The Effect of Dispersion and Attenuation on Fiber Optic Communication Systems

Eben A. Nornormey[1*], Nathaniel Awudu Nelson[2], Emmanuel Asare[3], Daniel Opoku-Akyea[4], Felix Okpoti[5], Reine Makafui McEben-Nornormey[6]

[1, 2,] Department of Electrical Engineering, Accra Institute of Technology, Accra, Ghana

[3]Department of Electrical/Electronic Engineering, Koforidua Technical University, Koforidua, Ghana

[4]Department of Procurement & Logistics, Ghana Communication Technology, Tesano-Accra, Ghana

[5]Department of Marine Electrical Engineering, Regional Maritime University, Nungua, Ghana

[6]Department of Mechanical Engineering, University of Technology and Economics, Budapest, Hungary

DOI: https://doi.org/10.51584/IJRIAS.2024.908032

Received: 11 July 2024; Accepted: 31 July 2024; Published: 06 September 2024

ABSTRACT

The paper describes how signal can be transmitted effectively using fibre optic communication system. Signal transmission through this system is facilitated by optical transmitter, fiber optic cable and optical receiver. The fibre cable is classified based on refractive index, materials used and mode of propagation of light. The mode of propagation of light and refractive index of the core are used to form step index-single mode fibres, graded index-single mode fibres, step index-multimode fibres and graded index-multimode fibres. This article demonstrated the mathematical principles underpinning light wave propagation through fibre optic cable. The paper also brought to the fore the importance of total internal reflection (TIR) in fibre optic communication. The researchers derived formulae to show the significance of Acceptance Angle, Numerical Aperture (NA), Fractional Refractive Index (Δ), Normalized Frequency and Number of Modes (N) in fibre optics. Features such as dispersion and attenuation found space in the paper, while dispersion distorts signal output and thereby limiting information capacity of the communication system, attenuation introduces signal losses into the system. The techniques and mechanism that can be used to minimize signal distortion and loss in the network were mentioned. The authors also discussed formulae used to determine values of material and waveguide dispersion coefficients and attenuation coefficient. These formulae and other parameters were used to formulate tables and graphs depicting effects of dispersion and attenuation in optical network. The authors also designed fibre optic networks between Accra to Cape Coast and Accra to Sogakope.

Keywords: Fibre Optic, Refractive Index, Signal Transmission, Cable, Propagation, Light, Total Internal Reflection, Dispersion, Attenuation.

INTRODUCTION

In this contemporary era, one cannot do without communication; one of these effective schemes is the Fiber Optic Communication System. This communication technique involves transmitting signal in a form of light energy through a medium known as fiber optic cable from one point to another. A signal that is conveyed through fiber optic cable in a form of light, is transformed from electrical or electronic signal. This light signal is converted back into electrical signal at the receiving point. The function light signal performs in optical fiber; electrical signal performs the same task in copper cable. The contrast between their performances is that, information flowing through copper cable is relatively slow while that propagating through fiber optic cable is incredibly fast. This light signal in the form of pulses, travels through the optical fiber at the speed of light, this signal is about 100 times faster than electrical signal**[1].** Power consumption in optical fiber communication is considerably lower than that of copper communication; the energy consumption is approximately 12 times less. Fiber optic cables are also immune to Electromagnetic Interference (EMI) and Radio Frequency Interference (RFI) **[2].**

Fiber optics cables are used in variety of areas, the most prominence being the Telecommunication Industry where these cables are used for Internet Communication, Video Conferencing, Telephone Signal Transmission and Cable Television Signal Transmission. Every fiber optic communication system is composed of three main parts: theOptical Transmitter, the Fiber Optic Cable and the Optical Receiver.

The Optical Transmitter

This is a device that transmit analog or digital information (electrical signal); if the signal is analog, it is first converted into digital pulses and sent through light source transmitter circuit where the information is transformed into light waves. This light may be either LASER (Light Amplification by Stimulated Emission of Radiation) or LED (Light-Emitting Diode)**[3].**

The Fiber Optic Cable

It is a cable that is connected to the transmitter output where the light signal in a form of LASER or LED passes. The fiber optic cable is also known as Cylindrical Dielectric Waveguide and made from low loss material such as glass (silica) or plastic. It has a diameter that lies between 0.25 and 0.5mm which is slightly thicker than human hair **[4].** The optical fiber is shown in figure 1.The fiber optic cable is made up of four major parts, these are:the core, the cladding, the buffer and the jacket.

