The Higher Institute of Telecommunication and Navigation

Transmission Department

# Introduction to Fiber Optics
# TR_165


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# Introduction

The field of fiber optics communication has exploded over the past two decades. Two instructors from the higher institute of Telecommunication and Navigation, Transmission department, have prepared this booklet very carefully. This booklet will guide you through the foundation of fiber optic. Moreover, this booklet will cover main parts such as, a brief history of fiber optics, basics of lights in fiber optics, reflection and snell's law, fiber optics structure, classification of fiber optics, losses in fiber optics and the future of fiber optics respectively.

Nevertheless, reading this booklet will put fiber optics and communications into context and how they go together

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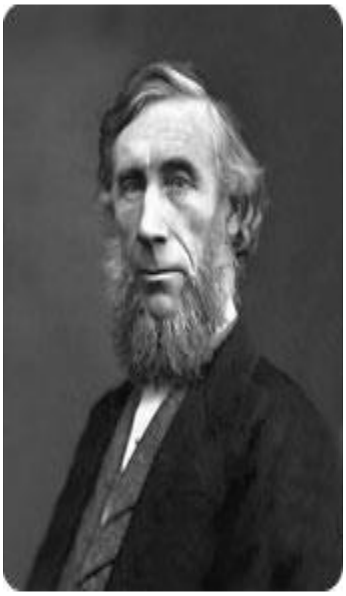
# Chapter 1: Introduction to Communication & Fiber Optics

## 1.0 Fiber Optics History


John Tyndall

In the 1840s, physicists Daniel Collodon and Jacques Babinet presented that light could be focused along jets of water for displays. In 1854, John Tyndall, a British physicist, demonstrated that light could travel through a curved stream of water thereby proving that a light signal could be bent. He proved this by setting up a tank of water with a pipe that ran out of one side. As water flowed from the pipe, he shone a light into the tank into the stream of water. As the water fell, an arc of light followed the water down.

Alexander Graham Bell untested an optical telephone system called the photophone in 1880. His earlier invention, the telephone, proved to be more realistic however. That same year, William wheeler invented a system of light pipes linedwith a highly reflective coating that illuminated homes by using light from an electric arc lamp placed in the basement and directing the light around the home with the pipes.

Doctors Roth and Reuss, of Vienna, used bent glass rods to illuminate body cavities in 1888. French engineer Henry Saint-Rene designed a system of bent glass rods for guiding light images seven years later in an early attempt at television. In 1898, American David Smith applied for a patent on a dental illuminator using a curved glass rod.

In the 1920s, John Logie Baird patented the idea of using arrays of transparent rods to transmit images for television and Clarence W. Hansell did the same for facsimiles. Heinrich Lamm, however, was the first person to transmit an image through a bundle of optical fibers in 1930. It was an image of a light bulb filament. His intent was to look inside inaccessible parts of the body, but the rise of the Nazis forced Lamm, a Jew, to move to America and abandon his dream of becoming a professor of medicine. His effort to file a patent was denied because of Hansell's British patent.

In 1951, Holger Moeller applied for a Danish patent on fiber-optic imaging in which he proposed cladding glass or plastic fibers with a transparent low-index material, but was denied because of Baird and Hansell's patents. Three years later, Abraham Van Heel and Harold H. Hopkins presented imaging bundles in the British journal *Nature* at separate times. Van Heel later produced a cladded fiber system that greatly reduced signal interference and crosstalk between fibers.

Also in 1954, the "maser" was developed by Charles Townes and his colleagues at Columbia University. Maser stands for "microwave amplification by stimulated emission of radiation."

The laser was introduced in 1958 as a efficient source of light. The concept was introduced by Charles Townes and Arthur Schawlow to show that masers could be made to operate in optical and infrared regions. Basically, light is reflected back and forth in an energized medium to generate amplified light as opposed to excited molecules of gas amplified to generate radio waves, as is the case with the maser. Laser stands for "light amplification by stimulated emission of radiation."

In 1960, the first continuously operating helium-neon gas laser is invented and tested. That same year an operable laser was invented which used a synthetic pink ruby crystal as the medium and produced a pulse of light.

In 1961, Elias Snitzer of American Optical published a theoretical description of single mode fibers whose core would be so small it could carry light with only one wave-guide mode. Snitzer was able to demonstrate a laser directed through a thin glass fiber which was sufficient for medical applications, but for communication applications the light loss became too great.

Charles Kao and George Hockham, of Standard Communications Laboratories in England, published a paper in 1964 demonstrating, theoretically, that light loss in existing glass fibers could be decreased dramatically by removing impurities.

## 2.0 Basic of Communications

### 2.1 Definition of Communication:

"Communication" can be defined as the exchange of information of any kind by any means from one location to another location. For example, telephone lines or computers.

Below is a map of communication that can indicate how communicating with others work:

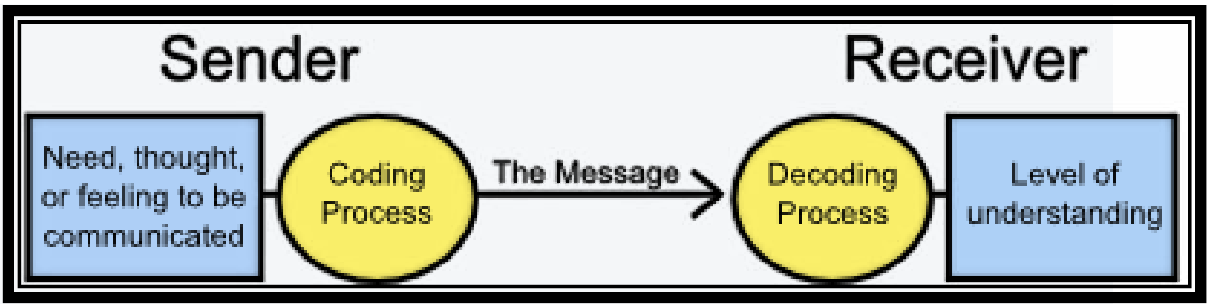



**Figure 1 : Communication between the send and the receiver**

The main components are a sender, receiver and a message over a channel. Each component has an added step of either coding or decoding a message. For example:

Coding messages can be either speech or writing or passing the message through the body language. The receiver then understands (decodes) the words hoping to arrive at an understanding of what the sender really means.

**Figure 2: Examples of Communications**

### 2.2 Communication system:

Communication system can be defined as the system that is involved to achieve the goal of information exchange

<u>For example:</u>

- Using a network to exchange voice signal between two phones
- Communication between a workstation and a server over a telephone network

### 2.3 Telecommunication:

Tele" is a Greek word means "Far" and "Communication" means exchange of information of any kind by any means from one location to another location. Thus, combination of Tele and Communication, which is an exchange of information between distant points.

In other word and to be specific, the study of telephones and the systems that transmits and receives telephone signal is called telecommunication.

Telecommunication includes telephony, telegraphy, satellite communication, optical fiber communication, radar communication etc.

## 2.4 Data Communication

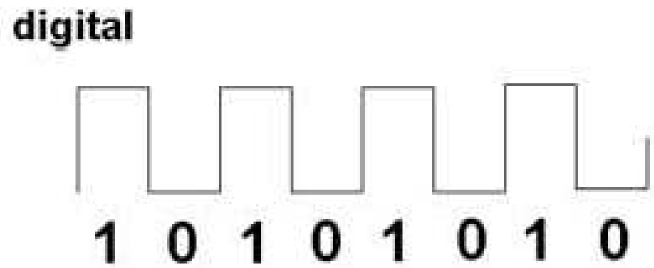
The word Data means information presented in whatever form is agreed upon by the individuals creating and using the data.

So, Data communication is the transfer of digital or analog data using digital or analog signals over some form of network.

### 2.4.1 Analog and Digital signals

Analog technologies defined as the information that is translated into electric pulses of varying amplitude. Whereas, in digital technology, translation of information is into binary format (zero or one) where each bit is representative of two distinct amplitudes


Analog signal represented as a sine




Digital signal with binary

**Figure 3: Differences between Analog & Digital Signals**

## 3.0 Introduction to Fiber Optics and Lights

For many years' fiber optics grew steadily with new technology creating new applications, in turn, supplying money to develop more new technology. Nonetheless, the growth sped out of control in the late 1990s as the Internet fed a seemingly limitless thirst for bandwidth that only optical fibers could provide.

However, fiber optics did not begin as a communications technology. Optical fibers evolved from devices developed to guide light for illumination or displays and were first used to look inside the human body. Bundles of optical fibers are still used to examine the stomach and the colon because they can reach into otherwise inaccessible areas.

Think of optical fibers as pipes that carry light most from glass or plastic. Lenses can bend light and mirrors can deflect it, but otherwise light travels in straight lines.

Most are roughly the diameter of a human hair, and they may be many miles long. Light is transmitted along the center of the fiber from one end to the other, and a signal may be imposed. Fiber optic systems are superior to metallic conductors in many applications. Their greatest advantage is bandwidth. Because of the wavelength of light, it is possible to transmit a signal that contains considerably more information than is possible with a metallic conductor – even a coaxial conductor.

### 3.1 Components of communication in Fiber Optics:

- Transmitter: Produces and encodes the light signals
- Optical fiber: Conducts the light signals over a distance

- Optical regenerator: May be necessary to boost the light signal (for long distances)
- Optical receiver: Receives and decodes the light signals

### 3.1.1 Transmitter

The **transmitter** receives and directs the optical device to turn the light "on" and "off" in the correct sequence. Hence, generating a light signal.

The transmitter is physically close to the optical fiber and may even have a lens to focus the light into the fiber. Lasers have more power than LEDs, but vary more with changes in temperature and are more expensive. The most common wavelengths of light signals are 850 nm, 1,300 nm, and 1,550 nm.

### 3.1.2 Optical Regenerator

Some signal loss occurs when the light is transmitted through the fiber, especially over long distances (more than a half mile, or about 1 km) such as with undersea cables. Therefore, one or more optical regenerators is spliced along the cable to boost the degraded light signals.

