MODULE 1

PHOTONICS

Photonics is a branch of physics that deals with the study of dynamics and associated properties of photons. Concept of photons was introduced by Einstein in his theory of photoelectric effect. Based on Max Planck's quantum theory of radiation, Einstein proposed that the light is associated with the quantized energy packets called photons. They do not possess mass but acquire properties of an elementary particle. In this module, role of photons in the production of laser and in applications of optical fibers is discussed.

1. LASER

LASER is the abbreviated form of ***L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.*

Difference between ordinary light (such as torch light or LED light) and LASER is that ordinary light diverges largely at every point on its path but laser beam diverges very negligibly.

***1.1.* Characteristics of laser**: Laser is a

(i) **monochromatic radiation**: single colored or single wavelength radiation.
(ii) **highly coherent beam**: the phase difference between any two rays in a beam is zero or constant and their wavelengths remain same.
(iii) **strongly unidirectional**: angle of divergence is very negligible during propagation.
(iv) **high intensity beam**: being an amplified radiation it has very high intensity

1.2. Principle (Interaction of radiation with matter)

Basic principle involved in producing laser is the excitation and deexcitation of electrons (or atoms or ions or molecules) in a material. It is natural in all states of matter that electrons emit radiations when they deexcite from a higher energy level to a lower energy level. Laser is one such radiation emitted under a special circumstance in selective materials. Let us understand the three different phenomena (also known as basic principles of laser or interactions of radiation with matter) occur when energy is provided to a material in form of a radiation.

(i) Induced absorption (excitation process)

This is a phenomenon in which electrons (or atoms) of a system absorb the energy (hγ) of photons of incident radiation and excite to a higher enenrgy level.

As depicted in Fig, 1.1, system (say elelctrons) absorbs energy when it is in ground state E_1 so that its energy elevates to E_2. Now elelctrons are said to be in the excited state E_2. The amount of energy absorbed by an electron, $\Delta E = h\gamma = E_2 - E_1$.

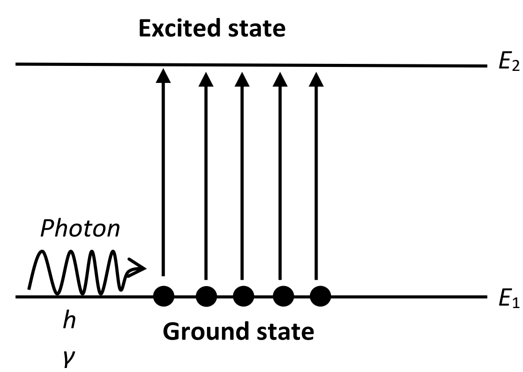

Fig. 1.1

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(ii) Spontaneous emission of radiation (spontaneous deexcitation)

Transition of a system (or electron) from an excited state E_2 to the ground state E_1 without the aid (support or assistance) of external source of energy is known as spontaneous deexcitation.

Emission of photons during such a transition is called spontaneous emission of radiation. Energy of a photon released is $\Delta E = h\gamma = E_2 - E_1$. *The photons so emitted are found to be incoherent, nonunidirectional, and nonmonochromatic*. Thus, laser will not be produced by this kind of transitions.

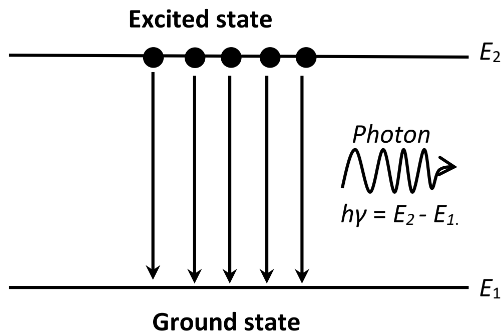

Fig. 1.2

(iii) Stimulated emission of radiation (stimulated deexcitation)

Transition of a system (or electron) from an excited state E_2 to the ground state E_1 due to the aid (support or assistance) of external source of energy is known as stimulated deexcitation.

Emission of photons during such a transition is called stimulated emission of radiation. This process occurs only in some selective materials having metastable states

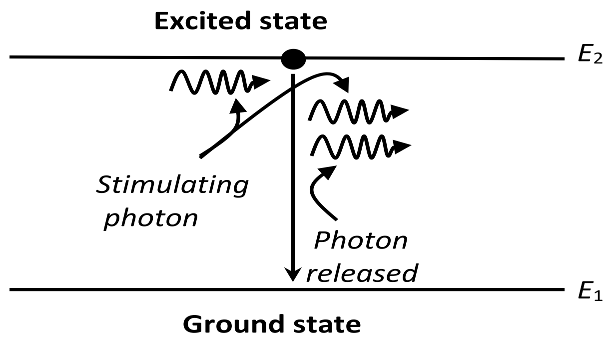

Fig. 1.3

When an incident photon called *stimulating photon* interacts (c an excited electron (or atom), the photon does not transfer its energy but makes electron to deexcite to lower energy level. As a result, electron emits a photon and stimulating photon accompanies it. Thus, virtually two photons are produced when one photon stimulates the electron or atom. These two photons may produce four photons by interacting with two more excited electrons and so on. This is how light is amplified. Moreover, *the photons emitted are found to be coherent, unidirectional, and monochromatic*. Thus, laser can be produced by stimulated transitions.

Expression for energy density of laser in terms of Einstein's coefficients

Energy density (E_γ) is the energy of the radiation emitted by a system of unit volume. In order to make a system to emit a radiation of energy density E_γ, at least the equal amount of energy density (i. e., E_γ) is to be provided to it. When it is provided, the system interacts in three ways as described below.

(i) Induced absorption

When a radiation of energy density (E_γ) is incident on a system of atoms, each atom absorbs a photon of frequency γ (= E_2– E_1/h). Number of such absorptions per second per unit volume is called rate of absorption (R_{12}). It is directly proportional to E_γ and the number density N_1 of atoms in the ground state.

i.e., $R_{12} \alpha E_\gamma N_1$

or $R_{12} = B_{12} E_\gamma N_1$ ----------------- (1)

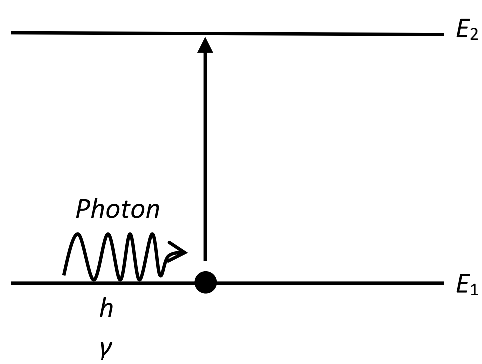

Fig. 1.4

B_{12} is known as Einstein coefficient of induced absorption (it is the probability of absorption per second per unit volume).

(ii) Spontaneous emission of radiation (spontaneous deexcitation)

Number of spontaneous deexcitations per second per unit volume is called rate of spontaneous transitions (R_{21sp}). It is independent of E_γ and depends only on the number density N_2 of atoms in the excited state.

i.e., $R_{21sp} \alpha N_2$

or $R_{21sp} = A_{21} N_2$ ----------------- (2)

A_{21} is known as Einstein coefficient of spontaneous transitions (it is the probability of spontaneous transitions per second per unit volume).

