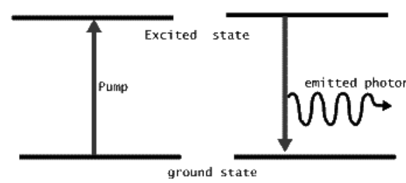
Unit IV LASERS

LASER is the acronym for Light Amplification by Stimulated Emission of Radiation. It is evident that the process of stimulated emission is the key to a LASER system. Einstein analyzed the interaction of radiation with matter and brought out the concept of stimulated emission.

Interaction of radiation with matter – Einstein's coefficients

The interaction of radiation with matter can be explained by the three processes namely

- Induced absorption (stimulated absorption)
- spontaneous emission and
- Stimulated emission.



In the induced absorption process an atom in the ground state / lower energy state (E_1) absorbs radiation and is excited to the higher state (E_2). The rate of absorption is dependent on the population of the ground state N_1 / lower energy state and the energy density of radiation (ρ(hν)) of the appropriate frequency such that E_2-E_1= hν. The rate of induced absorption $\boldsymbol{R_{ind\ abs} = B_{12} * N_1 * \rho(\nu)}$

An atom in the higher energy / excited state cannot normally remain in the excited state for a long time and generally de excites to the lower energy state spontaneously. The lifetimes of the excited states are generally of the order of nanoseconds. The rate of spontaneous emission is dependent on the population of atoms in the excited state N_2 only and = $\boldsymbol{R_{sp\ em} = A_{21} * N_2}$

If the process of spontaneous emission is predominant we can infer that $\boldsymbol{R_{sp\ em} = -\frac{dN_2}{dt} = A_{21} * N_2}$.

From this we can infer that $\boldsymbol{N_2 = N_2(0)e^{-A_{21}t}}$ and the Einstein's co-efficient for spontaneous emission can be understood to be $\boldsymbol{A_{21} = \frac{1}{\tau}}$ where τ is the average life time of electrons in the upper energy state for spontaneous emission.

An atom in the excited state can over stay for longer periods of time. Such states have a higher life time of the order of milliseconds and are referred to as meta stable states. Such excited atoms have to be stimulated to return to the lower energy state with an external intervention in the form of a photon whose energy is equal to E_2-E_1. In this process the energy of the excited atom is released as a photon whose characteristics remain the same as that of the stimulating photon. The rate of stimulated emission is then dependent on the population of atoms in the excited state and the energy density of radiation is given by $\boldsymbol{R_{st\ em} = B_{21} * N_2 * \rho(\nu)}$

where A_{21}, B_{12} and B_{21} are the Einstein's coefficients.

When the material is in thermal equilibrium with the radiation, the rate of absorption should be equal to the rates of emission due to different processes ie., $\boldsymbol{B_{12} * N_1 * \rho(\nu) = A_{21} * N_2 + B_{21} * N_2 * \rho(\nu)}$

This gives $$\boldsymbol{\rho(\nu)(B_{12} * N_1 - B_{21} * N_2) = A_{21} * N_2}$$

$$\boldsymbol{\rho(\nu) = \frac{A_{21} * N_2}{(B_{12} * N_1 - B_{21} * N_2)} = \frac{{A_{21}}/{B_{21}}}{\left(\frac{B_{12} * N_1}{B_{21} * N_2} - 1\right)}}$$

The distribution of electrons in the energy states are described by the Maxwell Boltzman distribution laws and gives $\frac{N_1}{N_2} = exp^{\frac{(E_2-E_1)}{kT}} = exp^{\frac{h\nu}{kT}}$. Substitution of this in the above equation gives the expression for the energy density of radiation at any frequency and temperature as

$$\rho(\nu) = \frac{A_{21} * N_2}{(B_{12} * N_1 - B_{21} * N_2)} = \frac{A_{21}/B_{21}}{\left(\frac{B_{12}}{B_{21}} exp^{\frac{h\nu}{kT}} - 1\right)} \qquad (1)$$

Comparing this with the Planck's expression for energy density of radiation

$$\rho(\nu) = \frac{8\pi h\nu^3}{c^3} \frac{1}{\left(exp^{\frac{h\nu}{kT}} - 1\right)} \qquad (2)$$

we observe that $A_{21}/B_{21} = \frac{8\pi h\nu^3}{c^3}$ and $\frac{B_{12}}{B_{21}} = 1$. This implies that $B_{12} = B_{21} = B$ i.e., the induced absorption coefficient is equal to the stimulated emission coefficient and the ratio of the coefficient of spontaneous emission to the coefficient of stimulated emission is proportional to ν^3.

