Module-1

LASERS

LASER is the abbreviation for Light Amplification by Stimulated Emission of Radiation. LASER is a device which is used to produce a parallel and highly coherent light beam of high intensity.

The production of laser light is a consequence of interaction of radiation with matter. There are three methods by which the radiation interacts with matter. The three methods are

(1) Induced absorption
(2) Spontaneous emission
(3) Stimulated emission.

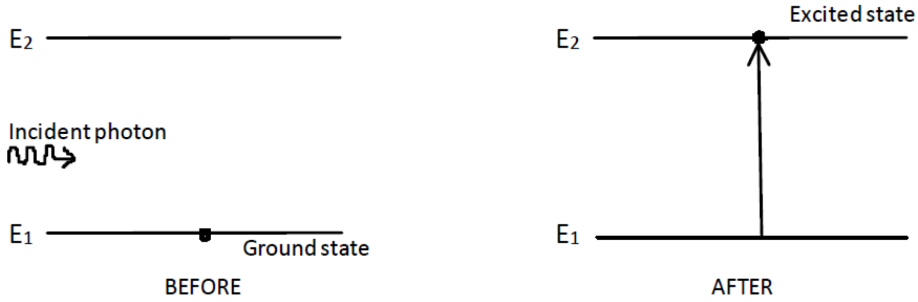
1) INDUCED ABSORPTION:

The process of absorption of incident photon by an atom and hence the excitation of the atom to the high-energy state is called Induced Absorption.

Explanation: Consider two energy levels E_1 and E_2 such that $E_2 > E_1$ as shown in the figure. Consider an atom in the lower energy state E_1. When a photon of energy equal to the energy difference between E_1 and E_2 is incident on the atom in the state E_1, it absorbs the photon. Due to the absorption of photon, the energy of the atom increases to the value of E_2. Therefore the atom gets excited to the energy state E_2. This process is known as induced absorption because the photon induces its energy to the atom.
It can be represented by:

Atom + Photon = Atom*

$$A + h\nu = A^*$$



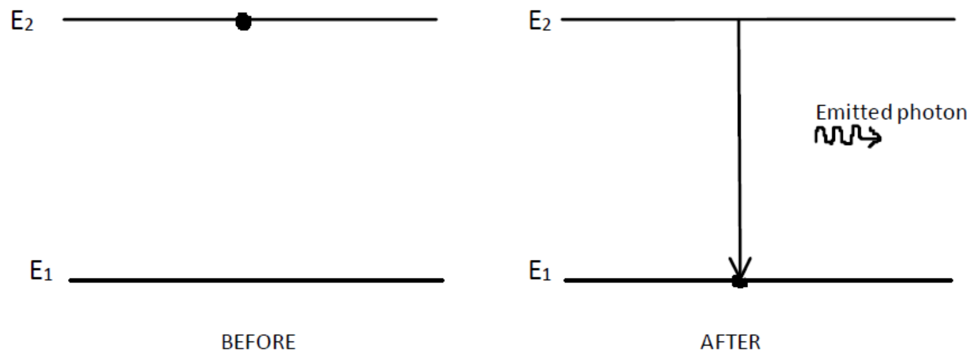
2) SPONTANEOUS EMISSION:

The process of emission of a photon of suitable frequency by an atom due to the transition from a higher energy state to a lower energy state without any supply of external energy is called spontaneous emission.

Explanation: Consider an atom in an excited state E_2. Let E_1 be its ground state energy. In the excited state the atom is unstable and hence it stays in the state E_2 only for 10^{-8} seconds and then undergoes transition to the ground state E_1 by emitting a photon whose energy is equal to the difference between the energy states E_1 and E_2. For this emission, the atom does not require any aid (extra energy). Therefore, the emission is known as spontaneous emission. The atom can emit photon in any direction. Two such photons emitted by two different atoms may or may not be in phase and their directions also may be different. Therefore the spontaneous emission is considered as incoherent emission. This kind of emission is observed in glowing electrical bulb, and candle flame.
It can be represented by:

Atom* = Atom + Photon

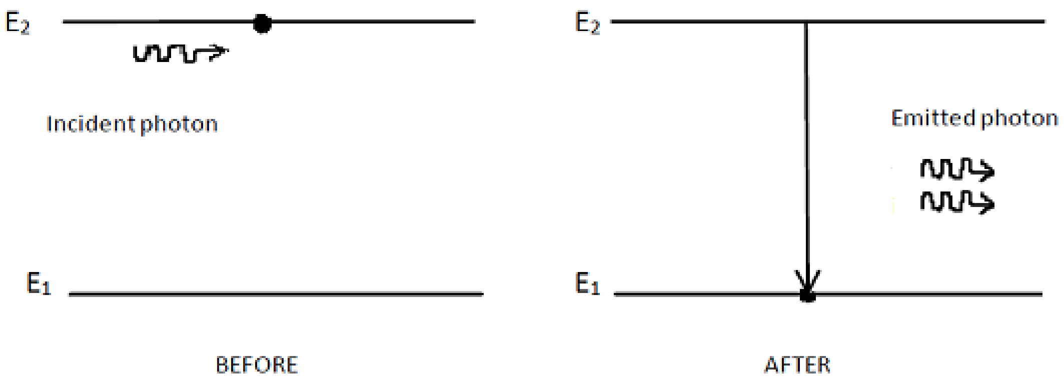
$A^* = A + h\nu$



3) <u>STIMULATED EMISSION:</u>

The process of emission of a photon by an atom in the excited state due to the incidence of an identical photon of same energy on the atom and hence the transition of the atom to a lower energy state is called stimulated emission.

<u>Explanation:</u> In this process the incident photon stimulates the atom to emit an identical photon. Hence this process is known as stimulated emission. In this process both incident photon and stimulated photon travel in the same direction and will be in phase. Hence, stimulated emission is called coherent emission and the photons are coherent photons. This kind of emission is suitable for laser action.



<u>Population of Energy States:</u>

The number of atoms in an energy state is known as the population of that energy state.

The population of different energy states are related to each other if the system is in thermal equilibrium. Consider two energy states E_1 and E_2 with populations N_1 and N_2 respectively such that $E_2 > E_1$. The relation between the two is given by Boltzmann factor,

$$N_2/N_1 = e^{(E1 - E2)/kT}$$

$$N_2/N_1 = e^{-(E2-E1)/kT}$$

But $E_2 - E_1 = \Delta E$,

$$N_2/N_1 = e^{(-\Delta E/kT)}$$

$e^{(-\Delta E/kT)}$ is always less than unity because ΔE is always positive.

Therefore,

$$N_2/N_1 < 1$$

$$N_2 < N_1$$

Or $N_1 > N_2$

Thus under ordinary conditions the population of any higher energy state is less than the population of its lower energy states.

If the population of any of the higher energy states is made more than the population of any of its lower states then **population inversion** is said to be achieved, or the system is said to have population inversion.

EXPRESSION FOR ENERGY DENSITY

Einstein's Coefficients

Einstein proposed three constants of proportionality to explain the transfer of energy of atoms during the interaction of radiation with matter. These constants are called by his name as Einstein's constants and are denoted as A_{21}, B_{12}, and B_{21}. Their origin is explained in the following way.

Consider two energy levels E_1 and E_2 of an atomic system such that $E_2 > E_1$. Let the population of E_1 and E_2 be N_1 and N_2 respectively. Let radiations of energy density U_v (energy per unit volume of the frequency range) with frequency ν, be incident on the atomic system. In case of induced absorption, when this energy is incident on an atom in the energy level E_1, it absorbs the energy and makes a transition to the energy level E_2. The number of such absorptions per second per unit volume is called rate of absorption. The rate of absorption depends on the number of atoms in the lower energy state and the energy density U_v of the incident radiation.

Rate of absorption is proportional to N_1U_v

Rate of absorption = $B_{12}N_1U_v$

Where, B_{12} is called Einstein's coefficient of induced absorption.

In case of spontaneous emission, an atom in the higher energy level E_2 undergoes transition to the energy state E_1, voluntarily by emitting a photon. The rate of spontaneous emission depends only on number of atoms (N_2) in the energy state E_2.

Rate of spontaneous emission is proportional to N_2

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

Where, A_{21} is called Einstein's coefficient of spontaneous emission.