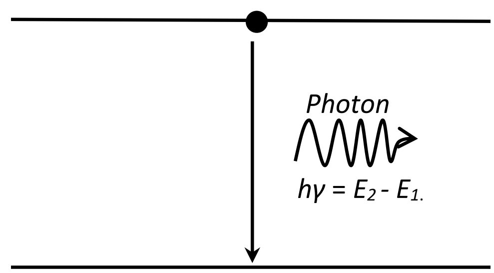

Fig. 1.5

(iii) Stimulated emission of radiation (stimulated deexcitation)

Number of stimulated deexcitations per second per unit volume is called rate of stimulated transitions (R_{21st}). It is dependent on E_γ as well as N_2

i.e., $R_{21st} \alpha E_\gamma N_2$

or $R_{21st} = B_{21} E_\gamma N_2$ ----------------- (3)

B_{21} is known as Einstein coefficient of stimulated transitions (it is the probability of stimulated transitions per second per unit volume).

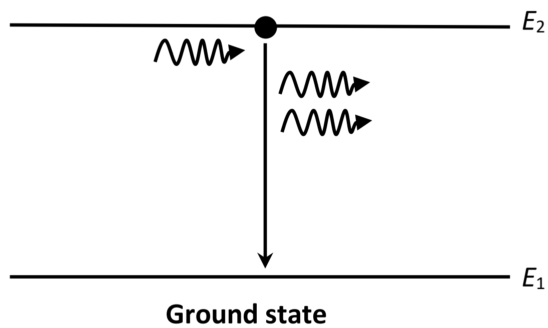

Fig. 1.6

At thermal equilibrium condition, $R_{12} = R_{21sp} + R_{21st}$

i.e., $B_{12} E_\gamma N_1 = A_{21} N_2 + B_{21} E_\gamma N_2$

$$B_{12} E_\gamma N_1 - B_{21} E_\gamma N_2 = A_{21} N_2$$

$$E_\gamma (B_{12} N_1 - B_{21} N_2) = A_{21} N_2$$

$$E_\gamma = \frac{A_{21} N_2}{(B_{12} N_1 - B_{21} N_2)}$$

$$E_\gamma = \frac{A_{21}}{(B_{12} \frac{N_1}{N_2} - B_{21} \frac{N_2}{N_2})}$$

$$E_\gamma = \frac{A_{21}}{(B_{12} \frac{N_1}{N_2} - B_{21})}$$

Boltzmann factor is given by $\frac{N_2}{N_1} = e^{-\frac{h\gamma}{kT}} or \frac{N_1}{N_2} = e^{\frac{h\gamma}{kT}}$

Where T is temperature, h is Planck's constant and k is Boltzmann constant

Thus, $$E_\gamma = \frac{A_{21}}{(B_{12}e^{\frac{h\gamma}{kT}} - B_{21})}$$

Or

$$E_\gamma = \frac{A_{21}}{B_{21}(\frac{B_{12}}{B_{21}}e^{\frac{h\gamma}{kT}} - 1)} \text{--------------------- (4)}$$

According to Planck's law of radiation,

$$E_\gamma = \frac{8\pi h\gamma^3}{c^3}\left(\frac{1}{e^{\frac{h\gamma}{kT}} - 1}\right) \text{----------------------(5)}$$

On comparing the Eq. (4) and (5), we get,

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\gamma^3}{c^3} \; and \; \frac{B_{12}}{B_{21}} = 1 \text{------------------ (6)}$$

Therefore Eq. (4) can be expresses as $$E_\gamma = \frac{A_{21}}{B_{21}(e^{\frac{h\gamma}{kT}} - 1)} \quad \text{-------------------(7)}$$

This is the expression for energy density of laser in terms of Einstein's coefficients

Inference (conclusion): Eq. (6) indicates that $B_{12} = B_{21}$. That means for the laser to be produced, probability of excitations must be equal to the probability of **stimulated** deexcitations. In other words, spontaneous transitions must be suppressed to produce laser.

1.3. Conditions for producing laser

A system or the material that produces laser has to satisfy the following two conditions

(i) ***Metastable state***

Definition: Metastable state is one among the excites states, which has the long life of the order of a milli second (10^{-3} s).

An ordinary excited state has very short life about 10^{-8} s only. Life of a metastable state is 1 lakh (10^5) times that of ordinary state. For example, as shown in Fig. 1.7, if an atom is excited from its ground state E_1 to an ordinary excited state E_3 by provoding energy, the atom returns to the ground state within 10^{-8} s. In case there is a metastable state E_2, the atom stays in this level for long time (10^{-3} s) and then gets deexcited to ground state either spontaneously or by stimulation.

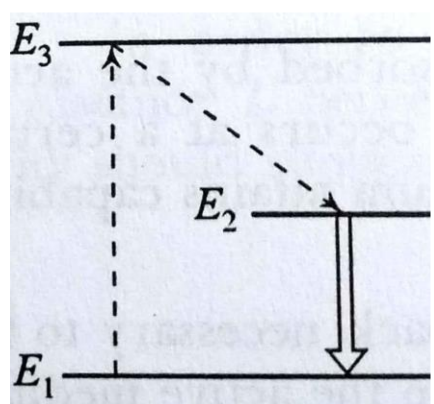

Fig. 1.7

(ii) Population inversion

Population means the number of atoms per unit volume (or number density) of a material. Let N_1 and N_2 be the number density of ground state and excited state, respectively. In the absence of external sources of energy, almost all atoms (or the system) will be in the ground state and the excited states are empty, so that $N_1 > N_2$. Now, if energy is supplied, the atoms get excited to higher energy levels. If these higher energy levels are ordinary states (like E_3) having 10^{-8} s life, the atoms deexcite spontaneously. If there is a metastable state such as E_2, it holds excited atoms for long time about 10^{-3} s. During this interval of time, almost all ground state atoms will be excited to metastable state. Now, therefore, $N_2 > N_1$. That means population is inverted.

Definition: Population inversion is defined as the inversion of number density of atoms such that the excited states are more populated than the ground state.

Necessity: Population inversion is essential to achieve stimulated transitions.

After the population is inverted, photons of incident radiation start interacting with the excited atoms and stimulate them to deexcite (because they find no or less atoms in the ground state!). Thus, laser can be produced if stimulated transitions occur; stimulated transitions occur only after population is inverted; population inversion happens only if there is a metastable state.

***1.4.* Requisites for a laser system** (of device)

A laser device being used to produce laser must be accommodated with the following three requisites (requirements)

(i) Source of energy for excitation

A source of energy is required to excite the system of atoms or ions. It may be an electrical power supply or a source of light. The excitation of system by the supply of electrical energy is known as ***electrical pumping.*** This process is used in gaseous and semiconductor lasers. Excitation of atoms by supplying optical (light) energy is called ***optical pumping.*** This process is used in some solid lasers such as Ruby laser.

(ii) Active medium

A system of atoms (or ions or molecules) that has the ability to undergo population inversion and to produce laser is known as active medium. For example, a mixture of helium and neon gases in He-Ne laser device and mixture of nitrogen and CO_2 molecules in CO_2 laser are active media.