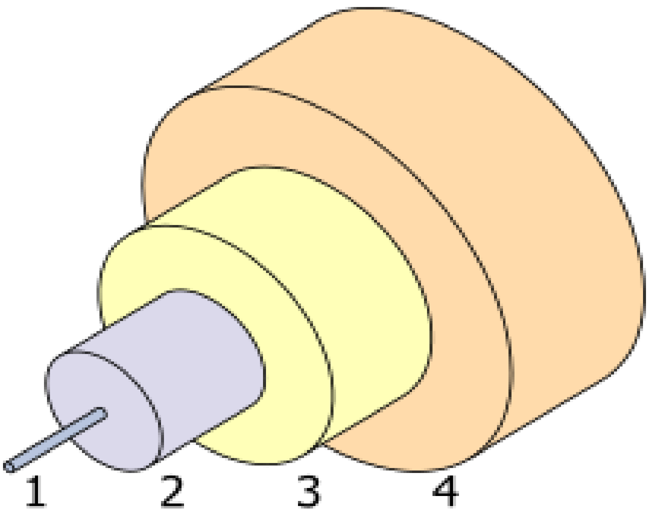


Fig 1: Optical Fiber

Where:

1. Core 8–9 µm diameter
2. Cladding 125 µm diameter
3. Buffer 250 µm diameter
4. Jacket 400-900 µm diameter

The Core: It is a central tube of very thin size made of optically transparent dielectric medium and carries the light from the transmitter to the receiver. The core diameter may vary from about 8um to 100 um depending on the application**[5]**. Due to total internal reflection, the light traveling within the core reflects from the core and the cladding boundary.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

The Cladding: It is an outer optical material surrounding the core and serves as a shield. Its main function is to reflect light back into the core. When light enters through the core (dense material) into the cladding (less dense material), it changes its angle, and then reflects back to the core **[6].**

The Buffer: It is a plastic coating that protects the fiber from damage; it is made of silicon rubber; typical dia--meter of the coating is 250-300 um**[7].**
The Jacket:It protects bundles of fiber optic cable. Jackets are available in different colours, colour yellow clearly signifies a single-mode cable, and orange colour indicates multimode **[8].**

The Optical Receiver

This is a device that has a photocell also known as light detector that captures or receives light signal from the output of the optical fiber cable. This signal is amplified and converted to digital signal to be received by a digital device. If the output source is analog device, then the digital signal is converted back to analog signal by a decoder circuit.

Another important component for fiber optic communication system that is necessary for long-distance data transmission is the optical regenerator or repeater. An optical repeater is a device used to regenerate original signal degraded during transmission through fibre optic cable to obtain a fresh copy before retransmission. Regeneration is achieved by converting optical signal to electrical or electronic signal and performing the 3R regeneration functions i.e. Re-amplification, Re-shaping and Re-timing before converting it back to optical form for retransmission**[9].** Due to this conversion of signal, this regenerator is referred to as optical-electrical-optical (OEO) repeater. Optical Repeaters have diverse generations based on regenerator spacing **[10]:**

- In the first generation, the spacing between two repeaters is 10 km.
- In the second generation, the spacing among two repeaters is 50 km
- In the third generation, the spacing among two repeaters is 100 km
- In the fourth and fifth generations, the spacing between two repeaters is 10,000 km and from 24,000 to 35,000 km respectively.

For cost efficiency, optical amplifiers have mostly substituted (OEO) repeaters for long-distance fibre optic communication systems**[11].** Figure 2 depicts the block diagram of Optical Fiber Communication system.

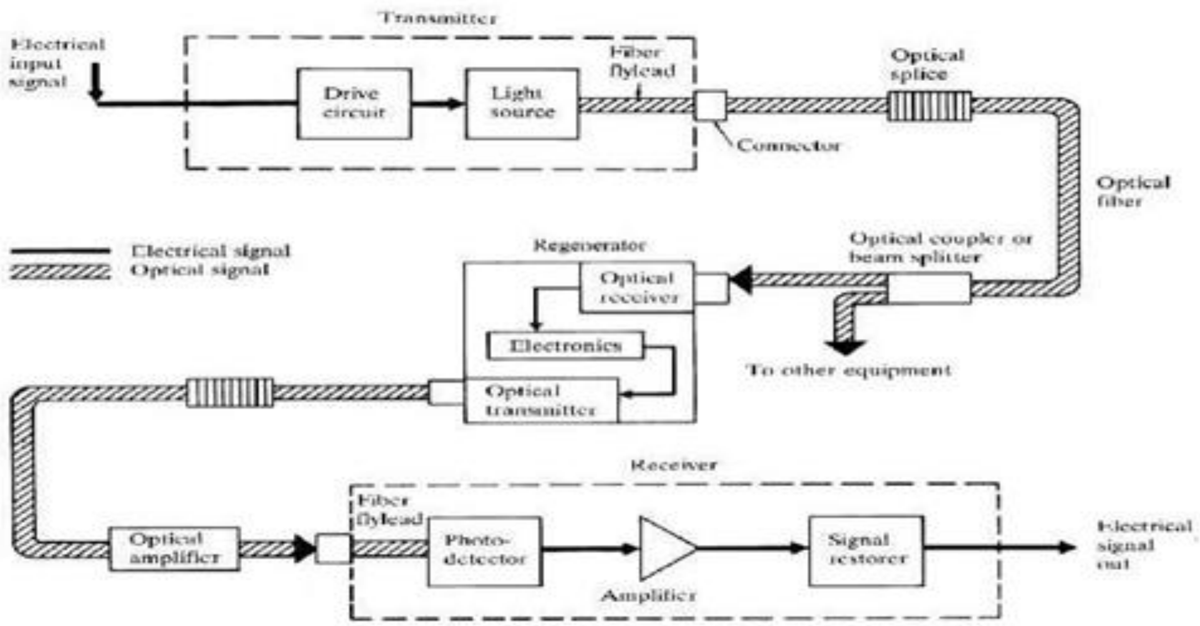


Fig 2: Optical Fiber Communication System Block Diagram

Types of Fibre Optic Cables

The types of fibre optic cables used in Optical Fiber Communication Systems depend on the:

- Refractive Index
- Materials Used
- Mode of Propagation of Light.

Classification based on the Refractive Index

There are two types of Refractive Index groupings in fibre optic cable, these areStep-Index Fibres and Graded-Index Fibres. In the step-index, the refractive index of both the core and the cladding are constant. Also the rays of light that propagate through it is in the form of meridional rays which cross the fiber axis during every reflection at the core-cladding boundary **[12].** In the graded-index, therefractive index of the core is non-uniform and gradually decreases from the centre towards the core-cladding interface while the cladding has uniform refractive index. The light rays propagate through it in a form of skew rays or helical rays and do not cross the fiber axis at any time.Also the refractive index of the optical fibre decreases as the radial distance from the fibre axis increases **[13].**

Classification based on the Materials Used

There are two types of materials used in fibre optic cable manufacture, they are Glass and Plastic. Glass fiber optic cables are made from extremely fine tiny strands of glass and bundled together inside a cover (sheathing). They have advantages of usage in high-temperature applications such as furnaces and ovens as well as in low-temperature areas like cold storage warehouses. Glass constructed fibre cores are efficient in transmitting light at higher transfer speeds and over long transmission distances. Glass fiber optic cables have the drawbacks of requiring highly trained technicians to install them and the equipment and tools used for their termination are prohibitive. They are also fragile and more amenable to breaking if not handled well. Plastic fiber optic cables are made from polymer; in this cable, both the core and the cladding are from polymeric material and usually carries just a single strand of fibre **[14].** They have the advantage of not requiring trained personnel to install them; polymeric material and plastic fiber optic installation with the associated equipment are inexpensive. Plastic fiber optic cables also have advantages of being flexible and solid and capable to bend farther without breaking. They however have disadvantages such as inability to withstand extreme temperature; very high signal attenuation, dispersion and limited to short distance.

Classification based on the Mode of Propagation of Light

There are generally three types of fibre optic cables based on mode (path) of propagation of light, they are: Single-Mode Optical Fibres, Multimode Optical Fibres and Plastic Optical Fibers. Single-Mode Optical Fibre also known as Single-Mode Fibre or Mono-Mode Fibre is a fibre that is used for long distance transmission, has a smaller core diameter of 8.3 micron (8.3 μm) and cladding diameter of 125 micron (125 μm)**[15]** as shown in figure 3. The smaller core enables this type of fiber cable to have negligible attenuation in the course of signal propagation. It has virtually no dispersion since there is no degradation of signal when the LASER light is travelling through the fibre cable.

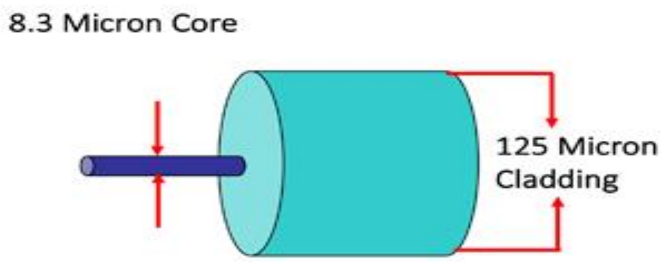


Fig 3: Core and Cladding Diameters of Single-Mode Optical Fibre

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

The disparity between refractive index of the core and the cladding is very small. Single-Mode Fibre has substantially higher bandwidth (between 1-10 Gigabits per second) and more expensive as compare to multimode fibre. The light source used in single-mode fibre is LASER. Single-Mode Optical Fibre allows only a single beam of light for that matter a single wavelength to be transmitted through the fibre as depicted in figure 4. Consequently, reducing light reflections significantly and thereby lower attenuation.

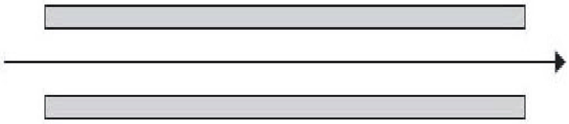


Fig 4: Single Beam of Light in Single-Mode Optical Fibre

Multimode Optical Fibre is a fibre that is used for short distance (300-550 m); the core diameter is available in two sizes, 62.5 or 50 micron (62.5 or 50 μm) and a cladding diameter of 125 micron (125 μm)**[16].** It is depicted in figure 5.

