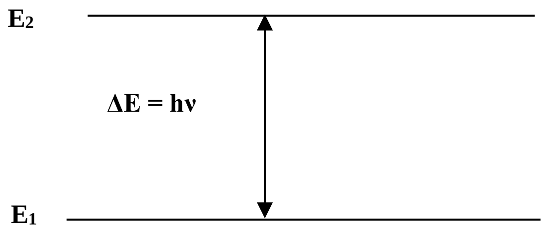
LASER

Introduction:

Laser is the acronym for Light Amplification by Stimulated Emission of Radiation (LASER). It is an optical device which amplifies the light. Laser requires an active medium for amplification by achieving population inversion between a pair of energy levels.

Principle and Production of lasers



[Explain the principle of LASER]

A material medium consists of identical atoms or molecules each of which is characterized by a set of discrete allowed energy states. An ideal atom can move from one energy state to another when it receives an amount of energy equal to the energy difference between those states. It is called quantum jump or transition.

The working principle of laser is based on the phenomenon of **interaction of radiation with matter.** Whenever radiation interacts with matter there are two processes. i.e (1) absorption and (2) emission

Let us consider two energy states E_1 and E_2 of an atom, E_1 is lower energy state while E_2 is excited state. Let a monochromatic radiation (streams of photons) of frequency **ν** be incident on the medium. The radiation energy,

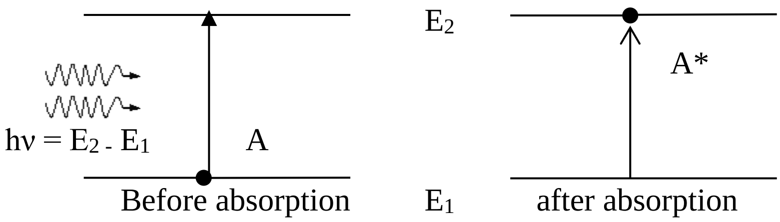
$$E_2 - E_1 = \Delta E = h\,\nu$$

or $$\upsilon = \frac{E_2 - E_1}{h} \quad \text{(Hz)}$$

The interaction of radiation with matter leads to three different processes in the medium.

1. Induced Absorption:-

Induced absorption is the absorption of an incident photon by an atom as a result of which atom makes a transition from a ground state (E_1) to an excited state (E_2) such that the difference in energy of the two states is equal to energy of the photon. It is also known as stimulated absorption.



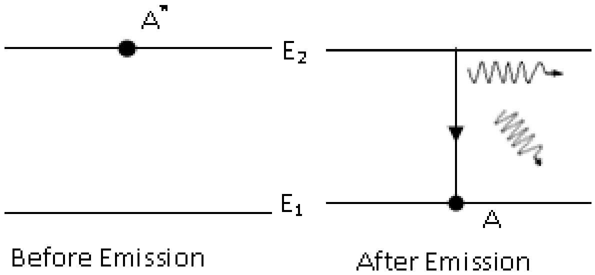
Consider a photon of energy, hν is incident on an atom in the ground state E_1 then atom absorbs the energy and get excited to higher energy state E_2. The process can be represented as,

Atom + Photon → Atom *

$A + h\nu \rightarrow A^*$, where A^* is an excited atom.

2. Spontaneous Emission:

Spontaneous Emission is the emission of a photon, when an atom transits from excited state (E_2) to lower energy state (E_1) without the aid of any external agency.



Excited atom with higher energy is inherently unstable because of natural tendency of atoms to seek out the lower energy configuration. Therefore, excited atoms does not stay in the excited state for relatively longer time, but tend to return to lower state by giving up excess of energy (ΔE) in the form of spontaneous emission. i.e $\Delta E = h\,\boldsymbol{\nu} = E_2 - E_1$

As shown in figure, consider an atom in the excited state E_2. It makes transition to ground state E_1 by the emission of a photon of energy **hv**. The process may be represented as,

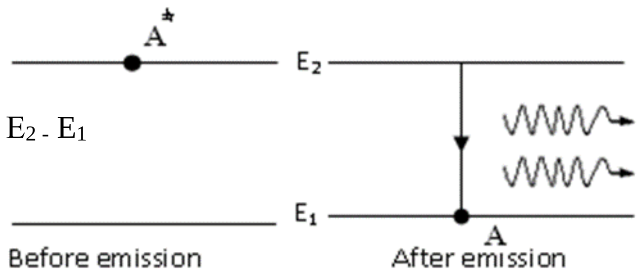
Atom* → Atom + Photon

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

3. Stimulated Emission:

The interaction of photon of relevant energy with an excited atom triggers the excited atom to drop to the lower energy state giving up a photon. The phenomenon of forced emission of photon is called stimulated emission.