(iii) Resonant or laser cavity

Laser cavity is a system of two parallel mirrors fixed to the two ends of the active medium. One mirror is partially silvered and the other is fully sivered. Fully silvered mirror reflects compltely the laser produced and the partially silvered one reflects partially and transmits the remaining laser which can be used for applications.

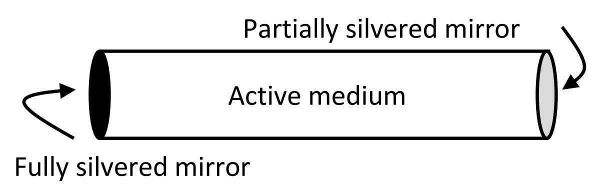

Fig. 1.8

The distance L between the mirrors is properly chosen such that the reflected rays intefere constructively. Condition for constuctive inteference is that the path difference between the interfereing waves must be integer multiple of wavelength, i.e., nλ. The relation with L is found to be **2 L = nλ**

As constructive interference increases the intensity of laser as happens in the resonance phenomenon, laser cavity is also called resonant cavity.

Types of Laser Sources

1. Solid laser (e.g., Ruby Laser)
2. Gas laser (e.g., He-Ne laser and CO_2 laser)
3. Semiconductor laser

Solid laser emits pulsating laser. Gas lasers produce laser of high energy and constant intensity. Semiconductor laser emits laser of lower energy.

Carbon Dioxide Laser

Modes of Vibrations of CO_2 molecules:

The energy levels corresponding to three modes of vibrations of CO_2 molecules are involved in producing laser by this device;

(i) Symmetric stretching mode

In this mode of vibration, oxygen (O) atoms oscillate along the axis of the molecule in such a way that they approch or recede from each other. Carbon (C) atom is stationary. The CO_2 molecule absorbs or emits *intermediate amount of energy* in this mode when compared to the other modes. This energy level is denoted as (100).

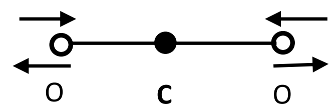

Fig. 1.9

(ii) Asymmetric stretching mode

In this mode, all the three atoms vibrate along the axis of the molecule. Both O atoms oscillate in one direction and C atom in opposite direction. The CO_2 molecule absorbs or emits *highest amount of energy* in this mode when compared to the other modes. This energy level is denoted as (001).

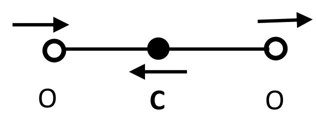

Fig. 1.10

(iii) Bending mode

In this mode, all the three atoms vibrate perpendicular to the axis of the molecule. Both O atoms oscillate in one direction and C atom in opposite direction. The CO_2 molecule absorbs or emits *lowest amount of energy* when compared to the other modes. Two energy levels exist in this mode denoted as (010) and (020). (020) level is closer to (100).

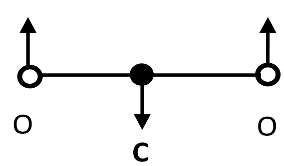

Fig. 1.11

CONSTRUCTION

CO_2 laser comprises of a quartz tube of 3 to 5 m length and 2 to 3 cm diameter. Two electrodes are inserted into it for electrical connections to a power supply.

BW-Brewster windows

M_1- Fully silvered mirror

M_2- Partially silvered mirro

P- Power supply

E_1, E_2 - Electrodes

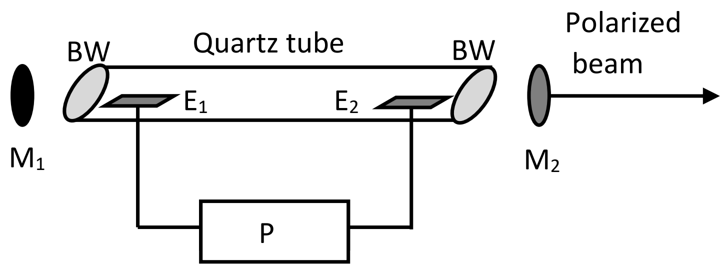

Fig. 1.14

Active medium is a mixture of CO_2, N_2 and He gases filled in the tube in the ratio 1:2:3. *Source of energy* for exciting the molecules is electrical power supply (AC or DC), so that electrical pumping is involved. Power supply is connected to electrodes to provide a potential difference. *Laser cavity* is provided in terms of Brewster windows and the mirrors. Brewster windows are the quartz crystals used to plane-polarize the laser beam. The laser rays reflected from the mirrors are made to undergo constructive interference. Partially silvered mirror transmits part of the laser produced.

WORKING

When a potential difference is applied between the electrodes gas discharge occurs. It means that the electrons are freed from the atoms and accelerate towards the positive electrode. During the movement, they collide with the molecules. *Collision of electrons with nitrogen molecules is called collision of first kind.* In this collision, electrons transfer their energy to N_2 molecules and hence they excite from ground state to their metastable state.

The excited N_2 molecules now collide almost simultaneously with the CO_2 molecules of the ground state. *This is known as collision of second kind.* In this collision N_2 molecules transfer the energy to CO_2 molecules of the ground state and excite from ground state to their (001) or E_5 state and population gets inverted.

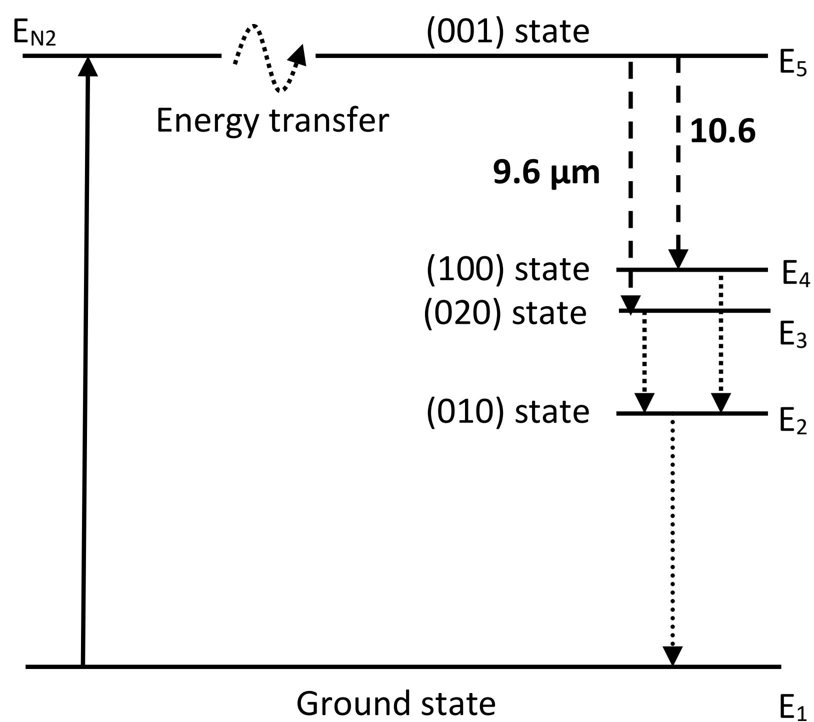

Fig. 1.15

Deexcitation of CO_2 molecules from E_5 to (100) or E_4 state emit an infrared (IR) laser of wavelength 10.6 μm and the transition to (020) state emits a laser of shorter IR wavelength 9.6 μm. Further transitions bring the molecules to E_2 level which is metastable state and hence population of E_2 level increases. This makes higher energy levels less populated and therefore laser emission ceases. In order to deexcite E_2 molecules, the diameter of the tube is made very small compared to the length. This helps E_2 molecules to collide with the wall of the tube and to deexcite to the ground state.