The ratio of the rate of stimulated emission to the rate of spontaneous emission $= \frac{B*N_2*\rho(\nu)}{AN_2} = \frac{\rho(\nu)}{\frac{A}{B}} \approx \frac{N_2}{N_1}$.

This implies that the rate of stimulated emission will be predominant over rate of spontaneous emission if $N_2 > N_1$ or the population of the higher energy state is higher than the lower energy state.

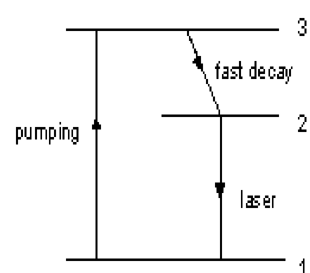
Conditions for the lasing action

The basic requirement for light amplification to occur is that the stimulated emission is the predominant emission mechanism over the spontaneous emission mechanism which is the natural response of a system.

From the discussion it is evident that stimulated emission is possible when the upper energy state has a higher population of occupation than the lower energy state. For a two level laser system this requires $N_2 > N_1$ or population inversion has to be established between the higher and lower energy states. But from the MB distribution function we find that $\frac{N_1}{N_2} = exp^{\frac{h\nu}{kT}}$ >1 which implies that T has to be negative if N_2 has to be greater than N_1. Or it is not possible to obtain population inversion between E_2 and E_1 in a two level system. Hence it may not be possible to get a LASER beam from absorption and emission between two energy levels or it is not possible to get a LASER if the same levels are involved in both the emission and absorption process.

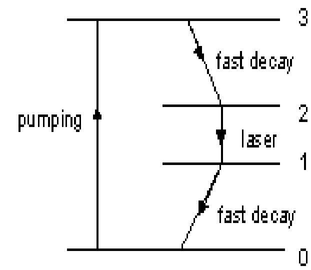
Three level systems:

The introduction of an intermediate level between the ground state and the upper excited state can result in decoupling the emission process and absorption process levels. The absorption process is between the ground state E_1 and the upper excited state E_3. The electrons from the upper energy state decays non radiatively to the intermediate meta stable state E_2. If this state is a meta stable state (life time of the electrons $\approx 10^{-3}$



seconds), electrons can accumulate in this state and the population of electrons in the meta stable state could be higher than the population of the ground state in a very short time resulting in a favorable condition for stimulated emission from E_2 to E_1. However, the drawback is that the ground state is quickly depleted resulting in a discontinuous phenomenon of stimulated emission. Generally three level systems give a pulsed LASER. This is because the ground state is still a common factor in the absorption and emission process.

Four level systems:

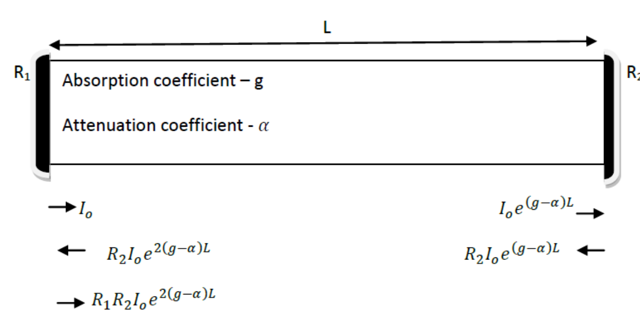


A four level system can effectively decouple the absorption levels and the emission levels. In a four level system the absorption is between the lower (ground) state E_1 and the higher excited state E_4. The electrons in the excited state decays non radiatively to the intermediate meta stable state E_3. The electrons are stimulated to transit to a lower energy state E_2 (above E_1). Finally the electrons from the level E_2 fall back to the ground state maintaining the population of the lower E_1 so that the process of excitation can continue. The absorption is between E_1 and E_4 whereas the stimulated emission is between E_3 and E_2. Thus the energy states in the two processes are completely decoupled. In this way the system can behave in a continuous mode and can produce a continuous LASER.

