LASER

Light Amplification by Stimulated Emission of Radiation

Lasers are devices that produce intense beams of light by **stimulated emission** which are **monochromatic**, **coherent**, and **highly collimated**. The wavelength (color) of laser light is extremely pure (monochromatic) when compared to other sources of light, and all of the photons (energy) that make up the laser beam have a fixed phase relationship (coherence) with respect to one another. Light from a laser typically has very low divergence. It can travel over great distances or can be focused to a very small spot with a brightness which exceeds that of the sun. Because of these properties, lasers are used in a wide variety of applications in all walks of life.

Differentiation between the light emitted by conventional sources and LASER sources

Conventional Source	LASER source
• Polychromatic (Constitute more than one wavelength) • Non-directional (Photons travel in different direction and exhibit high divergence) • Incoherent (The photons will not be in phase with each other) • Less intensity	• Monochromatic (Constitute single wavelength) • Highly directional (All photons travel in same direction and exhibit less divergence) • Coherent (All the photons have same phase and frequency) • High intensity

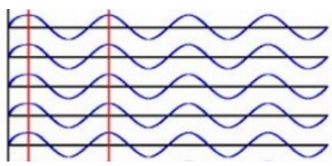
There are two types of coherence,

Temporal or Longitudinal coherence

Temporal coherence is the measure of the average correlation between the value of a wave and itself delayed by τ, at any pair of times. A beam of laser is said to exhibit temporal coherence if the phase difference of the waves crossing the two points lying on a plane parallel to the direction of the propagation of beam is independent of time.

Spatial or Transverse coherence

A laser beam is said to possess spatial coherence if the phase difference of the waves crossing the two points on a plane perpendicular to the direction of propagation of the beam is time independent. Spatial Coherence is also termed as transverse or lateral coherence.



Interaction of electromagnetic radiation with matter

The interaction of radiation with matter can be explained by considering the light radiation is made up of discrete packets of energy called **photons**. The energy will be absorbed or emitted by an atom takes through these quantum of energy called photons. Each photon has internal energy determined by the equation

$$E = h\nu \text{ or } E = \frac{hc}{\lambda} \left(\because \ \nu = \frac{c}{\lambda}\right)$$

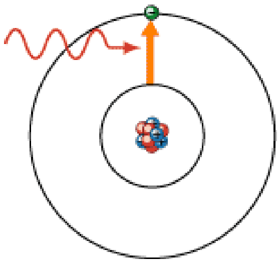
Where, ν is frequency (Hz), c is speed of light (3×10^8 m/s), h is Planck's constant (6.62×10^{-34} JS) and λ is the wavelength (m).

For an atom to absorb light (i.e., for the light energy to cause an electron to move from a lower energy state E_1 to a higher energy state E_2), the energy of a single photon must equal, almost exactly, the energy difference between the two states. Too much energy or too little energy and the photon will not be absorbed. Therefore the energy of photon must be equal to

$$E = \Delta E = E_2 - E_1 = \frac{hc}{\lambda}\ (Joule)$$

Three types of interactions are possible, they are as follows

Stimulated Absorption, Spontaneous Emission and Stimulated Emission

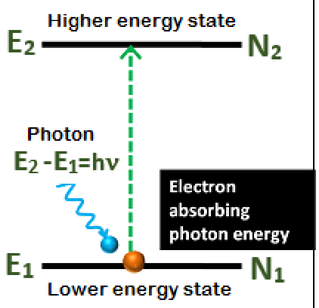


1. Stimulated Absorption

Absorption is the process in which atom absorbs a photon of right frequency ($E_2 - E_1 = h\nu$) and get excited to the higher energy level.

$$\boldsymbol{A + h\nu \rightarrow A^*}$$

The rate of stimulated absorption depends on the density of atoms (N_1) in the ground state (E_1) and the photon density, U_ν.



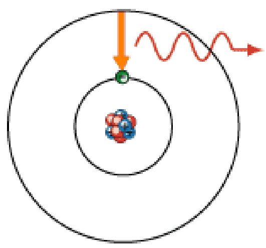
$$R^*{}_{12}\ \alpha\ N_1 \text{ and } R^*{}_{12}\ \alpha\ U_\nu$$

$$R^*{}_{12}\ \alpha\ N_1 U_\nu$$

$$R^*{}_{12} = B_{12}\ N_1\ U_\nu \text{ ---------- (1)}$$

Where, $\boldsymbol{N_1}$ is density of atoms in energy level $\boldsymbol{E_1}$, $\boldsymbol{U_\nu}$ is the photon density and $\boldsymbol{B_{12}}$ is the Einstein's coefficient for stimulated absorption.

