chapter-5

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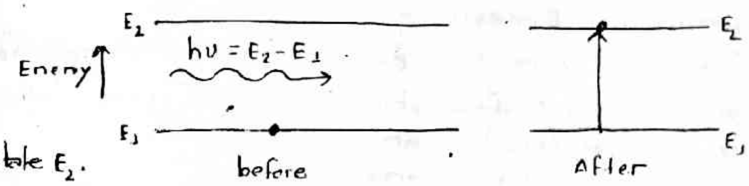
Laser and Fibre optics

* The word laser stands for Light amplification by stimulated emission of radiation. It becomes a valuable tool in a variety of field starting with medicine to communications. Laser is a light source but it is very much different from many of traditional light sources. Laser is not used for illumination purposes as we use the other light sources. Lasers produces a highly directional and high intensity beam with narrow frequency range than that available from the common type of light sources. They are more widely used as a high power electromagnetic beam rather than a light beam.

* The processes of laser beam -

① Absorption -



An atom at lower energy level E_1 may absorb the incident photon and jumps to the excited state E_2. This transiton is called induced absorption. corresponding to each absorption transition one photon disappears and one atom adds to the population at excited energy level.

This process may be represented as

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

A = ground state atom

A^* = Excited atom.

The number of atoms per unit volume that makes upward transition from lower state to upper state per sec is called absorption transition rate. It is represented by

$$R_{abs} = -\frac{dN_1}{dt}$$

- sign indicates that population of level E_1 is decreasing.

In terms of increase population in level E_2, the transition rate will be

$$R_{abs} = \frac{dN_2}{dt}$$

N_1 = number of atoms per unit volume in state E_1

N_2 = number of atoms per unit volume in state E_2

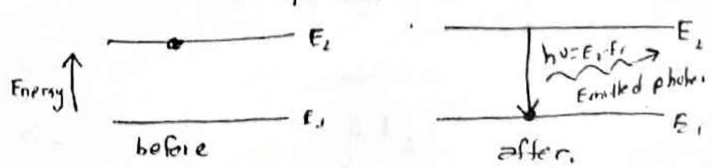
This transition rate is directly proportional to the number of photons per unit volume in incident beam and population of lower level.

i.e $\quad R_{abs} \propto \rho(\nu) N_1$

$$\Rightarrow R_{abs} = B_{12}\, \rho(\nu)\, N_1 \quad \text{---}(*)$$

where B_{12} is called Eistein coefficient of Induced absorption.

② spontaneous emission -



An excited atom can stay at the excited level for an average lifetime if it is not stimulated by any other agent during its short life-time, the excited atom undergoes a transition to lower energy level by its own. During this transition, it gives up excess of energy in the form of photon. This process in which an excited atom emits a photon all by itself and without any external impetus is known as spontaneous emission.

The process is represented by

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

The rate of spontaneous transition, $R_{sp} = -\frac{dN_2}{dt}$

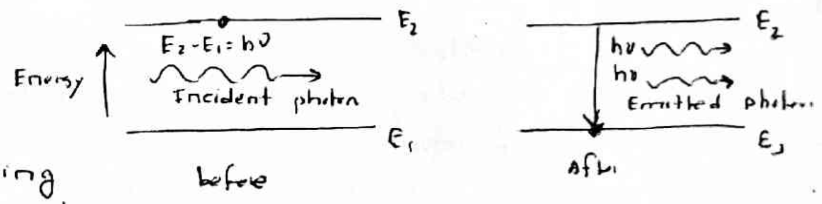
The number of photons generated will be proportional to the population of excited level only.

$$\therefore R_{sp} = A_{21} N_2 \quad --(**)$$

A_{21} = Eistein coefficient for spontaneous emission and is function of frequency and properties of the material, or it is the probability of spontaneous transition from level $2 \rightarrow 1$.

