UNIT-3

Part B: Fibre Optics

Syllabus:

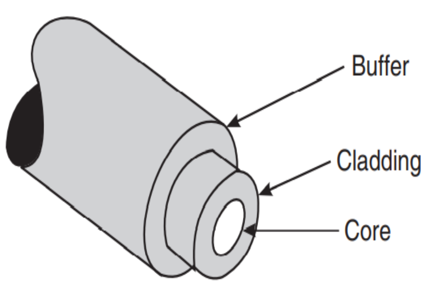
Introduction to Optical Fiber-Total Internal Reflection-Propagation of electromagnetic waves through optical fiber-Critical angle of propagation-Acceptance angle -Numerical Aperture-Classification of fibers based on Refractive index profile, modes-importance of V number-Medical Application (endoscopy) -Fiber optic Sensors- Block Diagram of Fiber optic Communication and its advantages.

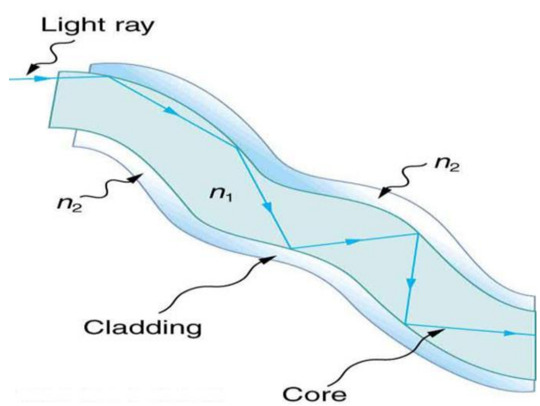
Optical fibre:

An optical fibre is a cylindrical wave guide made of transparent dielectric, (glass or clear plastic), which guides light waves along its length by total internal reflection.

Principle: The propagation of light in an optical fibre from one of its ends to the other end is based on the principle of total internal reflection. When light enters one end of the fibre, it undergoes successive total internal reflections from sidewalls and travels down the length of the fibre.

Structure:

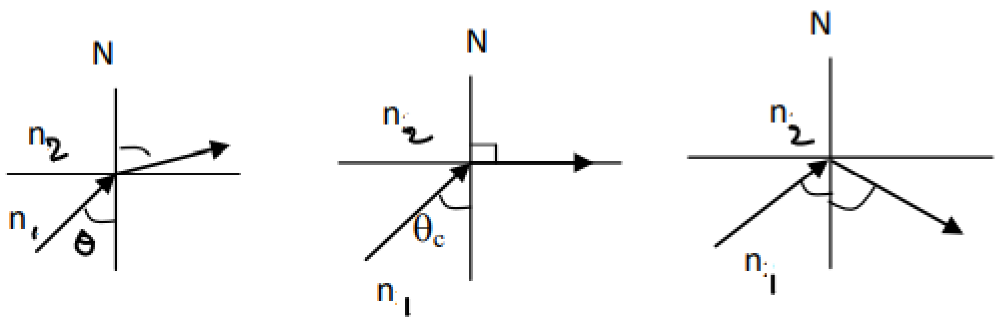




The innermost cylindrical region is the light guiding region known as the core. It is surrounded by a coaxial middle region known as the cladding. The diameter of the cladding is of the order of 125 mm. The refractive index of cladding (n2) is always lower than that of the core (n1). Light launched into the core and striking the core-to-cladding interface at an angle greater than critical angle will be reflected back into the core. Since the angles of incidence and reflection are equal, the light will continue to rebound and propagate through the fibre. The outermost region is called the sheath or a protective buffer coating. It is a plastic coating given to the cladding for extra protection.

TOTAL INTERNAL REFLECTION :

A medium having a lower refractive index is said to be an optically rarer medium while a medium having a higher refractive index is known as an optically denser medium. When a ray of light passes from a denser medium to a rarer medium, it is bent away from the normal in the rarer medium. If angle of incidence is greater equal to critical angle the ray graces the interface separating the two media.



But if angle of incidence is greater than critical angle light is reflected into same denser medium obeying lawsof reflection. This is called total internal reflection.

