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Study of Numerical Aperture of Single Mode Optical Fibre

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ABSTRACT

To use optical fibres it is useful to know their numerical apertures. In this paper we focus on the numerical aperture of the single mode optical fibre which a measure for its angular acceptance for incoming light. It is defined based on geometrical considerations and is thus a theoretical parameter which is calculated from the optical design. If it is sufficient to transmit the light at the input with an aperture lower than the theoretical aperture without core stopping, it is very useful to know the numerical aperture. We measure the numerical aperture by calculating the mean diameter and then the radius of the spot circle. We also measure the distance of the fibre from the target. Then make a ratio between the radius of the spot circle and the distance. From here we calculate the acceptance angle and then numerical aperture by sin of acceptance angle.

Keywords: Optical fibre, numerical aperture, acceptance angle

1. INTRODUCTION

Throughout history, people have used light to communicate, starting with signal fires and smoke signals. Ships at sea also used signal lamps to communicate. Alexander Graham Bell filed the first patent for an optical communication system in 1880. This system, called the photophone, used a beam of light to transmit information over a distance of 200 meters. The photophone worked by detecting variations in the intensity of light with a photosensitive selenium cell. However, all of these methods depend on the atmosphere as the transmission medium, which can be unreliable on foggy days. Many people have experienced this while driving.

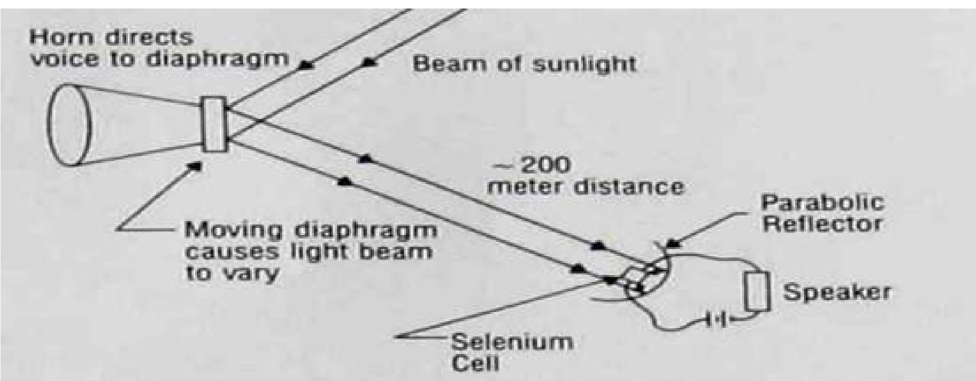


Figure-1; Schematic diagram of Alexander Graham Bell's Photophone

A reliable method for transmitting light is to use a waveguide made of non-conductive materials like glass or plastic. These materials are not affected by changes in the atmosphere. In 1870, John Tyndall showed that light could be guided through a stream of water, which led to the development of the dielectric waveguide theory by Hadrons and Debey.

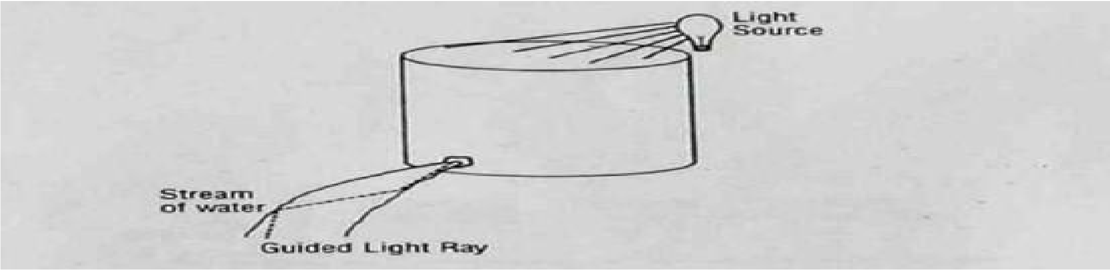


Figure-2; Tyndall's experiment showing that a stream of water will guide a beam of light

The popularity of optical fibre as a communication medium can be traced back to two significant events. Firstly, the creation of the first operating laser in 1960, and secondly, the calculation by Charles Kao and George A. Hackham in 1966, which suggested that if an optical fibre waveguide could transmit 1% of light over a distance of 1km, it could compete with existing coaxial cables used for communication. At that time, the existing fibres could only transmit light energy to 1% of its original value after 20 meters, and high-quality transmission was not predicted by materials experts. However, in the 1970s, Corning Glass Works developed high-silica glass for fibres, achieving transmission greater than 1% over a distance of 1km; later increased to greater than 40% over 1km.Nowadays, transmission up to 95-97% over 1km can be achieved.

Narinder Singh Kapany (31 October 1926 – 4 December 2020) was an Indian-American physicist best known for his work on fibre optics.[1][2][3] He is credited with inventing fiber optics, and is considered the 'Father of Fiber Optics'.[4][5]Fortune named him one of seven 'Unsung Heroes of the 20th century' for his Nobel Prize-deserving invention. He was awarded India's second highest civilian award the Padma Vibhushan posthumously in 2021. [6][7]He served as an Indian Ordnance Factories Service (IOFS) officer. He was also offered the post of Scientific Adviser to the Defence Minister of India, by the first Prime Minister of India, Jawaharlal Nehru.

Kapany was born on 31 October 1926, in a Sikh family in Moga, Punjab. He completed his schooling in Dehradun and went on to graduate from Agra University. He served as an Indian Ordnance Factories Service officer, before going to Imperial College London in 1952 to work on a Ph.D. degree in optics from the University of London, which he obtained in 1955.At Imperial College, Kapany worked with Harold Hopkins on transmission through fibers, achieving good image transmission through a large bundle of optical fibre for the first time in 1953. Optical fibers had been tried for image transmission before, but Hopkins and Kapany's technique allowed much better image quality than could previously be achieved. This, combined with the almost-simultaneous development of optical cladding by Dutch scientist Bram van Heel, helped jump start the new field of fibre optics. Kapany coined the term ' fibre optics' in an article in Scientific American in 1960, wrote the first book about the new field, and was the new field's most prominent researcher, writer, and spokesperson. Telecommunication is essential in modern life, and optical fibre plays a crucial role in this system. Optical fibre, also known as fibre optic cable, is a narrow cylindrical pipe that uses light pulses to transmit information from one point to another over long distances.[8][9] It is commonly used in telecommunications networks to transmit data, voice, and video signals, as well as in medical equipment, scientific research, and industrial applications.[10]The core of an optical fibre is less than 10 micrometres in diameter, which is thinner than a human hair. It is surrounded by a cladding layer that lets light travel through the core without escaping into the cladding layer. Total internal reflection is the principle on which optical fibres operate. This phenomenon occurs when the angle of incidence of a light ray is greater than the critical angle, causing the light to bounce off the boundary between the core and the cladding and allowing it to travel down the length of the fibre. Optical fibres have several advantages over traditional copper cables, including higher bandwidth, longer transmission distances, and greater resistance to electromagnetic interference. They are also lightweight and durable, making them ideal for use in harsh environments. We have discussed the basics of optical fibre, which include the definition of optical fibre, the principle of optical fibre which is Total internal reflection, and the conditions for Total internal reflection. And also gives a small idea of the types of optical fiber which are of two types (1) single-mode signal and, (2) multi-mode signal.