$h\nu = E_2 - E_1$



Consider a photon of energy equal to the energy difference between the states E_2 and E_1. When this photon interacts with an atom which is in the upper energy state E_2.Then, it may cause the atom to make a transition from E_2 to E_1 with the emission of a second photon called stimulated photon. This process is known as stimulated emission.

The stimulated photon will have same frequency and phase as that of incident photon. The two photons travel in exactly same direction and have same energy. Hence they are **coherent**. This kind of emission is responsible for **laser action**. The process may be represented as,

Atom * + Photon $\rightarrow$ Atom + 2 Photons (Photon + Photon)

$A^* + h\nu \rightarrow A + 2h\nu$.

Einstein's Coefficients and Energy density

[Derive / obtain an expression for energy density of photons in terms of Einstein's Coefficients under thermal equilibrium conditions]

Einstein explored the basic mechanisms involved in the interaction of radiation with the matter by assuming that the matter is in thermal equilibrium. Thermal equilibrium is a state in which the energy exchanges due to absorption and emission processes occur such that the population of each state remains unaltered. On the basis of the above assumption, Einstein provided a theory for the interaction of radiation with matter, which involved important parameters, known by his name as **Einstein's coefficients**. This co-efficient give the probability associated with the absorption and emission processes.

Consider two energy states E_1 and E_2 of a system of atoms. The number of active atoms occupying an energy state is called population. Let N_1 and N_2 be the populations or number density of lower energy state (E_1) and higher energy state (E_2) respectively. Let $U_\nu\, d\nu$ be the energy incident per unit volume of the system in the frequency range ν and $\nu + d\nu$. Then U_ν represents the energy density of frequency ν. Now consider the absorption and two emission processes one by one.

1. Case of Induced absorption:

In the case of induced absorption when an atoms in the ground state E_1 will absorb radiation and make a transition to upper level E_2. The radiation absorbed by atom of suitable radiation of frequency, $\boldsymbol{\nu} = \frac{E_2 - E_1}{h}$. The number of such absorption per unit time per unit volume is called rate of absorption.

The rate of absorption, proportional to

(i) the number density of lower energy state (N_1) and

(ii) the energy density of the incident radiation (U_ν)

$\therefore$ Rate of induced absorption α $N_1 U_\nu$

or **Rate of induced absorption = B_{12} N_1 U_ν** …………(1)

where, B_{12} is the constant of proportionality called Einstein's coefficient of induced absorption.

2. Case of Spontaneous Emission:

An atom in the excited state E_2 makes transition to ground state E_1 by the emission of photon of frequency **ν**. No. of such spontaneous emissions per unit time per unit volume is called rate of spontaneous emission. The number of spontaneous transitions undergoes during the time Δt is independent of the photons present in the incident radiation and depends only on the density of atoms in the higher energy state N_2.

Rate of spontaneous emission proportional to

(i) the number density of higher energy state (N_2)

$\therefore$Rate of spontaneous emission proportional α N_2

or **Rate of spontaneous emission proportional = A_{21} N_2** ……………(2)

where, A_{21} is a constant of proportionality called Einstein's coefficient of spontaneous emission.

3. Case of Stimulated emission:

The interaction of an external photon of radiation frequency, **ν** $= \frac{E_2 - E_1}{h}$, with an excited atom at E_2, which stimulates atom to make downward translation and causes the emission of stimulated photons. The number of stimulated transitions per unit time per unit volume is called rate of stimulated emission.

The rate of stimulated emission, proportional to

(i) the number density of the higher energy state (N_2) and

(ii) the energy density of the incident radiation (U_ν)

$\therefore$ Rate of stimulated emission α N_2 U_ν

or **Rate of stimulated emission = B_{21} N_2 U_ν** …………(3)

where, B_{21} is the constant of proportionality called the Einstein coefficient of stimulated emission.

At thermal equilibrium, the number of photons absorbed by the system per second is equal to the number of photons emitted by the system per second.

i.e Rate of induced absorption = (Rate of spontaneous emission) + (Rate of stimulated emission)

from equation 1, 2 and 3, we get

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

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

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

$$U\nu = \frac{A_{21}N_2}{\frac{B_{21}}{N_2}\left[\frac{B_{12}N_1}{B_{21}} - 1\right]}$$

$$U\nu = \frac{A_{21}}{B_{21}} \frac{1}{\left[\frac{B_{12}N_1}{B_{21}N_2} - 1\right]} \quad \ldots\ldots\ldots\ldots(4)$$

By Boltzmann law, we have

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

$$\text{or } \frac{N_1}{N_2} = e^{\frac{h\nu}{KT}} \quad \ldots\ldots\ldots\ldots\ldots(5)$$