When $\theta = \theta_c$ angle of refraction r is 90^0

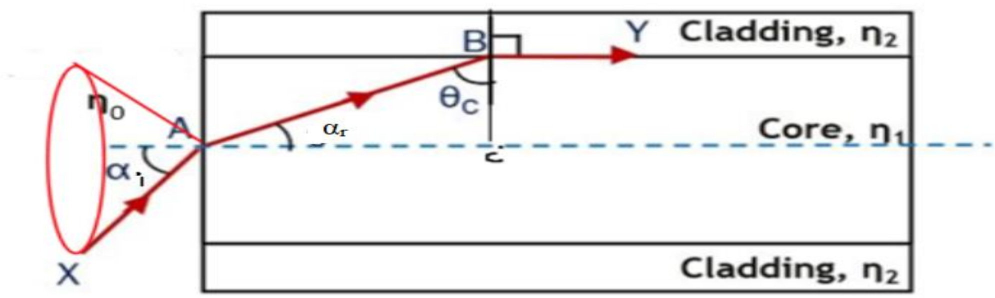
Applying Snell's law $\frac{sin\theta_c}{sin90} = \frac{n_2}{n_1}$

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

Acceptance angle and acceptance cone:

Acceptance angle :

It is the maximum angle that a light ray can have relative to the axis of the fibre so that it can undergo total internal reflection at core- clad interface and propagate down the fibre.



Let n_0 be the refractive index of the medium from which light is launched into the fibre. Assume that a light ray enters the fibre at an angle α_i to the axis of the fibre. The ray refracts at an angle α_r and strikes the core-cladding interface at an angle θ. If θ is greater than critical angle θ_c , the ray undergoes total internal reflection at the interface, since n1 > n2. As long as the angle θ is greater than θ_c , the light will stay within the fibre.

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

$$\frac{sin\alpha_i}{sin\alpha_r} = \frac{n_1}{n_0}$$

If α is increased beyond a limit,θ will drop below the critical value θ_c and the ray escapes from the sidewalls of the fibre. The largest value of $\alpha_{i\,max}$ occurs when $\theta = \theta_c$.

If the ray travelling at an angle $\alpha_{i\,max}$ is rotated about the axis of the fiber it traces a cone. This is called **acceptance cone**.

From the figure

$$sin\alpha_r = \sin(90 - \theta_c) = cos\,\theta_c$$

$$sin\,\alpha_{i\,max} = \frac{n_1}{n_0} cos\theta_c$$

$$\text{But} \quad sin\theta_c = \frac{n_2}{n_1}$$

$$\therefore cos\theta_c = \sqrt{(1 - sin^2\theta_c)} = \sqrt{1 - \frac{{n_2}^2}{{n_1}^2}}$$

$$\therefore sin\,\alpha_{i\,max} = \frac{n_1}{n_0}\sqrt{1 - \frac{{n_2}^2}{{n_1}^2}}$$

Or

$$sin\,\alpha_{i\,max} = \frac{\sqrt{{n_1}^2 - {n_2}^2}}{n_0}$$

$\alpha_{i\,max}$ is called acceptance angle and $sin\,\alpha_{i\,max}$ is called numerical aperture.

Numerical aperture: The numerical aperture (NA) is defined as the sine of the acceptance angle.

$$NA = sin\,\alpha_{i\,max} = \frac{\sqrt{{n_1}^2 - {n_2}^2}}{n_0}$$

If the medium at launching end is air $n_0 = 1$

$$NA = sin\,\alpha_{i\,max} = \sqrt{{n_1}^2 - {n_2}^2}$$

Also $\quad {n_1}^2 - {n_2}^2 = (n_1 + n_2)(n_1 - n_2)$

Assuming $n_1 \sim n_2, \quad {n_1}^2 - {n_2}^2 = 2n_1(n_1 - n_2)$

$$\therefore NA = \sqrt{{n_1}^2 - {n_2}^2} = \sqrt{2n_1(n_1 - n_2)} = \sqrt{2{n_1}^2\frac{(n_1 - n_2)}{n_1}}$$

