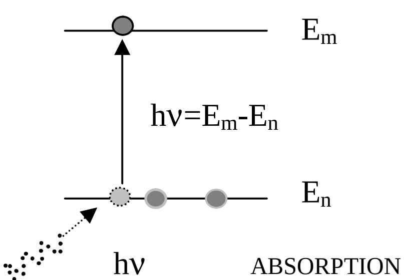
LASERS

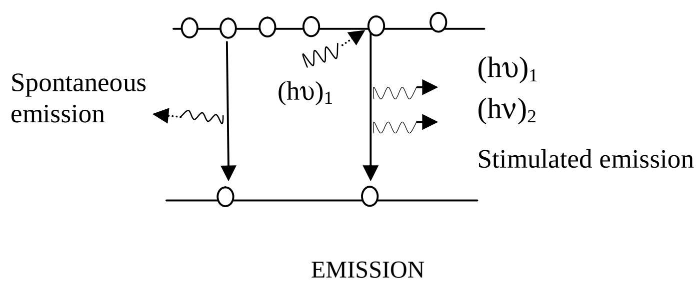
LASER is the acronym for *L̲ight A̲mplification by S̲timulated E̲mission of R̲adiation.* Light emitted by conventional light sources is generally incoherent since photons emitted by the different atoms do not bear any definite phase relation with each other. On the other hand, light emitted by a LASER source is highly coherent and also highly directional (i.e., light rays of laser are almost perfectly parallel). Because of these special features laser sources find applications in many diverse fields such as science, industry, medicine, military, …. and so on.

The basic principle of laser action is the phenomenon of ***stimulated emission of radiation*** which was predicted by Einstein in 1917.

Spontaneous and Stimulated Emission of Radiation.

Consider the energy levels E_n and E_m of an atom. E_n is the ground state and E_m is an excited state. The ground state atom is excited to the state E_m when it absorbs a photon of frequency ν whose photon energy $h\nu = E_m - E_n$. The atom is found in the excited state only for a very short duration (10^{-8}s or less) known as the 'life time of excited state'. This lifetime is so short that, no external stimulation can stimulate the excited state atom to return to its ground state. So, *the atom in the excited state spontaneously returns within its lifetime to the ground state by emitting radiation of the same frequency ν. Hence the resulting emission is termed as '**spontaneous emission'***





Thus ***'spontaneous emission'*** may be defined as the process of emission of radiation in which an excited state atom returns spontaneously to the ground state without any form of external stimulation. Spontaneously emitted photons have different random characteristics. The rate of spontaneous emission is only proportional to the number of atoms in the excited states.

When an incident photon $(h\nu)_1$ of frequency ν [= $(E_m-E_n)/h$] interacts with an atom in the high energy state E_m the atom may be stimulated to return to the ground state E_n. During this transition, a photon of same frequency ν is emitted. This is known as ***stimulated emission***.

In this case, characteristics of the stimulated emission photon [$(h\nu)_2$] and the characteristics of the stimulating photon $(h\nu)_1$ are identical. So they are highly coherent. Further, they travel in the same direction perfectly parallel to each other. *The high coherence and directionality are the special characteristics of photons emitted by* ***stimulated emission.***

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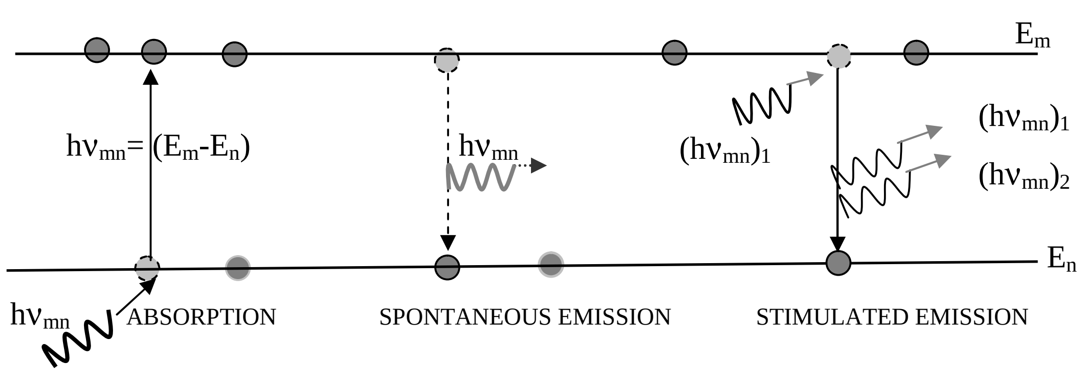
Interaction of radiation with matter

Einstein's Throry for Absorption and Emission -Detivation of Einstein's Coefficients.

The basic principle involved in laser action is the phenomenon of stimulated emission predicted by Einstein in 1917.

ABSORPTION

Consider a system of identical atoms. E_n and E_m are two of its energy states such that $E_m > E_n$. Let N_n and N_m be the number of atoms per unit volume in the states n and m respectively. An atom in the lower level E_n may absorb radiation of frequency $\upsilon_{mn} = (E_m - E_n)/h$. Then, it gets excited to the level E_m. *This process of excitation by absorption of radiation is called '**stimulated absorption**' or simply, '**absorption**'.*



Let $\rho(\nu_{mn})$ be the *energy density* of radiation of frequency ν_{mn} to which the atoms are exposed. $\rho(\nu_{mn})$ is a measure of intensity of radiation of frequency ν_{mn}. Then, the rate of absorption transition $R_{n\to m}$ is proportional to the number of atoms in the lower energy level , Nn, and the energy density of radiation $\rho(\nu_{mn})$.

$\therefore$ $R_{n\to m} = B_{n\to m} \cdot N_n \cdot \rho(\nu_{mn})$………………..(1) where

$\mathbf{B_{n\to m}}$ is the constant of proportionality known as ***'Einstein's coefficient for absorption'***.

EMISSION : Spontaneous and Stimulated Emission of Radiation.

When an atom in the excited state E_m returns to the lower energy state E_n it emits radiation of frequency ν_{mn} where $\nu_{mn} = (E_m - E_n)/h$. Einstein argued that the emission of radiation can occur in two different ways called *'spontaneous emission'* and '*stimulated emission*'.

If the excited atom returns to the lower energy state at the end of its lifetime without any external stimulation, it emits radiation of same frequency. This is known as '*spontaneous emission of radiation*'.

If an interaction of incident radiation of frequency ν_{mn} with the excited state atom triggers a radiative transition of the atom to its lower energy state, then the resulting emission is known as '*stimulated emission of radiation'*

Einstein assumed that

(i) the spontaneous emission occurs independent of the presence of any radiation and

(ii) the rate of spontaneous emission is proportional to the number of atoms (N_m) in the excited state

(iii) The rate of stimulated emission is proportional to both the energy density of the external radiation, $\rho(\nu_{mn})$ and the number of atoms in the excited state, N_m.

$\therefore$ Rate of spontaneous emission $R_{sp} = A_{m\to n} \cdot N_m$ ………(2) where the constant of proportionality $\mathbf{A_{m\to n}}$ is known as '***Einstein's coefficient for spontaneous emission*** '.

$\therefore$Rate of stimulated emission $R_{st} = B_{m\to n} \cdot N_m \cdot \rho(\nu_{mn})$ ………(3) where the constant of proportionality $\mathbf{B_{m\to n}}$ is known as ***'Einstein's coefficient for stimulated emission '.***

$\therefore$Total rate of emission $R_{m\to n} = R_{sp} + R_{st}$

i.e.,Total rate of emission $R_{m\to n} = A_{m\to n} \cdot N_m + B_{m\to n} \cdot N_m \cdot \rho(\nu_{mn})$

$$= N_m [\, A_{m\to n} + B_{m\to n} \cdot \rho(\nu_{mn})\,] \quad \text{………(4)}$$

Thus when a system of identical atoms with two energy levels E_m and E_n such that

$E_m - E_n = h\nu_{mn}$ is exposed continuously to radiation of frequency ν_{mn} , due to the interaction of radiation with matter (atoms), both absorption and emission take place simultaneously. When this interaction establishes a new equilibrium, both the rate of absorption and total rate of emission will be equal.

$\therefore$ $B_{n\to m} . N_n. \rho(\nu_{mn}) = N_m [A_{m\to n} + B_{m\to n} . \rho(\nu_{mn})]$ under equilibrium. {using eqns. (3) & (4)}

Rearranging, $$\frac{N_n}{N_m} = \frac{A_{m\to n} + B_{m\to n}.\rho(\nu_{mn})}{B_{n\to m}.\rho(\nu_{mn})} \quad \ldots\ldots. (5)$$

According to Maxwell Boltzmann statistics, $N_n \propto \exp(-E_n / kT)$ and $N_m \propto \exp(-E_m / kT)$

$$\therefore \qquad \frac{N_n}{N_m} = \exp\left(\frac{E_m - E_n}{kT}\right) = \exp\left(\frac{h\nu_{mn}}{kT}\right) \ldots\ldots\ldots\ldots\ldots\ldots(6)$$

where k is the Boltzmann constant and T is the absolute temperature in K.

Comparing eqns. (5) and (6) we have, $\frac{N_n}{N_m} = \frac{A_{m\to n} + B_{m\to n}.\rho(\nu_{mn})}{B_{n\to m}.\rho(\nu_{mn})} = \exp\left(\frac{h\nu_{mn}}{kT}\right)$ (or)

$$A_{m\to n} + B_{m\to n}.\rho(\nu_{mn}) = B_{n\to m}.\rho(\nu_{mn}).\exp\left(\frac{h\nu_{mn}}{kT}\right) \quad \text{Rearranging this,}$$

$$A_{m\to n} = \rho(\nu_{mn})\left(B_{n\to m}.\exp\left(\frac{h\nu_{mn}}{kT}\right) - B_{m\to n}\right) \qquad \text{(or)}$$

$$\rho(\nu_{mn}) = \frac{A_{m\to n}}{B_{n\to m}.\exp\left(\frac{h\nu_{mn}}{kT}\right) - B_{m\to n}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(7)$$

From Planck's theory of radiation, the energy density of radiation of frequency ν_{mn} is given by
$$\rho(\nu_{mn}) = \frac{8\pi h \nu_{mn}^{3}}{c^3}.\frac{1}{\exp\left(\frac{h\nu_{mn}}{kT}\right) - 1} \quad \ldots\ldots\ldots\ldots\ldots(8)$$

Both the eqns. (7) and (8) represent the same energy density $\rho(\nu_{mn})$of radiation of frequency ν_{mn} $\therefore$Comparison of eqns (7) and (8) yields that

$$\boxed{B_{n\to m} = B_{m\to n} \quad \ldots\ldots(9a)} \qquad \text{and} \qquad \boxed{A_{m\to n} = \frac{8\pi h \nu_{mn}^{3}}{c^3}.B_{m\to n} \quad \ldots\ldots.(9b)}$$

Eqns (9a) and (9b) give the expressions for Einstein's Coefficients for absorption and spontaneous and stimulated emissions.

In spite of the prediction of stimulated emission by Einstein in the brginning of 20th century, it took several decades to obtain visible laser by stimulated emission of radiation. The cause for this difficulty is explained below.

Using (9a) and (b) in eqn(7) we have,

$$\rho(\nu_{mn}) = \frac{A_{m\to n}}{B_{m\to n}\left[\exp\left(\frac{h\nu_{mn}}{kT}\right) - 1\right]} \quad \text{(or)}$$

$$\frac{A_{m\to n}}{B_{m\to n}} = \rho(\nu_{mn})\left[\exp\left(\frac{h\nu_{mn}}{kT}\right) - 1\right] \quad \ldots\ldots\ldots\ldots(10)$$

Equation (10) gives the ratio of Einstein's coefficient for spontaneous emission to that for stimulated emission.

CASE (I): when the energy level separation $(E_m - E_n) = h\nu_{mn}$ is large, $h\nu_{mn} > kT$. For visible radiation, the photon energy $h\nu_{mn}$ is between 2 to 3 eV. The thermal energy kT corresponding to room temperature (300K) is about 0.025eV only. Thus, for visible radiation, $h\nu_{mn} > kT$ (or) $\frac{h\nu_{mn}}{kT} > 1$ and so $\exp\left(\frac{h\nu_{mn}}{kT}\right) >> 1$.

$\therefore$ Using this in eqn (10), $\frac{A_{m\to n}}{B_{m\to n}} >> 1$ (or) $A_{m\to n} >> B_{m\to n}$

This implies that when the energy level separation $(E_m - E_n) = h\nu_{mn}$ is large (corresponding to visible or near visible region of electromagnetic spectrum), the spontaneous emission is more probable than the stimulated emission. Under ordinary conditions, only spontaneous emission is observed in the visible region and stimulated emission of visible radiation does not occur.

Case (ii):

when the energy level separation $(E_m - E_n) = h\nu_{mn}$ is small, $h\nu_{mn} < kT$ (or)

$$\left(\frac{h\nu_{mn}}{kT}\right) << 1 \text{ and hence } \exp\left(\frac{h\nu_{mn}}{kT}\right) = 1 + \left(\frac{h\nu_{mn}}{kT}\right) + \left(\frac{1}{2!}\right)\left(\frac{h\nu_{mn}}{kT}\right)^2 \ldots\ldots \approx 1 + \left(\frac{h\nu_{mn}}{kT}\right)$$

(or) $\exp\left(\frac{h\nu_{mn}}{kT}\right) - 1 \approx \left(\frac{h\nu_{mn}}{kT}\right) \ll 1$ Using this in (10),

$$\frac{A_{m\to n}}{B_{m\to n}} << 1 \quad \text{(or)} \quad A_{m\to n} << B_{m\to n}$$

For low frequencies such as microwave frequencies, stimulated emission dominates the spontaneous emission.

In fact, the first practical device for stimulated emission is a MASER *(Microwave Amplification by Stimulated Emission of Radiation*) which emitted highly coherent Microwave radiation by stimulated emission .

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The above discussion indicates that in atoms emitting visible or near visible radiations, the probability for stimulated emission is very small.

However, the stimulated emission can be made more probable if

(i) the lifetime of the excited state is considerably longer (of the order of milliseconds or more) and

(ii) number of atoms in the excited state is far greater than that in the lower state. $N_m >> N_n$

The excited levels with longer lifetimes of the order of 10^{-3}s or more are termed as '***meta stable'*** states. The condition when there is a larger number of atoms in the excited level than in the lower energy level is termed as '***population inversion'***. Population inversion can be achieved only in meta stable states.

Thus stimulated emission of radiation results when the atoms in the meta stable excited state under inverted population condition are stimulated to return to the lower level by intense radiation whose photon energy hυ is exactly the same as the energy of transition between these two levels of the atom.

The rate of stimulated emission is proportional to the number of atoms in the excited state and the intensity or energy density of the external, stimulating radiation.

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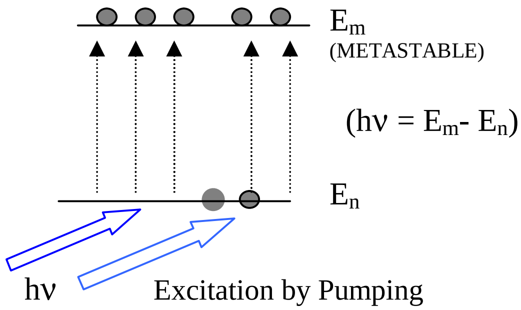
Basic requirements for a laser system

A Laser source system requires the following three as main components:

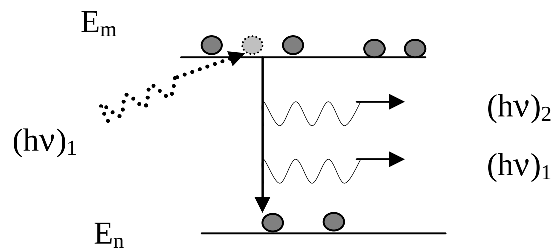
(i) Active medium, (ii) pumping source and (iii) optical resonator (or) resonant cavity.

(i) ACTIVE MEDIUM"

An active medium is a solid, liquid or a gas in which amplification of light waves by stimulated emission can occur. It consists of a collection of atoms, ions or molecules in which one or more excited states are Meta stable levels. Meta stable levels have a longer lifetime of the order of 10^{-3}s or more. These atoms or ions are known as *active centers*. A suitable intense *excitation mechanism* (known as *pumping*) can be used to achieve population inversion in the active medium. Under Population inversion, the number of atoms N_m in the excited Meta stable level is greater than the number of atoms N_n in the ground level. $N_m > N_n$.



Excitation by Pumping



Stimulated Emission

Now, incident radiation of appropriate frequency will stimulate the atoms in the Meta stable state to undergo stimulated emission.

(ii) Pumping and Pumping sources

PUMPING

The mechanism by which population inversion is achieved in an laser active medium is known as '*pumping*'. The external sources, which are used to provide this pumping mechanism, are known as pumping sources. Different pumping sources are employed in different laser systems. Some of them are given below.

1. ***Optical pumping***: In almost all the solid state lasers population inversion is achieved by intense light sources and the corresponding pumping mechanism is called optical pumping. For Ex., Xenon flash lamps are used in Ryby lasers; Krypton flash lamps are used in Nd : YAG lasers.

2. ***Electrical Pumping***: In gas lasers sufficiently intense electrical discharge is used to produce population inversion. The electrical discharge converts a part of atoms or molecules of the gas into plasma. Inelastic collisions of the active centers with free electrons and excited state atoms of additives lead to population inversion. (Ex: He – Ne Laser, CO_2 Laser)

3***. Chemical pumping***: It raises active centers into meta stable levels by means of suitable exothermic chemical reactions.

4. ***Carrier injection*** : In the case of semiconductor lasers population inversion is achieved by carrier injection through forward biasing of the p-n junction. Hence these lasers are also called carrier injection lasers.

Other methods of pimping are heat pumping, ***gas dynamic pumping***, ***Electro-ionising pumping*** etc.

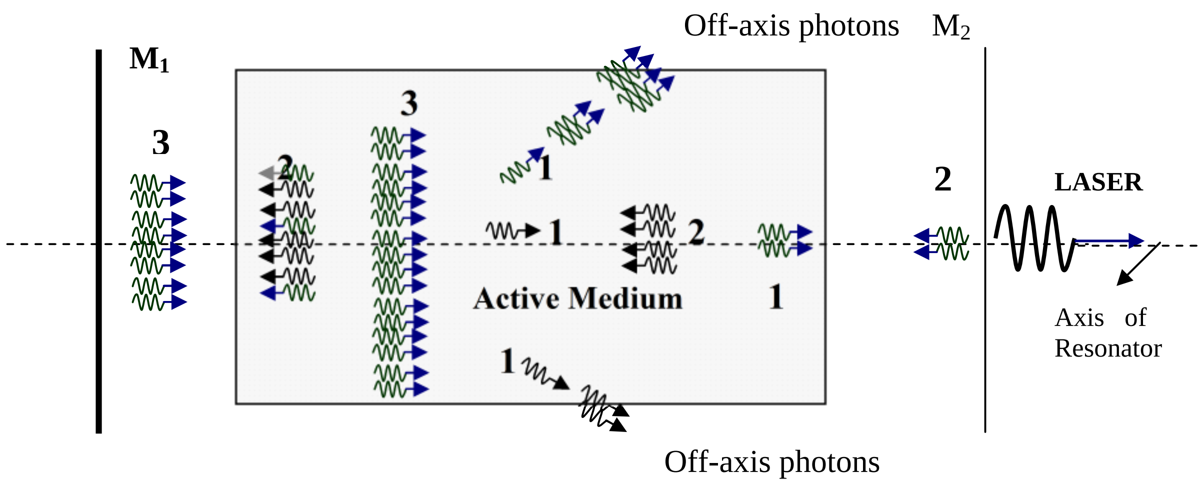
Threshold pumping

The minimum pumping power required to initiate sustained laser action is known as '*threshold pumping*'. Threshold pumping provides the minimum threshold population inversion for the sustained laser action without amplifying laser radiation. For amplification of laser radiation, the population inversion should be higher than the threshold value.