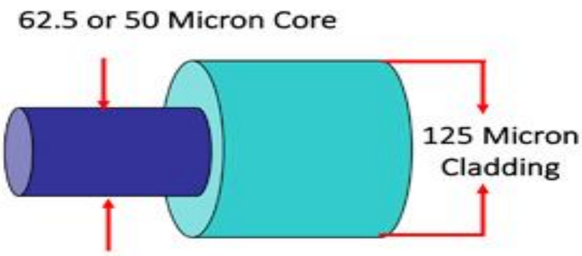


Fig 5: Core and Cladding Diameters of Multi-Mode Optical Fibre

This larger core diameter of multimode fibre permits multiple light pulses to be transmitted through the fibre cable as shown in figure 6. Due to the large size of the core, there is the possibility of signal loss (attenuation), signal reduction or signal interference. Multimode fibre uses LED as the light source to create the light pulses or signals through the cable. There is degradation of signal in this fibre optic cable that leads to signal dispersion. It has the capability of transmitting signal at a bandwidth up to 100 Gigabits per second. Multimode fibre has usage in patch cable applications including fibre-to-desktop or patch panel-to-equipment, data and audio/video applications in LANs (Local Area Networks) **[17]**. Due to the refractive index distribution of this fibre, it has been divided into two categories: Step Index Fibre and Graded Index Fibre.

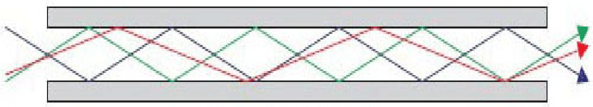
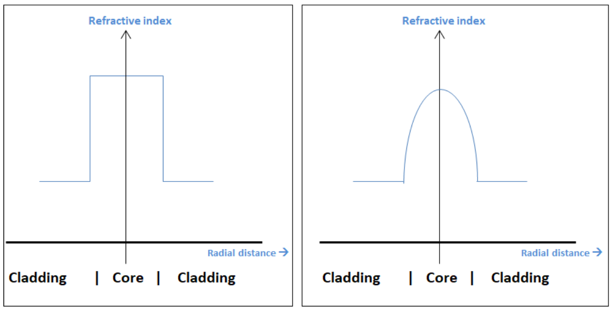


Fig 6: Multiple Light Signals in Multi-Mode Optical Fibre

Step Index Fibre has a constant refractive index in the core and a lower refractive index in the cladding; here, the light signals or rays travel in straight lines inside the core and are reflected at the core-cladding boundary. Where as in the Graded Index Fibre orGradient-index fiber, the fibre has varying refractive index in the core and a constant refractive index in the cladding **[18].** Figure 7 depicts the refractive index profiles of step index against graded index fibre optic cables.



Step-Index **Graded-Index**

Fig 7: Step-Index against Graded-Index Refractive Index Profiles

Plastic Optical Fiber (POF) is a special fibre made out of polymer; it is used for short distance (100 m) transmission due to its high attenuation and dispersion. There are multiplicity of optical polymers that are used in the manufacturing of Plastic Optical Fiber. These polymers include polymethyl-methacrylate (PMMA), amorphous fluorinated polymer (CYTOP), polystyrene (PS), and polycarbonate (PC) **[19]**. Its core diameter ranges from 150 to 2000 µm and can even go up to 20,000 µm**[20]**. It is of high mechanical flexibility and robustness making it possible to undergo bending and stretching without breaking. POF has low speed and is used if the applications do not necessitate high bandwidth. It less expensive making it a viable option for desktop LAN connection, digital home appliance interfaces, home, industrials and car networks. POF is called the "consumer" optical fiber because the fiber and associated optical links, connectors, and installation are all inexpensive **[21]**.

Classification based on Mode of Propagation of Light and Refractive Index of Core

The Mode of Propagation and Refractive Index of the core are used to form four combination types of optic fibres; these are as follows: Step Index-Single Mode Fibres (Single mode step-index fibers), Graded Index-Single Mode Fibres (Single mode graded-index fibers), Step Index-Multimode Fibres (Multimode step-index fibers) and Graded Index-Multimode Fibres (Multimode graded-index fibers).

In the Step Index-Single Mode Fibre**,** its light energy is concentrated in only one mode and therefore transmits light signal in only one mode as shown in figure 8. It is designed to have a Normalized Frequency Parameter (V-Number) of 2405 and does not undergo mode delay differences**[22]**. It has low Numerical Aperture (NA) and low Acceptance Angle.