In general, single-mode (SM) fibre is used for long distances or higher bandwidth needs and uses a laser as its light source while Multimode (MM) fibre uses an LED as its light source and is used for short distances or less bandwidth-intensive applications.
We discussed about the study of numerical aperture in single mode optical fibre and the experimental procedure of measuring numerical aperture.

2. Basics of optical fibre

Optical fibre is a technology that associated with data transmission using light pulses quickly and at higher bandwidth. It is made up of either glass or plastic to transmit light pulse. Optical fibres are long thin strand of very pure glass whose diameter is of the order of 10μm to 1mm.Optical fibre is a flexible transparent fibre and its diameter is slightly thicker than that of human hair.[11]It works on the principle of total internal reflection (TIR). This means that light travels in a zigzag pattern, and only a small number of light escapes through the side walls of the fibre. Most of the light comes out from the other end of the fibre.

STRUCTURE OF OPTICAL FIBRE: An optical fibre consists of three main components. Core, cladding and protective jacket or also called plastic coating. The coating protects the fibre from damage but does not contribute to its optical waveguide properties.[12]

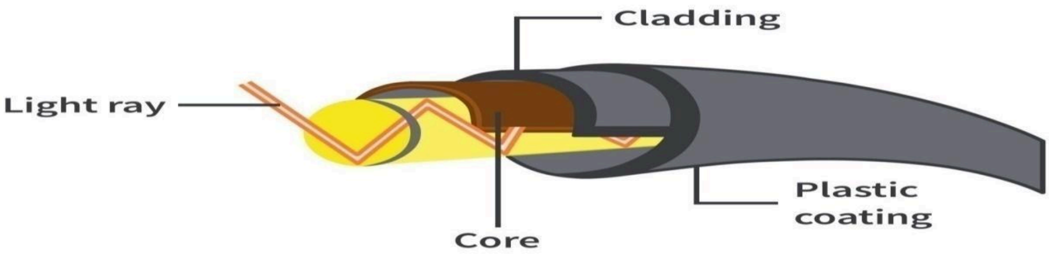


Figure 3 Structure of Optical fiber

Core: An optical fibre has a central part called the core. Its purpose is to guide light through the fibre. The core is very thin and can be made of glass or plastic. Its diameter ranges from 2 to 120 micrometers.
Cladding: The outer layer of an optical fibre that covers the core is called the cladding. It is a thin layer made of either glass or plastic and has different optical properties from the core material. The cladding is usually around 300 micrometers thick.
Cladding having the multiple functions:
(A) Reduces loss of light from core into the surrounding air.
(B) Reduces scattering loss at the surface of core.
(C) Add mechanical strength.
Protective jackets: The outer layer of an optical fibre is called the protective jacket. It is sometimes called the coating or buffer. The core and cladding are inside this jacket, which is usually made of plastic. The protective layer is meant to protect the fibre from physical harm like moisture, crusting, and other dangers.

Fibre attributes: Fiber attributes are those characteristics that are retained throughout cabling and installation processes.[13]

a) Core characteristics: They have several core characteristics that make them well-suited for these purposes:

- **Material:** The core is the innermost part of the optical fiber, typically made of high-quality glass or sometimes plastic. The material chosen for the core has a higher refractive index compared to the cladding, which is essential for total internal reflection.
- **Function:** The core is responsible for carrying the light signals over long distances by utilizing the principle of total internal reflection. This means that when light enters the core at an angle greater than the critical angle, it will be completely reflected back into the core and won't escape into the cladding.
- **Diameter:** The core diameter can vary, with single-mode fibers having a smaller core diameter (around 2-120 micrometers) and multi-mode fibers having a larger core diameter (typically around 50-62.5 micrometers). Single-mode fibers allow for a single mode (ray) of light to propagate, whereas multi-mode fibers can support multiple modes.
- **Refractive Index:** The refractive index of the core is higher than that of the cladding, which ensures total internal reflection can occur.

b) Cladding characteristics: They have several cladding characteristics that make them well-suited for these purposes:

- **Material:** The cladding is made of a material with a lower refractive index compared to the core. This is usually another type of glass or plastic.
- **Function:** The cladding serves to confine the light within the core by providing a lower refractive index medium. This lower refractive index prevents the light from escaping the core and facilitates total internal reflection.
- **Diameter:** The cladding surrounds the core and typically has a larger diameter than the core. It acts as a protective layer around the core.
- **Refractive Index:** The refractive index of the cladding is lower than that of the core. This ensures that the light is guided through the core.

c) Protective Jacket Characteristics:

Material: The outer layer, known as the protective jacket or coating, is usually made of a polymer material. It serves to protect the fiber from physical damage, moisture, and other environmental factors.
Thickness: The jacket is thicker than the cladding and provides mechanical strength to the fiber. It can range from a few hundred micrometers to several millimeters in thickness.
Flexibility: The jacket also contributes to the flexibility and bendability of the optical fiber. Different jacket materials have varying levels of flexibility.

3. LIGHT TRANSMISSION IN OPTICAL FIBRE

The optical fibres which are considered as waveguides can be applied to light transmission applications. The total internal reflection phenomena are necessary for the fine confinements of the light within the waveguide.

Total internal reflection: -

Refractive index is defined as the ratio of the velocity of light in vacuum to the velocity of light in the medium. A ray of light travels more slowly in higher denser medium than less denser medium. When light passes from one material to another with different refractive indices (for example, air and glass), it behaves according to certain rules. The light moves through the first material with a refractive index of n_1 and hits the boundary at an angle of θ_1. On the other side of the boundary, the material has a higher refractive index of $n_2$compared to n_1, which causes the light to bend and travel through the second material at an angle of $\theta_2$with respect to the normal. The angles of incidence θ_1 and reflection θ_2 are related to each other. Then the Snell's law of refraction which states that:

$$n_1 \sin sin\, \theta_1 = n_2 \sin sin\, \theta_2$$

Figure 4 Refractive index

From Snell's law the limiting case of refraction showing the critical ray at an angleθ_c.Total internal reflection where $\theta_1 > \theta_c$

$$\frac{sin\, \theta_1}{sin\, \theta_2} = \frac{n_2}{n_1}$$

Where, $n_1$andn_2 are the refractive index indices of the two materials.

θ_1 is the incident angle of light.

θ_2 is the angle of refraction.

θ_c is the critical angle.

When light goes from a medium with a higher refractive index n_1 to the lower refractive index n_2, some of the light reflects back into the original medium. This happens because of the difference in refractive indices. When the angle of refraction is 90º and the refracted ray emerges parallel to the interface between the dielectrics, the angle of incidence must be less than 90º. This is the limiting case of refraction and the angle of incidence is known as the critical angle θ_c. The value of critical angle is given by:

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

Hence, the above figure shows that total internal reflection occurs at the interface between two dielectrics of differing refractive indices when light is incident on the dielectric of lower index from the dielectric of higher index, and the angle of incidence of the ray exceeds the critical value.

