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P – II

LASER AND FIBRE OPTICS

UNIT- 2

LASER AND FIBRE OPTICS

Lect-10

* Coherence properties of Laser light :—

Basically, the light from a laser and from any normal source of light are both electromagnetic in nature but they differ basically in monochromaticity, directionality and other more detailed properties. The light that is emitted from a conventional light source is jumble of tiny, separate waves that reinforce or cancel each other in random fashion. The wavefront thus produce varies from point to point and changes instant to instant.

There are two types of coherence:-

1. Temporal Coherence :—

This type of coherence referers to the correlation between the field at a point at two different times ie the relation between $E(x,y,z,t_1)$ and $E(x,y,z,t_2)$. If phase difference between two fields is constant during the period covered by observation which is of the order of a few microseconds, the wave is said to be temporal coherence.

In a laser, in contrast to an ordinary light the optical resonant cavity is excited in different longitudinal

discrete frequencies of oscillations.
In optical resonator without the laser medium, the finite loss of resonator leads to an exponentially decaying output amplitude which leads to finite line width of output. While in an actual laser oscillating in steady state, the loss is exactly compensated by gain provided by laser medium and when the laser is oscillating in a single mode the output is essentially a pure sinusoidal wave. Superimposed on this are the random emissions arising out of spontaneous emissions and it is this spontaneous emission which limits the ultimate monochromaticity of laser.

While for the well controlled laser we obtain

$$\Delta\nu = 500\ Hz$$

$$t_c = 2\times10^{-3}\ sec$$

The corresponding coherence length is

$$\tau_c = 6\times10^{7}\ cm = 600\ km.$$

The long coherence length imply that the laser could be used for performing interference experiments with very large path difference.

2. Spatial Coherence :—

The wavefront of given electromagnetic wave, the two fields at two different points are said lo space coherente, if they preserve a constant phase difference over any time 't'. This is even possible when two beams are individually time incoherent as long as any phase change in one of the beam is occompained by simultaneous oqual phase change in the other beam.

In order lo understand concept of spatial coherence we consider the young's double slit experiment.

The measure of fringe contrast called fringe visibility serves a useful measure of coherence.

The visibility of fringes defined by Michelson is

$$V = \frac{E_{max} - E_{min}}{E_{max} + E_{min}}$$

E_{max} → relative energy of a bright fringe.

E_{min} → The energy of a dark fringe near bright fringe.

The visibility of fringe is unity ($E_{min} = 0$) only when fringes are produced by coherent beam of oqual amplitude, whereas that of fringes produced by non-coherent beam is zero ($E_{max} = E_{min}$) and thus there is no fringes. The two secondary sources are is degree of coherence or visibility of fringes.)

Lect 17

Interaction of Radiation with matter:

~~The~~ To understand the working principle of a laser quantum process that take place in material when it is exposed to radiation are studied. A material medium is composed of identical atoms or molecules each of which is characterised by set of discrete allowed energy states. An atom can move from one energy state to another when it recieves or releases energy equal to energy difference between those two states. It is termed as quantum jump or transition.

The interaction of radiation with matter (atoms) leads to the following distinct process in medium.

process-1 :— (Absorption) An atom residing in lower energy state E_1 may absorb the incident photon and jump to excited state E_2. The transition is known as stimulated absorption or induced absorption or absorption.

Mathematically

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

where A is an atom in lower state

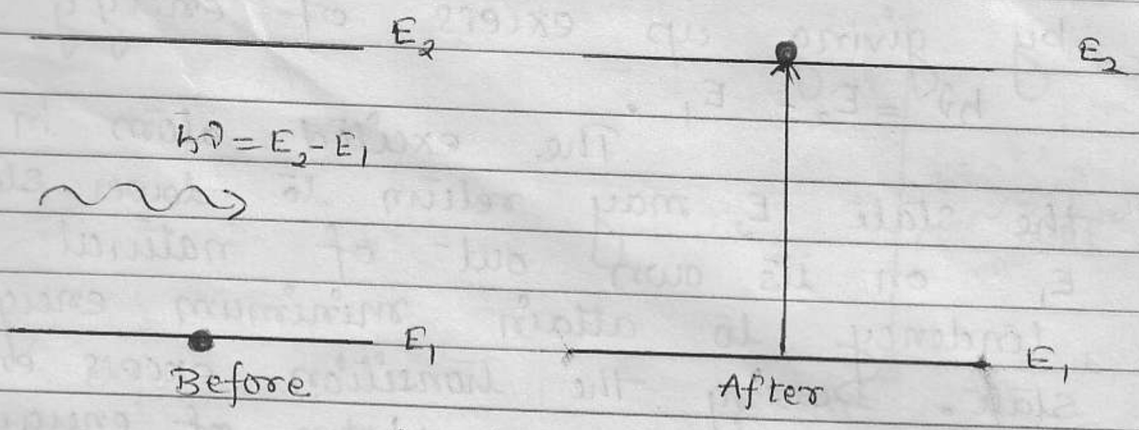


fig 2.D

The number of absorption transitions occuring in the material at any instant will be proportional to number of atoms in lower state E_1 and number of photon beams in incident beam. The number of atoms excited N_{ab} during Δt time is given by

$$\boxed{N_{ab} = B_{12} N_1 Q \Delta t}$$

where

$N_1 \rightarrow$ No. of atoms in E_1 state

$Q \rightarrow$ energy density of incident beam.

$B_{12} \rightarrow$ probability of absorption transition.

process-2 Spontaneous Emission :—

Atom can not reside in excited state for long time because of natural tendency of atoms to seek out by giving up excess of energy $h\nu = E_2 - E_1$.

The excited atom in the state E_2 may return to lower state E_1 on its own out of natural tendency to attain minimum energy state. During the transition excess energy is released as a photon of energy $h\nu = E_2 - E_1$. This type of process in which photon emission occurs without any external agent is called spontaneous emission. It may be represented as

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

The number of spontaneous emission taking place in Δt time depends only on number of atoms N_2 lying in the excited state E_2. It is given by

$$\boxed{N_{sp} = A_{21} N_2 \Delta t}$$

where

$N_2 \rightarrow$ number of atoms in state E_2

$A_{21} \rightarrow$ probability of spotaneous transition.

The light generated by spontaneous emission process is incoherent.

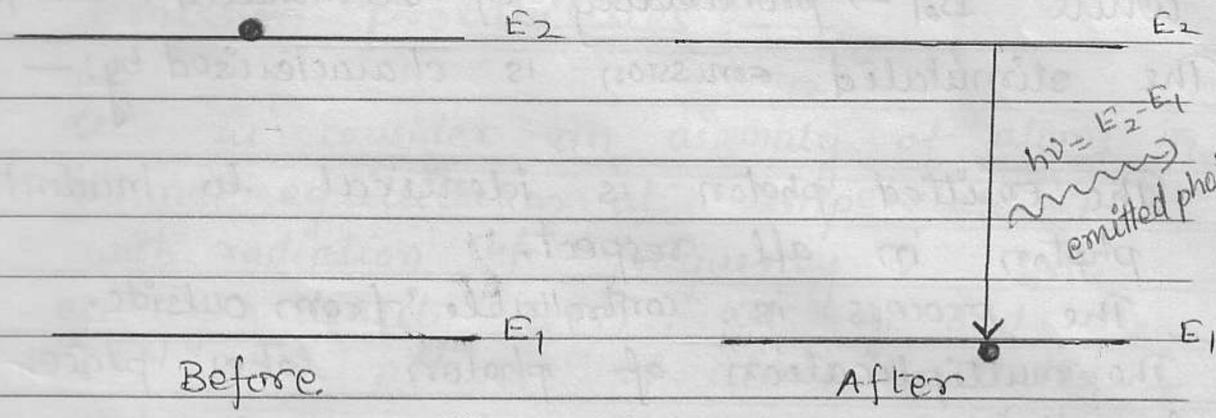


fig 2.1

process-3 Stimulated Emission :

An atom in excited state need not wait for spontaneous emission to occur. There exist another mechanism by which an excited atom can make downward transition and emit light. A photon of energy $h\nu = E_2 - E_1$ can induce the excited atoms to make a downward transition releasing energy in the form of photon. Thus the interaction of a photon with an excited atom triggers the excited atoms to drop to lower energy states giving up photons. The phenomenon of forced emission of photons is called induced emission or stimulated emission.

It may be represented as

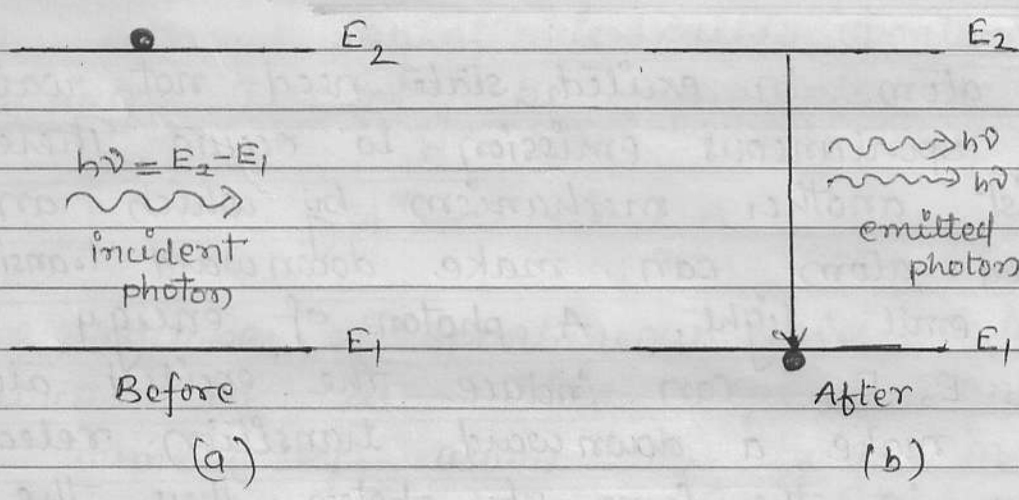
$$A^* + h\nu \rightarrow A + 2h\nu$$

The number of stimulated transitions N_{st} occuring in material during Δt time is

$$N_{st} = B_{21} N_2 Q \Delta t$$

where $B_{21} \rightarrow$ probability of stimulated emission.
The stimulated emission is characterised by:—

1. The emitted photon is identical to incident photon in all respect.
2. The process is controllable from outside.
3. The multiplication of photon takes place in this process.



