UNIT 3

PHYSICS OF LASER BEHIND PHOTONIC COMPUTING

3.0 FUNDAMENTALS OF LASER

Laser - a device that stimulates atoms or molecules to emit light at particular wavelengths and amplifies that light, thereby producing a very narrow beam of radiation. The emission generally covers an extremely limited range of visible, infrared, or ultraviolet wavelengths. *LASER* is an acronym for "light amplification by the stimulated emission of radiation".

3.1 Conditions for laser action

Laser action means the amplification of light by stimulated emission of radiation. To get laser action, it is necessary to have

(i) Stimulated emission.

(ii) There should be population inversion of atoms.

(iii) There should be a stimulating photon.

Population inversion

Stimulated emission of light can be produced through maintaining the population inversion, where there will be more number of atoms unit volume (N_2) in the higher energy level (E_2) than the other lower energy level (say E_1) between which the lasing action takes place; let N_1 represents the number of atoms / unit volume in E_1.

Then, Population Inversion represents $E_2 > E_1$ and $N_2 > N_1$which is possible under non-thermal equilibrium by pumping the atoms from lower energy level to higher energy level.

Optical Pumping

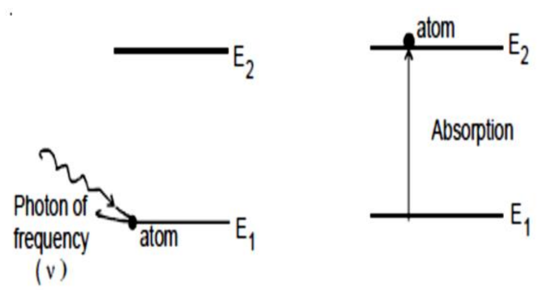


Fig. 3.1 Optical Pumping

The atoms in the lower energy level E_1 are made to go to the upper energy level E_2 by pumping technique, where, by absorbing a photon of frequency $\nu = (E_2 - E_1)/h$, the atom in lower energy level E_1, goes to the upper energy level E_2. The rate of absorption depends on the number of atoms present in the level E_1 and density of photons in the system (Fig.3.1).

Different pumping techniques such as optical pumping, chemical pumping, etc are available.

3.1.2. Spontaneous emission and stimulated emission

Spontaneous Emission

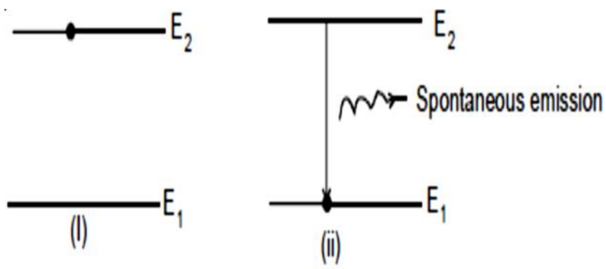


Fig. 3.2 Spontaneous Emission

Stimulated Emission

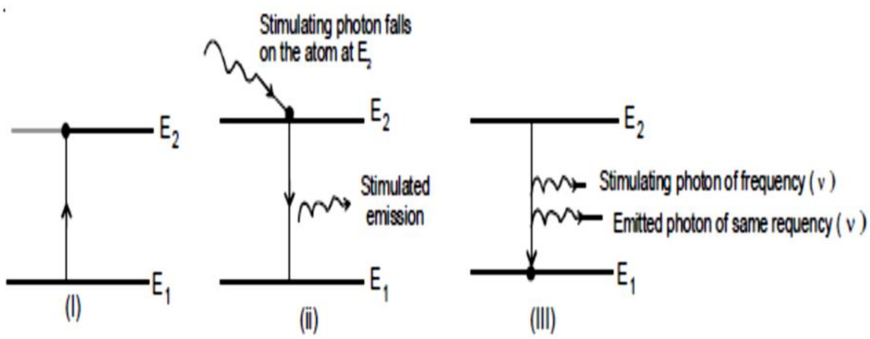


Fig. 3.3 Stimulated Emission

The atom in the exited level can come to the ground level either by spontaneous emission or bystimulated emission.

In spontaneous emission (Fig. 3.2), the atom in energy level E_2 make the transition to the lower energy level E_1 spontaneously without the help of any external agent and it emits a photon whose energy isequal to (E_2-E_1). The rate of emission depends on the number of atoms present in the higher energylevel.

Characteristics of photons emitted by spontaneous emission are polychromatic radiation, low intensity, incoherent, large divergence.

In stimulated emission (Fig.3.3), the atom in higher energy level E_2 can make a transition to the lower energy level E_1 with the help of an external photon of frequency, $(E_2 - E_1)/h$, where the stimulating photon and the emitted photon are in same phase with the same energy and they travel in the same direction. Characteristics of photons emitted by stimulated emission are monochromatic radiation, high intensity, coherent and high directionality

3.2 EINSTEIN'S COEFFICIENTS, RELATION BETWEEN SPONTANEOUS AND STIMULATED EMISSION PROBABILITY

3.2.1 *Excitation*

The Bohr's atom model expresses that the electrons are distributed in the permitted energy levels/orbits. The lowest energy level that occupied by electrons is ground state/lower energy state of the atom.

If the electron belongs to lower energy state absorbs the energy to reach the next higher energy level/state is known as Excitation /absorption. Then the energy required for excitation of atom is $E_2 - E_1 = hv$ where E_2 is the energy of excited state of electron in a atom and E1 the energy of ground state of electron in the same atom. This process is called excitation. The rate of excitation is directly proportional to number of atoms (N_1) in energy state E_1 and the energy density (Q) of incident radiation.

$$N_{ab} \infty N_1 Q$$

Therefore, the number of excitations occurring per unit time is given by $N_{ab} = B_{12} N_1 Q$

where $B_{12}$is a proportionality constant.

3.2.2. *Spontaneous emission*

Spontaneous emission is a continuous process. Since, the life time of excited electron at higher energy state is less (in the order of nano seconds), the electrons from higher energy could release the energy that gained during excitation by some mechanism and make the whole atom to get the excitation. The energy released will be $E_2 - E_1 = hv$

If the energy released is continuous in the form of radiation, which does not follow unique wave length then it must be due to spontaneous emission, The rate of spontaneous emission is directly proportional to the number of atoms in the excited energy state (N_2).

$N_{sp} \infty N_2$

Hence the number of transitions per second is given by $N_{sp} = A_{21} N_2$ (2)

Where

A_{21} is proportionality constant. This process is a **downward transition**.

3.2.3. Stimulated emission

Stimulated emission is a controlled de excitation. If the energy released in de excitation is controlled in the presence of some energy which is used for the excitation. This situation causes controlled emission of radiation following the unique wave length known as stimulated emission.

The rate of transition is directly proportional to the number of atoms in the upper energy level and the energy density of incident radiation.

