Unit – II (LASER& Fiber Optics)

Introduction to Laser: Spontaneous and Stimulated Emissions - Einstein's A and B Coefficients – Basic Principles of LASER – Population Inversion – Two, Three and Four Level Systems – Different Types of Pumping – Characteristics of LASER. Types of Laser: Nd-YAG LASER– CO_2 Laser – Semiconductor Laser - Applications of Laser

Fiber Optics: Structure and Principles of Optical Fiber – Acceptance Angle and Numerical Aperture – V-Number - Types of Fibers: Step Index, Graded Index, Single Mode &Multimode - Application of Optical Fibers

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Introduction to LASER

LASER stands for Light Amplification by Stimulated Emission of Radiation. A laser differs from other conventional sources as it produces highly coherent, highly monochromatic, high intense and highly directional light beams.

Lasers are used in optical disk drives, laser printers, barcode scanners, DNA sequencing instruments, fiber-optic communications, laser surgery, skin treatments, cutting and welding materials in the industry and also in range finding applications in military.

Characteristics of Laser:

Directionality: A laser emits light in only one direction. A laser can thus concentrate all its power in one point to generate light of extremely high intensities.

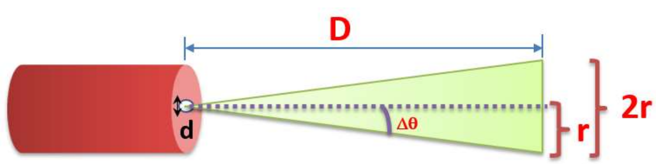
If there is any angular spread, it can be calculated using the formula $\Delta\theta = \frac{\lambda}{d}$.

Where λ is the wavelength of the light used and d is the diameter of the aperture from where the laser emits. Similarly, the radius of the spread (r) and area of the spread (A) can be calculated using the formulae.

$$r = \Delta\theta \times D$$

$$A = \pi\,(\Delta\theta \times D)^2$$

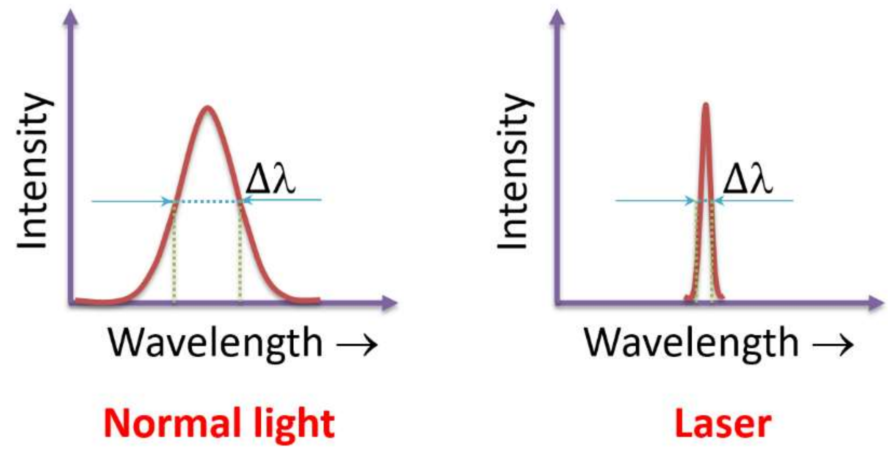
Where D is the distance between the source and screen and $\Delta\theta$ is the angular spread.



Monochromaticity: The light emitted from a laser is highly monochromatic as it has unique wavelength/colour. Hence, the energy of the emitted laser light is given by $E = \frac{hc}{\lambda}$ where c is the speed of light, h is a Planck's constant and λ is the wavelength of light.

Monochromaticity is determined by taking the ratio of $\frac{\Delta v}{v}$ or $\frac{\Delta\lambda}{\lambda}$

Where Δv *or* $\Delta\lambda$ is a measure of bandwidth.



The graph of wavelength *versus* the intensity of normal and laser light rays are shown above. It reflects that the value of $\Delta\lambda$ at FWHM is relatively very small in laser lights compared to normal light.

High intensity: Amazing feature of laser is its high light intensity. Since the photons in the laser beam are coherent and the intensity is proportional to the square of the amplitude, the intensity of the laser remains nearly constant over long distance.

The intensity of the laser can be calculated using the formula

The intensity of the beam $\mathrm{I} = \frac{\mathrm{P}}{\mathrm{A}}$

Where P is output power of the laser and

A is the Area of cross-section of the beam.

Also, the number of photons emitted by the laser device per second is given by $\mathrm{I} = \frac{\mathrm{P}}{\mathrm{h}\vartheta}$

Where $\mathrm{h}\vartheta \rightarrow$ Energy of one photon

Coherence: The laser beams are highly coherent. The waves are said to be coherent waves if they have the same phase or phase difference, the same amplitude, the same wavelength and travel in the same direction. Coherence can occur either temporarily or throughout the entire period of its travel. Based on that, we can classify the coherence into

(1) Temporal Coherence

Coherence between the waves occurs in a short period of time.

(2) Spatial coherence

Coherence between the waves occurs throughout the entire period of the travel.

Difference between ordinary and Laser lights

Properties	LASER light	Ordinary light
Coherence	Laser light has only one wavelength. Hence, all the photons emitted by laser light are in phase. Thus, laser light is coherent.	Ordinary light sources have many wavelengths. Hence, the photons emitted by ordinary light sources are not in the same phase. Thus, ordinary light is incoherent
Directionality	The laser beam is very narrow and all the light beams are concentrated on a very small area. This makes laser light highly directional.	Divergence is more for ordinary light. Hence they are non-directional.
Monochromaticity	The light waves from a laser contain only one wavelength or color, so it is known as monochromatic light.	They have more wavelengths, so they are polychromatic
Intensity	The energy is concentrated in a narrow region. Therefore, laser light has a greater intensity than ordinary light.	Ordinary light spreads, so the intensity will be less

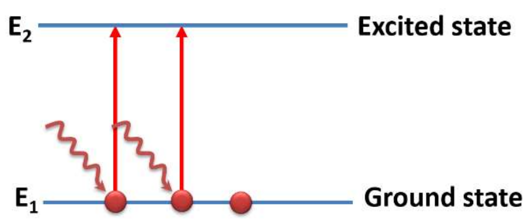
Basic Principle of laser

Radiation can interact with matter in three different ways. They are stimulated absorption, spontaneous emission and stimulated emission.

We can explain these processes by considering an atom with two energy levels E_1 and E_2. Let E_1 be the ground level and E_2 excited level. N_1 and N_2 are the number of atoms per unit volume in the ground and excited levels.

Induced or Stimulated absorption:

When a photon of energy hυ strikes this system, atoms in the ground level E_1 absorb the photon (hυ) and get excited to the higher level E_2. This process is called stimulated absorption.