The heat is produced during the transitions from E_3 to E_2, E_4 to E_2 and E_2 to E_1. This heat suppresses the efficiency of producing laser. In order to remove this heat, helium gas is used. Because of high thermal conductivity, He atoms conduct the heat towards the wall of the tube which is provided with a cold water circulating system. As a result, the system keeps thermal equilibrium condition.

Applications of laser

1. **Measurement of pollutants in the atmosphere**

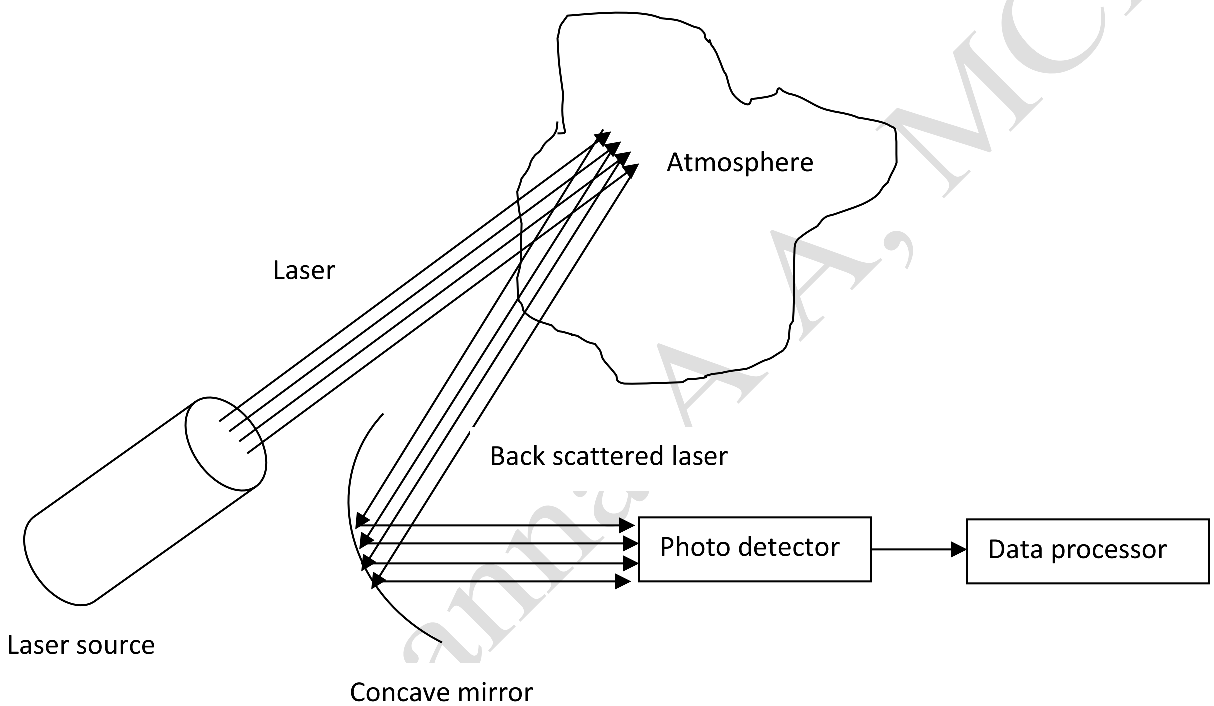

Fig. 1.18

LIDAR is a device used to measure pollutants such as oxides of nitrogen, carbon monoxide, sulphur dioxide, dust, smoke, etc., in the atmosphere. LIDAR is the short form of **LI**ght **D**etection **A**nd **R**anging. This device comprises of four important parts, namely, laser source, concave mirror, photodetector and data processor.

- A laser beam emitted by a high energy laser source such as CO_2 laser is made to scan the selected region of the atmosphere.
- The laser beam undergoes scattering by the particulate matter (particles of pollutants)
- The backscattered beam is received by the concave mirror.
- The beam that is reflected from the concave mirror is incident on the photodetector which converts optical signal into electrical signal.
- The electrical signal passes through a narrow band filter (not shown in the diagram) which removes unwanted signals and allows the signal of frequency corresponding to laser beam.

- The signal is provided to data processor which is a computer loaded with required softwares. It provides information about the distance, size and density of the pollutant. However, it does not provide details on composition of the pollutant.

There are two different techniques to identify the composition or type of pollutant;

(i) **Absorption technique**: In this technique, a laser beam is passed through the sample of the pollutant collected in a container and the intensity of transmitted laser is analyzed. As the different elements absorb varied intensity of laser, intensity analysis provides information on the composition.

(ii) **Raman backscattering technique**: In this case too, laser beam is passed through the sample of the pollutant, but the Raman spectrum is recorded (using Raman spectrometer). The number and the wavelengths of the Raman lines (spectral lines) provide details on the composition.

1.10. **Laser fencing** One of the most useful applications of laser is fencing. After the Indian government planned and partially installed laser fence across the Indo-Pakistan border, the global demand aroused for the border fencing. Previously laser was used to fence the agricultural lands in few western countries.

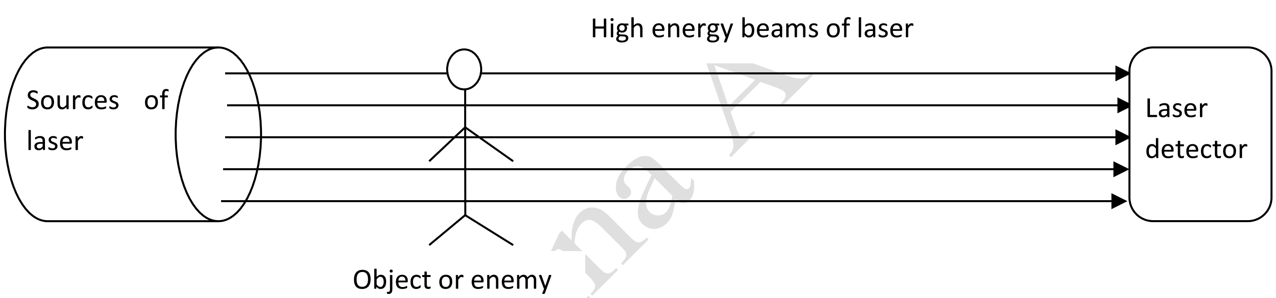

Fig. 1.19

Laser fencing system comprises of sources of laser and a detector. Beams of infrared laser are used to construct the fence of desired height. When an object or a person crosses the fence, the discontinuity will be detected by the detector and cautions the observer about the infiltration. If the fence is constructed by laser beams of very high energy, the beams can burn and destroy or injure the objects or intruders exposed to them.