$N_{st} \propto N_2Q$

The number of transitions per second $N_{st} = B_{21}N_2Q$ (3)

Where B_{21} is proportionality constant. This process is a **downward transition**.

The proportionality constants A_{12}, B_{12} and B_{21} are known as Einstein's coefficients A and B.

Under equilibrium condition, the number of downward and upward transitions per second is equal.

ie., $N_{sp} + N_{st} = N_{ab}$ (4)

Substituting from the eqns 1, 2 and 3, in eqn 4 we have,

$$A_{21} N_2 + B_{21} N_2 Q = B_{12} N_1 Q \quad (5)$$

Rearranging eqn 5 we have

$$B_{12} N_1 Q - B_{21} N_2 Q = A_{21} N_2$$

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

$$Q = A_{21} N_2/(B_{12} N_1 - B_{21} N_2) \quad (6)$$

Dividing numerator and denominator by $B_{21} N_2$, we have

$$Q = A_{21}/B_{21} \text{ x } 1/ (B_{12}/B_{21})(N_1/N_2) - 1 \quad (7)$$

On substituting $N_1/N_2 = e^{h\nu/kT}$ in eqn (7) we have

$$Q = A_{21}/B_{21} \text{ x } 1/ (B_{12}/B_{21})(e^{h\nu/kT}) - 1 \quad (8)$$

Planck's radiation formula for energy distribution is given by

$$Q = 8h\pi\nu^3/c^3(e^{h\nu/kT}) - 1 \quad (9)$$

Comparing the eqns (8) and (9),we have

$$B_{12}/ B_{21} = 1$$

$$B_{12} = B_{21} \quad (10)$$

and $A_{21}/ B_{21} = 8h\pi\nu^3/c^3$ (11)

Conclusion

The spontaneous emission is more predominant than the stimulated emission. The LASER light is due to stimulated emission. Therefore stimulated emission should be greater than spontaneous emission. To achieve this, population inversion is required.

The equation (11) gives the relation between spontaneous emission and stimulated emission coefficients. Since the ratio is proportional to ν^3, the probability of spontaneous emission increases with the energy difference between the two states.

3.3 LASER STRUCTURE

The important parts of a laser are- active medium, pumping system and laser resonator (Fig.3.4). Laser radiation is generated by stimulated transitions in an active medium. The active medium is a gain medium— propagation of radiation in the active medium results in an increase of the energy density of the radiation. The active medium in laser experience feedback from radiation stored in a laser resonator. A portion of radiation coupled out from the resonator represents the useful radiation. Part wise description is given below.

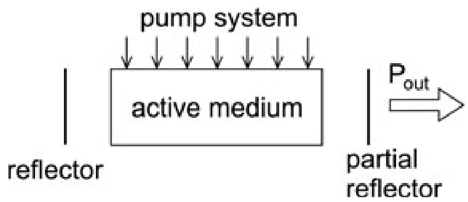


Fig. 3.4 Laser structure

- *Active medium* (the gain medium of the laser medium)- The active medium is able to amplify electromagnetic radiation. The active medium, located inside a resonator, fills out a resonator partly or completely. It is either a collection of atoms, molecules or ions of a solid, liquid,gas , semiconductor junction which is capable of sustaining the stimulated emission.

- *Pumping system*- It "pumps" the active medium and causes the population inversion between two energy levels. Methods of pumping are: optical pumping with another laser or a lamp; pumping with a gas discharge; pumping with a current through a semiconductor or a semiconductor heterostructure; chemical pumping.

- *Laser resonator*. The laser resonator has the task to store a coherent electromagnetic field and to enable the field to interact with the active medium — the active medium experiences feedback from the coherent field. The most common type of laser uses feedback from an optical cavity—a pair of mirrors on either end of the gain medium. Light bounces back and forth between the mirrors, passing through the gain medium and being amplified each time. Typically, one of the two mirrors, the output coupler, is partially transparent. Some of the light escapes through this mirror. Depending on the design of the cavity (whether the mirrors are flat or curved), the light coming out of the laser may spread out or form a narrow beam. Most practical lasers contain additional elements that affect properties of the emitted light, such as the polarization, wavelength, and shape of the beam.

3.4. LASER MATERIAL

Active medium is a medium where the actual laser action takes place. The medium may be a gas medium / a liquid medium / a solid medium.

Solid –

Certain crystals, typically doped with rare earth ions (e.g. neodymium, ytterbium, or erbium) or transition metal ions (titanium or chromium); most often yttrium aluminium garnet ($Y_3Al_5O_{12}$).

Glasses, e.g. silicate or phosphate glasses, doped with laser-active ions.

Semiconductors, e.g. gallium arsenide (GaAs), indium gallium arsenide (InGaAs), or gallium nitride (GaN).

Gases, e.g. mixtures of helium and neon (HeNe), nitrogen, argon, carbon monoxide, carbon dioxide, or metal vapors.

Liquids, in the form of dye solutions as used in dye lasers.

3.5. FIBRE LASER

Fiber lasers are usually meant to be lasers with optical fibers as gain media. In most cases, the gain medium is a fiber doped with rare earth ions such as erbium (Er^{3+}), neodymium (Nd^{3+}), ytterbium (Yb^{3+}), thulium (Tm^{3+}), or praseodymium (Pr^{3+}), and one or several fiber-coupled laser diodes are used for pumping. Therefore, most fiber lasers are *diode-pumped lasers*.

In comparison with other solid state lasers, fiber lasers are flexible and simple with respect to adjustment (or may not need adjustment at all).
The active medium of a fiber laser is a glass that is doped with rare earth ions.
The main features of a fiber laser (Fig. 3.5)-
• *Glass fiber* (length 1–10 m, or longer; diameter 5 μm), doped with ions.
• *Dichroitic end mirror*. It is highly reflecting for the laser radiation and transparent for the pump radiation.
• *Output coupling mirror*. In order to reach optimum efficiency, the reflectivity of the output coupling mirror is chosen appropriately.
• A fiber laser can be pumped with a semiconductor laser.
Fiber lasers are available in the 0.7–3 μm wavelength range. Rare earth ions in a

glass occupy sites of different strength of the crystalline electric field.

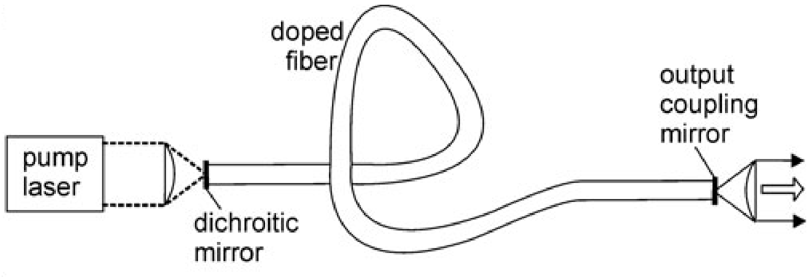


Fig. 3.5 Fibre laser

Operation of a fibre laser

In fibre laser the pumping is done using laser diodes. These diodes emit light that is sent into the fiber-optic cable. Optical components located in the cable are then used to generate a specific wavelength and amplify it. Finally, the resulting laser beam is shaped and released.