Substitute equation (5) in (4) we get,

$$U\nu = \frac{A_{21}}{B_{21}}\left[\frac{1}{\frac{B_{12}}{B_{21}} e^{\frac{h\nu}{KT}} - 1}\right] \quad \ldots\ldots\ldots\ldots(6)$$

According to Planck's law, the equation for energy density of radiation at given temperature

$$U\nu = \frac{8\pi h\nu^3}{C^3}\left[\frac{1}{e^{\frac{h\nu}{KT}} - 1}\right] \quad \ldots\ldots\ldots\ldots (7)$$

Comparing equation (6) and (7) term by term on the basis of positional identity, we get,

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} \quad \text{and}$$

$$\frac{B_{12}}{B_{21}} = 1 \quad \text{or} \quad B_{12} = B_{21}$$

This means that the probability of induced absorption is equal to the probability of stimulated emission. A_{21} and B_{21} can be represented as A and B respectively ie, A_{21} = A and B_{21} = B.

Then at thermal equilibrium the energy density is (from equation (6)),

$$\boxed{\mathbf{U\nu = \frac{A}{B}\left[\frac{1}{e^{\frac{h\nu}{KT}} - 1}\right]}}$$

Conclusions of Einstein co-efficient:

Dependence of nature of emission on frequency:

Consider $\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}$

If A_{21} has high value, the probability of spontaneous emission is high. If B_{21} has high value, the probability of stimulated emission is high.

Further $\frac{A_{21}}{B_{21}} = \nu^3$

Since ν= ΔE/h, in normal condition, the energy difference between the two levels E1 and E2 is large

$\frac{A_{21}}{B_{21}}$ >> 1 or A_{21} >> B_{21}

Thus the probability of spontaneous emission is more than the stimulated emission.

System in thermal equilibrium:

From equation (6), we have

$$U\nu = \frac{A_{21}}{B_{21}}\left[\frac{1}{e^{\frac{h\nu}{KT}}-1}\right] \qquad [\text{since } B_{12} = B_{21}]$$

$$\frac{A_{21}}{B_{21}U\nu} = e^{\frac{h\nu}{KT}} - 1 \quad ....(8)$$

Case-1: hν >> kT

When the frequency of radiation is high hν>> kT i.e. $e^{\frac{h\nu}{KT}}$ >> 1

Hence in eqn (8)

$\frac{A_{21}}{B_{21}}$ >> 1 i.e. A_{21} >> B_{21}

That is spontaneous emission is more than the stimulated emission.

Case-2: hν ≈ kT

For hν ≈ kT, $e^{\frac{h\nu}{KT}}$ will be low and comparable to 1

Therefore A_{21} and B_{21} become comparable, i.e. stimulated emission became significant.

Case-3: hν << kT

For hν << kT, ($e^{\frac{h\nu}{KT}} - 1$) << 1 and

$\frac{A_{21}}{B_{21}}$ << 1 or That is stimulated emission is more for lower frequency.

Hence for lower frequency, stimulated emissions dominate the emission process. This is what we observe at room temperature in the atomic transitions which generate microwave. Therefore first MASER (Microwave Amplification by Stimulated Emission of Radiation) came to exist.

Non-equilibrium conditions leading to amplification (Laser action):

We have the rate equation

$$\frac{\text{Rate of emission}}{\text{Rate of absorption}} = \frac{A_{21}N_2 + B_{21}N_2U_\gamma}{B_{12}N_1U_\gamma} = \frac{N_2}{N_1}\left[\frac{A_{21} + B_{21}U_\gamma}{B_{12}U_\gamma}\right]$$

According to Einstein's theory we have $B_{12} = B_{21}$

$$\frac{\text{Rate of emission}}{\text{Rate of absorption}} = \frac{N_2}{N_1}\left[\frac{A_{21}}{B_{21}U_{\gamma}} + 1\right] \quad \text{.............(9)}$$

From eqn (8) if

ΔE << KT i.e. $h\nu$<< KT, which makes ($e^{\frac{h\nu}{KT}} - 1$) very small

Then eqn (9) becomes

$\frac{A_{21}}{B_{21}U\nu} << 1$

Hence eqn (9) can be written as

$$\frac{\text{Rate of emission}}{\text{Rate of absorption}} = \frac{N_2}{N_1}$$

Under normal conditions in all the system, N_2 is always be lesser than N_1.

$N_2>N_1$ under non-equilibrium conditions (population inversion). It means that there should be more atoms present in the higher energy level than in the lower energy level for stimulated emissions to dominate over the spontaneous emission.

Conditions for Laser action:

Essentially two are the most important conditions of occurrence of the laser.

1. Population Inversion

An artificial situation in which the number of atoms in the excited state are greater than the number of atoms in the ground state is called population inversion.