Rate of stimulated absorption is given by,

$$R_{12} \propto N_1 \rho_v$$

or

$$R_{12} = B_{12} N_1 \rho_v$$

Where ρ_v – Number of photons emitted per unit time or Energy density of the radiation emitted per unit time

R_{12} gives us the number of upward transitions per unit time

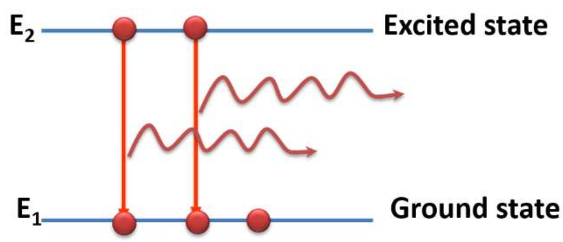
N_1 –Number of atoms per unit volume in the ground state

B_{12} - Einstein probability coefficient of stimulated absorption.

Atoms in the excited level are not stable so, they tend to return to the ground state through the following processes:

Spontaneous emission:

Atom in the excited state (E_2) emits its extra energy and de-excite to the ground state (E_1) without any inducement. This process is independent of the external radiation. When the excited state atoms undergo spontaneous transitions to the ground state, they emit a photon of energy equivalent to the energy difference between the excited state and the ground state, i.e., $h\upsilon=E_2-E_1$.



Rate of spontaneous emission

$$R_{21}(spontaneous) \propto N_2$$

or

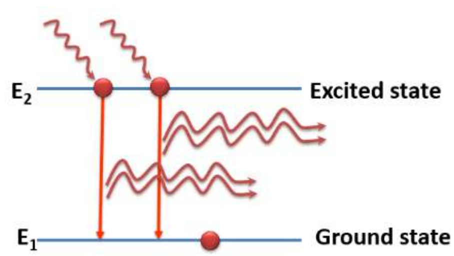
$$R_{21}\ (spontaneous) = A_{21}N_2$$

Where, A_{21} – Einstein's probability coefficient of spontaneous emission.
N_2 –Number of atoms per unit volume in the excited state

Spontaneous emission is a random process and it is uncontrollable.

Stimulated emission:

When a photon of energy $h\upsilon$ (E_2-E_1) strikes atoms in the excited state, it induces a stimulated emission process. During this stimulated emission process, two coherent photons of the same energy will be released. This process is known as stimulated emission



Rate of stimulated emission

$$R_{21}(stimulated) \propto N_2\rho_v$$

or

$$R_{21}(spontaneous) = B_{21}N_2\,\rho_v$$

B_{21} is Einstein's probability coefficient of emission per unit time.

Einstein Coefficients

Albert Einstein derived a mathematical expression to show the existence of stimulated emission of radiation. Let us consider a system consisting of two energy levels E_1 and E_2. Let N_1 and N_2 be the populations of these two energy levels. To find out the mathematical expression to show the possibility of stimulated emission of radiation, it was assumed that

1) The atoms and the radiation are in thermal equilibrium.
2) The radiation is identical to the blackbody radiation and consistent with Planck's radiation law for any value of T.
3) The population densities N_1 and N_2 at the lower and upper energy levels, respectively, are constant in time, and they obey Boltzmann's distribution Law.

The above conditions will become true only if the rate of absorption is equal to the rate of emission.

Rate of absorption = Rate of emission

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

Where A_{21}, B_{12} and B_{21} are known as Einstein Coefficients and are interrelated to one another.

$$B_{12}\rho_v N_1 - B_{21}\rho_v N_2 = A_{21}N_2$$

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

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

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

According to Boltzmann Distribution

$$\frac{N_2}{N_1} = e^{-h\upsilon/kT}$$

$$\rho_v = \frac{A_{21}/B_{21}}{\left[\frac{B_{12}}{B_{21}} e^{h\upsilon/kT} - 1 \right]} \quad ------(1)$$

As we know, the energy density of radiation emitted by the black-body is,

$$\therefore \qquad \rho_v = \frac{8\pi h\upsilon^3}{c^3 \left[e^{h\upsilon/kT} - 1 \right]} \quad ------(2)$$

Comparing Equs (1) and (2), We get,

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\upsilon^3}{c^3} \quad --------(3)$$

And

$$\frac{B_{12}}{B_{21}} = 1$$

Or

$$B_{12} = B_{21} \quad -------(4)$$

Equation 3 and 4 are the Einstein's relation.

Ratio of spontaneous emission to the stimulated emission:

The ratio of spontaneous emission to the stimulated emission can be written as,

$$\frac{Spontaneous\ emission}{Stimulated\ emission} = \frac{A_{21} N_2}{B_{21} N_2\, \rho_v} = \frac{A_{21}}{B_{21} \rho_v}$$

or

$$\frac{Spontaneous\ emission}{Stimulated\ emission} = \left(\frac{8\pi h v^3}{c^3} \right) . \frac{1}{\frac{8\pi h v^3}{c^3 \left(e^{hc/\lambda KT} - 1 \right)}} = e^{hc/\lambda KT} - 1$$

(i) At Low temperatures, when $\frac{h\upsilon}{kT} > 1$,

$$\left[e^{h\upsilon/kT} - 1\right] = \frac{A_{21}}{B_{21}\ \rho_v} \Rightarrow A_{21} >> B_{21}$$

$$\boxed{\text{Spontaneous emission dominates}}$$

(ii) At high temperatures, when $\frac{h\upsilon}{kT} < 1$

$$e^{h\nu/kT} - 1 = \frac{A_{21}}{B_{21}\ \rho_v} \Rightarrow B_{21} \gg A_{21}$$

$$\boxed{\text{Stimulated emission dominates}}$$

Difference between Stimulated and spontaneous emission process

Stimulated emission	Spontaneous emission
The external radiation induces a stimulated emission process.	It is a spontaneous process.
The rate of stimulated emission depends upon the concentration of atoms in the higher energy level and the energy density of the incident radiation per unit volume.	The rate of spontaneous emission depends only upon the concentration of atoms.
The emitted photons in this case are highly directional and coherent.	The emitted photons in this case are highly non-directional and incoherent.
High intense light photons are emitted.	Less intense light photons are emitted.
The spread of photon frequencies is relatively very narrow. As a result, the light is nearly monochromatic.	Photons of slightly different frequencies are generated. As a result, the light is not monochromatic.
Light amplification occurs due to multiplication of photons.	No light amplification occurs during spontaneous process.

Normal population:

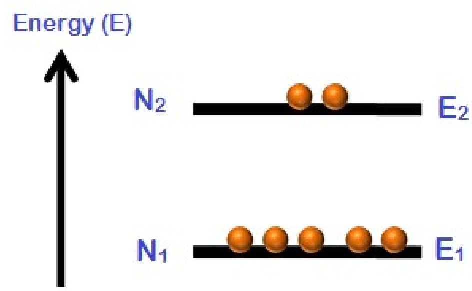
At thermal equilibrium (normal conditions), the number of atoms in the lower energy level will be more than the higher energy level $N_1 > N_2$. This is called normal population and the number of atoms in the state implies *normal state* or *equilibrium state.*

When the material is in thermal equilibrium, the population ratio is governed by the Boltzmann distribution

$$\frac{N_2}{N_1} = e^{-h\upsilon/kT}$$

Or

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



Where k-Boltzmann's constant, T-temperature

Population inversion:

At non-thermal equilibrium, the number of atoms in the excited level is greater than the ground level, i.e., $N_2 > N_1$. This is sometimes called an inverted state.