(3) Stimulated Emission -

An atom in the excited state need not to wait for spontaneous emission to occur. If a photon with appropriate energy ($E_2 - E_1 = h\nu$) interacts with the excited atom, it can trigger the atom to undergo transition to lower level and to emit another photon. The process of emission of photons by an excited atom through a forced transition occuring under the influence of an external agent is called stimulated emission. The process may be represented as



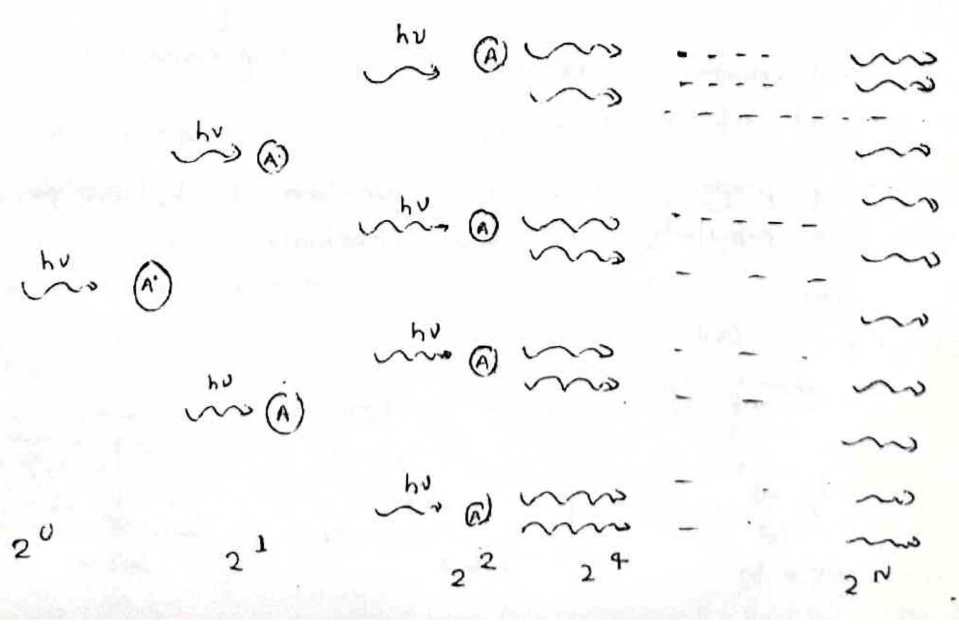
$$A^* + h\nu \longrightarrow A + 2h\nu$$

The rate of stimulated emission of photons is

$$R_{st} = B_{21}\, \rho(\nu)\, N_2 \quad ---(***)$$

The process of stimulated emission is controllable from outside. The photon emitted propagates in the same direction as that of stimulating photon. The light produced is directional, coherent and monochromatic.

Light amplification -



* population -

The atoms of each chemical element have their own characteristic system of energy levels. The energy difference betn the successive energy levels of an atom is of the order of 1 ev to 5 ev. The energy levels are common to all the atoms in a system which is composed of identical atoms. we can therefore say that a certain number of atoms occupy a certain energy state. The number of atoms per unit volume that occupy a given energy state is called population of that energy state. The population N of an energy level E depends on the temp.

Thus, $N = e^{-E/KT}$ ... [Boltzmann's equation]

In a material, atoms are distributed differently in different energy states. The atoms normally tend to be their lowest possible energy level which need not be the ground state. At temperatures above 0 K, the atoms always have some thermal energy and therefore, they are distributed among the available energy levels according to their energy.

* population inversion -

In general, the number of atoms in ground state (lower state) N_1, is higher than the atoms in excited state (N_2). If $N_2 > N_1$ then we can say that the population is inversed.

under the population inversion condition the stimulated emission can produce a cascade of light. The first few randomly emitted photons (spontaneous) trigger stimulated emission of more photons and those stimulated photons induce still more stimulated emission and so on.

* pumping -

In order to realize and maintain the state of population inversion, It is necessary that atoms must be continuously promoted from lower state to exited state. Energy is to be supplied somehow to the laser medium to raise atoms from the lower to excited level and for maintaining population at the excited level of a value grater than that of lower energy. The process by which atoms are raised from the lower to excited level is called pumping.

* pumping methods -
(a) optical pumping
(b) Electrical pumping
(c) X- ray pumping
(d) chemical pumping

* optical pumping -

optical pumping is the use of photons to excite the atoms. A light source such as a flash discharge tube is used to illuminate the laser medium and the photons of appropriate frequency excite the atoms to an uppermost level. From there, they drop to metastable upper laser level and create the state of population inversion. optical pump sources are flash discharge tubes continously operating lamps, spark gaps or an auxiliary laser is sometimes used as the pump source. The pump source must have frequency higher than emitted photon. And the pumping level of the atom must not be a narrow level.