(iii) Optical Resonator (or) Resonant Cavity:

In a laser active medium the pumping process creates population inversion. Stimulated emission is usually started by the initial spontaneously emitted photons which have random characteristics. If all such random photons are used as stimulating photons, then they generate different sets of stimulated photons having different characteristics. In this case the laser output will be incoherent. Therefore, in a laser system, an optical resonator is setup such that i) it selects the photon states, which have the required characteristics and ii) it allows the amplification of only these stimulated photon states. Amplification of other stimulated photon states is prevented.

Thus an ***optical resonator*** *is an arrangement which is used to select and amplify the stimulated radiation of particular characteristics while preventing the amplification of radiations of other unwanted characteristics.*



1 → First pass of photons from left to right

2 → 2nd pass of photons parallel to axis from right to left (after reflection from mirror M_2)

3 → 3rd pass of photons parallel to axis from left to right (after reflection from mirror M_1)

Laser output is obtained from the partially reflecting mirror M_2.

Off-Axis photons are not reflected back into the Laser Active Medium

In the simplest form, an optical resonator is a pair of optically flat, plane mirrors M_1 and M_2 kept exactly parallel to each other as shown above.. One of the mirrors (M_1) is perfectly reflecting while the other mirror (M_2) is partially reflecting with a reflectivity of about 90%. If λ is the wavelength of the stimulated radiation to be amplified, then the two parallel mirrors are separated by a distance equal to an integral multiple of $\lambda/2$. The direction perpendicular to the surfaces of the mirrors is known as the *'axis of resonator'* or '*optic axis*. The active medium is placed between the mirrors of the resonator along the optic axis.

When population inversion is achieved in the active medium, spontaneous emission results initially. These spontaneous photons travel in different directions within the active medium and each of them produce their own set of stimulated emission. If all of them are allowed to get amplified, the resulting radiation will be incoherent. Usually only the photons traveling parallel to the axis of resonator are allowed to grow, The mirrors reflect only those photons, which travel exactly parallel to the axis of the resonator back into the active medium again and again many times. These photons, when they are traveling in the active medium, amplify the stimulated emission by triggering more and more excited state atoms to emit stimulated radiation. All these stimulated photons travel parallel to the axis of the resonator.

On the other hand, photons traveling in other directions (Off-axis photons), will leave out through the 'transparent sides' of the active medium after a few or no reflections and therefore they will not be amplified. The output laser beam is obtained through the partially reflecting mirror M_2. All the laser rays travel exactly parallel to the axis of the resonator. This is shown in the above diagram.

Cavity Losses and Threshold Condition

Radiation bounces back and forth between the mirrors of the optical resonator through the active medium and gets amplified by stimulated emission. However it suffers losses in the cavity due to the following

1) Finite reflectivity of the mirror
2) Scattering and absorption at the active medium and mirrors of the resonant cavity and
3) Diffraction losses at the edges of the mirrors due to their finite dimensions

In order to start and sustain the laser oscillation in the optical cavity of a laser, it is essential that the *net losses* suffered by radiation is compensated for by the *gain* of the medium. This requires a minimum population inversion at which the cavity losses are just compensated by the gain of the medium. *The minimum population inversion which is needed for the sustained laser action inside the optical cavity is called the 'threshold population inversion'*. It is represented by $(N_m - N_n)$, When a higher population inversion than the threshold value is achieved, the stimulated radiation is amplified and a laser beam results.

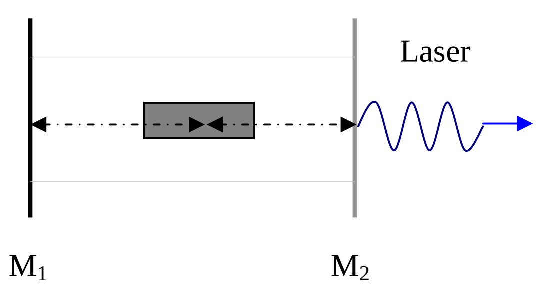
The minimum pumping power required to achieve the threshold population inversion is known as 'threshold pumping power'. The lower the threshold pumping power, the higher will be the efficiency of the laser system.

Different forms of Optical resonators

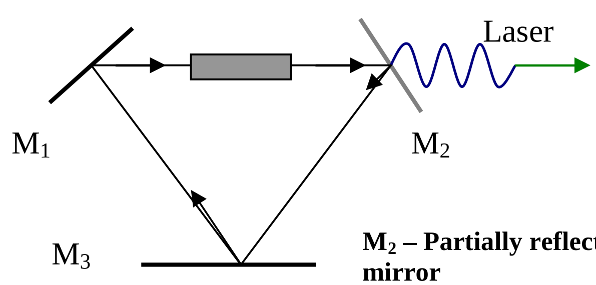
In a solid state laser external mirrors are not used for setting up of optical cavity. Instead, the solid active medium is taken in the form of a cylindrical rod with its two end faces perfectly parallel to each other. These two end faces are polished to form the mirrors of the resonant cavity; One end is polished to be fully reflecting while the other end is made partially reflecting. These two polished surfaces form the mirrors of resonant cavity.

Two external plane mirrors are used to form resonant cavity for liquid and gas lasers. In this case, the active medium (gas or liquid) is taken in a transparent container with a uniform shape (cylindrical or rectangular). It is placed between the mirrors of cavity. An optical resonator formed by using two plane parallel mirrors is

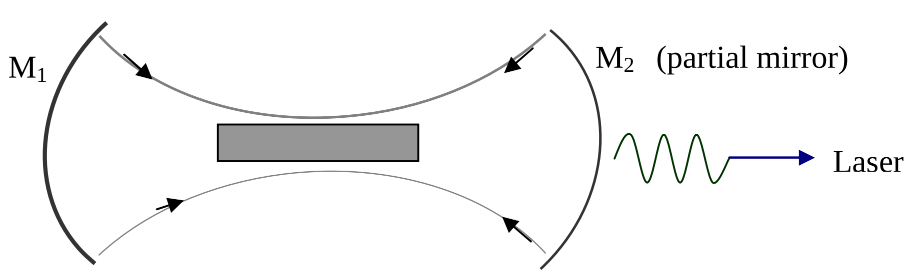
a) Linear resonator



b) Ring resonator



M$_2$ – Partially reflecting mirror
M1, M3- Fully Reflcting mirrors



(c) **Confocal resonator**

M$_1$, M$_2$ → Concave mirrors

called a *linear resonator*. Resonant cavities involving three or more mirrors called *ring resonators*. Spherical mirrors are also used to form resonant cavity. Are The *confocal resonator* obtained by using two concave mirrors is shown in the figure.

In the Confocal resonator, the volume bounded between the mirrors and the rays reflected at the extreme ends represents the section through the volume filled with rays bouncing back and forth. The diffraction losses are minimized in the case of laser systems using Confocal resonator.

In all these cases, output laser beam is obtained through the partially reflecting mirror, M_2.

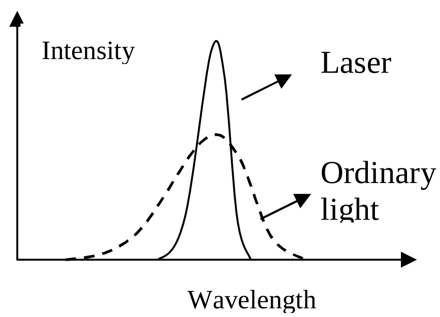
Special characteristics of Laser light

Generally, light from a laser source is highly monochromatic, highly directional and also highly coherent.

MONOCHROMATICITY

Light from ordinary sources is spread over many wavelengths around the wavelength at which the emission intensity is maximum.

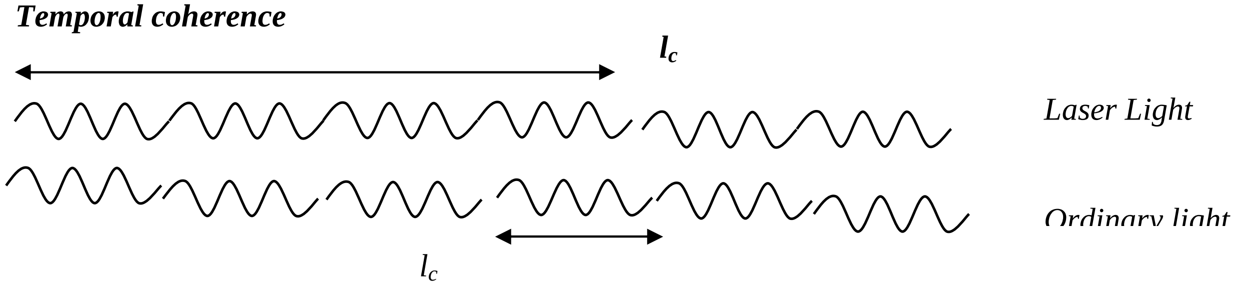
Monochromaticity is expressed interms of ***spectral line widths*** which is larger for ordinary light sources (200 – 300 nm) and is very small for laser sources (about 0.001nm).



COHERENCE

There are types of coherence: 1) ***Temporal*** and 2) ***Spatial*** coherence

Temporal coherence



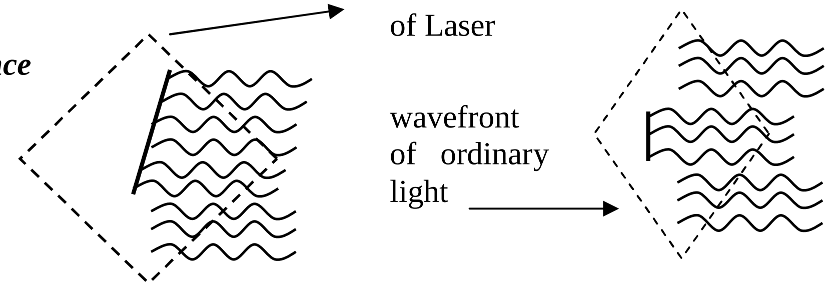
In ordinary monochromatic sources, light waves are due to spontaneously emitted photons and so there is no definite phase correlation between different wave trains. In lasers, both stimulating and stimulated photons are in phase with each other and hence a wave train of longer length is phase correlated. *The maximum length of the wavetrain over which any two points are well correlated in phase is known* ***as coherence length***, l_c.

. l_c. is about few tens of cm for lasers while it is only about a few 100s of μm for ordinary sources.

This temporal coherence is measured interms of a ***coherent time***, t_c defined by

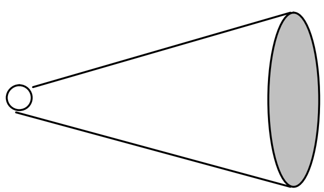
$t_c = (l_c$ / velocity of light)..

Spatial coherence

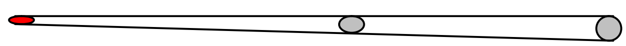


We know that different points on a wave front can be considered as point sources of light. The maximum separation between any two points on the wavefront between which light rays from all points have the same phase relationship all the time is known as ***Spatial coherence.*** Laser light is spatially coherent over longer distances (few cms) when compared to ordinary monochromatic sources of light (few tenths of an mm).

Directionality



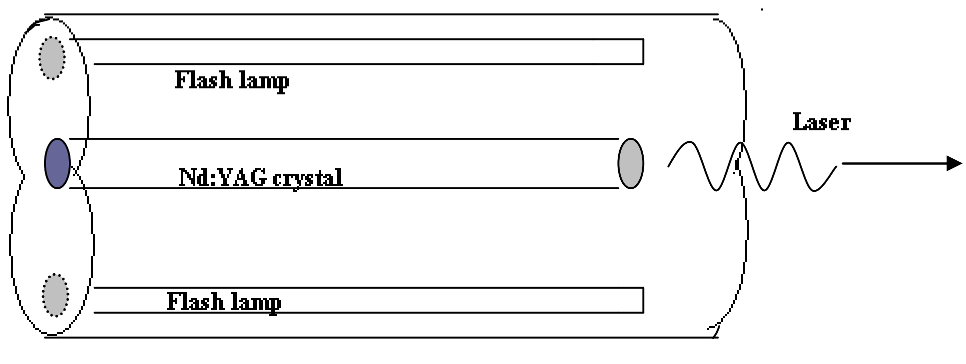
Light from a conventional source



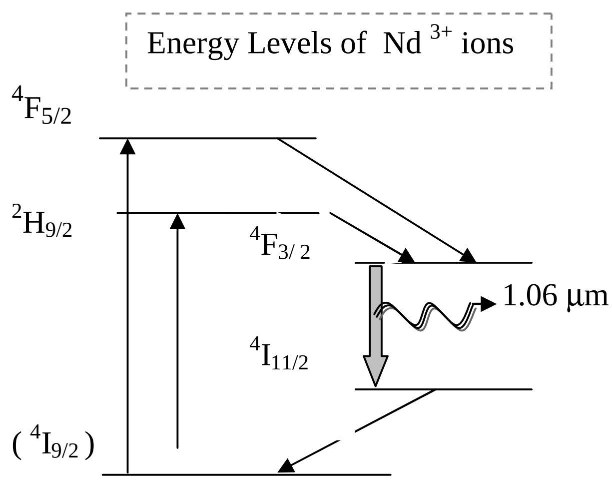
The width of light from ordinary sources spreads very rapidly as the distance from the source increases. In the case of a laser source, this spreding is extremely small due to the high directionality of the laser light. The directionality of lasers is measured by means of angle of divergenge. If D_1 and D_2 are the widths of laser beam at distances X_1 and X_2 from the laser source, then the angle of divergenge $\phi = (D_2 - D_1)/ (X_2 - X_1)$ in radians. .For laser sources, it is of the order of milli radians only.

Nd: YAG Laser

Single crystals of Neodymium doped Yttrium Aluminum Garnet (chemical formula = $Y_3Al_5O_{12}$) are used as active medium in Nd:YAG lasers. Nd^{3+} ions, which have replaced substitutionally some Y^{3+} ions of the YAG crystal lattice, are the active centers. Typical concentrations of the Nd3+ ions in an Nd:YAG laser are about $1.4 \times 10^{20}/cm^3$. Usually one or more Krypton flash lamps are used as the optical pumping source. In some cases, a xenon flash lamp (alone or in combination with a krypton flash lamp) could also be used as pumping source. A resonant cavity is set up by silver polishing two opposite ends of the crystal; one end is fully reflecting while the other end is made partially reflecting. Nd:YAG crystal is arranged at the common focus of a double elliptical cavity. Two Flash lamps are arranged at the two foci of the ellipses as shown in the figure.



Due to optical pumping by intense light. from a Kr flash lamp, most of the Nd^{3+} ions are raised from their ground level ($^4I_{9/2}$) to several excited states such as $^4F_{5/2}$ and $^2H_{9/2}$. Excitation to these two levels occurs due to absorption of 7300 AU and 8000 AU lights respectively. Then these excited ions relax quickly to $^4F_{3/2}$ which is a meta stable level producing population inversion in it. though various emission transitions are possible, a major portion of the energy (about 60%) is emitted in the $^4F_{3/2}$ to $^4I_{11/2}$.



The wavelength of the emitted radiation is 1.06µm. The resonant cavity is setup in such a way that only stimulated radiation of this wavelength is amplified. The laser output is obtained through the partial mirror. From $^4I_{11/2}$ level the Nd ions relax non-radiatively within a short time to $^4I_{9/2}$ ground state. Thus the Nd:YAG laser belongs to a four level laser system.

The advantages of this laser are

(1) It has a rather low excitation threshold
(2) Since it has a higher thermal conductivity than Ruby and other solid state lasers, it lends itself for generation of laser pulses at a higher pulse repetition rate or a quasi continuous wave operation.
(3) Its efficiency is relatively higher
(4) Peak output power is several kW.
(5) In a high power continuous wave operation, the laser is excited with a krypton lamp. At times YAG crystal is doped with Cr^{3+} ions (in addition to Nd ions) so that Xenon lamp can be used for pumping. The excited Cr^{3+} ions transfer their excitation energy to Nd^{3+}Ions.

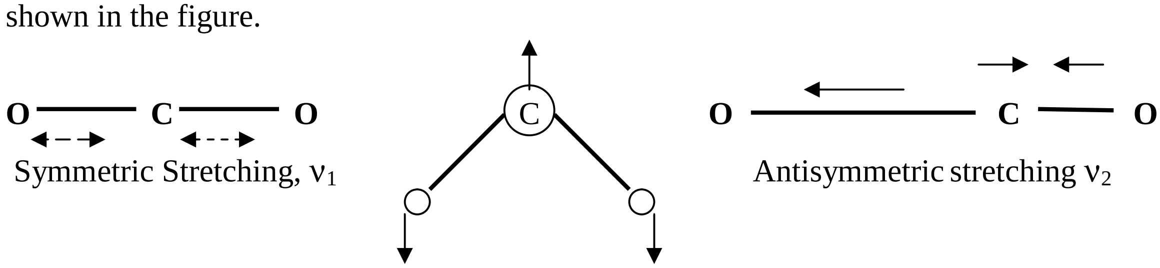
<u>USES:</u> (1) They find application in material processing such as drilling holes, welding and cutting etc. (2) They are used for resistor trimming, scribing, micro-machining operations etc in he electronic industry. (3) They are also used as range finders. (4) They are used in ophthalmologic surgeries.

CO_2 Laser

Carbon-dioxide lasers (known as CO_2 lasers) rank first among the lasers used for industrial applications such as cutting, welding, drilling holes etc. It is capable of operating continuously with a power output of 10 kW at a relatively high efficiency of about 40%.

The active medium of CO_2 lasers is a mixture of gases containing CO_2 (at a pressure of 0.33 Torr), N_2 (at 1.2 Torr), He (at 7 Torr) and also water vapour. The transitions taking place between different vibrational energy levels of the CO_2 molecules (active centers) lead to laser action in a CO_2 laser.

Carbon-dioxide (CO_2) molecule is a linear triatomic molecule with the carbon atom at its center and an O atom on either side. CO_2 molecule execute three types of vibrations, namely, '*symmetric stretching*', '*Bending vibration*' and '*asymmetrical stretching*' as shown in the figure.