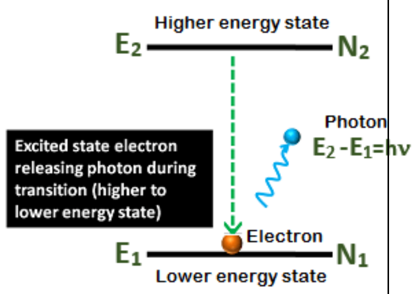
2 Spontaneous Emission



Atom in the excited energy level comes back to the lower energy level after spending relaxation time (10^{-8} s) by emitting a photon of energy, $E_2 - E_1 = h\nu$.

$$\boldsymbol{A^* \rightarrow A + h\nu}$$

The rate of spontaneous emission depends only on the density of atoms (N_2) in the higher energy state (E_2)

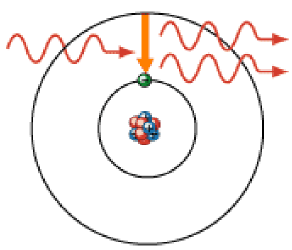


$$R_{21}\ \alpha\ N_2$$

$$R_{21} = A_{21}\ N_2 \text{ ------------- (2)}$$

Where, $\boldsymbol{N_2}$ is density of atoms in energy level $\boldsymbol{E_2}$ and $\boldsymbol{A_{21}}$ is the Einstein's coefficient for spontaneous emission.

3. Stimulated Emission



When a photon of right frequency is allowed to incident on the atom in the excited state, the atom is forced to come back to the ground state (E_1) by emitting photon of same energy and frequency.

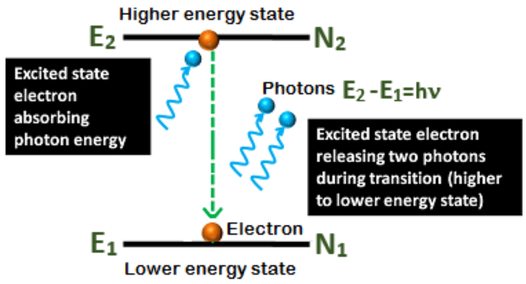
$$\boldsymbol{A^* \rightarrow A + 2h\nu}$$

The rate of stimulated emission depends on the density of atoms (N_2) in the excited state (E_2) and the photon density, U_ν

$$R^*{}_{21}\ \alpha\ N_2 \text{ and } R^*{}_{21}\ \alpha\ U_\nu$$

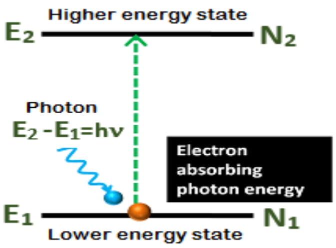
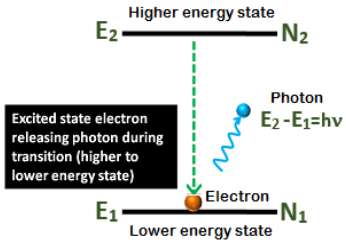
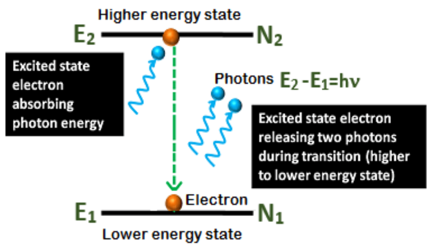
$$R^*{}_{21} \; \alpha \; N_2 U_\nu$$

$$R^*{}_{12} = B_{21} \, N_2 U_\nu \text{ -------------- (3)}$$



Where, N_2 is density of atoms in energy level E_2, U_ν is the photon density and B_{21} is the Einstein's coefficient for stimulated emission.