Figure 5 Total internal reflection in optical fibre

The phenomenon by virtue of which array of light travelling from a denser medium to rarer medium is sent back to the same denser medium provided it strikes the interface of the denser and the rarer media at an angle greater than the critical angle is called total internal reflection of light. Most modern optical fiber is weakly guiding, meaning that the difference in refractive index between the core and the cladding is very small.[17]

Figure 6 Total internal reflection

When light shines on the border between two substances of different densities at point Q, it changes direction along the line QQ'. The more the angle of incidence increases, the more the light bends towards the border. At a certain angle of incidence, the refracted light moves along the border and the angle of refraction becomes 90º, also known as the critical angle (C).

If the angle of incidence is greater than the critical angle, there won't be any refracted light and all of the incident light will be reflected in the denser substance. This is called total internal reflection.[18]

Conditions for Total Internal Reflection

(1) The light ray should travel from denser to rarer medium.
(2) The angle of incidence must be greater than the critical angle for the given pair of media.

Critical angle:

When the angle of incidence is continuously increased, there will be progressive increase of refractive angle. At some conditions the refractive angle become 90º to the normal. When this happens the refractive light ray travels along the interface. The angle of incidence at the point at which the refractive angle become 90º is called critical angle. The critical angle is defined as the minimum angle of incidence at which the ray strikes the interface of two media and cause an angle of refraction equal to 90º.[19]

$$\sin\theta_c = \frac{n_2}{n_1}\sin 90°$$

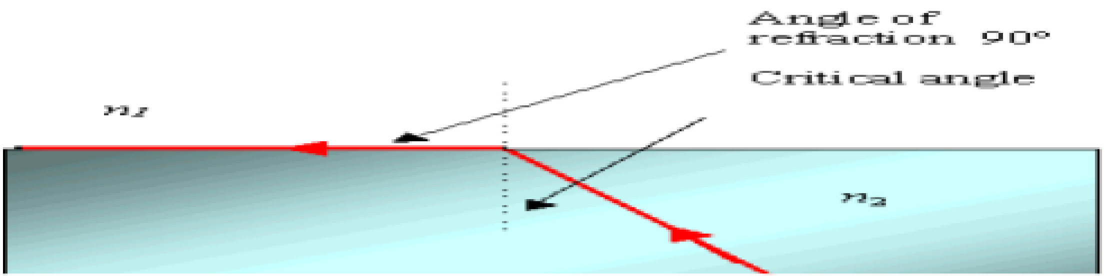


Figure 7 Critical angle

It is important to know about this property because reflection is also possible even if the surfaces are not reflective. If the angle of incidence is greater than the critical angle of a given setting, the resulting type of reflection is called total internal reflection, and it is the basis of optical fibre communication.

Acceptance angle:

The acceptance angle is $\frac{1}{2}$ angle of the maximum cone of light that can enter or exit the fibres. The incident angle is greater than the critical angle so that the light undergoes total internal reflection down the fibre. The acceptance angle of an optical fibre is defined based on a purely geometrical consideration; it is the maximum angle of ray hitting the fibre core which allows the incident light to be guided by the core.

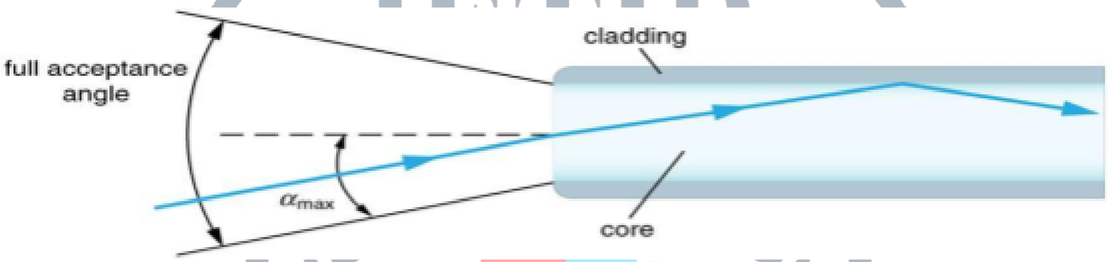


Figure 8 Acceptance angle

The angle of incidence on the core - cladding interface is less than the critical angle due to which part of incident light is transmitted.[20][21]

Hence the light will be transmitted through the fibre for the angle of incidence on the core which are less than the acceptance angle. The acceptance angle is the maximum angle of incidence on the core for which total internal reflection takes place inside the core. The light entering the core in a cone of semi-vertical angle is transmitted in the core through total internal reflection. This cone is known as acceptance angle.

Numerical aperture: Numerical aperture is a characteristic of any optical system. For example, photodetector optical fibre, lenses etc. are all optical system. Numerical aperture is the ability of the optical system to collect the entire light incident on it, in one area. The blue cone is known as the cone of acceptance. As you can see it is dependent on the acceptance angle of the optical fibre. Light wave within the acceptance cone can be collected in a small area which can then we sent into the optical fibre.

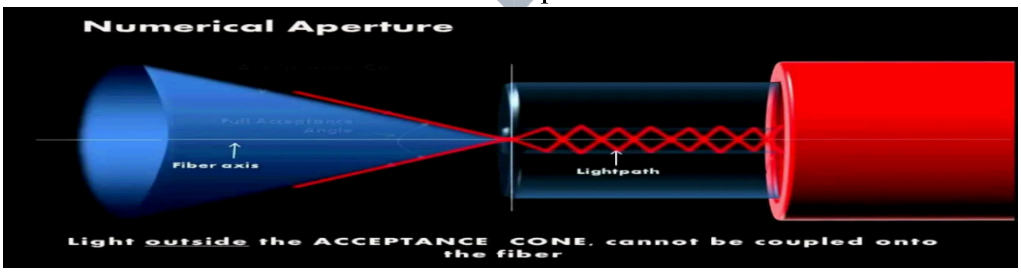


Figure 9 Numerical aperture

In the above figure the measure of maximum angle at which light rays will enter and we conducted down the fibre. This is represented by the following equations:

NA - Numerical Aperture

$$NA = \sqrt{\left(n_1^2 - n_2^2\right)} = n \sin sin \theta$$

Where n is the index of refraction of the medium in which the lens is working (1.00 for air, 1.33 for pure water, and typically 1.52 for immersion oil.[22]

Spectrum of electromagnetic wave: - The electromagnetic spectrum refers to the entire range of wavelengths of electromagnetic radiation, which includes various types of waves such as radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays. These waves differ in their frequencies and wavelengths. From longest to shortest wavelength, the electromagnetic spectrum is usually divided into the following regions:

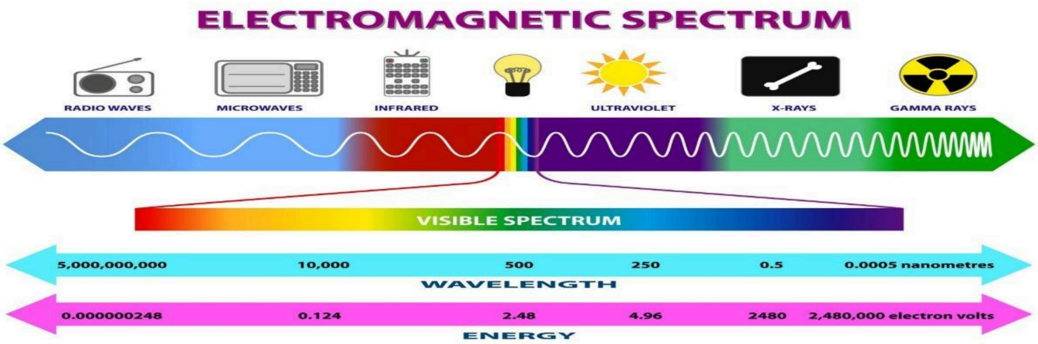


Figure- 10 Spectrum of electromagnetic wave

Electromagnetic waves are typically described by any of the following three physical properties: the frequency (f), wavelength (λ), or photon energy (E). Frequencies observed in astronomy range from 2.4×1023 Hz (1 GeV gamma rays) down to the local plasma frequency of the ionized interstellar medium (~1 kHz). Wavelength is inversely proportional to the wave frequency.[23]

Radio Waves: These have the longest wavelengths and lowest frequencies. They are used for communication, including television and radio broadcasts.

Microwaves: These have shorter wavelengths and higher frequencies than radio waves. They are used for things like microwave ovens, satellite communication, and radar.

Infrared Radiation: This is just beyond the visible spectrum. It's felt as heat and is emitted by warm objects. It's used in applications like night vision devices and infrared photography.

Visible Light: This is the range of wavelengths that our eyes are sensitive to. It spans from approximately 400 nanometres (violet) to 700 nanometres (red).

Ultraviolet Radiation: This has shorter wavelengths and higher frequencies than visible light. It's responsible for sunburn and can also be used for applications like germicidal lamps.

X-Rays: These have even shorter wavelengths and higher frequencies. They are used in medical imaging, security screening, and scientific research.

Gamma Rays: These have the shortest wavelengths and highest frequencies. They are produced by radioactive materials and nuclear reactions. They are used in medical treatments (radiation therapy) and in various scientific applications.

NOTE: - These divisions are useful for categorization, they are not strict boundaries. The transition from one type of wave to another is continuous, and there is some overlap between neighbouring regions.

Classification of optical fibres

1.) Based on refractive index profile
2.) Number of modes transmitted through fibre
3.) Tapered fibre

1.) Based on refractive index profiles: Optical fibres are classified into two types based on the refractive index profile of core and cladding. They are

- Step index fibre
- Graded index fibre.

2.) Based on the number of modes propagated through optical fibre:

Mode is the one which describes the nature of the electromagnetic wave in waveguide. Optical fibre is considered as a cylindrical waveguide. It is the allowed direction whose associated angles satisfy the conditions for total internal reflection. Based on the number of modes that propagates through optical fibre, they are classified as

1. Single mode fibres
2. Multimode fibres

1. Single mode or Mono mode fibres:

In a fibre, if only one mode is transmitted through it then it is said to be a single mode fibre. It has a very much smaller core that allows only one mode of light at a time to propagate through the core. While it might appear, the multimode fibre has higher capacity, in fact the opposite is true. Single mode fibre is designed to maintain spatial and spectral integrity of each optical signals over longer distances,allowing more information to be transmitted.

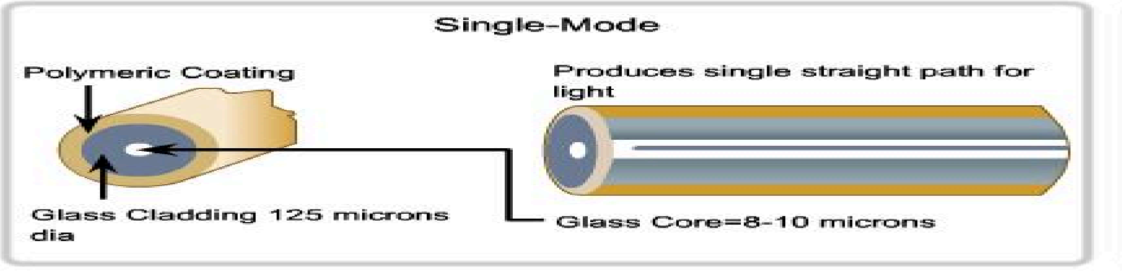


Figure 11 -Single mode fibre

2. Multimode Fibres:

Multimode fire was the first type of fiber to be commercialized. It has a much larger core than single-mode fiber, allowing hundreds of modes of light to propagate through the fiber simultaneously. Additionally, the larger core diameter of multimode fiber facilitates the use of lower-cost optical transmitters (such as light emitting diodes [LEDs] or vertical cavity surface emitting lasers [VCSELs]) and connectors.

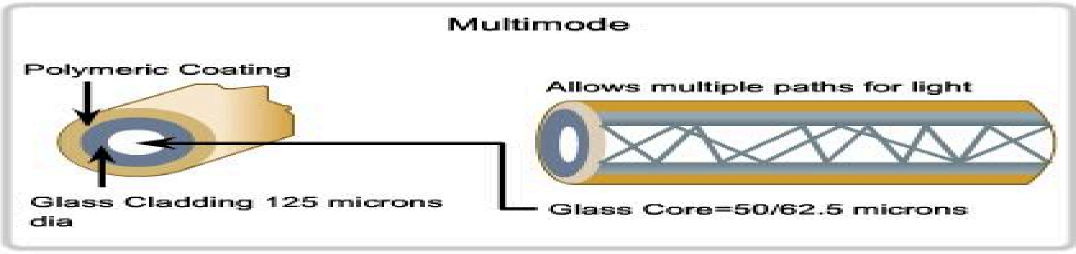


Figure 12 -Multimode fibre

Depending upon the refractive index profile and the number of modes propagated through the optical fibre, they are further classified as

. Step index single mode fibre
. Step index multimode fibre
. Graded index single mode fibre
. Graded index multimode fibre

- **Step index single mode fibre:** The core diameter of this type of fibre is very small i.e., of the order of wavelength of light to be propagated through the fiber. The refractive index profile has step change in the refractive index from core to cladding as shown in Figure

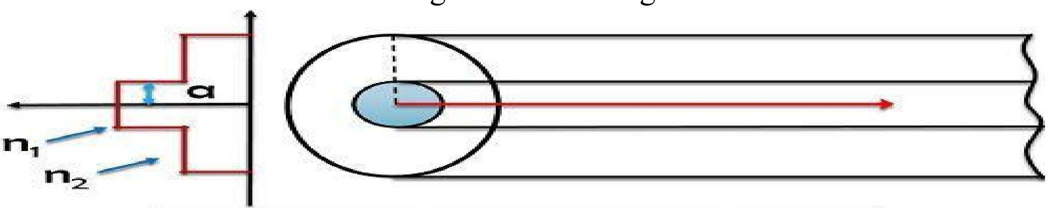


Fig-13 Step Index Single Mode Fibre

- **Step index multimode fibre**: Step-index multimode fibres are mostly used for imaging and illumination. Graded-index multimode fibres are used for data communications and networks carrying signals moderate distances - typically no more than a couple of kilometres.