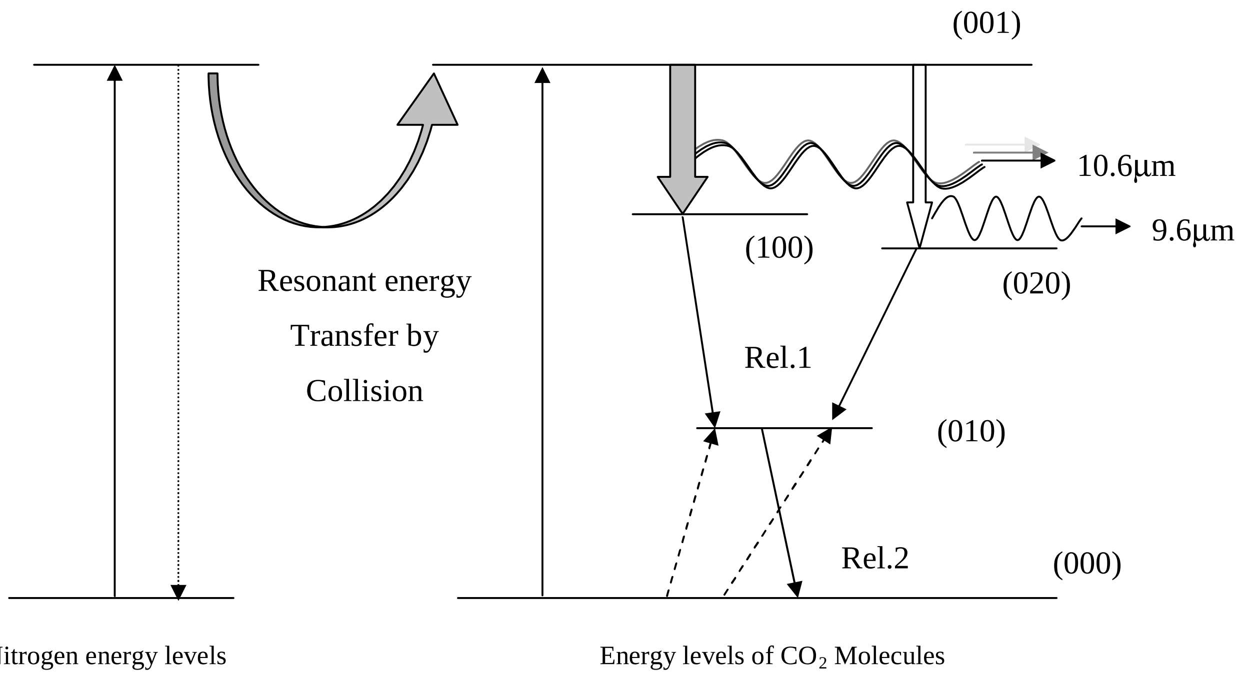
Symmetric Stretching, ν_1

Bending vibration, ν_2

Antisymmetric stretching ν_2

The state of vibration can be described by (x,y,z) where x, y and z are three integers which correspond to the degree of excitation in the above three types of vibrations respectively. [For example, the (0,0,0) vibrational state represents the ground state, the (0,0,1) state represents the first excited state of the asymmetrical stretching mode, (0,2,0) represents the second excited state of bending mode vibration and so on.]

If ν_1, ν_2 and ν_3 are the frequencies of these vibrational modes, then the quanta of energy of transition between successive energy levels are $h\nu_1 = 0.163$ eV for symmetric stretching, $h\nu_2 = 0.078$ eV for bending vibration and $h\nu_3 = 0.276$ eV for asymmetrical stretching respectively.



In CO_2 lasers the nitrogen molecules play the role of Helium atoms in He-Ne lasers. First, Nitrogen molecules are excited by the electrical discharge. Subsequently, when they collide with CO_2 molecules in the ground state, they excite them to (0,0,1) state by 'resonant energy transfer'. In addition, the population of the (0,0,1) state builds up by the inelastic collisions of the CO_2 molecules with free electrons produced by the plasma of the discharge also. The (0,0,1) state of CO_2 is the upper laser level while (0,2,0) and (0,1,0) are the two lower laser levels. While the transition (0,0,1) → (1,0,0) state yields an emission at a wavelength of 10.6 µm, (0,0,1) → (0,2,0) transition gives an emission at 9.4 µm. After the laser transitions, CO_2 molecules accumulate in the (0,1,0) state by resonant energy transfer when molecules in the (0,2,0) and (1,0,0) states collide with those in the ground (0,0,0) state as given in the following equations.

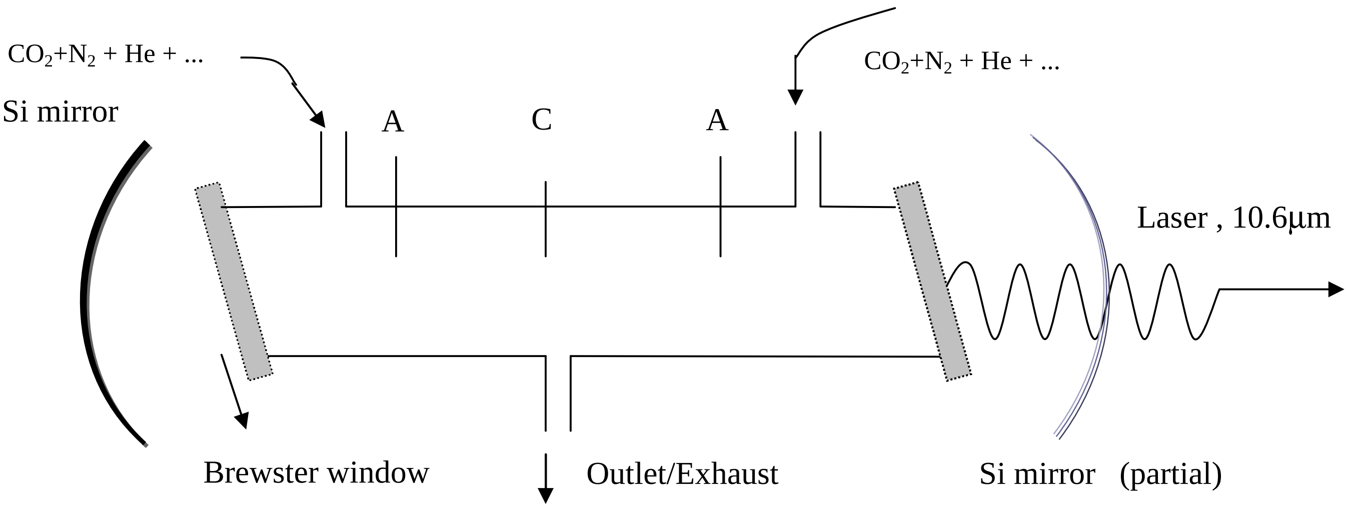
$CO_2(0,2,0) + CO_2\,(0,0,0) \rightarrow 2\,CO_2\,(0,1,0)$

$CO_2(1,0,0) + CO_2\,(0,0,0) \rightarrow 2\,CO_2\,(0,1,0)$

These two transitions are indicated by ‘Rel. 1’ in the diagram. Upon collision with the additives such as He and water vapour, the (0,1,0) molecules decay to the ground state (0,0,0) by the second relaxation process indicated as ‘Rel. 2’.

Construction of CO_2 laser.

CO_2 laser systems have several designs one of which is shown in the figure given below. The gaseous mixture of CO_2 , NO_2 ,He and water vapour is pumped through the lasing volume. The lasing volume is a discharge tube of 2.5 cm dia and length 1 to 5m.



The population inversion is achieved by a DC glow discharge. [A is anode and C is the. cathode]. NaCl Brewster windows are used at the two ends of the discharge tube. Confocal silicone mirrors coated with aluminum form the optical resonant cavity. Mostly, the length of the cavity is such that the 10.6 μm radiation is amplified

The glow discharge produces free electrons and also excites the nitrogen molecules. The partial pressures of the gases are so chosen that electronic excitation of N2 molecules and excitation of CO_2 molecules into the (0,0,1) states have the highest probability. In order to remove the unwanted CO molecules produced from CO_2 molecules by photo-dissociation during the laser action, the active medium is pumped through the lasing volume during the laser action.

[2 CO_2 $\xrightarrow{\text{photo-dissociation}}$ 2CO + O_2]. Now a days, sealed-off CO_2 lasers , which do not require the flow of the gases, are in wide use.

Advantages:

1. CO_2 lasers operate with a high efficiency (30%).

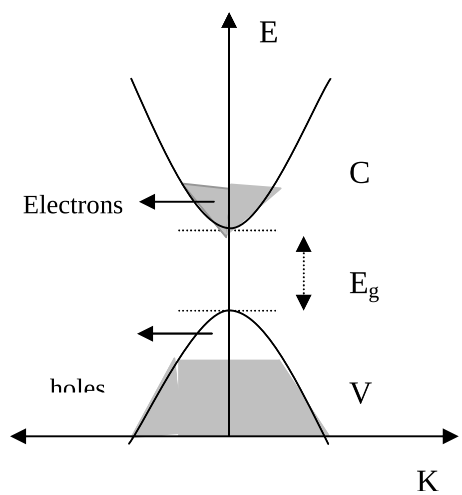
2. Still higher efficiencies (45%) can be achieved by having the gas flow transverse to the electric discharge.
3. Atmospheric attenuation of the 10.6 μm radiation is very low.

USES: OF CO_2 lasers

1. High power CO_2 lasers find applications in material processing , cutting, welding, hole drilling etc.
2. As the atmospheric attenuation of the 10.6 μm radiation is very low, it is used in open air communications.
3. Bloodless, precise surgeries are done by using CO_2 lasers with little damage to the surrounding tissues.Along with endoscopes , CO_2 lasers are widely used in angioplasty, neurosurgery, urology etc.
4. Laser remote sensing and environmental monitoring is possible by a laser radar which uses a CO_2 laser as a component.

Semiconductor lasers

Consider a direct band-gap semiconductor with a band gap energy of E_g. If a large number of electrons at the bottom of conduction band and holes at the top of valence are created simultaneously, then the presence of a photon of energy $h\nu \geq E_g$, has a higher probability of stimulating the electron-hole recombination. This will result in the stimulated emission of an identical photon. Thus stimulated optical radiation can be obtained at a frequency slightly larger than E_g /h.

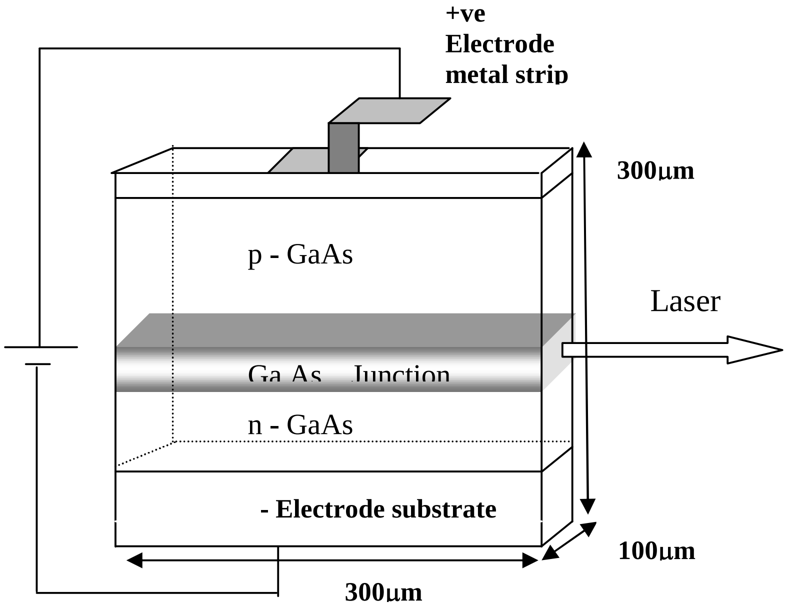


Laser action is observed only in direct band gap semiconductors. As the threshold pumping power of the intrinsic semiconductors is much larger, impurities doped extrinsic semiconductors are used for laser action.

Principle:

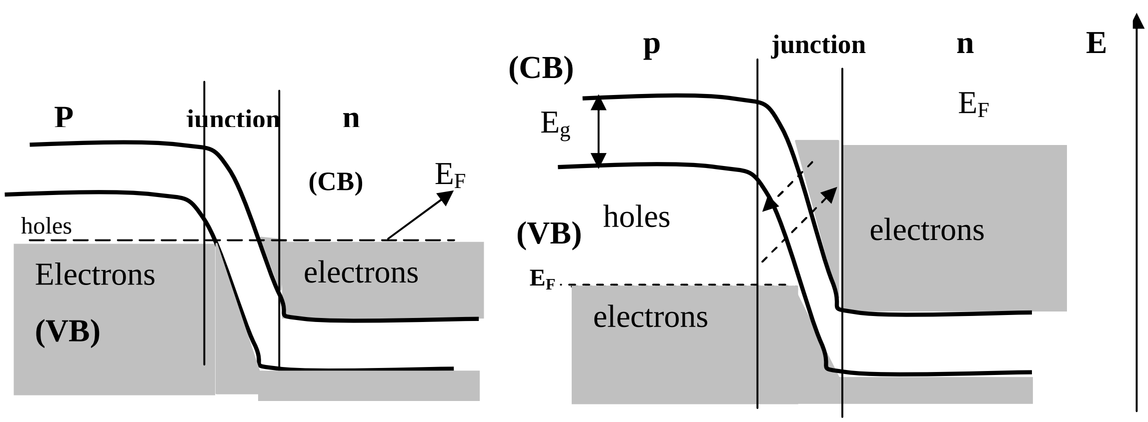
When a current is passed through a p-n junction under forward bias, the injected electrons and holes increase the density of electrons in the conduction band and that of holes in the valence band of the junction region. The electrons and holes recombine spontaneously emitting radiation with photon energy, $h\nu \geq E_g$. When the forward bias current is above a certain threshold value, suddenly a large number of electrons are raised into the conduction band and 'population inversion' occurs in the junction region. Under this population inversion condition the electrons and holes are stimulated by the spontaneously emitted photons to undergo recombination and hence stimulated emission of radiation results.

Construction of a semiconductor laser:



Homo-junction GaAs Laser

A ***homo-junction laser diode*** has a 0.2 μm thin pure GaAs junction sandwiched between n-type and p-type GaAs materials. It is fabricated by growing n-type GaAs (GaAs doped with 0.5×10^{18} Te atoms/cm^3) on a substrate which is also the –ve ekectrode. A p-type GaAs (GaAs doped with 1×10^{19} Zn atoms/cm^3) layer is deposited on this n-type GaAs material. A thin junction is formed between the n-type and p-type materials by the flow of excess electrons along the edges of n-type material into the p-type material filling the holes there. Further flow of electrons is prevented by the build up of a space charge due to ionized donors and acceptors in the junction region. For sufficiently heavy doping, the junction layer has a width of about 0.2μm. e resonant cavity is setup by cleaving the two opposite end faces along a crystallographic plane. Because of the high refractive index (3.5) of the crystal, the reflectivity at the interface between the cleaved layer and air is of the order of 30%. The reflectivity can be changed by adding dielectric



No Biasing ***Forward Biasing***

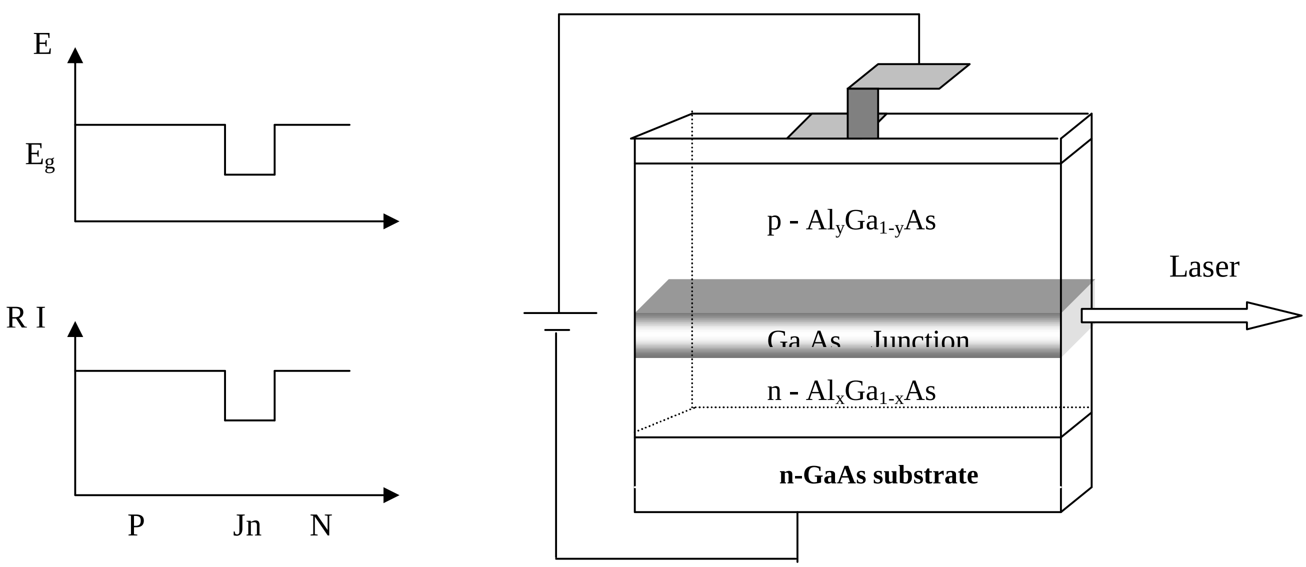
coating to the end faces or by chemically etching the faces. A narrow strip of metallic coating on the heterojunction provides electrical contact.

The p-n junctions effectively shifts the valence and conduction bands as shown in the band diagram. In equilibrium, the Fermi level occurs at the same energy.

When a current is passed through the p-n junction under forward bias, electrons are injected from the n-region towards p-region while holes are injected from p-region towards n-region. Also the Fermi levels E_F in the p and n regions are shifted in opposite directions as shown in the band diagram. The injected electrons and holes recombine radiatively near the junction. For low biasing currents this radiation is spontaneous and incoherent. When the forward bias current is increased above a certain ***threshold value***, densities of free electrons and free holes become very large leading to population inversion. Under these conditions, stimulated emission of radiation can occur; the amplification will overcome the cavity losses and hence the laser diode begins to emit coherent laser radiation.

Drawback of homojunction lasers : The threshold current density is very high (50,000 A/cm^2). This is because; there is no potential barrier in the active region to confine the free charge carriers within the active region. They leak through the junction and recombine outside the junction. The radiation emitted outside the junction will not be amplified. Further radiation emitted in the junction region is also not confined within the active region . So losses are very high.

A significant reduction in the threshold current densities was achieved by forming hetero-junctions. A hetero-junction is a junction formed between two dissimilar semiconductors. Multi-layered structures of $Al_xGa_{1-x}As$ with different doping grown epitaxially (by MBE, MOCVD etc methods) on a n-type GaAs substrate form the



Heterojunction GaAs Laser

hetero-junction lasers. In the $Al_xGa_{1-x}As$ alloy, x fraction of Ga atoms in GaAs are replaced by Al atoms. In the double hetero-junction (DH) laser a thin active layer of pure GaAs is sandwiched between p-type $Al_yGa_{1-y}As$ and n-type $Al_xGa_{1-x}As$ cladding layers. The energy band gaps of p- and n-type claddings are higher than the pure junction layer. This difference in energy gaps forms a potential barrier and hence injected carriers are confined within the active region by the potential barrier. Also, the refractive indices of the p- and n-type claddings are different from the junction layer. This change of RI across the junction confines the laser radiation within the active region. These changes reduce the carrier loss and optical loss drastically and hence the threshold current density flowing across the junction is about 800A/cm^2.only.

Generally, the wavelength of light λ, emitted by a Semiconductor laser whose band gap energy is E_g is given by $\lambda = h.c / E_g$, where h is the Planck,s constant amd c is the speed of light. This is obtained from $E_g = h\nu = h.c /\lambda$.