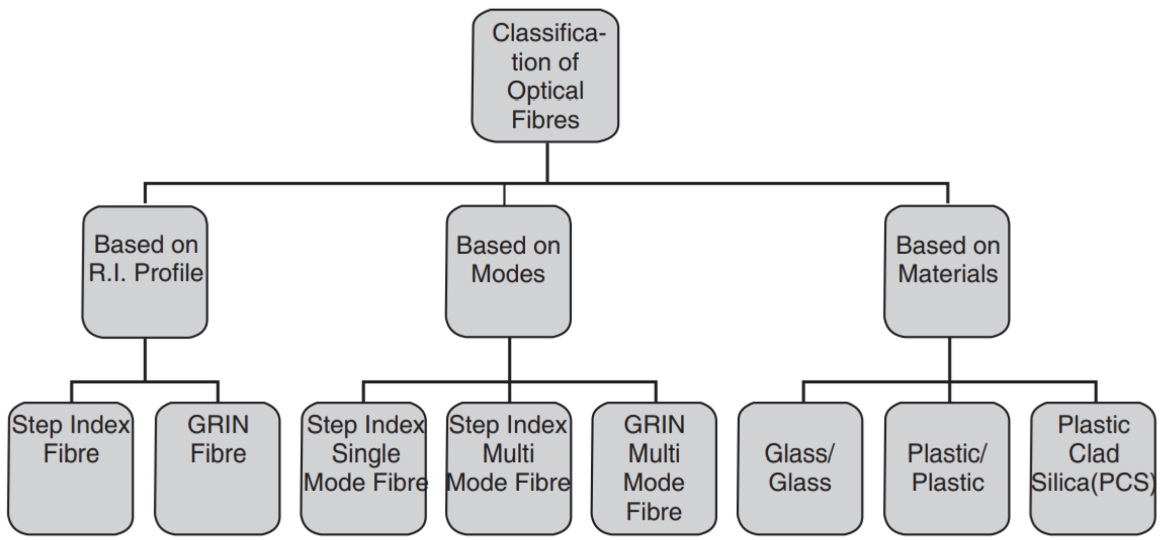
Or

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

Where $\Delta = \frac{(n_1 - n_2)}{n_1}$ is called relative refractive index.

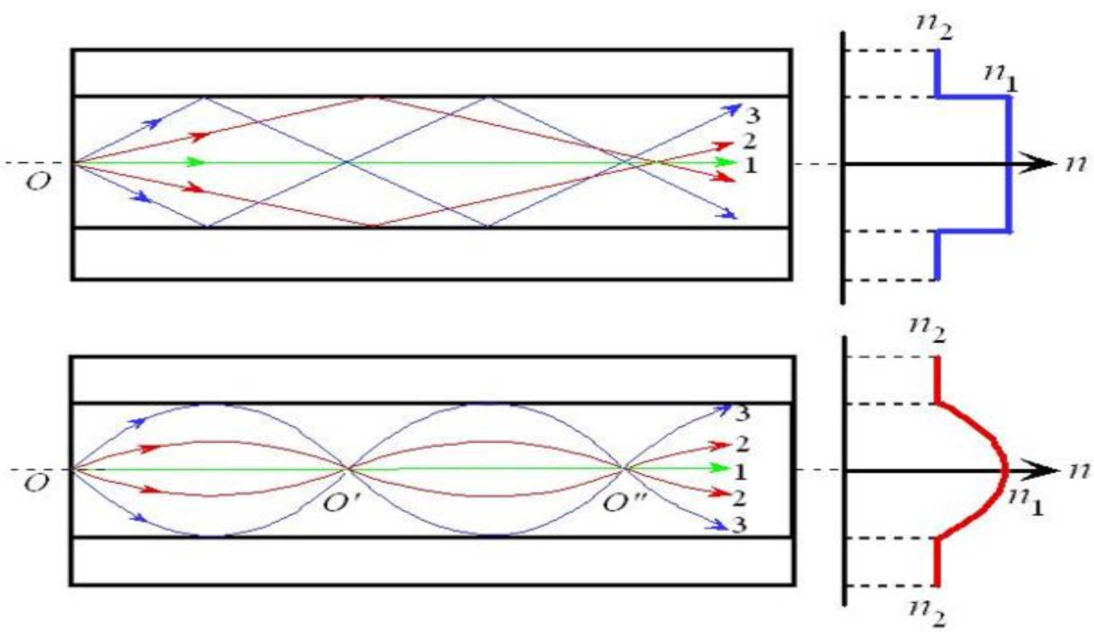
Numerical aperture determines the light gathering ability of the fibre.