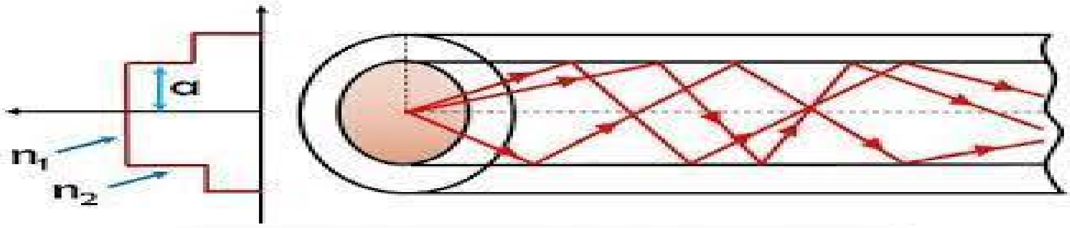


Fig 14 Step Index Multimode Fibre

❖ **Graded index single mode optical fibre: -**

Graded index optical fibre has a property of gradual variation in refractive index (increasing from the outside of the fibre core to the centre of it). The propagation of light through single mode graded index fibre is similar to that for step index fibre. The light wave travels along the centre of the optical fibre.

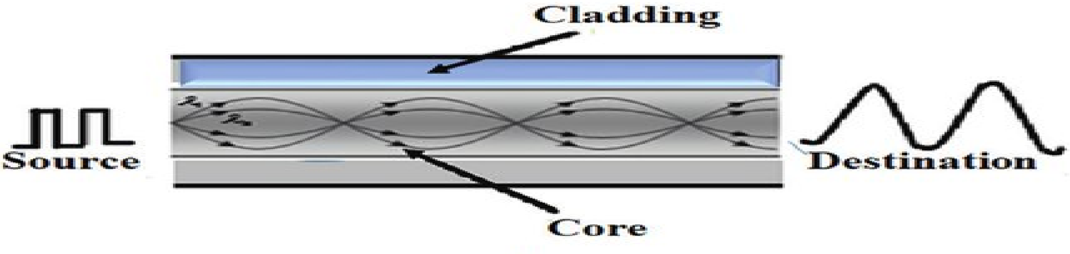


Fig 15 Graded Index Single mode fibre

Graded Index Multi Mode Fibre: -

From the figure it is quite clear that light waves or rays with large angle of incidence travel more path lengths than those with smaller angles. But we know that the decrease of refractive index allows a higher velocity of light energy propagation. Thus, all waves will reach a given point along the fibre at virtually same time. As a result, the transit time dispersion is reduced. This type of light propagation is referred as graded index multimode propagation through optical fibre.

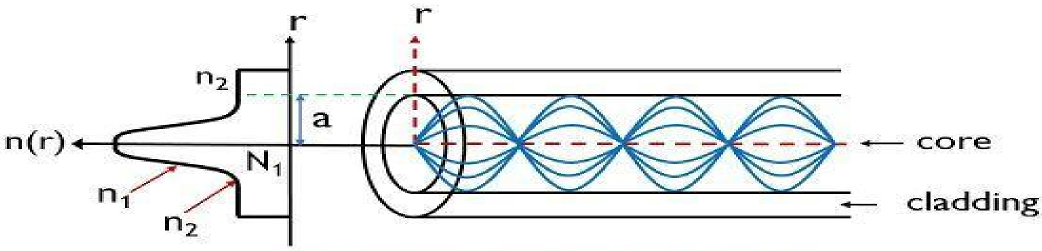


Fig 16 Graded Index Multi Mode Fibre

3.) Tapered fibre:-Tapered fibres are useful for getting maximum amount of power from a poor-quality laser spot into a fibre. The use of tapered optical fibre is an efficient low-cost method of transforming a poor-quality laser beam into a uniform output spot.

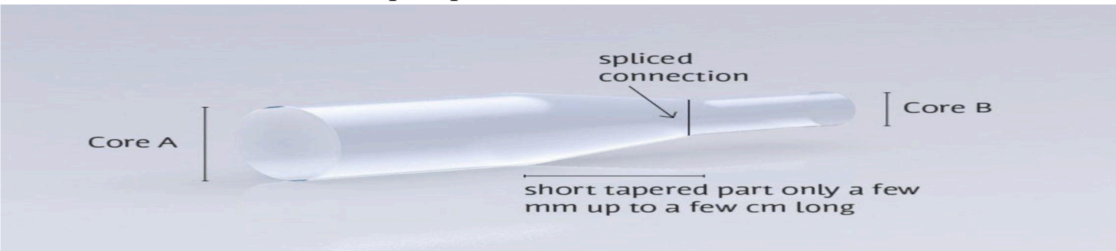


Fig 17 Tapered Fibre

OPTICAL FIBRE COMMUNICATION SYSTEM:

Sending information over long distances is done through optical fiber communication, which is a dependable and effective method. This process involves transmitting infrared or visible light pulses through a fiber optic cable. Due to the low attenuation characteristics of glass or plastic fibers, the light experiences minimal loss as it travels along the cable. To convert electrical signals into optical signals, a light source is used, which allows for the light signals to represent data in different ways, such as intensity or frequency modulation. Once at the destination, a light-sensitive device, like a photodiode, converts the optical signals back into electrical signals. These electrical signals can then be processed and utilized by communications.

BLOCK DIAGRAM OF OPTICAL FIBRE COMMUNCATION SYSTEM

A block schematic of an optical fibre communication system is shown in Figure. This system conveys either the analogy or digital signal from the information source to the destination over the optical fibre cable. The information source provides an electrical signal to a transmitter comprising the driver circuit, optical source and channel coupler. The optical source provides the electrical-optical conversion. It can be either a semiconductor laser or light-emitting diode (LED). The signal transmission medium consists of an optical fibre cable. The receiver consists of a channel coupler, photo-detector and electronic circuits for linear channel and decision circuit. Photodiodes may be used for the detection of the optical signal and the optical-electrical conversion and finally the electrical signal reach the destination. Optical fibre can be used in high transmission applications since they are waveguide. An outer layer of glass or plastic surrounds the optical fibre core, which has a lower refractive index than the fibre core. The complete internal reflection phenomena are necessary to achieve fine confinement of light within the waveguide. Calculate the majority of telecommunication network use fibre optic as data transmission medium.[32]