Step 1. Light is Created in the Laser Diodes

Laser diodes produces light energy to be pumped into the fiber-optic cable. For this reason, they are also known as the "pump source". The resulting light is pumped into the fiber-optic cable and is used to generate the laser beam.

Step 2. Pump Light is Guided in the Fiber-Optic Cable

By default light goes in all directions. To focus light into a single direction and obtain a laser beam, fiber-optic cables use two basic components: the fiber core and the cladding.

- The core is where light travels. It is made of silica glass and is the only part of the cable that includes a rare-earth element.
- The cladding is the material that surrounds the core. When light hits the cladding, it bounces back into the core. This occurs because the cladding provides total internal reflection. Total internal reflection occurs because the cladding has a lower refractive index than the core and thus light remains in the core and continues its path.

Step 3. Light is Amplified in the Laser Cavity

As pump light travels through the fiber-optic cable, it eventually enters the laser cavity—a small region of the cable where only light of a specific wavelength is produced. The fiber is "doped" in this region because it has been mixed with a rare-earth element.

As particles from the doped fiber interact with light, their electrons rise to a higher energy level. When they fall back to their basic state, they release energy in the form of photons or light. The laser cavity also acts as a resonator where light bounces back and forth and this leads to “Light Amplification by the Stimulated Emission of Radiation”, or LASER.

Step 4. Laser Light of a Specific Wavelength is Created

The wavelength produced by the doped fiber varies according to the doping element of the laser cavity. This is very important, as different wavelengths are used for different applications. The doping element could be erbium, ytterbium, neodymium, thulium, and so on. Ytterbium-doped fiber lasers, for example, generate a wavelength of 1064 nm.

Different doping elements produce different wavelengths because specific particles release specific photons. As such, photons generated in the laser cavity all have the same wavelength. This explains why each type of fiber laser generates a specific wavelength—and only that wavelength.

Step 5. The Laser Beam is Shaped and Released

Photons that exit the resonant cavity form a laser beam that is extremely well collimated (or straight) due to the fiber’s light guiding properties.

To give the laser beam a desirable shape, different components can be used, such as lenses and beam expanders.

3.6. SEMICONDUCTOR LASER

Semiconductor lasers (more accurately: bipolar semiconductor lasers) are available in the entire visible, the near UV, and the near infrared. The wavelength and the power (from the nW range to the 100mW range) of radiation generated by a semiconductor laser depend on its design. A stack of semiconductor lasers can produce radiation with a power up to the kW range.

These are solid state lasers that make use of conduction electrons in semiconductors.

Stimulated transitions are either due to electronic transitions between the conduction band and the valence band of a semiconductor — in bipolar lasers.

The physical origin of gain in an optically pumped semiconductor is - without pumping, most of the electrons are in the valence band. A pump beam with a photon energy slightly above the band gap energy can excite electrons into a higher state in the conduction band, from where they quickly decay to states near the bottom of the conduction band. At the same time, the holes generated in the valence band move to the top of the valence band. Electrons in the conduction band can then recombine with these holes, emitting photons with an energy near the bandgap energy. This process can also be stimulated by incoming photons with suitable energy.

Most semiconductor lasers are laser diodes, which are pumped with an electrical current in a region where an n-doped and a p-doped semiconductor material meet. However, there are also optically pumped semiconductor lasers, where carriers are generated by absorbed pump light, and quantum cascade lasers, where intraband transitions are utilized.

Common materials for semiconductor lasers are

GaAs (gallium arsenide), AlGaAs (aluminum gallium arsenide), GaP (gallium phosphide), InGaP (indium gallium phosphide), GaN (gallium nitride) etc.

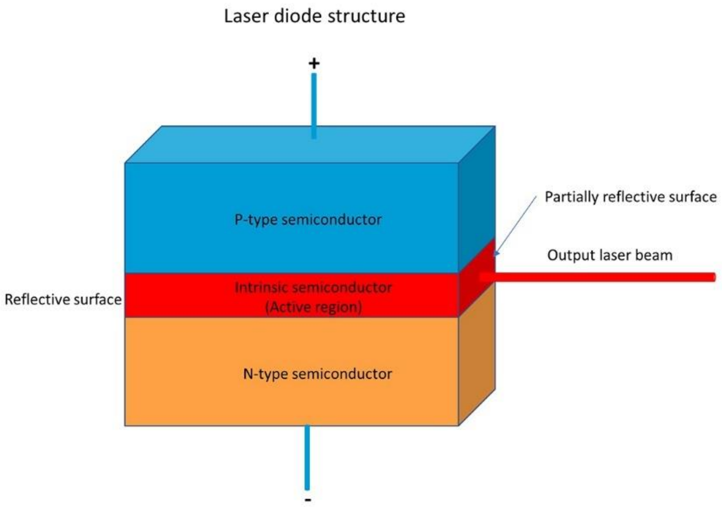


Fig. 3.6 Semiconductor laser

The most compact of all the lasers are semiconductor diode laser. It is also called injection laser. There are two types of semiconductor diode lasers (***i.) Homo - junction laser (ii.) Hetero- Junction laser.***

HOMO – JUNCTION SEMICONDUCTOR DIODE LASER

Definition

It is specifically fabricated p-n junction diode. This diode emits laser light when it is forward biased.

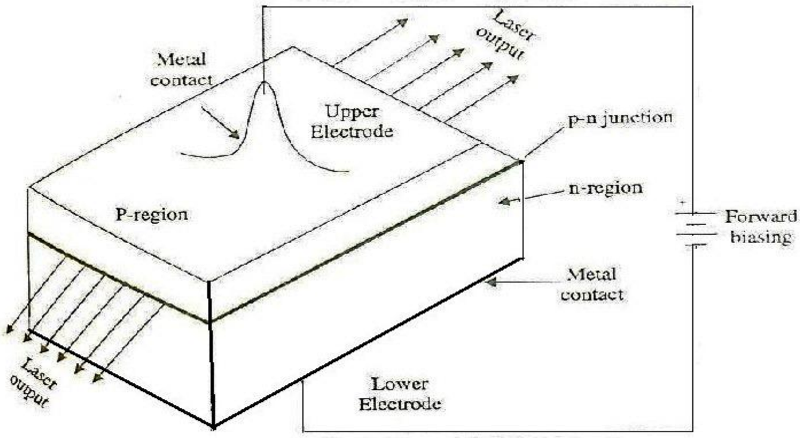
Principle

When a p-n junction diode is forward biased, the electrons from n – region and the holes from the p- region cross the junction and recombine with each other. During the recombination process, the light radiation (photons) is released from a certain specified direct band gap semiconductors like Ga-As. This light radiation is known as recombination radiation.