Validation:

Under such a non-equilibrium state or condition,

Rate of emission > Rate of absorption

$$A_{21}N_2 + B_{21}\rho_v N_2 \quad > \quad B_{12}\rho_v N_1$$

Since the external sources induce a stimulated emission process continuously, the occurrence of spontaneous emission is relatively small and can be ignored.

Therefore, the above equation becomes

$$B_{21}\rho_v N_2 \quad > \quad B_{12}\rho_v N_1$$

After canceling the common terms, we get,

$$N_2 > N_1$$

Metastable state

A metastable state is an excited state in which the atoms have a relatively longer lifetime than the higher excited state. The lifetime of atoms in the metastable state is of the order of 10^{-6} to 10^{-3} s, while the lifetime of atoms in the higher excited state is 10^{-8} s.

In other words, it is an intermediate state between the excited state and the ground state. Since its lifetime is 10^{3} to 10^{6} times greater than that of the higher excited state, the population at the metastable state can exceed the population at a lower level and establish the condition of population inversion in the lasing medium. It would be impossible to create the state of population inversion without a metastable state. The metastable state can be readily obtained in a crystal system containing impurity atoms.

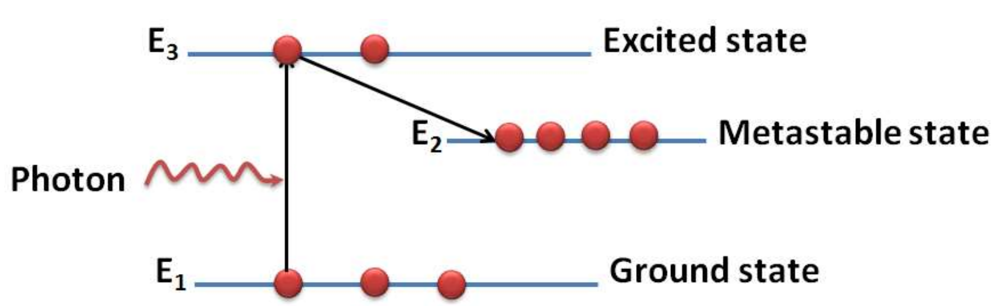
Various types of pumping Methods

Pumping is the process of increasing the number of atoms in the excited level.
The following pumping methods are usually employed in lasers

Optical pumping or Photon excitation:

It is the process of exciting an atom from a lower energy level to a higher energy level by a photon of energy hυ. It is also called “optical pumping”.

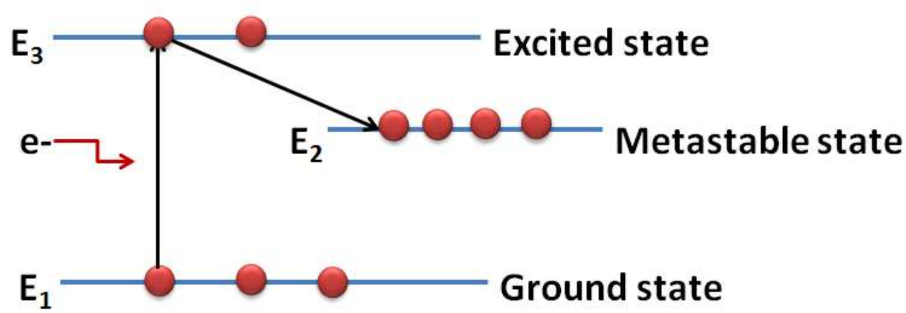
Light sources like flash lamps emitting a broad range of frequencies can be used for optical pumping in laser. The photon excitation is used in solid-state lasers such as Ruby Laser and Nd:YAG laser.



Electron excitation:

In gaseous lasers, the basic principle behind the laser operation is gaseous discharge. To produce gaseous discharge, a high amount of electric field is applied.

A high-voltage pulse initially ionizes the gas so that it conducts electricity. An electric current flowing through the gas excites the atoms to the excited level, from where they drop to the metastable state, leading to population inversion.

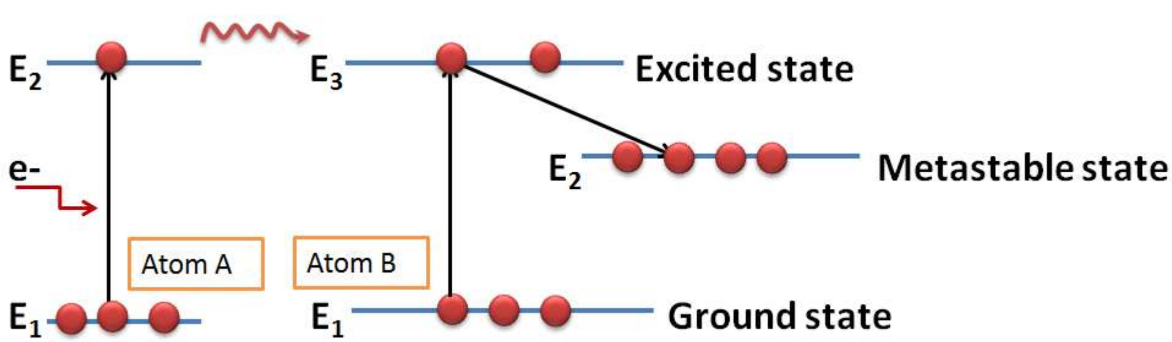


Inelastic atom-atom collision:

Two atoms having nearly the same excited energy take part in this pumping. In some gaseous lasers, a mixer of gases is used. Due to electron bombardment, one atom (A) gets excited (A*) into the higher energy level. The excited state atom (A*) further makes collisions with another gaseous atom in the ground state (B) and brings it into the higher excited state (B*).

$$(i) \quad A + e^{-} \rightarrow A^{*} + e^{-}$$

$$(ii) \quad A^{*} + B \rightarrow A + B^{*}$$



Direct conversion:

Electrical energy is directly converted into light energy due to the recombination of electrons and holes in certain semiconductor diode lasers.

Chemical reactions:

In the case of certain chemical lasers, due to the chemical reactions, the product is left in the excited state.

The chemical reaction between H_2 and F_2 brings the product HF molecule into the excited state. Here, the Energy released during the chemical reaction is used for exciting the active medium.

$$H_2 + F_2 \rightarrow 2(HF)^*$$

Basic components of a laser:

A laser normally requires three main components for its operation:

(1) Active medium with selectively populated energy levels.

(2) Suitable pumping source for population inversion between specified energy levels.

(3) Resonator to increase the number of coherent photons.

Active medium

It is a medium in which laser action (the process of producing a laser) takes place.

Examples: Solid medium-Ruby rod, Nd^{+3} atoms in Yttrium Aluminium Garnet (YAG),

Liquid medium – in the form of dye solutions rhodamine -6G, rhodamine –B, Fluorescein

Gas laser: Mixture of Helium and Neon in He-Ne laser, Argon in Argon laser,

Semiconductor laser: Gallium arsenide (GaAs), Indium gallium arsenide (InGaAs).