* Active medium -

Atoms in general are characterised by a large number of energy levels. However, all types of atoms are not suitable for laser operation. Even in a medium consisting of different species of atoms, only a small fraction of atoms of particular species are suitable for stimulated emission and laser action. Those atoms which causes light amplification are called active centers. The rest of the medium acts as host and supports active centres. The medium hosting the active centers is called as active medium.

An active medium is thus a medium which when excited, reaches the state of population inversion and eventually causes light amplification. The active medium may be solid, liquid or gas.

* Metastable states -

The metastable states are those state at which excited atoms lived upper level for an appreciable time. Atoms stay in metastable states for about 10^{-6} to 10^{-3} sec. This is 10^3 to 10^6 times longer than the time of stay of atom at excited levels. Therefore, It is possible for a large number of atoms to accumulate at a metastable state. The metastable state population can exceed the population of lower state and lead to the state of population inversion. If metastable states do not exist, there could be no population inversion, no stimulated emission and hence no laser operation.

Thus foundation of laser operation is the existence of metastable state.

* pumping scheme:

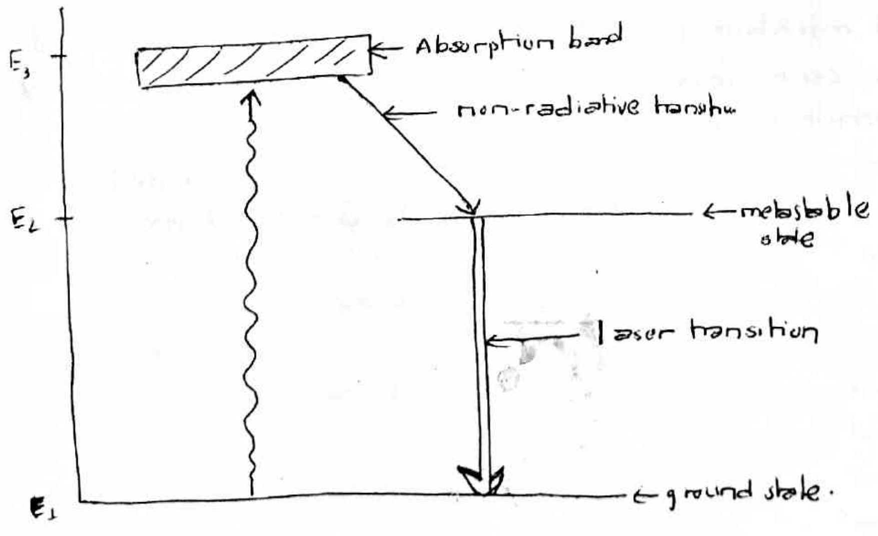


Fig: Three level scheme.

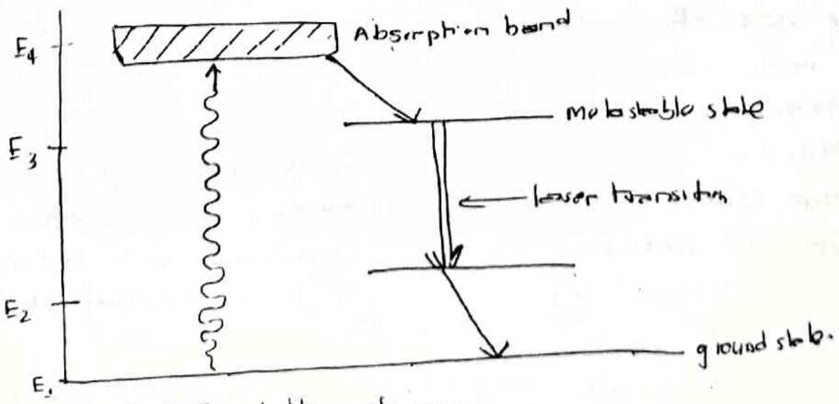
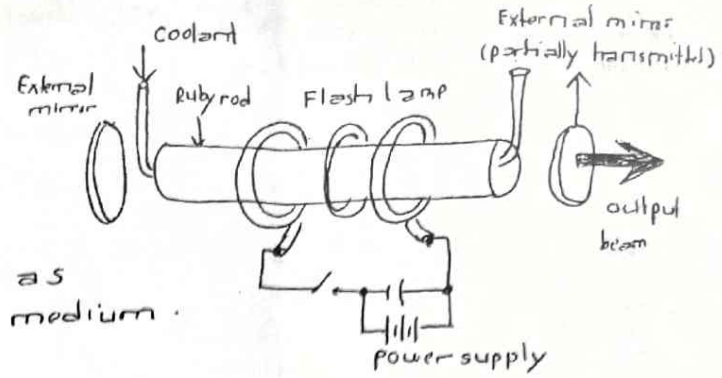


Fig: Four lable scheme.