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

Construction

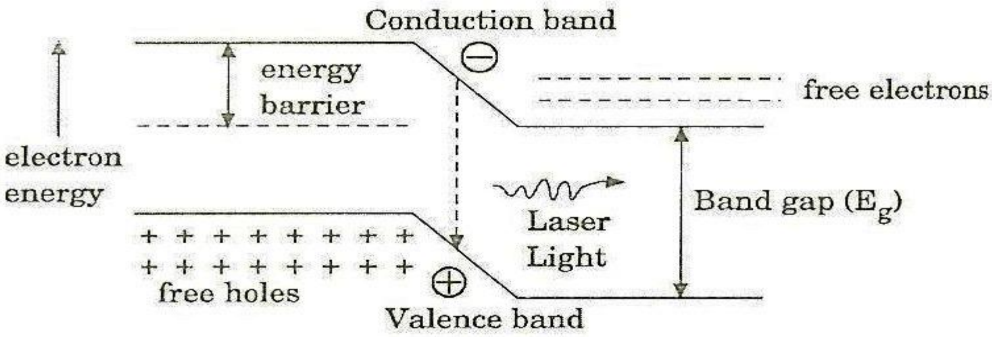
Figure shows the basic construction of semiconductor laser. The active medium is a p-n junction diode made from the single crystal of gallium arsenide. This crystal is cut in the form of a platter having thickness of 0.5μm. The platelet consists of two parts having an electron conductivity (n-type) and hole conductivity (p-type).



The photon emission is stimulated in a very thin layer of PN junction (in order of few microns). The electrical voltage is applied to the crystal through the electrode fixed on the upper surface. The end faces of the junction diode are well polished and parallel to each other. They act as an optical resonator through which the emitted light comes out.

Working

Figure shows the energy level diagram of semiconductor laser. When the PN junction is forward biased with large applied voltage, the electrons and holes are injected into junction region in considerable concentration. The region around the junction contains a large amount of electrons in the conduction band and a large amount of holes in the valence band.



If the population density is high, a condition of population inversion is achieved. The electrons and holes recombine with each other and this recombination's produce radiation in the form of light.

When the forward – biased voltage is increased, more and more light photons are emitted and the light production instantly becomes stronger. These photons will trigger a chain of stimulated recombination resulting in the release of photons in phase.

The photons moving at the plane of the junction travels back and forth by reflection between two sides placed parallel and opposite to each other and grow in strength.

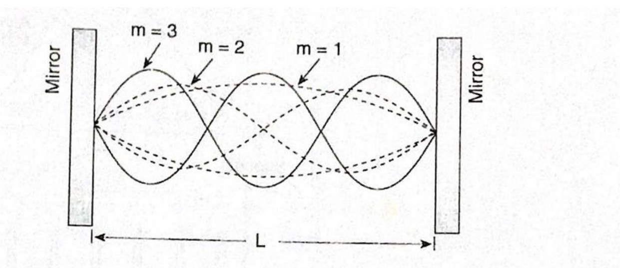
After gaining enough strength, it gives out the laser beam of wavelength 8400A^0

The wavelength of laser light is given by $E_g = h\nu = h\frac{C}{\lambda}$

$\lambda = \frac{hC}{E_g}$ where Eg is the band gap energy in joule.

3.7 FREQUENCY CONTROL OF LASER OUTPUT – OPTICAL RESONATOR Q FACTOR

The *Q factor* (quality factor) of an optical resonator is a quantity that measure the capability of the optical cavity to store electromagnetic energy inside. The way this energy is stored is by forming standing waves between the laser mirrors. The radiation in a resonator gives rise to a standing wave pattern with a node at each mirror. Thus, when the cavity resonates, the distance L between the mirrors has exactly integral multiple of half wavelength



$L = m\lambda/2$,   m= 1,2,3….

In terms of frequency

$$\boxed{\nu_m = \frac{(c/n)}{\lambda} = \frac{mc}{2Ln}}$$

where c is the speed of light in vacuum and n is refractive index of active medium.

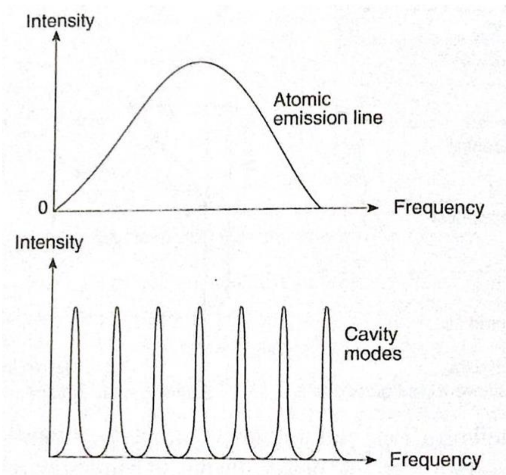
Thus, infinite number of cavity modes are possible. The frequency separation between two consecutive modes is

$$\Delta\nu = \nu_{m+1} - \nu_m = \frac{c}{2Ln}[(m+1) - m]$$

$$\text{or,} \quad \boxed{\Delta\nu = \frac{c}{2Ln} = \frac{c}{2L}}$$

taking n =1.

The important point to be noted is that resonant modes in cavity are narrower in frequency than the width of a single spontaneous emission line.



From the comparatively broad range of frequencies of an emission line, the cavity selects and amplify only certain narrow bands and by proper adjustment of separation of cavity modes it is possible to have only one mode in the band width of the emission line. This explains the extreme monochromaticity of laser radiation.

Q Factor is proportional to the ratio of the energy stored inside the standing wave and the wasted energy from the wave during round trip between the laser mirrors. High Q Factor value means that the energy is stored well inside the cavity. When both mirrors of the laser cavity have high reflectivity, the Q factor has high value. Low Q Factor value means that the energy is emitted from the cavity rapidly. When one of the laser mirrors has low reflectivity, the radiation will be emitted through this mirror, and the Q factor will have low value.

There are two different common definitions of the *Q* factor of a resonator:

- <u>Definition via energy storage</u>: the *Q* factor is 2π times the ratio of the stored energy to the energy dissipated per oscillation cycle.

$$Q = 2\pi \times \frac{\text{maximum energy stored per cycle}}{\text{energy dissipated per cycle}},$$

- <u>Definition via resonance bandwidth</u>: the *Q* factor is the ratio of the resonance frequency ν_0 and the full width at half-maximum (FWHM) bandwidth $\delta\nu$ of the resonance:

$$Q = \frac{\nu_0}{\delta\nu}$$

Both definitions are equivalent only in the limit of weakly damped oscillations, i.e. for high *Q* values.