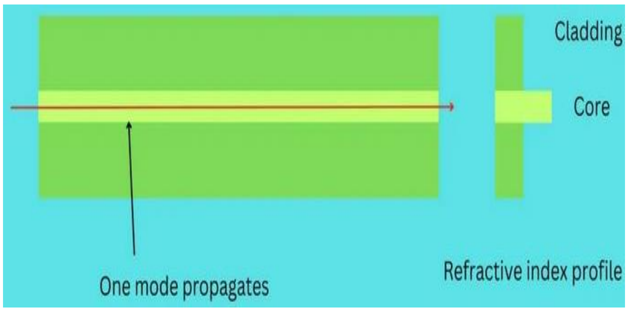


Fig 8: Step Index-Single Mode Fibre

In the Graded Index-Single Mode Fibre, the optical fibre has a constantly variable refractive index core that permits only one single mode of light signal to propagate along it as shown in figure 9. The design of this fibre is such that it reduces modal dispersion making it possible to be used for high-speed long-distance transmission by communication systems**[23]**. The graded index nature of this fibre enables the light signals or

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

rays to travel near the centre of the core and those travelling near the boundary or edge, reach the end of the fibre at about the same period and hence minimizing signal distortion.

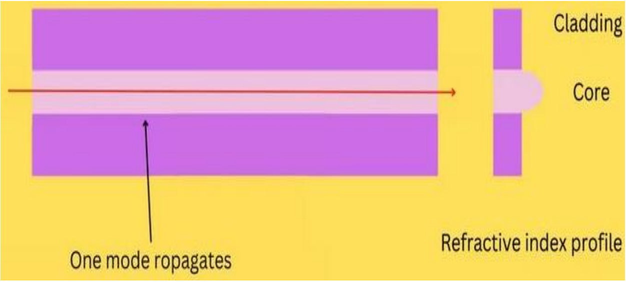


Fig 9: Graded Index-Single Mode Fibre

In Step Index-Multimode Fibre, a uniform index of refraction is maintained within the core. The cladding has a lower refractive index as compares to the core. Light signals travel through this fibre core axis in a zigzag manner since the light rays enter into the fibre at different incidence angles as shown in figure 10. Even though, each light ray travels through the core of the fibre at the same speed, the time it exits the receiving end depends on the angle at which it enters **[24]**. The steeper the angles at which the rays entered the fibre, the longer it takes for the rays to arrive at the receiving end. This type of fibre is used for short distance transmission.

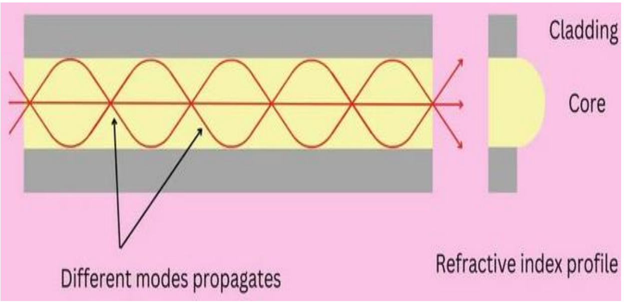


Fig 11: Graded Index-Multimode Fiber

In Graded Index-Multimode Fibre, the refractive index of the core reduces slowly from the centre axis of the core towards the cladding. The higher refractive index at the centre makes the light signals move down the axis gradually than those near the cladding **[25]**. The light signal in the core curves helically off the cladding as depicted in figure 11 decreasing its travel distance. In other words, the light rays propagating through the fibre cable do not follow straight line but rather parabolic path as a result of non-uniformity of the refractive index of the core.

To bring to the fore the characteristics underpinning features of the refractive index profiles of single mode and multimode fibre cables, the researchers tabulated table 1.

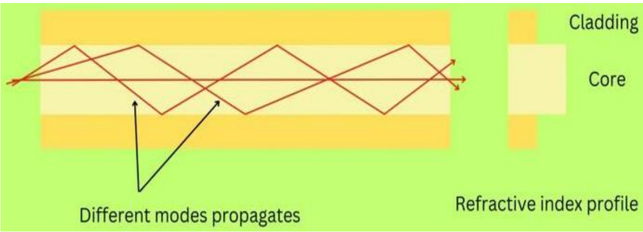


Fig 10: Step Index-Multimode Fibre

No	Parameter	Step-Index Single-Mode Fiber	Graded-Index Single-Mode Fiber	Step-Index Multimode Fiber	Graded-Index Multimode Fiber
1	Refractive Index	Uniform	Graded	Uniform	Graded
2	Core Diameter	Small	Small	Large	Large
3	Modal Dispersion	Minimal	Minimal	High	Reduced
4	Bandwidth	High	High	Low	High
5	Attenuation	Low	Low	High	Low
6	Distance	Long	Long	Short	Medium
7	Number of Modes	1	1	$M_N = \frac{V^2}{2}$	$M_N = \frac{V^2}{4}$
8	Applications	Telecommunications, High-Speed Communication Applications, Fiber Optic Sensing Systems	Data Centers, High-Speed Applications, Sensing and Biomedical Imaging Systems	Short Distance Data Transmission, Fiber Optic Lighting	Premises Networks, LANs, Fiber to the Desk, CCTV and other Security Systems
9	Advantages	Virtually Free from Modal Dispersion, Low Attenuation, and High Bandwidth	Offers a Good Balance of Performance and Cost for High-Speed Data Transmission	Large Core Diameter, Easy to Couple with Light Sources	Higher Bandwidth, Longer Transmission Distances than Step-Index Multimode Fiber
10	Disadvantages	Limited use in Short-Distance Data Transmission and Sensing Systems	Higher Cost than Multimode Fiber for High-Speed Transmission Applications	Limited use in High-Speed Data Communication Applications due to High Attenuation, Dispersion, and Lower Bandwidth	Limited use in Long-Distance Transmission due to Modal Dispersion

Equations of Fibre Optic Communication Systems

For light signal to travel through a fibre and successfully feed fibre optic communication system, it must follow certain mathematical principles. These principles start with propagation of light ray in fibre optic cable as shown in figure 12.