An optical regenerator consists of optical fibers with a special coating (doping). The doped portion is "pumped" with a laser. Moreover, when the degraded signal comes into the doped coating, the energy from the laser allows the doped molecules to become lasers themselves. The doped molecules then emit a new, stronger light signal with the same characteristics as the incoming weak light signal. Thus, the regenerator is a laser amplifier for the incoming signal.

### 3.1.3 Optical Receiver

It takes the incoming digital light signals, decodes them and sends the electrical signal to the other users. For example, computer, TV or telephone (receiving ship's captain). In addition, the receiver uses a photocell or photodiode to detect the light.

## 3.2 Main advantages of Fiber Optics include:

1. Electrical Isolation – Fiber optics do not need a grounding connection. Both the transmitter and the receiver are isolated from each other and are therefore free of ground loop problems. Also, there is no danger of sparks or electrical shock.

2. Freedom from EMI – Fiber optics are immune to electromagnetic interference (EMI), and they emit no radiation themselves to cause other interference.

3. Low Power Loss – This permits longer cable runs and fewer repeater amplifiers.

4. Less signal degradation - The loss of signal in optical fiber is less than in copper wire

5. Lighter and Smaller – Fiber weighs less and needs less space than metallic conductors with equivalent signal-carrying capacity.

6. Copper wire is about 13 times heavier. Fiber also is easier to install and requires less duct space.

7. Less expensive - Several miles of optical cable can be made cheaper than equivalent lengths of copper wire.

8. Light signals - light signals from one fiber do not interfere with those of other fibers in the same cable. Thus, clearer phone conversations or TV reception.

9. Flexible - Because fiber optics are so flexible and can transmit and receive light, they are used in many flexible digital cameras

Because of these advantages, you see fiber optics in many industries, most notably telecommunications and computer networks. For example, if you telephone Europe from Kuwait (or vice versa) and the signal is bounced off a communications satellite, you often hear an echo on the line. But with transatlantic fiber-optic cables, you have a direct connection with no echoes.

### 3.3 Fiber Optic Applications

Some of the major application areas of optical fibers are:

1. Communications – Voice, data and video transmission are the most common uses of fiber optics, and these include:
- Telecommunications
- Local area networks (LANs)
- Industrial control systems
- Avionic systems
- Military command, control and communications systems

2. Sensing – Fiber optics can be used to deliver light from a remote source to a detector to obtain pressure, temperature or spectral information. The fiber also can be used directly as a transducer to measure a number of environmental effects, such as strain, pressure, electrical resistance and pH. Environmental changes affect the light intensity, phase and/or polarization in ways that can be detected at the other end of the fiber.

3. Power Delivery – Optical fibers can deliver remarkably high levels of power for tasks such as laser cutting, welding, marking and drilling.

4. Illumination – A bundle of fibers gathered together with a light source at one end can illuminate areas that are difficult to reach – for example, inside the human body, in conjunction with an endoscope. In addition, they can be used as a display sign or simply as decorative illumination.

## Question to think about for Chapter 1:

Question 1: Put the correct answer with ( √ ) and wrong answer with ( X ) for the following:

1. Telephony and satellite are an example of telecommunication (  )
2. Data communication transfers only analog signals (  )
3. Fiber optics was first created to look inside the human body ( )
4. Light travels in straight lines ( )
5. Copper cables are weighs less and need less space ( )
6. Fiber optics can be used to deliver light from a remote source to a detector ( )

Question 2: Answer the following questions:

1. Who invested the telephone? What year?

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2. Who invested fiber optics? What year?

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3. What is the meaning of communication?

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4. What are the components of communication?

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5. What is meant by communication system?

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6. What is meant by telecommunication?

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7. What is data communication?

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8. Draw below the difference between analog and digital:

| | |
|---|---|
| | |
| Analog | Digital |

9. What is the difference between analog and digital?

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10. What are the components of fiber optics?

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11. What are the main advantages of using fiber optics?

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12. Where are fiber optics used?

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# Chapter 2: Light in Fiber Optics

# 4.0 Light in Fiber Optics

The light propagates along the fiber by the process of total internal reflection. In addition, the light is contained within the glass core and cladding by careful design of their refractive indices. The core material has a refractive index of **n1**, and the cladding has a refractive index of **n2**. The core has a higher refractive index than the cladding, which results in total internal reflection.

In this section, we shall mainly deal around the ray model of light and explain the propagation of light in an optical fiber treating light as a ray.

## 4.1 Light in space

In space light propagates with velocity **c =3x10$^8$ m/s**. In a transparent medium, the speed of light is affected by a factor **n**, the refractive index of the medium.

Refractive index of any medium formula:

$$n = \frac{\text{Speed of Light in Free Space}}{\text{Speed of Light in the Medium}}$$

Nonetheless, an optical fibers designed as a solid cylindrical glass rod called the core, through which light in the form of optical signals propagates. However, this rod is surrounded by another coaxial cylindrical shell made of glass of lower refractive index called the cladding. Thus, guides light over long distances.

By multiple total internal reflections at the core-cladding interface the light propagates throughout the fiber over very long distances with low attenuation.

For light to be guided in the core, it must be launched in the fiber from outside.

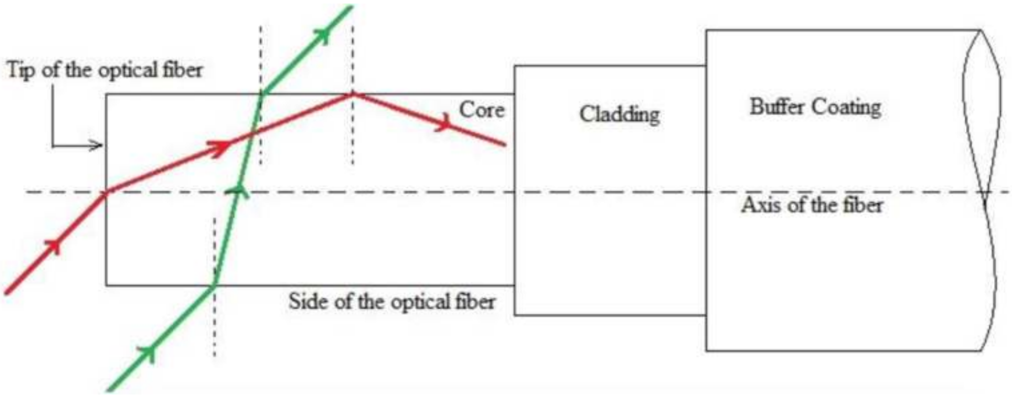



**Figure 4: Launching of light into an Optical Fiber**

The light energy in the form of optical signals propagates inside the core-cladding arrangement and throughout the length of the fiber by the Total Internal Reflection (TIR) of light indicated in Figure …... Moreover, this occurs only when the refractive index of core is greater than the refractive index of cladding and so the cladding is made from glass of lower refractive index.

## 5.0 Law of Reflection and Snell's Law

Snell's law is one of the key theories behind the propagation of light along a fiber. Snell's law is applied to any changes in light direction as it travels from a medium of one refractive index to another medium that has a different refractive index. Keeping in mind, refractive index is the factor by which light changes speed. In addition, law of reflection occurs when light bounces back in the same medium. Whereas, refraction occurs when light changes speed as it travels in the second medium and is bent or refracted.

### 5.1 Snell's law

Snells law states that a relationship exists between the refractive indices of the two media, n1 and n2 and the angle of incidence and refraction. This relationship is expressed in the formula below:

$$\mathbf{n_1 \sin\theta_1 = n_2 \sin\theta_2} \quad \textbf{(Snell's Law)}$$

#### 5.1.1 Law of Refraction

A ray of light changes direction when it passes from one medium to another. The change in direction of the light ray depends on how the speed of light changes.

The change in the speed of light is related to the indices of refraction of the media involved. In mediums that have a greater index of refraction the speed of light is less. Imagine moving your hand through the air and then moving it through a body of water. It is more difficult to move your hand through the water, and thus your hand slows down if you are applying the same amount of force. Similarly, light travels slower when moving through mediums that have higher indices of refraction.

The amount that a light ray changes its direction depends both on the incident angle and the amount that the speed changes. For a ray at a given incident angle, a large change in speed causes a large change in direction and thus a large change in angle.

The below figure illustrate a situation of a typical refraction taking place at the interface of two different medium having refractive indices n1 and n2:

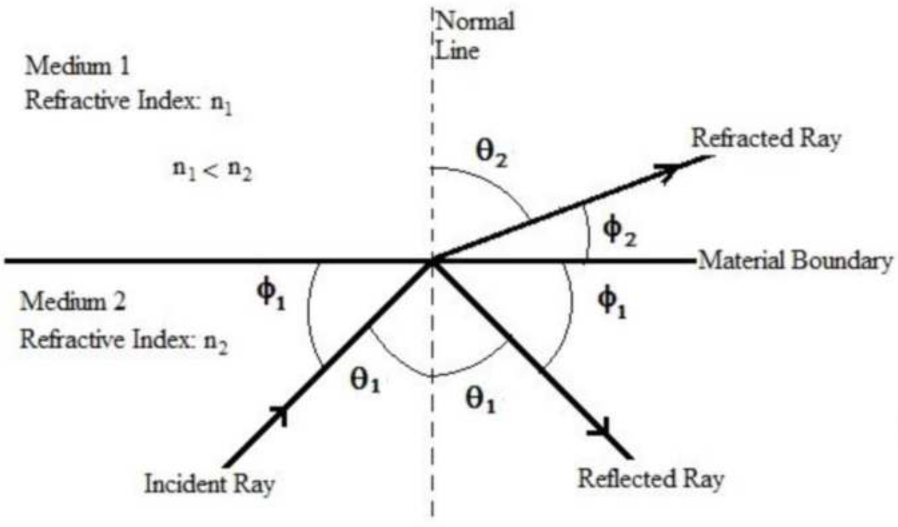



**Figure 5: Refraction at two different medium**

Angles measured in the expression for Snell's law are measured with respect to the normal to the media interface at the point of incidence. Here are some important point for Figure …. :

1. If n2 > n1, then the angle of refraction is greater than the angle of incidence and the refracted ray is said to have moved away from the normal.
2. If the angle of incidence (θ1) is increased further, the angle of refraction (θ2) also increases in accordance with the Snell's law.
3. at a particular angle of incidence the angle of refraction becomes 90° and the refracted ray grazes along the media interface. This angle of incidence is called the critical angle of incidence (θc) of medium 2 with respect to medium 1.

