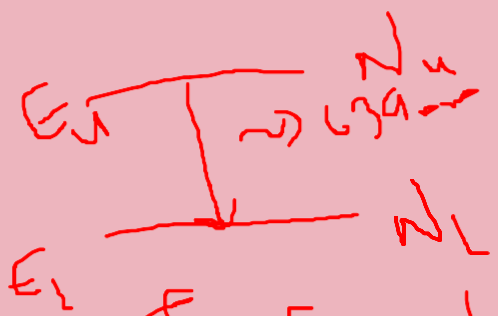
- **Rate of population in an excited state is given by**

$$\frac{dN}{dt} = -B_{UL}N_U\,\rho(\gamma) - A_{UL}N_u + B_{UL}N_U\,\rho(\gamma)$$

- **At thermal equilibrium condition $\frac{dN_u}{dt}$=0 ;** ***the number of transitions from E_u to E_L must be equal to the number of transitions from E_L to E_u.***

- That is
- $-B_{UL}N_U\,\rho(\gamma) - A_{UL}N_u + B_{UL}N_L\,\rho(\gamma)$ =0
- $B_{UL}N_U\,\rho(\gamma) + A_{UL}N_u = B_{UL}N_L\,\rho(\gamma)$ ——(1)

- $$\rho(\gamma)[B_{LU}N_L - B_{UL}N_U] = A_{UL}N_U$$



- $$\rho(\gamma) = \frac{A_{UL}N_u}{[B_{LU}N_L - B_{UL}N_U]}$$

- $$\rho(\gamma) = \frac{A_{UL}}{B_{UL}}\left[\frac{1}{\frac{N_L B_{LU}}{N_U B_{UL}} - 1}\right] \text{—(2)}$$

$E_u - E_L = hc/\lambda$

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

- $$\frac{N_U}{N_L} = \frac{e^{-E_U/kT}}{e^{-E_L/kT}}$$ ***Therefore,*** $$\frac{N_U}{N_L} = e^{-(E_U - E_L)\mathrm{T}kT}$$

- $$\frac{N_U}{N_L} = e^{-(h(\gamma))\mathrm{T}kT} \text{------(3}$$

- **Substituting eqn (3) in eqn (2)** $$\rho(\gamma) = \frac{A_{UL}}{B_{UL}}\left[\frac{1}{e^{(h(\gamma))\mathrm{T}kT}\frac{B_{LU}}{B_{UL}} - 1}\right] \text{---(4)}$$

- This is the formula for the energy density of photon of frequency (γ)in equilibrium with atoms in energy states L and U, at temperature T.

- Comparing eqn (4) with Planck's radiation formula
- $\rho(\gamma) = \frac{8\pi h(\gamma)^3}{c^3}\left[\frac{1}{e^{h(\gamma)TkT}-1}\right]$ ——(5)
- $B_{UL}=B_{LU}$
- $\frac{A_{UL}}{B_{UL}} = \frac{8\pi h(\gamma)^3}{c^3}$
- This gives the relationship between Einstein's A and B coefficients.

Significance of Einstein A and B Coefficients

1. **Einstein coefficients A_{UL}, B_{LU} and B_{UL} are all interrelated.**

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

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

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

$N_U>N_L$ leads to increase in $\rho(\gamma)$ and hence, amplification.
$N_L>N_U$ leads to decrease in $\rho(\gamma)$ and hence, attenuation.
For laser to operate, it is necessary that $N_U>N_L$.

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

Thus, stimulated emission plays a significant role only for temperatures in which kT is of, or greater than, the order of the photon energy $h\nu_{ul}$. The ratio is unity when $h\nu_{ul}/kT = \ln 2 = 0.693$. For visible transitions in the green portion of the spectrum (photons of the order of 2.5 eV), such a relationship would be achieved for a temperature of 33,500 K. Thus, in the visible spectrum, the dominance of stimulated emission over spontaneous emission normally happens only in stars, in high-temperature and -density laboratory plasmas such as laser-produced plasmas,

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

5. Although the relations A_{UL}, B_{UL} and B_{LU} were derived based on the condition of thermal equilibrium, they are valid and hold under any condition. The laser while operating is hardly an enclosure in thermodynamic equilibrium.