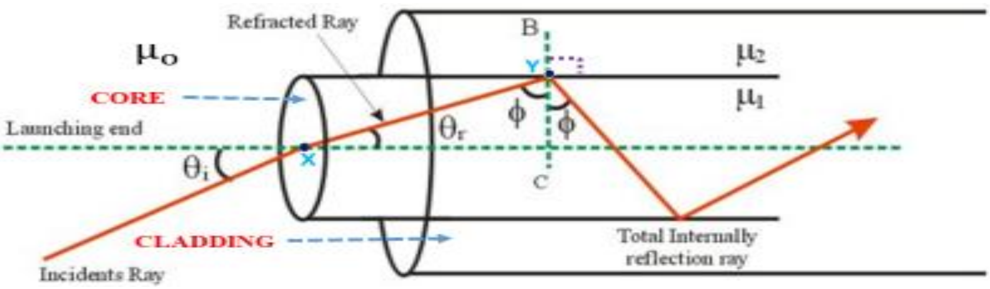


Fig 12: Propagation of Light Ray in Fibre Optic Cable

From figure 12:

μ_o = Refractive Index of the Air

μ_1 = Refractive Index of the Core

μ_2 = Refractive Index of the Cladding

θ_i =Angle of Incident

ϕ = Critical Angle

θ_r = Angle of Refraction

Refractive index is denoted by the symbolμ, it is an important optical property of a material and indicates light signal capability to bend through a medium. It is also known as refraction index; it is a number without a unit. This dimensionless number can be determined by using the expression in equation 1

$\mu = \frac{c}{s}$ ……………………………………………………….(1)

Where:

c= Speed of Light in Vacuum

s= Speed of Light in Material or Medium

In optical fibre, refractive index plays a major rule as to how light signal is propagated through the fibre optic cables. Refractive index attributed to the core (μ_1) is optically more dense and has a higher value than the one ascribed to the cladding (μ_2) which is less dense. Refractive index value of the core ranges between 1.46 to 1.55 while that of the cladding is 1.45. The refractive index of air is approximately 1; this parameter is dependent on factors such as temperature, humidity and pressure.

When the Angle of Incident ($\boldsymbol{\theta_i}$) is greater than the Critical Angle ($\boldsymbol{\phi}$) i.e. **($\boldsymbol{\theta_i > \phi}$),** the reflected rayreflects into the same medium. This phenomenon is known as Total Internal Reflection (TIR). Transmission of light signal through fibre optic cable from one end to another is based on this phenomenon. Total internal reflection is actually achieved by the cladding which causes light signal confinement to the core; this occurs at the interface between the core and the cladding. It should be noted that:

- When Angle of Incident ($\boldsymbol{\theta_i}$) is less than Critical Angle ($\boldsymbol{\phi}$), then the ray reflects into the secondary medium.
- When Angle of Incident ($\boldsymbol{\theta_i}$) is equal to Critical Angle ($\boldsymbol{\phi}$), then the ray travels along the interface.
- When Angle of Incident ($\boldsymbol{\theta_i}$) is greater than Critical Angle ($\boldsymbol{\phi}$), then the ray totally reflects back into the same medium.

Critical angle is measured within the fibre optic cable; it is the angle of incident beyond which light signals passing through a denser medium (core) to the surface of a less dense medium (cladding or air) are no longer refracted but totally reflected **[26].** Angle of Refraction is the angle obtained between the refracted light signal or ray and the normal (BC) to the boundary of a denser medium (core) and a less dense medium (cladding). This angle is very significant in fibre optic communication since it contributes to the principle of total internal reflection, enabling propagation of light signal through fibre optic cable. The rapport between the refractive indices, the critical angle and the angles of refraction and incidence are expressed in equations 2 and 4.

According to Snell's Law, at point X:

$\mu_o \sin \theta_i = \mu_1 \sin \theta_r$………………………………………..**(2)**

$\sin \theta_i = \frac{\mu_1}{\mu_o} \sin \theta_r$…………………………………………..**(3)**

According to Snell's Law, at point Y:

$\mu_1 \sin \phi = \mu_2 \sin 90°$ ……………………………………...**(4)**

But, $\phi = 90° - \theta_r$…………………………………………….**(5)**

Equation 5 was put into Equation 4 to obtain Equation 6

$\mu_1 \sin (90° - \theta_r) = \mu_2 \sin 90°$…………………………….**(6)**

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

From Trigonometry Identity:

A sin $\boldsymbol{\beta}$ = A cos ($\boldsymbol{\beta - 90°}$) and **A cos $\boldsymbol{\beta}$ = A sin ($\boldsymbol{\beta + 90°}$)**

Factoring the twotrigonometry identities above into Equation 6, Equations 7, 8 and 9 were derived.