#### 4.2.1 Critical angle

The critical angle is defined as the angle of incidence that provides an angle of refraction of 90°.

it is the largest angle of incidence for which refraction can still occur. For any angle of incidence greater than the critical angle, light will undergo total internal reflection. Hence, to make light travel down a fiber, the angle of incidence has to be greater than the critical angle.

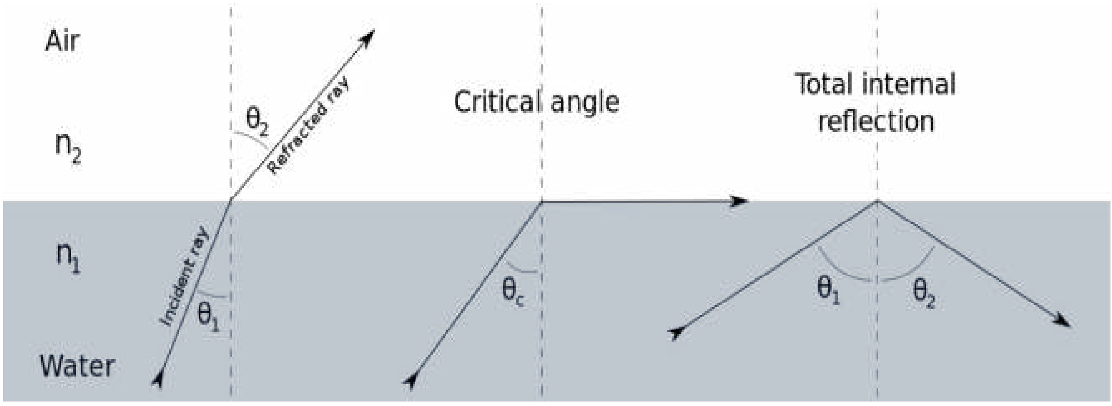



**Figure 6: Indicates how the critical angle is occurred**

<u>For example:</u>

Consider two mediums with refractive indices of n1 and n2 (n2<n1) and angle of incidence θ1, angle of refraction θ2, and critical angle θc. The value of sin θ2 is equal to 1, as value of θ2 is equal to 90°. Re-arranging Snell's law equation.

<u>The equation for critical angle is:</u>

$$\theta_c = sin^{-1}\frac{n_{cladding}}{n_{core}}$$

For any angle of incidence larger than the critical angle, Snell's law will not be able to be solved for the angle of refraction, because it will show that the refracted angle has a sine larger than 1, which is not possible. In that case all the light is totally reflected off the interface, obeying the law of reflection.

In optical fiber:

However, the light in optical fiber will hit the wall at an angle higher than the critical angle and will all be reflected back into the fiber. Even though the light undergoes a large number of reflections when traveling along a fiber, no light is lost.

**4.2.2 Acceptance Angle:**

Acceptance angle is defined as the greatest possible angle at which light can be launched into the core and still be guided through total internal reflection.

It can be derived by using the law of refraction, which is:

$$\theta_a = sin^{-1}(NA)$$

Here, $n_{core}$ and $n_{cladding}$ are the refractive indices of core and cladding, respectively, and $n_0$ is the refractive index of the medium around the fiber, which is close to 1 in case of air.

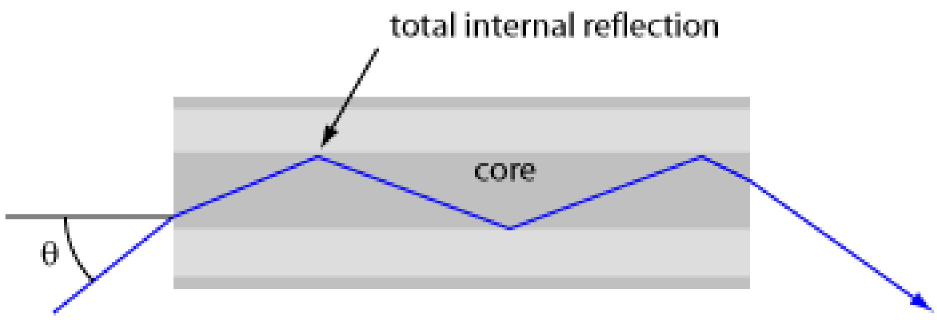



**Figure 7: Internal Reflection inside the Fiber Optics**

Figure 7 indicates an incident light ray is first refracted and then undergoes total internal reflection at the core–cladding interface. However, that works only if the incidence angle is not too large.

However, the acceptance angle gives at least some estimate concerning how large an incidence angle may be for efficiently launching light.

#### 4.2.3 Numerical aperture (NA)

Numerical aperture is defined as the sine of the acceptance angle of optical fiber. Which can be described as the light gathering ability of an optical fiber.

Nonetheless, the larger the NA, the greater the amount of light that can be accepted into the fiber. Hence, the greater the transmission distance that can be achieved. The NA value is always less than 1.

<u>The equation of Numerical Aperture:</u>

$$NA = \sqrt{{n_{core}}^2 - {n_{cladding}}^2}$$

By knowing both the critical angle and the acceptance angle for the fiber optics cable, we can figure out how the light will propagate along the fiber cable, as follows:

1. If the light angle (θ) is bigger than the critical angle ($\theta_c$), the light will be totally reflected out the fiber and it will be total loss.
2. If the light angle (θ) is smaller or within the critical angle ($\theta_c$), then the light will inter/propagate into the fiber. Depending on the fiber acceptance angle ($\theta_a$), it will determine the light propagation through the fiber as follows:

- If the light angle ($\theta$) is bigger than the acceptance angle of the fiber cable, then the light will propagate through the core with some loss through the cladding. Which results of partial loss into the cladding.
- If the light angle ($\theta$) is smaller or within the acceptance angle ($\theta_a$), then the light will propagate through the core without any loss.

This can be shown and understood by the following example:

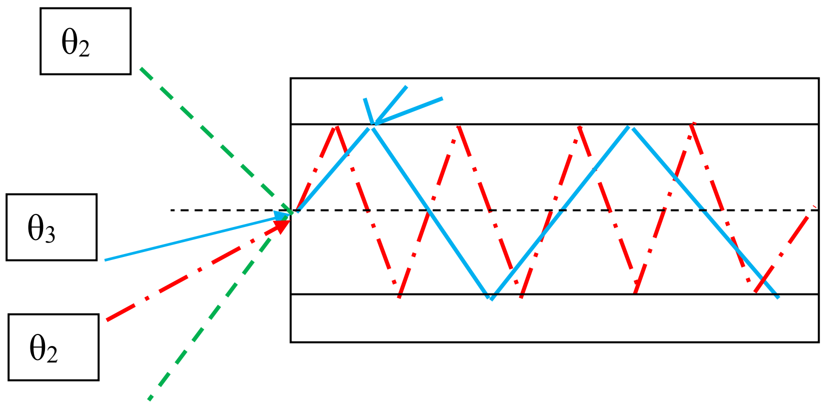
Fiber critical angle ($\theta_c$) = 45°, fiber acceptance angle ($\theta_a$) = 28°

And showing three cases of light angle as follows:

1- $\theta_1 = 12^o$

2- $\theta_2 = 50^o$

3- $\theta_3 = 25^o$




**<u>Example:</u>**

A fiber optics cable has **core** refractive index of 1.5, and **cladding** refractive index of 1.47. Find [(a)] the Critical angle ($\theta_c$), [(b)] the Numerical aperture (NA), and [(c)] the Acceptance angle ($\theta_a$)?

**Solution:**

a) $\theta_c = sin^{-1} \frac{n_{cladding}}{n_{core}}$

$= sin^{-1} \frac{1.47}{1.5}$

$= sin^{-1}(0.513)$

$\theta_c$ = 78.52°

b) $NA = \sqrt{{n_{core}}^2 - {n_{cladding}}^2}$

$= \sqrt{(1.5)^2 - (1.47)^2}$

= 0.298

c) $\theta_a = sin^{-1}(NA)$

$= sin^{-1}(0.298)$

$\theta_a$ = 17.36°

5.2 The law of reflection:

Total internal reflection happens when a propagating wave strikes a medium surface at an angle larger than a particular critical angle with respect to the normal to the surface. See figure below:

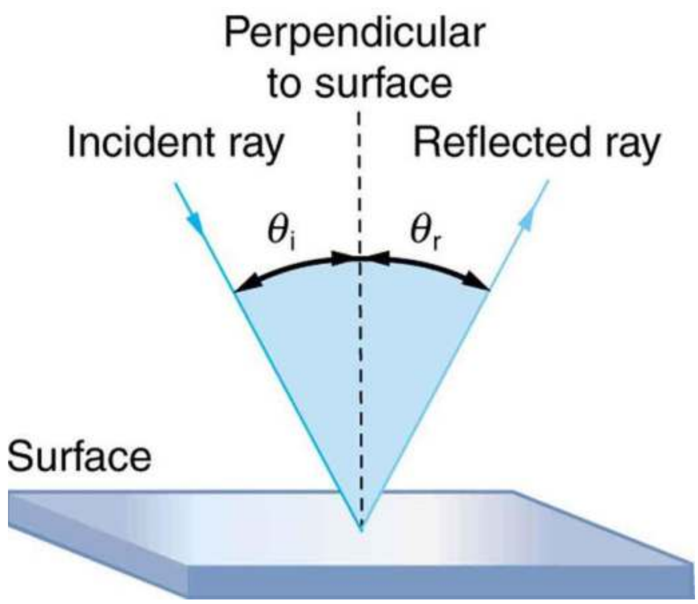



**Figure 8: The angle of reflection equals the angle of incidence: θr = θi**

<u>Law of reflection:</u>

Angle of Incidence = Angle of Reflection

The law of reflection is very simple: The angle of reflection equals the angle of incidence. When we see our reflection in a mirror, it appears that our image is actually behind the mirror — we see the light coming from a direction determined by the law of reflection. The angles are such that our image appears exactly the same distance behind the mirror as we stand away from the mirror. . Hence, the only way we can see an object that does not itself emit light is if that object reflects light.