The *Q* factor of a resonator depends on the optical frequency ν_0, the fractional power loss l per round trip, and the round-trip time T_{rt}:

$$Q = \frac{2\pi\nu_0 T_{rt}}{l}$$

(assuming that $l \ll 1$).

3.8 INJECTION LASER DIODE (ILD)

Injection Laser Diode is basically laser source that makes use of double hetero junction directband gap semi conductors as the active medium in order to achieve laser light of high quantumefficiency and high power output.

Hetero junction means a direct band gap p-n junction formed by two different semiconductingmaterials with different band gap energies. The material on one side of the junction differs fromthat on the other side of the junction.

Double hetero junction has two such hetero junctions.

Efficient wave guide structure, small beam divergence, high coherence, monochromaticity, carrier and optical confinement, high power output with low threshold current is possible withsuch hetero junction semi conductors.

3.8.1 Structure of ILD

It uses double hetero junction semi conductors. There are three layers, one is the central activelayer and the other two are the two adjacent layers. Active layer is of p-type material, usually$Ga_{(1-y)}Al_yAs$ of thickness 0.1 to 0.3 μm and of low energy band gap. The adjacent layers are madeup of n-type $Ga_{(1-x)}Al_xAs$ of high energy band gap. Here x is not equal to y and they determine theband gap of alloys. The adjacent layers are also known as injection layers/confinement layers, (Fig.3.7).

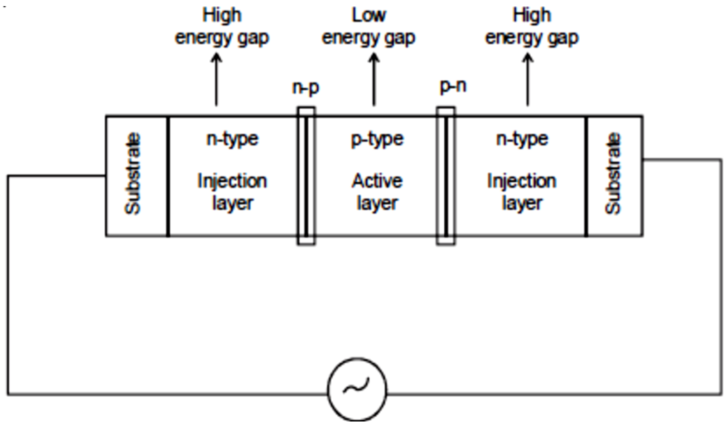


Fig.3.7 Structure of Double Hetro Junction Laser

n-type : $Ga_{(1-x)}Al_xAs$

p-type : $Ga_{(1-y)}Al_yAs$

3.8.2.Working of ILD

When drive current (I) is given to ILD, the excess electrons are moved from Ec of adjacent layer toE_c of active layer in order to achieve population inversion, a necessary condition to be satisfied forlaser action to start. Electron transition occurs in the active layer from E_c to E_v, since only lessenergy has to be crossed in the active layer. Due this transition, electron-hole recombination takes place in the active layer; thereby photon is released from the active layer. This photon can thenstimulate the release of coherent photons. Optical confinement that is necessary for amplificationis obtained by choosing $n_1>n_2$, where n1 is the refractive index of the active layer and n_2 is thatof the adjacent layer.The photon released in the active layer moves and gets totally internally reflected on hitting the n-p and p-n junction, since n1 > n2. Number of times it gets amplifiedand finally it results in the emission of light in 800 - 900 nm wavelength range, (Fig.3.8).

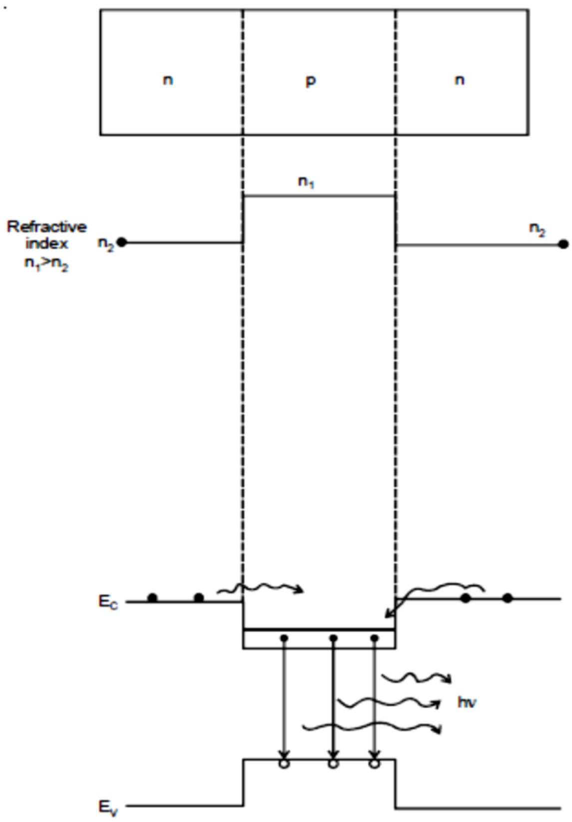


Fig. 3.8 Working of ILD

3.8.3.Merits of ILD

i. High directivity, coherent radiation, monochromatic, high output power.

ii. Acts as narrow spectral width source.

iii. Coupling efficiency is high hence used to couple laser light into the optical fiber.

iv. Used for long distance optical communication at higher bit rate > 200 Mb / sec.

v. Reduces chromatic dispersion.

3.8.4. Demerits of ILD

i. Shorter life time; 10 times expensive than LEDS.

ii. Wavelength of the output laser light is governed by the semiconductor band gap.

iii. More temperature dependent.

iv. In order to maintain population inversion, high power consumption is needed and it consequently increases the temperature of the laser.

v. Due to increase in temperature, (i) Efficiency of the laser decreases rapidly as the electronpopulations are smeared out through the wide band structure of available states. (ii) As thethreshold (J_{th}) current density depends on temperature, J_{th} also increases consequently.

Note: Threshold current density represents the minimum current density of the active mediumthat is needed to start and sustain laser action in such a way that the optical gain inside the laseris greater than or at least equal to the sum of the loss and useful laser output.

$$J_{th}(T) = J_{th}^{o} e^{\frac{T}{T_o}}$$

J^0_{th} - Threshold current density at 0°C.

T - Temperature of the active layer

T_o - Parameter which determines the relative temperature sensitivity of the device.

T_o - Parameter which determines the relative temperature sensitivity of the device.

This threshold current density also changes with the age of the laser. Output wavelength isgoverned by the semi conductor band gap. The problems in ILDs can be overcome to some extentby replacing the bulk semiconductor with a nanostructured semi conductors namely quantumwell, quantum wire and quantum dots.