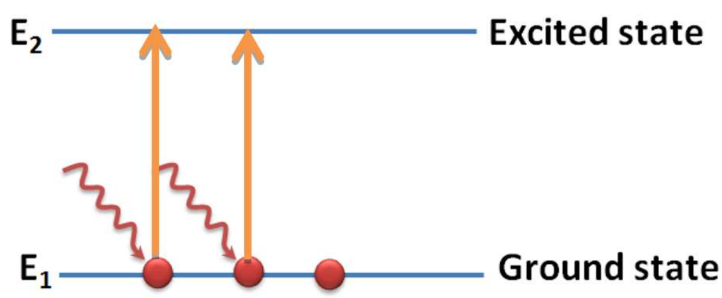
Pumping source: Under normal conditions number of electrons/atoms in the ground level will be more than the excited level (normal population). The source that supplies energy to the laser medium to increase the number of electrons/atoms in the excited level (population inversion) is called the pumping source. Ex. Xenon flash tube in Ruby laser, Excitation by electrons in Argon laser.

Resonator: It is a device which is used to increase the number of coherent photons passing through the laser medium. It consists of two mirrors on both sides of the active medium. On one side, nearly 99% reflector is used, and on the other side, a partially reflecting mirror is used. The emitted photons during the stimulated emitted process will move back and forth between the mirrors. Once the laser condition is satisfied, a high-intensity coherent light beam will come out of the partially silvered mirror. Example. Plane-parallel resonator, Large radius resonator. Confocal resonators and Spherical resonators.

Active medium and active center

The active medium is the material in which the laser action takes place. However, all the atoms in the crystal are not suitable for laser operation. Only a small fraction of atoms of a particular type have the energy levels in which population inversion can be achieved. Those atoms that cause laser action are called active centers.

Two level laser:

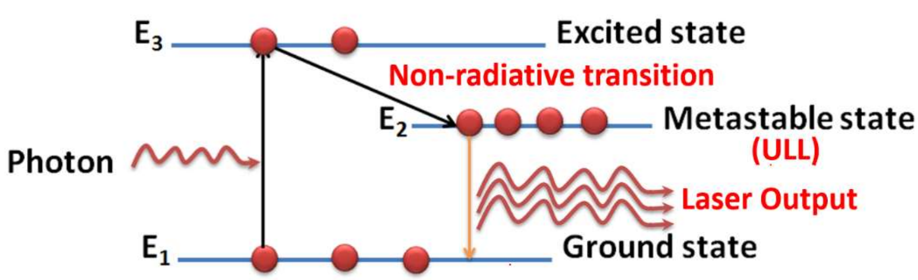


Let us consider a laser medium whose atoms have only two energy states: a ground state and one excited state. In such an idealized atom, the only possible transitions are excitation from E_1 to E_2 and de-excitation from E_2 to E_1.

Since the lifetime of the excited state is too short, there will not be enough excited atoms around to undergo stimulated emission in the two-level systems. Therefore, it is impossible to drive more than half of the atoms into the excited state to achieve population inversion. To produce effective pumping in a laser, three or four levels are necessary.

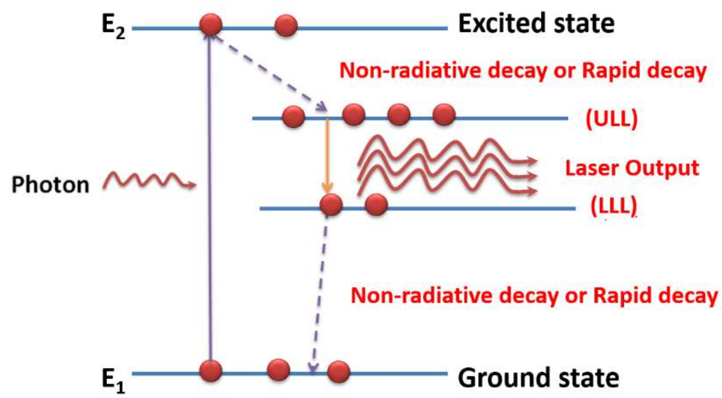
Three level laser:

Consider an atomic system with three energy levels E_1, E_2 and E_3.E_1- Ground level, E_3-Excited level/Pumping level, and E_2 –metastable state. Atoms at the ground level are excited to the level E_3 (short-lived state) by a photon of energy hυ. Since the E_3 state is unstable, they make a downward transition to E_2 (long-lived state) through a non-radiative transition (during this transition, excess energy is dissipated in the form of phonons, and there will not be a photon emission). The population of E_2 increases rapidly,y and population inversion condition is achieved between E_2 and the ground state E_1. When the random photon induces stimulated emission, the atoms in the energy level E_2 undergo the transition to the ground state (E_1). This results in the emission of laser light rays between E_2 and E_1.



Four level laser:

Let us consider an atom system consisting of four energy levels E_1, E_2, E_3 and E_4. E_1- Ground level, E_4- Excited level E_3-Metastable state (Upper lasing level (ULL)), E_2 - Intermediate state (lower lasing level (LLL). Atoms are excited from ground level (E_1) to the excited level (E_4) by absorbing a photon of energy $h\upsilon = E_4 - E_1$. Then, they spontaneously decay to upper lasing level (E_3) through the non-radiative transition. In some instances, the Population inversion is achieved between E_3 and E_2. Firstly, the atoms in the energy level (E_3) spontaneously decay to the lower lasing level (E_2) by emitting random photons. The random photons of energy $h\upsilon = E_3 - E_2$ striks the atoms in the energy level E_2 and produces stimulated emission processes. The repeated action of the stimulated emission process produces the laser beam between the levels E_3 and E_2. Then, the atoms in the energy level E_2 deexcite to the state E1 through the non-radiative transition.



Types of Laser

Based on the type of active medium, Laser systems are broadly classified into the following categories.

- **Solid State laser :** Ruby Laser, Nd:YAG laser
- **Gas laser :** He-Ne Laser, CO_2 Laser
- **Semiconductor Laser :** GaAs laser, GaAsP laser
- Liquid Laser : $SeOCl_2$ Laser, Europium Chelate Laser
- Dye laser : Rhodamine 6G laser, Coumarin dye laser

Nd:YAG Laser

Nd:YAG (neodymium-doped YAG) laser is invented by Joseph E. Geusic and Richard G. Smith at Bell Labs in the year 1964. Neodymium Yttrium Aluminium Garnet laser is a four-level solid-state laser. YAG ($Y_3Al_5O_{12}$) is an optically isotropic crystal. In the YAG crystal, a few Y^{3+} ions are replaced by neodymium ions Nd^{3+} without affecting the lattice structure. Nd^{3+} ions are active centers (responsible for laser emission), and YAG is a host material or active medium.

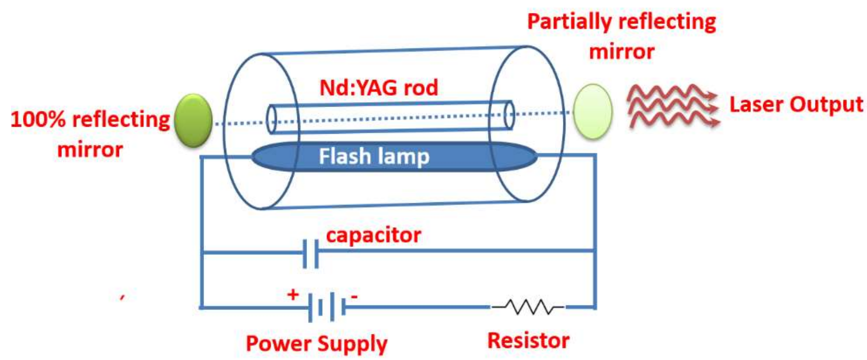
Principle:

The active medium Nd: YAG rod is optically pumped by Xenon flash tubes. The Neodymium ions (Nd^{3+}) are raised to excited levels. During the transition from metastable state to the ground state, a laser beam of wavelength 1.064μm is emitted.