According to Boltzmann's law, the ratio of the populations between two energy levels of a physical system at thermal equilibrium is given by

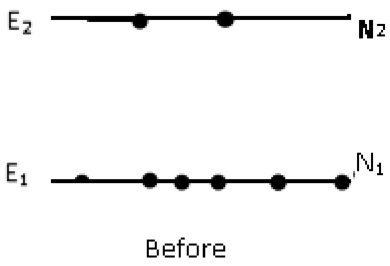
$$\frac{N_2}{N_1} = e^{-\left(\frac{E_2-E_1}{kT}\right)} \qquad \text{for } E_2 > E_1$$

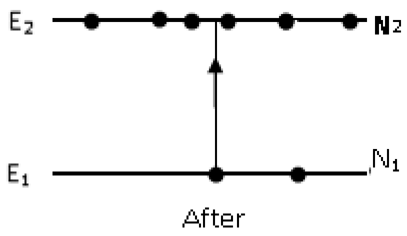
where, N_1 and N_2 are the populations corresponding to the energy levels E_1 and E_2 respectively and k is the Boltzmann constant.

Since $E_2 > E_1$, $\quad e^{-\left(\frac{E_2-E_1}{kT}\right)} < 1$

Therefore, $N_2 < N_1$. In a state of thermal equilibrium, there are more number of atoms in lower energy level than at the upper energy level and effective stimulated emission cannot be achieved.

Therefore, a non-equilibrium state is created in which the population of upper energy level exceeds to a large extent than lower energy level, ie $N_2 > N_1$ and population inverted. The population can be achieved by creating a special kind of excited energy state called metastable state.



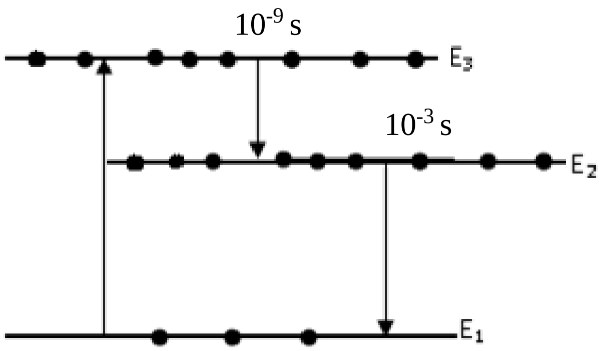


$N_1 > N_2$ $N_2 > N_1$

2. Metastable state

Under normal conditions the number of atoms in the excited state N_2 will be very much less than the number of atoms in the ground state N_1. An atom can be excited to a higher level by giving energy to it. Normally, the atom de-excite to the ground state within a few seconds (10^{-9} s) by emission of photons. It means that the atoms do not stay for a long enough time at the excited state for stimulation. Though, the pumping is continuous, the excited atoms undergo the spontaneous transition to a lower energy state. For stimulated emission, N_2 should be greater than N_1. In order to do so, the excited atoms are required to delay at a higher energy level till a large number of atoms accumulate at that level.

A metastable state is a state in which excited atoms stay for an appreciable time. Therefore, the metastable state allows the accumulation of a large number of excited atoms and creates population inversion and leads to lasers.



Consider three energy levels E_1, E_2 and E_3. Let E_2 be in a metastable state. After supplying energy, atoms get excited from E_1 to E_3 level, where the lifetime of atoms is very less (10^{-9} s), then atoms make a transition to metastable state E_2 which is the intermediate level between the ground state and the excited state. The atom in the metastable state can remain for a long time about 10^{-3} s. Therefore the population of E_2 state increases steadily. The population inversion occurs between E_2 and E_1 state, which leads to the stimulated emission of photons of the same wavelength, phase and direction. This increases to a very large number and builds up the laser light.

Components of laser construction or Requisites of a laser system

There are three requisites of laser systems.

1. Active medium.

2. Excitation source to achieve population inversion.

3. Optical resonant cavity or laser cavity to increase the intensity of laser beam.

1. Active Medium

The medium which contain active atoms or molecules or ions with a special system of energy levels. Where the population inversion is possible, those are called active centres and supporting to achieve this condition are called host. Depending upon the active medium used, the lasers can be classified into the following categories.

a) **Solid state laser**: Crystals and glasses doped by special ions as an active medium. Ex. Rubby laser, Nd:YAG laser.
b) **Gas laser**: Gases and mixture of gases as an active medium. Ex. He-Ne laser, CO_2 laser.
c) **Semiconductor laser**: p-n junction of a semiconductor as an active region. Ex. GaAs, InGaAs semiconductor diode laser.
d) **Liquid laser (Dye laser)**: Liquid as an active medium. Liquid materials called dye. Ex. Rhodamine B, sodium fluoresein.