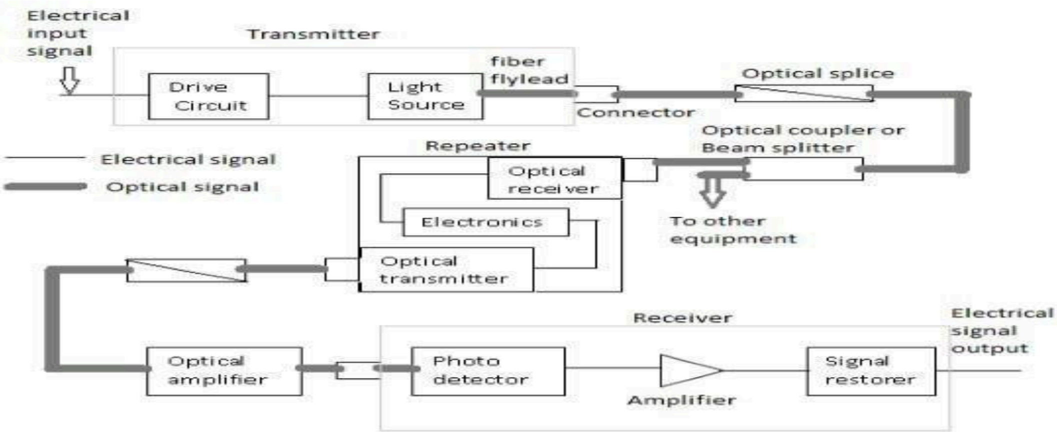


Figure 18 Block diagram of fibre optic communication system

Elements of fibre optic communication system:

Modern fibre-optic communication systems generally include optical transmitters that convert electrical signals into optical signals, optical fibre cables to carry the signal, optical amplifiers, and optical receivers to convert the signal back into an electrical signal. The information transmitted is typically digital information generated by computers or telephone systems.

a) **Transmitter:** A transmitter is a device or equipment that sends signals or information in the form of radio waves, electrical pulses, or other means to communicate with or control other devices. Transmitters are commonly used in various applications, including broadcasting radio and television signals, remote control systems, wireless communication, and more.
   - **Driver circuit:** Driver circuit drives the light source.
   - **Light source:** Light source converts electrical signal to optical signal. Light source is used to connect optical signal to optical fibre.

b) **Optical connector**: It is used for temporary non-fixed joints between two individual optical fibres.

c) **Optical splice:** Optical splice is used to permanently join two individual optical fibres.

d) **Optical coupler:** Optical coupler or splitter provides signal to other devices.

e) **Repeater:** Repeater converts the optical signal into electrical signal using optical receiver and passes it to electronic circuit where it is reshaped and amplified as it gets attenuated and distorted with increasing distance because of scattering, absorption and dispersion in waveguides, and this signal is then again converted into optical signal by the optical transmitter.
   - **Optical receiver:** The role of an optical receiver is to convert the optical signal back into electrical form and recover the data transmitted through the light wave system.

f) **Optical amplifier:** The principle of optical amplification was invented by Gordon Gould on November 13, 1957.[34] He filed patent No. 804,539 on April 6, 1959 titled "Light Amplifiers Employing Collisions to Produce Population Inversions" An optical amplifier is a device that amplifies an optical signal directly, without the need to first convert it to an electrical signal. An optical amplifier may be thought of as a laser without an optical cavity, or one in which feedback from the cavity is suppressed.

g) **Receiver:** Optical signal is applied to the optical receiver. It consists of photo detector, amplifier and signal restorer. The main component of an optical receiver is a photodetector which converts light into electricity using the photoelectric effect. The primary photodetectors for telecommunications are made from Indium gallium arsenide. The photodetector is typically a semiconductor-based photodiode.
   - **Photo detector:** Photo detector converts the optical signal to electrical signal. A photodetector (PDs) is an optoelectronic device that converts incident light or other electromagnetic radiation in the UV, visible, and infrared spectral regions into electrical signals.

- **Amplifier:** An amplifier is an electronic device that increases the voltage, current, or power of a signal. Amplifiers are used in wireless communications and broadcasting, and in audio equipment of all kinds.

h) **k Transmission channel:** It consists of a cable that provides mechanical and environmental protection to the optical fibres contained inside. Each optical fibre acts as an individual channel.

l) Signal restorers: Signal restorers and amplifiers are used to improve signal to noise ratio of the signal as there are chances of noise to be introduced in the signal due to the use of photo detectors. For short distance communication only, main elements are required.

4. Numerical aperture

We measure the numerical aperture of a single mode communications-grade optical fibre, which is a critical fibre parameter. We will also talk about how launching light into the fibre can affect this measurement. Finally, we will calculate the numerical aperture (NA) and the acceptance angle (θ_a).

Measurement of numerical aperture

Numerical aperture refers to a characteristic of the optical system, such as a microscopic or a lens. It's a measure of the ability of the system to gather and focus light.

Mathematically, the numerical aperture (NA) is defined as the sine of the maximum half-angle of the cone of light that can enter or exit the system. It determines the resolving power and light gathering ability of the optical system. Higher values of the numerical aperture generally result in better resolution and brighter images.

Numerical aperture (NA) = $sin\theta_a$

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

Where θ_a is the Acceptance Angle, n_1 is the refractive index of core, n_2 is the refractive index of cladding.

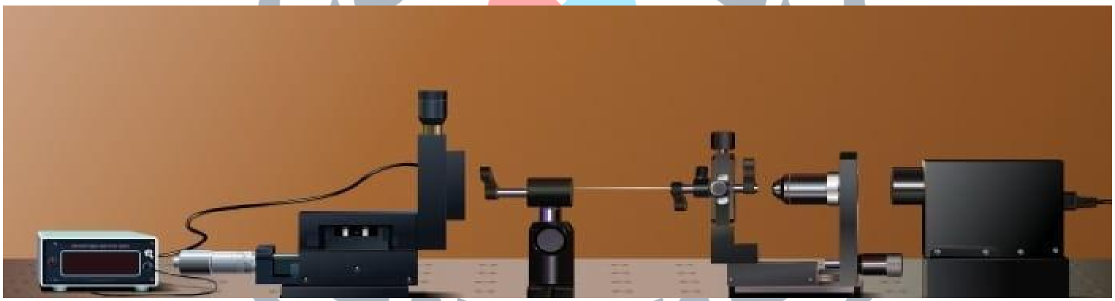


Fig-19: -Schematic diagram of laboratory setup for numerical aperture

Components used: -

- **Emitter: - A** substance that emits heat light or gas, especially when this causes harms.
- **Concentrator: -**A device for concentrating (= increasing the strength of) a substance by removing or reducing the amount of something such as water, or by collecting particular atoms or molecules together
- **Fibre**: - single mode optical fibre
- **Fibre stand**: - it is use to hold the fibre
- **Detector: -**An optical detector is a device that converts light signals into electrical signals, which can then be amplified and processed. Such detectors are one of the most important components of an optical fibre communication system and dictate the performance of a fibre optic communication link.
- **Current output unit: -**An ammeter is an instrument used to measure the current in a circuit. Electric currents are measured in amperes, hence the name. For direct measurement, the ammeter is connected in series with the circuit in which the current is to be measured.