Basic requirements of a laser system

1. **Active medium –** The active medium consists of the medium which possess the appropriate energy levels which are meta stable states. The presence of the meta stable states increases the probability of population inversion which is a prime condition for laser action. The active medium could be solids, liquids or gases depending on the type of lasers.
2. **Energy pump –** The constituents of the active medium have to suitably excited to the lasing high energy state from an external energy source. The external energy sources could be optical, thermal, electrical or chemical depending on the type of lasers. In the case of gas lasers, generally an electrical discharge is a sufficient source for exciting the medium.
3. **Resonating Cavity –** Once the lasing action is initiated it is essential that the stimulated emission in the desired wavelength is amplified to get a sustainable laser action of sufficient intensity. The design of the optical cavity is an important aspect of the laser system. In general the optical cavity has to be a narrow region whose length in the direction of propagation is a multiple of the desired wavelength. This also helps in eliminating undesired wavelengths which may be present in the lasing process and increase the monochromaticity of the system.

Round trip gain in a laser medium



The stimulated emission in the medium provides for gain with a optical feedback mechanism of reflecting mirrors on both ends of the cavity. This arrangement results in multiple travel of the trapped optical beam in the medium and ideally the beam should have a high intensity after few reflections. The gain of photons as the beam progresses is given by the intensity increasing as $\boldsymbol{I = I_o e^{gx}}$ where g is the gain coefficient.

However, there could be also losses in the medium due to absorption, scattering and the partial transmission from one of the mirrors. The reduction in the intensity due to scattering and absorption is described by $\boldsymbol{I = I_o e^{-\alpha x}}$ where $\boldsymbol{\alpha}$ is the loss coefficient.

In order to reach a steady-state with non zero intensity (oscillation) the gain due to stimulated emission must be sufficient to overcome these losses.

If I_0 is the starting intensity of photons from the mirror on one end, then the intensity after one round trip gain (a distance of 2L with the starting point as reference) is given by $\boldsymbol{I = I_0 R_1 R_2 e^{2(g_o - \alpha)L}}$

The amplification factor is then the ratio of the output intensity to the input intensity and should be equal to $R_1 R_2 e^{2(g_o - \alpha)L}$.

If $\boldsymbol{R_1 R_2 e^{2(g_o - \alpha)L}} > 1$, oscillations can build up and the laser is said to be above the threshold. The threshold of laser oscillations is then defined by $\boldsymbol{R_1 R_2 e^{2(g_o - \alpha)L} = 1}$

$$\boldsymbol{g_{th} = \frac{1}{2L}(2\alpha L - \ln(R_1 R_2))}$$

This implies that the gain of the system is dependent on the length of the cavity and the reflection coefficients of the two mirrors.

Properties of a LASER beam.

The most important properties of a LASER are attributed to the stimulated emission of photons (BOSONs which display identical properties)

- **Monochromaticity (spectral line broadening):** Light from a laser typically comes from an atomic transition with a single precise wavelength. So the laser light has a single spectral color and is almost the purest monochromatic light available. However, the laser light is not truly monochromatic. The spectral emission line from which it originates does have a finite width, if only from the Doppler Effect of the moving atoms or molecules from which it comes. Since the wavelength of the light is extremely small compared to the size of the laser cavities used, then within that tiny spectral bandwidth of the emission lines are many resonant modes of the laser cavity. The emission line widths are also limited by the uncertainty principle which limits the accuracy of the energy (ΔE) of the photons emitted by electrons which spend times with a spread in time (Δt). Generally LASER line widths are very small of the order of 10^{-6} Å as compared to 1 Å for ordinary monochromatic sources.
- **Coherence** - Coherence is a unique property of laser light. In the stimulated emission process triggered by a common, the emitted photons are "in phase" or have a definite phase relation to each other. This coherence is essential to produce high quality interference, which is used to produce holograms.

  Ordinary light is incoherent because it comes from independent atoms, which emit on time scales of about 10^{-8} seconds. There is a degree of coherence in sources like the mercury green line and some other useful spectral sources, but their coherence does not approach that of a laser.

Coherence can be of two types' temporal coherence and spatial coherence.

- **Temporal coherence** refers to the correlation between the field at a point and the field at the same point after an elapse of time. If the phase difference between the two fields is constant during the period (of the order of micro seconds), the wave is said to have said to have temporal coherence. If the phase difference changes many times and in an irregular way during the period of observation, the wave is said to be non-coherent.