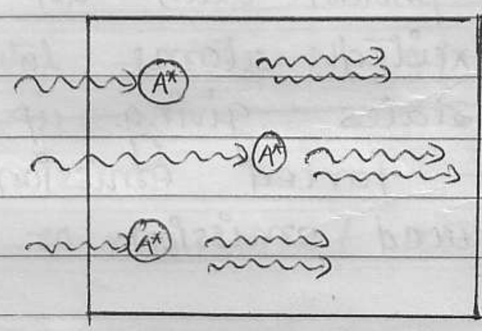


fig 2.2(c)

Relation between spontaneous and stimulated emission probabilities :—

Let us consider an assembly of atoms in thermal equillibrium at temperature 'T' with radiation of frequency ν and energy density $Q(\nu)$. Let N_1 and N_2 be the number of atoms in states 1 and 2 respectively at any instant. The number of atoms in state 1 that absorb a photon and rise to state 2 in ~~per unit~~ Δt time is,

$$N_{ab} = N_1 B_{12} Q \Delta t$$

The number of atoms in state 2 that drop to state 1, either spontaneously or under stimulation, emitted a photon in Δt time is

$$N_{sp} + N_{st} = A_{21} N_2 \Delta t + B_{21} N_2 Q \Delta t$$

$$N_{sp} + N_{st} = N_2 \Delta t \left(A_{21} + B_{21} Q \right)$$

In equillibrium state

$$N_{ab} = N_{sp} + N_{st}$$

$$N_1 B_{12} Q \Delta t = N_2 \Delta t \left(A_{21} + B_{21} Q \right)$$

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

$$N_2 A_{21}$$

$$Q = \frac{N_2 A_{21}}{N_2 B_{21}\left(\frac{N_1}{N_2}\frac{B_{12}}{B_{21}} - 1\right)}$$

$$Q = \frac{A_{21}}{B_{21}} \cdot \frac{1}{\frac{N_1}{N_2}\left(\frac{B_{12}}{B_{21}}\right) - 1}$$

Einstein proved thermodynamically that the probability of stimulated absorption is equal to the probability of stimulated emission

$$B_{12} = B_{21}$$

Then we have

$$Q(\nu) = \frac{A_{21}}{B_{21}} \frac{1}{\left(\frac{N_1}{N_2} - 1\right)}$$

The equillibrium distribution of atoms among different energy states is given by using Boltzmann's distribution law according to which

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

$$\text{or} \quad \frac{N_1}{N_2} = e^{(E_2 - E_1)/kT} = e^{h\nu/kT}$$

Therefore equation for energy density becomes

$$Q = \frac{A_{21}}{B_{21}} \cdot \frac{1}{\left(e^{h\nu/KT} - 1\right)} \quad \text{——} \ (1)$$

Comparing this equation with plank's radiation law (according to which the energy density of black body radiation of frequency ν at temperature T is given by)

$$Q(\nu) = \frac{8\pi h \nu^3}{c^3} \frac{1}{\left(e^{h\nu/KT} - 1\right)} \quad \text{——} \ (2)$$

∴ we get

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

This shows that the ratio of Einstein's coefficient of spontaneous emission to Einstein's coeff. of absorption of radiation is proportional to cube of frequency (ν^3).

Lect 17

Population Inversion :—

Laser operations requires obtaining stimulated emission almost exclusively. To achieve high percentage of stimulated emission an artificial situation known as population inversion is to be created.

In the state of thermal equillibrium there are more atoms in lower level than in upper level. In order to achieve stimulated emission exclusively. Therefore a non-equillibrium state is to be produced in which the population of the upper energy level exceeds to a large extent the population of the lower energy level. When this situation occurs, the population distribution between the levels E_1 and E_2 is said to be inverted, and the medium is said to ~~be~~ have gone into the state of population inversion.

Pumping :—

The process of achiving population inversion is known as "pumping" of atoms. Most commonly used methods are as follows—

(1) optical pumping (used in Ruby laser)
(2) electric discharge (used in Helium - Neon laser)
(3) Inelastic atom - atom collision.
(4) Direct conversion (used in CO_2 laser)

The principal pumping schemes :—

The transition between the two levels that generates stimulated emission is called a lasing transition. The terminal level is called the lower lasing level and upper level is called upper lasing level. Important pumping schemes are three level pumping and four level pumping schemes.

(i) Three level pumping scheme :—

Let us assume an atomic system has three energy levels. The state E_1 is ground state and E_2 and E_3 are the excited states. In the scheme atoms are excited to state E_3 (known as pumping level) when light of frequency ν_P (pump freq.) $= (E_3 - E_1)/h$ is incident on them.

Atoms do not stay at the E_3 level and undergo downward transition either to E_1 or E_2 levels. The probability of spontaneous transition $E_3 \to E_1$ is comparable to that of $E_3 \to E_2$. The E_2 is metastable state. The probability of spontaneous transition $E_2 \to E_1$ is extremely small. When the medium is exposed to radiation of frequency ν_P a large number of atoms will be excited to higher energy level (E_3. Some of these atoms make spontaneous transition to lowest level E_1 but many of them makes spontaneous transition to E_2 state through a non-radiative transition. As spontaneous transition from $E_2 \to E_1$ occurs rarely the atom get trapped in the E_2 state. after short time large number of atoms are accumulated at E_2 state, when more than half of the atoms are accumulated in E_2 a condition of population inversion occurs between E_2 and E_1. Now photon of energy $(h\nu = E_2 - E_1)$ can trigger stimulated emission of atoms in E_2 state.

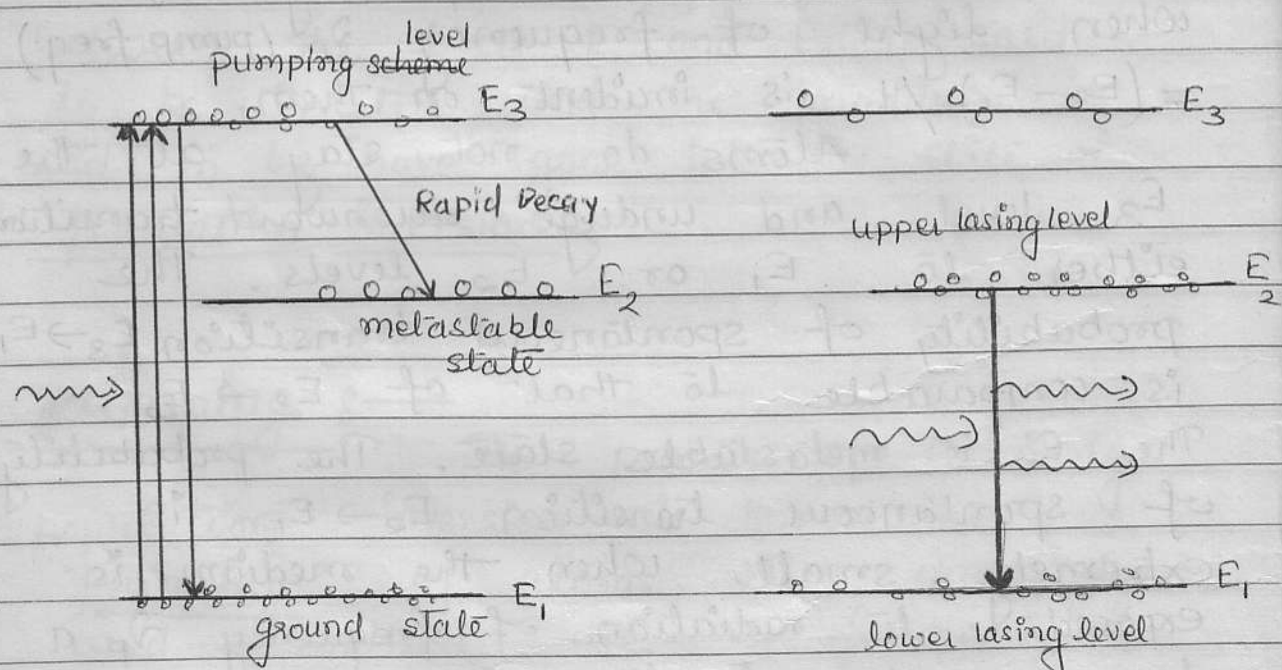


fig23 * A typical three level pumping.

(ii) Four-level pumping scheme :-

pumping frequency lifts the active centres from the ground level E_1 to the uppermost level E_4. From pumping level E_4 the atoms rapidly falls to the metastable state E_3. The population at this state grows rapidly while the level E_2 is virtually empty. Therefore population inversion is achived between the states E_2 and E_3. A photon of energy $h\nu = E_3 - E_2$ can start a chain of stimulated emissions, bringing the atoms into state E_2. from there atoms undergo non-radiative transitions to ground state E_1 and will be available once again to participate in the process.

