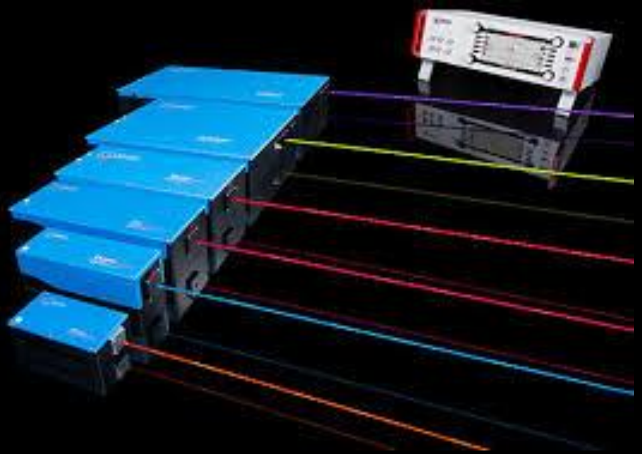
Introduction to LASERS



UNIT – IV LASER & LED's

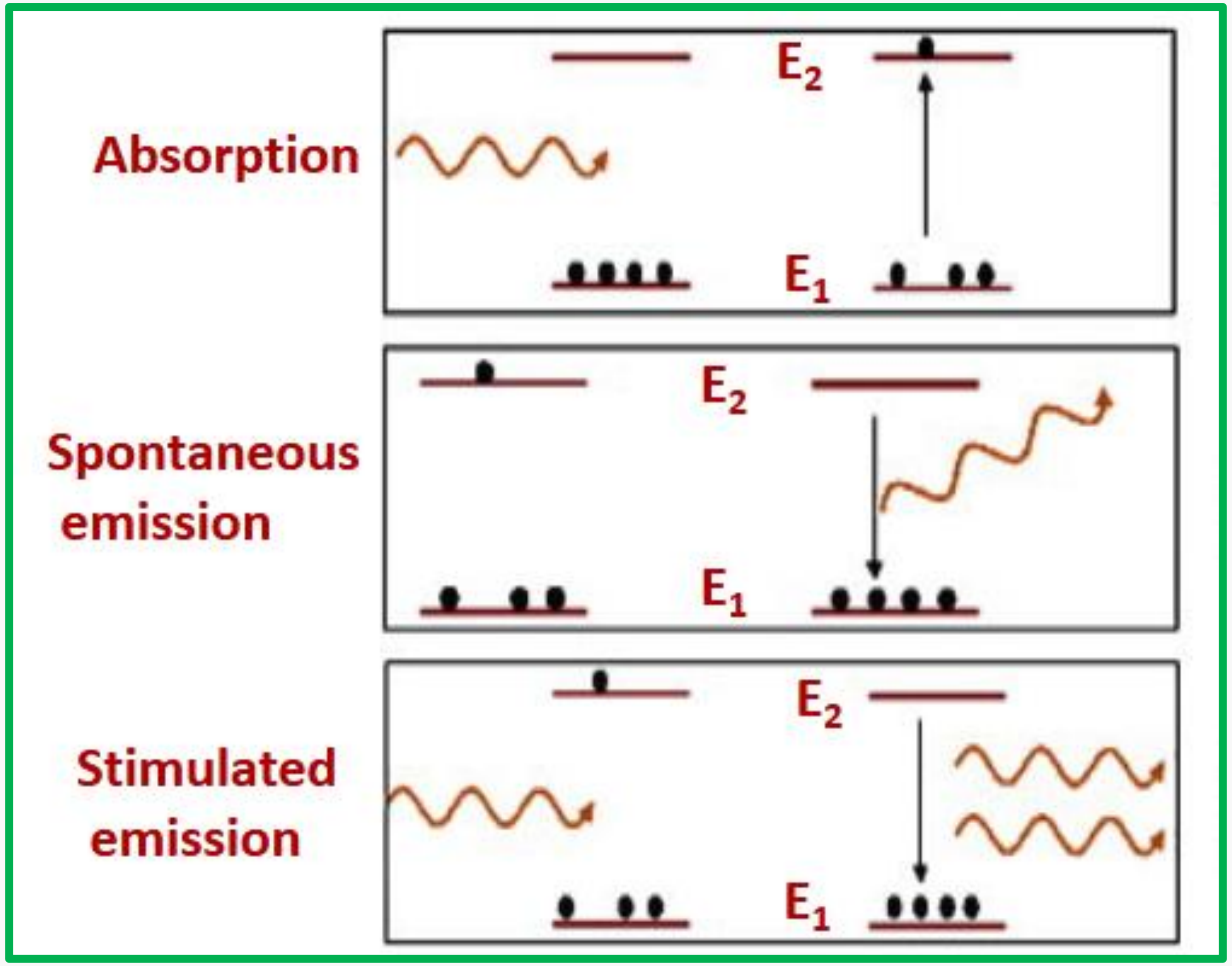
By: Dr. Vanita Thakur

WHAT IS LASER?

- It is an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.
- It is the most important optical device to be invented in past 50 years.
- Based on Einstein's idea of wave-particle duality of light.
- Invented in 1958 by Charles Townes (Noble prize in Physics in 1964) and Arthur Schawlow.
- Originally called MASER (where M = Microwaves). The MASER is similar to LASER but produced only microwaves.

Interaction of Radiation with Matter

According to Einstein Interaction of radiation with matter could be expressed in terms of 3 basic processes:



1. Induced Absorption
2. Spontaneous emission
3. Stimulated emission

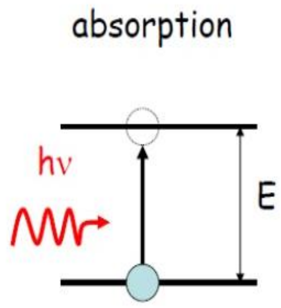
1. Induced Absorption

When an atom is at ground level (E_1) and an electromagnetic wave of suitable frequency υ is incident on the atom, there is possibility of the atom getting excited to higher level (E_2). The incident photon is absorbed. It is represented as :

Atom + Photon → Atom*

- If N_1 is the number density of the lower energy state and $\rho(\nu)$ is the energy density of incident radiation. Then,
  - ***Rate of absorption = $B_{12}N_1\rho(\nu)$***
- Where B_{12} is the proportionality constant called Einstein Coefficient of induced absorption.

$$\boxed{N_{ab} = B_{12}N_1\,\rho(\nu)\,\Delta t}$$



- E_1 = Ground state
- E_2 = Excited State
- E = hν (Photon Energy)

2. Spontaneous Emission:

The emission of a photon by the transition of a system from a higher energy state to a lower energy state without the aid of an external energy is called spontaneous emission.

Atom* → Atom + Photon

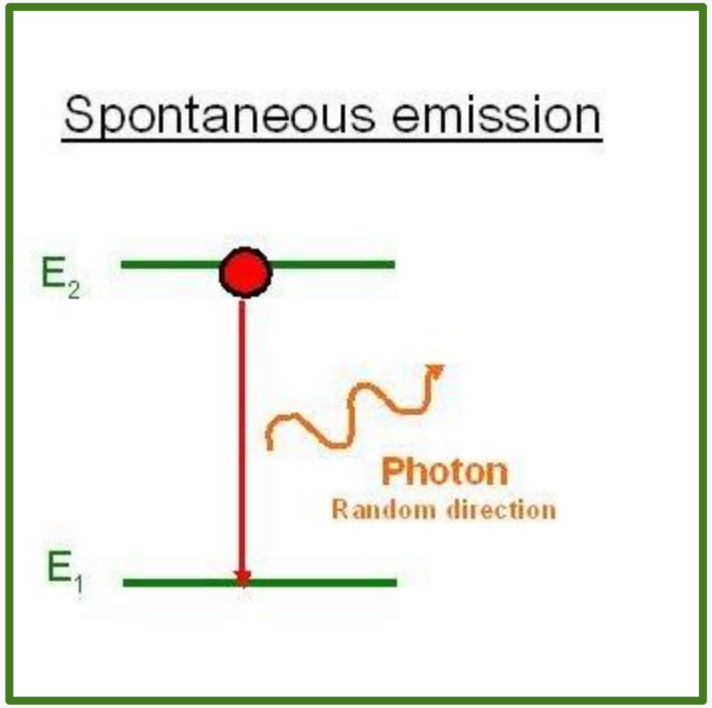
The photons emitted in spontaneous emission may not have same direction and phase similarities. It is incoherent. e.g.: Glowing electric bulbs, Candle flame etc.

Spontaneous emission depends on N_2 which is the number of atoms present in the higher level.

Rate of spontaneous emission = $A_{21}N_2$

where A_{21} is the proportionality constant called Einstein coefficient of spontaneous emission.

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



3. Stimulated Emission:

The phenomenon of **forced emission** of a photon by an excited atom due to action of an external agent is called stimulated emission. It is also known as induced emission.

The emitted two photons have same phase, frequency, direction and polarization with the incident photon. This kind of action is responsible for lasing action.

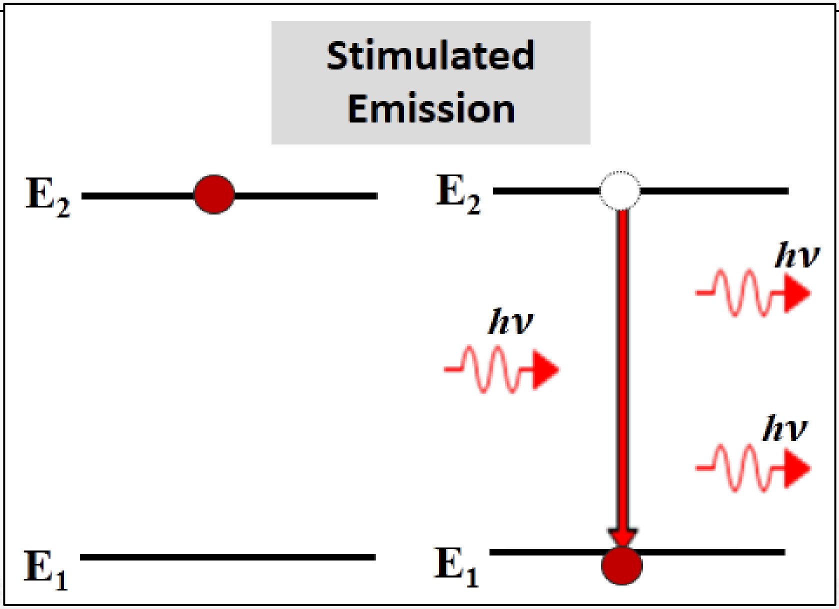
$$\text{Atom}^* + \text{Photon} \rightarrow \text{Atom} + 2\text{Photons}$$

- If N_2 is the number of atoms present in the higher energy level and $\rho(\nu)$ is the energy density.