Yet A and B coefficient relationships hold good because they are characteristic of the atom, are equally valid whether the atom is on the intense radiation field of a laser cavity or in a hot furnace that can be treated as a blackbody in thermodynamic equilibrium.

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

i) Stimulated emission that leads to light amplification.

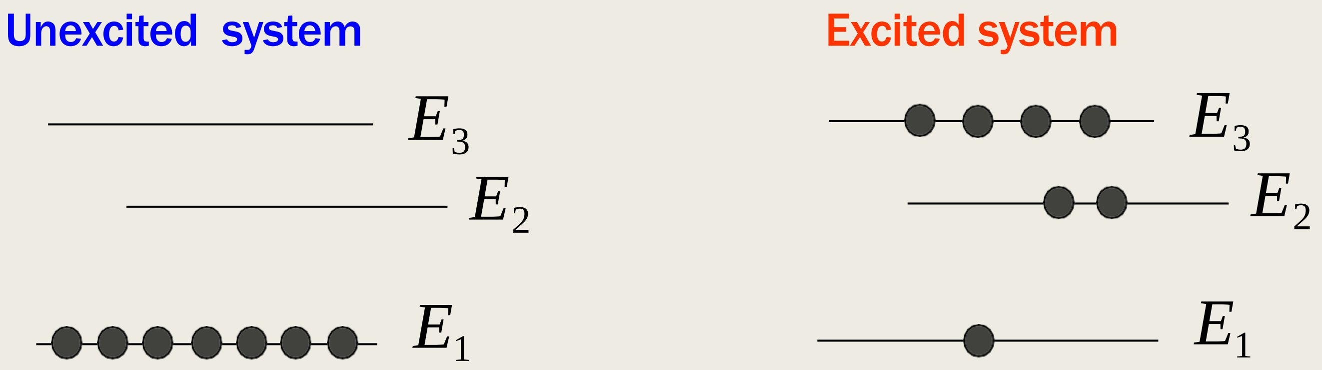
ii) $N_u > N_L$.

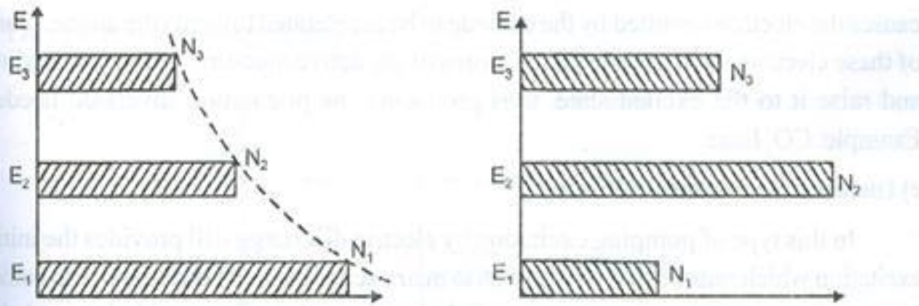
- For lasing action, stimulated emission must dominate.

- As determined by the Boltzmann factor, the population of the ground state > population of excited state.

- Hence, typically absorption dominates.
- For stimualted emission to be the dominant process, the excited state population must be larger than the lower state population.

- In other words, for a medium to produce laser light, there must be a "population inversion" where $N_{upper} > N_{lower}$





(a) Population in equilibrium

(b) Population inversion of E_2 with respect to E_1

Under the population inversion condition, the stimulated emission can produce a cascade of light.

- How can a population inversion be created when the population in the ground state is always greater that the population in the excited state?