If the energy density U_v is incident on an atom in the energy state E_2, it undergoes stimulated emission. The rate of stimulated emission is proportional to the number of atoms (N_2) in the energy state E_2, and the incident energy density U_v

Rate of stimulated emission is proportional to N_2U_v

Rate of stimulated emission = $B_{21}N_2U_v$

Where, B_{21} is called Einstein's coefficient of stimulated emission.

Derivation for the expression for energy density

At thermal equilibrium,

Rate of absorption = Rate of spontaneous emission + Rate of stimulated emission

$$B_{12}N_1U_v = A_{21}N_2 + B_{21}N_2U_v$$

$$B_{12}N_1U_v - B_{21}N_2U_v = A_{21}N_2$$

$$U_v (B_{12}N_1 - B_{21}N_2) = A_{21}N_2$$

$$U_v = (A_{21}N_2) \ / \ (B_{12}N_1 - B_{21}N_2)$$

$$U_v = (A_{21}N_2) \ / \ B_{21}N_2 \{(B_{12}N_1 / B_{21}N_2)-1\}$$

$$U_\nu = (A_{21} / B_{21}) [1 / \{(B_{12}N_1 / B_{21}N_2)-1\}] \text{ ------- } (1)$$

From Boltzmann’s law for thermal equilibrium of an atomic system we have

$N_2/N_1 = e^{-(E2-E1)/kT}$

But $E_2-E_1 = h\nu$

$N_2/N_1 = e^{-(h\nu/kT)}$

$N_1/N_2 = e^{(h\nu/kT)}$

Substituting this result in equation (1) we get

$$U_\nu = (A_{21} / B_{21}) \; [1/ \{(B_{12} / B_{21})(e^{(h\nu/kT)})-1\}] \text{ ------ } (2)$$

From Planck’s law of energy distribution, the energy density is given by,

$$U_\nu = (8\pi h\nu^3 / c^3) [1 / (e^{(h\nu/kT)}-1)] \text{ -------- } (3)$$

Comparing equations (2) and (3), we find

$$A_{21} / B_{21} = 8\pi h\nu^3 / c^3 \text{ ---------}(4)$$

And $B_{12} / B_{21} = 1$ --------- (5)

These two equations are called Einstein’s relations.

Equation (2) becomes

$$U_\nu = (A_{21} / B_{21}) [1 / \{(e^{(h\nu/kT)})-1\}]$$

From, $B_{12} = B_{21}$ we see that the rate of induced absorption is equal to the rate of stimulated emission, at thermal equilibrium.

CONDITIONS FOR LASER ACTION

The conditions for atomic systems to have laser action are

1) Presence of metastable states
2) Achieving population inversion

1) **Metastable State:**

An intermediate energy state between an excited state and the ground state of the atomic energy levels, in which the atoms stay for a long period of time the order 10^{-2} to 10^{-3} seconds, is called a metastable state.

When an atom in ground state absorbs certain amount of energy it transits to higher energy state. The lifetime of the atom in the excited state is 10-8 seconds. Since the lifetime of the atoms in this state is very less all the atoms return to the ground state immediately after excitation. Hence population inversion cannot be achieved in the higher energy states. But if a metastable state exists in an atomic energy system, then the atoms stay in that state for a period of the order 10-2 to 10-3 seconds, which is very large when compared to that of higher energy states. Hence, before the atoms undergo transition to the ground state from the metastable state, a large number of atoms collect in the metastable state due to the pumping action. Thus, population inversion can be achieved in the metastable state. The transition of the atoms from the metastable state to the ground state emits laser light. Thus the presence of metastable state in the atomic system is essential for the laser action to take place.

2) **Population Inversion:**

The process in which the number of atoms in a higher energy state of an atomic system is made more than the number of atoms in any of its lower energy states is called population inversion.

For achieving population inversion, the atomic energy levels should have a metastable state. The process of achieving population inversion can be explained in the following way. Consider three energy levels E_1, E_2 and E_3 of an atomic system, in such a way that $E_1 < E_2 < E_3$. Let E_2 be the metastable state. Under normal conditions the atoms remain in the lower energy state E_1. But when suitable amount of energy is supplied to them they start undergoing excitation to the state E_3.