Semiconductor lasers based on GaAs emit in the near infrared at 0.84μm (8400AU). Lasers based on InP/InGaAsP layered materials have laser emission at 1.55μm which have an important application in optical communications. Laser wavelengths have been extended to 0.63μm (red) in lasers based on GaAs/AlGaAs-layered materials. These lasers find applications such as laser pointer, bar-code readers etc. A new class of semiconductors based on Zn, Cd, Se and S materials are found to lase around 0.5μm (blue-green). The power output ranges from several mW to Watts.

The drawbacks of the semiconductor lasers are high sensitivity of operating characteristics on temperature, relatively poor coherence of the laser emission, relatively low output power and large beam divergence. However, in many applications, advantageous characteristics outweigh the disadvantageous ones.

The ***main advantages of semiconductor lasers*** are,

1. Compact and robust. Typical size is 300μmx300μmx100μm. This compactness is particularly important in many applications.
2. Highly efficient. Efficiency is of the order of 40% or higher.
3. The laser output power can be modulated at very high speeds by modulating the bias current. This feature is attractive in optical communication.
4. Available over a wide range of wavelengths (0.5μm to 1.55μm)

5. They are easily mass-produced by batch processing at much cheaper costs.
6. They are integrated monolithically with other electronic or opto-electronic devices.

The **semiconductor lasers** find **applications** in

1. Undersea fibre optical communication
2. Local area networks (LAN) which include high speed computer networks, avionic systems, satellite networks etc.
3. The semiconductor laser is used as the probe to read the informations from compact discs (CDs) as a result of irradiating the small grooves in the CD. This disc technique is also used for information storage and retrieval in computers.
4. Other uses of semiconductor lasers include high-speed printing, free-space communication, pump sources for some other laser systems, laser pointers and various medical applications.

Applications of lasers

In ***Scientific research***, lasers are used as high intensity, monochromatic coherent sources of light. For ex. Laser Raman spectrometers employing laser as intense source of light enable the study of symmetry properties of molecules and solids. Lasers are also used as coherent sources of light.in interference and diffraction experiments.

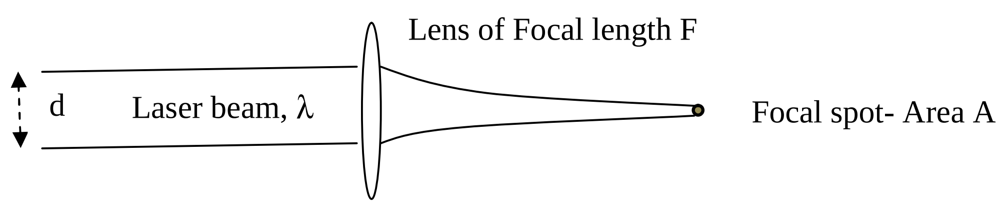
.*Industrial applications*

Lasers find application in material processing such as drilling holes, welding and cutting, surface heat treatments etc. High power CO_2 lasers and Nd:YAG lasers are widely used for this type of applications.in metal sheets and plates etc.

LASER CUTTING

A laser beam can be focused (by using suitable lenses) into light spot of diameter of 10-100 micrometers on the surface of a material. As a result, the energy of irradiation (called irradiance) is very high of the order of 10^7 watts/cm^2.

Suppose P is the power of the laser source in Watts and λ is the wavelength of laser radiation. Let **d** be the aperture of the laser beam (i.e., width). If F is the focal length of the focusing optics (lens) then ‘angular spread of the beam is given by $\boldsymbol{\theta = \lambda / d}$. Area of spread of laser spot around the focal point is given by $\mathbf{A = (F.\theta)^2}$. The irradiance ***I*** (or) intensity of the focused laser at the focal spot is given by $I = P/A = P/\mathbf{(F.\theta)^2}$..



Example : A laser beam emitting 1.44 μm radiation has power of 40mW and it has an aperture of 8 mm. It is focused with a lens of focal length 10cm. Calculate the area of spread and intensity of image.

Solution :

$\lambda = 1.44\ \mu m = 1.44 \times 10^{-6} m$; $d = 8mm = 8 \times 10^{-3} m$; $F = 10cm = 0.1m$,

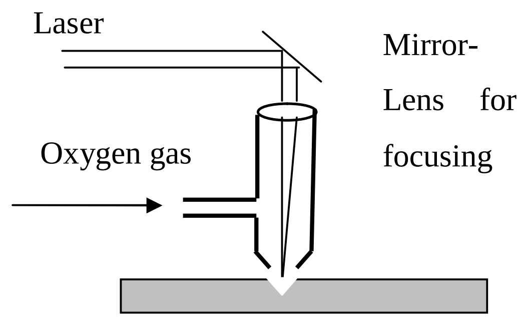
$P = 40mW = 40 \times 10^{-3}$ W

Angular spread $\theta = \boldsymbol{\lambda / d} = 1.44 \times 10^{-6} / 8 \times 10^{-3} = 0.18 \times 10^{-3}$ rad

Area of spread $A = (F.\lambda /d)^2 = (F.\theta)^2. = (0.1 \times 0.18 \times 10^{-3})^2 = 3.24 \times 10^{-10}\ m^2$

Intensity $I = P / A = 40 \times 10^{-3} / 3.24 \times 10^{-10} = 12.35 \times 10^{7}\ W/m^2$

This irradiance is sufficient to cause local melting, boiling and evaporation of the material at the spot of focus. The material being evaporated leaves a pit on the surface and if the evaporation is continued at the same region it grows into a hole. By moving the laser beam on the material along a line at a required speed, the material can be cut.



Paper, cloth, plywood, sheetmetals, ceramics etc can be cut rapidly with a very high precision. The width of the cut is extremely uniform along the entire length of the cut. Laser cutting does not introduce any additional impurities into the material. The required power output of laser for cutting applications depends on the material being cut. A 20kW pulsed laser is required for cutting 10mm thick glass. A 3 KW CO_2 cw laser cuts a 50mm thick titanium sheets at a spoeed of 50cm per min.. However, low power lasers (100-500kW) can also be used for cutting operations provided that the evaporated cut-material is blown off with a jet of oxygen gas as shown in figure. The oxygen jet blows away the cutting products and also it cools the adjacent edges of the cut material. Laser cutting is widely used in aerospace industry, automobile industry, textile industry etc. The laser cutting process is automated.

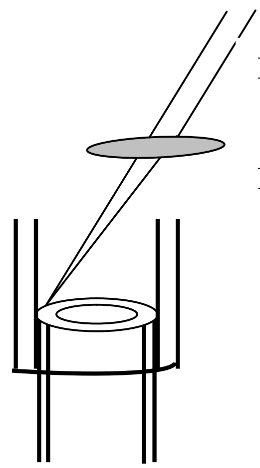
Laser Drilling

Suppose a material is heated by a powerful (few tens of KW) laser light pulses of 10^{-4} to 10^{-3} s duration. Intense melting and evaporation of the material at the focal spot leads to perforation of holes. CO_2 laser is suitable for drilling holes in almost all types of materials (metal, ceramic etc) while Nd:YAG lasers are used mainly for drilling metal sheets. The laser drilling can be performed in any desired direction with high precision. Drilling (i) fine holes which are very close to each other and (ii) holes near the edges of the objects can be done with extreme precision. The diameter of the drilled hole is uniform.

Laser Welding.:

Laser welding is far superior than conventional welding methods such as gas and arc

Weldings.
The main advantages are
1) It is a contactless method and hence it does not introduce any contamination or impurities in the welded region.
2) Inaccessible regions can also be welded with ease. (see diagram)
3) In temperature sensitive environments, spot welding can be done without affecting the adjacent areas . Ex. Spot welding of thin Ni wire connecting leads to the Ni alloy tab connected to the base of transistors.
4) Seam welding can be done using high power CO2 lasers.



It is used widely in aerospace and automobile industry. Ex. Welding of turbine bades to the turbine rotor.

LASERS IN NDT

Lasers are used in Non Destructive testing of materials to detect the presence of flaws.

A laser pulse incident on a solid surface produces rapid heating of the surface at the point of incidence. This results in a temperature rise which is localized around the point of incidence. This causes thermal expansion of the hot zone. When a series of very short high-energy light pulses of pulse length 100ps -20ns fall on the specimen, the hot zone suffers rapid heating and cooling alternately. This leads to rapid thermal expansion and contraction in the vicinity of the point of incidence resulting in high frequency vibrations. Due to this ultrasonic waves are generated on the surface of the specimen and they are transmitted into it. The frequency of the ultrasonic waves ranges from 1 to 100MHz. This laser induced ultrasonic waves are used for the Non Destructive Testing (NDT) of materials.

Advantages of the Laser NDT Technique include 1) This is a contactless testing technique 2) Data acquisition is very rapid and 3) Very high image ressolution

This contactless testing method facilitates the testing of ingots at red-hot condition for detecting flaws and surface cracks present in them. Also on-line testing of components during their manufacture or service is possible. For example, it is used for wall thickness measurements of red-hot tubes during manufacture. Other NDT methods are not suitable for these types of studies.

In ***electronic industry***, they are used for resistor trimming, scribing, micro-machining operations etc.

Laser remote sensing and environmental monitoring is possible by a laser radar which uses a CO_2 laser as a component. . They are also used as range finders

Medical applications Bloodless, precise surgeries are done by using CO_2 lasers with little damage to the surrounding tissues. Along with endoscopes , CO_2 lasers are widely used in angioplasty, neurosurgery, urology etc. Nd:YAG lasers are used in ophthalmologic surgeries

Communication

As the atmospheric attenuation of the 10.6 μm radiation of CO2 laser is very low, it is used in open air communications. The semiconductor lasers find applications in Fibre optic communication such as Undersea fibre optical communication, Local area networks (LAN) which include high speed computer networks, avionic systems, satellite networks

Computer applications

The semiconductor lasers are used as the probe to read the information from compact discs (CDs) as a result of irradiating the small grooves in the CD. This disc technique is also used for information storage and retrieval in computers. Other uses of semiconductor lasers include high-speed printing, free-space communication, pump sources for some other laser systems, laser pointers and various medical applications.

FIBER OPTICS

Introduction

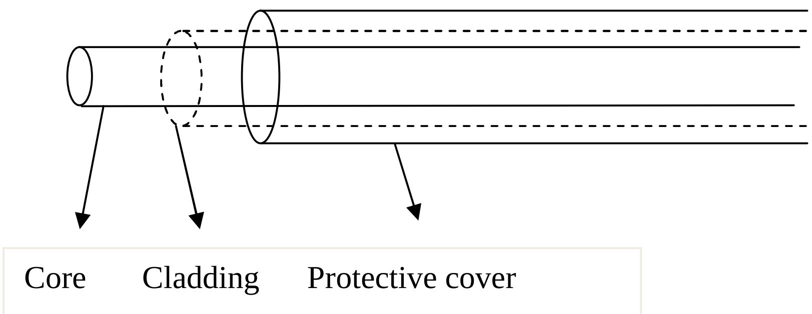
Communication refers to the transfer of information from a source point to a destination point by a communication system. If the source and destination are separated by a long distance an effective and efficient communication system is required.

Usually electromagnetic waves are used as 'carriers' of information signal. At the input (source) or transmitting end the information signal to be transmitted is modulated (I,e., superimposed) onto a suitable carrier and is transmitted through the communication system. This is detected at the output or 'Receiver' end (destination). The information signal is demodulated from the carrier wave, amplified and then it is concerted into the original form.

Earlier, communication systems were utilizing radio waves (frequency-10^6Hz) and microwaves (frequency-10^{10}Hz). In a *Fibre optic communication system*, light (frequency-10^{16}Hz) is used as the carrier of information signal. The light modulated by the information signal is guided through a thin glass/plastic fibre from source to destination. Hence this type of communication is termed as '*Fibre optic commmunication' (FOC)*.

Structure of an optical fibre

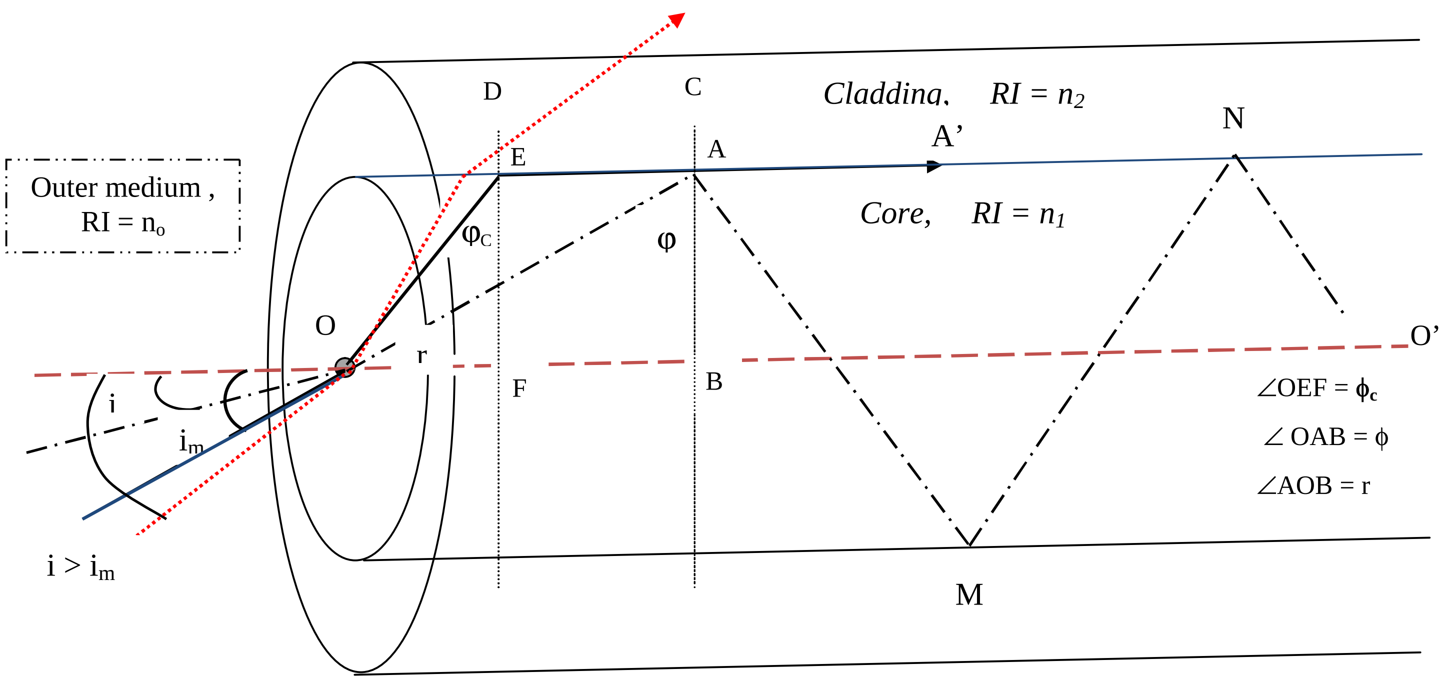
An optical fibre consists of a thin cylindrical *core* made of a dielectric glass (e.g. silica) or plastic. The core is surrounded by another glass called cladding. The refractive index of the core n_1 is slightly larger than the refractive index of the cladding n_2. The thickness of core and cladding varies depending on whether the type of fibre is single mode fibre or multimode fibre. The core has a diameter of 5-10 µm (for single mode fibre) or 50-100µm (multimode fibre). The thickness of the cladding is about 60-100µm (for single mode fibre) or 100-250µm (multimode fibre).



The core-cladding combination is covered by several protective covers in order to provide mechanical protection, to prevent corrosion, contamination and moisture and to prevent leakage of light outside or into the fibre.

<u>Principle of transmission of light through optical fibre</u>

Light rays entering an optical fiber are 'guided' (transmitted) through the optical fibre by the phenomenon of *Total Internal Reflection.*



Suppose a light ray entering the fibre through one end strikes the interface between the core and cladding at an angle of incidence ϕ which is greater than a *critical angle* ϕ_c. Then it suffers total internal reflection at the interface. The ray is reflected back into the core and it strikes the interface at the opposite side at the same angle of incidence, ϕ. Hence it is internally reflected again in the opposite direction.

Thus the light entering the fibre at one end is propagated through it by total internal reflection at the walls of the core and finally it exits from the other end of the fibre. Thus the optical fibre acts as a *wave guide* for light when the angle of incidence ϕ at the interface is greater than the critical angle of incidence ϕ_c , $\phi > \phi_c$.

The two conditions for total internal reflection to occur at the walls of the core are

1. The refractive index of the core must always be greater than the refractive index of cladding i.e., $n_1 > n_2$.
2. The angle of incidence at the core-cladding interface must be greater than the critical angle of incidence ϕ_c , $\phi > \phi_c$.

When the angle of incidence at the core-cladding interface ϕ just equals the critical angle of incidence ϕ_c , the light ray travels along the interface. When ϕ is less than ϕ_c the light ray will be refracted into the cladding and then out of the fibre. Hence the light ray with $\phi < \phi_c$ will not undergo total internal reflection and hence it will not be guided through the fibre. As, $\sin\phi / \sin r = n_2 / n_1 \rightarrow \sin\phi_c / \sin r_c = n_2 / n_1$

So, $n_1 \sin\phi_c = n_2 \sin r_c = n_2 \sin(90°) = n_2$, the critical angle of incidence is given by the equation $\sin\phi_c = \dfrac{n_2}{n_1}$ Or $\phi_c = \sin^{-1}\left(\dfrac{n_2}{n_1}\right)$

The critical angle of incidence at the interface ϕ_c is defined as the angle of incidence for which the angle of refraction r_c is 90°. It is given by $\phi_c = \sin^{-1}\left(\dfrac{n_2}{n_1}\right)$

where ***n_1 and n_2 are the refractive indices of core and cladding respectively.***

Generally, the optical fibres are characterized by two parameters, namely

1. *The acceptance angle and 2. Numerical aperture* *The **acceptance angle*** i_m may be defined as the maximum angle of incidence at the entrance side for which the angle of incidence at the interface of core-cladding ϕ just equals the critical angle of incidence.

All light rays entering the fibre with $i < i_m$ will propagate through it by total internal reflection. Hence, the acceptance angle may also be defined as the maximum angle of incidence at the entrance side of the optical fibre upto which the incident light will be transmitted through the fibre by total internal reflection.