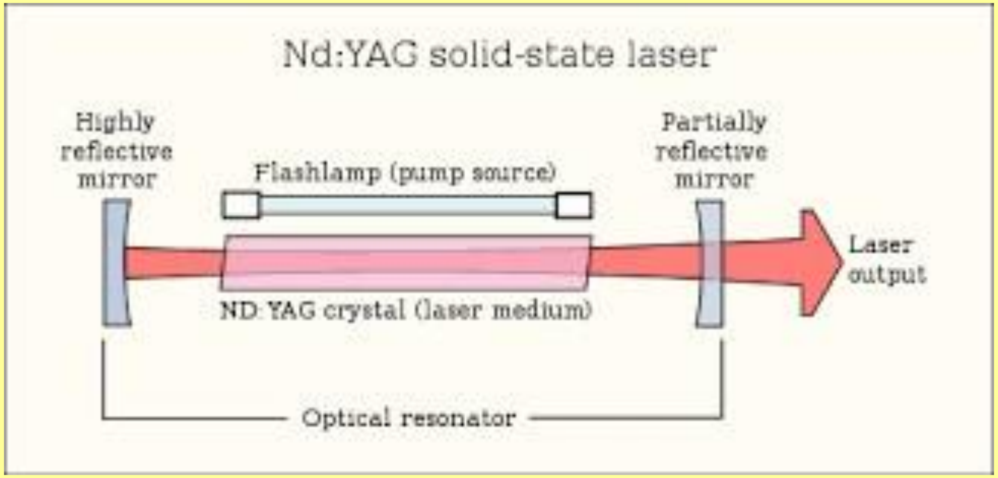
- What kinds of materials will "allow" for an inversion of population in its electronic states?

How can a population inversion be created?

- By excitation of the lasing atoms or molecules - this is called PUMPING.
- If the pump source is very intense, the number of atoms or molecules excited can be large.
- However, once excited, the atoms and molecules must say in the excited state long enough to create an excited population > ground state population

DIFFERENT PUMPING MECHANISMS :

i. ***Optical pumping :*** Exposure to electromagnetic radiation of frequency $\upsilon = (E_2-E_1)/h$ obtained from discharge flash tube results in pumping Suitable for solid state lasers.



ii. ***Electrical discharge :*** By inelastic atom-atom collisions, population inversion is established. Suitable for Gas lasers

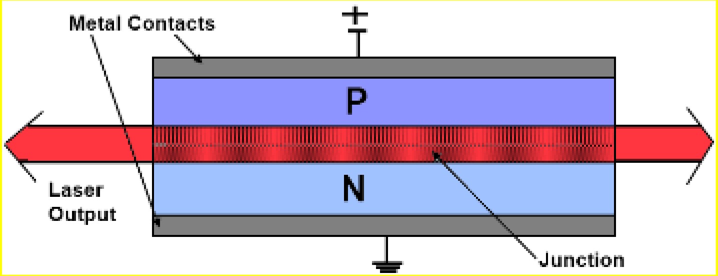
$$A+e^* \rightarrow A^*+e$$

$$A^*+B \rightarrow A+B^*$$

iii. ***Chemical pumping :*** **By suitable chemical reaction in the active medium, population of excited state is made higher compared to that of ground state Suitable for liquid lasers.**

iv. ***Injection current:***

In the case of semiconductor lasers it is not the atoms that are excited. It is the current carriers namely electrons and holes are excited and a population inversion is achieved in the junction region. The electrons recombine with holes in the junction regions producing laser light. Thus in semiconductor lasers, a direct conversion of electrical energy into light energy takes place.



Numericals

- Find the relative population of the two states in a ruby laser that produces a light beam of wavelength 694.3nm at 300K and 400K
- A laser medium at thermal equilibrium temperature 300K has two energy levels with a wavelength separation of 1μm. Find the ratio of population densities of upper level to lower level.
- A typical He-Ne laser emits a wavelength of 632.8nm. How many photons per second be emitted by a 1milliwatt He-Ne laser.
- Calculate the energy difference in eV between upper and lower levels involved in emission of laser wavelength 3.3913μm.