## Question to think about for Chapter 2:

1. Why does light change direction when passing from one material ( medium ) to another?

   …………………………………………………………………………

   …………………………………………………………………………

2. A fiber optics cable has **core** refractive index of 1.8, and **cladding** refractive index of 1.67. Find:
   a. the Critical angle ($\theta_c$)
   b. the Numerical aperture (NA)
   c. the Acceptance angle ($\theta_a$)

# Chapter 3: Classification of Fiber Optics

## 6.0 Fiber Optics Structure

Optical fiber cable is composed of several elements. The construction of a fiber optic cable consists of a core, cladding, coating buffer, strength member and outer jacket. The optical core is the light-carrying element at the center. The core is usually made up of a combination of silica and Germania. Figure-1 show the fiber optic cable structure.

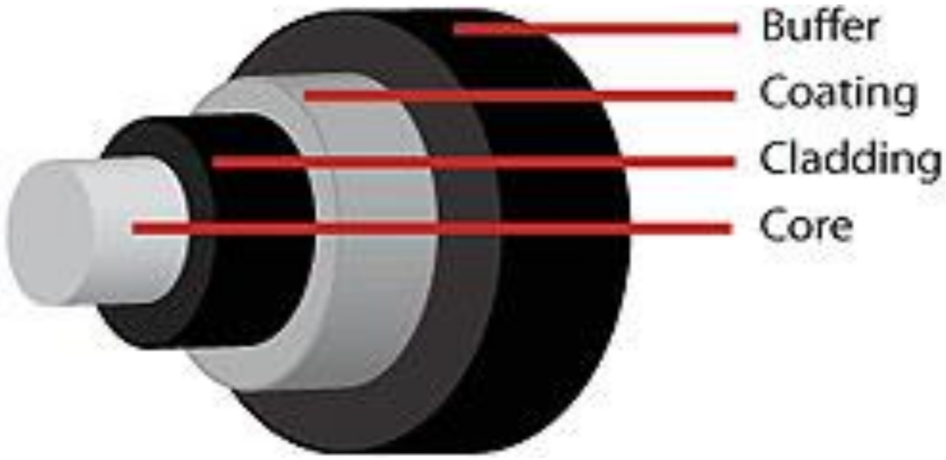



**Figure 9: Fiber Optics cable construction**

The cladding surrounding the core is made of pure silica. The cladding has a slightly lower index of refraction than the core. The lower refractive index causes the light off cladding and stay within the core. the refractive index of core and cladding is not equal, the relationship between both that always the core has bigger refractive index than the cladding for a scientific aim, to be discussed later in this book.

The core and cladding are usually made of ultra-pure glass. The fiber is coated with a protective plastic covering called the “primary buffer coating” that protects it from moisture and other damage. More protection is provided by the “cable” which has the fibers and strength members inside an outer covering called a “jacket”.

Each material or medium that could propagates light has it's unique or specific refraction index. The lowest refraction index (n) in all materials is 1, and it is related to the vacuum air. All other mediums that accept light to propagate through will be as higher as n = 1, depending on the material or medium itself.

The Refraction Index is the ratio of the velocity of light in a vacuum to the velocity of light in a material. And it can be calculated by the knowing the speed of light in vacuum and the velocity of light in the medium, using the following formula:

$$n = \frac{c}{v}$$

Accordingly, the velocity of light in fiber optic cable or material could be calculated as following formula:

$$v = \frac{c}{n}$$

The speed of light in a vacuum is equal to 300,000,000 ($300\times10^8$) meter per second. The speed of light in a material depends on the value of refractive index. The higher the index of refraction, the slower the speed of light through the material.

## 7.0 Classification of Fiber Optics

In general, fiber optic cable can be classified in different ways, according to the following:

1- Material.

2- Size or Mode.

3- Refractive Index.

### 7.1 Fiber Optics Classification by Material:

A fiber optic cable is made from a glass or plastic core that carries light surrounded by glass cladding that (due to its lower refractive index) reflects "escaping" light back into the core, resulting in the light being guided along the fiber.

From this point of view, we can classify fiber optic cable into three major categories, such as:

1. Glass fiber: Both the core and the cladding are made of glass. This type of fiber is widely used for long distance links and communications.

2. Plastic fiber: This type of fiber will have both the core and glass are made of plastic. This type is mostly used of short distance links communications.

3. Plastic-clad Silica (PCS): In this type of fiber, the core is made of glass, and the cladding is made of plastic.

### 7.2 Fiber Optics Classification by Size or Mode:

According to the core diameter of the fiber optic cable, we can classify fiber into two types:

#### 7.2.1 Single Mode Fiber

This type of fiber has core diameter ranged from 8-10 microns. The single mode fiber that usually glass is very narrow diameter has one mode of transmission. Meaning of which only one mode will propagate through 1310 nm and 1550 nm propagation windows, carries higher bandwidth than multi-mode fiber but a light source with a narrow spectral width. Single mode fiber presents a very high transmission rate (speed) that reaches up to 50 times more distance than multi-mode fiber. But it also cost more. Single-mode fiber has a much smaller core than multimode. The small core and single light-wave virtually eliminate any distortion that could result from overlapping light pulses, providing the least signal attenuation and the highest transmission speeds of any fiber cable type.

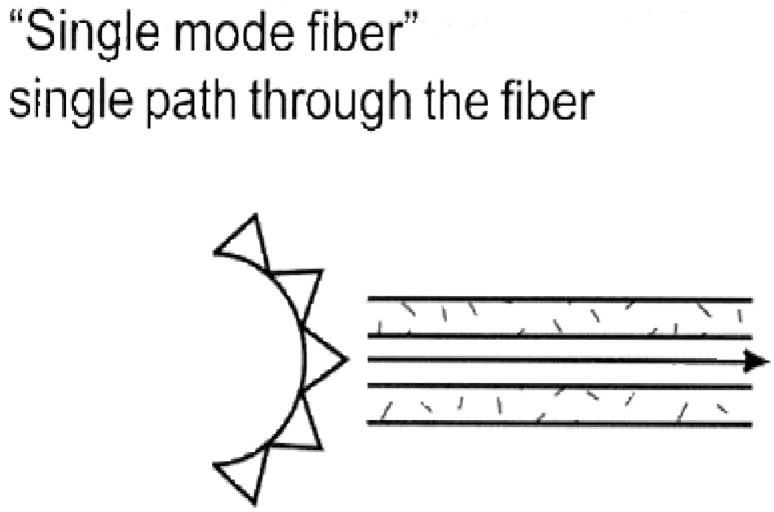



**Figure 10: Single mode fiber path.**

#### 7.2.2 Multi-Mode Fiber

This type of fiber comes in different core diameter sizes which bigger than single mode core diameter. It has different core diameters, which are 50, 62.5, and 100 microns. Multi-mode fiber presents lower speed than single mode fiber in shorter distance. And has lower cost. Light waves are dispersed into numerous paths, or modes, as they travel through the cable's core typically 850 or 1300 nm transmission windows.

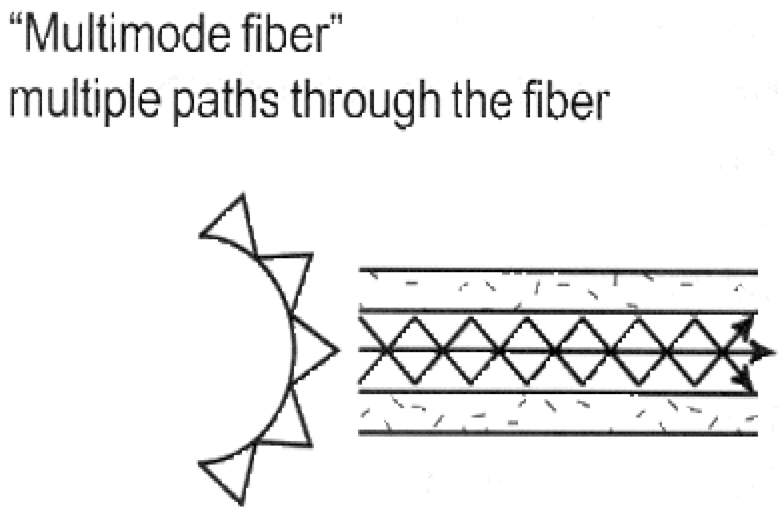



**Figure 11: Multi-mode fiber path.**

**Single mode Vs. Multi-mode Fiber:**

Single mode means the fiber enables one type of light mode to be propagated at a time. While multimode means the fiber can propagate multiple modes (2-10,000 mode). The difference between single mode and multimode fiber mainly lies in fiber core diameter, wavelength, light source and bandwidth.

1. <u>Core Diameter</u>

Single mode fiber core diameter is much smaller than multimode fiber. The typical core diameter is 9µm even if there are others available. And multimode fiber core diameter is 50µm and 62.5µm typically, which enables it has higher "light gathering" ability and simplify connections. The cladding diameter of single mode and multimode fiber is 125µm.

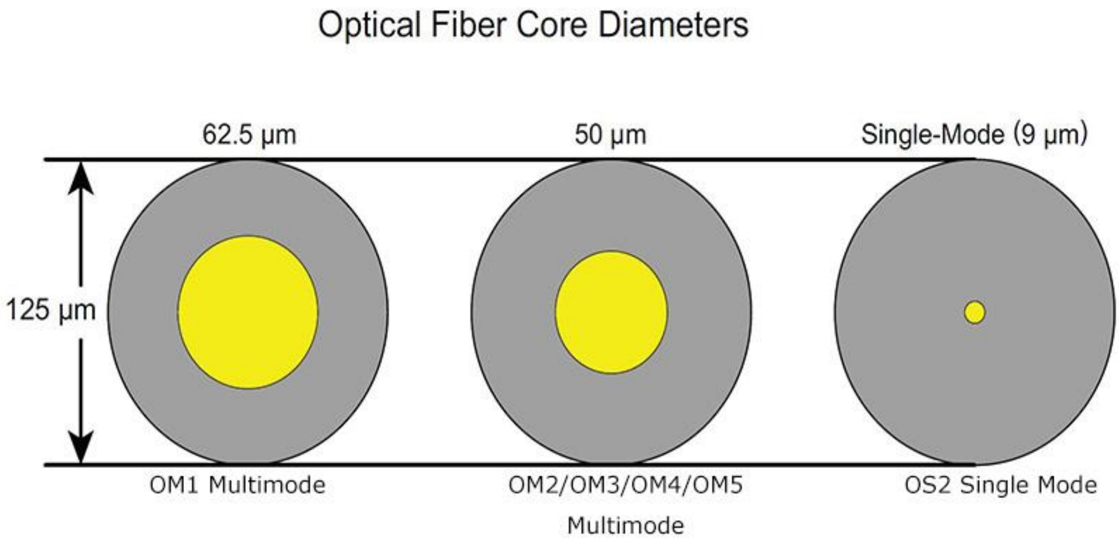



**Figure 12: Optical Fiber core diameter.**

2. Wavelength & Light Source

Due to the large core size if multimode fiber, some low-cost light sources like LEDs (light-emitting diodes) and VCSELs (vertical cavity surface-emitting lasers) that works at the 850 nm and 1310 nm wavelength are used in multimode fiber cables. While the single mode often uses a laser or laser diodes to produce light injected into the cable. And the commonly used single mode fiber wavelength is 1310 nm and 1550 nm.