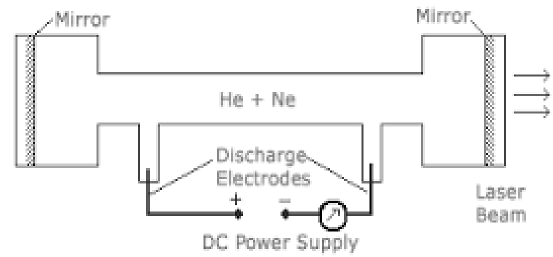
  Temporal coherence is characteristic of a single beam of light. The temporal coherence is evaluated as $\tau_c = \frac{1}{\Delta\nu}$ where $\Delta\nu$ is the spread in the frequency. The coherence length defines the largest distance for which interference can be well defined and is given by $l_c = \tau_c . c$ where c is the velocity of light.

  The length in which the coherence exists may be of the order of kilometers for LASERs compared to few centimeters for ordinary light.

- **Spatial coherence -** Two fields at two different points of a wave front is said to be spatially coherent if they preserve a constant phase difference over any time t. Two beams of light originating from different parts of a source will have been emitted by different groups of atoms. Each beam will be time incoherent and will have random phase changes. Two such beams are said to be spatially incoherent and the interference pattern produced by these will have a poor visibility. When visibility of the interference pattern as a function of the size of the source then we have spatial coherence and is described by the coherence width $l_w \approx \frac{\lambda}{\theta}$.

- **Divergence** (directionality) – LASER is characterized by a very low divergence which ensures that the beam profile is small over long distances. The divergence of a LASER beam is given by $\theta = \frac{\lambda_o}{\pi\omega_o}$ where λ_o is the wavelength, and ω_o is the spot size. Typically the divergence is of the order of mill radians (0.001^o.) A common lab laser beam of a wavelength of 532nm and a radius of 1mm on the surface of the earth would have a diameter of 6.10 km on the surface of the moon. (θ = (2/π) * (532 e-9 / 2* 10^{-3}) = 1.7 *10^{-4} This is then multiplied by the distance to the moon (3.844 *10^8 m), which gives the spot size to be 61000 m.)
- **Intensity** – The high intensity of a Laser arises out of the properties of monochromaticity, coherence and low divergence. Typically very low power LASERs of about 1 to 2mW output with a beam diameter of 1 mm can result in an intensity of about 10 kW/m^2 as against a intensity of 10W/m^2 produced by a 20W bulb.

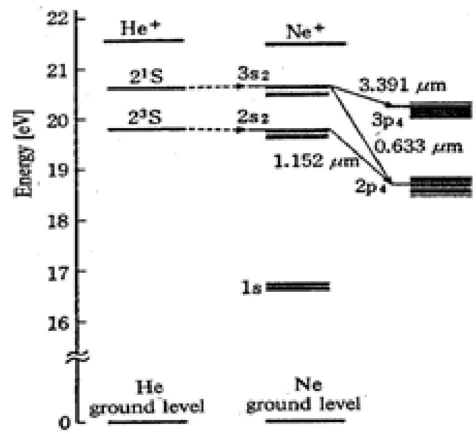
He Ne LASER



Active medium: The HeNe LASER is a atomic species laser where the active medium is the HeNe gas mixture contained in a quartz tube of narrow diameter and maintained at a low pressure which forms the active medium.

Energy pump: The energy pump is enabled by maintaining an electrical discharge across the length of the Quartz tube by either a high voltage DC source or a RF source.

Resonant cavity: The cavity is the Quartz tube of appropriate lengths with reflecting mirrors on both ends of the axis of the tube. Additional polarisers may be placed in the path of the beam to ensure a polarized beam of LASER.



He and Ne mixed in the ratio of 10:1 is the active medium where the absorption levels are in the He atoms and the lasing levels are in the Ne atomic transitions. The He atoms are excited with an electrical discharge and the two excited states of helium atom, the 2 ^{3}S and 2 ^{1}S which are Meta stable. These excited He atoms transfer their energy to Ne atoms by collisions and the excites the Neon atoms to the $2s_2$ and $3s_2$ levels as the energy levels of these states are close to the He excited states. (This process is referred to resonant energy transfer.)

A large number of Ne atoms due to collision with He atoms get to the excited state create a population inversion with the ground state. The excited states of Ne are not meta stable and hence de-excites to the ground states through the intermediate states of 3p and 2p. The transition between the 3s to the 2p intermediate states gives the characteristic red laser of Ne with a wavelength of 632.8 nm. The transitions from the 3s to 3p and 2s to 2p lines give rise to radiations with wavelengths in the Infra red of 3.39 micrometers and 1.152 micrometers.