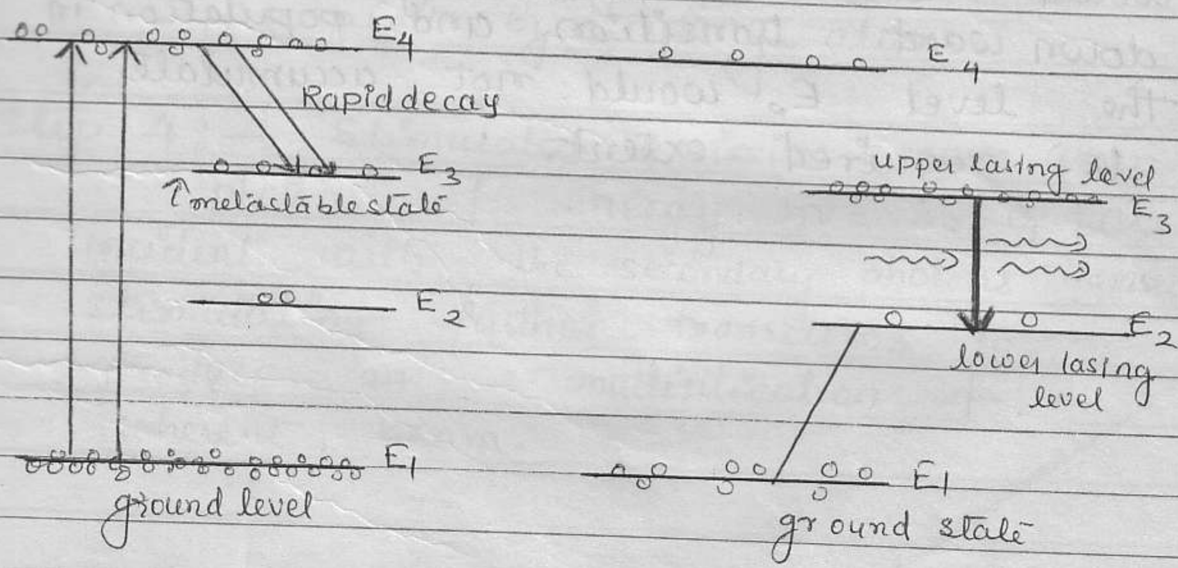


fig 2.4 :- A typical four level pumping

(iii) Two-level pumping Scheme:-

A two level pumping is not suitable for obtaining population inversion. The time span Δt for which atoms have to stay at upper level E_2 must be longer for achiving population inversion condition. According to Heisenberg's uncertainity principle

$$\Delta E \cdot \Delta t \geq \hbar$$

Δt is longer if ΔE is smaller ie E_2 is narrow. If ΔE is smaller pumping efficiency is smaller as a consequence less number of atoms are excited. Though the sharp energy level supports the population inversion, enough population cannot be excited to E_2 state. The result is that the upward transition would be accompained by premature down ward transition and population in the level E_2 would not accumulate to required extent.

principle of laser :-

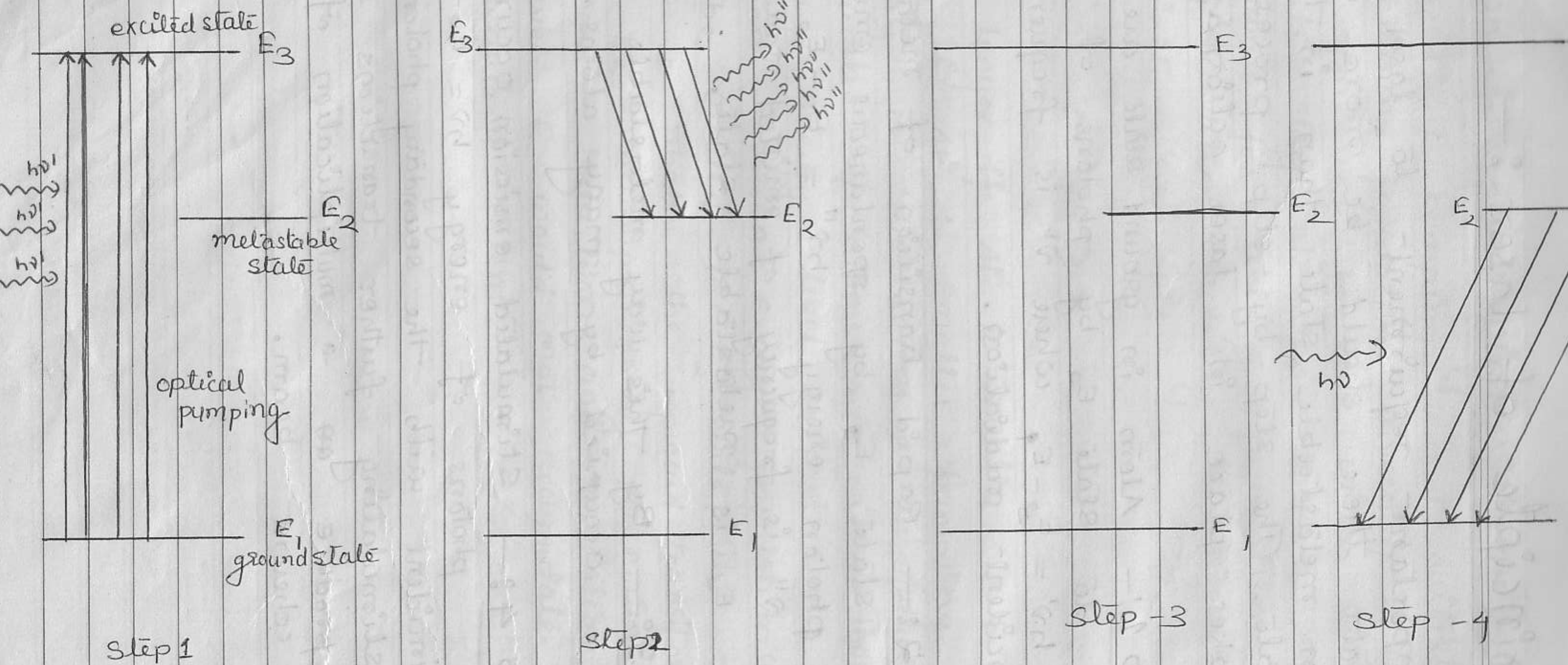
Important requirment to laser action is that there should be more atoms in metastable state than in the ground-state. The step-by-step process that takes place in laser action are -

Step 1 :- Atom in ground state are pumped to state E_2 by photons of energy $h\nu' = E_3 - E_1$ where ν' is frequency of incident radiation.

Step 2 :- Rapid transition of metastable state E_2 by spontaneous emission of photon energy $h\nu'' = E_3 - E_2$ where ν'' is frequency of emitted radiation and E_2 is metastable state.

Step 3 :- By this way metastable state are accupied by many atoms.

Step 4 :- Stimulated emission occurs when photons of energy $h\nu = E_2 - E_1$ are incident with the secondary photons themselves stimulating further transitions to produce a multiplication of coherent beam.



excited state
E_3
metastable state
E_2
optical pumping
E_1 ground state
$h\nu'$
step 1
$h\nu''$
step2
step -3
$h\nu$
step -4

fig 2·5 —

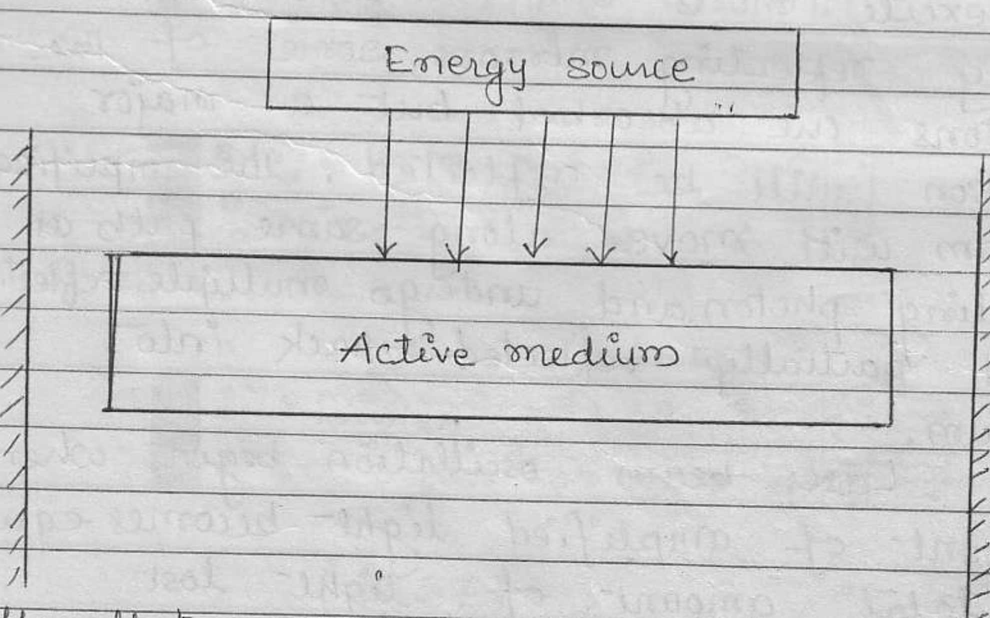
Components of Laser :—

A laser requires three components for operation. These are

(1) <u>Energy source</u> :— that will raise the system to excited state.

(2) <u>Active medium</u> :— which when excited achieves population inversion. The active medium may be a solid, liquide, or gas.

(3) <u>Optical Resonator</u> :— It consists of two mirrors facing each other. The active medium is enclosed by this cavity. One of the mirror is fully reflective while other mirror is partially transparent. The optical cavity is made use of to make stimulated emission possible in more number of atoms in active medium.