4. Comparison between Absorption, Spontaneous emission and Stimulated emission.

Stimulated Absorption	Spontaneous emission	Stimulated emission
It is a process in which an atom in the ground state absorbs a photon of right frequency and excite to higher energy state. $\boldsymbol{A + h\nu \rightarrow A^*}$ 	It is a process in which an atom in the excited state spontaneously comes back to ground state after relaxation time. $\boldsymbol{A^* \rightarrow A + h\nu}$ 	It is a process in which an atom in the excited state is incident by a photon of suitable frequency and comes back to ground state emitting photons of same frequency. $\boldsymbol{A^* \rightarrow A + 2h\nu}$ 
Rate equation: $R^*{}_{12} = B_{12} \, N_1 \, U_\nu$	Rate equation: $R_{21} = A_{21} \, N_2$	Rate equation: $R^*{}_{21} = B_{21} \, N_2 U_\nu$
	i. Wavelength, direction and polarization of emitted photons are different compared to each other. ii. The photons emitted will not be in phase (incoherent) with each other.	i. Wavelength, direction and polarization of emitted photon is same as that of incident photon. ii. Emitted photon is in phase (coherent) with the incident photon.

Expression connecting Energy density and Einstein's coefficients

The rate of stimulated absorption depends on the density of atom (N_1) and the photon density, U_ν.

$$R^*{}_{12} = B_{12} \, N_1 \, U_\nu \qquad \text{------------ (1)}$$

The rate of spontaneous emission depends only on the density of atoms (N_2) in the higher energy state (E_2)

$$R_{21} = A_{21} \, N_2 \qquad \text{------------- (2)}$$

The rate of stimulated emission depends on the density of atoms (N_2) in the excited state (E_2) and the photon density, U_ν

$$R^*{}_{21} = B_{21} \, N_2 U_\nu \qquad \text{-------------- (3)}$$

At thermal equilibrium condition for the system,

$$\textbf{Rate of Absorption}\left(R^{*}_{12}\right) = \textbf{Rate of spontaneous emission}\left(R_{21}\right) + \textbf{Rate of stimulated emission}\left(R^{*}_{21}\right)$$

From equations (1), (2) and (3),

$$B_{12}\, N_1 U_\nu = A_{21}\, N_2 + B_{21}\, N_2 U_\nu$$

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

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

$$U_\nu = \frac{A_{21}\, N_2}{B_{21}\, N_2 \left(\frac{B_{12}}{B_{21}} \frac{N_1}{N_2} - 1\right)}$$

$$U_\nu = \frac{A_{21}}{B_{21}} \left[\frac{1}{\left(\frac{B_{12}}{B_{21}} \frac{N_1}{N_2} - 1\right)}\right] \qquad \text{------- (4)}$$

From Boltzmann's law, the Boltzmann's factor is

$$\frac{N_1}{N_2} = e^{\frac{hc}{\lambda KT}} \qquad \text{----- (5)}$$

Substituting equation (5) in (4),

$$U_\nu = \frac{A_{21}}{B_{21}} \left[\frac{1}{\left(\frac{B_{12}}{B_{21}} e^{\frac{hc}{\lambda KT}} - 1\right)}\right] \qquad \text{---- (6)}$$

From Planck's law of radiation, wkt

$$U_\nu = \frac{8\pi h \nu^3}{c^3} \left[\frac{1}{e^{\frac{hc}{\lambda KT}} - 1}\right] \qquad \text{---- (7)}$$

Comparing equation (6) and (7) $\frac{A_{21}}{B_{21}} = \frac{8\pi h \nu^3}{c^3}\ and\ \frac{B_{12}}{B_{21}} = 1$

There fore equation 6 can be written as, $U_\nu = \dfrac{A}{B\left(e^{\frac{hc}{\lambda KT}} - 1\right)}$

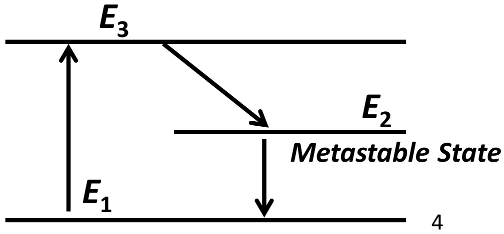
Ratio of stimulated emission to spontaneous emission

$$\frac{R^{*}_{21}}{R_{21}} = \frac{B_{21}\, N_2 U_\nu}{A_{21}\, N_2} = \frac{B_{21}}{A_{21}} U_\nu$$

$$\frac{R^{*}_{21}}{R_{21}} = \frac{U_\nu}{A_{21}/B_{21}}$$

$$\frac{R^{*}_{21}}{R_{21}} = \frac{\frac{8\pi h \nu^3}{c^3}\left[\frac{1}{e^{\frac{hc}{\lambda KT}} - 1}\right]}{\frac{8\pi h \nu^3}{c^3}} = \frac{1}{e^{\frac{hc}{\lambda KT}} - 1}\ \boldsymbol{or}\ \frac{1}{\frac{N_1}{N_2} - 1}$$