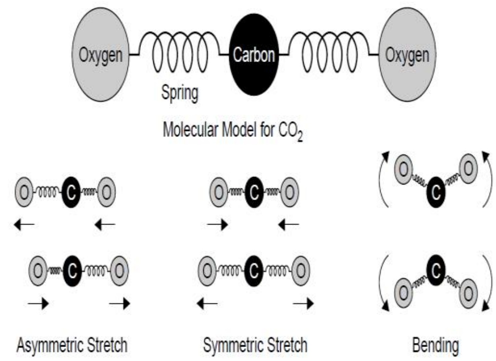
The transitions from the 3p and 2p levels to the 1s intermediate level (close to the ground state) is non radiative. However this is a meta stable state and has to be quickly depopulated. This is achieved by making the tube narrow enabling collisions of the atoms with the sides of the walls of the tube.

Once in the ground state the Ne atoms are pumped back and the system gives a continuous output.

The cavity consists of reflecting mirrors and the path length adjusted for the visible radiation at 632.8 nm, which also suppress the IR radiations. Additionally some gases which have absorption in the Infra red are added in small quantities to suppress the IR radiations.

Light from the system can be partially polarized (the polarization state of the stimulating photon). The addition of Brewster's windows at the ends of the discharge tube before the reflecting mirrors would ensure that the emitted beam would be fully polarized in the plane of incidence. However the addition of the Brewster's window would eventually lead to a reduction in the output by a factor of 40% to 50%.

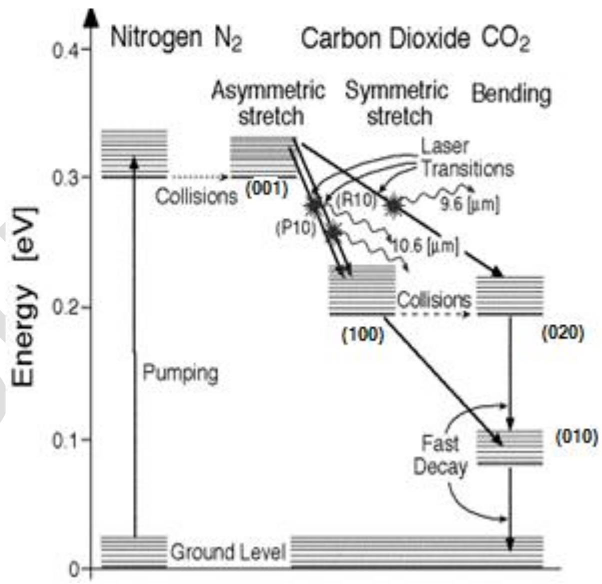
Carbon dioxide laser



The carbon dioxide laser is a high power gas laser with immense industrial applications.

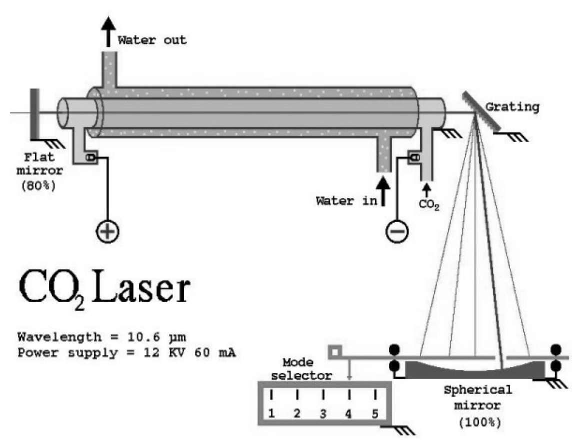
In the CO_2 molecule, the Oxygen atoms are bound to the Carbon atom by the bonding force which acts like a harmonic oscillator. Molecules can be excited to vibrate about their mean positions. Additionally the molecules may rotate and spin because they are in a gaseous state. The rotational and vibrational states are quantized.

Transitions between vibrational energy states/levels results in photon emission in the infrared, while transitions between rotational states emit photons in the microwave region.



If the CO_2 molecules are excited and made to relax they emit in the infra red producing heat. This mode of emission could be mimicked to a **stimulated emission** if the population of molecules in the excited states is greater than the population in the ground state, thus creating a LASER with infra read wavelengths.