3.9. QUANTUM CASCADE LASER (QCL)

It is basically an Injection Laser Diode (ILD), where the bulk semiconductor is replaced by thenanostructured Multiple Quantum Wells(MQW) that act as the active medium and emit laserlight in the Infra red (IR) and in far IR region of the electromagnetic spectrum.

3.9.1. Working of QCL

The structure of QCL is the similar to that of ILD, with the change that n-p-n semiconductors arenanostructured (refer the diagrams of ILD). Initially QWs of slightly different band width andhence different energy states are chosen similar to that as in ILD. In QCL, when drive current isapplied, the electrons cascade down a series of steps emitting a sequence of phonons - quantum oflattice vibrations, hence the name Quantum Cascade Laser Fig. 3.9 (a) & (b).

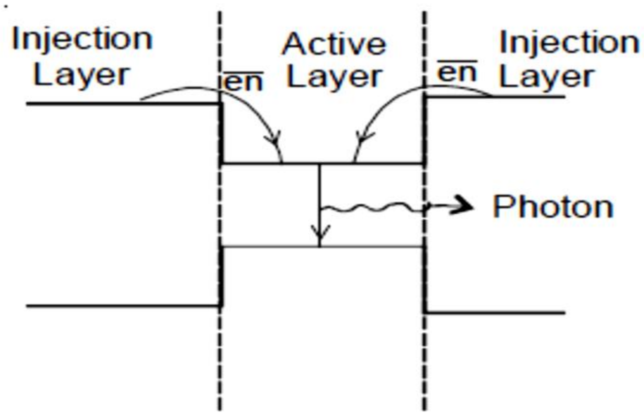


Fig. 3.9 (a) Injection laser Diode

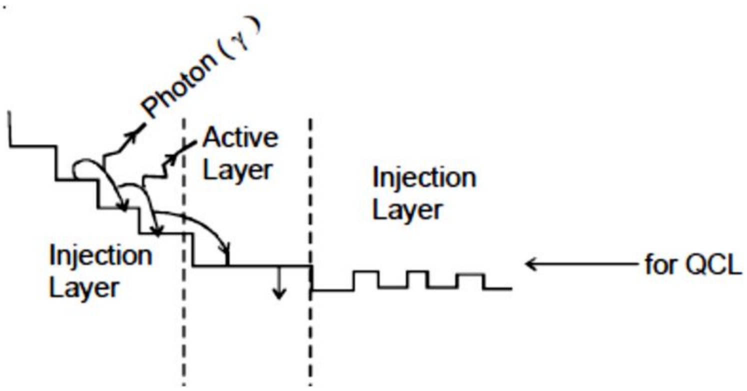


Fig. 3.9 (b) Quantum Cascade Laser

Energy levels of QCL, before the application of bias voltage is shown below:

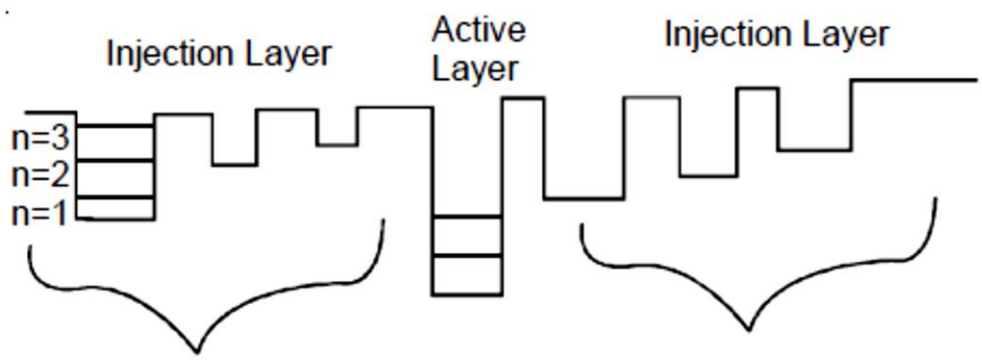


Fig. 3.10 Energy levels of QCL, before the application of bias voltage

Energy levels of QCL, after the application of bias voltage is shown below:

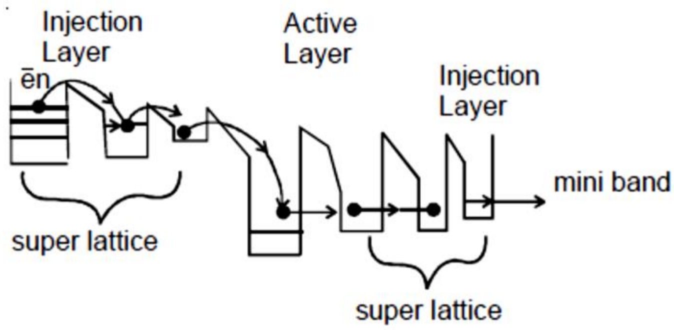


Fig. 3.11 Energy levels of QCL, after the application of bias voltage

Here, the energies of QWs are tuned by adjusting the thickness of each QW so that they matchwith the bias voltage. Hence, the applied bias voltage brings the energy states of these QWs intoresonance creating super-lattice with the required mini-bands.

The fig. 3.11 explains the case when electrons fall from n = 3 to n = 2 and they fall to n=1 state.They excite the miniband of 1st QW and move to the next QW through the active region andphotons are released.Recently developed QCL, has laser output at 3.1μm wavelength at 20k and3.6μm wavelength at room temperature.

3.10. Differences between injection laser diode and quantum lasers are listed below:

ILD	QCL
1. Active medium - bulk semiconductors. 2. Size of the active medium -0.1 to 0.3μm 3. Active region behaves as a 3D box 4. Electrons / holes spread over wideenergy range with small DOS at the bandgap edge. 5. DOS depend on the energy of the electron. 6. Thershold current density is 800A/cm^2 7. Output wavelength is governed by semiconductor band gap;hence control of output wavelength isnot possible. 8. High power consumption; more temperature dependant.	1. Active medium - nano structured semiconductors. 2. 50Å - 100Å 3. Active region behaves as a 2D thin film. 4. Electron's energy is spread over asmall range with increased DOS at theband gap edge. 5. DOS is independent on energy ofelectron. 6. Here is is 60 A/cm^2 -which is easy toobtain at room temperature itself. 7. Output wavelength depends on thicknessof nano structured semiconductorhence precise required wavelength oflight can be made to be emitted.

9. Downward transition from conduction band to valence band leads to emission of laser light – interband device. 10.They are interbandbiploar device.	8. Reduced operating current and are less temperature sensitive. 9. Downward transition between conduction band states of different confined QWs - intraband device. 10.They are intraband unipolar device

3.10.1 Merits of QCL

i. High optical power output.
ii. Tuning is possible to get the required wavelength λat far IR.
iii. Possibility of room temperature operation.
iv. Lower operating current.
v. Faster operating speed.