Meta Stable State



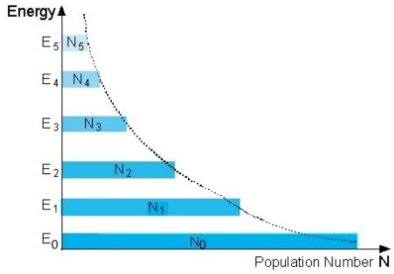
In general, the excited atoms stay in that state for about ~ 10^{-8} s, then comes back to the lower state by emitting a photon spontaneously. This time is insufficient for the excited atoms to interact with the photons available to make stimulated emission. It requires a metastable state where the excited atoms stay for longer duration ~ 10^{-3} s, for the excited atoms to get sufficient time to interact with the available photons. This state plays an important role in lasing action.

Definition: It is the energy state in which the excited atoms remains in the state for longer time compare to the normal excited state.

In metastable state, atoms stay for the duration of ~10^{-3} to 10^{-2} second. Therefore the atoms get sufficient time to interact with the photons and de-excite to lower energy level by stimulated emission.

Population Inversion

In thermal equilibrium condition, from Boltzmann's distribution function, the atoms densities in the lower energy state (N_1) will be more compared to that of higher energy state (N_2), i.e., $N_1 >> N_2$



$$\frac{N_1}{N_2} = e^{\frac{hc}{\lambda KT}}$$

It is impossible to achieve stimulated emission in thermal equilibrium condition and hence the lasing action is impossible. Therefore, the atoms are pumped by using various pumping technique (optical, electrical, chemical etc.,) with metastable state to create a situation where density of atoms in N_2 is greater than that of the N_1. This situation is called population inversion.

Definition: It is the state of the system at which the number density of atoms in higher energy level (N_2) is greater than that of the lower energy level (N_1).

Pumping:

It is the process of exciting atoms from lower energy level to higher energy level. It can be achieved by different methods.

i) Optical pumping: The process of exciting atoms using high intensity light or by operating flash tube. Ex: Ruby Laser.

ii) Electric Discharge: The process of exciting atoms by applying very high potential between the plates of discharge tube. Ex: Argon Laser, He-Ne Laser.

iii) Atom-Atom Collision: Excited atoms collide with other types of atom and transfer its energy to bring other atoms to excited state. Ex: He-Ne Laser.

iv) Using Current: In semiconductor diode laser the tuning of current input brings the charge carriers to achieve population inversion

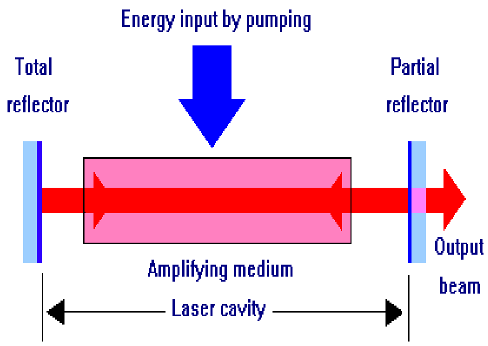
The necessary conditions for lasing action

1. **Population inversion** - In order to have stimulated emission the population inversion must be achieved. This is done using external energy to pump atoms from ground state to excited state.
2. **Metastable state** - In order to sustain population inversion there should be metastable state.

3. **Resonating cavity** - This cavity is used to amplify the laser beam.