* Ruby Laser-

The Ruby laser consists of a synthetic ruby crystal Al_2O_3, doped with chromium ions at a concentration of about 0.05% by weight. The chromium ions constitute the active centres as they have a set of three energy levels suitable for realzing lasing action where as aluminium and oxygen atoms ae active medium.

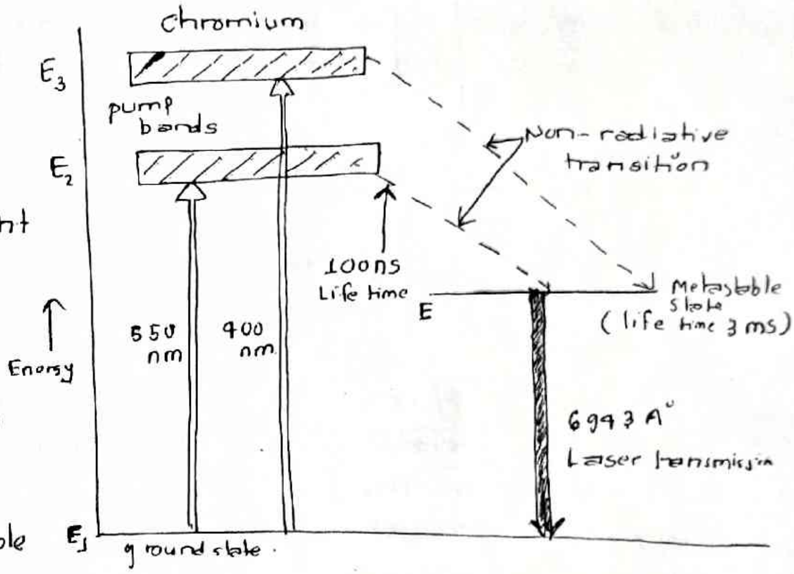


construction-

The ruby rod is in the form of cylinder with 4 cm long and 0.5 cm in diameter. The rod is fitted with helical flash tube. The tube is filled with xenon gas. At the end of the tube two external mirrors are fixed, one is fully reflecting and other is partially transmitting type. The system is cooled with the help of a coolant circulating around the ruby rod.

working-

It is a three level laser system. The energy level of chromium ions are as shown in fig. when the ruby rod is irradiate with an intense brust of white light from the xenon lamp the ground state cr^{+3} ions absorbs light in two pump bands one centered near 5500A° and other at 4000A°. They have average life time of 10^{-9} sec. Therefore, the excited cr^{+3} ions rapidly lose some of their energy and undergo non-radiative transition to level E. The level E becomes metastable states having lifetime of 3×10^{-3} sec.

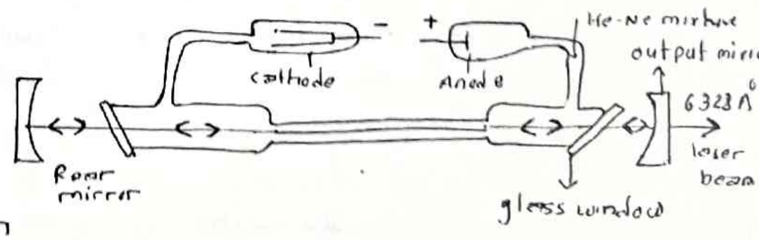


The transition from E to E_1 is radiative and under normal population condition produces spontaneous red fluorescence typical of ruby with a peak near 6943 A°.

under the intense excitation, population inversion occurs in E with respect to ground state E_1. Then one of the spontaneously emitted photons travelling parallel to the axis of ruby rod would initiate stimulated emissions. The photons make many passes through the medium building up the stimulated emissions in large way. The photons travelling in any other direction would be lost after few reflections.