Construction:

- A small amount of Yttrium ions (Y^{3+}) is replaced by Neodymium (Nd^{3+}) in the active element of Nd: YAG crystal.
- This active element is cut into a cylindrical rod of diameter 6 to 9 mm and length 5 to 10 cm.

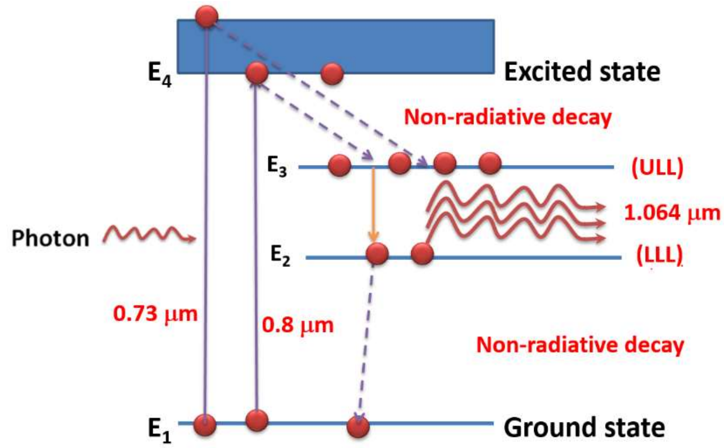
- This cylindrical rod (laser rod) and a pumping source (flash tube) are placed inside a highly reflecting elliptical reflector cavity.
- The optical resonator is formed by using two external reflecting mirrors M_1 and M_2 kept at the sides of the active medium and parallel to each other. M_1 is a fully reflecting mirror and M_2 is a partial reflector.
- The flash lamp is connected with the necessary power supply.



Working:

When the Xenon flash lamp is switched on, by the absorption of light radiation of wavelengths 0.73 μm and 0.8 μm, the Neodymium (Nd^{3+}) ions are raised from ground level E_1 to upper-level E_4. The Nd^{3+} ions at E_4 further make transitions to E_3 by non-radiative transition. E_3 is a metastable state or ULL. The Nd^{3+} ions are collected in the level E_3 and the population inversion is achieved between E_3 and E_2. Firstly, the Nd^{3+} ion spontaneously transitions from E_3 to E_2 by emitting a photon of energy hυ.

The spontaneous photon stimulates another excited atom (at E_3) to move downward to E_2. This emitted photon will trigger a chain of stimulated photons between E_3 and E_2. The photons thus generated will travel back and forth between the mirrors (optical resonators). After some time, the photon number multiplies more rapidly. After enough strength is attained (condition for laser being satisfied), an intense laser light of wavelength 1.064 μm is emitted through the partial reflector. Finally, the depopulation of atoms at the energy level E_2 occurs through non-radiation decay.



Advantages:

- ✓ It produces a high energy output.
- ✓ It is much easier to achieve population inversion.

Disadvantages:

- ✓ The electron energy level structure of Nd^{3+} in YAG is complicated.

Applications:

- ✓ It is widely used in engineering applications, for example, micro-machining operations such as welding, drilling etc.
- ✓ It finds many medical applications such as endoscopy, urology, neurosurgery, ENT, gynecology, dermatology, dental surgery and general surgery.

Characteristics of Nd: YAG laser

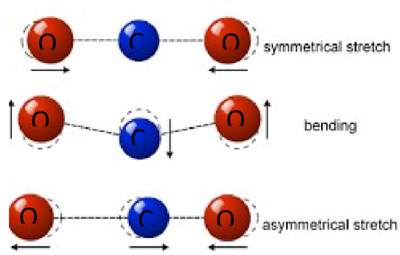
Type	**Doped Laser/ Four level Laser**
Active medium :	Yttrium Aluminium Garnet
Active center :	Neodymium
Pumping method :	Optical Pumping
Pumping source :	Xenon or Krypton Flash Lamp (Quartz-Halogen Lamp)

Optical resonator :	Ends of the rods silver coated Two external mirrors: partial and fully reflecting mirrors
Power output :	20 kW
Nature of the output :	Pulsed/Continuous
Wavelength emitted :	1.064 µm

CO2 Laser

C.K.N. Patel invented the carbon dioxide laser (also known as molecular gas laser) in the year 1964 at Bell Telephone Labs, USA. In the case of the CO2 laser, in addition to the quantized electronic levels of the atoms, a transition takes place between the vibrational and the rotational states of the molecules.

A carbon dioxide molecule is a tri-atomic molecule consisting of two oxygen atoms covalently bonded to a central carbon atom. Such a molecule can vibrate in three fundamental modes namely, symmetric stretching, asymmetric stretching and bending.

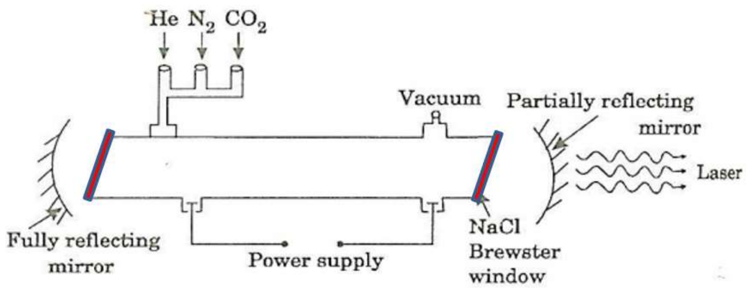


In the symmetric stretching mode, the Carbon atom remains stationary at the center. The two oxygen atoms simultaneously oscillate along the axis of the molecule, either away from or toward each other.

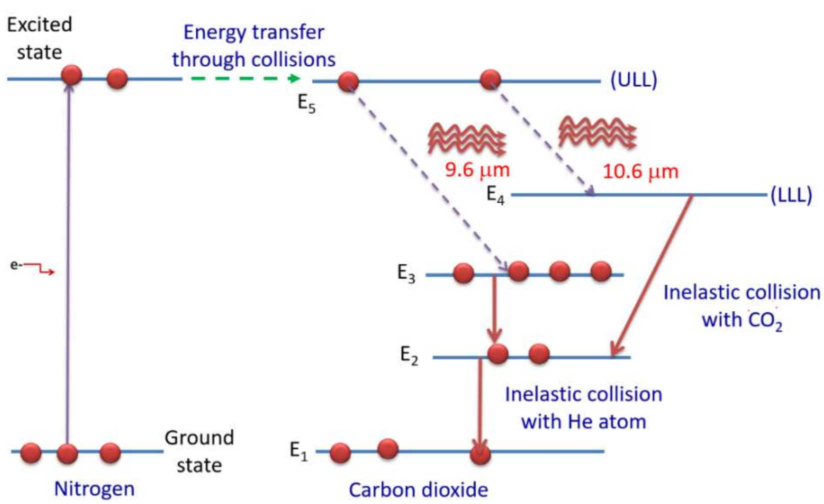
In bending mode, all the molecules vibrate perpendicular to the axis. Two oxygen atoms vibrate vertically upwards and carbon downwards and vice-versa.