$\mu_1 sin\ (90° - \theta_r)$ = $\mu_1\ cos\ \ (90° - \theta_r - 90°)$ =$\mu_1 sin\ (90° - \theta_r)$ =$\mu_1\ cos\ \ (-\theta_r)$……………………………………………**(7)**

$\mu_2\ sin\ 90°$=$\mu_2\ cos\ (90° - 90°) = \mu_2\ sin\ 90°$=$\mu_2\ cos\ \ 0$….**(8)**

$\mu_1\ cos\ \ (-\theta_r)$ =$\mu_2\ cos\ \ 0$…………………………………...**(9)**

From Trigonometry Identity:

$\boldsymbol{cos\ \ 0}$**= 1** and$\boldsymbol{cos\ \ (-\theta_r)}$**=** $\boldsymbol{cos\ \theta_r}$

Factoring the two trigonometry identities above into Equation 9, Equations 10 and 11 were obtained;

$\mu_1\ cos\ \theta_r\ = \mu_2$ ……………………………………………**(10)**

$\boldsymbol{cos\ \theta_r\ = \frac{\mu_2}{\mu_1}}$………………………………………………**(11)**

From Trigonometry Identity:

$$sin^2\ \theta_r + cos^2\ \theta_r = 1$$

Taking into consideration the trigonometry identity above Equations (12) and (13) were obtained.

$sin^2\ \theta_r = 1 - cos^2\ \theta_r$ ……………………………………..**(12)**

$sin\ \theta_r = \sqrt{1 -\ cos^2\ \theta_r}$ …………………………………..**(13)**

Putting Equation **(11)** into Equation **(13)** Equation **(14)** was obtained

$sin\ \theta_r = \sqrt{1 - \frac{\boldsymbol{\mu_2}^2}{\boldsymbol{\mu_1}^2}} = \sqrt{\frac{\boldsymbol{\mu_1}^2 - \boldsymbol{\mu_2}^2}{\boldsymbol{\mu_1}^2}}$…………………………**(14)**

Putting Equation 14 into Equation 3 Equation 15 was derived;

$sin\ \theta_i = \frac{\mu_1}{\mu_o}\left(\sqrt{\frac{\boldsymbol{\mu_1}^2 - \boldsymbol{\mu_2}^2}{\boldsymbol{\mu_1}^2}}\right) = \frac{\mu_1}{\mu_o}\left(\frac{\sqrt{\boldsymbol{\mu_1}^2 - \boldsymbol{\mu_2}^2}}{\mu_1}\right) = \left(\frac{\sqrt{\boldsymbol{\mu_1}^2 - \boldsymbol{\mu_2}^2}}{\mu_o}\right)$.. (1**5)**

The sin inverse of Equation 15 is expressed as depicted in Equation 16;

$\theta_i = sin^{-1}\left(\frac{\sqrt{\boldsymbol{\mu_1}^2 - \boldsymbol{\mu_2}^2}}{\mu_o}\right)$…………………………………**(16)**

Thissin inverse known as Acceptance Angle or Maximum Angle

∴**Acceptance Angle,** $\boldsymbol{\theta_i = sin^{-1}\left(\frac{\sqrt{\mu_1^2 - \mu_2^2}}{\mu_o}\right)}$

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

The acceptance angle is measured outside the fibre optic cable; it is the maximum value of the angle of incidence at the entrance end of the fibre optic cable, at which the angle of incidence at the core-cladding interface is equal to the critical angle of the core medium **[27].** This angle ensures that light signal is efficiently propagated through the core of the fibre optic cable. Acceptance Angle can be said to be amaximum angle at which light enters the fiber core and still propagates down the length of the fiber; it can be liken to a tunnel.With the aid of Acceptance Angle, Numerical Aperture, NA can be determined. Numerical Aperture is the sine of the acceptance angle, as demonstrated in Equation 17,which incident beam has Total Internal Reflection in the core of fibre optic cable; it is dimensionless.

Numerical Aperture, NA=sin $\left[sin^{-1}\left(\frac{\sqrt{{\mu_1}^2-{\mu_2}^2}}{\mu_o}\right)\right]$……..**(17)**

Equation 17 was simplified to obtain Equation 18.

NA= $\left[sin^{1}sin^{-1}\left(\frac{\sqrt{{\mu_1}^2-{\mu_2}^2}}{\mu_o}\right)\right]=\left(\frac{\sqrt{{\mu_1}^2-{\mu_2}^2}}{\mu_o}\right)$……………..**(18)**

If the refractive Index of Air Medium is equal to Unity (1) then Equation 18 can be expressed as shown in Equation (19).