3. Bandwidth

Since single mode fiber has less modal dispersion than multimode fiber, SM fiber has a higher bandwidth than multimode fiber.

## 7.3 Fiber Optics Classification by Refractive Index:

This describes the relationship between the refractive index of core and refractive index of cladding. There are two main relationships, which are step index fiber and graded index fiber.

### 7.3.1 Step Index

As known, the core refractive index ($n_1$) is made slightly bigger amount than the cladding refractive index ($n_2$) in all types of fiber. This is because the refractive index profile for this type of fiber makes a step change at the core–cladding interface, as indicated in Figure-5, which illustrates the two major types of step index fiber.

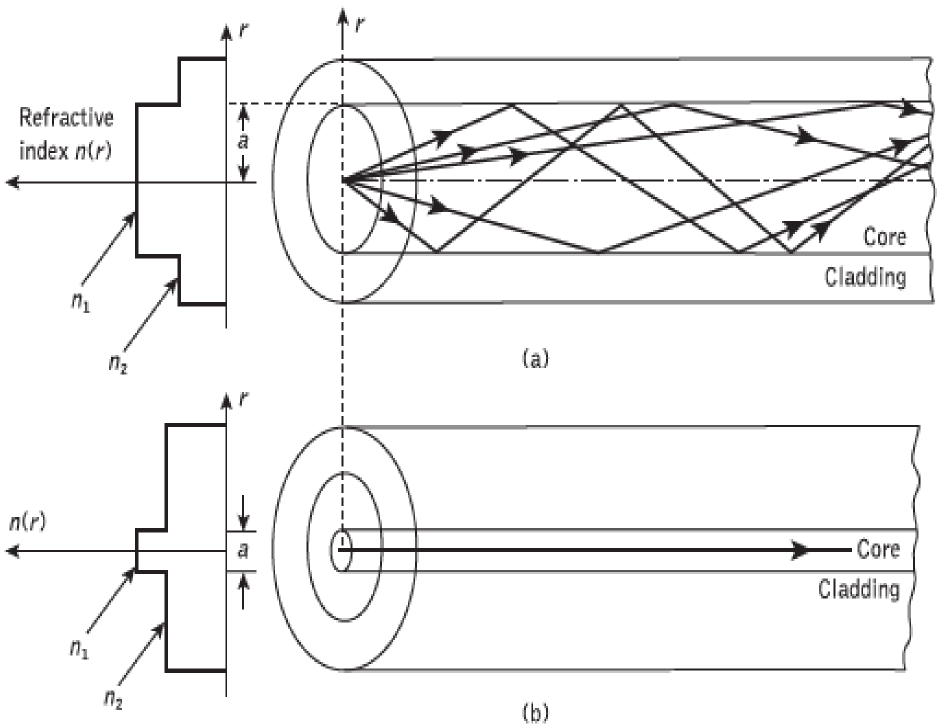



**Figure 13: refractive index profile and ray transmission in step index fibers: (a) multimode step index fiber; (b) single-mode step index fiber**

Figure 13 (a) shows a multimode step index fiber with a core diameter of around 50 µm or greater, which is large enough to allow the propagation of many modes within the fiber core. This is illustrated in Figure 11(a) by the many different possible ray paths through the fiber. Figure 10 (b) shows a single-mode step index fiber which allows the propagation of only one transverse electromagnetic mode (typically HE11), and hence the core diameter must be of the order of 2 to 10 μm. The propagation of a single mode is illustrated in Figure 10 (b) as corresponding to a single ray path only (usually shown as the axial ray) through the fiber.

The single-mode step index fiber has the distinct advantage of low intermodal dispersion (broadening of transmitted light pulses), as only one mode is transmitted, whereas with multimode step index fiber considerable dispersion may occur due to the differing group velocities of the propagating modes (see Section 3.10). This in turn restricts the maximum bandwidth attainable with multimode step index fibers, especially when compared with single-mode fibers. However, for lower bandwidth applications multimode fibers have several advantages over single-mode fibers. These are:

(a) the use of spatially incoherent optical sources (e.g. most light-emitting diodes) which cannot be efficiently coupled to single-mode fibers.

(b) larger numerical apertures, as well as core diameters, facilitating easier coupling to optical sources.

(c) lower tolerance requirements on fiber connectors.

Multimode step index fibers allow the propagation of a finite number of guided modes along the channel. The number of guided modes is dependent upon the physical parameters (i.e. relative refractive index difference, core radius) of the fiber and the wavelengths of the transmitted light which are included in the normalized frequency $V$ for the fiber.

There is a cutoff value of normalized frequency ($V_c$) for guided modes below which they cannot exist. However, mode propagation does not entirely cease below cutoff. Modes may propagate as unguided or leaky modes which can travel considerable distances along the fiber. Nevertheless, it is the guided modes which are of paramount importance in optical fiber communications as these are confined to the fiber over its full length. It can be shown that the total number of guided modes or mode volume *(M*s) for a step index fiber is related to the *V* value for the fiber by the following formula:

$$Ms = \frac{V^2}{2}$$

which allows an estimate of the number of guided modes propagating in a multimode step index fiber.

#### 7.3.1 Graded Index

Graded index fibers do not have a constant refractive index in the core, but a decreasing core index $n(r)$ with radial distance from a maximum value of $n_1$ at the axis to a constant value $n_2$ beyond the core radius $a$ in the cladding. This type of core is called a non-uniform core, the index highest at the center and it gradually decreased until it matches the index of the cladding.

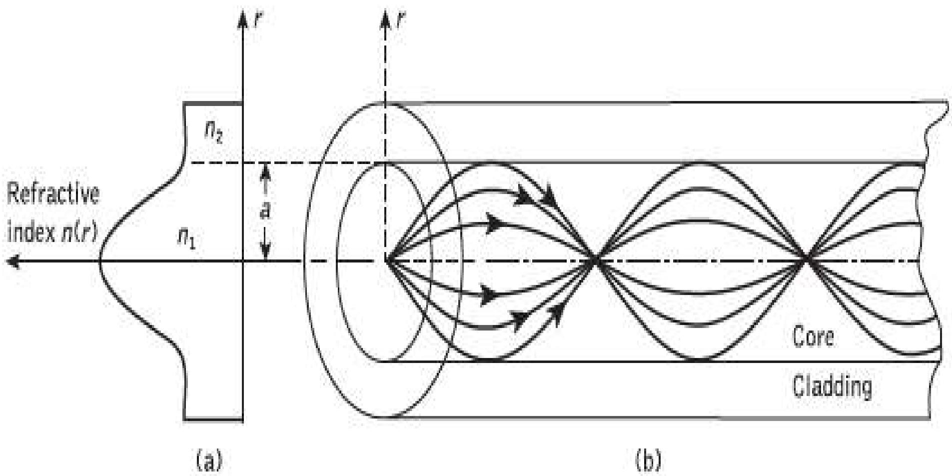



**Figure 14: The refractive index profile and ray transmission in a multimode graded Index fiber.**

A multimode graded index fiber with a parabolic index profile core is illustrated in Figure-6. It may be observed that the meridional rays shown appear to follow curved paths through the fiber core. Using the concepts of geometric optics, the gradual decrease in refractive index from the center of the core creates many refractions of the rays as they are effectively incident on a large number or high to low index interfaces. This mechanism is illustrated in Figure-7 where a ray is shown to be gradually curved, with an ever-increasing angle of incidence, until the conditions for total internal reflection are met, and the ray travels back towards the core axis, again being continuously refracted.

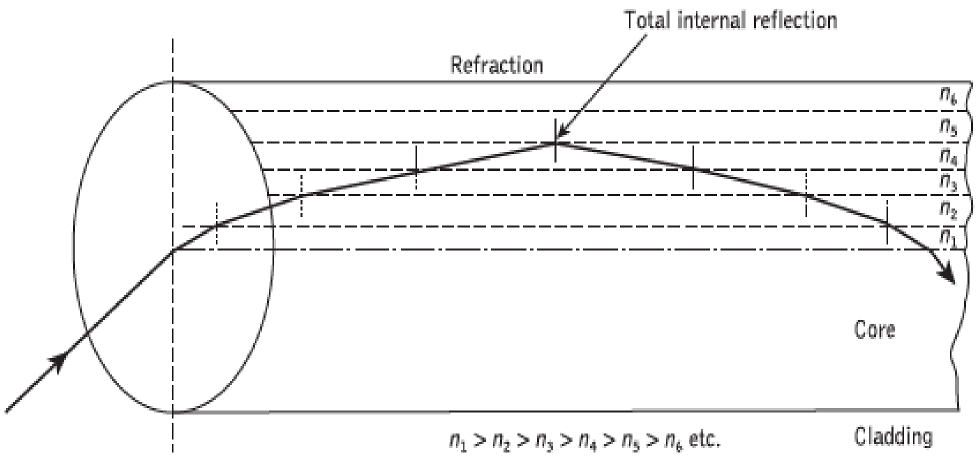



**Figure 15: An expanded ray diagram showing refraction at the various high to low index interfaces within a graded index fiber, giving an overall curved ray path.**

Multimode graded index fibers exhibit far less intermodal dispersion than multimode step index fibers due to their refractive index profile. Although many different modes are excited in the graded index fiber, the different group velocities of the modes tend to be normalized by the index grading. Again, considering ray theory, the rays traveling close to the fiber axis have shorter paths when compared with rays which travel into the outer regions of the core. However, the near axial rays are transmitted through a region of higher refractive index and therefore travel with a lower velocity than the more extreme rays. This compensates for the shorter path lengths and reduces dispersion in the fiber. A similar situation exists for skew rays which follow longer helical paths, as illustrated in Figure-7. These travel for the most part in the lower index region at greater speeds, thus giving the same mechanism of mode transit time equalization. Hence, multimode graded index fibers with parabolic or near-parabolic index profile cores have transmission bandwidths which may be orders of magnitude greater than multimode step index fiber bandwidths. Consequently, although they are not capable of the bandwidths attainable with single-mode fibers, such multimode graded index fibers have the advantage of large core diameters (greater than 30 μm) coupled with bandwidths suitable for long distance communication.