INSTRUCTION SET

To begin the experiment, follow these steps: -

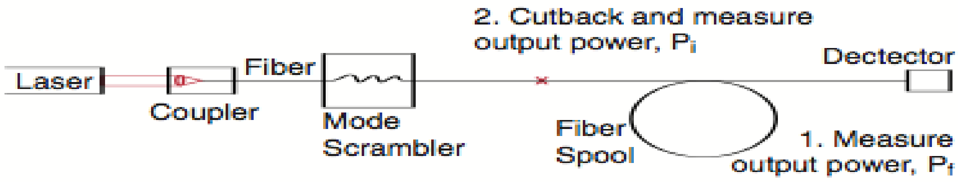


Figure – 20 Phasor diagram numerical aperture

1. Make all connections
2. Connect one end if the optical fibre cable to the optical fibre trainer and other end to the numerical aperture
3. Procedure for simulator Controls
    - **Start button:** To start the experiment.
    - **Switch on**: To switch on the Laser.
    - **Select Fibre:** To select the type of fibre used.
    - **Select Laser:** To select a different laser source.

Detector distance (Z): Use the slider to vary the distance between the source and detector. (ie toward the fibre or away from the fibre).
Detector distance(x): Use the slider to change the detector distance i.e. towards left or right w.r.t. the fibre.
Show Graph: To displays the graph.
Reset: To resets the experimental arrangement.
4. Preliminary Adjustment: -

- Drag and drop each apparatus into the optical table as shown in the figure below.
- Then Click the “Start” button.
- Switch On (now you can see a spot in the middle of the detector)
- After that select the fibre and Laser for performing the experiment from the control options.

4. Set the detector distance Z (say 4mm). We referred to the distance as “d” in our calculation.

5. Vary the detector distance X by an order of 0.5mm, using the screw gauge (use up and down arrow on the screw gauge to rotate it).
6. Measure the detector reading from the output unit and tabulate it.
7. Plot the graph between X in x-axis and output reading in y-axis.
8. Find the radius of the spot r, which is corresponding to Imax/2.71
9. Repeat the experiment by putting the detector distance Z= 8 mm (constant)
10. Compute the numerical aperture (NA) of the optical fiber by using the

$$\text{Formula (NA)} \quad \sin sin\,\theta_a = \sqrt{n_1^2 - n_2^2}$$

where Ө is called as the acceptance angle is the maximum angle of incidence at the input end of the optical fibre so that He optical ray can just propagate within the optical fibre.

NOTE: The laser should be turned on and left on for ~30 minutes before taking any measurements to ensure proper stability.

Precautions

1. The optical fibre cable should be free from twists and folds so as to avoid the power loss.
2. Connections should be proper and tight.

Measurement of numerical aperture

Readings of numerical aperture as shown in observation table below: -
Pitch= Distance moved by the screw/ number of rotations by the screw = 0.5mm

Least count = pitch /no of division of circular scale

$$L.C = \frac{0.5}{50} mm$$

L.C = 0.01mm

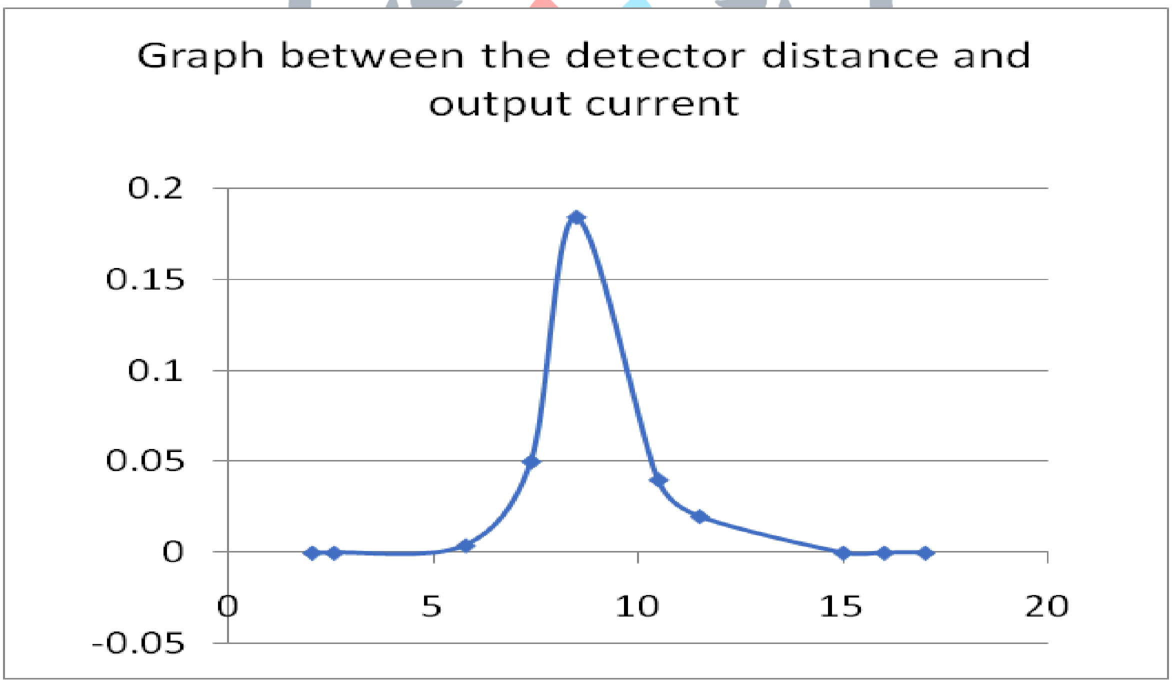
- **Detector distance (Z) is fixed to 4 mm**

Observation Table:

TABLE -1

Sr. no.	Detector distance (x)mm	o/p current reading
1	2+49*0.01= 2.49	0.000000005
2	4+20*0.01=4.20	0.04963072
3	4.5+11*0.01=4.61	0.15655311
4	5+5*0.01=5.05	0.161114465
5	5.5+1*0.01=5.51	0.045533382
6	6+43*0.01=6.43	0.004576182
7	6.5+35*0.01=6.85	0.000154
8	7+31*0.01=7.31	0.000001043
9	7.5+25*0.01=7.75	0.000000003
10	8+19*0.01=8.19	0
11	8.5+49*0.01=8.99	0.184
12	10.5+11*0.01=11.61	0.04
13	11.5+19*0.01=11.69	0.02
14	15+41*0.01=15.41	0
15	16+48*0.01=16.48	0

GRAPH - 1



Calculations:

Numerical aperture (NA) = $sin\theta_a$

$I_{max} sin\,\theta_a = \sqrt{n_1^2 - n_2^2}$

where θ_a is the acceptance angle

n_1 is the refractive index of core and n_2 is the refractive index of cladding

$$I_{max} = 0.1847$$

Radius of the spot, which is corresponding to $\frac{I_{max}}{2.71}$

$$=\frac{0.1847}{2.71}= 0.06$$

$$NA= sin\theta_a =\frac{P}{H} = \frac{r}{\sqrt{r^2+Z^2}} = \frac{1.4}{\sqrt{1.4^2+4^2}} = 0.33$$