Carbon dioxide molecule has three possible vibrational states – an excited asymmetric stretch (001 state), a lower symmetric stretch (100 state) and bending states(020 and 010 states). The asymmetric stretch states have a higher life time (molecular excited states have higher life times of the order of 1ms to a fraction of a second) and higher energy than the symmetric and bending modes. An excited carbon dioxide molecule in the higher anti symmetric stretch state can relax into the symmetric stretch state giving a radiation at 10.6 µm (0.117eV) and into the bending mode with emission of IR at 9.6 µm (0.129 eV).



Construction and Principle of Operation

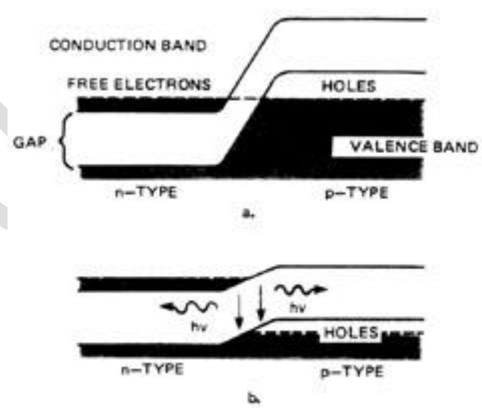
All lasers consist of three components: a gain (or laser) medium, an energy source (also known as a pump) and an optical resonating cavity. The three components of a Carbon dioxide laser system comprise of :

- **THE ACTIVE MEDIUM -** A mixture of carbon dioxide, nitrogen, and helium gases serve as the gain medium. Typical gas mixtures have an CO_2: N_2: He ratio of 1:2:8. The N_2 molecules are excited with energy close to the excited states of CO_2 which results in the excitation of CO2 to the asymmetric stretch mode.

- **THE ENERGY PUMP** - **Electrical discharge current** — serving as the laser pump — which excites the gas medium to higher energy states through the electrical discharge of the He gas, which collides with the N_2 gas to excite them into the higher energy states.
- **OPTICAL CAVITY** - A **specialized optical resonator**. Because CO_2 lasers operate solely within the infrared spectrum and can attain high power outputs, their optical components are typically made of specialized (and often expensive) materials such as Germanium, Zinc Selenide, Silver, Gold, and Diamond. Since the CO_2 lasers work in the Infra red region all parts connected with the laser cavity have to have suitable infra red absorption coatings and an effective cooling system is required for the system as a whole. The hot helium atoms must then be cooled to maintain a population inversion (a sufficient difference between excited and lower energy atoms to produce optical gain) with the excited carbon dioxide molecule.

Homo junction Semiconductor lasers

Light emitting diodes work on the principle of recombination of electron and holes in the depletion region of a pn junction diode which result in the emission of a photon. The photon emission in this case is highly non coherent and has no directionality.



To convert a LED into a laser it is essential conditions of population inversion in the depletion region, stimulated emission and a resonating cavity are satisfied.

Semiconductor lasers use heavily doped direct band gap semiconductors like GaAs which is the active medium. The heavy doping results in an extremely thin depletion region and, moves the Fermi level of the n type into the conduction band and the Fermi level of the p type into the valence band.

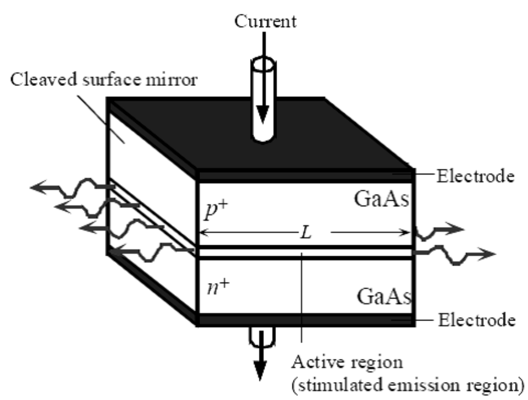
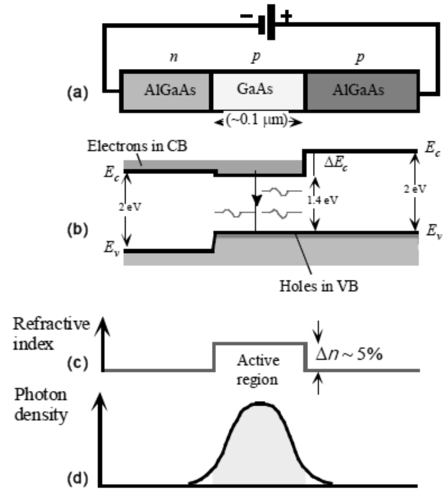


Figure 1a shows the depletion region of a heavily doped PN junction in the unbiased condition where the in electrons and holes are present in the "depletion region", however they are not in a favorable state for recombination.