2. Excitation source

Pumping is a process of exciting the atoms from lower energy state to a higher energy state by supplying energy from external sources in order to achieve population inversion. The energy source used for this purpose is called excitation source of pumping source. Based on the type of source used for pumping, the pumping technique are classified as

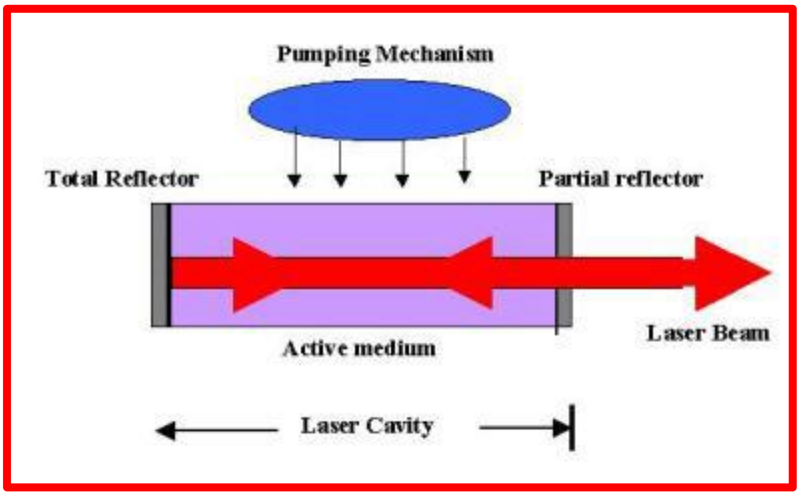
a) Optical Pumping: In optical pumping light source such as a flash discharge tube is used.

b) Electrical Pumping, eg. Gas lasers, where its required to apply high voltage across the electrodes

3. Optical resonator cavity (laser cavity)

Generally, laser cavity consists of two opposing parallel plane mirrors placed between active materials. One of the mirrors is semi-transparent while the other one is made of 100% reflecting. The mirrors set normal to the optic axis of the material. This forms a cavity in which two types of waves exist, one type comprise of waves moving to the right and the other one to left.

The two waves interfere constructively, if there is no phase difference between the two. Their interference becomes destructive, if the phase difference is $\pi/2$. Constructive interference takes place within the active medium and the optical path L between two mirrors should be an integral multiple of the wave length.



Thus, $L = m\frac{\lambda}{2}$,

where, m = 1, 2, 3, 4… mode number, and λ is the wavelength of light within the material. Therefore, the active medium is optical resonator at the wavelength,

$\lambda = \frac{2L}{m}$, $\quad$ $c = f.\lambda \Rightarrow f = \frac{m\,c}{2L}$

Semiconductor Laser:

[Explain the principle, construction and working of Semiconductor Laser with the help of energy level diagram]

A semiconductor diode laser is a specially fabricated pn junction device that emits coherent light when it is forward biased. It is widely used in fiber optics communication.

Construction

The Gallium Arsenide (GaAs) laser diode is a single crystal consists of a heavily doped p and n sections. The n-region is obtained by doping GaAs with tellurium and p-type is by zinc. The doping concentration is very high of the order of 10^{17} to 10^{19} doping atoms per cm^3. A schematic diagram of a homo-junction semiconductor laser is as shown in the Fig. 1. The diode is extremely small in size with size of the order of 1 mm. The top and bottom surfaces are provided with ohmic contacts to pass current through diode. The front and real parallel faces of a crystal polished at right angles to the pn layer. The polished faces constitute as resonator. The other two opposite faces are roughened to prevent reflection of the photons so that they will not develop lasing. The active region consists of a layer of about 1 μ m thickness.

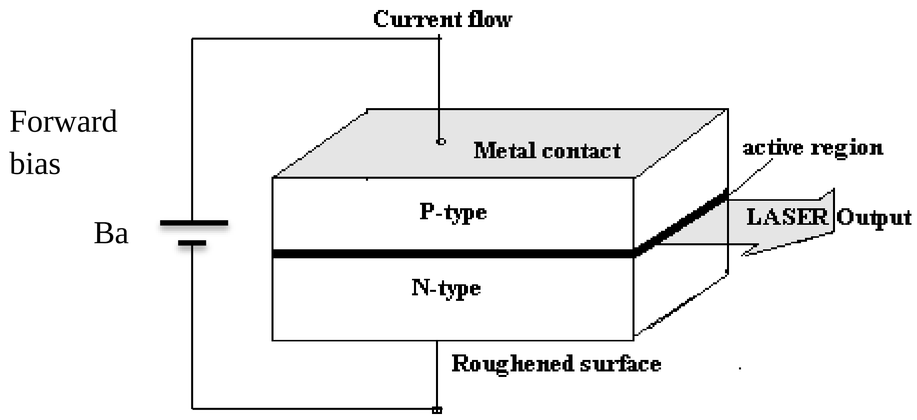


Fig. 1. Semiconductor laser.