In the asymmetric stretching mode, two oxygen atoms vibrate in one direction and carbon in the opposite direction along the axis. So, one oxygen atom comes closer to the central carbon atom, and the other atom moves away from the center carbon atom.

Construction:



- It is basically a discharge tube (Quartz tube) having a bore of a cross-section of about 1.5 mm^2 and a length of about 260 mm.
- The tube is filled with a mixer of CO_2, N_2 and He in the ratio of 1:4:5 respectively.
- The active centers are the CO_2 molecules. The laser action takes place between the vibrational levels of the electronic ground state.



Working:

When the current passes through the mixture of gases, the N_2 molecules get excited. The N_2 molecules undergo inelastic collisions with ground-state CO_2 molecules and excite them into the energy level E_5. Also, some of the CO_2 molecules are also excited to the upper-level E_5 through collisions with electrons. The E_5 level is the upper lasing level and E_4, E_3 levels act as lower lasing levels. As the population of CO_2 molecules builds up at E_5, the population inversion is achieved between E_5 level and at E_4 and E_3. Random photons are emitted spontaneously by few atoms at the energy level E_5. The spontaneous photons traveling through the gas mixture trigger stimulated emissions between E5 and E4 as well as between E5 and E_3. The stimulated emissions between E_5 and E_4 emit a light of wavelength 10.6 μM (far IR radiation). The stimulated emissions between E_5 and E_3 emit a light of wavelength 9.6 μM (far IR radiation). The excited CO_2 molecules at E_4 and E_3 fall to the lower level E_2 through inelastic collisions with normal CO_2 molecules. As the gaseous mixture heats up, the E_2 level, which is closer to the ground state, tends to be populated due to thermal excitations. The helium atoms de-excite the CO_2 molecules through inelastic collisions and decrease the population density of CO_2 at E_2.

Advantages:

- ✓ The output power, even up to 60 kW, is achieved using a CO_2 laser.
- ✓ The efficiency of CO_2 laser is about 30%.
- ✓ The CO_2 laser produces both pulsed and continuous wave lasers
- ✓ It has a long life of about 20,000 Hours.

Disadvantages:

- ✓ Divergence of CO_2 laser is greater than He-Ne and argon laser.
- ✓ It produces harmful effects on our eyes. So, precautions are required even with a low-powered CO_2 laser.
- ✓ It requires a cooling system.

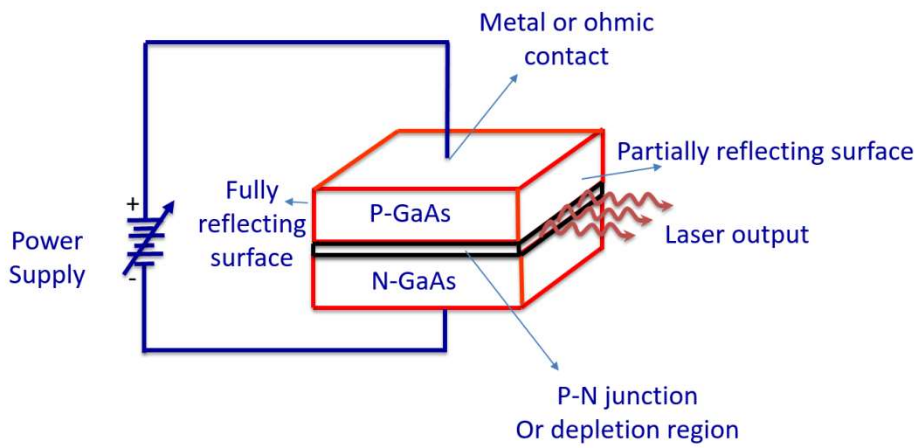
Applications:

- ✓ CO_2 laser is used in industry for welding and cutting of metals.
- ✓ Because the atmosphere is quite transparent to infrared light, CO_2 lasers are also used for military range finding using **LIDAR** techniques.
- ✓ It is used in soft tissue surgery and skin resurfacing.

Semiconductor Laser:

Principle:

The active medium in a semiconductor laser is a p-n junction diode. It works on the principle of the emission of the recombination energy in the form of light in certain semiconducting materials such as GaAs, GaAlAs, etc. By heavily doping the p-n junction diode and applying a high current density, the stimulated emission of light is produced, and hence, the laser operation is made possible in the semiconductor laser.



Construction:

The p-n junction of a semiconductor laser is prepared using N-GaAs and P-GaAs and they are heavily doped. The height, width and breadth of this laser are 1 mm x 1mm x 1mm respectively. The width of the depletion layer is nearly 1 µm. The upper and bottom surfaces of the p-n junction are used as ohmic contacts. The front and back surfaces are made perfectly parallel to each other. One end is made fully reflecting whereas the other is partially reflecting. The remaining two surfaces are made rough, so as to avoid the leakage of the light through these faces.

Working:

If the diode is forward biased with a voltage equal to the energy gap voltage, cap V equals cap E end subscript sub g over e, then the recombination of the holes and electrons takes place. In order to produce and maintain the stimulated emission continuously, a high current density nearly of the order of 20 kA/cm^2 is applied. Due to the high current density, more number of electrons is injected into the n-region, and more holes are injected into the p-region. The heavy doping of the p-type and n-type regions produces population inversion in the depletion region of the diode. Hence, the continuous emission of light is made possible. Since more charge carriers are injected, this laser is also called an injection laser. The output laser beam emerges from the p-n junction of the partially reflecting surface.

For a GaAs diode laser, $E_g = 1.44\ eV$, therefore the wavelength of the emitted light is

$$\lambda\ = hc/E_g = \frac{6.626\ \times 10^{-3}\ \ \times 3 \times 10^{8}}{1.44\ \times 1.602 \times 10^{-19}} = 862.7\ nm$$

If the single crystalline material is used to prepare the n-type and p-type regions (For example n-GaAs, p-GaAs), then it is known as Homojunction semiconductor Laser. If two different materials are used to n-type and p-type material (n-GaAs, p-GaAlAs), it is known as Heterojunction semiconductor Laser.

Advantages:

- ✓ The diode laser is small in size and low cost.
- ✓ The efficiency of the diode laser is about 10%. The efficiency can be increased up to 100% by lowering the temperature to liquid nitrogen temperature (77K).
- ✓ The output can be tuned to any desired wavelength by varying the band gap of the material.

Disadvantages:

- ✓ Since the size is very small, preparing the cavity resonator is very difficult.
- ✓ The p-n junction width is nearly 1 μm. The laser beam emitted from this junction has a width of nearly 25 to 40 μm. Hence, it has poor coherence and monochromaticity.