$$\textit{Rate of stimulated emission} = B_{21}N_2\rho(\nu)$$

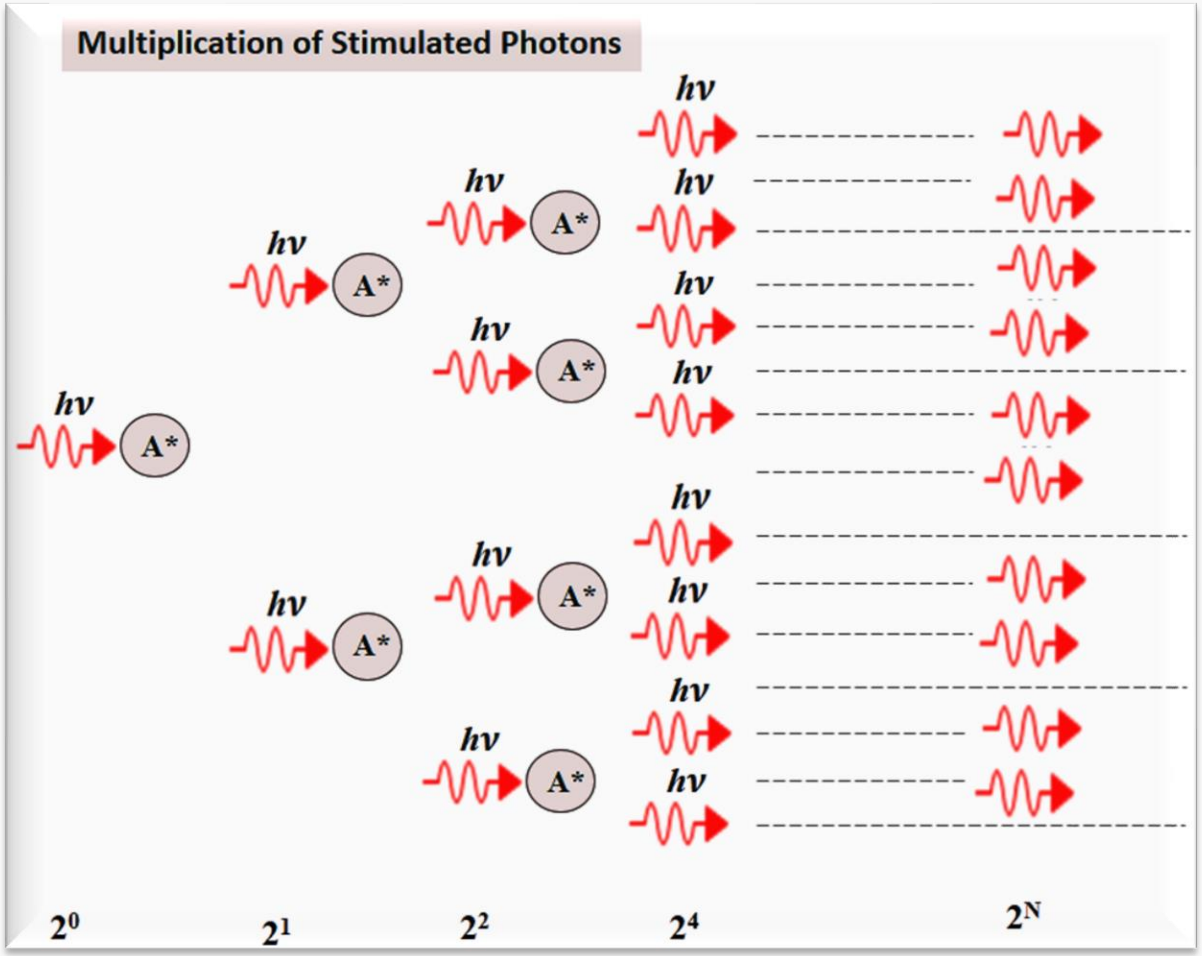
where B_{21} is the proportionality constant called Einstein's Coefficient of stimulated emission.

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



Stimulated Emission:

The emitted two photons have same phase, frequency, direction and polarization with the incident photon. This kind of action is responsible for lasing action.



Comparison: Spontaneous and Stimulated Emission

	Spontaneous emission	Stimulated emission
1.	The spontaneous emission was postulated by Bohr.	The stimulated emission was postulated by Einstein
2.	It is a random process.	It is not a random process.
3.	Additional photons are not required in spontaneous emission.	Additional photons are required in stimulated emission.
4.	One photon is emitted in spontaneous emission.	Two photons are emitted in stimulated emission.
5.	Light is non-directional.	Light is produced is highly directional.
6.	The emitted radiation is Incoherent.	The photons emitted in this process are all in phase. Hence, emitted radiation is coherent.
7.	The emitted radiation is less intense.	The emitted radiation is high intense.
8.	Emitted radiation is not monochromatic.	The emitted radiation is nearly monochromatic.
	Example: light from sodium or mercury lamp.	Example: light from laser source.

STEADY STATE

- Under steady state condition, absorption and emission balance each other.

$$N_{ab} = N_{spon.\ em} + N_{st.em}$$

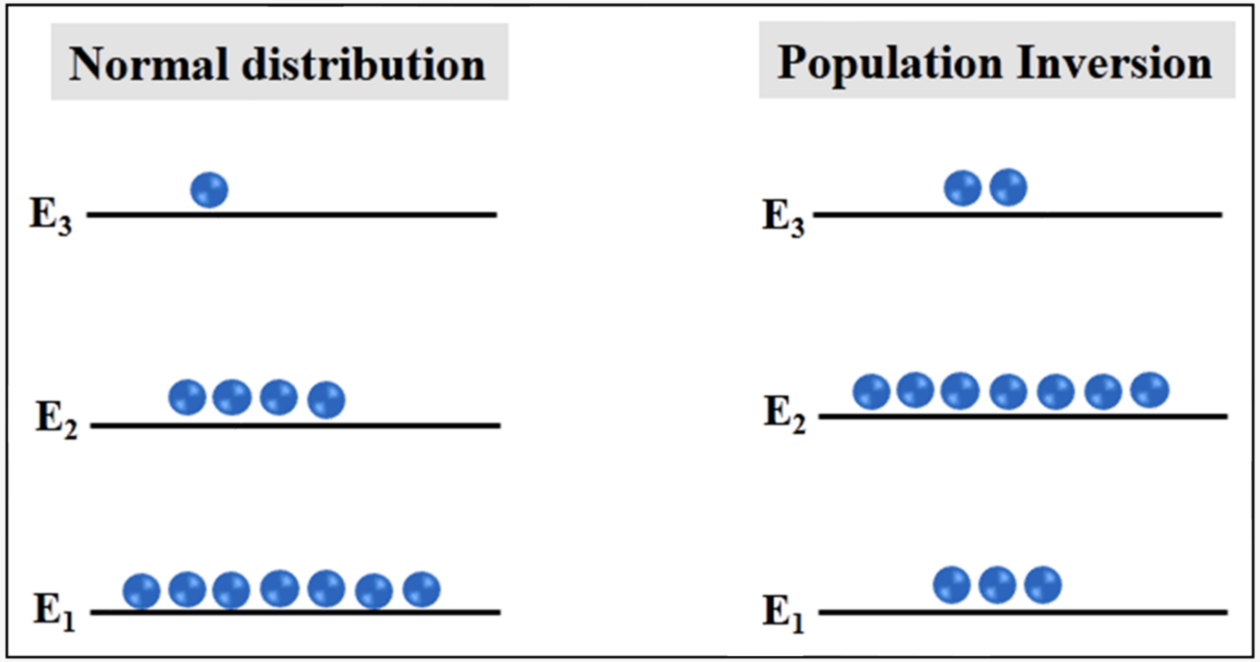
$$B_{12}N_1\,\rho(\nu)\Delta t = A_{21}N_2\,\Delta t + B_{21}N_2\,\rho(\nu)\,\Delta t$$

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

Population inversion

A non-equilibrium state in which the number of atoms present in the excited state (N_2) is greater than the number of atoms present in the ground state (N_1) i.e. ($N_2 >> N_1$) is called population inversion.

This is also known as inverted state.



Population inversion

According to Boltzmann's distribution the population of an energy level E_i at temperature T is given by

$$N_i = N_0 e\,(-E_i/kT)$$

Where N_0 *is* the population of the lower level or ground state and k is the Boltzmann's constant.

Population inversion is achieved by the process called Pumping.

At thermal equilibrium, the population is maximum in the ground state and decreases exponentially as one goes to higher energy states.

If N_1 and N_2 are the populations in two states, a lower state E_1 and a higher state E_2 we have:

$$\frac{N_2}{N_1} = \frac{e^{-E_2/kT}}{e^{-E_1/kT}}$$

$$N_2 = N_1 e^{-(E_2-E_1)/kT}$$

clearly, $N_2 < N_1$ since $E_2 > E_1$

Pumping

- **For maintaining a state of population inversion atoms have to be raised continuously to excited state. It requires energy to be supplied to the system.**
- **The process of raising the atoms/molecules from their lower energy state to higher energy state is known as pumping. The pumping is needed to achieve population inversion.**

Commonly used pumping types are : —

1.Optical pumping: Light/ flash tube is used to raise the atoms to higher energy states. Optical pumping is used in solid lasers.

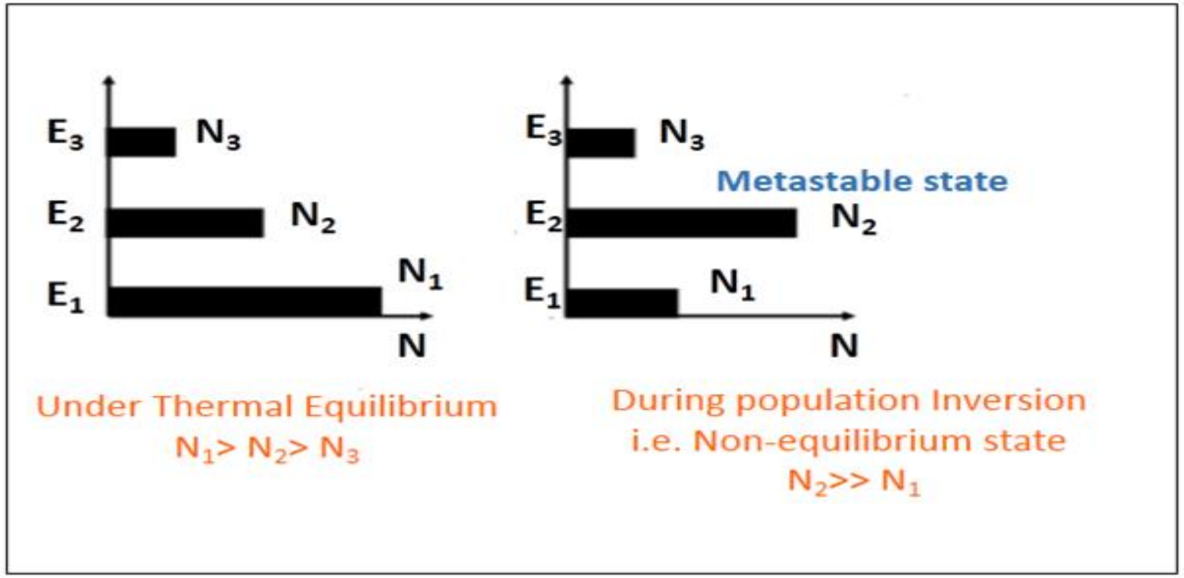
2.Chemical pumping: Chemical reactions are used to raise the atoms.

3.Electrical pumping: A strong field is applied to the atomic system with the help of high voltage power supply. The high energy electrons collide with the atoms and transfer their kinetic energy to the later. As a result, atoms rise to the higher states.

4.Direct conversion: In this method the electrical energy directly creates the state of population inversion and laser is produced. This pumping mechanism is used in semiconductor lasers.

Metastable State

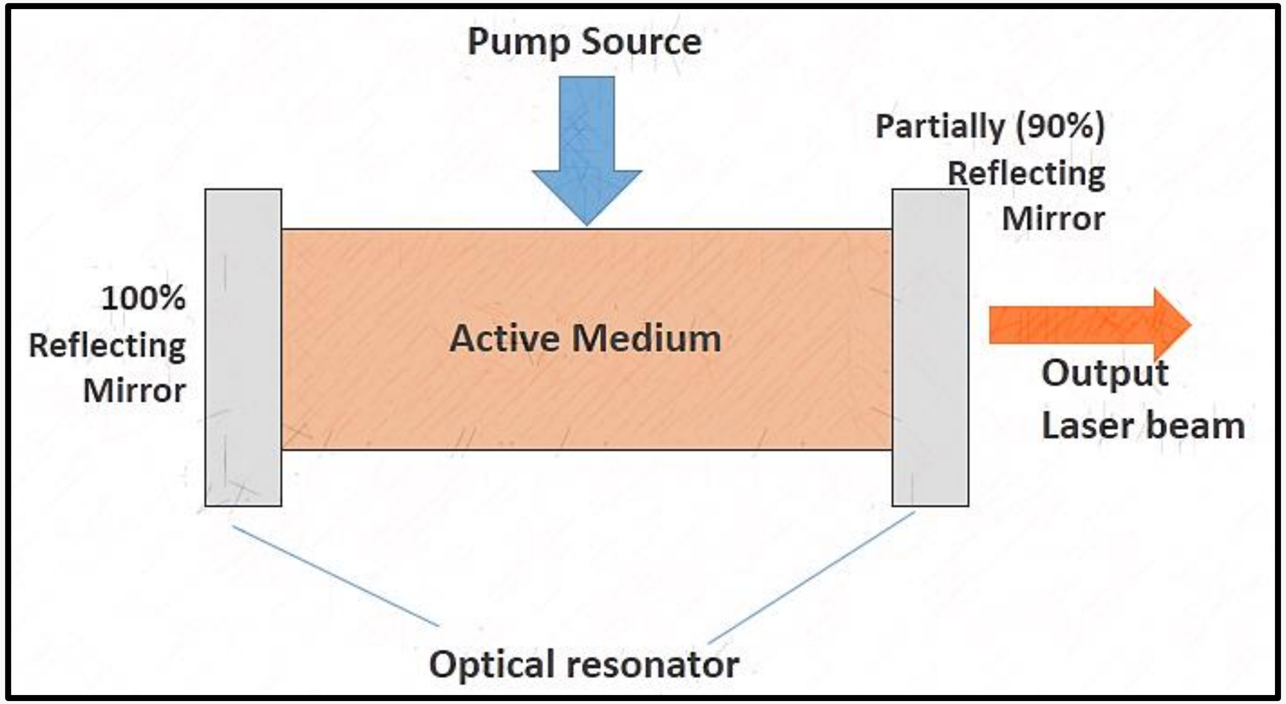
- Metastable state is an excited state of an atom or other system with a **longer lifetime** than the other excited states. Atoms in the metastable state remain excited for a considerable time in the order of **10^{-6} to 10^{-3} s.**
- A large number of excited atoms are accumulated in the metastable state.
- The population of metastable state can exceed the population of a lower level thereby establishing the population inversion between metastable state and the lower energy level.
- Population inversion could not be created without a metastable state.