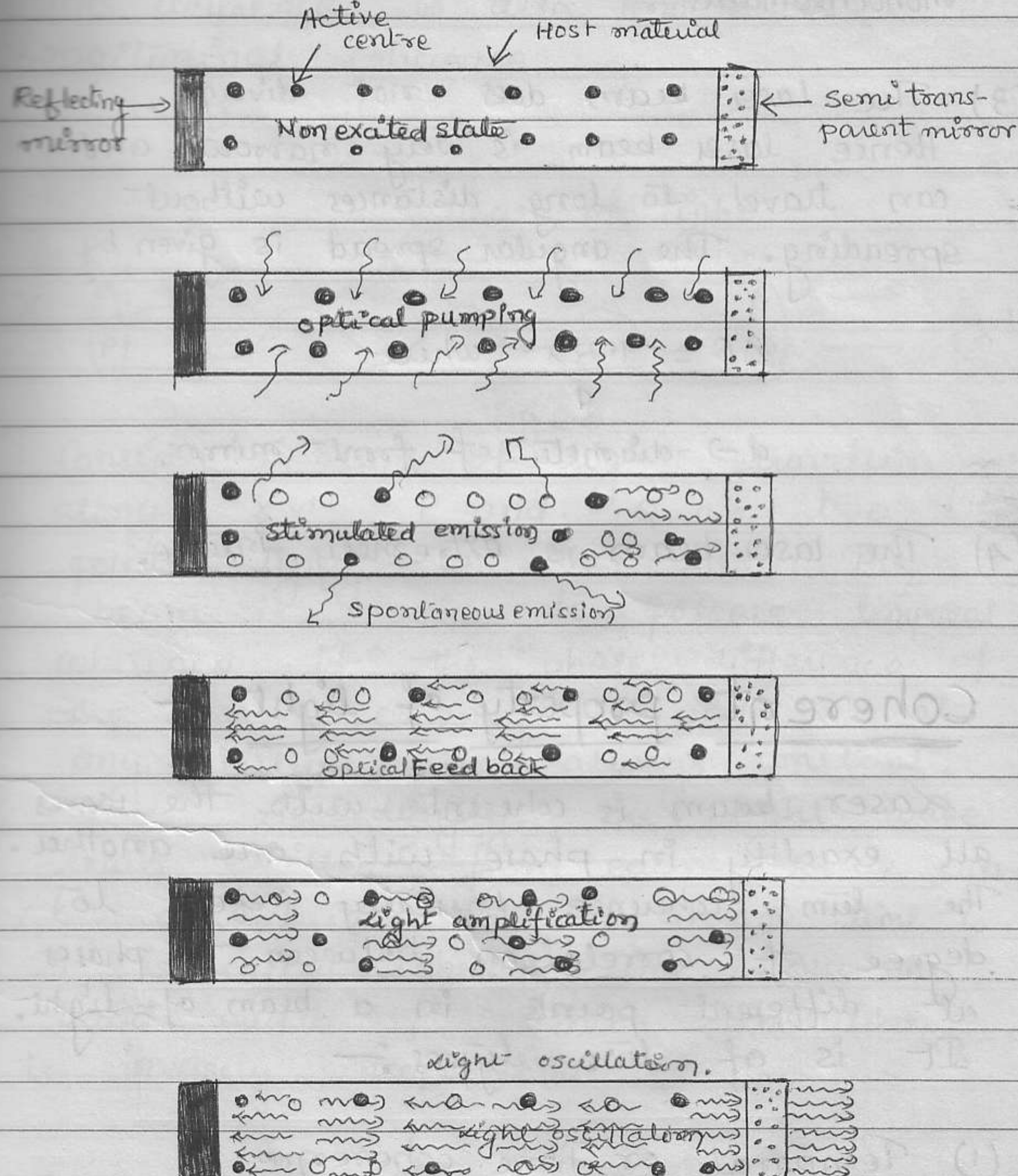


Action of optical Resonator :—

Initially the active centres in the medium are in ground state. Medium is in non-excited state. After suitable pumping process the material is taken into population inversion state. Spontaneous photons are emitted in the initial stage in all directions. To generate a coherent light output the photons that travels in specific direction are selected while other are rejected and attain the maximum possible amplification of light, the stimulated photons are made to pass through medium a number of times. The mirrors constituting the resonator cause directional selectivity. On reaching semitransparent mirror some of the photons are transmitted out and part of them are reflected back.

After reflection from the semi-transparent mirrors photons de-excite more and more atoms. At fully reflecting mirrors, some of the photons are absorbed but a major portion will be reflected. The amplified beam will move along same path as starting photon and undergo multiple reflection, and partially reflected back into medium.

Laser beam oscillation begins when amount of amplified light becomes equal to total amount of light lost through sides of the resonator, through the mirrors and through absorption by medium. As the oscillations built-up to enough intensity it emerges through the front mirror as highly collimated intense beam (laser light).



(fig 2.7)

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Properties of Laser Beam :—

(1) The laser beam is coherent, with the waves all exactly in phase with one another.

(2) The laser light is almost perfectly monochromatic

(3) The laser beam does not diverge. Hence laser beam is very narrow and can travel to long distances without spreading. The angular spread is given by

$$\Delta\theta = \frac{1.22\lambda}{d} \quad \text{where}$$

$d \rightarrow$ diameter of front mirror.

(4) The laser beam is extremely intense.

Coherent property of light :—

Laser beam is coherent with the waves all exactly in phase with one another. The term coherence basically refers to degree of correlation between the phases at different points in a beam of light. It is of two types :—

(1) Temporal or Time coherence
(2) Spatial coherence.

Temporal or Time Coherence :—

If the phase difference of waves crossing the two points lying along the direction of propogation of beam is time dependent then the beam of light is said to ~~be~~ possess temporal or time coherence. This coherence is also known as longitudinal coherence.

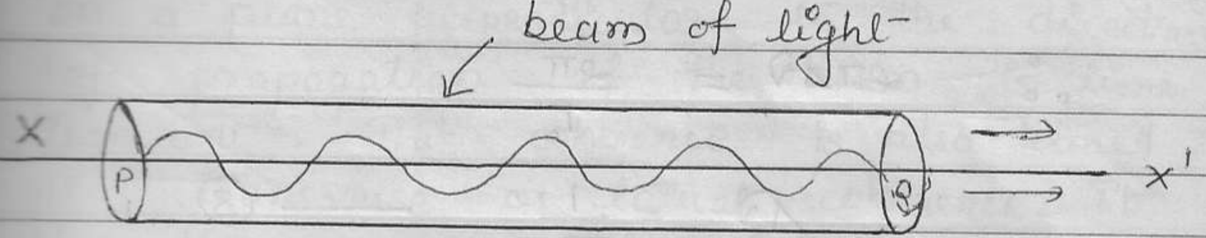

fig 2.8.

Consider a beam of light travelling along XX'. P and Q are two points lying on this line. The beam is said to possess temporal coherence if the phase difference of the waves crossing P and Q at any instant is always constant.

Accordingly, the light wave train emitted from each source can be characterized by an average time T_0. It is called coherent time. Also the band width of spectral distribution is inversely proportional to T_0.

$$\Delta\omega = \frac{2\pi}{T_0} \quad \text{—} \; (1)$$

The average length of wave train is

called coherent length. If the velocity of light is c then coherent length L_c is given by

$$L_c = c T_0 \quad \text{--- (2)}$$

Since $\Delta\omega = 2\pi \Delta\nu$

where $\Delta\nu$ is the frequency in Hz.

$$\therefore \quad 2\pi\Delta\nu = \frac{2\pi}{T_0}$$

$$\Delta\nu = \frac{1}{T_0} \quad \text{--- (3)}$$

Again $\nu = \frac{c}{\lambda}$

$$\therefore \quad |\Delta\nu| = +\frac{c}{\lambda^2}\Delta\lambda \quad \text{--- (4)}$$

from (2) and (3) we get

$$\Delta\nu = \frac{c}{L_c} \quad \text{--- (5)}$$

F equation (4) and (5) we get

$$\frac{c}{L_c} = \frac{c}{\lambda^2}\Delta\lambda$$

(1)

(2) Sp is

$$\therefore \boxed{\Delta\lambda = \frac{\lambda^2}{L_c}}$$

where $\Delta\lambda$ is called the natural line width. Hence temporal coherence depends upon the value of coherent length and coherent time.

(ii) Spatial Coherence :—

A laser beam is said to possess spatial coherence, if the phase difference of the waves crossing the two points lying on a plane perpendicular to the direction of propogation of the beam is time independent. This coherence is also termed as transverse or lateral coherence. It is the measure of minimum separation across the wave from where two waves remain coherent.

Consider a beam travelling along the line xx'. Here abcd is plane perpendicular to $x'x$. The beam is said to possess spatial coherence if the phase difference of the waves crossing p and p' at any instant is constant.

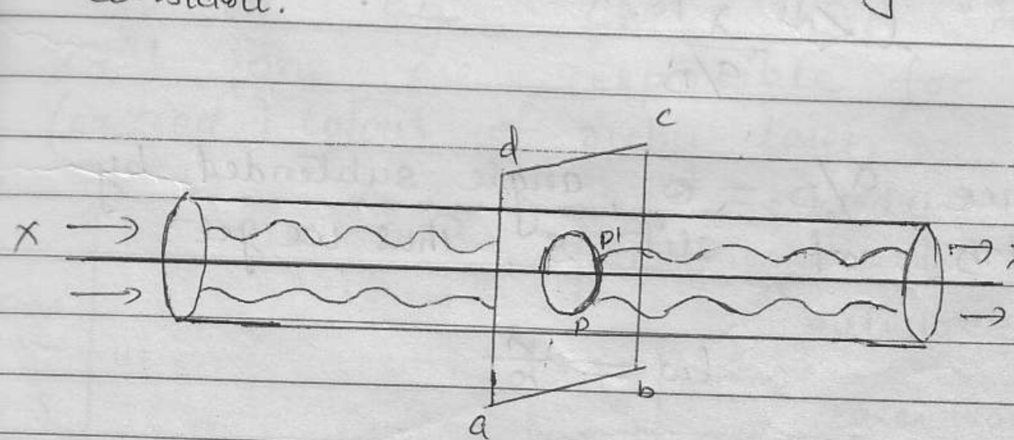

fig 2.9

In second figure S is a source and S_1 and S_2 are two slits of separation 'l' and interference occurs for $l_{max} = l_w$ then this dimensions is called spatial coherence length of the source.