Applications:

- ✓ It is mainly used as an optical source in fiber optic communication
- ✓ It is used to read optical discs (i.e. CD, DVD, etc.,)
- ✓ It is used in Laser printers, Laser microscopes, pointing markers
- ✓ It is used for measuring distances of roads and between cars and building height.

Unit - II (LASER) problems

Important Formulae

Divergence of the beam

(1) Angle of divergence $\varphi = \frac{d_2 - d_1}{l_2 - l_1}$ radians

Where d_1 is the diameter of the spot 1 at distance of the spot from the source (l_1)

Where d_2 is the diameter of the spot 2 at distance of the spot from the source (l_2)

(2) Beam divergence $\theta = \frac{\varphi}{2}$

(3) Angular spread of the beam $d\theta = \frac{\lambda}{d}$

Where d is the diameter of the aperture from where laser emits.

(4) Radius of the spread $r = D \times d\theta$

Distance between the source and the screen.

(5) Areal Spread of the beam = $(d\theta \times f)^2$

Where *f* is the focal length of the lens.

(6) Area of the spread = $\pi(D \times d\theta)^2$

Intensity

(1) Intensity of the beam $I = \left[\frac{10}{\lambda}\right]^2 P$

Where P is power of the laser.

λ is the wavelength of the laser.

(2) Intensity of the laser $I = \frac{\text{Power of the Laser}}{\text{Area of cross section of the beam}} = \frac{P}{A}$

(3) Intensity of the laser $I = \frac{\text{Power of the Laser}}{\text{energy of one photon}} = \frac{P}{h\upsilon} = \frac{P\lambda}{hc}$

Efficiency of the laser

Efficiency = $\frac{\text{Power output}}{\text{Power input}}$

Population density

(1) The ratio of population between the two states

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

Where E_1 and E_2 are the energies of the energy levels

N_1 and N_2 are the number of atoms or populations in the energy levels E_1 and E_2, respectively.

(2) The ratio between the stimulated emission to spontaneous emission is given by

$$\frac{\text{Stimulated emission}}{\text{Spontaneous emission}} = \frac{1}{\left(e^{\frac{(E2-E1)}{kT}} - 1\right)} = \frac{1}{\left(e^{\frac{hc}{\lambda kT}} - 1\right)}$$

Wavelength of the emitted light in semiconductor laser

$$\lambda = \frac{hc}{E_g}$$

Where E_g is the band gap of the semiconductor.

Problems

1) A 10 mW laser has a beam diameter of 1.6 mm. What is the intensity of the light assuming that it is uniform across the beam?

Given data:

Power of the laser$P \ = \ 10\, mW = 10 \ \times 10^{-3}\, w$

Diameter of the beam = 1.6 mm

Solution:

Intensity of the laser $I = \frac{\text{Power of the Laser}}{\text{Area of cross section of the beam}} = \frac{P}{A}$

$$I = \frac{P}{\pi r^2} = \frac{10 \ \times 10^{-3}\, W}{3.14 \ \times (0.8 \times 10^{-3}\, m)^2}$$

Therefore, the intensity of the laser is

$$\boxed{\begin{array}{l} I = 4.9761 \times 10^3\ W/m^2 \\ \text{or} \\ I = 4.9761\ kW/m^2 \end{array}}$$

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2) A laser beam of wavelength λ=6000 Å on earth is focused by the lens of diameter 2m on to a crater on the moon. The distance between the moon and the earth is 4 x 10^8 m. How big would the spot on the moon.

Given data:

Wavelength of the laser λ= 6000Å or 6000 x 10^{-10} m

Diameter of the lens d = 2 m

Solution:

Areal spread of the spot on the moon = $(d\theta \times f)^2 = \left(\frac{\lambda}{d} \times f\right)^2$ $\quad$ $As\ we\ know\ d\theta = \frac{\lambda}{d}$

Areal spread of the spot on the moon= $\left(\frac{6000 \times 10^{-10}}{2} \times 4 \times 10^8\right)^2$

Therefore, the size of the spot on the moon $\boxed{= 1.44 \times 10^4\ m^2}$

---

3) A Laser beam has a power of 50 mW. It has an aperture of 5 x 10^{-3} m and wavelength 7000 Å. The beam is focused with a lens of focal length of 0.2 m. Calculate the areal spread and intensity of the image.

Given data:

Wavelength of the laserλ= 7000 Å or 7000 x 10^{-10} m

Power of the laser P = 50 mW

Focal length of the lens f = 0.2 m.

Solution:

(i) Areal spread = $(d\theta \times f)^2 = \left(\frac{\lambda}{d} \times f\right)^2$

Areal spread $= \left(\frac{7000 \times 10^{-10}}{5 \times 10^{-3}} \times 0.2\right)^2$

$\boxed{\text{Areal spread} = 7.84 \times 10^{-10} m^2}$

(ii) Intensity of the image $I = \frac{Power}{Area\ of\ cross\ section\ of\ the\ beam}$

$$I = \frac{50 \times 10^{-3}}{7.84 \times 10^{-10}} = 63.7755 \times 10^6 W/m^2$$

Therefore, the intensity of the image $\boxed{I = 63.7755 \times 10^6\ W/m^2}$

----

4) Calculate the divergence of light beam issuing out by He-Ne laser which produces spot diameters of 4 mm and 6 mm at 1 m and 2 m distances respectively.

Given data:

The diameter (d_1) of the spot at distance 1 m (l_1) = 4 mm = 4 x 10^{-3} m

The diameter (d_2) of the spot at distance 2 m (l_2) = 6 mm = 6 x 10^{-3} m

Solution:

As we know the divergence of the beam $\theta = \frac{\varphi}{2} = \frac{1}{2}\frac{(d_2 - d_1)}{(l_2 - l_1)}$

$$\theta = \frac{1}{2}\frac{(6-4) \times 10^{-3}\ \text{m}}{(2-1)\ m} = 10^{-3}\text{radians}$$

Therefore, the beam divergence is

$$\boxed{\theta = 10^{-3}\text{radians}}$$

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5) A laser beam of wavelength 600 nm is made fall on a wall that lies at a distance of 5 m and if it produces a spot having a diameter of 1 mm, calculate the angular spread and the area of the angular spread.

Given data:

Wavelength of the lightλ= 600nm or 600 x 10^{-9} m

Distance between the source and the screen D = 5 m

Diameter of the spot d = 1 mm

Solution:

(i) Angular spread $d\theta = \frac{\lambda}{d} = \frac{600\times10^{-9}}{1\times10^{-3}}$

$$\boxed{d\theta = 6 \times 10^{-4}\ \text{radian}}$$

(ii) Area of the spread $A = \pi(D \times d\theta)^2 = 3.14 \times (5 \times 6 \times 10^{-4})^2$

$$\boxed{\mathrm{A} = 2.826 \times 10^{-5}\mathrm{m}^2}$$

---

6) A laser beam has a power of 50 mW and it illuminates radiation of wavelength 7000 Å. Calculate the intensity of the light beam.