1.11. **Other applications**

i. The heat energy associated with laser is used for welding metal pieces,
ii. It is also used in cutting metal and nonmetal plates and in textile industries to cut a pile of clothes.
iii. Holes of very small diameters of the order of fraction of a millimeter can be drilled using strong laser beam.
iv. In defense, laser is used in missiles to fix the target (laser guided missiles).
v. Laser beam of a l**aser rangefinder**, also known as a laser telemeter, is used to determine the distance to an object.

vi. Laser road profiler uses a combination of laser and accelerometer to measure the longitudinal elevation profile of a road for accurate highway speeds.

vii. The laser Doppler vibrometer system is a non-contact, non-destructive method of measuring the vibration and displacement of bridges.

viii. A laser speed gun measures the round-trip time for light to reach a vehicle and reflect back. A laser speed gun shoots a very short burst of infrared laser light and then waits for it to reflect off the vehicle. The gun counts the number of nanoseconds it takes for the round trip, and by dividing by 2 it can calculate the distance to the car.

Laser safety

Laser, being a highly energy-concentrated beam, is injurious to body organs if exposed. Required precautions are to be taken while handling the laser in applications.

- Moderate and high power laser is injurious to eyes; hence, wearing of laser safety goggles is essential to protect eyes from potential damage.
- The laser can burn or destroy the biological tissues; in order to protect from such damages, laser resistive clothes are to be used
- Exposure to laser for long time is to be avoided

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2. Optical Fibers

Optical fiber is a fiber of transparent glass or plastic used to guide light for propagation by total internal reflection. This is mostly used for telecommunication.

2.1 Fabrication (construction)

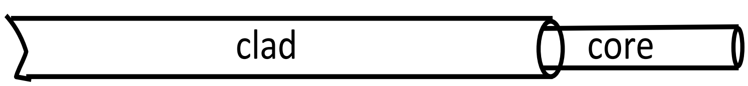


Fig. 2.1

Optical fiber is fabricated using a transparent glass or plastic material. Most used material is silica glass. As shown above, each fiber consists of a CORE surrounded by CLADDING. Both the core and cladding are made of the same material (silica) but of different refractive indices. For supporting the total internal reflection, **core is made to have higher refractive index (RI) than that of the clad**. In order to protect it from the unexpected stresses a polyurethane jacket covers the cladding.

2.2 Principle

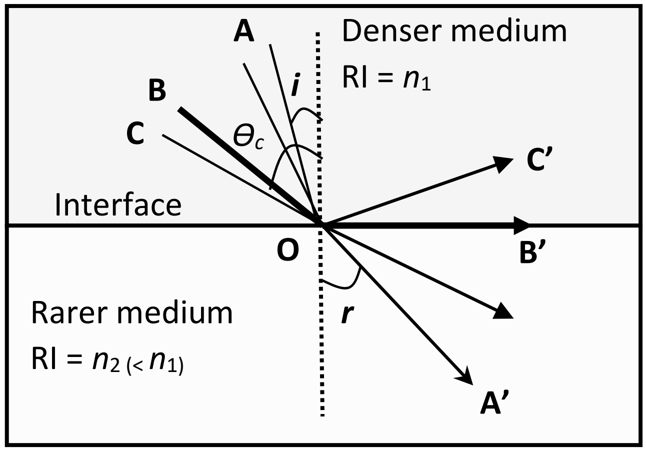


Fig. 2.2

Working principle** of an optical fiber is **total internal reflection (TIR). TIR is the phenomenon in which a light ray reflects completely in to the medium of incidence. This happens only (i) when the light ray propagates from the denser medium (medium of higher refractive index, n_1) to a rarer medium (of smaller refractive index, n_2) and (ii) if the angle of incidence is above a critical value, Θ_c, called **critical angle of incidence**. **Reason for using TIR** for ray propagation in an optical fiber is that ***ideally* energy of totally internally reflected light is not lost** during propagation.

For example, in Fig. 2.2, incident ray AO, whose angle of incidence is below Θ_c, refracts in to the medium of refractive index (RI) n_2. The ray BO incident at Θ_c just grazes the interface with angle of refraction 90^o. Ray CO undergoes TIR as its angle of incidence falls above Θ_c.

Snell's law for refraction of ray BO provides the relation

$$n_1 \sin\theta_c = n_2 \sin 90^o$$

$$\sin\theta_c = \frac{n_2}{n_1}$$

$$\theta_c = \sin^{-1}\frac{n_2}{n_1}$$

2.3. Propagation of light in an optical fiber (mechanism of propagation)

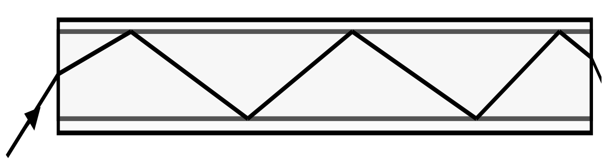


Fig. 2.3

The core is made to have higher refractive index (RI) than that of the cladding. So that core is denser medium and clad is rarer. Therefore, when a ray of light is incident on the core-clad interface at an angle greater than the critical angle Θ_c, it undergoes total internal reflection within the core as shown in Fig. 2.3. The ray propagation continues as long as the angle of incidence remains greater than Θ_c. As a result, light is ideally not absorbed by the cladding. This is the reason to name the optical fiber as **wave guide** (it guides the ray of light to propagate for a long distance).

2.4. Expression for numerical aperture and condition for ray propagation (with definitions of acceptance angle/half cone angle and numerical aperture)

(OR derivation of expression relating the numerical aperture, acceptance angle and refractive indices of core and clad)

Explanation: Consider an optical fiber of core refractive index n_1 and clad refractive index n_2, surrounded by a medium of refractive index n_o, as shown in Fig. 2.4. If the angle of incidence of a ray of light (AO) is carefully adjusted to Θ_0 on the cross-section of the core, the ray will incident at critical angle Θ_c at the core-clad interface B, and refracts with angle 90° along BC. All those rays that enter the core with angle of incidence above Θ_0 will be refracted in to cladding and those rays entering the core with angle of incidence below Θ_0 will undergo total internal reflection in to core. Hence the angle Θ_0 is known as acceptance angle or half angle of acceptance cone. Acceptance cone is imagined to be formed when the ray AO is rotated about O. Rays entering from within this cone are available for TIR.

Hence***, acceptance angle Θ_0 is defined as the maximum angle of incidence for a ray of light at the cross-section of the core of an optical fiber to undergo total internal reflection within its core***.

Sine of angle of acceptance is called numerical aperture (NA).

i.e., $NA = \sin\Theta_0$

NA is the measure of ability of an optical fiber of guiding rays of light to propagate without loss of energy.