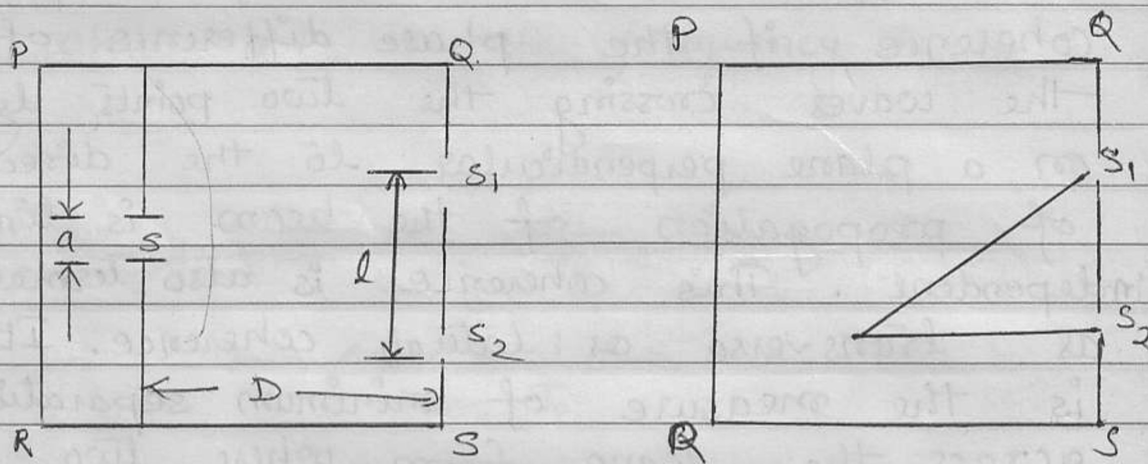

fig 2.10

From figure 2.10 the source S_1 is at a distance D from slits S_1 and S_2, the condition for coherence of S_1 and S_2 is

$$\frac{\lambda}{a} > \frac{l}{D}$$

$$l < \frac{\lambda}{a/D}$$

Since $a/D = \theta$, angle subtended by width of slit S. Thus we get

$$l_w = \frac{\lambda}{\theta}$$

In this case interference have not been observed for separation ~~S, and S~~ S_1S_2 as small as 10^{-3} cm. Thus no constant phase relation exists between S_1 and S_2.

Ruby Laser :—

Ruby laser is based on three level pumping.

Construction :— this laser consists of a pink ruby cylindrical rod whose ends are optically flat and parallel. One end is fully silvered and other is only partially silvered. Upon the rod is wound a coiled flash lamp filled with xenon gas.

The ruby rod is basically a Al_2O_3 (aluminium oxide) crystal doped with 0.05% (by weight) of chromium oxide (Cr_2O_3). The Al^{3+} ions are replaced by Cr^{3+}. These "impurity" Cr^{3+} ions are responsible for pink (or red) colour of ruby laser.

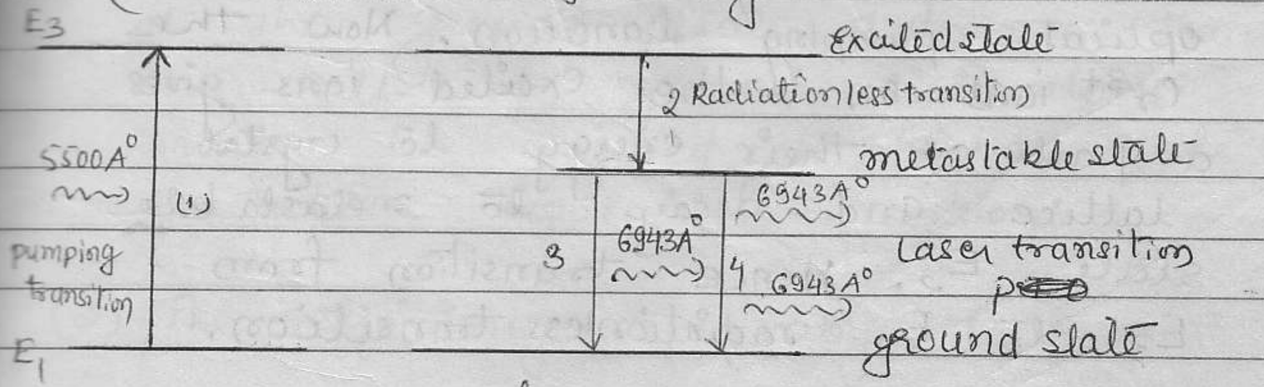

fig 2.11

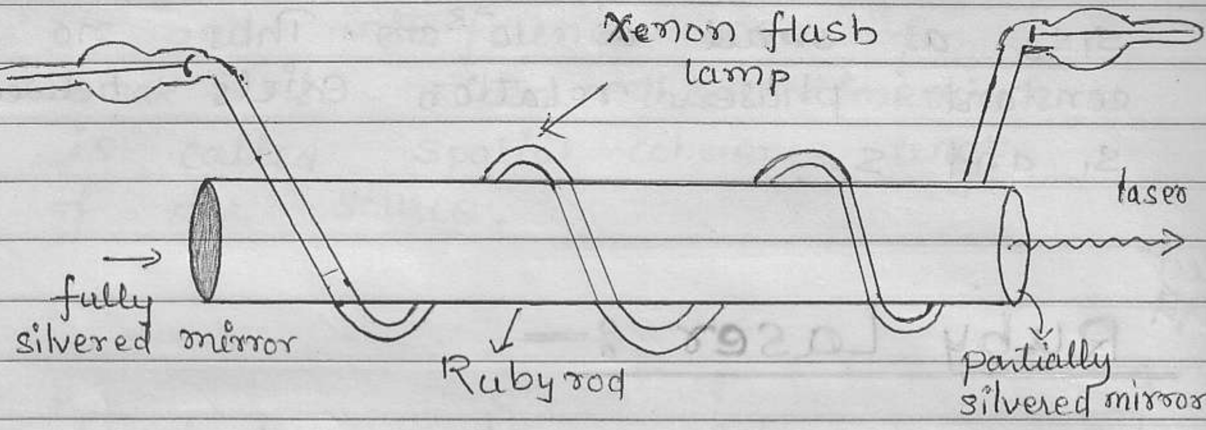

fig 2.12

Working :— The energy level of Cr^{3+} ions on crystal lattice are shown. It consists of three level system. Upper energy level is short lived state E_3 above the ground state energy level E_1. This is intermediate excited state level E_2 which is metastable having life time of 3×10^{-3} sec

Normally, most of chromium ions (Cr^{3+}) are in ground state E_1. When a flash of light falls upon ruby rod, the 5500 A° radiation photon are absorbed by the Cr^{3+} ions which are pumped to excited state E_3. The transition from E_1 to E_3 is optical pumping transition. Now the Cr^{3+} ions on the excited ions gives a part of their energy to crystal lattice and decay to metastable state E_2. Hence transition from E_3 to E_2 radiationless transition.

Metastable state E_2 is long lived hence number of Cr^{3+} ions goes on increasing while, due to pumping, the number in ground state E_1 goes on decreasing. Thus population inversion is establised between metastable state E_2 and ground state E_1.

A spontaneous photons emitted by a Cr^{3+} ion at E_2 level initiates the stimulated emission by the other Cr^{3+} ions in metastable state. The wavelength of the photon (beam) is 6943 A°. This photon travels through the ruby rod and if it is moving along axial direction and repeated reflected. This results in amplified strong laser beam of wavelength 6943 A°. This stimulated transition 4 is the laser transition. The laser beam is sufficiently intense, part of it emerges through partially silvered end of the crystal.

Draw backs :—

(1) The laser requires high pumping power because the laser transition terminates at the ground state and more than one-half of ground state atoms must be pumped to higher state to achieve population inversion.

(2) The efficiency of ruby laser is

very low because only green component of pumping light is utilized while rest component of light is rejected.

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Helium - Neon Laser :—

Helium Neon Laser is a four level laser

Construction :—

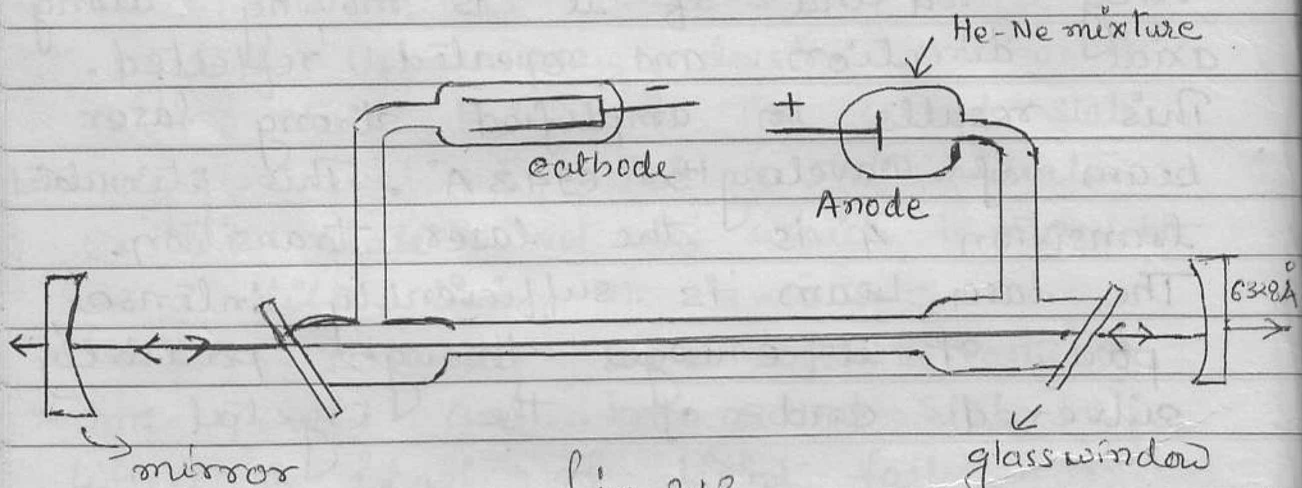


fig 2.13

It consists of a long discharge tube of length about 50 cm and diameter 1 cm. The tube is filled with mixture of Helium and neon gases in ratio 10:1. Electrodes are provided to produce a discharge in the gas ~~the~~ and they are connected to high voltage power supply. On the axis of the tube two reflectors are fixed which forms the Fabry - perot resonator. The distance between the mirror is adjusted such that it equals $m\lambda/2$ and supports standing wave pattern.