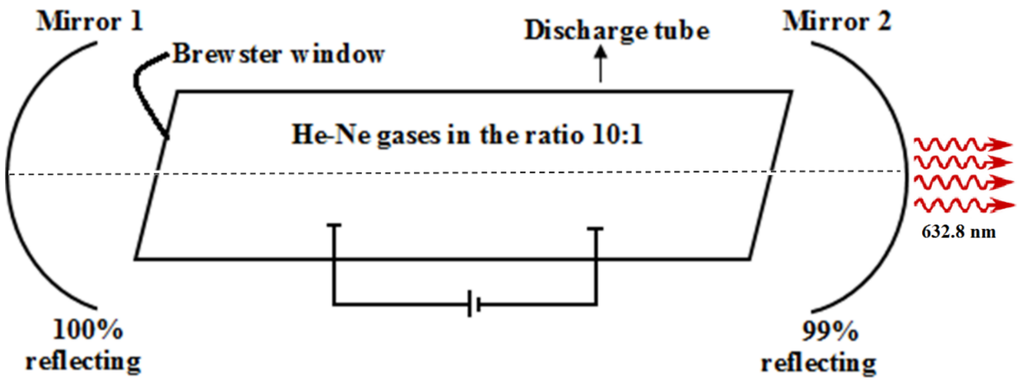
The resonating cavity consists of two mirrors, one fully reflecting and the other partially reflecting, placed parallel to each other outside the resonating cavity.

The length of the cavity is given by the equation $L = \frac{n\lambda}{2\mu}$ where L is length of the cavity, λ is the wavelength of the beam, n is the number of possible modes inside the cavity and μ is the refractive index of the medium.

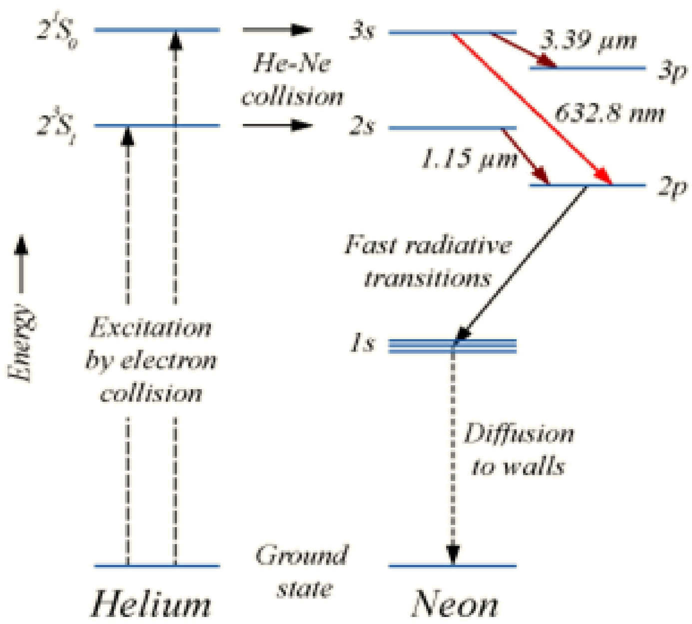


He-Ne laser

Schematic diagram



Energy level diagram



Construction

i. The He-Ne laser consist of a discharge tube of length ~ 1 m and diameter ~5 mm.
ii. The discharge tube is filled with He and Ne gas in the ratio 10:1.
iii. The two ends of the discharge tube are fitted with Brewster's window.
iv. Two mirrors placed outside the discharge tube forms resonating cavity.
v. The tube is fitted with high voltage battery to create electric discharge.

Active Medium

i. A mixture of He and Ne gases at partial pressure of ~1mm and ~0.1mm, respectively is the active medium.
ii. Ne is the lasing atom and He is used to pump the Ne atom to the excited state.

Pumping

This is a two stage process in He-Ne lasers.

i. Electric discharge passed through the gaseous mixture by applying a high voltage excites He atom.
ii. He atom collides with Ne atom and excites it to higher energy through atomic collision.

Working

i. Electric discharge produces electrons (e^-) with high kinetic energy moving inside the tube.
ii. He atoms are raised from ground state (1s) to excited state (2s) by collisions with electron moving with high KE