For efficient transmission, an optical fibre should be able to accept and transmit as much light from the source as possible. This light gathering ability is determined by a factor called *"Numerical Aperture"*

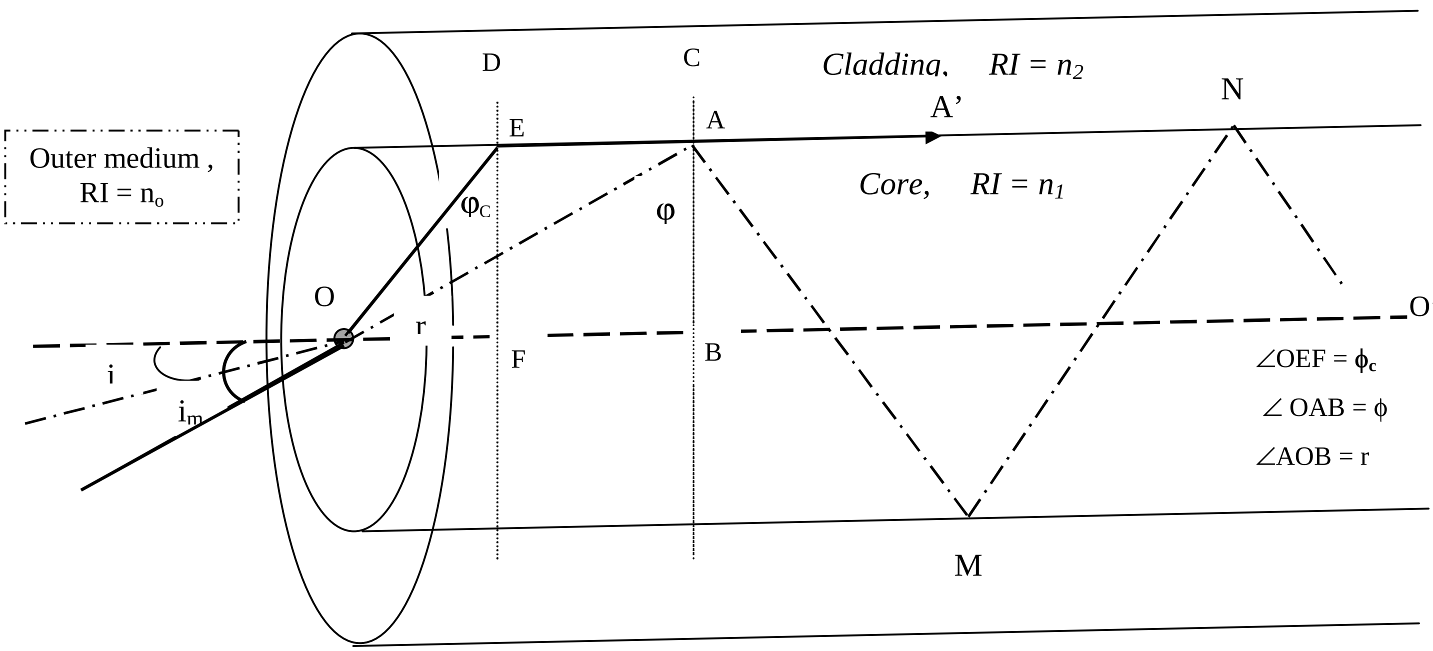
Numerical Aperture is defined as the sine of the angle of acceptance.

Numerical Aperture, NA = sin (i_m) = sin $\sqrt{(n_1^2 - n_2^2)}$ → (2)

Fractional change of refractive index: It is defined as the ratio of difference in refractive index of core and cladding to the refractive index of the cladding. It is given by $\Delta = (n_1 - n_2)/n_1$. For light rays to be guided through the fibre, $\Delta << 1$. Usually it is of the order of 0.01.

DERIVATION FOR ACCEPTANCE ANGLE AND NUMERICAL APERTURE

Let n_o be the refractive index of the outer medium (say, air) from where light is launched into the fibre. Let n_1 and n_2 be the refractive indices (RI) of core and the cladding respectively such that $n_1 > n_2$. OO' is the axis of fiber. Let ϕ_C be the critical angle of incidence at core-cladding interface of the fiber for total internal reflection to occur. In the optical ray diagram, the angle between the axis of fiber and the incident ray, is the angle of incidence at which the light is launched into the core from the outer medium. Consider a ray which is incident at O with an angle of incidence i. It is refracted into the core along OA at an angle of refraction ∠AOB = r.



It strikes the interface between core and cladding at A. The line CAB is normal to axis OO' of the fiber, passing through the point of incidence A. ∠OAB = ϕ is the angle of incidence at the core-cladding interface. As $\phi > \phi_c$. then the ray incident at A will be reflected internally along AM and then along MN and so on within the core. Thus, ϕ_c is the minimum angle of incidence at the interface for total internal reflection to occur.

For the ray entering from outside into the core, from snell's law, $\frac{\sin i}{\sin r} = \frac{n_1}{n_0}$ (or) $\sin i = \frac{n_1}{n_0}.\sin r \rightarrow (1)$

This means that r increases with increasing i.

In the right angled ΔOAB, $r + \phi = 90°$ (or) $\phi = 90° - r \rightarrow (2)$.

Hence, if r increases, ϕ decreases and vice versa. By comparing eqns (1) and (2) we find that if i decreases, ϕ increases and vice versa.

The critical angle of incidence at the interface is given by $\sin \phi_c = \frac{n_2}{n_1} \rightarrow (3)$

In ΔOAB, $\sin r = \sin(90 - \phi) = \cos\phi \rightarrow (4)$. Using (4) in eqn. (1), we have,

$$\sin i = \frac{n_1}{n_0}.\cos\phi \qquad \rightarrow (5)$$

Eqn (5) means that i and ϕ are inversely related to each other. Hence, a minimum value for ϕ corresponds to a maximum value for i. Let i_m be the maximum angle of incidence at the entrance of the fibre core which corresponds to the critical (minimum) angle of incidence at the interface ϕ_c. Then, eqn (5) can be written as

$$\sin i_m = \frac{n_1}{n_0}.\cos\phi_c \qquad \rightarrow \quad (6)$$

$$\text{But } \cos\phi_c = \sqrt{(1-\sin^2\phi_c)} = \sqrt{1-\left(\frac{n_2}{n_1}\right)^2} \qquad \text{[using eqn(3)]}$$

$$\text{i.e., } \cos\phi_c = \sqrt{1-\left(\frac{n_2}{n_1}\right)^2} = \sqrt{\frac{n_1^2 - n_2^2}{n_1^2}} = \frac{1}{n_1}.\sqrt{n_1^2 - n_2^2} \rightarrow \quad (7).$$

Substituting this in eqn. (6), we have,

$$\sin i_m = \frac{n_1}{n_0}.\cos\phi_c = \frac{n_1}{n_0}.\frac{1}{n_1}.\sqrt{n_1^2 - n_2^2} = \frac{1}{n_0}.\sqrt{n_1^2 - n_2^2}$$

$$\sin i_m = \frac{1}{n_0}.\sqrt{n_1^2 - n_2^2} \qquad \text{(or)}$$

acceptance angle, $i_m = \sin^{-1}\left[\frac{1}{n_0}.\sqrt{n_1^2 - n_2^2}\right]$

The maximum angle of incidence at the entrance side of the optical fibre up to which the incident light will be transmitted through the fibre by total internal reflection is defined as the "***acceptance angle'***.

i.e., light rays with angle of incidence i between zero and i_m will be propagated through the fibre. Other rays will not be transmitted.

Thus the acceptance angle $i_m = \sin^{-1}\left[\frac{1}{n_0}.\sqrt{n_1^2 - n_2^2}\right]$

For air, $n_0 = 1$. Therefore, ff light is launched into the fibre from air, then,

Acceptance angle for light entering from air, $i_m = \sin^{-1}\sqrt{n_1^2 - n_2^2}$ → (8)

As ***Numerical Aperture*** is defined as the sine of the angle of acceptance, we have

Numerical Aperture, NA = $\sin(i_m) = \sqrt{(n_1^2 - n_2^2)}$ → (9)

Note: Interms of the fractional change of Refractive Index, Δ, numerical aperture can be expressed as given below.

Fractional change of RI, $\Delta = \frac{n_1 - n_2}{n_1}$ (Or) $n_1.\Delta = (n_1 - n_2)$ → (10)

Numerical aperture, NA = $\sin\sqrt{(n_1^2 - n_2^2)}$ [from eqn. (9)]

But $(n_1^2 - n_2^2) = (n_1 + n_2)(n_1 - n_2)$

$= (n_1 + n_2).\, n_1.\, \Delta$ →(11) [using eqn. (10)]

Since n_1 and n_2 are very close to each other, we can write ½ . $(n_1 + n_2) \approx n_1$ (or) $(n_1 + n_2) \approx 2n_1$

Using this in eqn. (11), we have, $(n_1^2 - n_2^2) = (n_1 + n_2).\, n_1.\, \Delta = 2n_1^2.\, \Delta$

∴ Numerical aperture NA = $\sin\sqrt{(n_1^2 - n_2^2)} = \sin\sqrt{(2n_1^2.\, \Delta)} = \sin[\, n_1\sqrt{(2\Delta)}\,]$

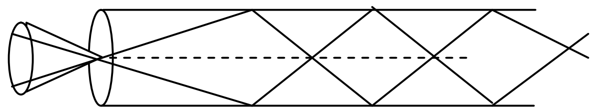
This is the expression for numerical aperture interms of RI of the core, n_1, and fractional change of RI of the fibre, Δ.

Classification of optical fibres

Optical fibres are classified into different types based on a) modes of propagation b) refractive index profile and c) materials using which the fibres are made

Modes of propagation

When a cone of light rays is launched into an optical fibre at one end, the rays will be propagated through the fibre by total internal reflection, provided the semi-angle of the cone is less than the acceptance angle i_m.. All rays entering the fibre with $i < i_m$ will be following different zigzag paths between the walls of the core. However, even with $i < i_m$, rays with only certain ray directions (zigzag paths) are allowed for the propagation through the fibre to its other end. Along these



zigzag paths the rays will be in phase with each other resulting in reinforcement. In other directions, the rays will be out of phase with each other resulting in destructive interference. So, the rays traveling along these directions will not be propagated.

Each allowed direction (zigzag path) is known as a mode of the fibre. The ray entering the fibre along its axis (axial ray) is the lowest order mode (000 mode in 3D).It is also known as *axial mode*. With increasing angle of incidence i at the entrance of fibre (upto i_m), the order of the mode increases. Inside the fiber, higher order modes travel longer optical paths than the lower order modes.

The number of modes in a fibre can be calculated using a parameter called ***"V number"*** or "normalized frequency". V number is given by $V = \frac{2\pi R}{\lambda}.\sqrt{n_1^2 - n_2^2} = \frac{2\pi R}{\lambda}.(NA)$ where R is the radius of the core. The number of modes N in a step index fibre is given by N = $\frac{V^2}{2} = \frac{2\pi^2 R^2}{\lambda^2}\left(n_1^2 - n_2^2\right)$ and in graded index fibre it is N = $\frac{V^2}{4} = \frac{\pi^2 R^2}{\lambda^2}\left(n_1^2 - n_2^2\right)$. These equations imply that the Number of propagating modes in a fibre is large when

1). radiusof the core R is large

2). the wavelength of light is small

3). numerical aperture is large (i.e., when difference between the RI of core n_1 and the RI of cladding n_2 is large)

SINGLE MODE AND MULTIMODE FIBRES

The number of modes propagated through a fibre is given by

N = $\frac{\pi^2 R^2}{\lambda^2}\left(n_1^2 - n_2^2\right)$ where R is the radius of the fibre and λ is the wavelength of propagating light. Only a single mode can propagate through a **single mode fibre** while more than one mode can propagate through **multi mode fibres**.

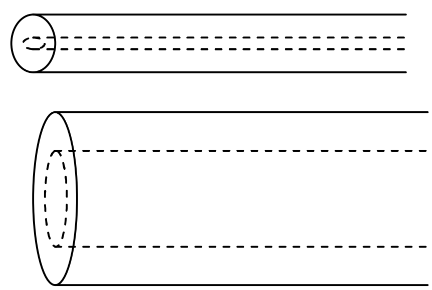
SINGLE MODE FIBRES

1. A fibre which can support the propagation of only a single mode (i.e. N=1) is known as ***a single mode fibre.*** A single mode fibre allows only the axial mode (with i = 0) to propagate through it. Higher order modes with i > 0 are not propagated in this fibre. A step index optical fibre will be a single mode fibre if it is fabricated such that the V-number is less than 2.405. This requires that the diameter of the core and the numerical aperture of the fibre are very small. Single mode step index fibres have a central core of diameter 5-10μm surrounded by a cladding of outer diamwter of about 60-70μm. Due to this small size, only a diode laser can be used as optical source for single mode fibres and not LEDs.

   A Single mode fibre has

   i) a very small diameter of core (5-10 μm) and cladding (60-70μm)
   ii) very small difference between n_1 and n_2
   iii) very small Numerical aperture
   iv) low or nil pulse dispersion
   v) Higher bandwidth

Single mode Fibre
diameter of core : 5-10μm
diameter of cladding : 60-70μm
Multimode Fibre
diameter of core : 50-100μm
diameter of cladding : 100-250μm



The **advantages and uses** of a Single mode fibre are

1. there is no pulse dispersion and it has a much higher bandwidth.
2. They are **used** for long distance communications such as telephone communication, cable telecommunications etc..

Their **disadvantages** are

2. The fabrication of Single mode fibres and coupling them to transmitters and receivers are very difficult.
3. A diode laser must be used as optical source for single mode fibres and not LEDs.

MULTIMODE FIBRES

An optical fibre which supports the propagation of more than one mode through it is called a ***multimode fibre***. If V-number is greater than 2.405 it will be a multimode fibre. The number of modes N in a step index fibre is given by $N = \frac{V^2}{2} =$

$\frac{2\pi^2R^2}{\lambda^2}\left(n_1^{\ 2}-n_2^{\ 2}\right)$ and in graded index fibre it is N = $\frac{V^2}{4}$ $=\frac{\pi^2R^2}{\lambda^2}\left(n_1^{\ 2}-n_2^{\ 2}\right)$ provided V > 2.405.

In a multimode fibre, the diameter of core is between 50-100μm and the diameter of its cladding is about 100-250μm. .They have a higher numerical aperture and acceptance angle. So an LED is sufficient to launch the light signals into the fibre. In a multimode step index fibre, light is propagated in different modes with different zigzag paths. Higher order modes making larger angle i with the axis of fibre traverse longer optical paths when compared to lower order modes (i close to 0). As a result, light rays entering the fibre at the same time reach the outer end of fibre at different times.This results in the broadening of the input pulse at the output end. Its amplitude is reduced at the output end resulting in the weakening of the signal. Hence the multimode fibres are not suitable for long haul communications.

The **advantages and uses** of a multimode fibre are

1. Easy to fabricate and easy to couple them to transmitter and receiver ends
2. A LED is sufficient to launch the light signals into the fibre.
3. They are **used** for short communications such as Local Area Networks (LAN)

Their **disadvantages** are

Higher puse dispersion and lower bandwidth

1. Not suitable for long haul communication

Difference between single mode and multimode fibres

Single mode fibre	Multimode Fibre
1. Light propagates through the fibre only in a single mode. 2. Diameter of core is small (5-10μm) 3. Difference between the RI of core and cladding must be small. 4. Numerical aperture is small. 5. It has large band width 6. No pulse dispersion occurs. 7. LED can not be used as optical source. Only a diode laser can be used as optical source. 8. Fabrication of single mode fibre is difficult. 9. Coupling the fibre ends to transmitter and receiver ends is not easy. 10. Cost of production is higher. 11. Used in long distance	1. Light propagates through the fibre in a large number of modes. 2. Diameter of core is large (50-100μm) 3. Difference between the RI of core and cladding can be larger. 4. Numerical aperture is large. 5. It has a relatively smaller band width 6. Pulse dispersion occurs. 7. A LED can also be used as optical source. 8. Fabrication of multimode fibre is relatively easier. 9. Coupling the fibre ends to transmitter and receiver ends is relatively easier. 10. Cost of production is cheaper. 11. It is not suitable for long distance

telecommunications.	telecommunications. They are used only for short distance communications such as Local Area Networks.

ATTENUATION IN FIBRES

Optical signal propagating through the optical fibre is attenuated due to several reasons. The attenuation of signal is defined as the ratio of the optical power output from a fibre to the input optical power. If P1 and P2 are the input and output powers respectively, then, the loss in power in units of decibels (dB) is given by power loss = $10.\log_{10}\left(\frac{P_1}{P_2}\right)$.

Mechanisms of attenuation in optical fibres

1) Absorption losses

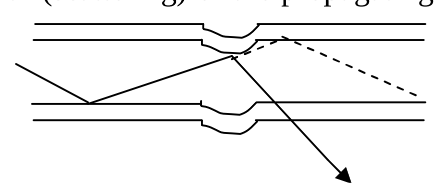
The loss of optical signal by absorption of light in the optical fibre is known as '*absorption loss'*. Presence of some impurities such as OH-, copper, iron, nickel, cobalt, chromium, manganese etc, leads to the strong absorption in various wavelength regions in the visible region and near UV and near IR regions. Presence of such impurities in the material of the optical fibre (glass/plastic) leads to heavy loss in the intensity of light transmitted. The absorption losses in optical fibres can be minimized by minimizing the presence of these light absorbing impurities in the material of the optical fbre.

2) Scattering losses

Impurities, inclusions and other defects present in the glass material of an optical fibre may scatter the light propagating along some direction into some other directions. Light signal may also be scattered by local variations in density of the glass which cannot be prevented. The local variations in density at microscopic levels lead to a local variation in refractive index. Due to this, a change of path (scattering) of the propagating light occurs leading to a loss of signal.

3) Wave guide and microbend losses

Microbends and other structural variations in the optical fibre causes a change in the angle of incidence at the interface,ϕ. This results in a change of path of the propagating light and its loss.

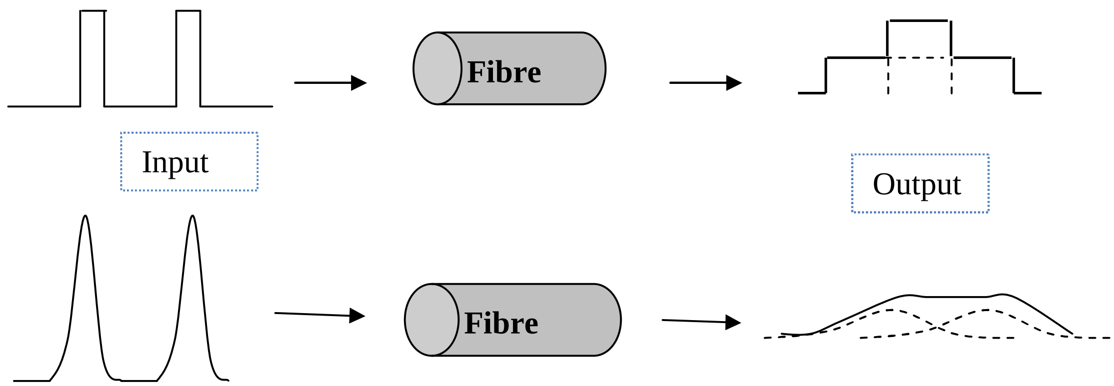


Change of path at a microbend

Dispersion in fibres In digital communication systems, the signal to be transmitted is first coded into pulses. These pulses are then transmitted through the optical fibre to the receiver coupled to the fibre at the other end. The '*information carrying capacity'* of a fibre is higher if it can transmit a larger number of pulses per unit time. This capacity is limited by '*pulse dispersion*'.

pulse dispersion

Light rays are launched into the fibre in the form of pulses of certain amplitude (height) and time width. Inside the core, they travel along different zigzag paths (i.e., different modes). The rays making larger angles with the axis (i.e, higher order modes) have to



If the broadening is higher, adjacent pulses may overlap with each other at the output end. Hence the transmitted pulses will not be resolved at the output end due to such overlap. No information can be retrieved from such overlapping pulses. To avoid this, successive pulses at the input end are separated in time such that they do not overlap at the output end. This limits the number of input pulses that can be transmitted per unit time. This in turn restricts the information carrying capacity of an optical fibre.

Thus, information carrying capacity of an optical fibre system will be higher when the pulse dispersion is small.

<u>Material Dispersion</u>

Light from any optical source will contain a group of wavelengths. We know that the speed of light v varies with wavelength in any material medium of RI μ $\left[\because \text{ RI } \quad \mu = \frac{c}{v}\right]$. So, a pulse of light rays of different wavelengths launched at the same time at the input end and traversing the same optical path inside the fibre (i.e., same mode), reach its output end at different times. This results in a broadening of the pulse called '*material dispersion*'.