The total number of guided modes *(Ms)* in graded index fiber could be calculated by the following formula:

$$Ms = \frac{V^2}{4}$$

## Question to think about for Chapter 3:

1. How could fiber optics be classified in general?

   ...............................................................................................

   ...............................................................................................

2. Classify fiber according to material?

   ...............................................................................................

   ............................................................................................

3. Classify fiber according to size/mode?

   ...............................................................................................

   .............................................................................................

4. Classify fiber according to refractive index?

   ...............................................................................................

   ...............................................................................................

5. Show by drawing the fiber optics cable structure, name all details and parts.

6. Calculate the velocity of light in fiber cable that has refractive index of 1.33?

   ...............................................................................................

   ...............................................................................................

# Chapter 4: Decibels in Fiber Optics

## 8. Decibels in Fiber Optics Circuits

To understand the decibels as required for the field of fiber optics we must explain first the decibel as *logarithmic* unit. The word logarithm, as abbreviated to the friendlier *log*.

Look to this:

$10 \times 10 = 100$

We can use powers of ten to write this in another form:

$10^{2} = 100$

This is simple enough, and we can say 10 squared is equal to 100, or even 10 to the power of 2 is 100.

But how would we describe the number 2 in this situation?

It is called logarithm, or *log* of 100. It is the number to which 10 must be raised to equal 100.

As $10^2 = 100$ and the log of 100 is 2, and $10^3 = 1000$ and the log of 1000 is 3, it follows that the log of any number between 100 and 1000 must be between 2 and 3. We cannot work them out for ourselves, so we must use a calculator.

**For the log of 200**

On the calculator:

► press the log button

► enter 200

And the answer 2.301029996 appears. So, ignoring some of the decimal places, we can say that 2.301 is the log of 200 or $10^{2.301} = 200$.

To perform a multiplication like $100 \times 1000 = 100000$ we could add the logs of the numbers to be multiplied:

Log of 100 = 2

Log of 1000 = 3

Log of 100000 = 2+3 = 5 or 100 × 1000 = $10^5$

Similarly:

$$\frac{100000}{1000} = 100$$

Or, by subtracting logs:

5 – 3 = 2

Or:

$$\frac{100000}{1000} = 10^2$$

Summary:

► to multiply, add logs

► to divide, subtract logs

### 8.1 Use the decibels in Fiber Optics circuits

We use decibels to compare the power coming out of a circuit or part of a circuit to the power level at the input. So basically, it is an output power/input power compression. The decibel is a logarithmic unit and obeys the same rules as logs. The formula is:

The power gain in decibels = $10 \log \left(\frac{power_{out}}{power_{in}}\right) dB$

Note the abbreviation for decibels; small d, capital B, never put an s on the end. An amplifier has a higher output power than its input power, so it is said to have a power gain. This is the case in Figure-8a:

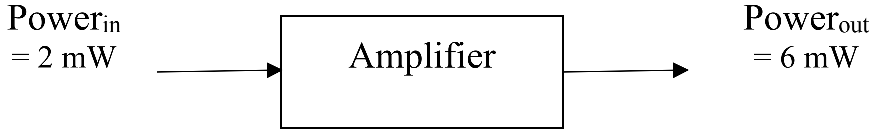



**Figure 16a: What is the gain in decibels?**

gain = $10 \log \left(\frac{power_{out}}{power_{in}}\right) dB$

insert the values:

gain = $10 \log \left(\frac{6\times10^{-3}}{2\times10^{-3}}\right) dB$

simply be dividing out the figures in the brackets. This gives:

gain = 10 log 3 dB

take the log of 3:

gain = 10 × 0.477 dB

simply by multiplying:

gain = +4.77 dB

so, this amplifier could be said to have a gain of 4.77 dB.

An attenuator, as shown if Figure-8b, has less output power than input power:

gain = $10 \log \left(\frac{power_{out}}{power_{in}}\right) dB$

keep the same formula for gains and losses. It makes life simpler. To prove it, we're just going to follow the same steps as in the last example.

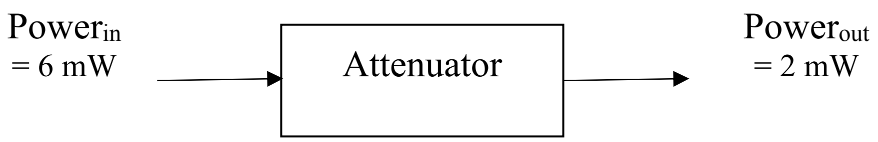



**Figure 16b: Find the loss in decibels.**

Insert the values:

Gain = $10 \log \left(\frac{2\times10^{-3}}{2\times10^{-3}}\right) \; dB$

Simply by solving out the contents of the brackets:

Gain = 10 log 0.03334 dB

Taking the log we get:

Gain = 10 × (-0.477) dB

Multiplying out we have:

Gain = -4.77 dB

The attenuator result was -4.77 dB. If we were to ask someone what the result was, they may will answer, the attenuator has a loss of 4.77 dB, or they mat reply, it has a gain of minus 4.77 dB.

In the first answer the fact that they mentioned "loss" will alert us to the fact that an attenuation or loss has occurred. In the second example, the minus sign serves the same purpose.

We must be very careful not to fall into the double negative trap. It is best to avoid saying that the system has an overall loss of -4.77 dB. The "loss" and the minus could leave the sentence open to differing interpretations.

To summarize

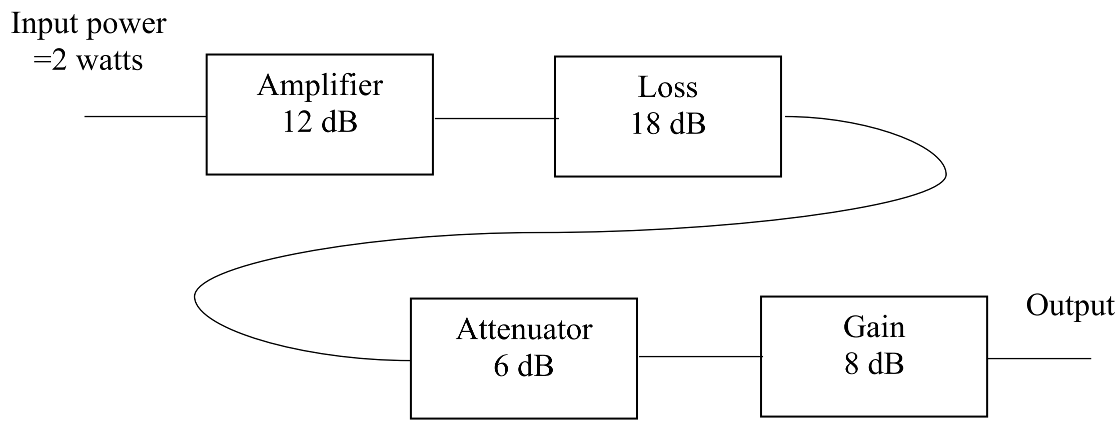
If the number of decibels is negative, the result is a loss of power or an attenuation. If the result is positive, it indicates a gain or an amplification:

- ► + = gain/amplification.
- ► - = loss/attenuation.

The big advantage in using decibels is when a circuit consists of several gains and losses as will happen n real in real situations.

### 8.2 Decibels in a real circuit

What is the output power of the circuit shown in Figure-9?




**What is the output power in decibels?**

1. Express each change of power level in decibels.

An amplifier with gain of 12 dB is represented by +12 dB

A loss of 16 dB is shown as -16 dB

An attenuator of 6 dB is shown as -6 dB

A gain of 8 dB is shown as +6 dB

Add all the decibels to give as overall result:

(+12) + (-16) + (-6) + (+8)        taking away the brackets

+12 – 16 – 6 + 8 = -2 dB

The result is an overall loss of 2 dB, so the circuit could be simplified to that shown in Figure-10.

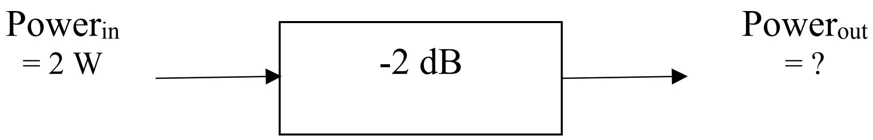



Figure-10: The simplified circuit

2. looking at the formula for decibels:

$$\text{Gain} = 10\log\left(\frac{power_{out}}{power_{in}}\right)\ dB$$

And knowing the result to be -2 dB and the input power to be 2 Watt, we can write:

$$-2 = 10\log\left(\frac{power_{out}}{2}\right)\ dB$$

In this formula we know everything except the power out, so we can transpose to find it.

It isn't obvious transportation, so we will work through it one step at a time.

3. Dividing both sides by 10 we have:

$$\frac{10}{2} = \log\left(\frac{power_{out}}{2}\right)\ dB$$

Or:

$$-0.2 = \log\left(\frac{power_{out}}{2}\right)\ dB$$

<u>4. To undo the effect of the "log" we must "antilog" it</u>

This is done by raising both sides to a power of 10.