Components of Laser

- Every LASER consists of three basic components. These are –

1. Lasing material or active medium.
2. The Pump
3. Optical resonator.



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1. Active Medium:

- The **active medium is the material in which lasing action takes place.**
- **An active medium is a medium which when excited reaches the state of population inversion and promotes stimulated emissions leading to** light amplification.
- Semiconductors, gases (He, Ne, CO_2, etc), solid materials (YAG, sapphire (ruby) etc.) are usually used as lasing materials and often LASERs are named for the ingredients used as a medium.

2. The Pump: The excitation source, pump source provides energy which is needed for the population inversion and stimulated emission to the system. Pumping can be done in different ways – optical method, electrical discharge method and direct conversions. Examples of pump sources are electrical discharges, flash lamps, arc lamps, light from another laser, chemical reactions etc.

3. Optical Resonator: The active medium is enclosed between a fully reflective mirror and partially reflective mirror. These mirrors constitute the optical cavity or resonator.

The reflectors enhance the stimulated emission process by reflecting the photons into the active medium. As a result we get high-intensity monochromatic and coherent laser light through the partially reflecting portion of the mirror.

PROPERTIES OF LASER BEAM

- Laser radiation has the following important characteristics over ordinary light source. They are:

i) **Monochromaticity:**

i.e. laser light consists of nearly one color or single wavelength.

ii) **Directionality:**

i.e. the laser beam is well collimated and travels a long distance with very little spread (low divergence).

$$\text{Divergence } (\phi) = \frac{\text{diameter of beam}}{\text{distance covered}}$$

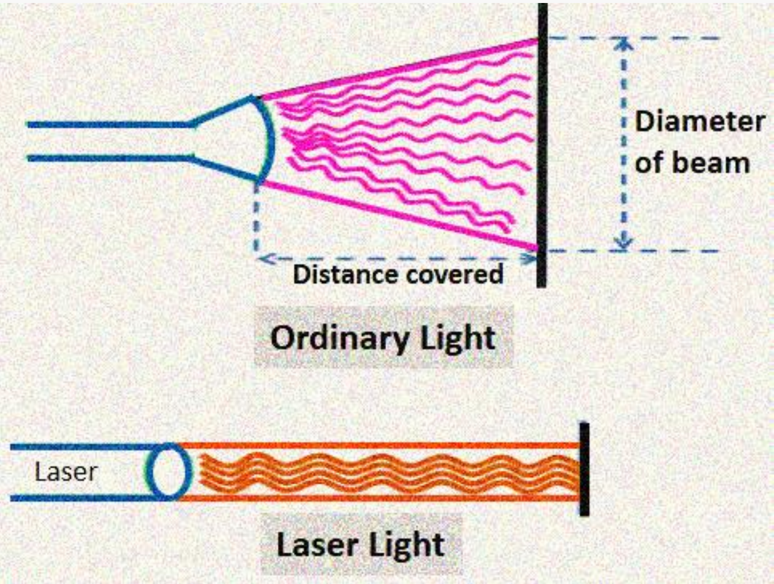
iii) **Coherence:**

i.e. all the emitted photons of laser light have constant phase relationship with each other in time and space.

iv) **High Irradiance:**

i.e. power of em radiation emitted per unit area

- The energy of the laser beam is approximately given by:
  - $I = \left(\frac{10}{\lambda}\right)^2 P \quad (W/m^2)$
- where P is the power radiated by the laser.



Coherence

Requirements for Achieving Laser Action

1. Population inversion

2. Metastable states

3. Confining radiation within the medium

LASER Action

1. Pumping
2. Population Inversion
3. Spontaneous emission
4. Stimulated emission
5. Amplification
6. Oscillations

Lasing Action

LASER production in an optical cavity:(Laser production in lasting material)

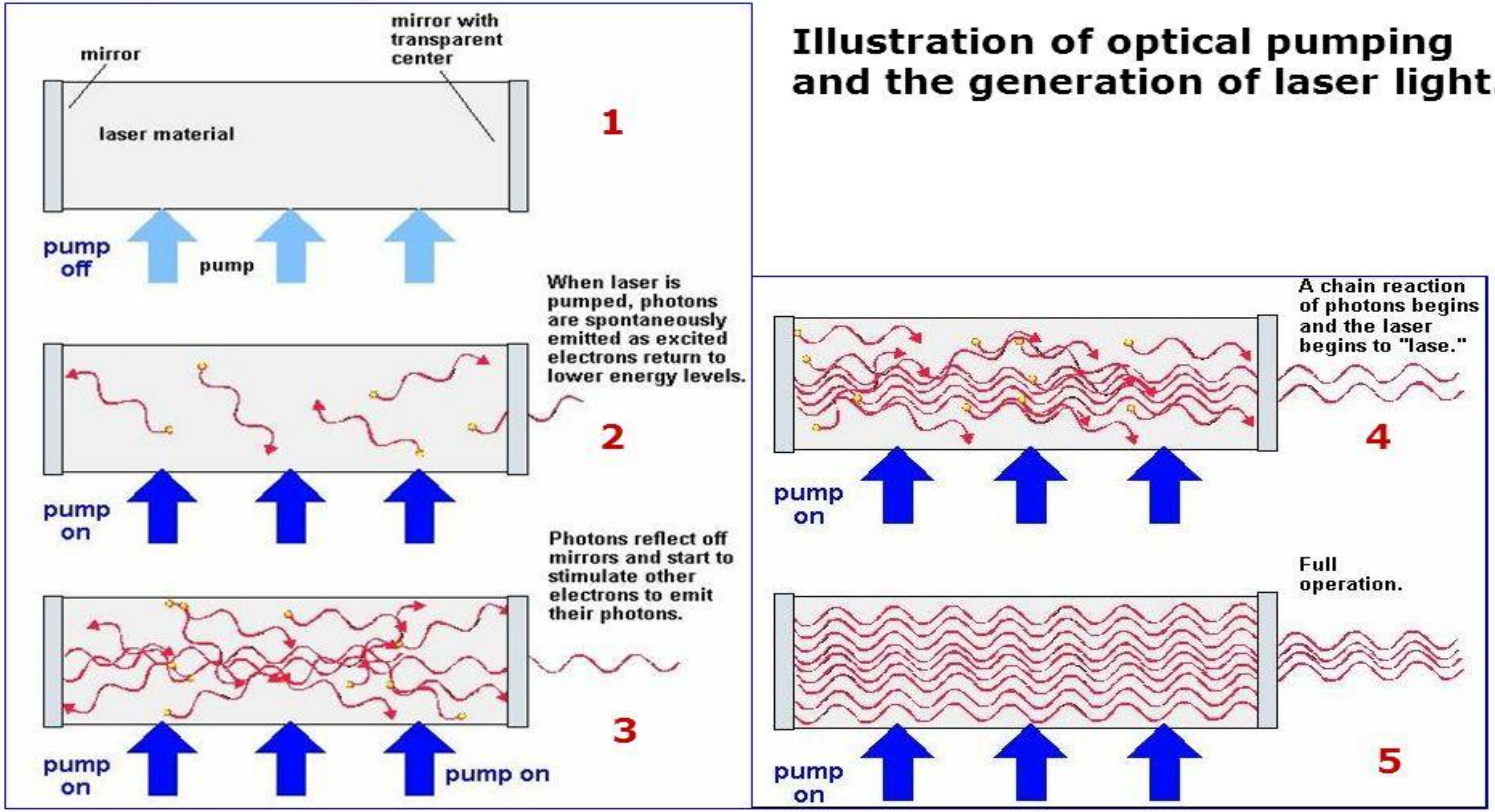
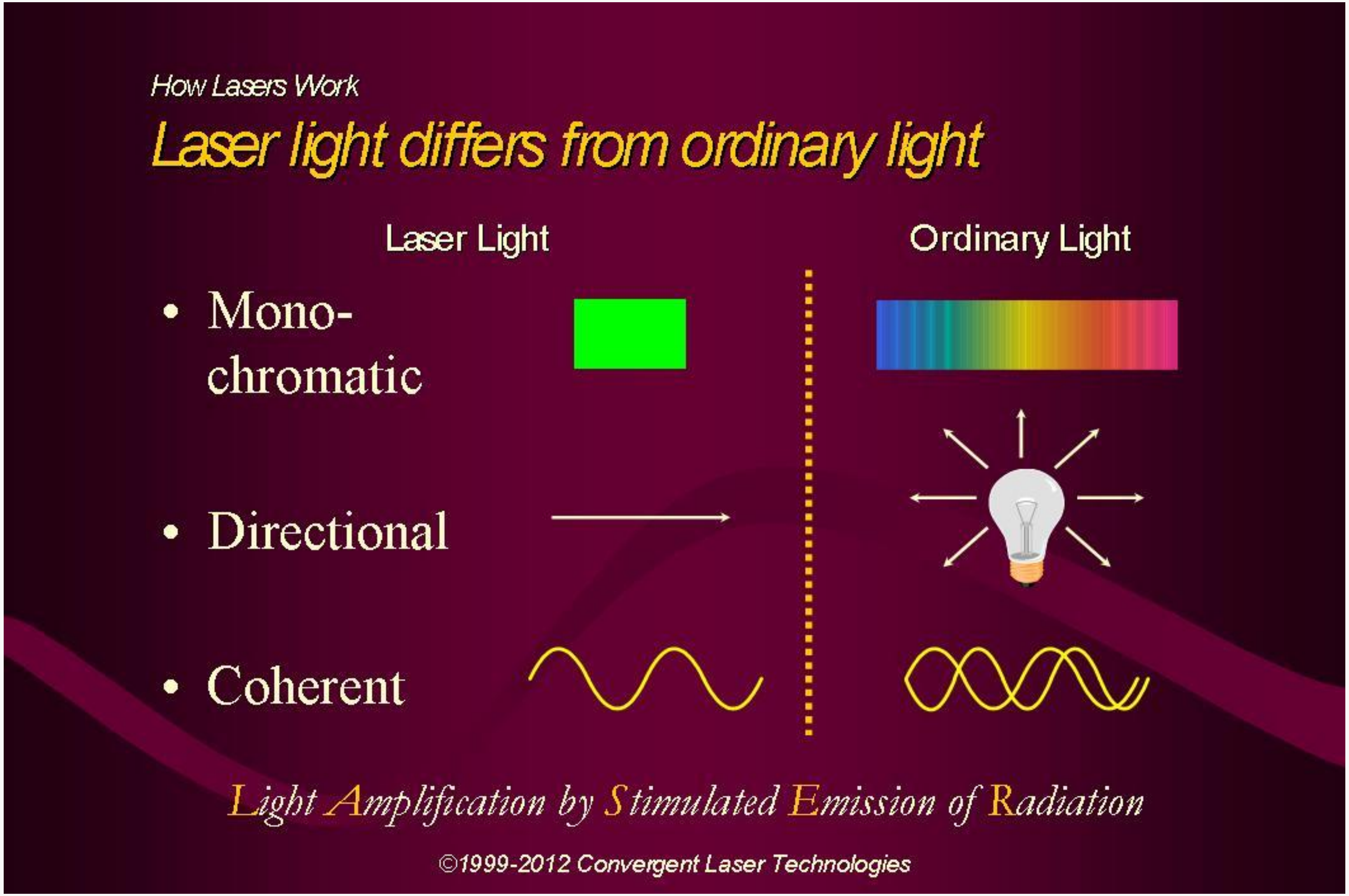


Illustration of optical pumping and the generation of laser light.


How Lasers Work
Laser light differs from ordinary light
Laser Light
Ordinary Light
• Mono-chromatic
• Directional
• Coherent
Light Amplification by Stimulated Emission of Radiation
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Types of LASER

LASERs are categorized on various parameters.

1. By active medium

❖ **Solid State laser:** In this kind of lasers solid state, materials are used as active medium.

e.g. Ruby laser, Nd:YAG laser, Ti:Sapphire laser

❖ **Gas Laser:** In this kind of lasers gases are used as active medium.

e.g. He-Ne laser, CO2 laser, Argon-ion laser.