$$e^- \text{ (High KE)} + He \rightarrow He^* + e^- \text{ (Low KE)}$$

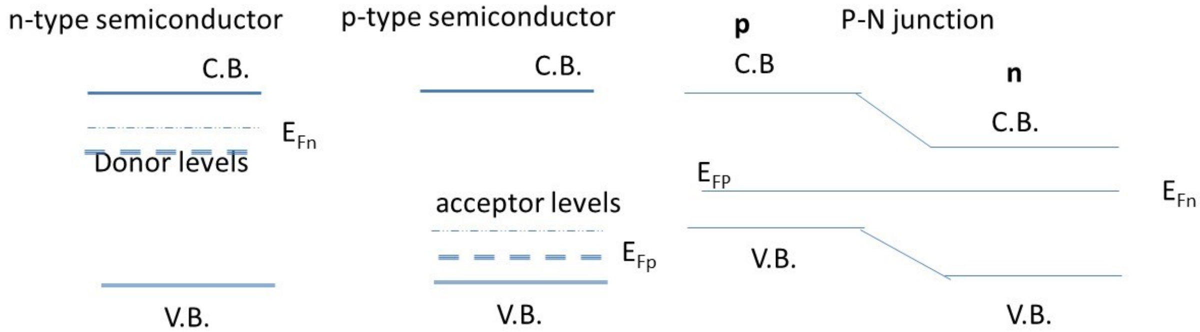
iii. Excited He atom collide with Ne atoms and transfer Ne atom to 3s and 2s excited levels.

$$He^* + Ne \text{ (ground)} + \text{KE of He} \rightarrow Ne^* + He$$

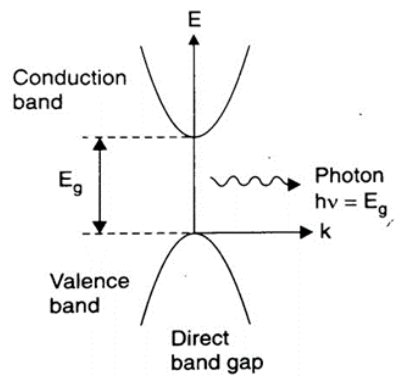
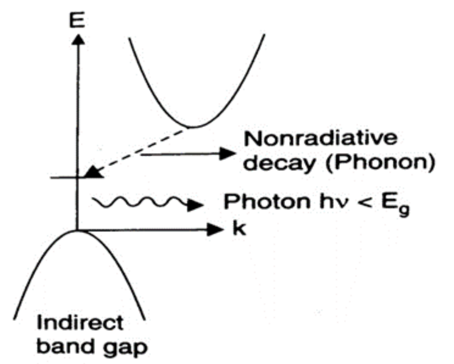
iv. Population inversion occurs between 3s & 2p, 3s & 2s and 2s & 2p. The corresponding transitions are
3s to 3p → 3.39 µm
3s to 2p → 632.8 nm
2s to 2p → 1.15 µm
v. Ne atom decays to 1s level by spontaneous emission and decay to ground state by colliding with the walls of the discharge tube.
vi. The wavelength of 632.8 nm is selectively amplified by adjusting the distance between the mirrors.
vii. The photons moving parallel to the axial direction are reflected back and forth between the mirrors until sufficient intensity is built to transmit from partially reflecting mirror.
viii. The output is the plane polarized and continuous laser of wavelength 632.8 nm.

Semiconductors

Energy band diagrams of p and n type semiconductors and p-n junction



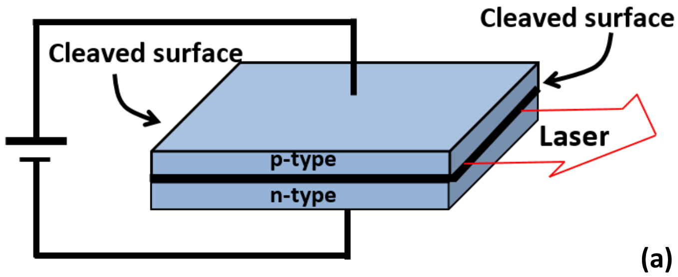
Direct and indirect band gap semiconductors

Direct Band Gap	Indirect Band Gap
	
Energy is liberated as photon	Energy is liberated as both phonon and photon
Ex: GaAs, InP	**Ex:** Ge, Si
Can be used for light emittion purpose	Cannot be used for light emittion purpose