The excited atoms in the state E_3 stay for a period of 10^{-8} seconds and then undergo non-radiative transition to the metastable state E_2, where they stay for a long duration of the order 10^{-2} seconds. If the pumping of atoms from E_1 to E_3 is maintained continuously, then the population of E_1 decreases continuously. The atoms excited to the state E_3 undergo immediate downward transition to E_2, as a result of which the population of E_2 increases more. Due to this process a stage will reach at which the population of E_2 will be more than that of E_1. This stage of operation is known as population inversion.

REQUISITES OF A LASER SYSTEM

The following are the three requisites of a laser system

1) Active medium:

A material medium in which the population inversion and hence the lasing action can be achieved is called active medium. Active medium provides energy levels for atomic transitions and helps for lasing action.A material will be chosen as active medium only if it possesses metastable states and by which we can achieve population inversion from which we can have more stimulated emissions.

Depending on the type of active medium used, the lasers are classified into four groups in the following way

a) Gas lasers: They consist of a mixture of gases as the active medium.
Example: He-Ne laser, CO_2 laser
b) Solid-state lasers: They consist of crystals as the active medium,
Example: Ruby laser, Yttrium Aluminium garnet (YAG) laser
c) Semiconductor lasers: They consist of semiconductors as the active medium.
Example: Gallium Arsenide (GAS) laser
d) Liquid lasers: They consist of chemicals as the active medium.
Example: Dye lasers

2) Energy Source:

(Pumping: The process of exciting atoms from a lower energy state to a higher energy state, by supplying energy from an external source is called pumping**)**

The population inversion in the laser action is achieved by pumping the atoms from the lower energy state by supplying energy from an external energy source.

Depending on the type of energy source used for pumping, there are four types of pumping as follows

a) Optical pumping: optical energy
b) Electrical pumping: electrical energy
c) Heat pumping: thermal energy
d) Chemical pumping: chemical energy

The energy supplied is used not only for pumping, but also for stimulated emission in some cases.

3) **Resonant cavity:**

An arrangement used in a laser device to increase the emitted photon energy density is called resonant cavity. It consists of two mirrors fixed on either side of the length of the active medium oriented in particular direction. One of the mirrors is completely silvered and contributes only to the reflection of the emitted photons. The other is partially silvered and it acts as both a reflector and exit for the laser beam. Mirrors are separated by a distance L for a particular emitted wavelength **λ,** satisfying relation L = m **λ/2,** where m =1,2,3… determines order of modes. These mirrors acts like a optical resonating cavity, reflects the photons back and forth by which large number of stimulated photons will be released and results in constructive interference between the light waves resulting standing wave pattern and thus helps to build large output intensity.

Principle of LASER action

(Given for a proper understanding, not important from an examination point of view)

Laser action is based on the phenomenon of population inversion and stimulated emission. When the number of atoms in the metastable state is made more than the number of atoms in any of the lower energy states a system is said to have achieved population inversion. If light of a suitable frequency is incident on such a system, then there will be more stimulated emission from the atoms in the metastable state than induced absorption by atoms in the lower energy states. The photons emitted by the stimulated emission travel in the same direction with the same phase, and possess same wavelength. When they are incident on the other atoms, they stimulate them to emit photons, which in turn cause further stimulated emission. The process repeats and results in the emission of a large number of coherent photons. This beam of light having large number of photons is said to be amplified. Thus the process involves amplification of light by stimulated emission. Hence it is abbreviated as LASER. Laser acts as a source which produces a highly intense, coherent and monochromatic beam of light.

SEMICONDUCTOR LASER (**Gallium Arsenide Laser)**

Principle

Semiconductor laser is one in which the active medium is semiconducting material. Among the semiconductors there are two different groups. They are direct band gap semiconductors and indirect band gap semiconductors. Direct band gap semiconductor is one in which a electron in conduction band directly recombine with the hole in valence band and the recombination process leads to emission of light whereas in indirect band gap semiconductors direct recombination of conduction electron with hole in valence band is not possible and recombination of an electron and hole produces heat in the material.

So in a direct band gap semiconducting material when transition of electron from conduction band to valence band takes place, excess energy may be released in terms of photons. Thus electron hole recombination is basic mechanism responsible for emission of light.