Working :—

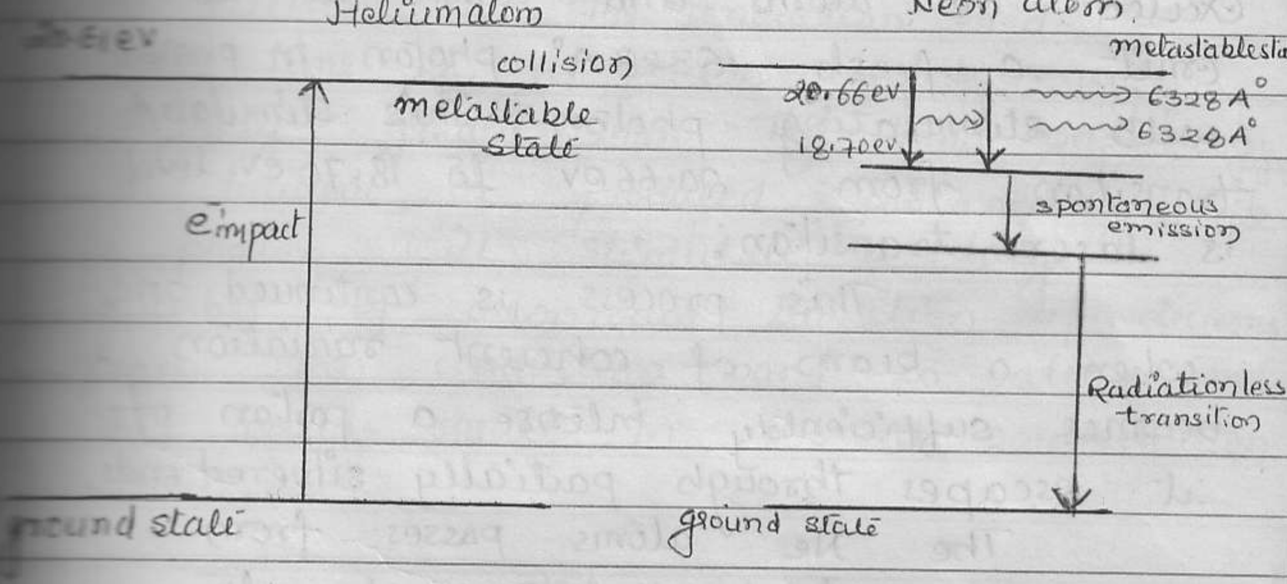


fig 2.14

when the power is switched on, the electrons from discharge collide with and pump the He and Ne atoms to metastable state 20.61 ev and 20.66 ev respectively above the ground states. Some of the excited atoms (He) transfer their energy to ground state Ne atoms in collisions with the 0.05 ev of additional energy being provided by the kinetic energy of the atoms. Thus the purpose of He atom is to help in achieving population inversion in Ne atoms. When an excited Ne atoms passes, from the metastable state at 20.66 eV to an excited state of 18.70 eV, and it emits a photon of wavelength 6328 A°. This photon travels through gas mixture and if it is moving parallel to the axis of the tube, is reflected back and forth by the mirror ends until it stimulates an excited Ne atoms and causes it to emit a fresh 6328 A° photon in phase with stimulating photon. This stimulated transition from 20.66 eV to 18.70 eV level is laser transition.

This process is continued and when a beam of coherent radiation becomes sufficiently intense a portion of it escapes through partially silvered ends.

The Ne atoms passes from the 18.7 eV level spontaneously to the lower metastable state emitting incoherent light and finally neon atoms comes down to the ground state through collision with tube walls. This transition from lower metastable state to the ground state is radiationless transition.

In He-Ne, transition does not terminates at the ground level, hence the power needed for excitation is less than that in three-level laser.

~~Solid~~ - State

Semiconductor laser

principle :— In semiconductor by increasing temperature, the transition of electrons takes place from top of valence band to conduction band. If by some process we are able to excite a large number of electrons to the conduction band. At this time if a photon having energy slightly greater than the band gap energy is incident or produced spontaneously, such a photon will stimulate a large number of downward transition of electrons from the conduction band to valence band. This would result in coherent amplification.

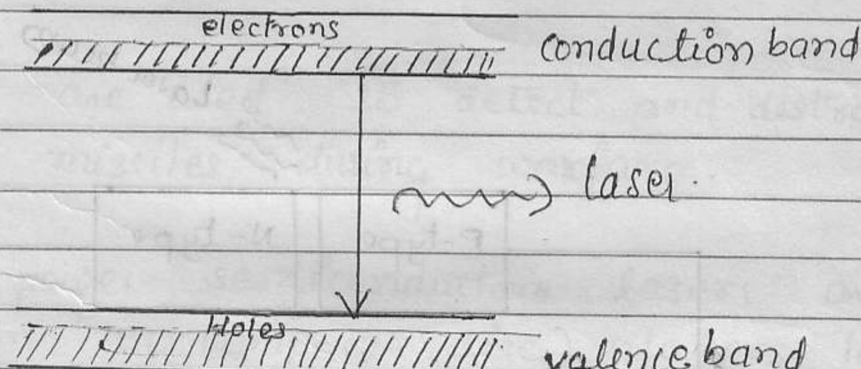
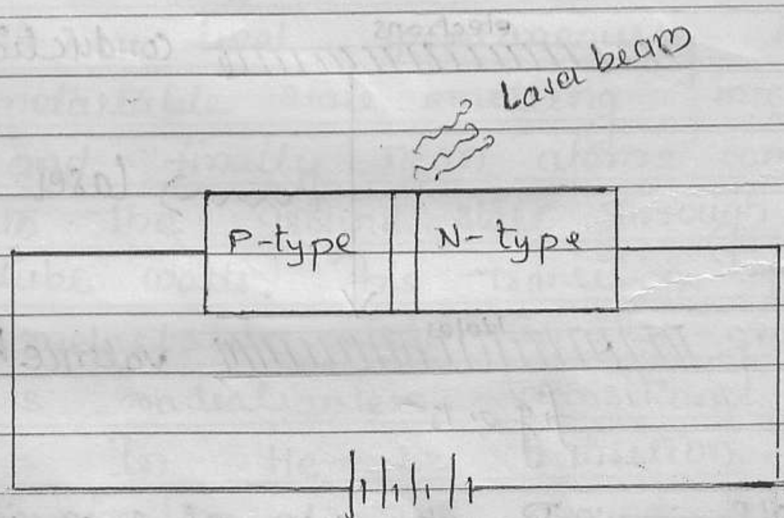


fig 2.15

Working :— By the use of p-n junction the process of population inversion is easily obtained. If p-type semiconductor is connected to positive terminal of a direct current source and n-type to the negative terminal, due to which flow of electrons and holes starts into the junction region. These electrons and holes recombine to produce radiation. Thus deexcitation of electrons from conduction band to valence band takes place. If the current is sufficiently large then one may have laser action.

In a p-n junction laser, laser emission is restricted to a very thin region nearly about 1 μm around the junction. Due to this laser emerges over a wide angle.

The semiconductor laser is extremly small in physical dimension. As the direct conversion of electrical current into light energy is easily achieved, it is also very efficient.



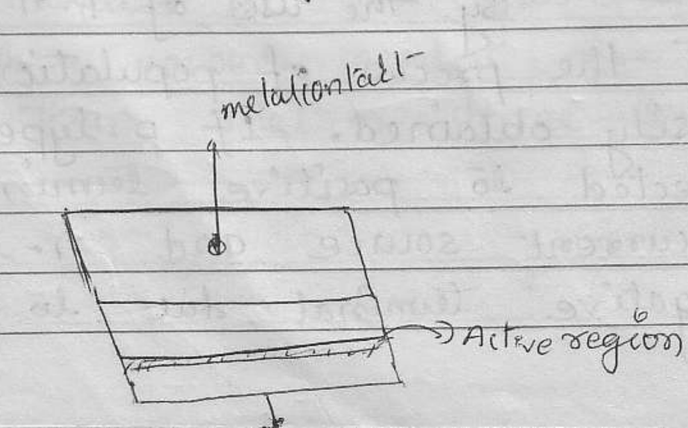


fig 2.16

Application of Laser :—

The common application of Laser are as follows :—

(1) Metallic rods are melted and joined by means of a laser beam.

(2) The laser beam is used to vapourise unwanted material during the manufacture of electronic circuits on semiconductor chips.

(3) CO_2 laser about 100 W output are helpful in surgery because they seal small blood vessels while cutting through tissue by vapourising water in the path of their IR beams.