Derivation:

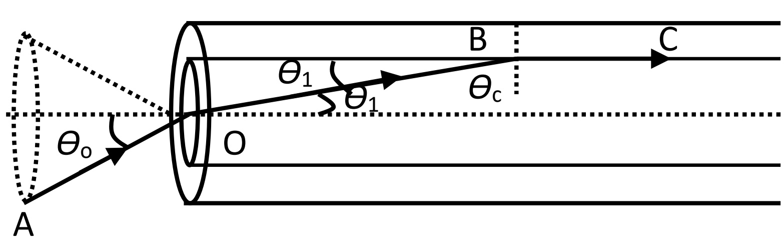


Fig. 2.4

Applying the Snell's to the point of incidence O, we get

$$n_0 \sin\theta_0 = n_1 \sin\theta_1$$

$$\sin\theta_0 = \frac{n_1}{n_0}\sin\theta_1$$

$$NA = \frac{n_1}{n_0}\sin\theta_1$$

$$NA = \frac{n_1}{n_0}\sqrt{1-\cos^2\theta_1} \quad \text{------------------------ (1)}$$

[Here, recall that $\sin^2\theta_1 + \cos^2\theta_1 = 1$

or $\sin^2\theta_1 = 1-\cos^2\theta_1$

or $\sin\theta_1 = \sqrt{1-\cos^2\theta_1}$]

Now, applying the Snell's law for the point of incidence B, we obtain,

$$n_1 \sin\theta_c = n_2 \sin 90^o$$

$$\sin(90-\theta_1) = \frac{n_2}{n_1}$$ (Because sin90° = 1 and Θ_c = 90- Θ_1 from Fig. 2.4)

$$cos\theta_1 = \frac{n_2}{n_1}$$

Substituting this relation in Eq. 1,

$$NA = \frac{n_1}{n_0}\sqrt{1-\frac{n_2^2}{n_1^2}}$$

$$NA = \frac{n_1}{n_0}\sqrt{\frac{n_1^2-n_2^2}{n_1^2}}$$

$$NA = \frac{n_1\sqrt{n_1^2-n_2^2}}{n_0 n_1}$$

$$NA = \frac{\sqrt{n_1^2-n_2^2}}{n_0} \quad \text{------------------------ (2)}$$

This is the expression for numerical aperture

If the surrounding medium is air, for which refractive index n_0 = 1,

$$NA = \sqrt{n_1^2 - n_2^2} \text{ --------------------------- (3)}$$

Condition for ray propagation:

It is clear from the above description that the ray undergoes TIR only if its angle of incidence (say, Θ_i) on the core-cross-section is smaller than the acceptance angle, Θ_0,

That is, $\Theta_i < \Theta_0$

OR $\sin\Theta_i < \sin\Theta_0$

$\sin\Theta_i < NA$ (because $NA = \sin\Theta_0$)

Using Eq. (3), we get

$$\sin\theta_i < \sqrt{n_1^2 - n_2^2}$$

This is known as *condition for ray propagation* within the core of an optical fiber.

2.5 Fractional refractive index change or difference (Δ)

This is the ratio of difference between the refractive indices of core n_1 and cladding n_2 to refractive index of the core n_1

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

Question: *Show that* $NA = n_1\sqrt{2\Delta}$ *when optical fiber is in air or establish relation between NA and* Δ

We have NA in air, $NA = \sqrt{n_1^2 - n_2^2}$

$$NA = \sqrt{(n_1 - n_2)(n_1 + n_2)}$$
$$NA = \sqrt{(n_1\Delta)(n_1 + n_2)}$$
$$NA = \sqrt{(n_1\Delta)2n_1}$$

Here $n_1 \approx n_2$ is considered as n_1 is slightly greater than n_2 for an optical fiber, therefore,

$$NA = n_1\sqrt{2\Delta}$$

2.6 Modes of propagation

A mode of propagation of light is defined as the least possible quantity of light that propagates within the core of lowest possible diameter. Consequently, a mode of light can be thought of as equivalent to a ray of light. Higher modes are the integer multiple of this fundamental mode. **Number of modes N** propagated through the core of **diameter d** can be estimated from a parameter **V** known as **V-number,**

$$N \approx \frac{V^2}{2}$$

Where

$$V = \frac{\pi d}{\lambda}(numerical\ aperture)$$

$$V = \frac{\pi d}{\lambda}\left(\frac{\sqrt{n_1^2 - n_2^2}}{n_0}\right)$$

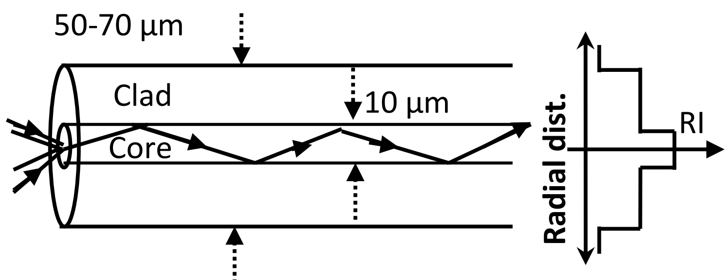
When optical fiber is in air whose refractive index $n_0 = 1$, $V = \frac{\pi d}{\lambda}\sqrt{n_1^2 - n_2^2}$

Here, d is diameter of the core, λ is the wavelength of the light that propagates, n_1 and n_2 are refractive indices of core and cladding, respectively.

2.7 Types of optical fibers

Based on the number of modes of propagation and refractive index of the core, optical fibers are classified in to three categories as follows

(i) Single mode step index optical fiber



This is an optical fiber that propagates only one mode (or ray) of light. It is so because the diameter of the core is too small about 8 to 10 µm as shown in the geometry of the cross-section of the fiber.

This is called step index fiber because the refractive index profile (graph of refractive index against radial distance) looks like step. This is due to the reason that the refractive index (RI) of the core remains constant or uniform throughout its body. At the core-clad interface, RI sharply falls to the value of RI of Cladding which also has the constant RI but smaller than that of the core. Further, RI is shown to be dropped to a very low value which is equal to the RI of the surrounding medium such as air.

Merit: Intermodal dispersion does not arise.

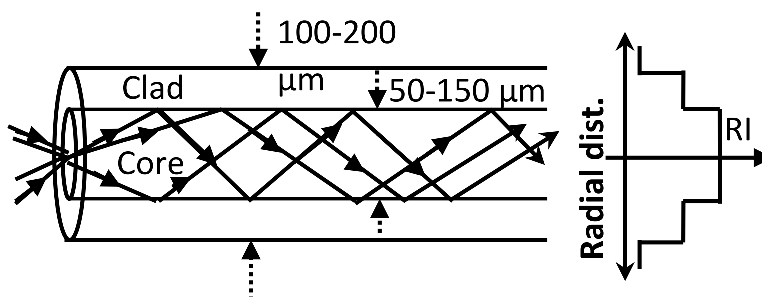
Demerit: Manufacturing cost is high when compared to that of other two optical fibers.

Use: This optical fiber is useful for long distance communication including submarine (under-water) cable system. Hence, it requires LASER source for light.

(ii) Multimode step-index optical fiber

This is an optical fiber that propagates two or more modes (or rays) of light. It is so because the diameter of the core is large about 50 to 200 μm as shown in the geometry of the cross-section of the fiber. This is also called step index fiber because the refractive index profile (graph of refractive index against radial distance) looks like step as in the previous case.

This optical fiber encounters with a demerit known as **intermodal dispersion**. *This is an optical phenomenon in which the different rays propagating in the core reach the receiving end at different instants of time.* This results in noise. This can be explained as follows; a ray that enters the core with larger angle of incidence undergoes more total internal reflections (TIR) and therefore traverses longer path, but the ray that enters with smaller angle of incidence undergoes less TIRs and traverses short



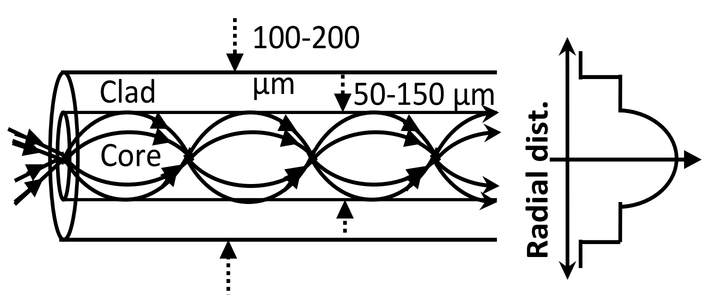
path. However, both the rays travel in the medium of constant refractive index and therefore the constant velocity. As a result they reach the receiving end at different instants of time.