When a large forward bias is applied to the PN junction, which is the energy pump, large number of electrons in the n side and holes in the p side are in a favorable state for recombination in a narrow energy band. This recombination result in the generation of photons in the depletion region. This emission is of the stimulated type. A suitably designed laser cavity with appropriate dimensions and cleaving the surface carefully for maximum reflection, results in the emission of laser along the direction with 98% reflection.

The homo junction lasers are not very efficient and require a very high forward current density of the order of 10000 A cm^{-2} at room temperature and hence are operated at very low temperatures or in the pulsed condition.

Heterojunction lasers.



The problems in a homojuction laser can be overcome with the design of a hetero junction laser. The double heterojunction device ensures higher efficiency by

1. ***Carrier confinement:*** Confine the injected electrons and holes to a narrow region about the junction. This requires less current to establish the required concentration of electrons for population inversion. A double hetero structure diode has two junctions which are between two different band gap semiconductors (GaAs and AlGaAs).
2. ***Photon confinement:*** Construct a dielectric waveguide around the optical gain region to increase the photon concentration and increase the probability of stimulated emission. The n and p type AlGaAs on either side have higher refractive index and hence This reduces the number of photons lost traveling off the cavity axis

Single hetero junction lasers require a current density of about 1500 A cm^{-2} whereas double hetero junction lasers operate at lower currents of 600 A cm^{-2}.

Practical hetero junction lasers however consist of many layers to improve the efficiency of the carrier and photon confinements and operate at much lower operating currents.

Problem set

1 The ratio of the population of two energy levels is 1.5 x 10^{30}. The upper level corresponds to a meta stable state. Find the wavelength of light emitted at 330K (**Ans 628 nm**)

2 An hypothetical atom has energy levels uniformly separated by 1.2 ev. Find the ratio of the no of atoms in the 7th excited state to that in the 5th excited state. (**Ans: 5.22 x 10^{-41}**)

3 A pulsed laser has a power of 1mW and lasts for 10 ns. If the no. of photons emitted per second is 3.491 x 10^7, calculate the wavelength of the photons.(**Ans: 693 nm**)

4 If R_1 is the rate of stimulated emission and R_2 is the rate of spontaneous emission between two energy levels, show that $\lambda = hc / [kT \ln\{(R_2/R_1)+1\}]$.

5 Find the ratio of the rate of stimulated emission to the rate of spontaneous emission for a system emitting a wavelength of 632.8 nm at 300K. (**Ans : 1.11 x 10^{-33}**)

6 If B_{10} = 2.7 x $10^{19}$$m^3$/W-$s^3$ for a particular atom, find the life time of the 1 to 0 transition at (a) 550nm and (b) 55nm (answer: (a)370ns (b) 0.37ns)

7 The energy levels in a two-level atom are separated by 2eV. There are 3 x 10^{18}atoms in the upper level and 1.7 x 10^{18} atoms in the ground level. The coefficient of stimulated emission is 3.2 x 10^5 m_3/W-s^3 and the spectral radiance is 4 W/m^2-Hz. Calculate the stimulated emission rate?

8 For an ordinary source, the coherence time τ_c = 10^{-10} second. Obtain the degree of non-monochromaticity for wavelength λ_0 = 5400 Å.

9 Calculate the coherence length of a laser beam for which the band width $\Delta\nu$ = 3000 Hz.

10 The lifetime of transitions in a Na atoms emitting wavelength of 589.6nm is estimated to be 16.4ns. Calculate Einstein's coefficients A and B. Calculate spectral broadening and the coherence length of radiations.

11 The spectral line width of a HeNe laser emitting 632.8 nm is 10^{-16} m. Calculate Einstein's coefficients A and B and the coherence length of radiations.

12 Calculate the threshold gain factors of a helium–neon laser, which has a loss factor of 0.05 m^{-1} if the configuration of the system is as follows:

(a) A 50-cm tube with one mirror 99% reflecting and the output coupler 90% reflecting

(b) A 20-cm tube with one mirror 99% reflecting and the output coupler 95% reflecting

(c) A 20-cm tube with one mirror 99% reflecting and the output coupler 97% reflecting

Comment on the results obtained.