Classification of Fibres:



1. Step index fibres and Graded index (GRIN) fibres.

Step index refers to the fact that the refractive index of the core is constant along the radial direction and abruptly falls to a lower value at the cladding and core boundary .

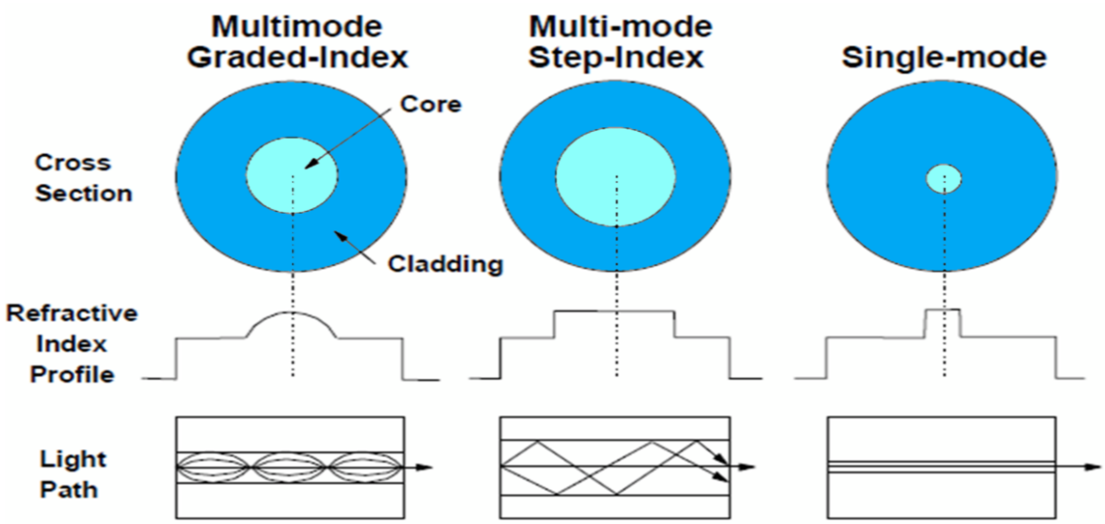


In case of GRIN fibres, the refractive index of the core is not constant but varies smoothly over the diameter of the core. It has a maximum value at the center and decreases gradually towards the outer edge of the core. At the core-cladding interface the refractive index of the core matches with the refractive index of the cladding. The refractive index of the cladding is constant.

Single mode fibres (SMF) and Multimode fibres (MMF).

Single mode step index fibre

A single mode step index fibre has a very fine thin core of diameter of 8 mm to 12 mm. It is usually made of germanium doped silicon. The core is surrounded by a thick cladding of lower refractive index. The cladding is composed of silica lightly doped with phosphorous oxide. The external diameter of the cladding is of the order of 125 mm. Light travels in SMF along a single path that is along the axis. Obviously, it is the zero order mode that is supported by a SMF. Both Δ and NA are very small for single mode fibre.



A multimode step index fibre is very much similar to the single mode step index fibre except that its core is of larger diameter. The core diameter is of the order of 50 to 100 mm, which is very large compared to the wavelength of light. The external diameter of cladding is about 150 to 250 mm. Multimode step index fibres allow finite number of guided modes. The path length along the axis of the fibre is shorter while the other zigzag paths are longer. Because of this difference, the lower order modes reach the end of the fibre earlier while the high order modes reach after some time delay.

Multimode GRIN fiber

A graded index fibre is a multimode fibre with a core consisting of concentric layers of different refractive indices. the refractive index of the core varies with distance from the fibre axis. It has a high value at the centre and falls of with increasing radial distance from the axis. In the graded index fibre, rays making larger angles with the axis traverse longer path but they travel in a region of lower refractive index and hence at a higher speed of propagation. Consequently, all rays traveling through the fibre, irrespective of their modes of travel, will have almost the same optical path length and reach the output end of the fibre at the same time

V- number

Let us consider a narrow beam of monochromatic light launched on the front end of a step-index fibre, at an angle less than the acceptance angle of the fibre. It appears to us from the ray concept that all the rays contained in the beam propagate along the fibre, such that there can be infinite modes of propagation. However, in practice, only a limited number of modes of propagation are possible in an optical fibre which can exhibit constructive interference on reaching the other end of fibre.