As the one flash is used then another flash is fallowed. Therefore Ruby laser is a pulse laser and is not contineous.

* Helium - Neon laser-



Helium Neon laser is an atomic laser which employs a four-level pumping scheme. The active medium is the mixture of 10 parts of Helium and 1 part of Neon. Neon atoms are active centre and have energy level suitable for laser transition.

construction- It consists of glass discharge tube about 30 cm long and 1.5 cm in diameter. The tube is filled with Helium and Neon gas in the ratio 10:1. Electrodes are provided in the tube to produce a discharge in a gas. They are connected to high voltage (10 kV) power supply. The tube is sealed with glass windows oriented at Brewster angle to the axis of tube. And mirrors are arranged externally.

Working-

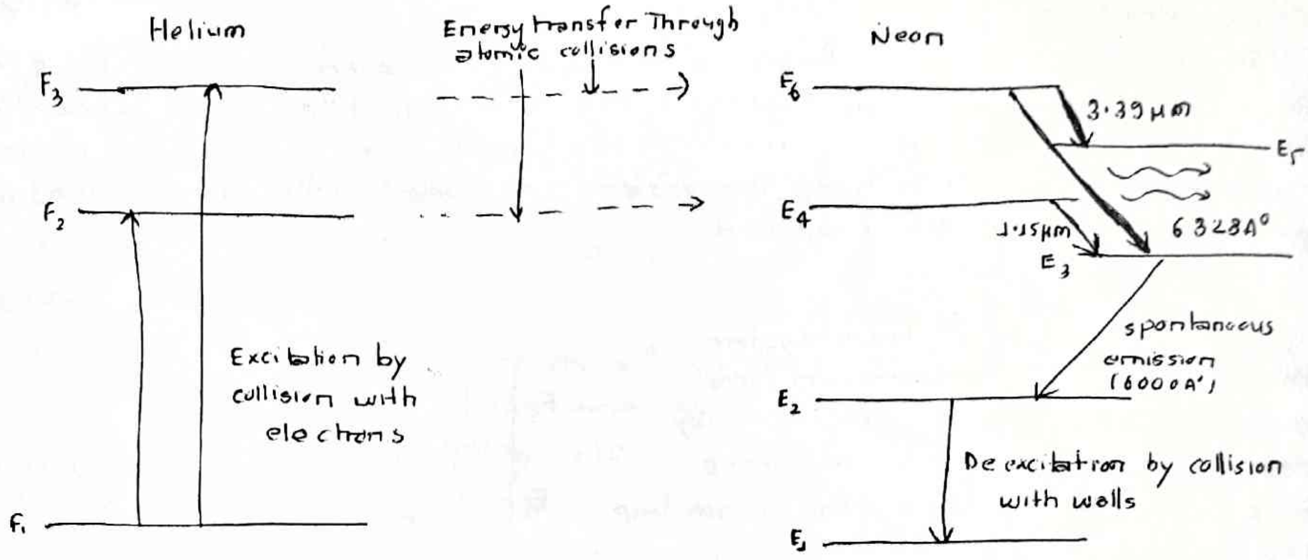
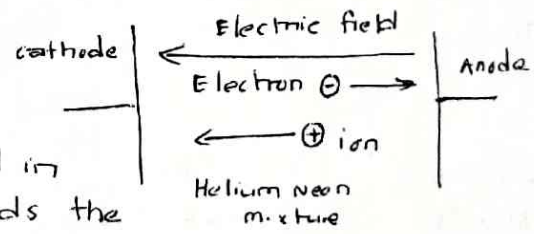


Fig: Energy levels of Helium and Neon atoms and transition betn the levels.



when the power is switched on with high voltage about 10kV across the gas, It is sufficient to ionize the gas. The electrons and ions produced in the process of discharge are acclerated towards the anode and cathode resp. As shown in fig.

As electrons have smaller mass, they have higher velocity and transfer their kinetic energy to atoms of Helium and exites them to the level F_2 and F_3 as in fig at energy 19.81 eV and 20.16 eV resp. The excited helium atoms can return to the normal state by transfering their energy to neon atoms through collision. It is called resonance transfer of energy.

The energy level E_4 and E_6 of Neon concide with energy level F_2 and F_3 of Helium. Therefore Neon atoms excited to level E_4 and E_6. This is the pumping mechanism of He-Ne laser.