(4) Lasers are used to detect and destroy enemy missiles during warfare.

(5) low power semiconductors lasers are used in CD (compact disc) players, laser printers, laser copiers etc.

(6) Semiconductor lasers are ideal for fibre optic transmission lines in which the electric signal that would normally sent along copper wires are first converted into series of pulses according to standard code. The lasers then

turn the pulses into flashes of IR light that travel along thin glass fibres and at the other end are changed back into electric signals.

(7) Lasers are also being employed for separating the various isotopes of an elements.

(8) Lasers are used in producing three dimensional image of an object in holography.

(10) Laser beams are used in the ~~production~~ "inertial confinement" of plasma.

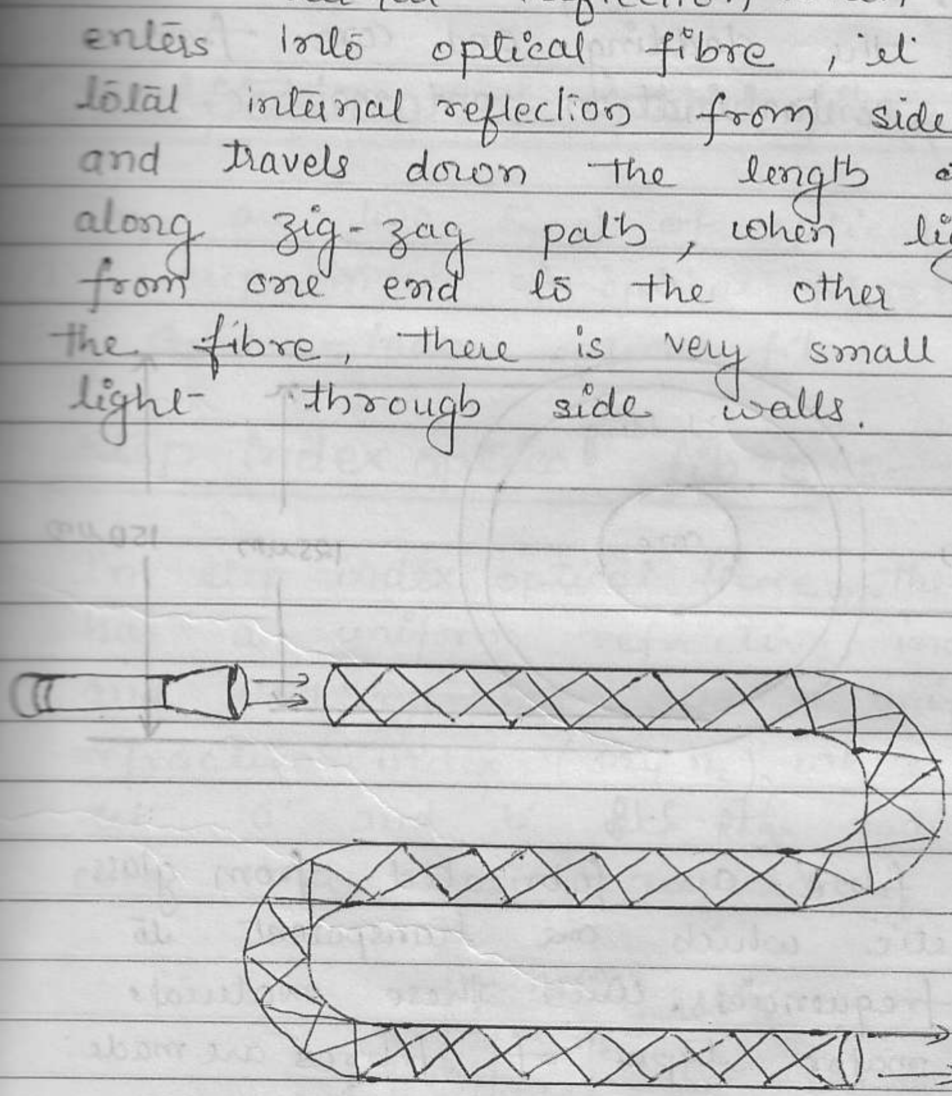
(11) The narrow red laser beam is used in supermarket to read bar codes.

Lect- 18 (Holography)

FIBRE OPTICS :—

Fibre optics deals with the trasmission of light through fibres of glass, plastic or other transparent materials and works on the principle of total internal reflection.

Principle:— Optical fibres are glass or plastic pipes, as thin as human hair, that guide light waves through them and work on the principle of total internal reflection when light enters into optical fibre, it undergoes total internal reflection from side walls and travels down the length of fibre along zig-zag path, when light travels from one end to the other end of the fibre, there is very small loss of light through side walls.



In case of optical fibres, it is essential that there must be ~~there~~ very little of light as it travel through long distance inside optical fibre.

Structure of optical Fibre :—

optical fibre consists of essentially three regions. The central region is known as core. The middle region is called the cladding. The outer region is protective sheath. The refractive index of cladding is always lower than that of the core. Thus cladding keeps the light wave within the core. The cladding also provides some strength to the core. The outer protective sheath protects the cladding and core from abrasions, contamination and moisture.

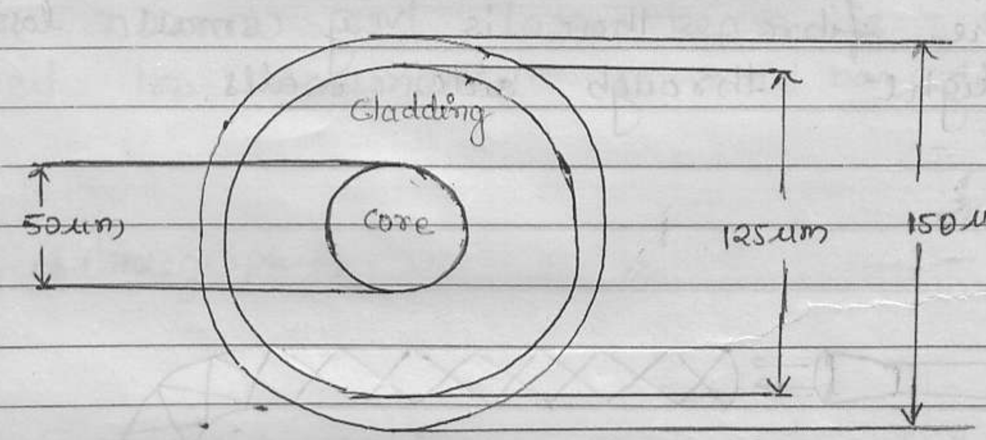


fig-2.18

Optical fibre are fabricated from glass or plastic which are transparent to optical frequencies. With these materials three major types of fibres are made:

(i) plastic core with plastic cladding

(ii) glass core with plastic cladding

(iii) glass core with glass cladding.

The diameter of sheath ranges from 100 - 150 um. Core diameter range from 5 to 600 um whereas cladding must have a minimum thickness of one or two wavelength of light.

In the case of plastic, the core can be polystyrene or polymethyl-meta acrylate, the cladding is generally silicon or teflon. The glass is made of silica.

Classification of optical fibre :-

There are two types of optical fibre

(i) step index of optical fibre

(ii) Graded - index optical fibre

Step index optical fibre :-

In step index optical fibre, the core has a uniform refractive index (n_1) and cladding has also a uniform refractive index (say n_2) where $n_1 > n_2$. Let 'a' and 'b' be the radius of core and cladding respectively.

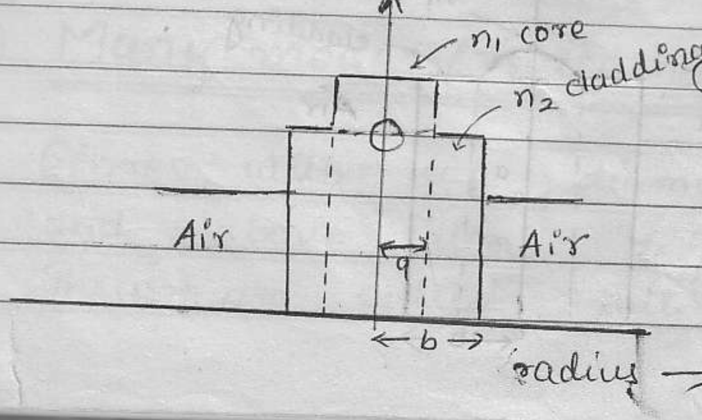


fig 2.19

The path of rays in step-index fibre, is shown. Two rays entering at different angles of incidence with the axis. The two rays travel different path lengths and emerges out at different times.