If the wavelength of the light is λ_0 and the diameter of the fiber is d, each mode has a definite value of V-number below which the mode is cut off.

V-number is more generally called normalized frequency of the fibre.

$$V = \frac{\pi d}{\lambda_0}(NA)$$

$$V = \frac{\pi d}{\lambda_0} n_1 \sqrt{2\Delta}$$

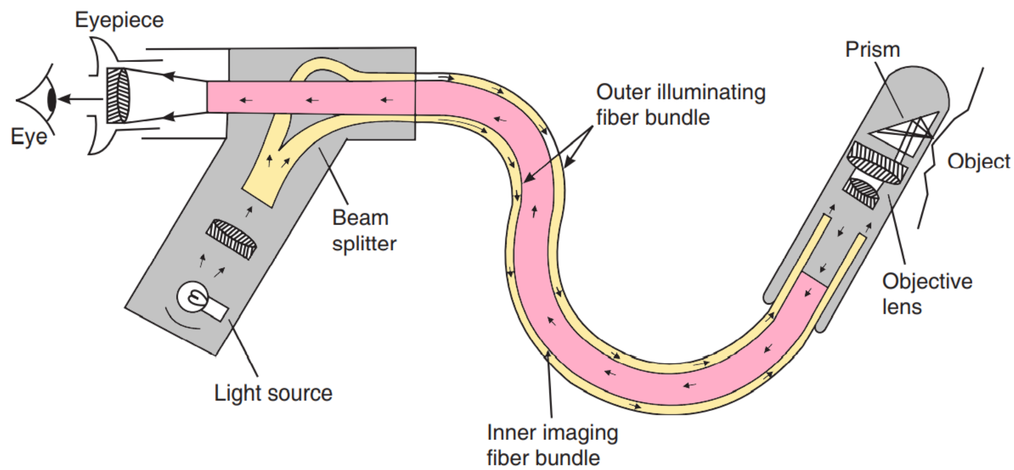
The maximum number of modes Nm supported by a Step index fiber is given by

$$N_m = \frac{1}{2} v^2$$

For single mode transmission in a MMF, V must be less than 2.405. The wavelength at which the fibre becomes single mode is called cutoff wavelength, λc of the fibre.

Applications:

Endoscopy:

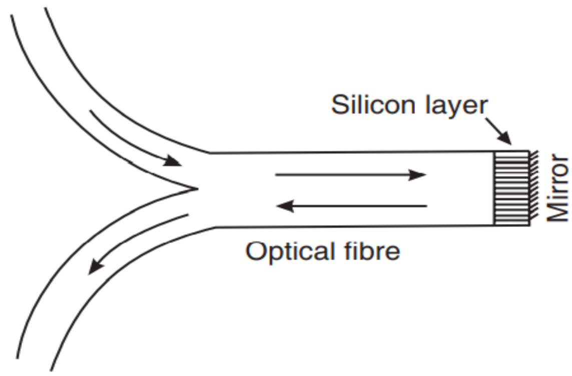


An endoscope is an optical instrument which facilitates visual inspection of internal parts of a human body. There are two fiber bundles in an endoscope. One of them is used to illuminate the interior of the body and the other is used to collect the reflected light from the illuminated area. A telescope system is added in the internal part of endoscope for obtaining a wider field of view and better image quality. At the object end, there is an assembly of objective lens and prism which are kept in a transparent glass cover and at the viewing end, there is an eye lens. The input end of the endoscope contains a powerful light source. The light rays are focused and coupled to the illuminating fiber bundle. The light rays are finally incident on the surface of the object under study. The light rays reflected from the object surface are received by the objective lens through a prism and are transmitted through the imaging fibre bundle to the viewing end of the scope. Here the eye piece reconstructs the image of the object and one can view the image of the surface of the object.