The levels E_6 and E_4 of Neon atoms are metastable states. Therefore, as the collisions go on, neon atoms accumulate in E_4 and E_6. At ordinary temperature E_5 and E_3 levels are sparsely populated thus population inversion is acheived betn E_6 to E_5, E_6 to E_3 and E_4 to E_3.

(i) $E_6 \rightarrow E_3$ corresponds to the laser transition of red colour at 6328 A°

(ii) $E_4 \rightarrow E_3$ corresponds to IR beam at wavelength 11500 A°

(iii) $E_6 \rightarrow E_5$ corresponds to IR region at 33900 A°

The one of the spontaneously emitted photon (E_3 to E_2) may trigger laser action. Finally the Neon atom is de excited by collision with walls and fresh cycle is started.

process

$He + e \longrightarrow He^* + e_1$ (same electron with laser action)

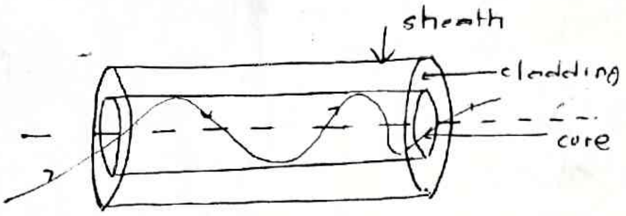
$He^* + Ne \longrightarrow Ne^* + He$

* uses of laser –

(1) Laser is used in material processing such as cutting, drilling, welding etc.
(2) Laser is used in nuclear energy.
(3) It is used in micromaching. In this process a laser beam is focused which gives extremly high energy density on a very small area which causes vaporization of material.
(4) It is also used in communication. since laser beam has enormous bandwidth and it permits 10 million telephone conversation or 8000 TV programmes simultanealy.
(5) It is also used by military for war purposes.
(6) It is also used in Radars.
(7) Lasers are presently used for a variety of application in the medical field. Lasers are especially successful in the areas of opthalmolosy, Neurosurgery, Gastroenterology, dermatology, Gynecology etc.

* optical fibre-

An optical fibre is made of glass or clear plastic design to transmit light signal along its length. It works on the principla of total internal reflection.



A practical optical fibre has three co-axial region. The central layer is the light guiding region known as core. The middle layer is known as cladding whose function is to make the light to be confined to the core. The outer most region is called sheath whose function is to protect the cladding and core from harmful influence of moisture. The diameter is about 150 μm.

* Types of optical fibre

optical fibre
- monomode
- multi-mode
  - step index
  - gradded index

* mono-mode optical fibre –

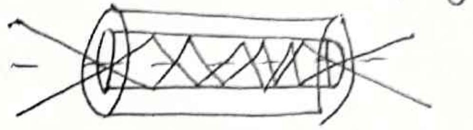
The mono-mode optical fibre is one in which core is thin about 9 μm in diameter and cladding is very thick. The mode is the path followed by the light signal, therefore in mono-mode fibre there is only one path for the transmission and it is along the axis of fibre.

* Multi-mode -

The multimode fibre is one in which core is thick about 100 μm in diameter. It is further divided into two types -

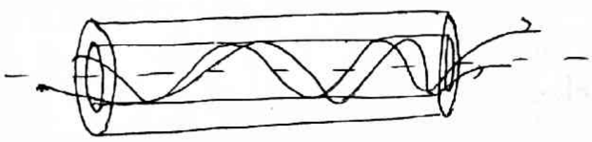
(a) step index -

In the step index fibre the refractive index of core is about 1.52 and the refractive index of cladding is about 1.48 and both refractive index are constant. Therefore there is a certain change in refractive index as we go towards cladding surface. Thus the path followed by light signal is zig-zag. The transmission of signal is not ~~com~~ smooth.

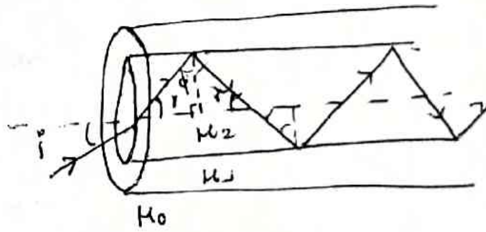


(b) Gradded index -

In case of gradded index fib~~r~~e the refractive index is gradually decreasing from core to cladding surface. Therefore refractive index is maximum at core and minimum at cladding surface. Therefore it causes the periodic focusing of light propagating through the fibre, thus manufacturing is more complex.