Working

The GaAs laser diode is subjected to a forward bias as shown in the Fig. 1. Due to the bias, the electrons from the n-section and holes from p-section flow across the junction. During the flow, whenever a hole meets an electron recombination takes place resulting in the emission of a photon. Simple way of achieving population inversion in a semiconductor is in the form of the use of the heavily doped pn-junction with forward bias. The band diagram of such a pn-junction diode is as shown in Fig. 2(a). In the absence of electric potential, n-side donor levels of the conduction band are occupied by electrons and the Fermi level lies within the conduction band. Similarly, on the heavily doped p-side, the acceptor levels are unoccupied and holes exist in the valance band and the Fermi level lies within the valence band. When a forward bias is applied to the junction, the energy levels shift and the new distribution is shown in Fig. 2(b). The electrons and holes are injected into the depletion region which results in a decrease in its width. The injected electrons and holes appear in high concentrations in this transition region. At a low forward bias current level, the electron-hole recombination causes spontaneous emission of photons, and the junction act as an LED. The bandwidth of the emitted light will be larger. As the current is increased, the intensity of light increases linearly. When the current reaches a threshold value the carrier concentration in the depletion region will reach very high values.

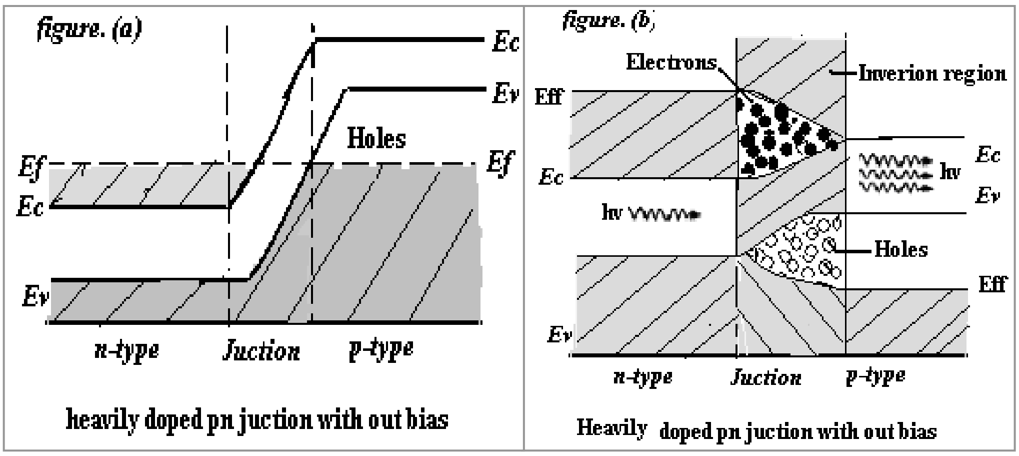


Fig. 2. Energy level of n-p junction

The upper levels in the depletion region are having high population density of electrons while the lower levels in the same region are vacant. This is state of population inversion. The narrow region where the state of population inversion is achieved is called inversion region or active region. The stimulated electron-hole recombination causes emission of coherent radiation of very narrow band width. The energy gap of GaAs is 1.4 eV and hence wavelength is 8400 Å in IR region.

$E_g = \frac{hc}{\lambda}$ or $\lambda = \frac{hc}{E_g}$ = 8400 A°

Properties (or characteristics) of laser beam:

Laser beam has the following characteristics which differ from ordinary light.

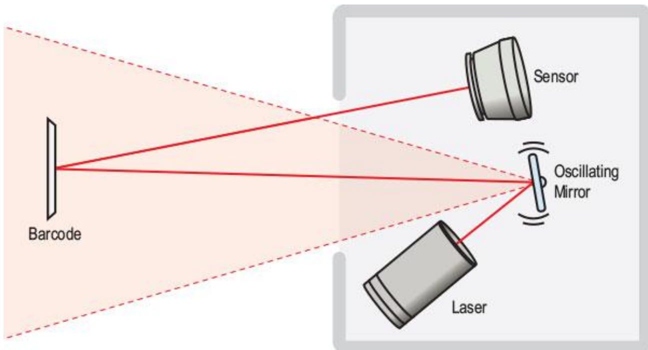
1. **Monochromatic**: A light emitted by a laser is highly monochromatic than that of ordinary monochromatic light.
2. **Coherence**: The waves emitted by a laser will be in phase and are of the same frequency and moves with the same velocity and direction. In other words, the laser has a high degree of coherence.
3. **Directionality**: Ordinary light emits in all directions whereas Lasers emits only in one direction and laser light travels as a narrow beam.
4. **Intensity**: Laser light is highly intense since it gives out light into a narrow beam and its energy is concentrated in a small region. The laser light is more intense than the light starting from an equal area on the surface of the sun.
5. **Focus ability**: Since ordinary light is highly divergent, it cannot come exactly to a focus point. Laser light is highly monochromatic and it can be brought to a sharp focus by a lens.