❖ **Semiconductor Laser:** In these type of **lasers**, junction diodes are used.

e.g Group III-V, Group II-VI, Group VI-VI

2. By mode of operation

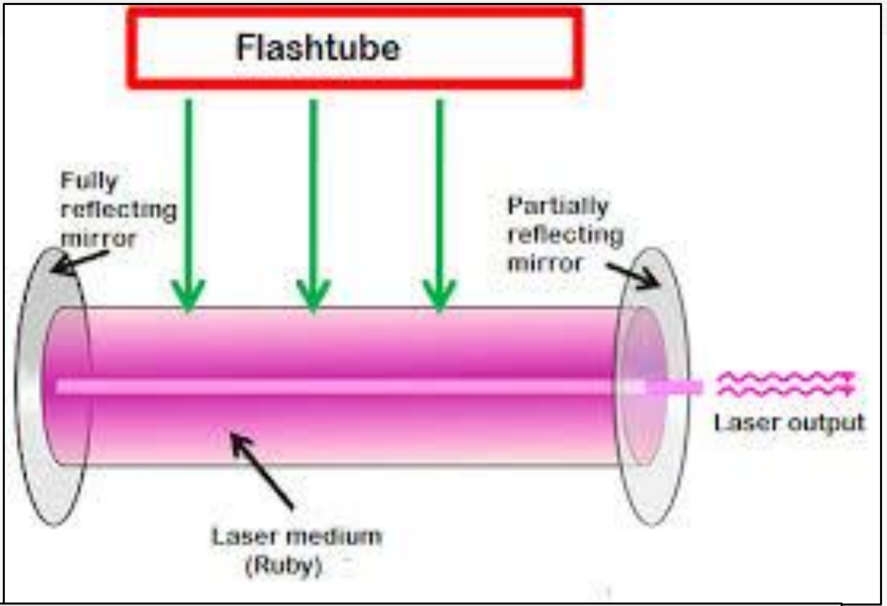
- ❖ Continuous Wave (CW)
- ❖ Pulsed mode

3. By pumping and laser levels

- ❖ 3-level laser
- ❖ 4-level laser

CONSTRUCTION AND WORKING OF RUBY LASER

- ✓ Ruby laser is the type of solid state laser
- ✓ It is the first successful laser developed in 1960.
- ✓ It produces visible red light of wavelength 694.3 nm.
- ✓ Uses 3-level pumping scheme.



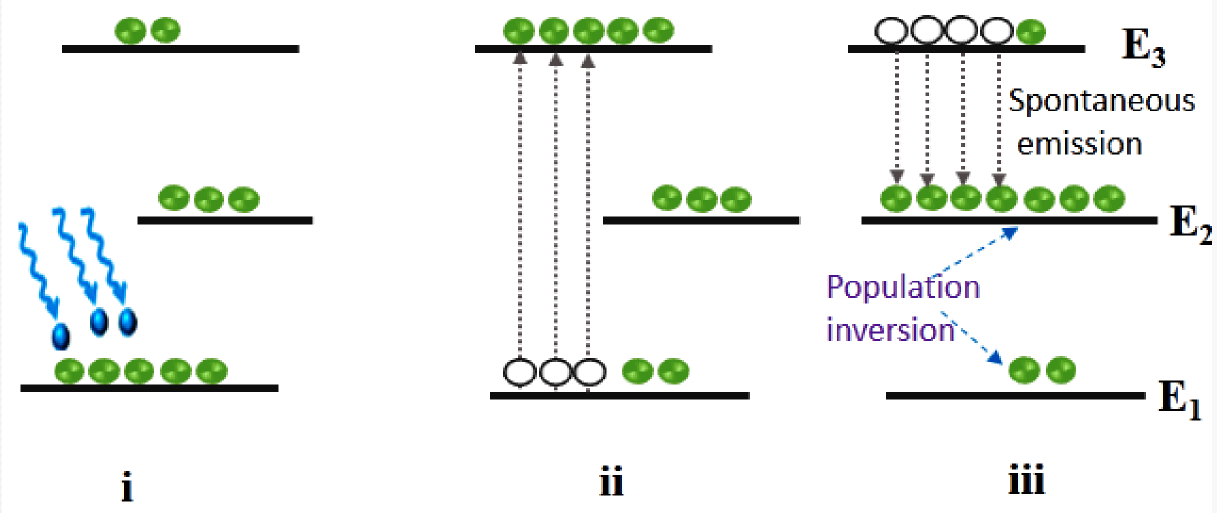
Construction: Ruby laser consists of 3 main parts:

▪**Active medium:** Al_2O_3 crystal containing about 0.05% Cr^{+3} ions.
Ruby rod. length≈ 4 cm. diameter ≈ 1 cm.

▪**Pump source:** **Optical pumping (Xenon flash lamp)**

▪**Optical resonator:** The ruby rod is placed between two mirrors which are silvered. One mirror is fully silvered whereas, another mirror is partially silvered.

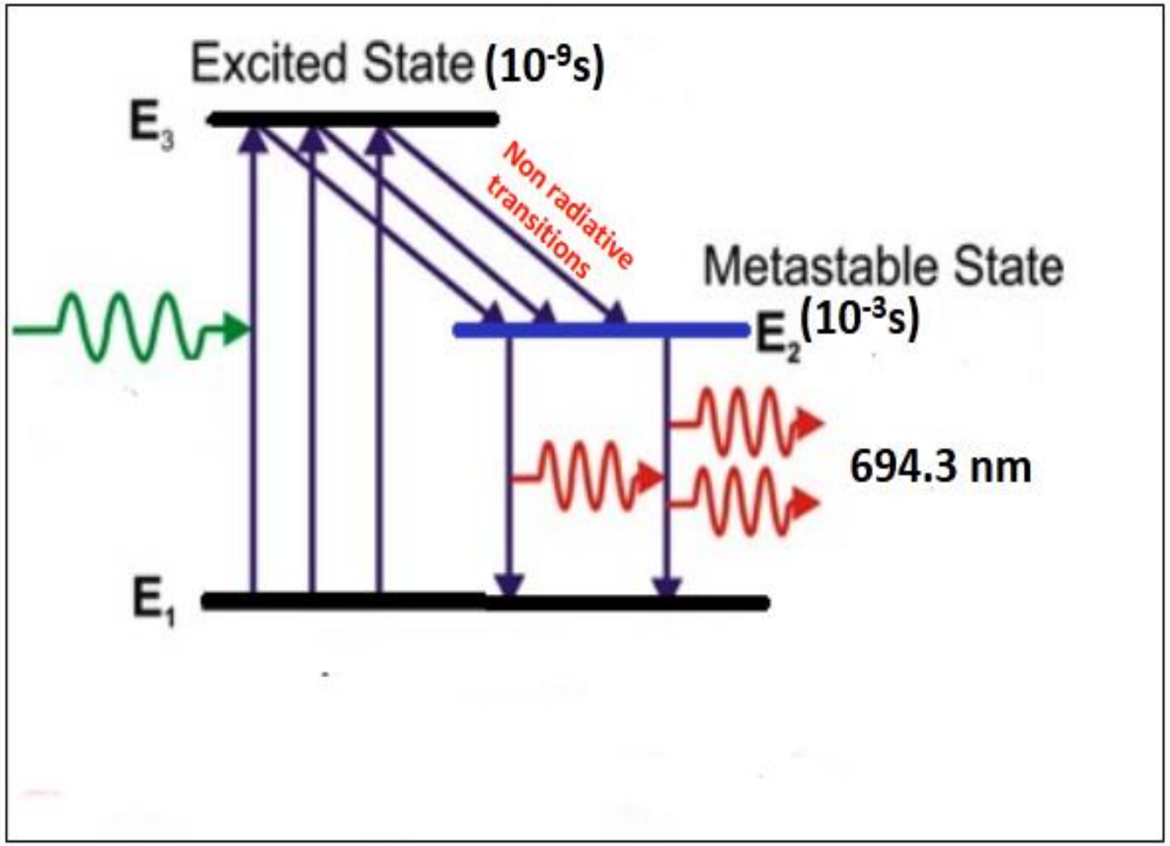
how population inversion is achieved??



- An atom In ground state absorbs energy and transits to an excited state.
- The atom stays at the excited state falls to an intermediate state called metastable state after 10^{-8}s.
- It stays at the metastable state for a rather long time: around 10^{-3} to 10^{-6} seconds.
- The lifetime of metastable state E_2 is 10^{-3} s, which is much greater than the lifetime of state E_3. So, the Cr^{+3} ions stay there for a longer time duration.
- Hence, population inversion is achieved between Ground state (E1) and metastable state (E2)

Energy level diagram

- After some time, the Cr^{+3} ions in the metastable state E_2 falls into the lower energy state E_1 via spontaneous emission and emit photons.
- These photons then initiate a chain of stimulated emissions by triggering the excited ions to fall to ground state E_1.
- Photons (light) of wavelength 694.3 nm are produced in the medium. They travel along the axis of the ruby rod and will bounce back and forth between the two end mirrors. Hence, light is amplified, and a strong, intense beam of red light emerges out of the partially reflecting mirror.



Salient features of Ruby laser:

- ✓ Uses a 3-level pumping scheme.
- ✓ Active centers are Cr^{+3} ions.
- ✓ Light from xenon flash tube acts as a pumping source.
- ✓ Operates in Pulsed mode.
- ✓ Has poor efficiency.

CONSTRUCTION & WORKING OF HE-NE LASER

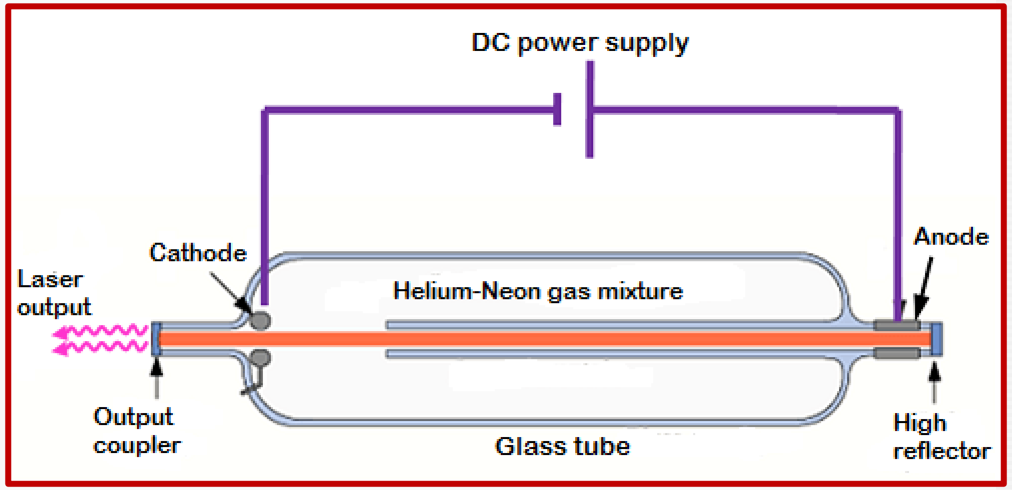
- It is a type of gas laser.
- Uses 4-level pumping scheme.
- It emits a laser beam of wavelength of 632.8 nm in the red portion of the visible spectrum.

Construction:

Active Medium: Mixture of He and Ne gases in the ratio 10:1 placed in glass tube.

Pump source: High voltage DC power supply (~10 kV)

Resonating cavity: The glass tube (containing a mixture of helium and neon gas) is placed between two parallel mirrors which are silvered(which forms Fabrey –Perot optical resonator). One mirror is fully silvered whereas, another mirror is partially silvered.



- ✓ In He-Ne laser discharge tube is generally made up of 80 cm length and 1 cm diameter.
- ✓ The output power of these gas lasers depends on the length of the glass discharge tube and the pressure of the gas mixture.
- ✓ Distance between the mirrors is adjusted to be $m\lambda/2$.

Working:

High voltage (10kV) produces energetic electrons

↓

These electrons travel through gas mixture

↓

Transfer some energy to He atoms in gas

↓

Lower state electrons in He atoms get excited (higher/metastable state)

↓

These can not return to ground state by spontaneous emission

↓

But can return to ground state by transferring their energy to Ne atoms

↓

As a result Ne atoms get excited to higher/metastable state and He atoms fall to ground state

Thus, He atoms help Ne atoms in achieving population inversion.

- This excited state of neon atoms is a metastable state and, thus, have a longer lifetime. Therefore, a large number of neon atoms will get accumulated in the metastable states and so, population inversion is achieved.