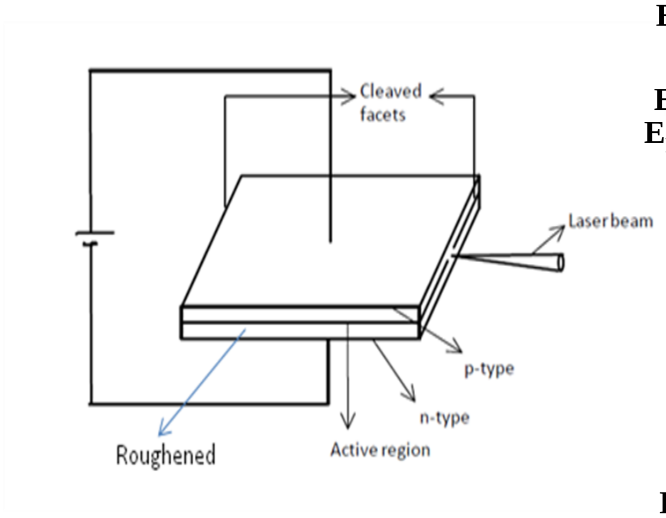
Construction:

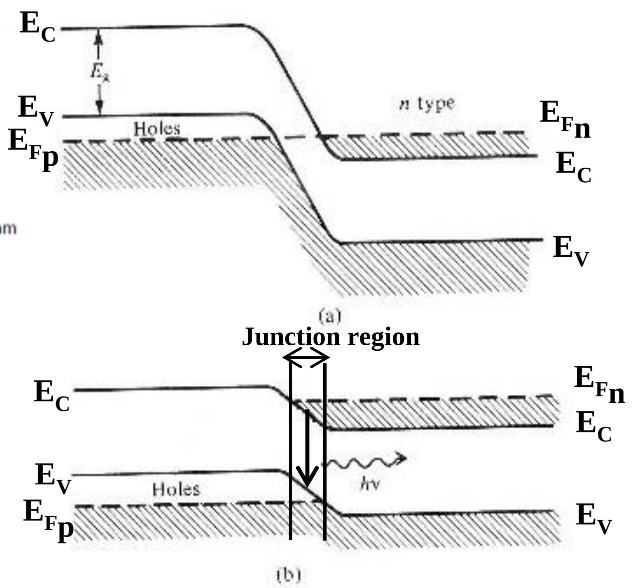
It a single crystal of **GaAs** which consists of heavily doped *n* and *p* sections and doping concentration is of the order of 10^{17} to 10^{19} dopant atom/cm^3.

The n-section is derived by doping GaAs with Tellurium and the p-section by doping GaAs with Zinc.

1) A pair of parallel planes of the crystal is **polished** at right angles to the p-n layer. These planes play the role of reflecting mirror. The other two sides perpendicular to the junction are **roughened** to suppress reflections of the photons.
2) The end surfaces of the p and n sections parallel to the plane of the junction are provided with **electrodes** in order to apply a forward bias voltage.

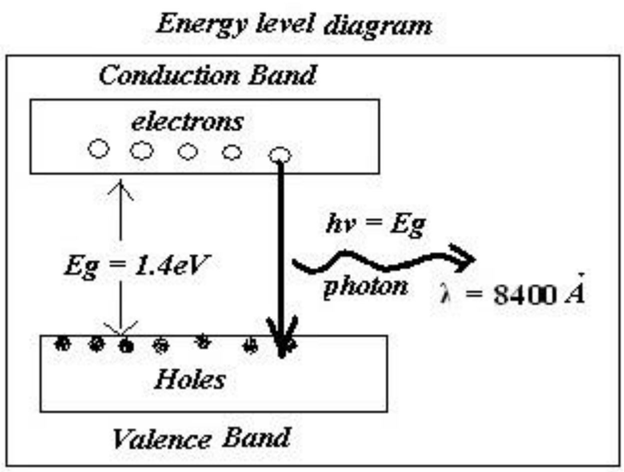
3) The diode is extremely small in size and each side is of the order of 1mm with junction layer of the order of 1 μm to 100 μm.