Engineering applications of Laser:

1. Barcode scanner

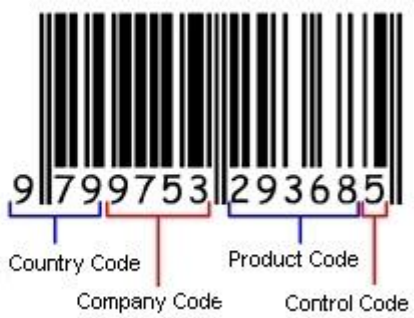
A barcode reader is an optical scanner that can read printed barcodes, decode the data contained in the barcode to a computer. It consists of a light source, a lens and a light sensor for translating optical impulses into electrical signals.

In the early days of 1D codes, codes could only be read by lasers. 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. A barcode scanner works by directing a beam of light across the barcode and measuring the amount of light that is reflected. The dark bars on the barcode reflect less light than the white spaces between them. The scanner then converts the light energy into electrical energy, which the decoder then converts into data and forwards to a computer. It uses a red diode laser (e.g., GaInP or AlGaInP; typical wavelengths are 635, 650 and 670 nm) to read the reflectance of the black and white spaces in a barcode.



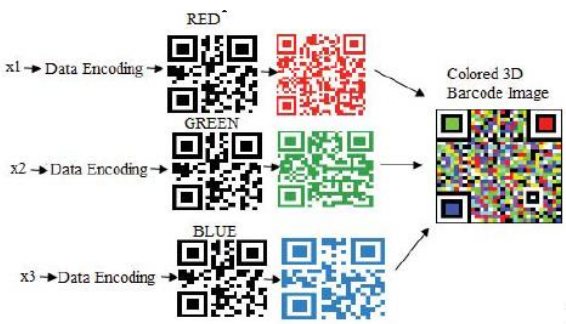
A laser scanner uses a system of mirrors and lenses that allow it to read barcodes regardless of their position. It performs up to 500 scans per second to reduce the possibility of errors. A standard range barcode scanner easily reads up to 15 fee. On the other hand, specialized long-range scanners can take readings up to 50 feet away. Laser scanners often come as handhelds or as stationary units

A 3D barcode would have data encrypted on a X, Y, and Z axis. 2D barcodes are encrypted on a X and Y axis. 1D barcodes are only encrypted on a X or Y axis. So then, 3D barcodes are encrypted with patterns, shapes, and dots for characters (X and Y axis) and have a raised pattern that can be physically felt (Z axis).



1-D Barcode

2-D Barcode



3-D Barcode

Benefits: Laser scanners do not require an image processor. They are also fast, and capable of conducting up to 1,300 scans per second. Finally, because they use lasers—collimated beams of light that essentially do not diverge no matter how far the light travels from the source—they can read 1D barcodes from relatively long distances with the use of special optics.

Limitations: Laser scanners have trouble that is poorly printed, low-contrast, distorted, or damaged.

Problems on Lasers

1. The ratio of population of two energy levels, out of which upper one corresponds to a metastable state, is $1.059\text{x}10^{-30}$. Find the wavelength of light emitted at 330 K.

Solution:

Given $\frac{N_2}{N_1}=1.059x10^{-30}$; T=330K; K=$1.38\text{X}10^{-23}\text{JK}^{-1}$; C=$3\text{x}10^{8}\,\text{ms}^{-1}$

λ = **?**

$$\frac{N_2}{N_1}=e^{-\left(\frac{h\nu}{KT}\right)}=e^{-\left(\frac{hC}{\lambda KT}\right)}$$

$$e^{\left(\frac{hC}{\lambda KT}\right)}=\frac{N_1}{N_2}=\frac{1}{1.059x10^{-30}}=0.944x10^{30}$$

$$\frac{hC}{\lambda KT}\log_e e=\ln(0.944x10^{30})=69.02$$

$$\lambda=\frac{hC}{69.02Xkt}=\frac{6.63x10^{-34}X3X10^{8}}{69.02X1.38X10^{-23}X330}=6327A^{0}$$

2. A laser beam at thermal equilibrium temperature 300K has two energy levels with a wavelength separation of 1 μm.Find the ratio of population densities of the upper and lower levels.