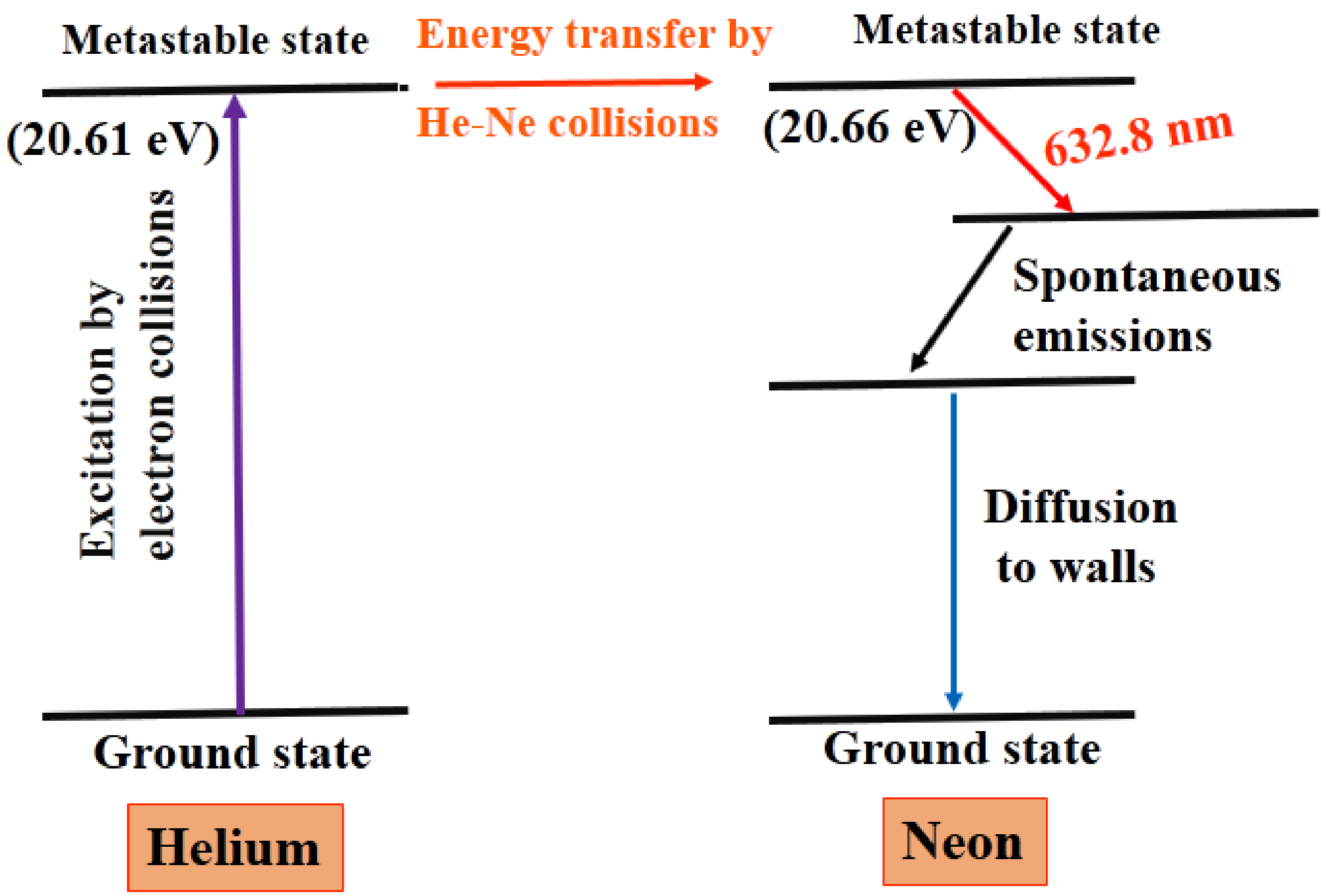
- After some time, Ne atoms in the metastable states (E_4) will spontaneously fall into the lower energy states (E_3) by releasing photons of wavelength 632.8 nm.

- These photons will further trigger a chain of stimulated emissions, which will produce photons of wavelength 632.8 nm.

- These photons will bounce back and forth between the end mirrors, causing more and more stimulated emissions with each passage. Hence, light is amplified, and a strong, intense laser beam comes out from the partially reflecting mirror.

- The excited neon atoms come to the ground state through frequent collisions with the walls of the glass discharge tube and again available for excitation to higher energy levels and participation in laser action. It is important for the continuous wave (CW) operation.

Energy level diagram



Energy level diagram of He-Ne Laser

❖ Salient features

Uses a 4-level pumping scheme.
Active centers are Neon atoms.
The electric discharge is the pumping source.
Operates in continuous wave (CW) mode.
Low efficiency and low power output.

❖ Advantages of Helium-Neon laser

- ✓ Helium-Neon laser emits laser light in the visible portion of the spectrum.
- ✓ It has high stability.
- ✓ It is of low cost.
- ✓ It operates at a higher temperature without any damage.

❖ Disadvantages of Helium-Neon laser

- ✓ It gives low efficiency
- ✓ Its applications are limited to low power tasks only.

Semi-conductor Laser

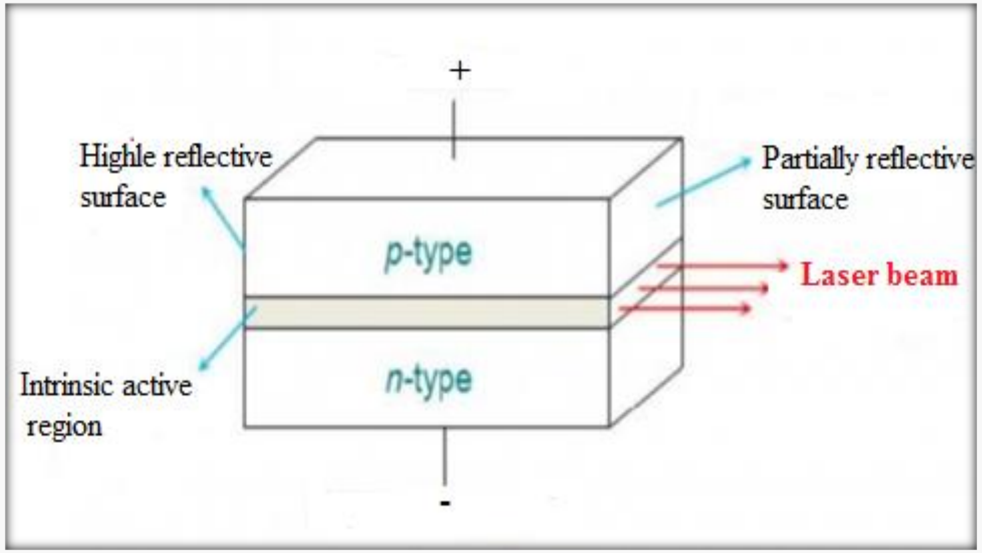
- It is a solid state semiconductor laser.
- Gallium arsenide (GaAs) laser gives infrared radiation in the wavelength 8300 to 8500 *A* .
- It emits light when it is forward biased.
- Emitted light is in near IR region.

Construction:

- **Active Medium:** A pn junction diode made of single crystal of GaAs is used as an active medium.
- **Pump source:** The direct conversion method.
- **Resonating cavity:** The end faces of the junction diode which are well polished and parallel to each other, act as an optical resonator through which the emitted light comes out.

A typical semiconductor laser consists of following parts:

- **Metal Contact**
- **P-type Material**
- **Active/Intrinsic Region**
- **N-type Material**
- **Metal Contact**



Principle:

When a p-n junction diode is under forward bias, the electrons from n-region and holes from p-region cross the junction.

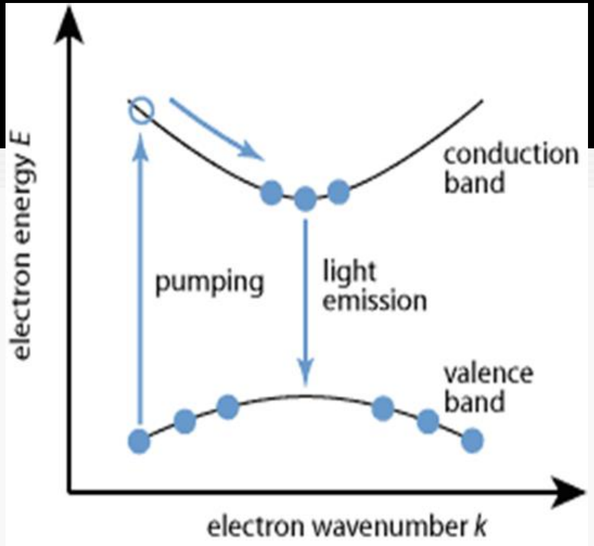
In the process, electrons from the conduction band jump into a hole in the valence band and excess energy is released in the form of photons.

This electron-hole recombination is the basic mechanism responsible for the emission of light in laser diodes.

The wavelength of light emitted is given by the relation:

$$\lambda = hc/E_g$$

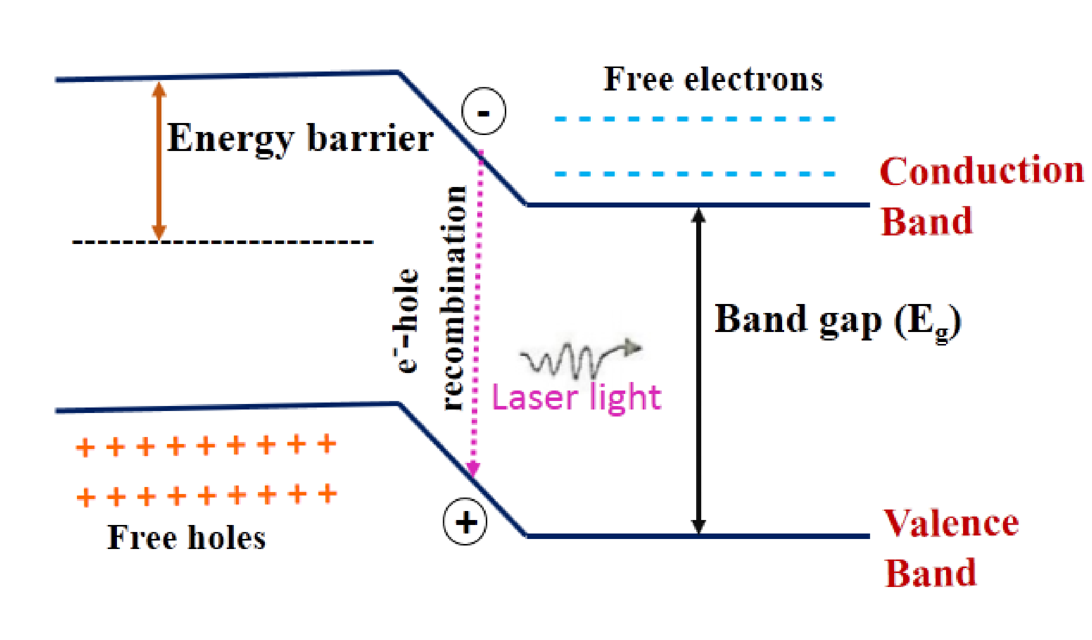
Working…



- When a p-n junction diode is **forward biased**, the electrons from n–region and the holes from the p-region cross the junction and recombine with each other.

- During the **recombination process**, the light radiation (photons) is released from a certain specified direct band gap semiconductors like Ga-As. This light radiation is known as recombination radiation.

- The photon emitted during recombination **stimulates** other electrons and holes to recombine. As a result, stimulated emission takes place which **produces laser.**



Advantages & Applications of Laser diode

❖ Advantages:

1. It is very small in size and very simple and compact (0.1mm).
2. It has high efficiency (≈40%).
3. The laser output can be easily increased by controlling the junction current
4. It is operated with lesser power than ruby and CO_2 laser.
5. It can have a continuous wave output or pulsed output.

❖ Applications:

1. It is widely used in fiber optic communication.
2. It is used in laser printers and CD writing and reading.
3. It is also used as a pain killer.

Advantages of Lasers

1. It has high information carrying capacity and hence is used in communication domain for transmission of information.

2. It is free from electro-magnetic interference. This phenomenon is used in optical wireless communication for telecommunication as well as computer networking.

3. Laser based fiber optic cables are very light in weight and hence are used in fiber optic communication system.

4. It is less damaging compared to X-rays and hence widely used in medical field for treatment of cancers. It is used to burn small tumors on eye surface and also on tissue surface.

5. High intensity and low divergence of laser is used for knocking down the enemy tank with accurate range determination. For this purpose neodymium and carbon dioxide laser types are used.

6. Single laser beam can be focused in areas smaller than 1 micro diameter. One square micro area is needed to store 1 bit of data. This helps in storing 100 million data in one square cm. Due to this fact, laser is being used in laser CDs and DVDs for data storage in the form of audio, video, documents etc.