<u>Working</u>

1) Because of very high doping on n-side, the donar levels are broadened and extend into conduction band. The Fermi level is also pushed into the conduction band and electrons occupy the portion of conduction band below Fermi level.
2) Similarly, on the heavily doped p-side the Fermi level lies within the valence band and holes occupy the portion of valence band that lies above the Fermi level.
3) At thermal equilibrium, the Fermi level is uniform across the junction as shown in fig (a).
4) The GaAs laser diode is subjected to a forward bias using a DC source. Electrons from the n-section and holes from the p-section flow across the junction. An **active region** is formed in the junction where electrons and holes recombine and emit photons. This is spontaneous emission.
5) Under normal conditions, the concentration of electrons in the valence band is greater than that in the conduction band. Thus population inversion is not possible.
6) If the current flowing through the diode exceed a certain **threshold** value then the amount of electrons jumping from the valence band to the conduction band is great enough for population inversion to be achieved within junction region as shown in fig (b).
   Spontaneous emission will take place, and a photon will be released due to recombination. This photon interacts with an electron in the conduction band resulting in a **stimulated emission** which gives the required laser action.



Since the energy gap of a GaAs semiconductor is 1.4 ev,
From, $E_g = hc/\lambda$
$\lambda = 8400\ A^o$
This is the frequency of the emitted radiation.

Applications of semiconductor diodes:

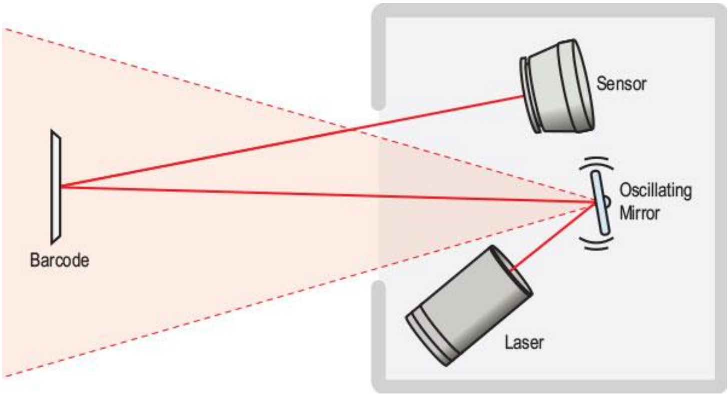
1) Optical communication
2) Reading devices for compact disc players, CD- ROMs

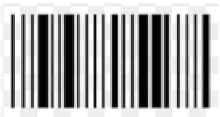
PROPERTIES OF LASERS

1) Directionality: Laser emission takes place in only one direction
2) Monochromaticity: Lasers have a high degree of monochromaticity
3) Coherence: Lasers have high spatial and temporal coherence
4) Intensity: Laser beams are highly intense
5) Focussability: Since a laser is highly monochromatic and highly directional, it can be brought to sharp focus by a lens. Hence it is said to have high focussability.

APPLICATIONS OF LASERS

1. LASER BARCODE SCANNER



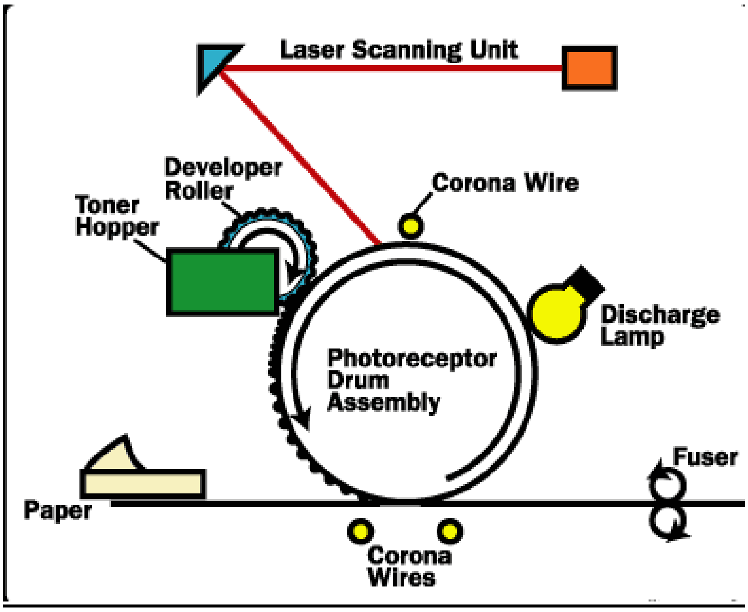


barcode

A barcode is a printed series of parallel bars or lines of varying width that is used for entering data into a computer system.