On the right-hand side, this has the effect of removing the "log" from the equation as shown:

$$10^{-0.2} = \frac{power_{out}}{2}$$

<u>5. Simply the left-hand side:</u>

$$10^{-0.2} = 0.63$$

So:

$$0.63 = \frac{power_{out}}{2}$$

Calculator note: the left0hand side can be simplified by punching in -0.2 and hitting the $10^2$ or inv log button. The -0.2 is often entered as 0.2 followed by the -/+ key.

<u>6. Multiplying both sides by 2 gives:</u>

1.26 = power out

And since we have been working in watts the output power is 1.26 watts. Notice how we made life easy by simplifying the circuit to obtain a single overall figure in decibels before the conversion. Masochists, on the other hand, may enjoy the difficult approach of calculating the power out of the first amplifier in watts, then repeating the whole procedure to find out the power out of the next section and through the circuit.

A summary of converting decibels to a ratio of two powers

Method:

1. Divide both sides by 10.
2. Find the antilog of each side.
3. Transpose to find the wanted term.

### 8.3 Using a decibel as power level

The essential point about a decibel is that it is used to express the ratio between two powers.

In the formula:

$$\text{Gain} = 10\log\left(\frac{power_{out}}{power_{in}}\right)\ dB$$

We have two power levels mentioned, the output and the input power. If we wish to use decibels as a measurement of power, we have to get around the ratio problem by assuming a value for input power.

So, the formula is easily changed from:

$$\text{Gain} = 10\log\left(\frac{power_{out}}{power_{in}}\right)\ dB$$

To:

$$\text{Power level in decibels} = 10\log\left(\frac{power\ level}{assumed\ power\ level}\right)\ dBm$$

The assumed power is usually 1 mW so the formula becomes as follows:

$$\text{Power level in decibels} = 10\log\left(\frac{power\ level}{1\ mW}\right)\ dBm$$

For this to be of use, two points are important:

1. There must be a standard power level which is assumed and understood by everyone. In fiber optics, as with other branches of electronics, we use 1 mW.

2. We must indicate that we are now referring to a power level. This is done by changing the symbol to dBm, where dBm means decibels relative to 1 mW.

**Converting power to dBm**

Example: Express 5 Watts as a power level in decibels.

Method

1. Start with the formula:

   Power level in decibels = $10 \log \left(\frac{power\ level}{1\ mW}\right)\ dBm$

2. Put in 5 Watts:

   Power level in decibels = $10 \log \left(\frac{5}{1 \times 10^{-3}}\right)\ dBm$

3. Simply by dividing out the bracket:

   Power level in decibels = 10 log $(5 \times 10^{-3})\ dBm$

4. Take the log $5\times 10^{-3}$ :

   Power level in decibels = $10 \times 3.699$ b=dBm

5. Multiply out:

   Power level in decibels = 36.99 dBm

   So:

   5 watts = 36.99 dBm

Example: Converting dBm to a power level

A light source for fiber optic system has an output power quoted as -14 dBm. Express this power in watts.

Method

1. Always start with the formula:

   Power level in decibels = $10 \log \left(\frac{power\ level}{1\ mW}\right)\ dBm$

2. Put in figures that we know:

$-14 = 10 \log\left(\frac{power\ level}{1\times10^{-3}}\right)\ dBm$

3. <u>Divide both sides by 10:</u>

$-1.4 = \log\left(\frac{power\ level}{1\times10^{-3}}\right)\ dBm$

4. <u>Find the antilog of both sides:</u>

$0.0398 = \frac{power\ level}{1\times10^{-3}}\ dBm$

5. <u>Multiply both sides by $1 \times 10^{-3}$:</u>

$0.0398 \times 1 \times 10^{-3}$

Or:

$39.8 \times 10^{-6}$= power level

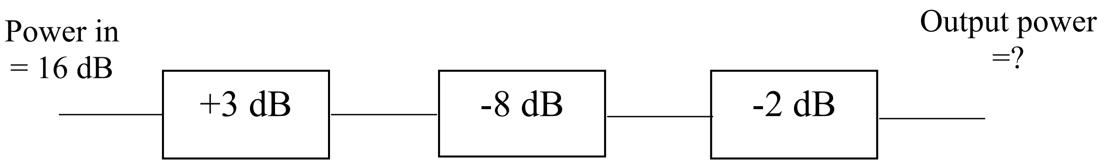
So, a power of -14 dBm is the same as 39.8 µW.

### 8.4 Decibels used in a system design

Work in decibels for as long as possible. Converting backwards and forward between decibels and watts is no fun and it is easy to make mistakes.

The nice thing is that dBm and dB are completely compatible – we can just add them up around the circuit to get a final result.

Method of solving the problem in below figure.




What is the output power in watts?

1. <u>Add the decibels:</u>

+16 dBm + 3 dB + (-8 dB) – 2 dB

= +16 +3 -8 -2 dBm

= +9

As the input power is quoted in dBm, the output power is +9 dBm. To find the output power in watts, we must convert out answer into a power level as we did in the previous example.

2. Start with the formula:

   Power level in decibels = $10 \log \left(\frac{power\ level}{1\ mW}\right)\ dBm$

   Put in the figures that we know:

   $9 = 10 \log \left(\frac{power\ level}{1{\times}10^{-3}}\right)\ dBm$

3. Divide both sides by 10:

   $0.9 = \frac{power\ level}{1{\times}10^{-3}}\ dBm$

4. Take the antilog of both sides:

   $7.943 = \frac{power\ level}{1{\times}10^{-3}}$

5. Multiply both sides by $1 \times 10^{-3}$:

   $7.943 \times 10^{-3} = power\ level$

   So, a power level of +9 dBm is the same as 7.943 mW.

Some dB values that are worth remembering:

► -3 dB = half power.

► 3 dB = a doubling of power.

► 10 dB = a tenfold increase.

► -10 dB = a tenth power.

Power loss on an optics fiber:

Light power on an optic fiber is lost during transmission either by leakage or due to lack of clarity of the material.

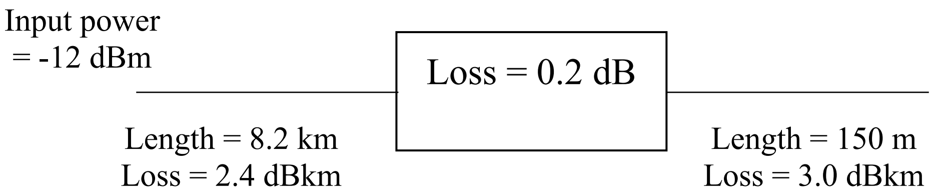
The loss is expressed in decibels per kilometer and written as dBkm.

For silica glass fibers we are looking at values around 3 dBkm for the fibers used for medium range transmissions. This corresponds to about half the power being last for each kilometer of travel. For long distance telecommunication fiber, the figures are typically 0.3 dBkm giving losses only 7% per kilometer.

If a kilometer has a loss of 3 dB, then 2 km will have a total loss of 2×3 = 6 dB it is, after all, just the same as having two connected in series. So, to obtain the total loss of a fiber, we simply multiply the loss specification in dBkm by the length of the fiber (measured in kilometers of course).

<u>Example:</u>

What is the power, in watts, in the circuit shown in following figure?




Method

1. **Loss is a length of fiber = loss per km × length in km**

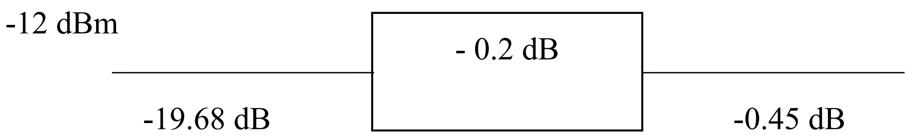
   So, in the first length we have a loss of:

   2.4 × 8.2 = 19.68 dB

   And in the second case:

   3.0 × 0.15 = 0.45 dB

   (remembering to convert the 150 m to 0.15 km).
2. **The circuit can now be simplified to that shown in figure-a.**
3. **This gives a total of -12 - 9.68 - 0.2 – 0.45 = -32.33 dBm**
4. **Convert this output to watts by previous method, giving a result of 0.58 µW.**



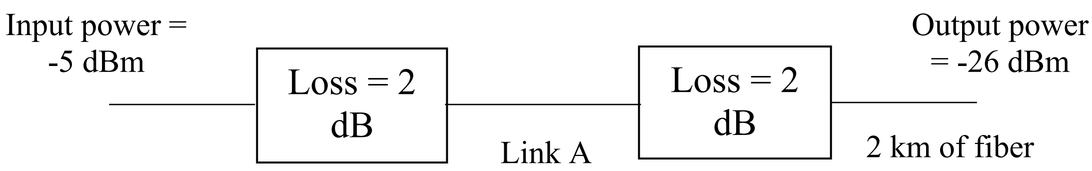

A simplified version

## Question to think about for Chapter 4:

: Chose the best answer for the following:

1. A power level of 50 µW could be expressed as:
   a) 1.69 dBm
   b) -4.3 dBm
   c) 1 dBm
   d) -13 dBm

2. The length of the link shown in figure is:
   a) 1 km
   b) 3 km
   c) 5 km
   d) 7 km




3. If a power of 0.25 mW is launched into a fiber optic system with an overall loss of 15 dB the output power would be:
   a) 250 µW
   b) 31.6 µW
   c) 7.9 µW
   d) 15 dBm

4. A system having an input power of 2 mW and an output power of 0.8 mW has a loss of:
   a) 2.98 dBm
   b) 3.98 dBm
   c) 3.98 μW
   d) 1.98 mW

5. An output of -10 dB means that the power has been:
   a) halved in value
   b) increased by a factor of 10
   c) reduced by a factor of 10
   d) doubled

# Chapter 5: Fiber Optics Losses

## 8.0 Losses in Fiber Optics

Attenuation

The loss or attenuation in fiber depends on the wavelength of the light propagating within it. There are three main bandwidth 'windows' of interest in the attenuation spectrum of fiber. The *1st window* is at 800-900nm, here there is a good source of cheap silicon based sources & detectors. The *2nd window* is at 1260-1360nm, here there is low fiber attenuation coupled with zero material dispersion. The *3rd window* of interest is at 1430-1580nm where fiber has its attenuation minimum. Typically, the telecommunications industry use wavelengths in the 3rd window which coincides with the gain bandwidth of Fiber Amplifiers. In the future, the search for greater bandwidth is likely to open up other windows for fiber transmission.