Given data:

Power of the laser $P = 50\ mW = 50 \times 10^{-3} W$

Wavelength of the lightλ= 7000 Å or 7000 x 10^{-10} m

Solution:

The intensity of the beam $I = \left[\frac{10}{\lambda}\right]^2 P$

$$I = \left[\frac{10}{7000 \text{ x } 10^{-10}}\right]^2 \times 50 \times 10^{-3}$$

Therefore, the intensity of the beam is

$$\boxed{I = 1.0204 \times 10^{13} \frac{W}{m^2}}$$

---

7) A 10 mW He-Ne laser has efficiency of 1%. Assume that all input energy is utilized in pumping the atoms from the ground state to the excited state which is 20 eV above the ground state. Find how many atoms are promoted to the excited state in one second.

Given data:

Output power of the laser = 10 mW = 10×10^{-3}W

Efficiency of the laser = 1% or 0.01

Energy of the excited state = 20 eV.

Solution:

$$\text{Power input} = \frac{\text{power output}}{\text{Efficiency}}$$

$$\text{Power input} = \frac{10 \times 10^{-3}\text{W}}{0.01}$$

$$\text{Power input} = 1\ \text{Wattor}\ \ 1\ \text{Joule}$$

This power input gives us the energy input in one second.

$$\text{Therefore, the number of atoms excited in one second} = \frac{1\ \text{Joule}}{20\ eV} = \frac{1\ \text{Joule}}{20 \times 1.602 \times 10^{-1}}$$

$$\boxed{\text{The number of atoms excited in one second} = 3.311 \times 10^{17}\ \text{atoms/second}}$$

---

8. A He-Ne laser produces an output power of 5 mW. If it emits light of wavelength 632.8 nm, calculate the number of photons emitted by the laser in one second.

Given data:

Output power of the laser = 5 mW = 5×10^{-3}W

Wavelength of the emitted light = $632.8\ nm = 632.8 \times 10^{-9}\ m$

Solution:

$$\text{Number of photons emitted in one second} = \frac{\text{Output power}}{\text{Energy of one photon}} = \frac{P}{(hc/\lambda)}$$

$$= \frac{5 \times 10^{-3}}{\left(\frac{6.626 \times 10^{-3} \times 3 \times 10^{8}}{632.8 \times 10^{-9}}\right)}$$

$$= \frac{5 \times 10^{-3}}{3.1413 \times 10^{-19}}$$

$$\boxed{\text{The number of atoms excited in one second} = 1.5917 \times 10^{16} \text{ photons/second}}$$

---

9. A transition between the energy levels E_2 and E_1 produces a light of wavelength 632.8 nm, calculate the energy of the emitted photons.

Given data:

Wavelength of the emitted light = $632.8\ nm = 632.8 \times 10^{-9}\ m$

Solution:

$$\text{Energy of the emitted photon E} = \text{h}\upsilon = \frac{hc}{\lambda}$$

$$= \frac{6.626 \times 10^{-34} \times 3 \times 10^{8}}{632.8 \times 10^{-9}}$$

$$\text{Energy of the emitted photon } \mathrm{E}_{(\text{Joules})} = 3.1413 \times 10^{-19}\text{J}$$

$$\text{Energy of the emitted photon } \mathrm{E}_{(\text{eV})} = \frac{3.1413 \times 10^{-19}}{1.602 \times 10^{-19}} = 1.9609 \text{ eV}$$

$$\boxed{\text{The energy of the photon emitted E} = 3.1413 \times 10^{-19}\text{J} \quad \text{or} \quad 1.9609 \text{ eV}}$$

---

10. A system has three energy levels E_1, E_2, and E_3. The energy levels E_1 and E_2 are at 0 eV and 1.4 eV respectively. If the lasing action takes place from the energy level E_3 to E_2, and emits a light of wavelength 1.2 μm, find the value of E_3.

Given data:

The value of the first energy level E_1 = 0 eV

The value of the second energy level $E_2 = 1.4$ eV

Wavelength of the emitted light $\lambda = 1.2$ µm $= 1.2 \times 10^{-6}\ m$.

Solution:

The energy of the third energy level can be determined as follows,

The energy of the emitted photon will be equivalent to the difference between the lasing levels.

i.e

$$E_3 - E_2 = \frac{hc}{\lambda}$$

$$\text{The energy of the third energy level } E_3 = E_2 + \frac{6.626 \times 10^{-34} \times 3 \times 10^8}{1.2 \times 10^{-6} \times 1.602 \times 10^{-19}}$$

$$E_3 = 1.4\ eV + 1.0340\ eV$$

$$\boxed{\text{Therefore, the energy of the third energy level } = 2.4340 \text{ eV}}$$

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11. The band gap of GaAsis 1.5 eV. What is the wavelength of the laser beam emitted by the GaAs diode laser.

Given data:

Band gap of the diode laser $E_g = 1.5$ eV

Solution:

The wavelength of the emitted laser beam

$$\lambda = \frac{hc}{E_g} = \frac{6.626 \times 10^{-34} \times 3 \times 10^8}{1.5 \times 1.602 \times 10^{-19}}$$

$$\lambda = 8.2722 \times 10^{-7} m$$

$$\boxed{\text{Therefore, the wavelength of the emitted laser } = 827.22 \text{ nm}}$$

---

12. Calculate the relative population of the energy levels N_1 and N_2 at 300 K, λ = 600 nm.

Given data:

Temperature of the system T = 300 K

Wavelength $\lambda = 600\, nm = 600 \times 10^{-9}\, m$

Solution:

From Maxwell Boltzmann Law, the relative population is given by

$$\frac{N_2}{N_1} = e^{-\frac{(E2-E1)}{kT}} = e^{-\frac{hc}{\lambda kT}}$$

Or

$$\frac{N_1}{N_2} = e^{\frac{hc}{\lambda kT}} = e^{\left(\frac{6.626 \times 10^{-3} \times 3 \times 10^{8}}{600 \times 10^{-9} \times 1.38 \times 10^{-23} \times 300}\right)}$$

$$\frac{N_1}{N_2} = e^{\frac{hc}{\lambda kT}} = e^{(80.0242)}$$

$$\frac{N_1}{N_2} = 5.6763 \times 10^{34}$$

The relative population between N_1 and N_2 is 5.6763×10^{34}

---

13. Estimate the possibility of stimulated emission at 300 K and λ=600 nm.

Given data:

Temperature of the system T = 300 K

Wavelength $\lambda = 600\, nm = 600 \times 10^{-9}\, m$

Solution:

The ratio between the stimulated emissions to the spontaneous emission is given by,

$$\frac{\text{Stimulated emission}}{\text{Spontaneous emission}} = \frac{1}{\left(e^{\frac{(E2-E1)}{kT}} - 1\right)} = \frac{1}{\left(e^{\frac{hc}{\lambda kT}} - 1\right)}$$

$$\frac{\text{Stimulated emission}}{\text{Spontaneous emission}} = \frac{1}{e^{\left(\frac{6.626\times10^{-3}\ \times3\times10^{8}}{600\ \times10^{-9}\times1.38\times10^{-23}\times300}\right)} - 1}$$

$$= \frac{1}{e^{(80.0242)} - 1} = 1.7617\ \times 10^{-35}$$

The ratio between the stimulated emissions and spontaneous emission is $1.7617\ \times 10^{-35}$. The stimulated emission is possible only after approximately 10^{35} times spontaneous emission. Under such conditions, the laser action is impossible to occur.