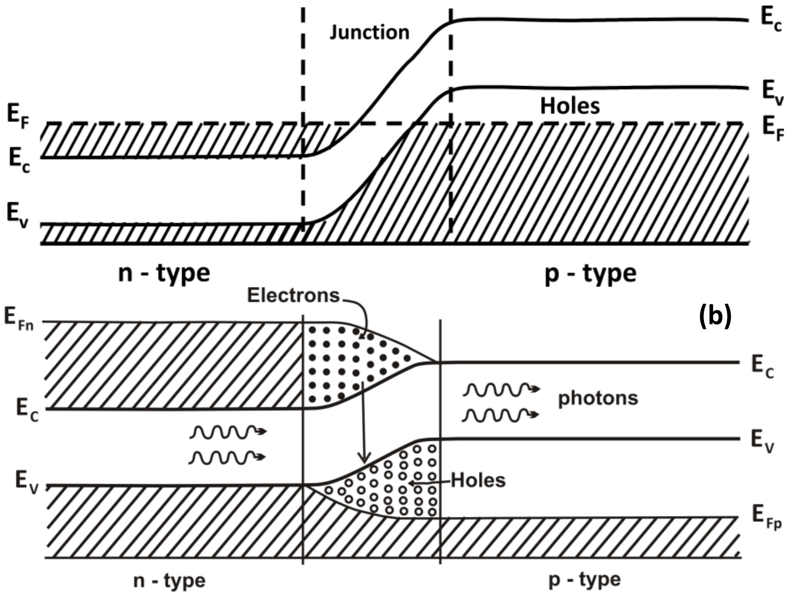
Semiconductor laser:

A Semiconductor diode laser is a specially fabricated p-n junction device that emits coherent light when it is forward biased. In the case of germanium and silicon based diodes, this energy is released in the form of heat because of recombination of carriers take place through interaction with the atoms of the crystal. But in the case of GaAs, the energy is released in the form of photons as the atoms of the crystal are not involved in the release of energy. The wavelength of the emitted photon depends upon the activation energy of the crystal.

Construction: A schematic diagram of semiconductor laser is as shown in the figure. The diode is very small size with sides of the order of 1mm. The junction lies in a horizontal plane. The top and bottom surfaces are metalized and ohmic contacts are provided for external connection. The front and rear faces are polished. The polished faces constitute the Fabry-perot resonator. The other two faces are roughened to prevent lasing action in that direction. The active region consists of about 1μm thickness.



(a)



(b)

Energy level diagram of p-n junction diode laser
(a) Before biasing (b) After biasing

The emitted photon stimulates the recombination of the other carriers.

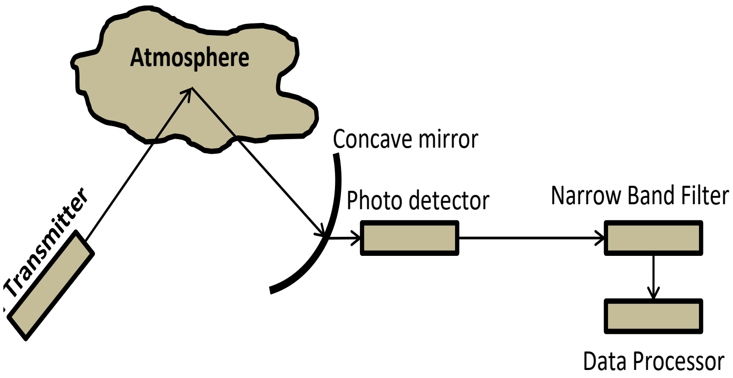
Working: The energy band diagram (Fig a) of heavily doped p-n junction in unbiased condition is as shown. At thermal equilibrium, the Fermi level is uniform across the junction. Because of very high doping on n-side, Fermi level is pushed into the conduction band and electrons occupy the portion of the conduction band lying below the Fermi level. On p-side, the Fermi level lies within the valence band and holes occupy the portion of the valence band that lies above the Fermi level.

When the junction is forward biased electrons and holes are injected into the junction region in high concentrations. At low forward current, the electron-holes recombination results in spontaneous emission of photons and the junction acts as a LED. As the forward current is increased gradually and when it reaches a threshold value the carrier concentration in the junction region there will be large concentrations of electrons within the band. As a result condition of population inversion is attained in the narrow region. This narrow zone in which population inversion occurs is called as an active region, at that stage a photon emitted spontaneously triggers stimulated emission. This stimulated electron-hole recombination produces coherent radiation.

Since the energy band gap of GaAs is 1.41 eV, the wavelength of emitted light is ~ 840 nm.