Disadvantages of pulse dispersion.

1. If successive pulses at the receiver end overlap due to a higher pulse dispersion, no information can be retrieved at the receiver end.
2. Pulse dispersion limits the bandwidth of a fibre

The pulse dispersion in optical fibres can be reduced in two ways:

(i) by using single mode step index fibres or (ii) by using graded index fibres

Classification of optical fibres

Optical fibres are classified into different types based on

a) modes of propagation, b) refractive index profile and
c) materials using which the fibres are made.

a) Types of optical fibres based on refractive index profile:

Step index and Graded index Fibres

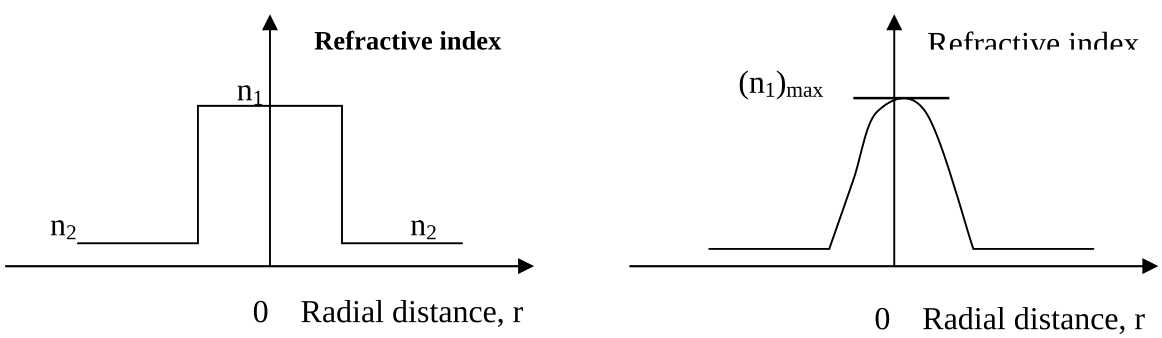
A curve representing the variation of refractive index as a function of radial distance from the axis of the fibre is known as ***refractive index profile***. Optical fibres are classified into two types based on refractive index profile. They are 1) Step index fibres and 2)Graded index Fibres .

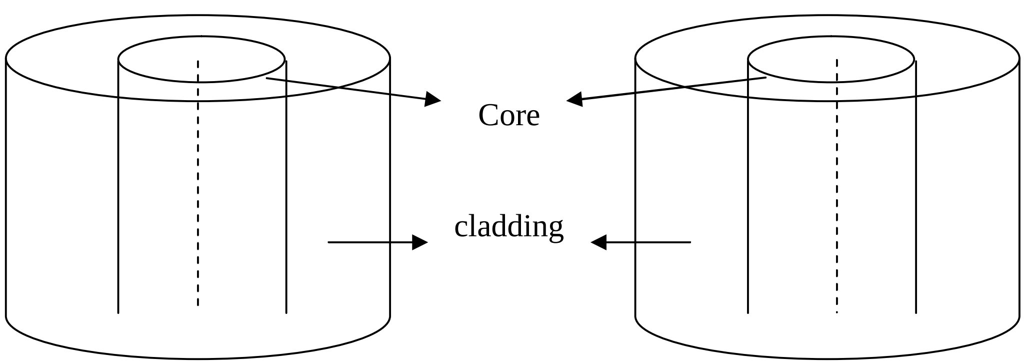
Step indexFibres

In a step index fibre both the central core and its cladding have uniform refractive indices n_1 and n_2 respectively such that $n_1 > n_2$. As seen in figure, the refractive index changes abruptly at the interface between the core and cladding from n_1 to n_2 and vice versa. The refractive index profile appears like a step. Hence this type of fibre are called as *'step index fibres'*. There are two types of step index fibres based on the number of modes supported by the fibre. They are

1) single mode step index fibres and 2) multi mode step index fibres.

Single mode step index fibres support the propagation of only a single mode and ***multi mode step index fibres*** support the propagation of many modes. Multimode step index fibres are easily fabricated but they suffer from the drawback of pulse dispersion. There is no pulse dispersion in single mode step index fibres but their fabrication is difficult.





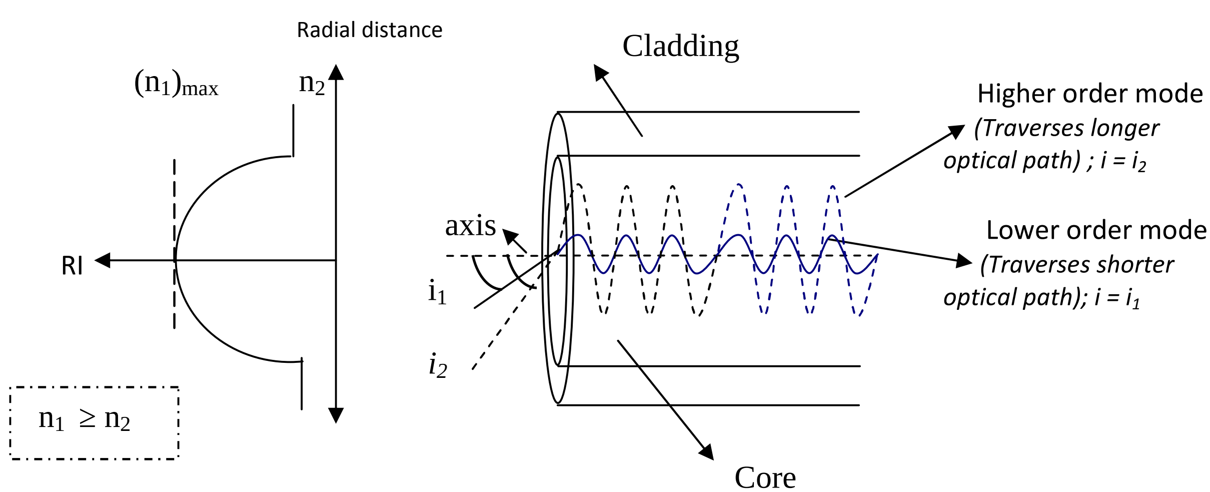
STEP INDEX FIBRE	GRADED INDEX FIBRE

Graded index Fibres

In a ***Graded Index Fibre (GRIN Fibre)*** the refractive index (RI) of the core n_1 is not constant. However, the Refractive Index n_2 of its cladding is a constant. The refractive index of core is maximum along the axis and it decreases nearly parabolically with increasing radial distance r from the axis. Due to such variations of n_1 with r, the acceptance angle and numerical aperture also decrease with r. At the core-cladding interface $n_1 = n_2$. Thus, the relation between RI of core and cladding in a GRIN Fibre is $n_1 \geq n_2$. The core is fabricated by depositing concentric layers of gradually decreasing refractive indices. The cladding has a uniform refractive index n_2.

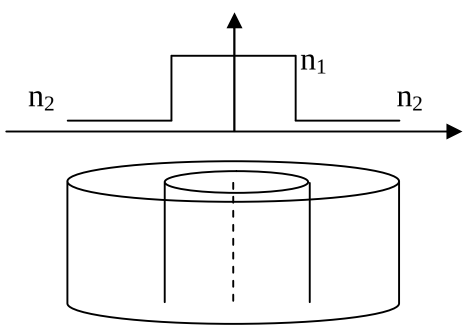
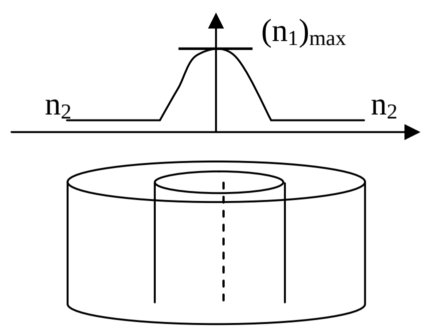
As the RI of core decreases with increasing radial distance r from the axis, a ray entering the fibre is continuously bent towards the axis of the fibre. This is according to Snell's law. Hence, for a medium with parabolical refractive index profile, the path of the rays inside the core are sinusoidal as shown in the diagram.

Higher order modes traverse longer optical paths than the lower order modes. In step index fibres this results in pulse dispersion. However, in a multimode GI fibre, there is no or less pulse dispersion. This is explained below.



Let i_1 and i_2 be the angle of incidence for the rwo incident rays. The rays with larger angle i_2 traverse longer optical paths than those with smaller i_1. The rays with smaller angle i_1 travel along the region surrounding the axis where the RI of core n_1 is relatively larger. But, the rays making larger angle with the axis traverse through the regions where n_1 is smaller. As the velocity of light in a medium is inversely proportional to its refractive index, it means that light rays tend to move slower in the regions closer to the axis and in the regions away from the axis light moves faster. So, the average velocity of light rays in different modes are nearly the same. Thus, all rays in different modes launched at the same time into the fibre reach the output end nearly at the same time. Hence there is no pulse dispersion in multimode graded index fibres.

Difference between Step Index and Graded Index Fibres

Step Index Fibres	Graded Index Fibres
1.Refractive index (RI) of core n_1 is constant and similarly RI cladding n_2 is also constant. But $n_1 > n_2$. 2. At the interface between the core and cladding, RI changes abruptly. 3. Due to the above reason, the refractive index profile of step index fibre appears like a step. Hence it is given the name *'step index fibre'*.  4. Light rays follow different zig zag paths (modes) inside by total internal reflection. 5..Number modes propagating in a multimode fiber is given by N = $\frac{V^2}{2} = \frac{2\pi^2 d^2}{\lambda^2}\left(n_1^2 - n_2^2\right)$ 6. These are meridional rays. 7. Higher order modes traverse longer optical paths than lower order modes. As the velocity of light everywhere inside the core is constant, different modes reach the receiver end at different times. 8. So, Pulse dispersion occurs in multimode step index fiber.	1.RI of cladding is uniform. But the RI of core is not uniform. Itvaries nearly parabolically with radial distance from the axis of fibre. 2. At the interface between the core and cladding, RI is the same and it does not change abruptly. 3. Refractive index of core is the same as that of the cladding at the interface and it increases gradually (in a nearly parabolic manner) to a maximum value along the axis. Hence it is given the name *'graded index fibre'*  4. Light rays follow different sinusoidal paths (modes) by total internal reflection. 5. Number modes propagating in a multimode fiber is given by N = $\frac{V^2}{4} = \frac{\pi^2 d^2}{\lambda^2}\left(n_1^2 - n_2^2\right)$. 6. These are skew rays. 7. Higher order modes traverse longer optical paths than lower order modes. But as the velocity of light decreases with increasing radial distance from the axis, all modes traverse the core for the same duration. Hence all modes reach the receiver end nearly at the same time. 8. So, Pulse dispersion does not occur in multimode graded index fibre.

CLASSIFICATION OF OPTICAL FIBRES BASED ON MATERIALS

Generally optical fibres are made by using (i) high content silica glass (ii) multicomponent silica glass and/or (iii) Plastics.

There are three major types of optical fibresbased on materials. They are

optical fibres with 1) **P**lastic **C**lad **P**lastic core (PCP fibre)

2) **P**lastic **C**lad Silica glass core (PCS Fibre)

3) Silica Clad Silica core (SCS Fibre)

PCP FIBRE: In a plastic clad plastic (PCP) fibre, both the central core and its cladding are made of some transparent plastics. Examples of the plastic materials used in a PCP fibre are:

vi) Polystyrene core with a methyl methacrylite cladding

vii) Polymethyl methacrylate core with a clAddinbg of its co-polymer.

Advantages:

1). Highlyflexible 2). Easy to install 3). PCP fibres can withstand relatively higher mechanical stresses 4). 60% lesser weight than silica glass fibre

Disadvantage : Attenuation of light is very high.

Use: They are used for short distance computer applications with information capabilities of about 6Mbps over a distance of 50-200m.

PCS FIBRES: These are fibres with plastic cladded silica core.

The **advantages** of these fibres are

1) Relatively lower attenuation characteristics 2) Less affected by radiations.

They find **uses** in militarybapplications.

SCS FIBRES: These are optical fibres with silica glass core surrounded by a cladding made of another silica glass.

Example: A core made of P_2O_5 doped silica (SiO_2:P_2O_5) surrounded by a cladding of SiO_2.

The **advantages** of these fibres are

1) Much lower attenuation characteristics than other types of fibres. 2) Best propagation characteristics and 3) Easy to fabricate

Disadvantages: 1) They are not highly rugged 2) Under the influence of radiation, attenuation of light increases.

Applications: Used for long haul telecommunications and LANs.

Requirements on the materials for the fabrication of optical fibres

The materials used for fabricating optical fibres should fulfil the following requirements.

!) Easy fabrication of long, thin and flexible fibres from the material should be possible.

2) Materials used for making the core and cladding should be compatible with each other.

3) They should be completely transparent to the wavelength of light that is to be

transmitted.

1) Physical properties such as thermal expansion, melting temperature, viscosity, light scattering etc., of core and cladding must be similar.

7. The refractive index of the material of core should be larger than that of cladding. Usually, a difference in the refractive index of core and cladding is introduced by adding dopants such as TiO_2, Al_2O_3, GeO_2 etc with the basic silica glass material.

Applications of optical fibres

Important applications of optical fibres are in

1) Fibre optic communications

2) various Fibre optic sensors to detect variations in environmental conditions (Pressure, Temperature, humidity, gas etc) and measurement of small displacements, acceleration etc

1) FIBRE OPTIC COMMUNICATION

It is the transmission of information from one place to another achieved by the use of optical fibres. The information is carried through the fibre in the form of light. The signal to be transmitted (voice, image, data etc) is first converted into electrical signal by using an input transduer which in turn is used to produce optical signal from some optoelectronic device (semiconductor LED or Laser). The optical signal is launched into the fibre from end and it is propagated through the fibre by the phenomenon of total internal reflection. At the other end of the fibre, the transmitted light signal is detected by a receiver (photodetector) which converts the light signal back into electrical signal. Then it is converted to the original form by using amplifiers and output transducer.

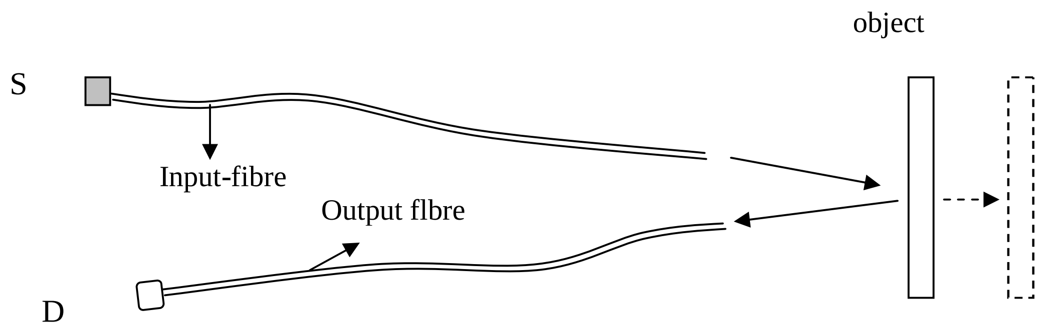
Fibre optic communication systems are broadly classified as (1) short and middle range communication systems such as local area networks (LAN) and (2) long distance communication systems such as telephone systems.

2) Fibre optic sensors

Fibre optic sensors are used to sense various physical variables such as pressure, temperature, electric and magnetic fields, current, humidity, displacements, acceleration etc. When compared to conventional sensors, Fibre optic sensors are superior and cost effective. Fibre optic sensors are categorized into *intrinsic and extrinsic*.

In Extrinsic fibre optic sensors, the optical fibre merely acts as an optical wave guide. The interaction between the quantity to be measured and the light to be transmitted takes place outside the fibre. Ex. Displacement sensor.

To measure very small displacement of an object, two optical fibres are used. One end of a fibre (input fibre) is connected to an optical source S while one end of the other fibre (output fibre) is connected to a photo detector D. Light from the source passes through the input fibre and the light leaving it through its free end is made to fall on the object.



The free end of the output fibre is positioned such that the light reflected by the object is launched into it. The transmitted reflected light is detected at the photodetector producing a photocurrent. The magnitude of photocurrent depends on the intensity of reflected light which inturn depends on the distance between the source and reflecting surface of the object. Thus when the object is displaced by a small amount, the photocurrent in the detector also changes. This enables the detection of displacement.

In the ***intrinsic type sensors***, variation of the fibre characteristics with physical quantity to be measured is used for the sensor applications. For example, consider that an optical fibre is subjected to a pressure or temperature change. Hence, the resulting changes in dimensions of the fibre (diameter of core and cladding, length of fibre), density variations etc cause changes in refractive indices of core and cladding thereby causing a change in the characteristics of the light transmitted through the fibre. Analysis of the change in the characteristics of the transmitted light, enables their measurement.

3)Military applications

Communication equipments utilizing fibre optics in warships and warplanes are light weight and free from interception by enemies. Fibre guided missiles are used in wars.

4) Medical applications

A ***fibre optic endoscope*** is used for the inspection and diagnosis of internal organs such as stomach, intestine etc. In cardiology, it is used in the removal of arterial block of blood flow. Used for certain treatments of cancer, Depending on the body part,
each type of endoscopy has its own special term, such as

• ***laryngoscopy (vocal cords)*** ‘• ***bronchoscopy (lungs)*** • ***colonoscopy (colon)***

• ***Esophagoscopy (esophagus)*** • ***gastroscopy (Stomach)*** • ***Hysteroscopy (uterus)***

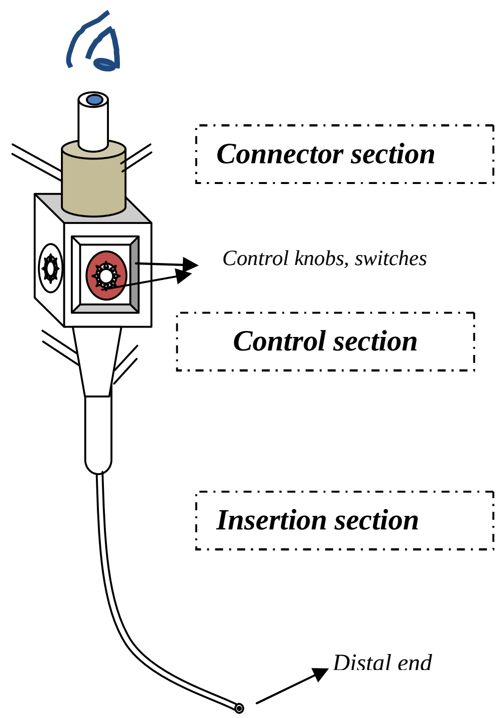
Endoscopy

Endoscopy means *looking inside. It* is a minimally invasive diagnostic medical procedure performed under conscious sedation or Total Anesthesia. . It is used for the examination of internal body cavities using a specialized medical instrument called an ***endoscope***.

An ***Endoscope*** gives visual evidence of the problem (e.g. cancer, ulceration or inflammation). It can also be used to collect a sample of tissue or remove problematic tissue. It is also used to take photograph of the hollow internal organs. A surgeon introduces the endoscope into the body either through a body opening, such as the mouth or the anus, or through a small incision in the skin.

Fiberoptic Endoscopy **instruments** are based on Fiber optic bundles which are 2–3·mm in diameter. Each bundle has about 20·000–40·000 fine glass optical fibers (diameter, about 10·µm each)that are packed tightly together.