A barcode scanner/reader is a device with lights, lenses, and a sensor that decodes and captures the information contained in barcodes. Laser scanners use a laser beam as a light source and typically employ oscillating mirrors or rotating prisms to scan the laser beam back and forth across the barcode. A photodiode then measures the reflected light from the barcode. An analog signal is created from the photodiode, and is then converted into a digital signal.

2. **LASER PRINTER**



Laser printers ware invented at XEROX in 1969 by by researcher Gary Starkweather.Laser Printers are digital printing devices that are used to create high quality text and graphics on plain printer. A Diode Laser is used in the process of printing in LASER Printer.

Working Principle

1. A laser beam projects an image of the page to be printed onto an electrically charged rotating Photo sensitive drum coated with selenium.

2. Photo conductivity allows charge to leak away from the areas which are exposed to light and the area gets positively charged.

3. Toner particles are then electrostatically picked up by the drum's charged areas, which have been exposed to light.

4. The drum then prints the image onto paper by direct contact and heat, which fuses the ink to the paper.

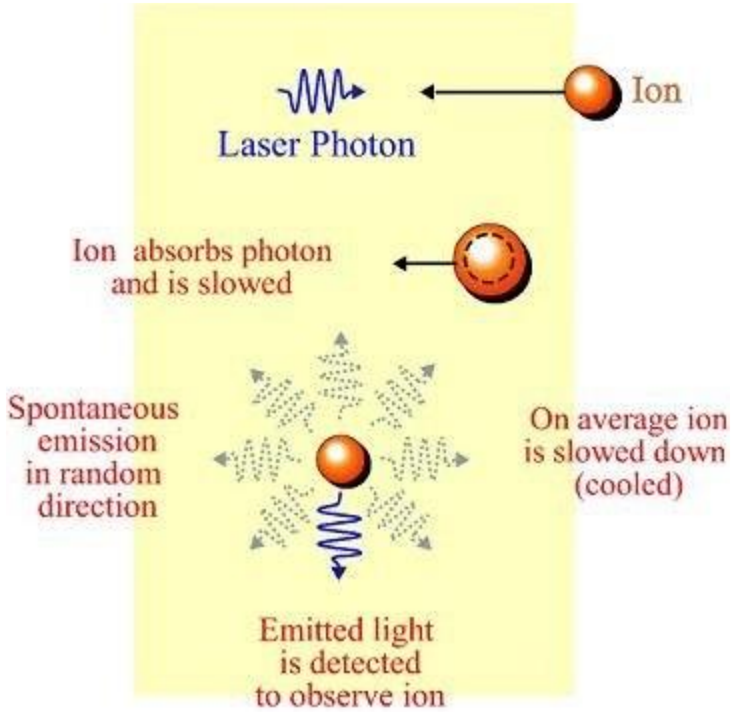
Advantages

1. Laser printers are generally quiet and fast.
2. Laser printers can produce high quality output on ordinary papers.
3. The cost per page of toner cartridges is lower than other printers.

Disadvantages

1. The initial cost of laser printers can be high.
2. Laser printers are more expensive than dot-matrix printers and ink-jet printers

3. LASER COOLING



Principle of LASER Cooling Laser cooling is the use of dissipative light forces for reducing the random motion and thus the temperature of small particles, typically atoms or ions. Depending on the mechanism used, the temperature achieved can be in the millikelvin, microkelvin, or even nanokelvin regime.

If an atom is traveling toward a laser beam and absorbs a photon from the laser, it will be slowed by the fact that the photon has momentum $p = \frac{E}{c} = \frac{h}{\lambda}$. It would take a large number of such absorptions to cool the sodium atoms to near 0K. The follwing are the types of laser cooling

a) **Doppler cooling**: Doppler cooling involves light with frequency tuned slightly below an electronic transition in an atom. Because the light is detuned to the "red" (i.e. at lower frequency) of the transition, the atoms will absorb more photons if they move towards the light source, due to the Doppler Effect.

b) **Sisyphous Cooling**: It involves the use of specially selected laser light, hitting atoms from various angles to both cool and trap them in a potential well, effectively rolling the atom down a hill of potential energy until it has lost its kinetic energy. It is a type of laser cooling of atoms used to reach temperatures below the Doppler cooling limit.