Fiber Optics Sensor:

Temperature Sensor:

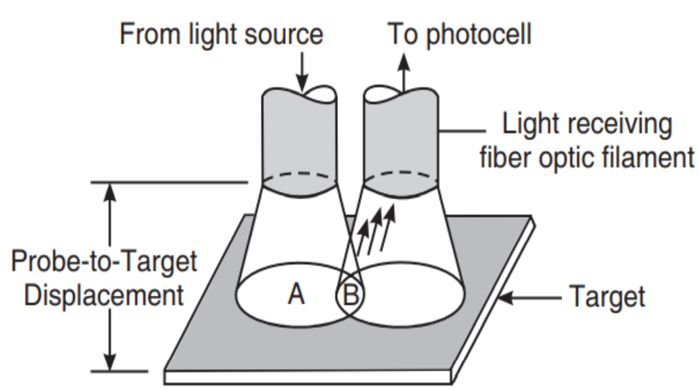
A multimode fibre is coated at one end with a thin silicon layer. The silicon layer is in turn coated with a reflective coating at the back. The silicon layer acts as the sensing element.



The light from a light source is launched into the fibre from one of the ends of one of its branches as shown. It passes first through the fibre and then through the silicon layer. The mirror coating at the other end of the silicon layer reflects the light back which again travels through the silicon layer. The reflected light emerges out through another branch of multimode fibre and is collected by a photodetector. The amount of the reflected light is converted into voltage by the photodetector. The absorption of light by the silicon layer varies with temperature and the variation modulates the intensity of the light received at the detector. Temperature measurements can be made with a sensitivity of 0.001 °C.

Displacement sensor

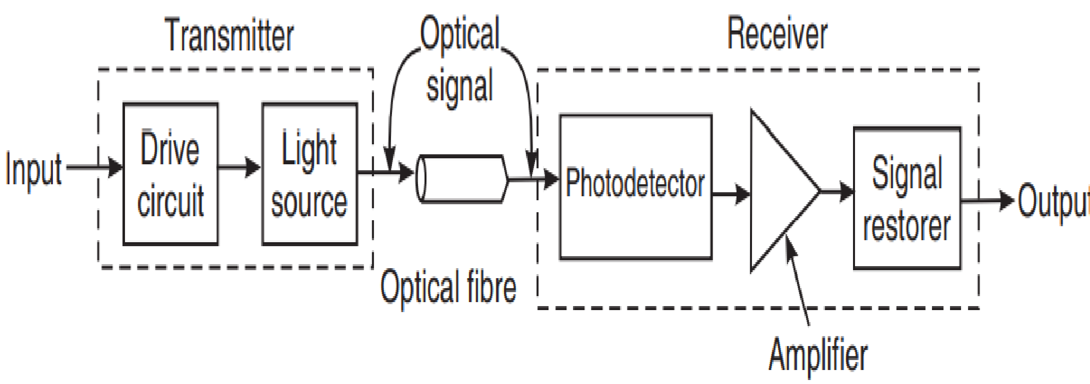
Two separate optical fibres are positioned adjacent to each other. One of them transmits light coming from a light source. The other fibre receives light reflected from the object under study and passes it on to a photodetector.



Light from the transmitting fibre element is incident on the object under study. The light receiver fibre element is positioned adjacent to the transmitting fibre. If the gap between the object and the fibre elements is zero, the light from the transmit fibre would be directly reflected back into itself and little or no light would go into the receive fibre. When the object moves away, the gap increases and some of the reflected is captured by the receive fibre which in turn is carried to the photodetector. By proper calibration, we can obtain the displacement of the object in terms of the strength of the output signal of the photodetector.

FIBRE OPTIC COMMUNICATION SYSTEM:

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



The transmitter consists of a light source supported by necessary drive circuits. A transducer converts a non-electrical message into an electrical signal and is fed to a light source. By varying the intensity of the light beam from the laser diode or LED, analog modulation is achieved. The transmitter feeds the analog or digitally modulated light wave to the transmission channel, namely optical fibre link. The optical signal travelling through the fibre will get attenuated progressively and distorted due to dispersion effects. Therefore, repeaters are to be used at specific intervals to regenerate the signal. At the end of the fibre, an output coupler directs the light from the fibre onto a semiconductor photodiode, which converts the light signals to electrical signals. The photodetector converts the light waves into electrical signals which are then amplified and decoded to obtain the message. The output is fed to a suitable transducer to convert it into an audio or video form.