Each individual fiber has glass core clad by another glass of a lower RI. Light is transmitted from one end of fiber to the other by total internal reflection (TIR) at the core-cladding interface. Light loss is prevented by TIR. There are two bundles. One bundle of fibers carries light into the examined organ. Illumination is provided by an external source, either a xenon arc or a halogen-filled tungsten filament lamp. The second bundle is a coherent bundle and it transmits the image from the organ interior to the viewing optic.



Schematic diagram of Fiber optic endoscope

. **Parts of the endoscope**

- ***Connector Section***
- ***Control Section***
- ***Insertion Section***

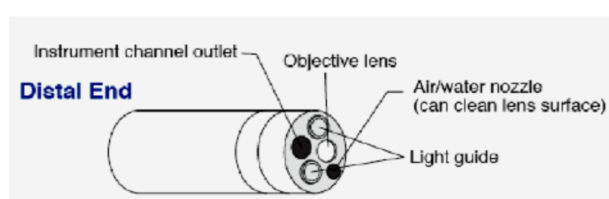
Control section

- It can be Held in the operator's one hand.

It has two stacked angulation control knobs;
One for directing the fiber up/down and the other for left/right deflection of the endoscope tip.

- It also has air/water and suction valves. Remote switches to modify or capture the ideo image are also attached.

Fiber optic instruments have an eyepiece located at the top of the control section for direct image viewing.



Insertion Section

This portion of the endoscope is flexible and it is inserted into the patient. The insertion tube contains the following:

i) One or two instrument channel(s), ii) An air channel, iii) a water channel, iv) Either an image guide bundle or a CCD chip with wire connections, and v) angulation wires.

The instrument channels are provided for passage of diagnostic and therapeutic instruments as well as for suctioning. It is possible to connect a variety of other accessories at the insertion end of the fibre (called distal end). Some of the accessories that can be attached are biopsy forceps, Graspers, Baskets, Injectors, Dilators, Knives etc. Air and water channels permit distention of the bowel and cleaning of the lens.

Connector section: The connector section has the following: • A light guide, • An air-pipe • Electrical contacts compatible with the processor/light source. \• Side connectors for a water container, suction, CO_2 etc. An S (safety)-cord connecting mount, which grounds the endoscope, reducing the electrical shock hazard to the operator. one or more instrument channels are provided for passage of diagnostic and therapeutic instruments as well as for suctioning.

Viewing:

These endoscopes are generally direct-viewing endoscopes; therefore the endoscopist looks directly into an eyepiece provided at the top end. Alternatively, a small video camera may be placed on the end of the endoscope and the image viewed on a video screen.. An optical beam splitter allows a second observer to view the image.

The addition of sidearms and external video screens introduces optical interference, which reduces visual clarity.

• ***Limitations***

• The image quality of a fibreoptic bundle, though excellent, can never equal that of a rigid lens system or a video-endoscope

Advantages

• Fiberoptic bundles are extremely flexible having Small diameter • Direct view (monitor not necessary)

• Complete visualization of the entire small bowel to the terminal ileum

• Can do therapeutic interventions

• Allows for sampling/biopsying of small bowel mucosa

• Allows for resection of polyps

• Placement of stents or dilation of small bowel strictures

• **Disadvantages**

• Technically difficult procedure

• Very time consuming (Procedure can take > 3 hours)

• Patient may need to be admitted to the hospital

• Higher risk of small bowel perforation

FIBRE OPTIC COMMUNICATION SYSTEM

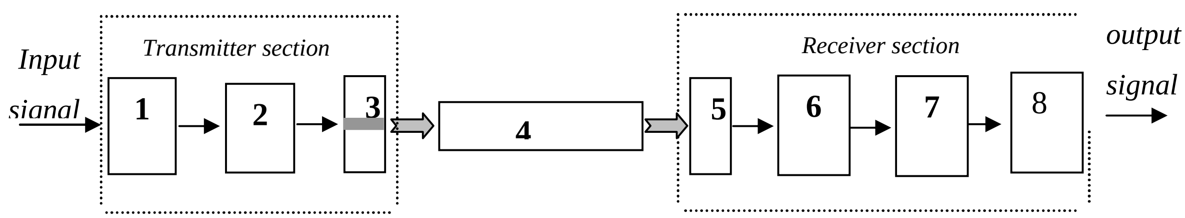
Signals transmitted through open atmosphere are severely attenuated and distorted due to scattering and absorption by the atmosphere. Hence, open atmosphere communication is not suitable for long distance communication, In a communication system, the transmitting medium should not affect or modify the signals being transmitted. This is achieved in Fibre Optic Communication (FOC) which uses Optical Fibres as transmitting medium.

<u>Optical Fibres and the principle of wave guiding in FOC</u>

IN FOC, an optical fibre made of silica glass and/or plastic is the guiding is the guiding (transmitting) medium for optical signals. An optical fibre consists of a thin cylindrical *core* made of a dielectric glass (e.g. silica) or plastic. The core is surrounded by another glass called cladding. The refractive index of the core n_1 is slightly larger than the refractive index of the cladding n_2. Light rays entering the fibre such that the angle of incidence at the core-cladding interface is greater than a crtical angle of incidence are guided through the fbre by

total internal reflection between the walls of the core. To avoid leakage of light signal or interference from other sources, the optical fibres are sheathed in opaque plastic covers.

The schematic diagram of an FOC system is as shown below.



1. ***Input Transducer*** *(converts the signal to be transmitted into continuous electrical signals)*
2. ***Encoder*** *(Converts continuous electrical signals into pulses by using AD converters))*
3. ***LED or Laser diode*** *(converts electrical pulse signals into optical signal)*
4. ***Optical fibre*** *(Transmits optical signals by total internal reflection of light)]*
5. ***Photo-Detector*** *(Photo-diode or Photo-Multiplier tube) [Detects optical signals and converts it to electrical signals}*
6. ***Decoder (****Converts Pulsed electrical signals into continuous electrical signals by using AD converters)*
7. ***Signal amplifier***
8. ***Output transducer*** *(converts the electrical signals into the original form of the signal at the input end)*

The transmitter involves a miniature LED or diode laser based on GaAs as optical source. They emit light under forward biasing which is modulated by the signal by changing the drive current according to the signal to be transmitted.

- **1**. ***input transducer*** First, the signal to be transmitted (Voice, optical signals etc) is converted into a continuous electrical signal by using an input transducer**.**
- **2.** ***encoder***.Then this continuous electrical signal is coded into digital electrical pulses by means of AD converters (*encoder).*
- **3. Light Source** A semiconductor LED or diode Laser is used as the optical source for FOC. The drive current of the optical source (LED/diode Laser) is modified according to the strength of the electrical pulses of the signal and hence the light from the source is modulated by the signal.
- **4) Optical Fibre** The optical fibre is the transmitting medium which transmits light signal to the receiver end of the fibre by total internal reflection.

  One end of **a** low-loss optical fibre is coupled to the optical source and the *coded optical signal*s from the source are launched into it. They are transmitted through the fibre by total internal reflection. The other end of the optical fibre is coupled to a photodetector by using suitable couplers.
- **5).** ***photodetector*** At the receiver end, the fibre is coupled to a *semiconductor based* ***photodetector*** (such as PIN or avalanche diode) by using suitable optical couplers.

  The ***photodetector*** receives the optical signals and converts them into electrical pulses. A ***PIN diode*** or ***Avalanche photodiode*** is used as a photodetector**.**

  A ***PIN diode*** is fabricated by separating p-type and n-type semiconductor layers by a thin intrinsic region. For photodetection, it is operatd in the reverse-biased mode. The charge carriers generated by absorbing light photons constitute the flow of electric current in the external circuit. ***Avalanche photodiode*** is similar to a PIN diode but it is operated at high voltages close to breakdown voltage. This shows an effect of amplifying the detected signal current.
- **6) A** ***decoder*** converts these electric pulses into continuous electrical signals by using DA converters.
- **7).** ***signal amplifier*** These continuous electrical signals are amplified in a signal amplifier**.**
- **8)** ***output*** **transducer** An appropriate output transducer converts these electrical signals back into the original form of signals.

  This is the broad outline of the functioning of the Fibre Optic Communication system.

Advantages of Fibre optic commmunication

1. *Very high information carrying capacity* Very high frequency of optical radiation and the large band width of transmitted frequencies by an optical fibre (upto 100GHz) enables a FOC system to carry far more information than radio and microwave communication systems utilizing copper metallic cables.

2. *No electrostatic interference* Since information is transmitted in the form of liht radiation through a non-metallic optical fibre, external electrical noise and lightning do not affect or interfere with the transmitting signal.
3. *Elimination of cross-talk.* Unlike the case of metallic cables FOC systrms are immuned to cross0talk between cabkes caused by magnetic inducti9n.
4. Since optical fibres are very thin, they are light weight and occupy a small space.
5. *Low cost* Cost is lower since the basic raw material is cheaper.
6. Greater security of information.
   The information through optical fibre is more secure since it is very difficule to intercept or tap the information in the middle of transmission
7. There is no environmental corrosion.
8. Long life-span and easy to maintain.

APPLICATIONS OF FOC

Fibre optic communication is broadly classified as (1) short and middle range communication systems such as local area networks and (2) long distance communication such as telephone systems.

1) ***Local Area Networks (LAN)***: In LAN, a number of computer terminals are interconnected over a common server by optical fibres. This allows each computer to use data and programs from any other.
2) ***Long haul communication*** These are employed for communication over a long distance of about 10 km or more. Telephone cables within a country and Telephone cables connecting carious countries come under this category.

Numerical Examples on Lasers

1. A laser beam has a power of 50mW. It has an aperture of 5x10

Given : power of laser , P = 50mW = $50\text{x}10^{-3}$W;

Wavelength λ = 700nm = $700\text{x}10^{-9}$m;

Aperture of beam, d = $5\text{x}10^{-3}$ m;

rea of spread, A = $0.48\text{x}0^{-8}$ m^2

Formula & solution:

Angle of spread, $\Delta\theta = \lambda / d$ = $700\text{x}10^{-9} / 5\text{x}10^{-3}$ = 0.14 radians

Intensity, I = P / A = $50\text{x}10^{-3} / 0.48\text{x}0^{-8} = 1.042\text{x}10^{7}$ W/m^2

2. Calculate the wavelength of light emitted by a semiconductor laser whose band gap energy is 1.85eV.

wavelength of light emitted, $\lambda = h.c / E_g$

Planck's constant $h = 6.624x10^{-34}$J.s

Speed of light $c = 3x10^8$m/s

Band gap of semiconductor, Eg = 1.85eV = $1.85x1.602x10^{-19}$J

So, $\lambda = h.c / E_g = (6.624x10^{-34}\ x3x10^8)/(\ 1.85x1.602x10^{-19}) = 6.705x10^{-7}$m = 6705AU

3. A certain Nd:YAG laser emits 2.0 J pulses of light whose wavelength is 1.06 μm. What is the minimum number of Nd^{3+} ions in Nd:YAG laser crystal?

Total energy of pulse emitted E = 2.0 J

Wavelengthof light , λ = 1.06 μm = $1.06x10^{-6}$m

So, energy of each photon, $\varepsilon = h\nu = h.c/\lambda$

where Planck's constant $h = 6.624x10^{-34}$J.s and Speed of light $c = 3x10^8$m/s

energy of each photon $\boldsymbol{\varepsilon} = (6.624x10^{-34}\ x3x10^8) / 1.06x10^{-6} = 1.875x10^{-19}$ J

So total number of photons in each pulse, $n = E/\varepsilon = 2 / 1.875x10^{-19} = 1.067x10^{19.}$

If we assume that each and every Nd ion contained in the Nd:YAG is involved in the emission process, then there must be a total of $1.067x10^{19}$ Nd ions in the crystal.

{Actually not all the Nd activator ions are involved in the emission process and hence this is only a minimum value}

4. The diameters of the output laser beam spot from a laser source are 2mm and 3mm at distances of 2m and 4m from the laser source respectively. Find the angle of divergence.

Angle of divergenge ϕ = (D2 – D1)/ (X2 – X1)

Diameter D1 = 2mm = $2x10^{-3}$m at distance X1 = 2m

Diameter D2 = 3mm = $3x10^{-3}$m at distance X2 = 4m

So, Angle of divergenge ϕ = (D2 – D1)/ (X2 – X1)

$= (3-2)x10^{-3} / (4-2)$

$= 0.5x10^{-3}$ rad

5. Calculate the relative population of the energy levels N1 and N2 at 300K , λ = 500nm ***(PEC, May 2015)***

As $N_i \propto \exp\left(\frac{E_i}{kT}\right)$ for any ith state of energy E_i,

relative population , $\frac{N_1}{N_2} = \exp\left(\frac{E_2 - E_1}{kT}\right) = \exp\left(\frac{h\nu}{kT}\right) = \exp\left(\frac{hc}{\lambda kT}\right)$

where $E_2 - E_1 = h\nu = hc/\lambda$

c = velocity of light, h = Planck;s constant

Given, T = ***300K*** and λ = 500nm = 500×10^{-9}m Boltzmann const k = 1.38×10^{-23} J/K

Planck;s constant, h = 6.626×10^{-34}J.s, velocity of light, c = 3×10^{8}m/s

$$\therefore \frac{N_1}{N_2} = \exp\left(\frac{h\nu}{kT}\right) = \exp\left(\frac{hc}{\lambda kT}\right) = \exp\left(\frac{6.626\times10^{-34}\times3\times10^{8}}{500\times10^{-9}\times1.38\times10^{-23}\times300}\right) = 5.1\text{x}10^{41}$$

6)An Nd-YAG laser emits light at a wavelength of 1.063x10^{-6}m. If the output power is 20W, then how many photons are emitted in 10 min when the laser is in operation?

(PEC, Dec. 2016)

laser emits light of wavelength λ = 1.063×10^{-6}m;

Energy of one photon of wavelength λ is e = hc/λ = $\left(\frac{6.626\times10^{-34}\times3\times10^{8}}{1.063\times10^{-6}}\right)$

output power = 20W = 20J/s,

Total energy emitted in 10mins (= 600s) is E = 20x600= 1.2×10^{-4}

Number of photons emitted in 10 min = E/e = $\left(\frac{1.2\times10^{4}\times1.063\times10^{-6}}{6.626\times10^{-34}\times3\times10^{8}}\right)$=$6.4 \times 10^{22}$

7. Calculate the number of photons emitted per second by 5mW laser assuming that it emits light of wavelength 6328AU. ***(PEC, May 2017)***

laser emits light of wavelength λ = 6328AU = 6.328×10^{-7}m;

Energy of one photon of wavelength λ is e = hc/λ = $\left(\frac{6.626\times10^{-34}\times3\times10^{8}}{6.328\times10^{-7}}\right)$

output power = 5mW = 5×10^{-3} J/s,

Total energy emitted /sec is E = 5×10^{-3} J/s

Number of photons emitted/sec = E/e = $\left(\dfrac{5\times10^{-3}\times6.328\times10^{-7}}{6.626\times10^{-34}\times3\times10^{8}}\right)$=

9. The output wavelength and power of He Ne laser are 630nm and 3mW respectively. Calculate the number of photons emitteb per second by the device. {Planck's const = 6.62x10-34 Js. Speed of light = 2.0x108 m/s.] ***(PEC, Jan. 2018)***

10Calculate the wavelength of emission from a GaAs semiconductor laser whose bandgap energy is 1.44eV (PEC, May 2018)

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Numerical Examples on Optical Fibers

1. The RI of Core and Cladding of an optical fiber are 1.55 and 1.53 respectively. Calculate its numerical aperture and Acceptance Angle and critical angle.

Given : $n_1 = 1.55$ and $n_2 = 1.53$

numerical aperture NA = Sin (i_m) = $\sqrt{n_1^2 - n_2^2} = \sqrt{1.55^2} - 1.53^2 = 0.248$

Acceptance Angle i_m = $\sin^{-1}\sqrt{n_1^2 - n_2^2} = \sin^{-1}(NA) = \sin^{-1}(0.248) =$ 14.36

critical angle φ_c = n_2 / n_1 = 1.53 / 1.55 = 0.987 radians = °

2. The RI of Core of an optical fiber is 1.50. If the Acceptance Angle is 15° , Calculate its numerical aperture, RI of Cladding and critical angle.

Given : $n_1 = 1.50$, i_m = ***15°.*** $\therefore$ NA = Sin (i_m) = Sin (***15°***) = 0.259

Also, $NA = \sqrt{n_1^2 - n_2^2}$. So, $n_2 = \sqrt{n_1^2 - (NA)^2} = \sqrt{(1.50)^2 - (0.259)^2} = 1.4775$

critical angle φ_c = n_2 / n_1 = 1.4775 / 1.50 = 0.985 radians = °

3. For a multimode step index fiber, the refractive indices of core and cladding are 1.53 and 1.50 respectively. If the radius of core is 50 μm, calculate the Numerical Aperture, Acceptance angle, normalized frequency of the fiber (i.e, V number) and number of guided modes. The wavelength of light propagated is 1μm.

What should be the largest radius of this fiber so that it is a single mode step index fiber .

<u>Formulae</u>

Numrical Aperture, $NA = \sqrt{n_1^2 - n_2^2}$

Acceptance Angle i_m = $\sin^{-1}\sqrt{n_1^2 - n_2^2} = \sin^{-1}(NA) = \sin^{-1}() =$

$$Normalized\ Frequency, V = \frac{2\pi R}{\lambda}.\sqrt{n_1^2 - n_2^2} = \frac{2\pi R}{\lambda}.(NA)$$

For a multimode step index fiber, Number of modes, N = V^2 / 4

For a single mode step index fiber, V < 2.405 and so

$$V = \frac{2\pi R}{\lambda}.\sqrt{n_1^2 - n_2^2} = \frac{2\pi R}{\lambda}.(NA) < 2.405$$

$$So,\ \text{Radius of single mode fiber, } R_s < \frac{2.405\times\lambda}{2\pi\times(NA)}$$

<u>*Given*</u>

the refractive index of core n_1 = 1.53 and refractive index of cladding , n_2= 1.50

radius of core, R = 50 μm = $50\text{x}10^{-6}$m

The wavelength of light propagated, λ = 1μm = $1\text{x}10^{-6}$m .

<u>*Solution*</u>s

$$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{1.53^2 - 1.50^2} = 0.3015$$

Acceptance Angle i_m = $\sin^{-1}\sqrt{n_1^2 - n_2^2} = \sin^{-1}(NA) = \sin^{-1}(0.3015) = 17.55^o$

$$Normalized\ Frequency, V = \frac{2\pi R}{\lambda}.(NA) = \frac{2\times3.143\times50\times10^{-6}\times0.3015}{1\times10^{-6}} = 94.76$$

$$N = \frac{V^2}{4} = \frac{(94.76)^2}{4} = 2244.86 = 2245$$

Core Radius R_s of fiber to be single mode fiber is, $R_s < \dfrac{2.405\times\lambda}{2\pi\times(NA)}$

$$R_s < \frac{2.405\times\lambda}{2\pi\times(NA)} = \frac{2.405\times1\times10^{-6}}{2\times3.143\times0.3015} = 1.2667\times10^{-6}\,m$$

$$R_s < 1.2667\times10^{-6}\,m$$

So maximum value of core radius is 1.2667 μm

4. In a step index fiber, the refractive indices of core and cladding are 1.461 and 1.458 respectively. If the radius of core is 5 μm,show that the fiber is single moded for wavelength of radiation greater than 1.22 μm. Also Calculate the number of modes

supported by the fibr at a wavelength of 0.6micrometer. [Hint; Use

$V = \frac{2\pi R}{\lambda}.\sqrt{n_1^2 - n_2^2} < 2.405$ for a single mode fiber.