Applications of Lasers

Lasers in Communications

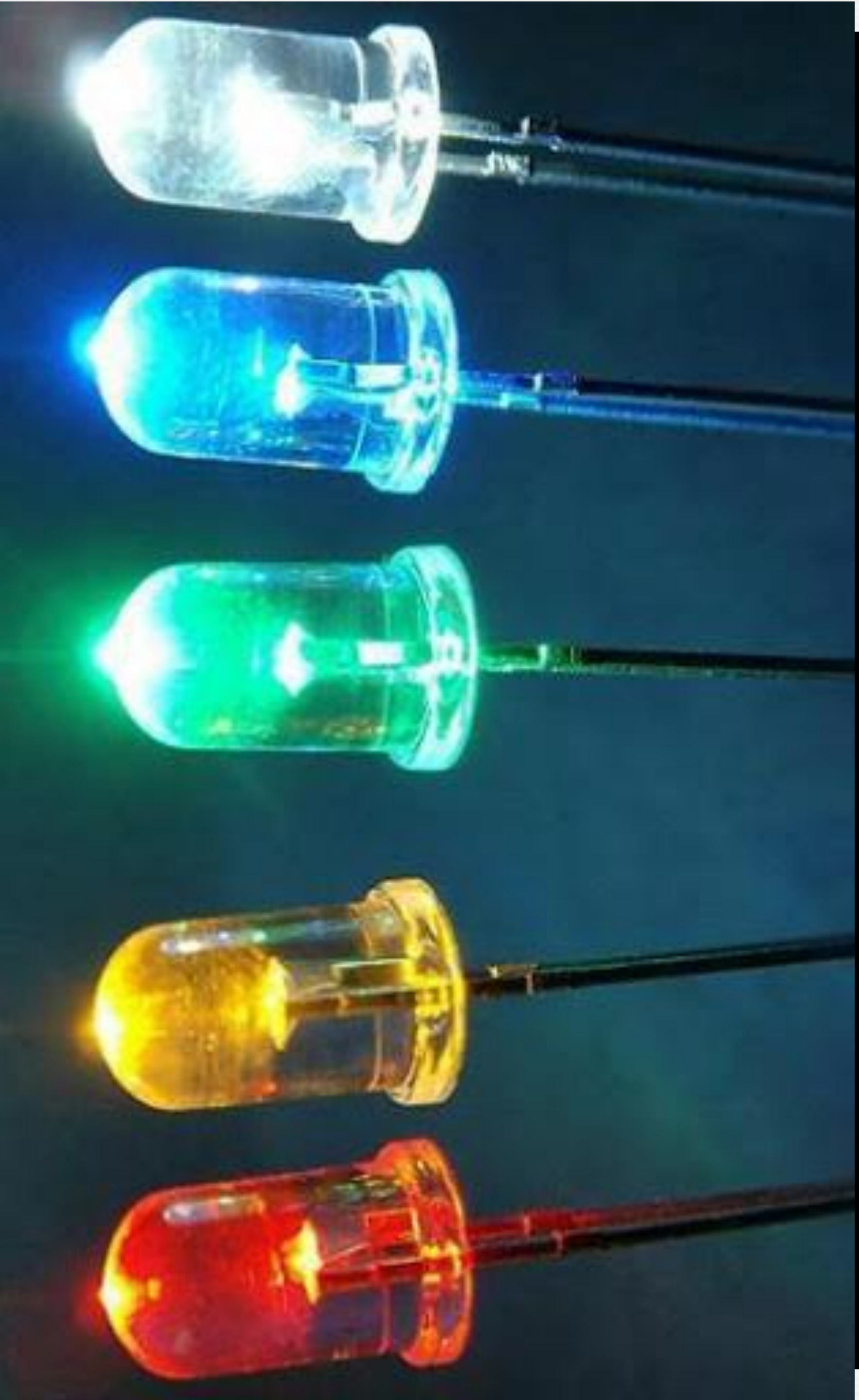
1. Laser light is used in optical fiber communications to send information over large distances with low loss.
2. Laser light is used in underwater communication networks.
3. Lasers are used in space communication, radars and satellites.

Lasers in Industries

1. Lasers are used to cut glass and quartz.
2. Lasers are used in electronic industries for trimming the components of Integrated Circuits (ICs).
3. Lasers are used for heat treatment in the automotive industry.
4. Laser light is used to collect the information about the prefixed prices of various products in shops from the bar code printed on the product.

Lasers in Science and Technology

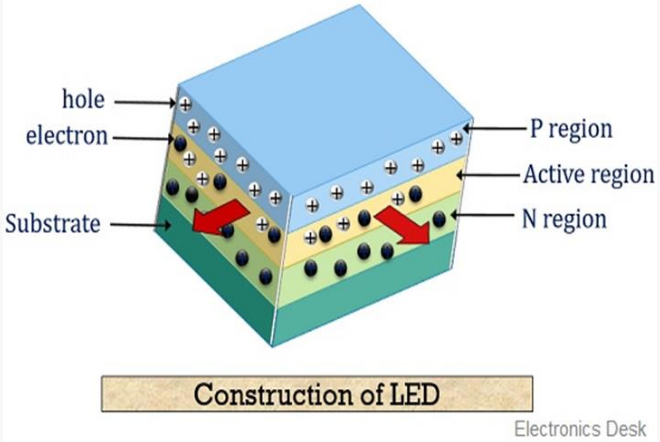
1. Lasers are used in computers to retrieve stored information from a Compact Disc (CD).
2. Lasers are used to store large amount of information or data in CD-ROM.
3. Lasers are used to measure the pollutant gases and other contaminants of the atmosphere.
4. Lasers are used in computer printers.
5. A gallium arsenide diode laser can be used to setup an invisible fence to protect an area.



LIGHT EMITTING DIODE (LED)

LED

- ✓Its an acronym for Light Emitting Device
- ✓LED was first developed in 1960
- ✓It a p-n junction diode
- ✓Works in forward biasing
- ✓Incoherent light
- ✓Principle: Electroluminescence
- ✓Converts electrical energy into light energy



Types of Luminescence

Luminescence is defined as the emission of optical radiation due to electronic excitation. When the excited system goes back to the ground state energy is emitted in the form of EM radiation. There are different types of luminescence, depending on how the electronic excitation is originally created:

- **Photoluminescence:** electronic excitation is created by ***incident light i.e. photons***
- **Cathodoluminescence** electronic excitation is created by an ***electron beam***.
- **Radioluminescence:** electronic excitation is created by ***ionizing radiation*** (β-rays)
- **Electroluminescence:** **electronic excitation is created by an *electrical field*.**

LEDs usually work by electroluminescence. Electric current, i.e. electron and holes, are passed to the device by an applied bias. These electrons and holes recombine to emit light.

Phenomenon	Mode of excitation
Photoluminescence (fluorescence, phosphorescence, delayed fluorescence)	Absorption of light (photons)
Radioluminescence	Ionizing radiation (x-rays, α, β, ϒ)
Cathodoluminescence	Cathode rays (electron beam)
Electroluminescence	Electric field
Thermoluminescence	Heating after prior storage of energy (e.g., radioactive irradiation)
Chemiluminescence	Chemical reaction (e.g. oxidation)
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Characteristic Time (τ_c)

- It is the the time between the emission and absorption of an EHP.

- If $\tau_c \leq 10^{-8}$ sec , the emission is fluoroscence, where emission occurs simultaneously with incident radiation.
- If $\tau_c \geq 10^{-8}$ sec , the emission is phosphoroscence, in which there is a delay between emission and absorption.

RADIATIVE TRANSITIONS

- In LEDs, electroluminescence (EL) is created by injected carriers in a pn junction. These recombine to give photons.
- EL occurs in both direct and indirect band gap semiconductor, though the efficiency of radiative transition is higher in a direct band gap semiconductor.
- LEDs depend on recombination of electrons and holes.

There are 3 main mechanisms of this recombination

- 1. Interband transitions
- 2. Defect transitions
- 3. Intraband transitions

Not all these transitions are radiative. In LEDs the radiative transition must be maximized relative to the nonradiative transition.

This can be accomplished by choosing the right materials and the right external bias.

1. Interband transitions-– band to band transition

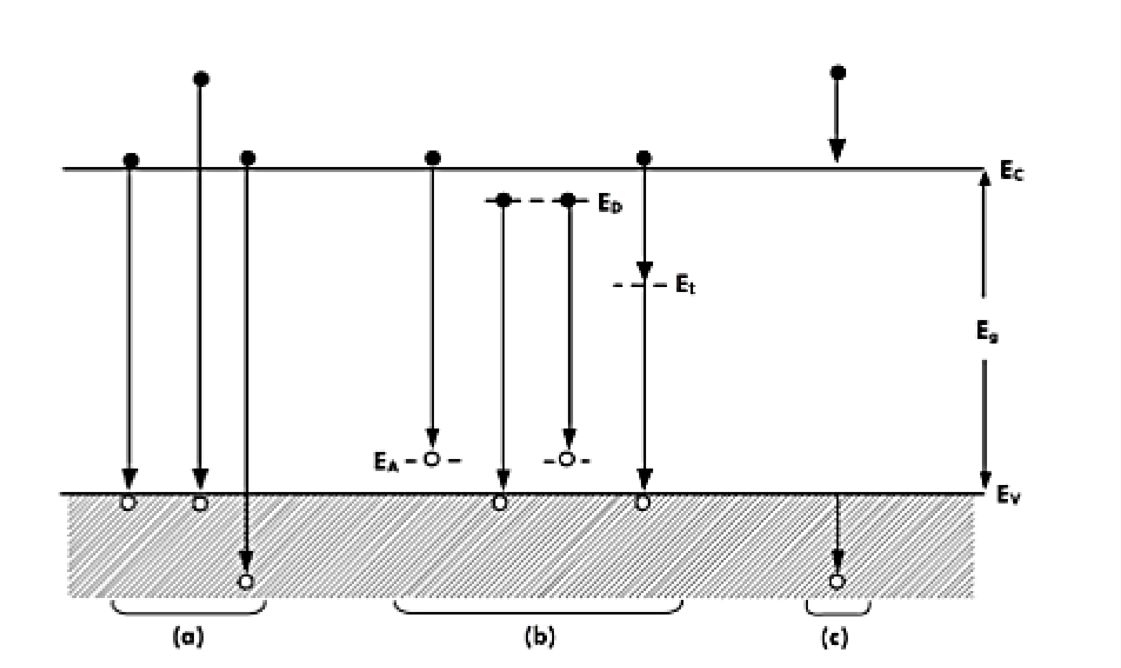
- Electron at the bottom edge of CB falls and occupy the hole at the top edge of VB
- Deep electron in CB may fall and occupy the hole at the top edge of VB
- Electron at the bottom edge of CB fall and occupy the shallow hole (well in bulk semiconductor) in VB

2. Defect transitions

When a semiconductor is doped with impurities or if defects are formed, then allowed energy states are developed in the forbidden gap,these states are called donors / acceptor levels (also known as shallow traps) if they formed near to the edges of CB or VB.

These are also known as deep traps if they formed near the mid of energy gap.

- Electron at the bottom edge of CB may combine with hole in acceptor level.
- Electron in donor level may combine with hole at the top edge of VB
- Electron in donor level may combine with hole in acceptor level.
- Electron in CB may first fall to deep trap and then combine with hole in VB.



3. Intra Band Transitions: An electron in CB or VB may combine with hole in CB or VB.

LED

- The basic structure of the LED is the pn junction.
- A pn junction under equilibrium and forward bias is shown in figure 3. In this figure, the n region is heavily doped so that the depletion width lies mostly in the p side.
- At equilibrium the Fermi levels line up and there is a built in potential.
- When a forward bias is applied, electrons and holes are injected into the depletion region. These recombine, and radiation is emitted whose wavelength depends on the band gap of the p type material. This is called injection EL.
- Recombination is a statistical spontaneous process and emission takes place in all directions.
- When the pn junction is made of the same material then it is called a **homojunction.**
- If we can confine the electrons and holes to a small region (like a potential well) then it is possible to increase radiative recombination efficiency. This can be achieved by using a **heterojunction**.

Homojunction LED:

When the LED is fabricated using two differently doped semiconductors that are the same material then it is called a homojunction LED.

Heterojunction LED

When LED's are fabricated using different band gap materials they are called a heterostructure device. A heterostructure LED is brighter than a homojunction LED. In heterojunction, we can confine the electrons and holes to a small region (like a potential well) then it is possible to increase radiative recombination efficiency.

Construction and Working of Homojunction LED

- An LED is a semiconductor PN junction that under forward biased condition can emit spontaneous radiation in the UV, visible and IR region of an electromagnetic spectrum.
- Basically it is a device capable to convert electrical energy to light energy. The basic principle involved in working of LED is electroluminescence.