3.10.2 Demerits of QCL

When QCL is operated continuously at room temperature, it generates heat. As a result, electron's energy is wasted and there is a possibility of exciting even from the upper lasing state itself before making a downward transition.

3.10.3 Applications

i. Spectroscopic applications such as gas monitoring, pollution monitoring in atmosphere.
ii. Space communication system, medical diagnostics such as breath analysis, etc.

3.11. APPLICATIONS OF LASER IN OPTICAL/PHOTONIC COMPUTING

Optical-computing or photonic-computing uses photons produced by lasers or diodes for computation. For decades, photons have shown promise to enable a higher bandwidth than the electrons used in conventional computer.

Most research projects focus on replacing current computer components with optical equivalents, resulting in an optical digital computer system processing binary data. This approach appears to offer the best short-term prospects for commercial optical computing, since optical components could be integrated into traditional computers to produce an optical-electronic hybrid. However, optoelectronic devices consume 30% of their energy converting electronic energy into photons and back; this conversion also slows the transmission of messages. All-optical computers eliminate the need for optical-electrical-optical (OEO) conversions, thus reducing electrical power consumption.

Application-specific devices, such as synthetic-aperture radar (SAR) and optical correlators, have been designed to use the principles of optical computing. Correlators can be used, for example, to detect and track objects, and to classify serial time-domain optical data.

Laser scanner

Laser scanning is the controlled deflection of laser beams, visible or invisible. Scanned laser beams are used in some 3-D printers, in rapid prototyping, in machines for material processing, in laser engraving machines, in ophthalmological laser systems for the treatment of presbyopia, in confocal microscopy, in laser printers, in laser shows, in Laser TV, and in barcode scanners. Laser scanners collect information in the form of point cloud data, which consists of millions of 3D coordinates (XYZ coordinates).

Modern laser scanners can collect detailed point clouds, and with point cloud processing software, these datasets can create digital 3D models of the scanned environment.

Present-day laser scanning procedures use laser beams, advanced sensors, Global Positioning Systems (GPS), Inertial Measurement Units (IMU), receiver electronics, and photodetectors. Using all of these components, laser scanners can calculate accurate coordinates of surfaces and structures.

How the process goes?

First, laser scanning systems throw out light waves that bounce off of surfaces and reflect back to the sensor. The sensor then calculates how far away the surface is by measuring the time taken for the light beam to complete its journey. This process is known as the “time of flight” measurement. The distance measured is then used to calculate a coordinate for the tiny section of the surface hit by the laser beam. All of this happens in just seconds, and during a single scan, a laser scanner will collect millions of 3D coordinates.

When the point clouds from laser scans are processed, they form a digital representation of the scanned surfaces, demonstrating the dimensions and spatial relationships of topographic features and structures.

Optical disc:

An optical disc is any computer disc that uses optical storage techniques and technology to read and write data. It is a computer storage disk that stores data digitally and uses laser beams (transmitted from a laser head mounted on an optical disk drive) to read and write data.

An optical disk is primarily used as a portable and secondary storage device. It can store more data than the previous generation of magnetic storage media, and has a relatively longer lifespan. Compact disks (CD), digital versatile/video disks (DVD) and Blu-ray disks are currently the most commonly used forms of optical disks. These disks are generally used to:

- Distribute software to customers
- Store large amounts of data such as music, images and videos
- Transfer data to different computers or devices
- Back up data from a local machine

How optical storage disks are made?

1. All modern formats use the same basic sandwich of materials structure. A hard plastic substrate forms the base, and then a reflective layer -- typically aluminum foil for mass-produced disks -- is used to encode the digital data. Next, a layer of clear polycarbonate protects the foil and allows the laser beam to pass through to the reflective layer.
2. Optical disks rely on a red or blue laser to record and read data. Most of the optical disks are flat, circular and 12 centimeters in diameter. Data is stored on the disk in the form of microscopic data pits and lands. The pits are etched into a reflective layer of recording material. The lands are the flat, unindented areas surrounding the pits.
3. When producing prerecorded disks in bulk, manufacturers first build a glass master and, from this master, create a negative disk image made from nickel. They then use this nickel image to physically stamp the digital pits into the reflective foil layer.
4. The type of material selected for the recording material depends on how the disk is used. Prerecorded disks such as those created for audio and video recordings can use cheaper material like aluminum foil. Write-once disks and rewritable disks require a more expensive layer of material to accommodate other types of digital data storage.
5. Data is written to an optical disk in a radial pattern starting near the center. An optical disk drive uses a laser beam to read the data from the disk as it is spinning. It distinguishes between the pits and lands based on how the light reflects off the recording material. The drive uses the differences in reflectivity to determine the 0 and 1 bits that represent the data

6. Optical disks that are intended for digital data storage include different materials for the reflective layer, depending on whether the disk is write-once or rewritable. A write-once optical disk includes an organic dye layer between the unwritten reflective foil and the polycarbonate. Rewritable optical disks swap the aluminum foil for an alloy that is a phase-change material so it can be erased and rewritten multiple times.

Optical tweezers:

Optical tweezers (also called single-beam gradient force trap) are scientific instruments that use a highly focused laser beam to hold and move the microscopic and sub-microscopic objects like atoms, nanoparticles and droplets, in a manner similar to tweezers. Dielectric and absorbing particles can be trapped, too.

- Opticaltweezers are used in biology and , nanoengineering and nanochemistry (to study and build materials from single molecules), quantum optics and quantum optomechanics (to study the interaction of single particles with light).

- Optical tweezers are capable of manipulating nanometer and micron-sized dielectric particles by exerting extremely small forces via a highly focused laser beam. The beam is typically focused by sending it through a microscope objective. The narrowest point of the focused beam, known as the beam waist, contains a very strong electric field gradient. Dielectric particles are attracted along the gradient to the region of strongest electric field, which is the center of the beam. The laser light also tends to apply a force on particles in the beam along the direction of beam propagation. This is due to conservation of momentum: photons that are absorbed or scattered by the tiny dielectric particle impart momentum to the dielectric particle. This is known as the scattering force and results in the particle being displaced slightly downstream from the exact position of the beam waist, as seen in the figure (Fig 3. 12).
- For quantitative scientific measurements, most optical traps are operated in such a way that the dielectric particle rarely moves far from the trap center. The reason for this is that the force applied to the particle is linear with respect to its displacement from the center of the trap as long as the displacement is small. In this way, an optical trap can be compared to a simple spring, which follows Hooke's law.

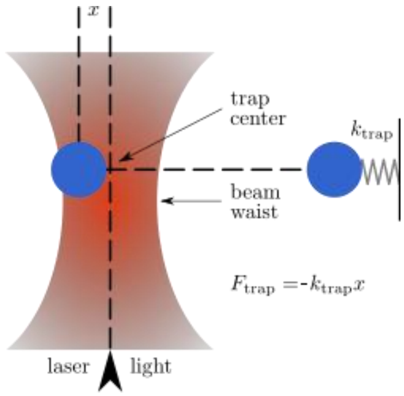


Fig. 3.12. Schematic of optical tweezer

How does it work?