Dispersion

Light from a typical optical source will contain a finite spectrum. The different wavelength components in this spectrum will propagate at different speeds along the fiber eventually causing the pulse to spread. When the pulses spread to the degree where they 'collide' it causes detection problems at the receiver resulting in errors in transmission. This is called Intersymbol Interference (ISI). Dispersion (sometimes called *chromatic dispersion*) is a limiting factor in fiber bandwidth, since the shorter the pulses the more susceptible they are to ISI.

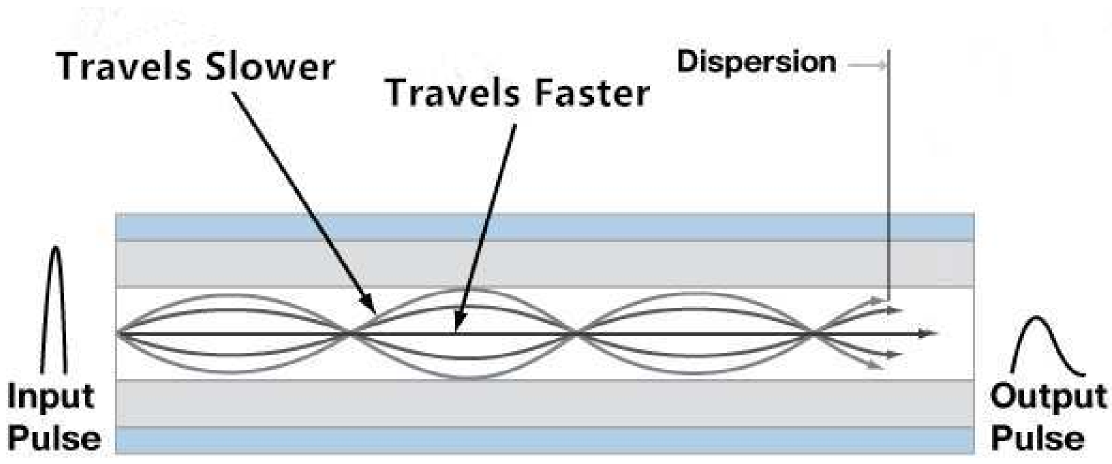



**Figure 17: Dispersion in Fiber Optics**

Nonetheless, when a beam of light carrying signals travels through the core of fiber optic, the strength of the light will become lower. Thus, the signal strength becomes weaker. This loss of light power is generally called fiber optic loss or attenuation. This decrease in power level is described in dB. During the transmission, something happened and causes the fiber optic loss. To transmit optical signals smoothly and safely, fiber optic loss must be decreased. The cause of fiber optic loss located on two aspects: internal reasons and external causes of fiber optic, which are also known as:

- Intrinsic fiber core attenuation
- Extrinsic fiber attenuation.

### 8.1 Intrinsic fiber core attenuation

Internal reasons of fiber optic loss caused by the fiber optic itself, which is also usually called intrinsic attenuation. There are two main causes of intrinsic attenuation which are:

1. light absorption
2. scattering.

### 8.1.1 Light absorption

Light absorption is a major cause of losses in optical fiber during optical transmission. The light is absorbed in the fiber by the materials of fiber optic. Thus light absorption in optical fiber is also known as material absorption. Actually the light power is absorbed and transferred into other forms of energy like heat, due to molecular resonance and wavelength impurities. Atomic structure is in any pure material and they absorb selective wavelengths of radiation. It is impossible to manufacture materials that are total pure. Thus, fiber optic manufacturers choose to dope germanium and other materials with pure silica to optimize the fiber optic core performance.

### 8.1.2 Scattering

Scattering is another major cause for losses in optical fiber. It refers to the scattering of light caused by molecular level irregularities in the glass structure. When the scattering happens, the light energy is scattered in all direction. Some of them is keeping traveling in the forward direction. And the light not scattered in the forward direction will be lost in the fiber optic link as shown in the following picture. Thus, to reduce fiber optic loss caused by scattering, the imperfections of the fiber optic core should be removed, and the fiber optic coating and extrusion should be carefully controlled.

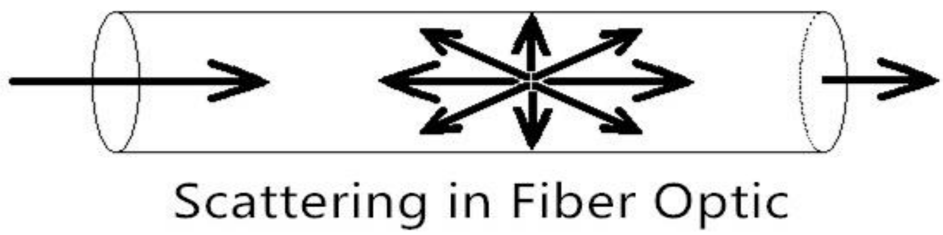



**Figure 18: scattering**

## 8.2 Extrinsic fiber attenuation.

Intrinsic fiber core attenuation including light absorption and scattering is just one aspect of the cause in fiber optic loss. Extrinsic fiber attenuation is also very important, which are usually caused by improper handling of fiber optic. There are two main types of extrinsic fiber attenuation which are:

1. bend loss
2. splicing loss.

### 8.2.1 Bending loss

Bending loss is the common problems that can cause fiber optic loss generated by improper fiber optic handling. Literally, it is caused by fiber optic bend. There are two types, which are:

One is micro bending

Macro bending

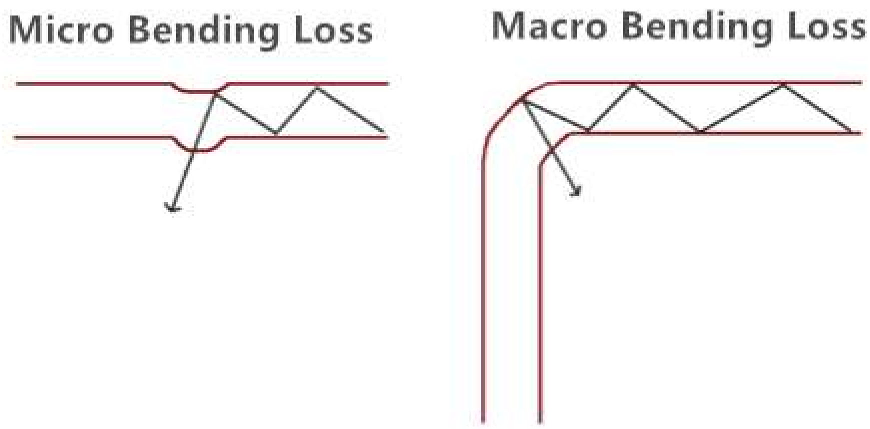



**Figure 19: Bending**

To reduce fiber optic loss, the following causes of bend loss should be noted:

- Fiber core deviate from the axis;
- Defects of manufacturing;
- Mechanical constraints during the fiber laying process;

- Environmental variations like the change of temperature, humidity or pressure.

### 8.2.2 Splicing loss

fiber optic splicing is another main causes of extrinsic fiber attenuation. It is inevitable to connect one fiber optic to another in fiber optic network. The fiber optic loss caused by splicing cannot be avoided, but it can be reduced to minimum with proper handling. Using fiber optic connectors of high quality and fusion splicing can help to reduce the fiber optic loss effectively.

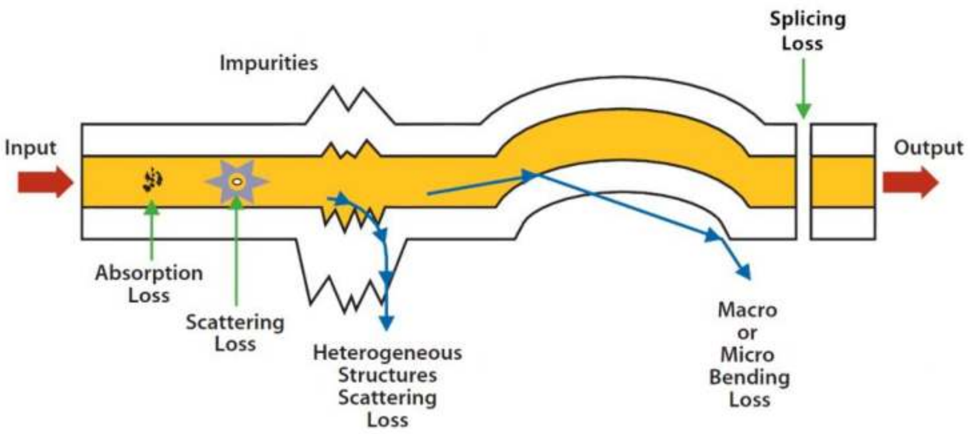



**Figure 20: Splicing**

The above picture shows the main causes of losses in optical fiber, which come in different types. To reduce the intrinsic fiber core attenuation, selecting the proper fiber optic and optical components is necessary. To decrease extrinsic fiber attenuation to minimum, the proper handling and skills should be applied.

**8.3 Limits in the optical transmission distance**

Generally, the maximum transmission distance is limited by dispersion in fiber optic cable. There are two types of dispersion that can affect the optical transmission distance:

Chromatic dispersion. which is the spreading of the signal over time resulting from the different speeds of light rays.

Modal dispersion. Representing the spreading of the signal over time resulting from the different propagation mode.

Multimode transmission is largely affected by the modal dispersion, because of the fiber imperfections, these optical signals cannot arrive simultaneously and there is a delay between the fastest and the slowest modes, which causes the dispersion and limits the performance of multimode fiber. (shown in the following picture) For single-mode fiber, it is not model dispersion but chromatic dispersion that affects the transmission distance. This is because, the core of the single-mode fiber optic is much smaller than that of multimode fiber. That's the main reason why single-mode can transmit signals over longer distance than multimode fiber.

## Question to think about for Chapter 5:

1. Why single mode can transmit for longer distance rather than the multimode?

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……………………………………………………………………………………………………………

2. What are the 2 types of attenuation?

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3. Draw how dispersion is occurred in a fiber optics:

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