Solution: $\frac{N_2}{N_1}=--$ T=300 K; $\Delta\lambda=1\mu m$ =10^{-6} m;

K=$1.38\text{X}10^{-23}\text{JK}^{-1}$; C=$3\text{x}10^{8}\,\text{ms}^{-1}$

$$\frac{N_2}{N_1}=e^{-\left(\frac{h\Delta\nu}{KT}\right)}=e^{-\left(\frac{hC}{\Delta\lambda KT}\right)}=e^{\left(\frac{-6.63X10^{-34}X3X10^{8}}{10^{-6}X1.38X10^{-23}X300}\right)}=e^{-48.007}$$

$$\boxed{\frac{N_2}{N_1}=1.415X10^{-21}}$$

3. Find the ratio of population of two energy levels, out of which one corresponds to a metastable state, if the wavelength of light emitted at 330 K is 632.8 nm.

Solution: $\frac{N_2}{N_1}=?$ T=330 K; $\lambda=632.8nm$ =10^{-6}m; K=$1.38\text{x}10^{-23}\text{JK}^{-1}$;C=$3\text{x}10^{8}\,\text{ms}^{-1}$

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

$$= e^{-\left(\frac{hC}{\lambda KT}\right)} = e^{\left(\frac{-6.63X10^{-34}X3X10^{8}}{633{,}8X10^{-9}X1.38X10^{-23}X330} = e^{-68.96}\right)}$$

$$\boxed{\frac{N_2}{N_1} = 1.1x10^{-30}}$$

4. A pulse from laser with power 1mW lasts for 10nS.If the number of photons per second is $3.491x10^{7}$, calculate the wavelength of laser.

Solution: $\boldsymbol{\lambda}$**=?**

Total energy of the laser $E_t=Pt=1x10^{-3}x10x10^{-9}=10^{-11}J$----- (1)

Number of photons emitted =n=$3.491x10^{7}$

Energy of one photon = E= $h\nu = \frac{hC}{\lambda} = \frac{6.63X10^{-34}X3X10^{8}}{\lambda} ---(2)$

Total energy=number of photons X Energy of one photon

$$E_{total} = n\frac{hC}{\lambda}$$

Substituting (1) and (2) gives

$$10^{-11} = 3.491X10^{7}X6.63X10^{-34}X3X10^{8}X\frac{1}{\lambda}$$

λ = 694 nm

5. A He-Ne laser is emitting a beam with an average power of 4.5 mw. Find the number of photons emitted per second by the laser. The wavelength of the emitted radiation is 6328 A^0.

Solution: n = **?**; λ= 6328A^0; t = 1 s

Total energy of the laser $E_t=Pt=4.5x10^{-3}X1=4.5X10^{-3}J$----------- (1)

Energy of one photon=E= $h\nu = \frac{hC}{\lambda} = \frac{6.63X10^{-34}X3X10^{8}}{6328X10^{-10}} ---(2)$

Total energy=number of photons X Energy of one photon

$$E_{total} = n\frac{hC}{\lambda}$$

Substituting (1) and (2) gives

$$4.5X10^{-3} = nX6.63X10^{-34}X3X10^{8}X\frac{1}{6328x10^{-9}}$$

***n*= 1.4316x10^{16}**

6. A pulsed laser emits photons of wavelength 780nm with 20 mw average/pulse. Calculate the number of photons contained in each pulse, if the pulse duration is 10 ns.

Hint: $E_t = n\frac{hC}{\lambda}$ Answer n=$7.86X10^{17}$

7. Find the number of modes of the standing waves in the resonant cavity of length 1m of He-Ne laser operating at wavelength 632.8 nm.

Solution: L=1m; λ= 632.8nm; n = **?**

$$\mathbf{2L=m\lambda}$$

$$n = 2L/\lambda = 2X1/632.8X10^{-9}$$

$$\mathbf{n=3.16x10^6}$$

8. A Ruby laser emits pulse of 20 ns, with average power pulse being100 kW.If the number of photons in each pulse is $6.981x10^{15}$ calculate the wavelength of laser.

Solution:

t = 20 ns

Number of photons emitted=n=$3.491X10^7$

Energy emitted in in 1S= 100KW=10^5J

Total energy emitted 20n---E=$_t10^5x20x10^{-9}=2x10^{-3}$J----(1)

Energy of one photon=E= $h\nu = \frac{hC}{\lambda} = \frac{6.63X10^{-34}X3X10^8}{\lambda} ---(2)$

Total energy=number of photons X Energy of one photon

$$E_{tot} = n\frac{hC}{\lambda}$$

Substituting (1) and (2) gives

$$\lambda = \frac{nhC}{E_{tot}} = \frac{6.981X10^{15}X6.63X10^{-34}X3X10^8}{2X10^{-3}} = 6942A^0$$

9. Calculate on the basis of Einstein's theory, the number of photons emitted per second by a He-Ne laser emitting light of wavelength $6328A^0$ with an output power of 10 mw.

Hint: $E_t = n\frac{hC}{\lambda}$ Answer n=$3.18x10^{16}$

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