* working of optical fibre
(Angle of acceptance)



optical fibre works on the principle of total internal reflection at the cladding surface. The signal is transmitted through the core and finally emerges out through another end due to multiple reflection. The maximum angle of incidence at which total internal reflection takes place is called angle of acceptance. The angle of incidence at cladding surface must be equal to or greater than critial angle.

Let μ_0 be the refractive index of the medium from which light enters and μ_1 and μ_2 be the refractive index of cladding and core resp. such that $\mu_2 > \mu_1$.

Let i be the angle at which light enters the fibre and 'r' be the angle of refraction. Let ϕ be the angle of incidence at cladding surface.

From mell's law, to the launching face,

$$ {}_0\mu_2 = \frac{\sin i}{\sin r} \quad --(1) $$

but $r = 90 - \phi$

$$ \Rightarrow \sin r = \sin(90 - \phi) $$

$$ \Rightarrow \sin r = \cos\phi \quad --(2) $$

From (1) and (2) $$ {}_0\mu_2 = \frac{\sin i}{\cos\phi} $$

$$\Rightarrow \frac{\mu_2}{\mu_0} = \frac{\sin i}{\cos\phi}$$

$$\Rightarrow \mu_2 = \frac{\sin i}{\cos\phi} \quad [\mu_0 = 1]$$

If $\phi = \phi_c$ (critical angle) then,

$$\mu_2 = \frac{\sin i}{\cos\phi_c}$$

$$\Rightarrow \cos\phi_c = \frac{\sin i}{\mu_2} \quad ---(3)$$

Again, from core to cladding, $\mu_1 = \frac{\sin\phi_c}{\sin 90}$ [when $\phi = \phi_c$]

$$\Rightarrow \frac{\mu_1}{\mu_2} = \sin\phi_c \quad ---(4) \quad [\sin 90° = 1]$$

squaring and adding (3) and (4)

$$\sin^2\phi_c + \cos^2\phi_c = \frac{\mu_1^2}{\mu_2^2} + \frac{\sin^2 i}{\mu_2^2}$$

$$\Rightarrow 1 = \frac{\mu_1^2 + \sin^2 i}{\mu_2^2}$$

$$\Rightarrow \sin^2 i = \mu_2^2 - \mu_1^2$$

$$\Rightarrow \sin i = \sqrt{\mu_2^2 - \mu_1^2}$$

$$\Rightarrow i = \sin^{-1}\sqrt{\mu_2^2 - \mu_1^2} \quad ----(5)$$

This is the angle of acceptance at air side or angle of acceptance at which the light signal is transmitted from one end to another.

* uses of optical fibre -

① optical fibre is used mainly for the transmission of signal to a large distance in the form of cable. It is used in telecommunication, about 500000 talks through one fibre at a time.

② It is used for Television broadcasting.

③ It is useful in computer networking.

④ The fibre optic endoscope is used to inspect internal organ for diagonstic purposes.

⑤ It is used as direction signalling radars for war weapon

* Advantages -

① optical fibres are made from silica (SiO_2) which is one of the most abundant materials of the earth. The overall cost of fiber optic communication is lower than that of an equivalent cable communication system.

② They are smaller in size, lighter in weight and flexible yet strong.

③ In optical fibres information is carried by photons. photons are electrically neutral and can not be distrubed by high voltage fields, lightining etc.

(4) As the optical fibre is made from insulator, It is not hazardous and no chance of sparking.

(5) The light waves propagating along the optical fibre are completly trapped within the fibre and can not leak out. The possibility of cross talk is minimized when optical fibre is used. Therefore transmission is more secure and private.

(6) The transmission loss per unit length of an optical fibre is about 4 dB/km. Therefore, longer cable runs betn repeaters are feasible. If coppor cables are used, the repeaters are to be spaced at interval of 2 km. In case of optical fibres, the interval can be as large as 100 km and above.

* Fibre optic communication system -

A fibre optic communication system is very much similar to a traditional communications system and has three major components. A transmitter converts electrical signal to light signals, an optical fibre transmits the signals and a receiver captures the signals at the other end of the fibre and converts them to electrical signals.