Optical tweezers are based on the principle of light carrying momentum proportional to its energy and propagation direction.

When a laser beam passes through an object, it bends and changes direction (called refraction) and alters its momentum. According to Newton's third law, the object undergoes an equal and opposite momentum change, a reaction force, for the system to conserve the total momentum.

Figure 3.13 illustrates the transfer of light momentum occurring when a light beam travels through a bead. In a typical optical tweezers configuration, the incoming light originates from a focused laser beam through a microscope objective and focuses on a spot in the sample. The spot subsequently creates a trap able to hold a small object in place.

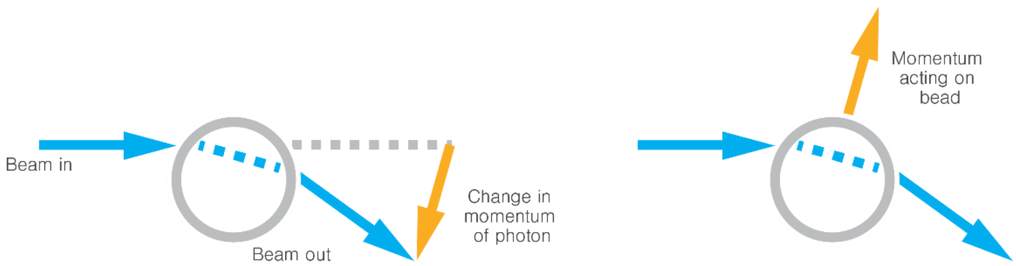


Fig. 3. 13 Re-direction of a light path and change of momentum as it passes through a microscopic particle or "bead" with high index of refraction related to the medium (at left). Momentum of equal and opposite force is transferred from the photons to the bead according to Newton's Law of energy conservation at (right).

The total forces experienced by the object, or bead in most experimental settings, consist of a scattering force and a gradient force. The scattering force arises when a light beam is scattered by the surface of the object. This scattering produces a net momentum transfer from the light photons to the object and causes the bead to be pushed towards the beam propagation. The gradient force results from the intensity profile of the laser beam which acts as an attractive force, drawing the bead towards the region with greater light intensity. In the case of a focused laser beam with a Gaussian intensity profile (a normal distribution), the gradient force pulls the object into the center of the focal plane.

The reason the object stays in the center of the beam is because of the sum of the forces acting upon it. In the center, rays of light refract or scatter through the object the same way on both sides of the vertical plane, which cancels forces from moving the object sideways. If the object drifts to one side, it returns to the center. **Figure 3.14** shows how the gradient force restores an off-centered bead towards the center of the focal plane, effectively trapping the object in all dimensions.

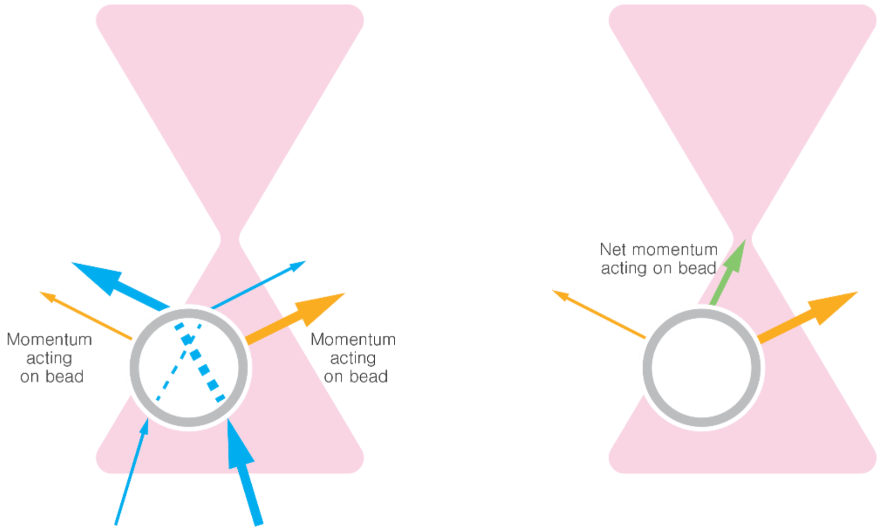


Fig. 3.14 Two light paths passing through a dielectric micron sized bead. Due to the light gradient, the path originating from the center of the beam carries more photons than the light path commencing from the outlines of the beam, resulting to a larger force pulling the bead towards the focal point.

Just to know

Maiman

On May 16, 1960, at Hughes' Malibu, California, laboratories, Maiman's solid-state pink ruby laser emitted mankind's first coherent light, with rays all the same wavelength and fully in phase. Maiman documented his invention in Nature and published other scholarly articles describing the science and technology underlying his laser.

Maiman had begun conceptualizing a solid-state laser design even before he undertook the maser project at Hughes. Moving the microwave frequency of masers up the electromagnetic spectrum 50,000-fold to the frequency of light would require finding a feasible lasing medium and excitation source and designing the system.

Richard Feynman

Richard Feynman gave a 1959 talk which many years later inspired the conceptual foundations of nanotechnology. The American physicist Richard Feynman lectured, "There's Plenty of Room at the Bottom," at an American Physical Society meeting at Caltech on December 29, 1959, which is often held to have provided inspiration for the field of nanotechnology. Feynman had described a process by which the ability to manipulate individual atoms and molecules might be developed, using one set of precise tools to build and operate another proportionally smaller set, so on down to the needed scale. In the course of this, he noted, scaling issues would arise from the changing magnitude of various physical phenomena: gravity would become less important, surface tension and Van der Waals attraction would become more important.

QUESTIONS

PART A

1. Expand LASER.
2. Write the conditions for laser action.
3. What do you mean by population inversion?
4. What is optical pumping?
5. Differentiate between spontaneous and stimulated emission.
6. Explain laser structure.
7. What is the function of a laser resonator?
8. Name different types of laser materials.
9. Write the important features of a fibre laser.
10. Briefly explain the operation of a semiconductor laser.
11. Define Q factor. Write about its implications.
12. Difference between IDL and QCL.

PART B

13. Explain relation between spontaneous and stimulated emission probability. Derive an expression for Einstein's Coefficient

14. Describe the structure and working principle of ILD with its necessary diagram. Write its merits and demerits.

15. Describe

    (i) Structure and working of Quantum cascade laser (QCL) with diagram

    (ii) Merits and demerits of QCL.

16. Write a short note on working of a laser scanner.

17. Explain how does optical disc store data.

18. Elaborately explain the operation of an optical tweezer.