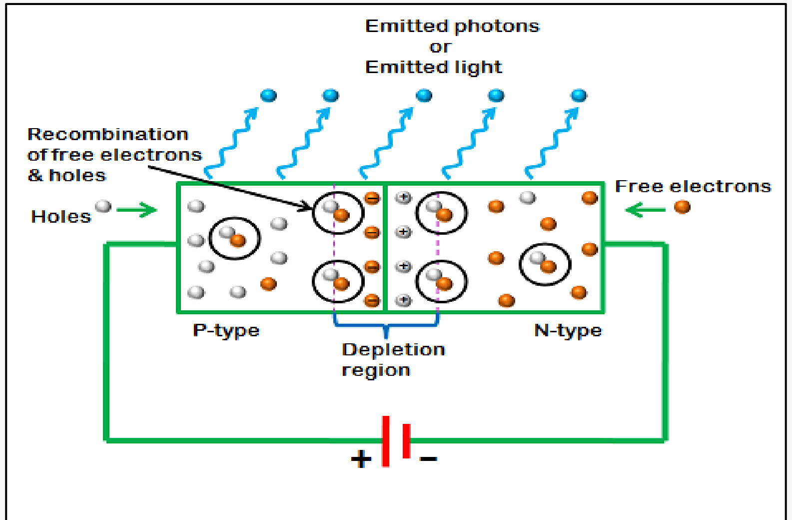
- **Principle:** When a PN junction is forward biased, minority carriers flow in large number into regions where they can recombine with majority carriers producing light in the visible, or UV or IR regions.

Construction:

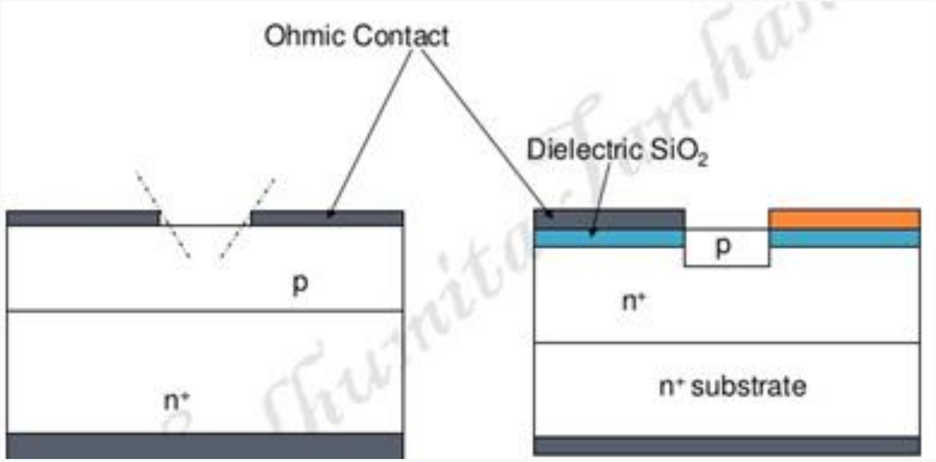
The basic structure of an LED is a PN junction made by direct band gap semiconductors.

It is usually formed with a heavily doped N- type semiconductor (n^+) and a lightly doped P – type so that the depletion width lies mostly in the P side. An n^+ layer is grown on suitable substrate on which a p-type layer is grown by the process of diffusion.

The p-type layer is made thin to prevent loss of photons due to absorption in the layer. Metal contacts are made at the edges of the p-layer and at bottom edge of substrate.



Light Emitting Diode (LED)



WORKING:

- ✓ Due to formation of PN junction, a built in potential, called barrier potential is developed. This potential prevents the diffusion of charge carriers across the junction.

- ✓ Under forward bias, when P – side of the junction is connected to the positive terminal of a battery and the N-side to the negative terminal, the barrier height gets reduced. This allows the electrons from the n^+ side to get injected into the p-side. Since electrons are the minority carriers in the p-side, this process is called **minority carrier injection**.

- ✓ Minority carriers are injected from both sides of the junction. But the hole injection from the p side to n^+ side is very less and so the current is primarily due to the flow of electrons into the p-side.

- ✓ At the vicinity of the junction, there is an excess of carriers over their equilibrium values and recombination will take place in the depletion region (also called the **active layer**) resulting in an emission of radiation. This is called **injection electroluminescence** because charge carriers are injected in order to generate light.

✓ These photons should be allowed to escape from the device without being reabsorbed.

✓ The wavelength of the emitted light depends on the band gap of the semiconductor.

$$h\nu = E_g$$
$$hc/\lambda = E_g$$
$$\lambda = hc/ E_g$$

✓ The band structure of biased and unbiased PN junction is shown in figure.

✓ **The emission that takes place is spontaneous** and takes place in all directions. Electrons not only in the depletion layer but even in bulk semiconductor also combine with holes. When PN junction is made of the same material then it is called homo junction.

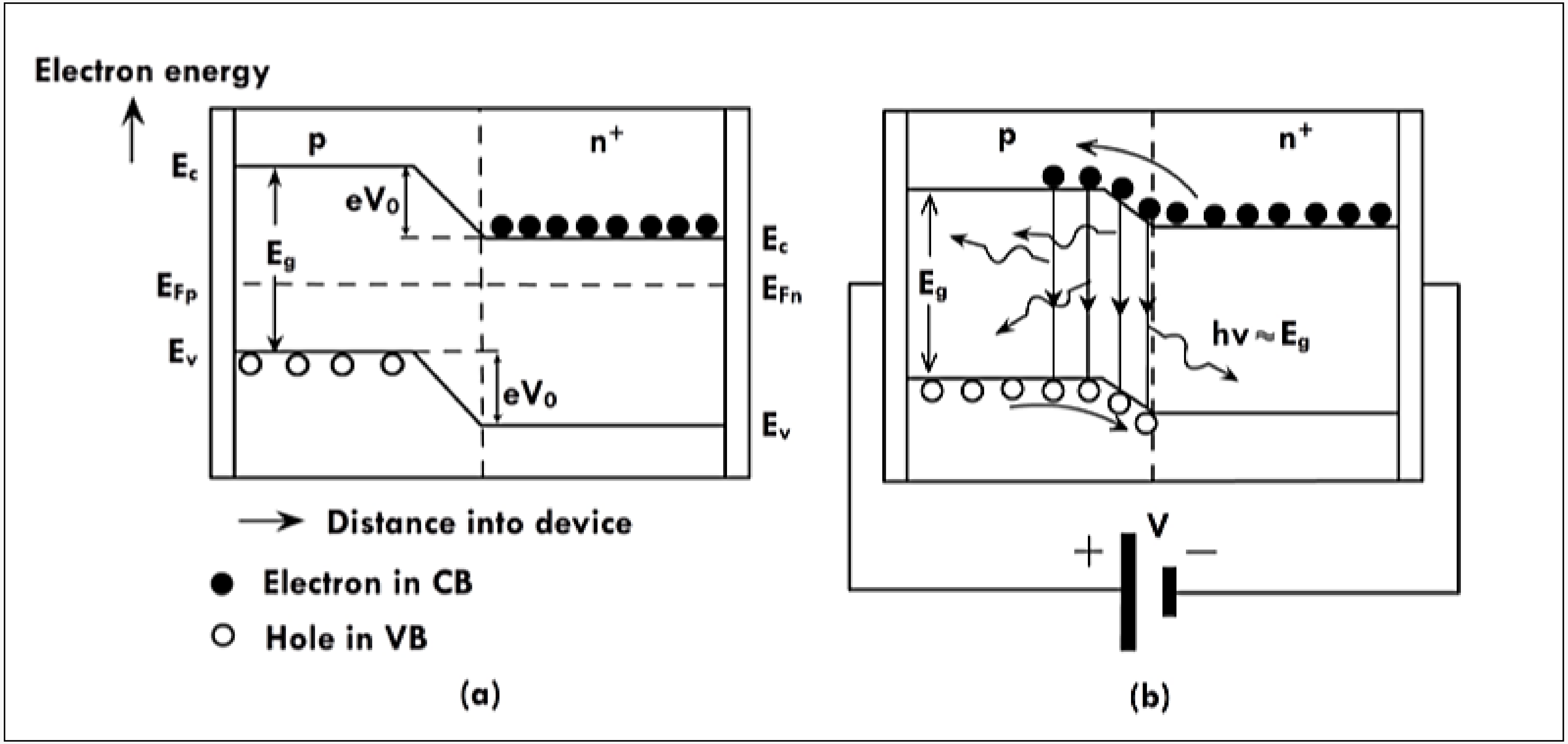


Figure : pn junction LED at (a) equilibrium and (b) forward bias.
(a) In equilibrium there is a depletion region and a built in potential.
(b) In forward bias, this potential is reduced and electrons and holes are injected into the depletion region.

Different Types of Losses

1. Reabsorption losses: Generally recombination takes place only near the junction and photons that generated propagate through rest of the semiconductor (outside the active region). While propagating they get re-absorbed by the same material resulting more number of electron – hole pairs.

2. Reflection losses: The photons incident on the semiconductor – air interface a part of it get reflected into the device and only the remaining part get refracted into the air. Hence, typically LEDs, are made with a dome – type encapsulation, which acts a lens so that more of the photons can be extracted.

e.g. In case of GaAs, $n_1 = 3.6$, n(air)=1

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 = \left(\frac{3.6-1}{3.6+1}\right)^2 = 0.32$$

i.e. 32% light is reflected.

3. Loss due to TIR:

When photon strikes the end face at an angle greater than critical angle it totally get reflected into the device without emerging out.

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) = \sin^{-1}\left(\frac{1}{3.6}\right) = 16^\circ$$

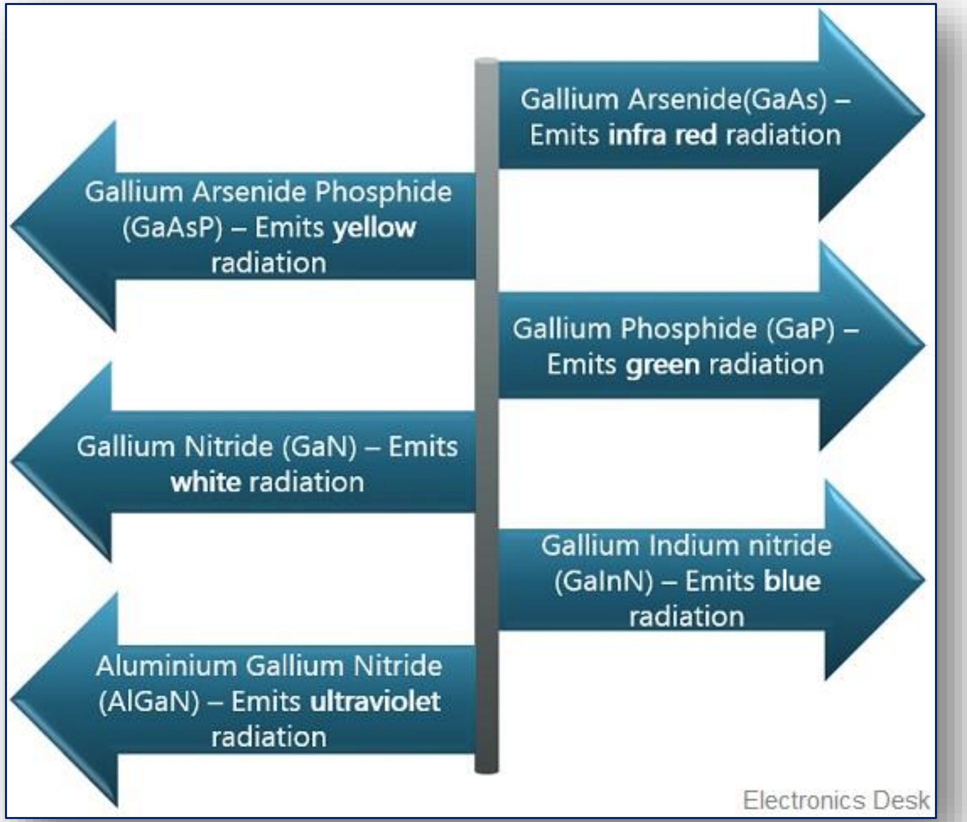
i.e. the rays incident at angles gretaer than 16^o will be lost. Those which fall within 16^o will only come out.

Advantages of Double Heterojunction LED:

- **Avoid Reabsorption losses**: Photons that are released, move through the material having high band gap. Therefore it cannot be re-absorbed as in case of homo-junction. This avoids reabsorption losses.
- **Carrier Confinement:** Charge carriers get accumulated in the active region as a result the carrier concentration increases.
- **Optical Confinement**: In a given material system, a region which has higher bandgap has lower refractive index. As a result photons have less probability to get totally reflected and optical energy is confined in active region.
- It refers to the optical energy which is generated in active region is confined because of optical wave guiding action.