Acceptance angle $(\theta_a) = sin^{-1}(0.24) = 19.26$

Measurement of numerical aperture

Readings of numerical aperture as shown in observation table 2 below: -

Pitch= Distance moved by the screw/ number of rotation by the screw = 0.5mm

Least count = pitch /no of division of circular scale

$L.C=\frac{0.5}{50}mm$

L.C = 0.01mm

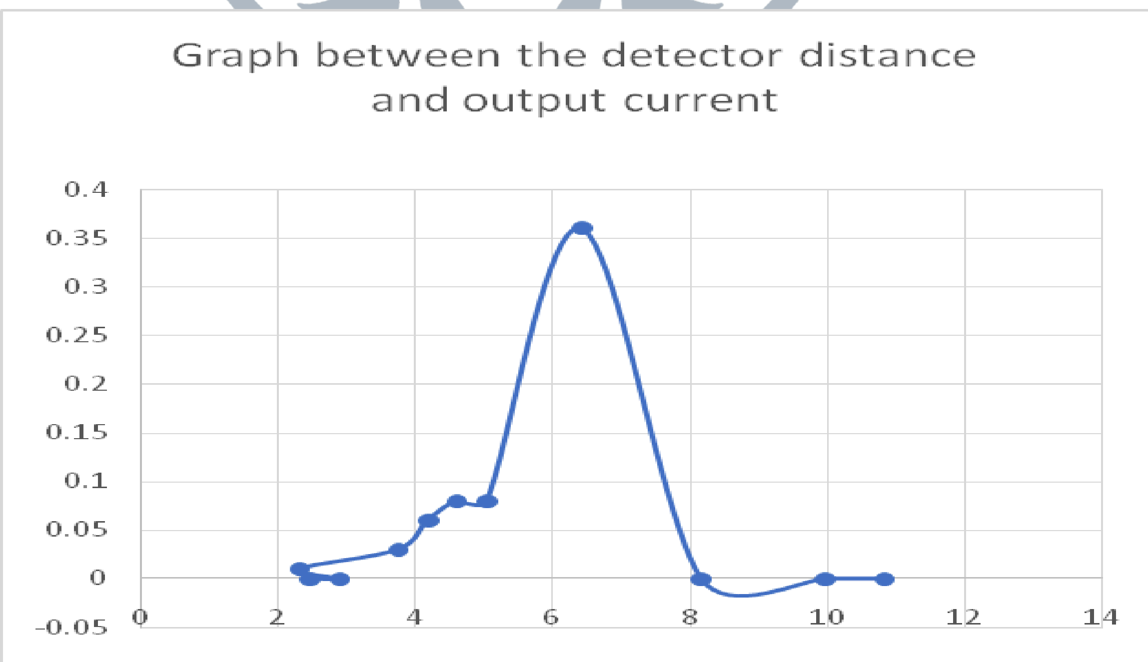
- **Detector distance constant at 8mm**

ObservationTable: -

TABLE - 2

Sr. no.	Detector distance (x)mm	o/p current reading
1	2+46*0.01= 2.46	0.001085859
2	3.5+32*0.01=3.76	0.03664313
3	4+20*0.01=4.19	0.066497273
4	5+5*0.01=5.05	0.089258661
5	5.5+1*0.01=5.51	0.095533382
6	6+43*0.01=6.43	0.3664313
7	8+17*0.01=8.17	0.000181694
8	9.5+48*0.01=9.98	0.000000139
9	10.5+34*0.01=10.84	0
10	12+15*0.01=12,15	0

GRAPH -2



Calculations:

Numerical aperture (NA) = $sin\theta_a$

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

Where θ_a is the acceptance angle

n_1 is the refractive index of core and n_2 is the refractive index of cladding

$$I_{max} = 0.366$$

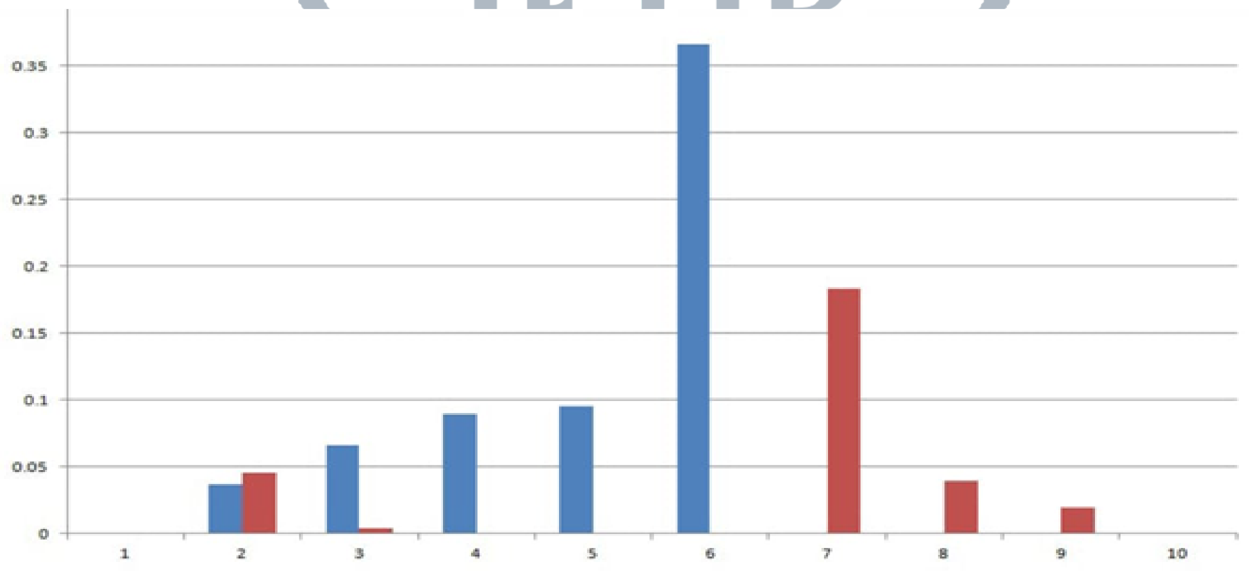
Radius of the spot, which is corresponding to $\frac{I_{max}}{2.71}$

$$= \frac{0.366}{2.71} = 0.168$$

$$NA = sin\theta_a = \frac{P}{H} = \frac{r}{\sqrt{r^2+Z^2}} = \frac{1.4}{\sqrt{1.4^2+8^2}} = 0.17$$

Acceptance angle (θ_a) = $sin^{-1}(0.23)$ = 17.96.

GRAPH -3



Graph shows the variation of current verses detector distance.

CONCLUSION

First of all we have put the detector distance fixed at 4mm then the values of numerical aperture are 0.33 and the angle of acceptance is 19.26. While we have put the detector distance fixed at 8mm then the values of numerical aperture and angle of acceptance changes i.e., numerical aperture is 0.17 and angle of acceptance is 17.21

So we concluded that as the numerical aperture shows the light collecting ability of the fiber thus its value must be high. As higher the value of NA, superior will be the optical fiber

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