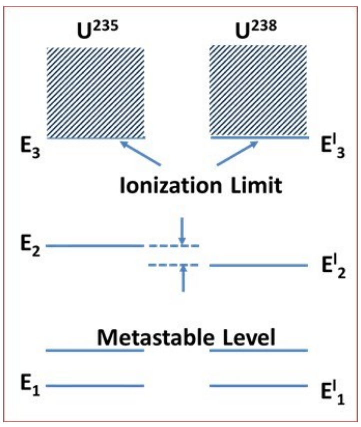
Applications of LASER

LiDAR (Light Detection and Ranging) in atmospheric pollutant studies



- A pulsed laser source is used to direct the laser beam into the atmosphere
- Due to the presence of particulate matter in the atmosphere, scattering will occur.
- The amplitude and direction and wavelength of the scattered beam depends on the concentration, composition and dimension of the pollutants
- The backscattered beam is collected by a detector and analyzed by a processor.
- As a general rule, more the aerosols present in the atmosphere more will be the backscattering.
- Using multiple wavelengths one can tell about the size distribution of aerosols, and depolarization data can be used to determine the shape.

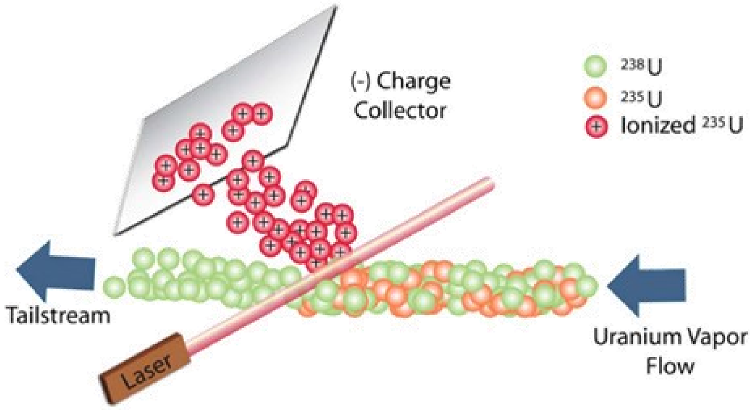
Laser Isotope Separation (LIS)



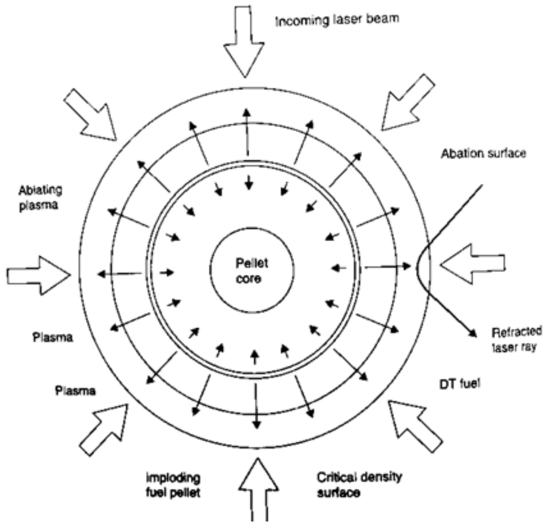
Uranium ore consists of 99.25 % of ^{238}U and 0.72 % of ^{235}U. ^{235}U is the fissile isotope which is needed as fuel for the nuclear reactors. Therefore it is important to enrich ^{235}U.

- LIS is a two stage process
  - In First stage ^{235}U is selectively excited to the level E_2 using a laser beam of frequency $\nu_1 = (E_2 - E_1)/h$.
  - A second laser of frequency $\nu_2 = (E_3 - E_2)/h$ is used to ionize the ^{235}U and these ions are collected by collector (negatively charged collector).

- Since the E_2' energy state of ^{238}U is at a lower energy compared to E_2 energy state of ^{235}U, the atoms of ^{238}U will remain in the ground state.



Laser Induce Fusion (LIF)



- When two light nuclei fuse together to form a heavier nucleus enormous energy is produced. This process occurs in the sun and the stars. It is the most abundant and pure form of energy in nature.
- Plenty of fusion fuel is found in both seawater and the Earth's crust.
- A Fusion process requires very high temperature (~10^8 K) and pressure(~10^{12} atm)
- Laser beams are focused confined area to achieve very high temperature (~10^8 K) and pressure (~10^{12} ATM) to have a new fusion system in the laboratory. Laser fusion is based on internal confinement
- The main lasers used in these systems are CO_2 or Nd:YAG laser.
- Fuel pellet is simultaneously irradiated with large number of short pulse laser beams and it will heat the pellet in short time
- This causes vaporization of the outer surface of the pellet to form plasma. The rapid heating causes the solid boundary to leave the rest of the pellet with high speed and this initiates the fusion.