Types of Light Emitting Diode

- ✓ As we know that light of different colors is emitted by the LED.
- ✓ we can differentiate the LEDs on color basis.
- ✓ Due to the semiconductor material used during diode formation, various colors of light is emitted by the device.



LED Materials

- LEDs are made of direct band gap semiconductors. For LEDs the frequency or wavelength of the emitted photon is governed by the band gap of the semiconductor as given by the relation: $E = hc/\lambda$
- **For display applications**, since the human eye is only sensitive to light of energy ($h\nu \geq 1.8$eV) or $\lambda \leq 0.7\mu$m, semiconductors of interest must have energy bandgaps larger than this value.

Most the commonly used LEDs are based on the GaAS system. GaAs is a direct band gap semiconductor, but its band gap lies in the IR region (1.42 eV). So higher band gap materials like AlGaAs, GaAsP, GaP are used with suitable substitutional doping to ‘tune’ the band gap to the required value.

An important class of commercial LEDs that cover the visible spectrum are the III-V. ternary alloys based on alloying GaAs and GaP which are denoted by $GaAs_{1-y}P_y$. InGaAlP is an example of a quarternary (four element) III-V alloy with a direct band gap.

Typical materials that operate in different regions of the EM spectrum are enumerated below

Typical LED Characteristics			
Semiconductor Material	Wavelength	Colour	V_F @ 20mA
GaAs	850-940nm	Infra-Red	1.2v
GaAsP	630-660nm	Red	1.8v
GaAsP	605-620nm	Amber	2.0v
GaAsP:N	585-595nm	Yellow	2.2v
AlGaP	550-570nm	Green	3.5v
SiC	430-505nm	Blue	3.6v
GaInN	450nm	White	4.0v

Characteristics of LED

- **I – V characteristics**: As LED is forward biased PN diode, the volt – ampere characteristics are same as that of PN junction diode.
- **Optical power output (Light-Current characteristics)**: The ideal light output power against current characteristic for an LED is shown in fig. Intrinsically the LED is a very linear device in comparison with the majority of injection lasers and hence it tends to be the most suitable for analog transmission.
- Therefore as current increases the output power increases linearly and reaches saturation after certain value of current.

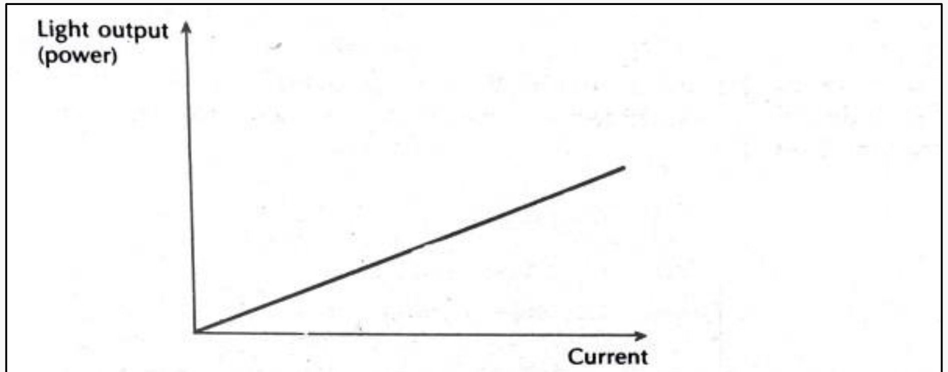
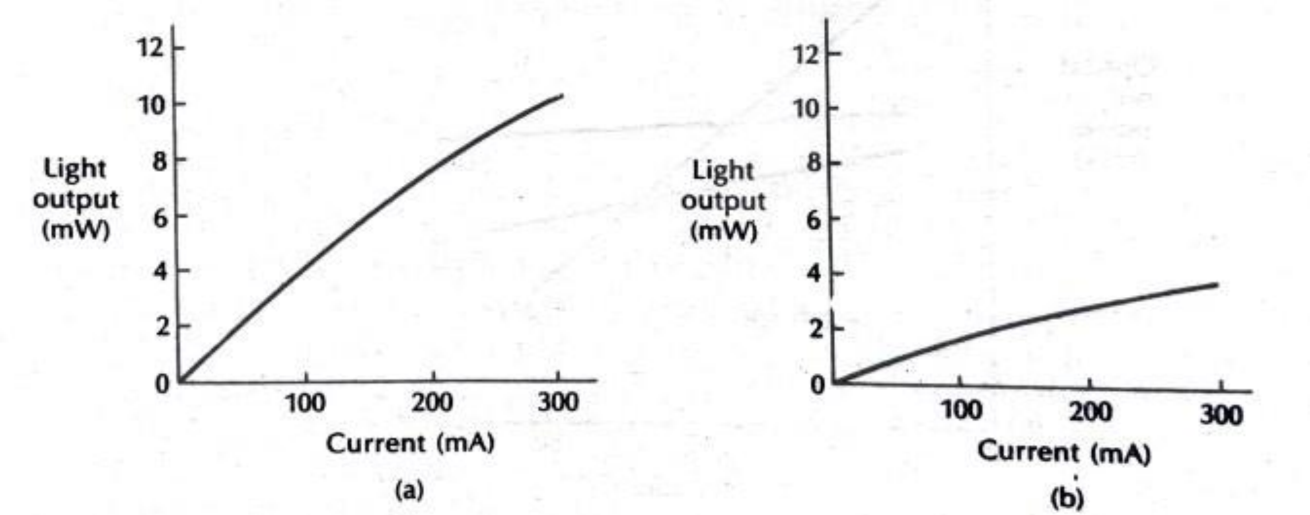


Figure 7.14 An ideal light output against current characteristic for an LED.



Spectral Distribution (Wavelength Spectrum)/ Line Width

Transitions from conduction band to valence band depends only on thermal excitation. Most of the electrons and holes are located at the edge of conduction band and valence band. But at any given temperature there is always thermal excitation of charge carriers as a result the transition may takes place from any one available state in conduction band to any one state in valence band. It results broadening of the peak which gives certain line width or spectral width to the output.

- Line width depends on the number of states that are available for electrons and holes to occupy and also on the probability of occupancy.

$$\Delta\lambda = \frac{1.8KT}{hc}\lambda^2$$

For materials with lower band gap energy, bandwidth increases.

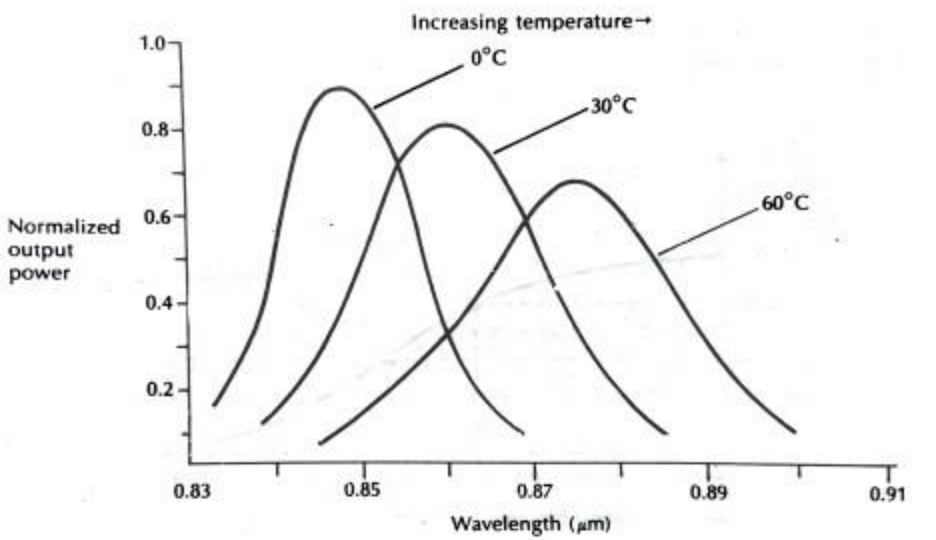


Figure 7.20 Typical spectral variation of the output characteristic with temperature for an AlGaAs surface-emitting LED.

LED EFFICIENCY

- There are different metrics to define the efficiency of a LED. Three metrics are commonly used:
- 1. Internal quantum efficiency
- 2. External quantum efficiency
- 3. Power efficiency

Internal quantum efficiency (η_{int})

It is defined as the ratio of radiative recombination to the total number of recombinations.

$$\eta_{in} = \frac{\text{no of photons generated internally}}{\text{no of carriers passing through the junction}}$$

$$\eta_i = \frac{r_r}{r_r + r_{nr}} = \frac{\frac{1}{\tau_r}}{\left(\frac{1}{\tau_r}\right) + \left(\frac{1}{\tau_{nr}}\right)} = \frac{\frac{1}{\tau_r}}{\left(\frac{1}{\tau}\right)} = \frac{\tau}{\tau_r}$$

where r_r and r_{nr} are the rates of radiative and non-radiative transitions and these are inversely related to the associated lifetimes (τ_r and τ_{nr}).

$$\eta_{int} = \frac{\textit{Photons emitted per sec}}{\textit{total carriers lost per sec}} = \frac{\Phi_{ph}}{I/e} = \frac{P_{int}/h\nu}{(I/e)}$$

The internal efficiency is a function of the quality of the material and the structure and composition of the layer.

External Quantum Efficiency (η_{ext})

A very important metric of an LED is the external quantum efficiency η_{ext}. It quantifies the efficiency of the *conversion of electrical energy into emitted optical energy*. It is defined as the light output divided by the electrical input power.

$$\eta_{ext} = \frac{\text{no of photons emitted externally}}{\text{no of carriers passing the junction}}$$

$$\eta_{ext} = \eta_{in}\,\eta_{op}$$

where η_{op} is the optical efficiency of the system. This is related to the device optics and how the light is extracted out of the device.

$$\eta_{ext} = \frac{P_o/h\nu}{(I/e)}$$

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Extraction efficiency (η_{ee}) :

It is defined as the fractional power that is extracted from the total power generated. It gives how much power can be extracted from the total power generated. It depends on the device structure.

$$\eta_{ee} = \frac{\text{Power emitted externally in the device}}{\text{Power generated internally in the device}}$$

$$\eta_{ee} = \frac{P_{ext}/h\nu}{P_{int}/h\nu} = \frac{P_{ext}/h\nu}{P_{int}/h\nu}$$

$$= \frac{P_{ext}/h\nu}{\eta_{int}(I/e)}$$

$$P_{ext} = \eta_{ee}\,\eta_{int}(I/e)\,h\nu = \eta_{ext}\,(I/e)(hc/\lambda) = \eta_{ex}\,(hc/e)\,(I/\lambda)$$

$$P_{ext} = \eta_{ext}\,(1.24/\lambda_{(\mu m)})\,I$$

Power Efficiency (η_p)

$$\eta_p = \frac{\text{optical power out}}{\text{input power}}$$

$$\eta_p = \frac{\text{no of photons} \times h\nu}{I\,V} \approx \eta_{ext}$$

Advantages of LED

- Led have a number of distinct advantages:
- **Simple fabrication**: Fabrication is not complex as there is no need to prepare mirror faces
- **Cost:** The simpler construction of the LED leads to reduced cost.
- **Reliability**: The LED does not exhibit degradation.
- **Simpler drive circuitry**: It is due to lower driver currents and reduced temperature dependence.
- **Linearity:** Ideally, the LED has a linear light output against current characteristics.
- **Long service life:** The average LED lasts 50,000 operating hours to 100,000 operating hours or more. That is 2-4 times as long as most fluorescent, metal halide, and even sodium vapor lights. It is more than 40 times as long as the average incandescent bulb.
- LEDs are currently the most energy-efficient source of much less energy consumption and generally consume very low amounts of power.
- **Heat transfer** – LEDs, compared to traditional lighting, generate small amounts of heat due to their high performance.
- **Ecology** – the advantage of the LED lighting is also the fact that LEDs do not contain toxic materials such as mercury and other metals dangerous for the environment
- LEDs turn on and off instantaneously. In many cases LEDs operate on very low voltages.

Applications of LED

- **Applications of LED's are very wide and can be categorized into three kinds**
- First is for **display systems**: LED's are widely used in seven segment display systems (all numbers 0 to 9 and alphabets A to Z can be displayed using this system). Typical day to day examples are panel displays in different electronic equipments, panel displays in automobiles, computer screens, calculators, clocks and watches, outdoor signs and traffic lights etc.
- **Second category is for illumination:** all traditional incandescent light bulbs are now replaced with LED's. Flash light, book light, automobile head lights etc. comes under this category.
- **Third** application is as **light source** in optical communication systems: For low and medium data rates (<1Gb/s) over short and medium distances (< 10km) IR LED's are more suitable.

Thank You!!!!!