Merit: Manufacturing cost is less when compared to that of single mode fiber.

Demerit: Intermodal dispersion that causes noise at the receiving side.

Use: It is used only for short distance communications (because intermodal dispersion increases with increasing distance).

(iii) Graded index multimode optical fiber (GRIN optical fiber)



Geometry (or dimensions of core and clad) of this optical fiber is same as that of the step index multimode optical fiber as shown in Fig. 2.7. Difference is that its core has graded refractive index (RI). The RI is maximum at the centre and decreases gradually towards the core-cladding interface as shown in the RI profile. However, RI of clad is maintained constant. The graded index helps reducing the intermodal dispersion as explained below.

A ray of light suffers TIR at every point on its path as there is continuous change in RI at those points.

A ray that enters the core with larger angle of incidence can even touch the interface and therefore traverses longer path, but its majority part travels in the medium **of lower refractive index** which makes its **velocity high**. The ray that enters with smaller angle of incidence travels in the middle portion of the core where RI is high, hence, traverses shorter distance with lower velocity. As a result, both the rays reach the receiver almost simultaneously.

Merit: Manufacturing cost is moderate
Demerit: Splicing (connection of broken or damaged fibers) is difficult.
Use: Due to reduced intermodal dispersion, GRIN optical fiber is useful for medium distance communications.

2.8. Attenuation

Definition: Attenuation in optical fibers is defined as the loss of optical signal (or energy) during propagation.

Equation to estimate attenuation: $\alpha = -\frac{10}{L}\log_{10}\frac{P_o}{P_i}$ (*unit is dB/km if L is in km or dB/m if L is in m*)

Here, L is length of the optical fiber, P_o is output power and P_i the input power.

Explanation: Different sources (or types) of attenuation are described below.

(i) **Absorption losses:** This kind of loss arises from two origins; (a) absorption by intrinsic material and (b) absorption by impurity atoms

The absorption of light signal by the atoms of the material of the core itself is known as intrinsic absorption. The impurity atoms or ions such as iron, chromium, hydroxy (OH) ions remained within the core during preparation also absorb the optical energy which is known as extrinsic or impurity loss. Now-a-days using the advanced technology, this loss is reduced to negligible level.

(ii) **Scattering losses**: While preparing the core, there is a probability that regions of nano or angstrom size, with refractive indices different from that of the core are formed. A ray that encounters with such a region will be deviated from its path and enters into the clad.

Such regions of very small dimensions can cause Rayleigh scattering which is the phenomenon of scattering of a radiation by the particles of size smaller than the wavelength. In Rayleigh scattering, intensity of scattered radiation is inversely proportional to fourth power of wavelength. Thus, if a light signal of shorter wavelength is used for propagation, scattering loss is significant. For this reason in long distance telecommunication applications, **infrared laser (it is long wavelength radiation) is used** to reduce the loss.

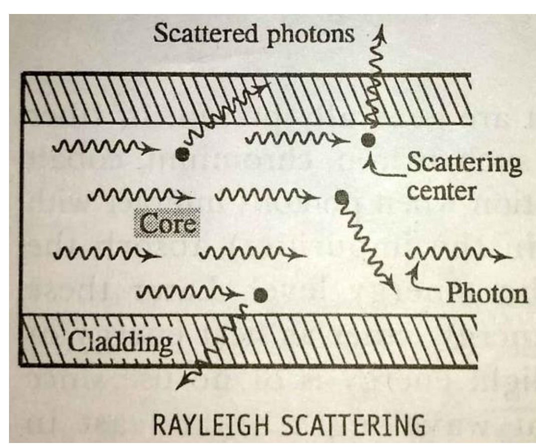


Fig. 2.8

(iii) **Radiative losses (or bending losses)**: The loss of light energy due to bending of optical fibers is known as radiative loss. There are two types; macroscopic and microscopic bending losses.

(a) Macroscopic bending loss:

If the fiber is bent to very small radii as in Fig. 2.9, angle of incidence at the core-clad interface may fall below the critical angle. As a result, the ray enters the cladding without suffering total internal reflection (TIR). Thus, the ray will be lost. TIR will be completely stopped if the radii of curvatures fall below a critical (threshold) value. This loss can be prevented by avoiding sharp bending of the fibers.

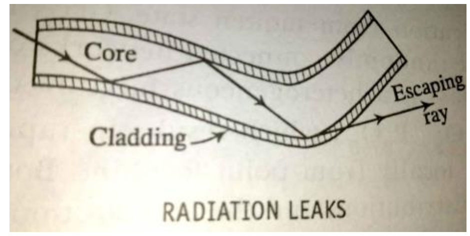


Fig. 2.9

(b) Microscopic bending loss:

During manufacturing process, nonlinearity in the core-clad interface may be occurred at microscopic scale. At such nonlinear interface, the angle of incidence of the light ray may fall below the critical angle. This leads to transmission of the ray through the cladding.

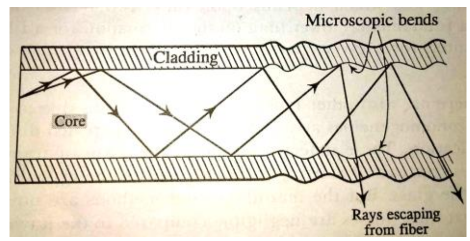


Fig. 2.10

2.9. Applications

(i) **Point to point communication**

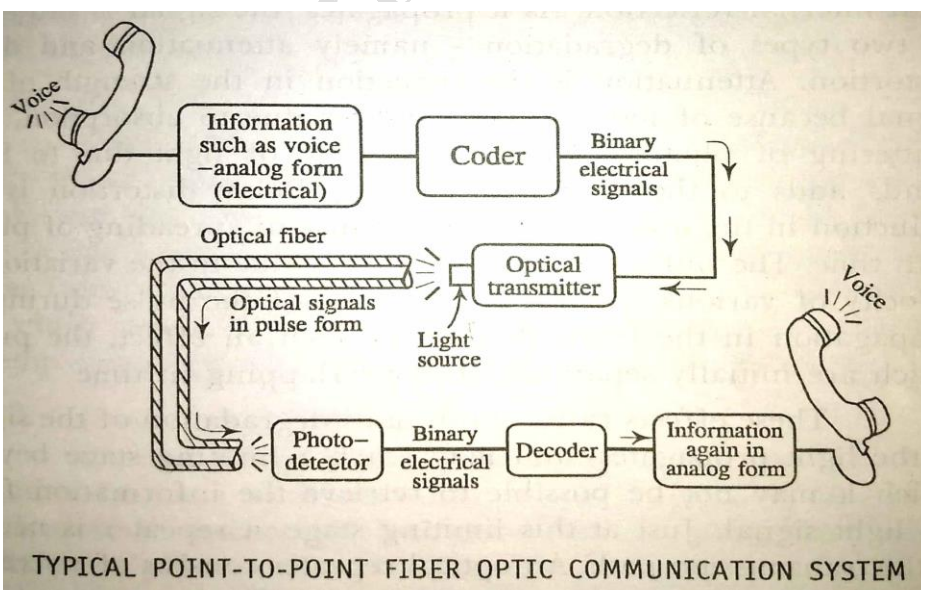


Fig. 2.11

As depicted in the bock diagram, Fig. 2.11, point to point communication system employing the optical fiber involves various stages. On the transmitting end, voice is converted into analog electrical signal by the **microphone** of the telephone instrument. A digital electronic circuit called **coder** converts the analog signal to digital form (binary data). This signal is input to an **optical transmitter** which may be a LASER or LED depending on the distance of communication. The light emitted is made to enter the **optical fiber** which guides it to desired distance.