$(Or) \quad \frac{2\pi R}{2.405}.\sqrt{n_1^2 - n_2^2} < \lambda \qquad i.e., \qquad \lambda > \frac{2\pi R}{2.405}.\sqrt{n_1^2 - n_2^2} > 1.22\times10^{-6} m$

For λ = 0.6 μm radiation, calculate number of modes, N = V^2 /2 = $\frac{2\pi^2 R^2}{\lambda^2}.\left(n_1^2 - n_2^2\right)$

5. The core & cladding of an optical fiber have refractive indices of 1.55 and 1.50 respectively. Determine the maximum acceptance angle when the fiber is kept in air and also when kept in water. (RI of water = 1.33) (PEC, May 2015)

Given: RI of core = n_1 = 1.55, RI of cladding, n_2 = 1.50

RI of air =1, RI of water = 1.33

Formula : Acceptance Angle i_m = $\sin^{-1}\left(\frac{1}{n_0}\right)\sqrt{n_1^2 - n_2^2}$

When fiber is kept in air n_0 =1; so Acceptance angle of fiber kept in air

$i_m = \sin^{-1}\left(\frac{1}{1}\right)\sqrt{1.55^2 - 1.50^2} = \sin^{-1}\left(0.391\right) =$

When fiber is kept in water n_0 =1.33; so Acceptance angle of fiber kept in water

$i_m = \sin^{-1}\left(\frac{1}{1.33}\right)\sqrt{1.55^2 - 1.50^2} = \sin^{-1}\left(0.294\right) =$

6. Calculate the numerical aperture, acceptance angle, and the critical angle of a fiber having RI =1.50 and the cladding RI =1.47 (PEC, Dec 2014)

7. Calculate the RI of core and cladding materials of an optical finer from the following date : (i) NA = 0.26 and (ii) refractive index difference is 0.015 (PEC, May 2016)

Given : NA = 0.26 & $n_1 - n_2$ =0.015

To find : n_1 = ? & n_2 =?

$NA = 0.26 = \sqrt{n_1^2 - n_2^2} = \sqrt{\left(n_1 - n_2\right)\left(n_1 + n_2\right)} = \sqrt{0.15\times\left(n_1 + n_2\right)}$

Squaring both sides and rearranging, $0.15x(n_1 + n_2) = (0.26)^2$

(or) $(n_1 + n_2) = (0.26)^2 / 0.015 = 4.507$

Solve $n_1 - n_2 = 0.015$ and

$(n_1 + n_2) = 4.507$

$n_1 = 2.33$ and $n_2 = 2.18$

8. An optical fibre has a core material with refractive index 1.55 and its cladding material has a refractive index of 1.50. The light is launched into it in air. Calculate its numerical aperture and also the fractional index change. (PEC, Dec. 2016)

Given : $n_1 = 1.55$& $n_2 = 1.50$

$$NA = \sqrt{n_1^{\,2} - n_2^{\,2}} = \sqrt{1.55^2 - 1.50^2} = 0.391$$

$$i_m = \sin^{-1}(NA) = \sin^{-1}(0.391) = 23°$$

Fractional change of RI, $\Delta = \dfrac{n_1 - n_2}{n_1} = \dfrac{1.55 - 1.50}{1.55} = 0.032$

9. Find the numerical aperture of an optical fibre having a refractive index of 1.55 and cladding of refractive index 1.50. (PEC, May 2018)

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Short Answer Questions

1. What is meant by Spontaneous and stimulated emission of radiation?

When an atom in an excited state returns to a lower energy state (or ground state), it emits the excess energy in the form of radiation. If this happens without any external stimulation, the emission is called ***Spontaneous emission.*** If an interaction of a photon induces the excited state atom to return to lower energy state, then the emission is called ***stimulated emission.***

. Distinguish between Spontaneous and stimulated emission of radiation

2. What are the special characteristics of lasers over conventional light sources?

Generally, light from a laser source is highly monochromatic, directional and also highly coherent. Light emitted by ordinary sources are incoherent and are divergent.

3. What are the components of a laser system?

A Laser source system requires the following three as main components: (i) Active medium, (ii) pumping source and (iii) optical resonator (or) resonant cavity

4. What is a Laser Active mediu?,

An active medium is a solid, liquid or a gas in which amplification of light waves by stimulated emission can occur. It consists of a collection of atoms, ions or molecules in which one or more excited states are Meta stable levels. Meta stable levels have a longer lifetime of the order of 10^{-3}s or more. These atoms or ions are known as *active centers*. . A suitable intense *excitation mechanism* (known as *pumping*) can be used to achieve population inversion in the active medium

5. What is meant by metastable levels?

The excited levels with longer lifetimes of the order of 10^{-3}s or more are termed as ‘***meta stable’*** states. Population inversion can be achieved only in meta stable states.

6. What is meant by population inversion?

In a system containing a large no of identical atoms, usually, the number of atoms in its ground state energy level is more than the atoms in any excited state. This is normal population condition.

Under *Population inversion*, the number of atoms in some excited state level is greater than the number of atoms in the ground level. Population inversion can be achieved only in meta stable excited states.

7. What is meant by pumping?

The mechanism by which population inversion is achieved in an laser active medium is known as '***pumping***'. The external sources, which are used to provide this pumping mechanism, are known as pumping sources.

8. Mention the various pumping methods used in different laser systems.

Optical pumping	-	Solid state Laser (Ruby, Nd:YAG), Dye Laser
Electrical Pumping	-	Gas Lasers (He-Ne, CO_2 Lasers)
Chemical pumping	-	molecular Ion lases
Carrier injection	-	Semiconductor lasers

9. ***What is meant by Threshold population inversion?***

The minimum population inversion at which the cavity losses are just compensated by the gain of the Laser medium is called the ***'threshold population inversion'***. Stimulated radiation is amplified and a laser beam results when population inversion is higher than this threshold value.

10 What is meant by Threshold pumping?

The minimum pumping power required to achieve the threshold population inversion is known as ***'threshold pumping power'***. The lower the threshold pumping power, the higher will be the efficiency of the laser system.

11 What is meant by Resonant cavity or optical resonator?

An optical resonator is an arrangement which is used to select and amplify the stimulated radiation of particular characteristics while preventing the amplification of radiations of other unwanted characteristics. In the simplest form, an optical resonator is a pair of optically flat, plane mirrors M1 and M2 kept exactly parallel to each other. The active medium is placed between the mirrors of the resonator along the optic axis of resonator..

12 What are the merits and demerits of
i) Nd:YAG, ii) CO_2 iii) Semiconductor laser

The advantages of ***Nd:YAG*** laser are

1. It has a rather low excitation threshold

2. It has a higher thermal conductivity than Ruby and other solid state lasers. Laser pulses are generated at a higher pulse repetition rate. Hence it operates *as if* it is a continuous wave laser (i.e., a *quasi* continuous wave operation).
3. Its efficiency is relatively higher
4. Peak output power is several kW.

Drawbacks:

1. Operated only in pulsed form
2. Laser light is less monochromatic than the laser light from gas lasers.
3.

Advantages CO_2 laser

1. CO_2 lasers operate with a high efficiency (30%).
2. Still higher efficiencies (45%) can be achieved by having the gas flow transverse to the electric discharge.
3. Atmospheric attenuation of the 10.6 μm radiation is very low. Hence it is very useful for open-air communication.

The main **advantages of semiconductor lasers** are,

1. . Compact and robust. Typical size is 300μmx300μmx100μm. This compactness is particularly important in many applications.
2. Highly efficient. Efficiency is of the order of 40% or higher.
3. The laser output power can be modulated at very high speeds by modulating the bias current. This feature is attractive in optical communication.
4. Available over a wide range of wavelengths (0.5μm to 1.55μm)
5. They are easily mass-produced by batch processing at much cheaper costs.
6. They are integrated monolithically with other electronic or opto-electronic devices.

The **drawbacks of semiconductor lasers** are

1. high sensitivity of operating characteristics on temperature,
2. relatively poor coherence of the laser emission,
3. elatively low output power and
4. large beam divergence.

However, in many applications, advantageous characteristics outweigh the disadvantageous ones.

13 Write the uses of i) Nd:YAG, ii) CO_2 , iii) Semiconductor laser

i) USES OF ***Nd:YAG*** LASERS:

(1) They find application in material processing such as drilling holes, welding and cutting etc.

(2) They are used for resistor trimming, scribing, micro-machining operations etc in the electronic industry.

(3) They are also used as range finders.

(4) They are used in ophthalmologic surgeries.

ii) USES OF CO_2 lasers

1. High power CO_2 lasers find applications in material processing , cutting, welding, hole drilling etc.
2. As the atmospheric attenuation of the 10.6 μm radiation is very low, it is used in open air communications.
3. Bloodless, precise surgeries are done by using CO_2 lasers with little damage to the surrounding tissues.Along with endoscopes , CO_2 lasers are widely used in angioplasty, neurosurgery, urology etc.
4. Laser remote sensing and environmental monitoring is possible by a laser radar which uses a CO_2 laser as a component.

iii) **USES OF SEMICONDUCTOR LASERS**

Semiconductor lasers find applications in

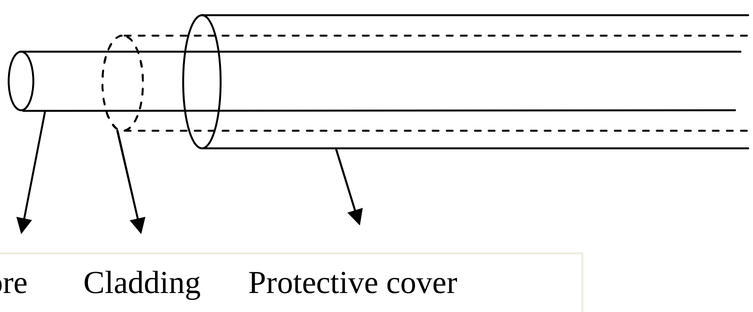
1. Undersea fibre optical communication
2. Local area networks (LAN) which include high speed computer networks, avionic systems, satellite networks etc.
3. The semiconductor laser is used as the probe to write and read the information from compact discs (CDs
4. Other uses of semiconductor lasers include high-speed printing, free-space communication, pump sources for some other laser systems, laser pointers and various medical applications.

14. Mention the important industrial/medical/computer applications of lasers.

(See the Previous answer)

15. Write the structure of an optical fibre

An optical fibre consists of a thin cylindrical *core* made of a dielectric glass (e.g. silica)



or plastic. The core is surrounded by another glass called *cladding*. The refractive index of the core n_1 is slightly larger than the refractive index of the cladding n_2.

The core-cladding combination is covered by several protective covers in order to provide mechanical protection, to prevent corrosion, contamination and moisture and to prevent leakage of light outside or into the fibre.

16. Write the principle of transmission of light through an optical fibre

Light is 'guided' (transmitted) through the optical fibre by the phenomenon of *Total Internal Reflection.* If the light entering the fibre through one end strikes the interface between the core and cladding at an angle of incidence ϕ greater than a *critical angle* ϕ_c Then it is propagated through it by total internal reflection at the walls of the core and finally it exits from the other end of the fibre.

17. Write the conditions for transmission of light through an optical fibre

Light is 'guided' (transmitted) through the optical fibre by the phenomenon of *Total Internal Reflection.* The two conditions for total internal reflection to occur at the walls of the core are

1. The refractive index of the core must always be greater than the refractive index of cladding i.e., $n_1 > n_2$.

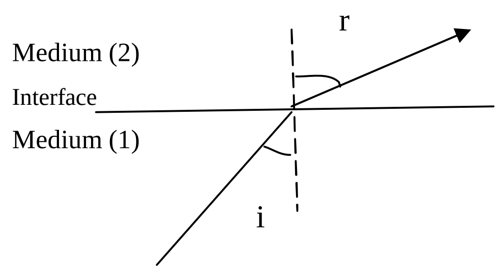
2. The angle of incidence at the core-cladding interface must be greater than the critical angle of incidence ϕ_c , $\phi > \phi_c$.

18. Define critical angle

Suppose light is refracted from one medium into another. (i is angle of incidence and r is the angle of refraction.) The critical angle of incidence at the interface between the two media is defined as the angle of incidence for which the angle of refraction r is 90°. It is denoted by ϕ_c.

In figure, r = 90° = r_c when i = ϕ_c.

In this case the refracted ray travels parallel to interface.



19. Define angle of acceptance

The ***acceptance angle*** i_m may be defined as the maximum angle of incidence at the entrance side for which the angle of incidence at the interface of core-cladding ϕ just equals the critical angle of incidence.

20. Define numerical aperture

For efficient transmission, an optical fibre should be able to accept and transmit as much light from the source as possible. This light gathering ability is determined by a factor called *"**Numerical Aperture**"*

Numerical Aperture is defined as the sine of the angle of acceptance.

Numerical Aperture, NA = sin ($\sqrt{(n_1^2 - n_2^2)}$)

21. How are optical fibres classified according to i) modes of propagation, ii) Refractive index profile, iii) Material?

Basis of Classification	***Name of Optical Fiber***
modes of propagation	Single mode fiber, Multimode fiber
Refractive index profile	Step Index Fiber, Graded Index Fiber
Materials	Plastic Clad Plastic (PCP) Fiber Plastic Clad Silica Glass (PCS) Fiber Silica Clad Silica (SCS) Fiber

22. What is meant by Step index Fiber?

In a ***Step index Fiber,*** Refractive indices (RI) of both the core (n_1) and cladding (n_2) are uniform such that $n_1 > n_2$. At the interface between the core and cladding, RI changes abruptly. Due to the above reason, the refractive index profile of step index fibre appears like a step. Hence it is given the name 'step index fibre'. The light rays guided through a step index fibre follow different zigzag straight-line paths.

23. What is meant by graded index Fiber?

In a ***<u>Graded Index Fibre (GRIN Fibre),</u>***The Refractive Index n_2 of cladding is a constant. But, the refractive index of core n_1 is maximum along the axis and it gradually decreases nearly parabolically with increasing radial distance from the axis. Due to such variations of n_1, a ray entering the fibre is continuously bent towards the axis of the fibre. *Hence, for a medium with parabolical refractive index profile, the path of the rays inside the core are sinusoidal* . Different modes travel different sinusoidal paths.

24. What is a single mode fibre?

A fibre which can support the propagation of only a single mode (i.e. N=1) is known as ***a single mode fibre.*** It allows only the axial mode to propagate. Single mode step index fibres have a central core of diameter 5-10μm surrounded by a cladding of outer diamwter of about 60-70μm.

25. Write the significant Characteristics of single mode fibre

A Single mode fibre has

- i) a very small diameter of core (5-10 μm) and cladding (60-70μm)
- ii) very small difference between n_1 and n_2
- iii) very small Numerical aperture
- iv) low or nil pulse dispersion
- v) Higher bandwidth

26. Write the Merits and demerits of Single mode fiber

The **advantages and uses** of a Single mode fibre are

1. there is no pulse dispersion and it has a much higher bandwidth.

2. They are used for long distance communications such as telephone communication, cable telecommunications etc..

Their **disadvantages** are

1. The fabrication of Single mode fibres and coupling them to transmitters and receivers are very difficult.
2. A diode laser must be used as optical source for single mode fibres and not LEDs.

27. What are multimode fibres?

An optical fibre which supports the propagation of more than one mode through it is called a ***multimode fibre***. In a multimode fibre, the diameter of core is between 50-100μm and the diameter of its cladding is about 100-250μm. .They have a higher numerical aperture and acceptance angle.

28. Write the Merits and demerits of multi mode fiber

The **advantages and uses** of a multimode fibre are

1. Easy to fabricate and easy to couple them to transmitter and receiver ends
2. A LED is sufficient to launch the light signals into the fibre.
3. They are **used** for short communications such as Local Area Networks (LAN)

Their **disadvantages** are

1. Higher puse dispersion and lower bandwidth
2. Not suitable for long haul communication

29. . Write the important differences between

i) Stepindex and graded index fibres

ii) Single mode and multimode fibres

iii) Fibres with plastic and glass cores

30) What are the advantages of single mode fibres over multimode fibres?

Advantages of single mode fibres ***over multimode fibres*** are

i) low or nil pulse dispersion

ii) Higher bandwidth

31) What are the different losses observed in optical fibers?

1) Absorption losses 2) Scattering losses

3) Wave guide and microbend losses and 4) Dispersion losses

32. What is meant by pulse dispersion?

Different light rays making different angles with the axis are launched into the fibre at the same time in the form of pulses. Inside the core, they travel along different zigzag paths called modes. The rays making larger angles with the axis traverse longer optical paths (zigzag paths) than the rays which make smaller angles with the axis. In a step index fibre, velocity of light in the core is constant. So different modes reach the other end of fiber at different time. Because of this, at the other end of fiber (Receiver end) the height of the pulse is decreased while its width is increased. This is known as ***pulse dispersion.***

33. How does the pulse dispersion affects the light transmission through optical fibers?

Due to pulse dispersion, at the output end, the height of the pulse is decreased while its width is broadened. If the broadening is higher, adjacent pulses may overlap with each other at the output end. Hence the transmitted pulses will not be resolved at the output end due to such overlap. No information can be retrieved from such overlapping pulses. To avoid this, successive pulses at the input end are separated in time such that they do not overlap at the output end. This limits the number of input pulses that can be transmitted per unit time. This in turn restricts the information carrying capacity of an optical fibre.

34 ***What are the advantages of Graded index fibres over step index fibres?***

The pulse dispersion is a major problem in a multimode step-index fiber. This is not present in a multimode graded-index fiber. So information carrying capacity of multimode graded-index fiber is greater than that of multimode step-index fiber.***)***

35. What are the applications of optical fibres?

Important applications of optical fibres are in

1) Fibre optic communications 2) various Fibre optic sensors to detect variations in environmental conditions (Pressure, Temperature, humidity, gas etc) and measurement of small displacements, acceleration etc

36) What is meant by Fibre optic communication?

37) What are the components of a Fibre optic communication system?

38) What are the advantages of Fibre optic communication system over conventional Communication systems?

39) Write the uses of FOC.

<u>Detailed Answer Questions</u>

1) ***What are Einstein's coefficients? Discuss the the theory of interaction of radiation with matter and derive expressions for Einstein's coefficients.***
2) ***Describe the construction and working of i) Nd:YAG/ CO_2 / Semiconductor laser***
3) ***Discuss the applications/industrial applications of lasers.***
4) ***Explain the structure of an optical fibre and the principle of transmission of light through them. Derive expressions for numerical aperture and acceptance angle.***
5) ***Distinguish between***

i) single mode and multimode fibres.
ii) Stepindex and graded index fibres

6. *Describe the different losses in fibres. Explain what is meant by pulse dispersion in multimode step index fibres. How is it eliminated in Graded index fibres?*

7. ***Discuss the different classifications of fibres based on refractive index, modes of propagation and materials.***

8) ***Discuss with neat sketch, the construction, working and uses of Fiber optic endoscope.***

With a neat sketch of a schematic diagram, Describe the various components of a Fibre optic communication system and explain their functions.