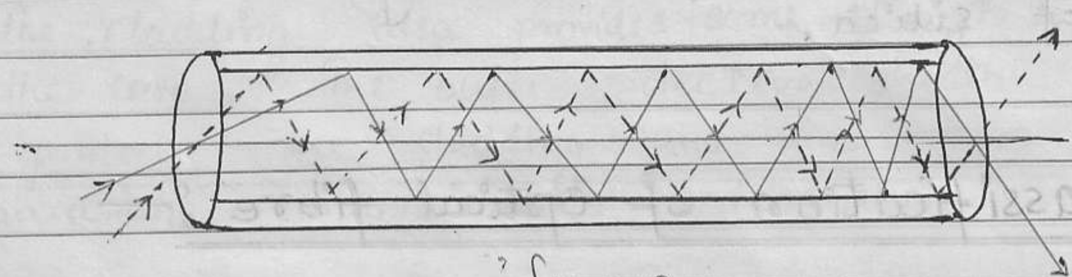
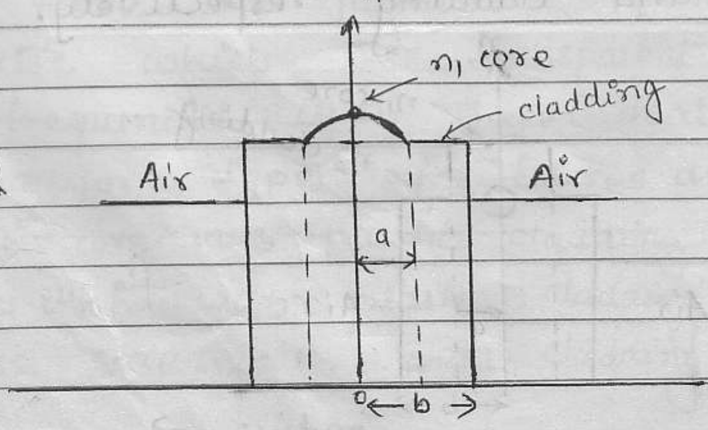


fig 2.20

Graded - index optical fibre :-

If the core has a non-uniform refractive index that gradually decreases from the centre towards the core-cladding interface, the fibre is called a graded index fibre. The cladding has a uniform refractive index. The refractive index profile of graded index fibre is shown in figure.

fig 2.21



The path of ray is shown in figure. It is obvious from the figure that a ray is continuously bent and travels periodic path along the axis. The rays entering at different angles follows different paths with the same period both in space and time. Thus there is a periodic self focussing of the rays. It should be noted that pulse dispersion is less as compared with step index fibre.

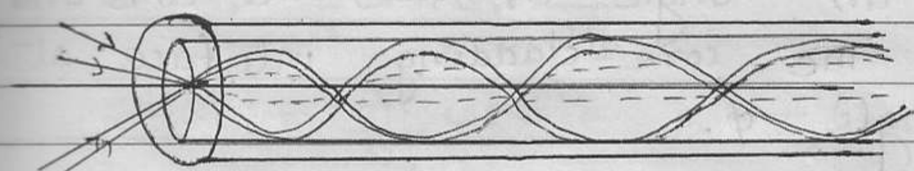


fig 2.22

Optical fibres may be classified depending upon the types of propogation in the guide ie

(a) <u>One mode (single mode fibre):</u>

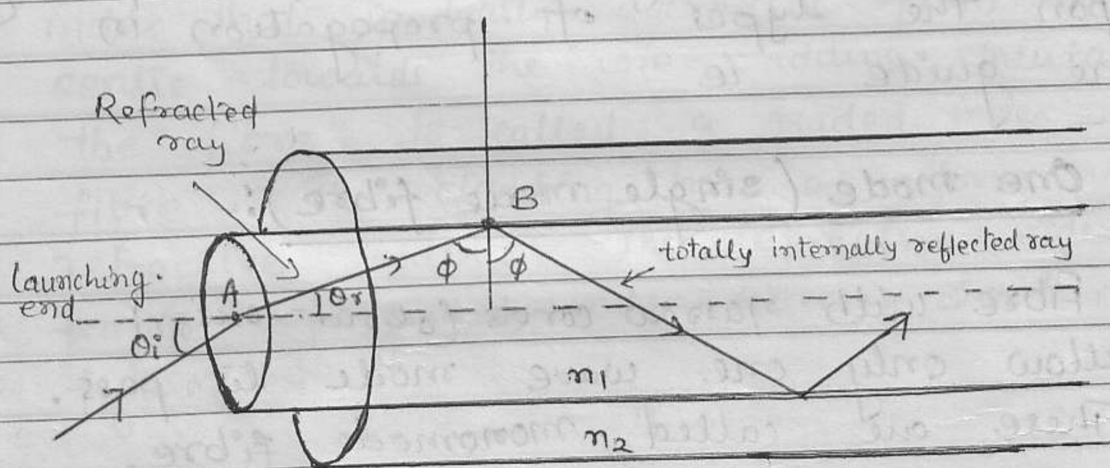
Fibre with narrow cores (about 10 um) allow only one wave mode to pass. These are called monomode fibre.

(b) <u>Many modes (multi mode fibre):</u>

Fibres with core diameters about 50 um and above allow different wave modes. These are called multimode fibre.

Light propagation in fibres :—

Let us consider light propagation in an optical fibre. The end at which the light enters the fibre is called launching end. Let the refractive index of the core be n_1 and the refractive index of cladding be n_2 (i.e $n_2 < n_1$). Let the outside medium from which light is launched into fibre have a refractive index of n_0. Let the light ray enters the fibre at an angle θ_i to the axis of fibre. Let the refracted ray make an angle θ_r with the axis and strikes the core-cladding interface at an angle ϕ.



fi 2.23

If $\phi > \theta_c$ (critical angle), the ray undergoes total internal reflection at the interface. As long as the angle $\phi > \theta_c$, the light remains within the fibres.

Applying Snell's law to launching face of fibre, we get

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_1}{n_0} \quad \text{--- (1)}$$

Now largest value of θ_i occurs when $\phi = \phi_c$

From ΔABC we have

$$\sin\theta_r = \sin(90-\phi) = \cos\phi \quad \text{--- (2)}$$

From equation (1)

$$\sin\theta_i = \sin\theta_r \frac{n_1}{n_0}$$

$$\sin\theta_i = \frac{n_1}{n_0}\cos\phi \quad \text{--- (3)}$$

when $\phi = \phi_c$, $\theta_i = \theta_{max}$

$$\sin\theta_{max} = \frac{n_1}{n_0}\cos\phi_c \quad \text{--- (4)}$$

But $\sin\phi_c = \frac{n_2}{n_1}$

$$\therefore \quad \cos\phi_c = \frac{\sqrt{n_1^2 - n_2^2}}{n_1} \quad \text{--- (5)}$$

Substituting the expression (5) into (4) we get

$$\boxed{\sin\theta_{max} = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}}$$

If $(n_1^2 - n_2^2) \geq n_0^2$ then for all values of θ_i, total internal reflection will occur. Assuming $n_0 = 1$, the maximum value of $\sin\theta_i$ for a ray to be guided is given by

$$\sin\theta_m = \sqrt{n_1^2 - n_2^2}$$

$$\therefore \quad \boxed{\theta_m = \sin^{-1}\left(\sqrt{n_1^2 - n_2^2}\right)}$$

The angle 'θ_m' is called the acceptance angle of the fibre. Acceptance angle may be defined as maximum angle that a light ray can have relative to the axis of the fibres and propagates down the fibre.

The light rays contained within the cone having a full angle $2\theta_m$ are accepted and transmitted along fibre. This cone is known as acceptance cone.

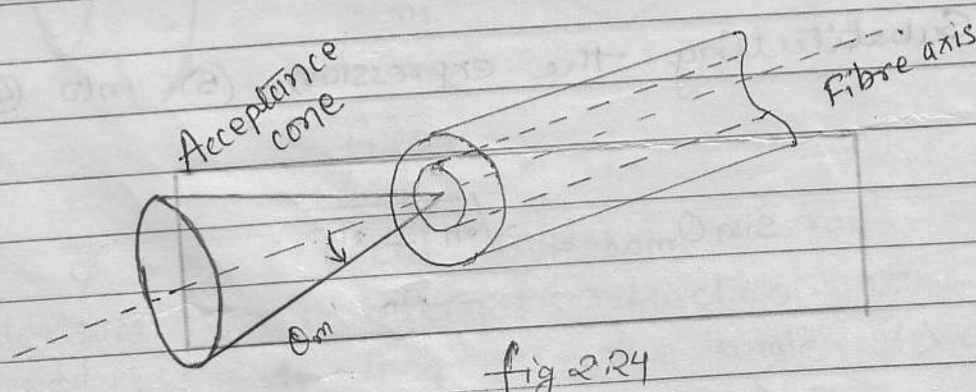


fig 2.24

Fractional refractive index change :-

This parameter is defined as the ratio of difference between the refractive indices of core and cladding to the refractive index of core. It is denoted by Δ and expressed as

$$\Delta = \frac{n_1 - n_2}{n_1}$$

Δ is always positive because refractive index of core is always greater than the refractive index of cladding for total internal reflection condition.

Numerical Aperture :-

The numerical aperture is defined as the sine of acceptance angle. This angle is measure of light-gathering ~~of~~ power of the fibre. It is expressed as —

$$NA = \sin \theta_m = \sqrt{n_1^2 - n_2^2}$$

$$NA = \sqrt{n_1^2 - n_2^2} = n_1 \sqrt{2\Delta}$$

Because $n_1^2 - n_2^2 = (n_1 + n_2)(n_1 - n_2) = \frac{(n_1 + n_2)}{2} \frac{(n_1 - n_2)}{n_1} 2n_1$

Approximating $\frac{n_1 + n_2}{2} \approx n_1$, we can ~~expressed above relation as~~

$$(n_1^2 - n_2^2) = 2 n_1^2 \Delta$$

Numerical aperture is a measure of the amount of light that can be accepted by a fibre. For a typical optical fibre $n_2 = 1.458$, $\Delta = 0.01$ and the corresponding $NA \approx 0.2$. Thus the fibre would accept light incident over a cone with a semi angle $\sin^{-1}(0.2) = 11.5^\circ$ about the axis.

2) Attenuation :-

An optical signal propagating through a fibre will get progressively attenuated. The signal attenuation is defined as the ratio of the optical output power from a fibre of length L to the input optical power. It is expressed in decibel per kilometer dB/km

$$\alpha = \frac{10}{L} \log\left(\frac{P_i}{P_o}\right)$$

where P_i is the power of optical signal launched at one end of the fibre and P_o is power of the optical signal emerging from other end of the fibre. In case of an ideal fibre P_o/P_i and attenuation will be zero dB/km. A typical attenuation of 3 dB/km is usual in practice.

The attenuation is wavelength dependent, and therefore the wavelength should also be specified.

optical computing