On the receiving side, the light transmitted from the optical fiber is **first amplified** to strong signal and then fed to a **photo detector** such as photodiode. Its function is to convert the optical signal into electrical signal which is originally in digital form. Digital signal is then converted back to analog form and fed to the receiver (telephone). Its speaker converts the electrical signal into sound.

(ii) Optical fibers are also used in sensors to sense the parameters such as pressure, voltage or current.

(iii) They are used in local area networks (LAN) for data exchange between the terminals available within short distances.

(iv) These are used for imaging in hard to reach areas in complex machines or devices. It's also known as industrial endoscopy.

(v) In medical field, the optical fibers are useful for imaging of internal parts of human body. (Also known as medical endoscopy)

2.10 Advantages of optical fiber communication over the conventional one

1. Optical fibers carry very large amount of data (or information), i.e., the signals of large bandwidth of frequencies can be communicated.

2. As the materials used are silicon dioxide or plastic for making the optical fibers, they do not corrode and therefore the life is very long (about 40 years).

3. The raw materials used to make them are easily available and economically cheaper than the metal cables.

4. Due to their light weight, easily transportable.

5. No interference of external electromagnetic s waves with the signal communicated.

6. No information tapping is possible.

7. Since optical signal is used, no chances for sparking or short circuits.

2.11 Demerits or Limitations

When the fibers are broken, it's difficult to connect them (called splicing) precisely. They may expand or contract with temperature changes.

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PROBLEMS

Constants: Planck's constant h = 6.625 x 10^{-34} Js, Boltzmann constant k = 1.38 x 10^{-23} J/K, speed of light in vacuum c = 3 x 10^{8} m/s, electron mass = 9.1 x 10^{-31} kg, charge of electron e = 1.6 x 10^{-19} C, Avogadro no. N_A = 6.023 x 10^{23} /mole,

Sl. No.	Problem
1/CW	An active medium of a laser device has a wavelength separation of 1 μm between its ground state and an excited state at 300 K of temperature. Determine the ratio of population of atoms in the upper state to that in the ground state. **Solution:** $\frac{N_2}{N_1} = e^{-\frac{h\gamma}{kT}} = e^{-\frac{hc}{\lambda kT}}$ = 1.365 x 10^{-21}
2/CW	Ratio of population of atoms in the upper state to that in the ground state is 1.06 x 10^{-30}. Calculate the wavelength of light emitted by spontaneous emissions at 300 K. **Solution:** $\frac{N_2}{N_1} = e^{-\frac{h\gamma}{kT}} = e^{-\frac{hc}{\lambda kT}} \Rightarrow \lambda = 696nm$
3/CW	A semiconductor emits a laser of wavelength 1240 nm. Estimate the band gap in eV. **Solution:** $E_g = \frac{hc}{\lambda} = 1eV$
4/CW	Core and cladding of an optical fiber have refractive indices 1.5 and 1.48, respectively. Calculate the numerical aperture and acceptance angle. **Solution**: $NA = \frac{\sqrt{n_1^2 - n_2^2}}{n_0} \Rightarrow NA = 0.244$ (where n_o = 1 for air) NA = $\sin\Theta_0$; Θo = 14.1°
5/CW	Core and cladding of an optical fiber have refractive indices 1.55 and 1.5, respectively. Calculate the numerical aperture, acceptance angle and fractional index difference if the optical fiber is placed in air. **Hint**: $NA = \frac{\sqrt{n_1^2 - n_2^2}}{n_0} \Rightarrow NA = 0.39$ (where n_o = 1 for air) NA = $\sin\Theta_0$; Θo = 23° $\Delta = \frac{n_1 - n_2}{n_1}$ = 0.032
6/CW	An optical fiber of refractive index 1.5 is to be clad with another glass to ensure total internal reflection that will contain light travelling within 5° of the fiber axis. What maximum index of refraction is allowed for the cladding? **Solution**: Given angle of incidence is 85°. $n_1 \sin 85° = n_2 \sin 90°$; n_2 = 1.49
7/CW	Numerical aperture of an optical fiber is 0.2 when surrounded by air. Determine the refractive index of its core if the refractive index of the cladding is 1.59. Also find the acceptance angle when the fiber is in water. Assume the refractive index of water as 1.33. **Solution**: $NA_{air} = \sqrt{n_1^2 - n_2^2} \Rightarrow n_1 = 1.6$ $NA_{water} = \frac{\sqrt{n_1^2 - n_2^2}}{n_0} \Rightarrow NA = 0.01504$; $NA_{water} = \sin\Theta_0$; Θo = 8.65°

8/HW	Angle of acceptance of an optical fiber is 30° when kept in air. Find the angle of acceptance when it is in a medium of refractive index 1.33. **Ans**: 22°
9/CW	Calculate the number of modes propagated in an optical fiber of core refractive index 1.55 and clad refractive index 1.5 and core diameter 40 μm. The laser of wavelength 1400 nm is used for communication when optical fiber is placed in air. $V = \frac{\pi d}{\lambda}(numerical\ aperture)$ $V = \frac{\pi d}{\lambda}\left(\frac{\sqrt{n_1^2 - n_2^2}}{n_0}\right) \Rightarrow V = 35$ $N = \frac{V^2}{2} \Rightarrow 612$
10/HW	610 number of modes are propagated in an optical fiber of core refractive index 1.55 and clad refractive index 1.5 and core diameter 40 μm. Calculate the wavelength of laser used for communication when optical fiber is placed in air. **Ans**: 1.4 x 10^{-12} m
11/CW	Calculate the attenuation in an optical fiber of length 0.5 km when a light signal of power 100 mW emerges out of the fiber with a power 90 mW. **Solution**: $\alpha = -\frac{10}{L}\log_{10}\frac{P_o}{P_i}$ =0.915 dB/km
12/HW	The attenuation of light in an optical fiber is 3.6 dB/km. What fraction of its initial intensity remains after 3 km? **Solution**: $\alpha = -\frac{10}{L}\log_{10}\frac{P_o}{P_i} \Rightarrow \frac{P_o}{P_i} = 10^{-(\frac{\alpha L}{10})} = 0.0832$
13/HW	An optical fiber loses 85% of its power after traveling a distance 400 m. What is fiber loss? **Ans**: α =1.7645