NA= $\sqrt{{\mu_1}^2-{\mu_2}^2}$……………………………………………**(19)**

Numerical aperture demonstrates the efficiency and how much light ray is collected inside the fibre by optical system for propagation. The higher the value of numerical aperture, the more is the light signal collected for transmission in the fibre optic cable **[28].** It is therefore regarded as, light collecting facility of the cable. Numerical aperture is considered as one of the most basic characteristics of optical fibre.

Fractional Refractive Index (Δ) is the ratio of the difference between Refractive Indices of the Core and the Cladding to the Refractive Index of the Core; this is shown in Equation 20. It is also called Relative Refractive Index Difference or Fractional Change Refractive Index. It has a value which is less than one (1) and positive since$\mu_1 > \mu_2$; else, Total Internal Reflectance cannot be realized.

$\Delta = \frac{\mu_1-\mu_2}{\mu_1}$……………………………………………………..**(20)**

Equation **(20)** can be expanded as shown in Equation **(21)**

$\mu_1\,\Delta = \mu_1 - \mu_2 = \mu_1 - \mu_2 = \mu_1\,\Delta$………………………… **(21)**

Factorizing Equation19 and putting Equation21 into it, Equation22 was obtained;

NA= $\sqrt{{\mu_1}^2-{\mu_2}^2}=\sqrt{(\mu_1-\mu_{2)}(\mu_1+\mu_2)}=\sqrt{\mu_1\,\Delta\,(\mu_1+\mu_2)}$………………………………………**(22)**

If $\mu_1 \approx \mu_2 \Longrightarrow \mu_1 + \mu_2$ will be $\mu_1 + \mu_1$ = $2\mu_1$, then Equation (22) can be expressed as shown in Equation 23;

NA = $\sqrt{\boldsymbol{\mu_1}\,\Delta\,(\,2\boldsymbol{\mu_1})} = \sqrt{\boldsymbol{\mu_1}^2\,2\Delta} = \boldsymbol{\mu_1}\sqrt{2\Delta}$…………… **(23)**

Another characteristic of fibre optic cable is the Normalized Frequency otherwise known as V-Number and represented by V. It is a dimensionless parameter and ratio between the core radius of the fibre optic cable and its numerical aperture to the Wavelength, Normalized Frequency may also be said to be a frequency of light that propagates through an optical fiber cable or waveguide; it is expressed as in Equation 24:

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

$$\mathbf{V} = \frac{2\pi a NA}{\lambda} = \frac{2\pi a}{\lambda}\mu_1\sqrt{2\Delta} \quad \text{.......................................}\mathbf{(24)}$$

Where:

a = Radius of the core of the fibre, metre (m)

λ = Wavelength of light traveling through the fibre, metre (m)

2a = d, the diameter

∴V-Number can also be expressed as:

$$\mathbf{V} = \frac{d\pi}{\lambda}\mu_1\sqrt{2\Delta} \quad \text{..}\mathbf{(25)}$$

It should be noted that, the Normalized Frequency provides valuable information about the fibre's ability to capture and transmit light signal efficiently.

The Number of Modes (N) that propagate through fibre optic cable increase with increase Numerical Aperture, NA. The Normalized Frequency (V) aids in its determination and while it is expressed in:

Step Index-Multimode Fibre as N $=\frac{V^2}{2}$, it expressed as N $= \frac{V^2}{4}$ in Graded Index-Multimode Fiber. It is proven that in single mode fibre, V is less than 2.405 (V< 2.405) and multi-mode fibre is more than 2.405 (V> 2.405).

FACTORS MILITATING AGAINST FIBRE OPTIC COMMUNICATION

Dispersion and attenuation are two causes that affect the performance of Fibre Optic Communication Systems. These two phenomena impact on the systems in different manner.

DISPERSION

Dispersion in communication system does not necessarily result in loss of signal but rather spreads the output pulse of a link over time and thereby reduces its bandwidth and creates distortion. The reduction of the bandwidth will end up limiting the information carrying capacity of the fiber. Dispersion is divided into the following categories as shown in figure 13.

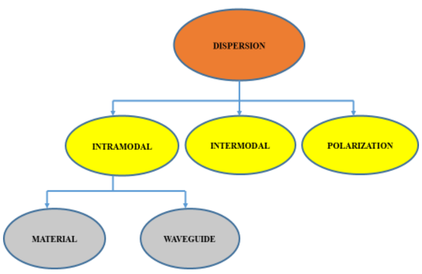


Fig 13: Types of Dispersion

Intramodal Dispersion, also known as Chromatic Dispersion occurs in all types of fiber optic cable.In this dispersion, the optical signal in the fibre travels at different wavelengths, at different velocities, arriving at the receiving end at different times and causing the signal to spread out as shown in figure 14. Chromatic dispersion is classified into two categories: Material Dispersion and Waveguide Dispersion. While material dispersion is caused by different wavelengths of light traveling at different speeds through the fiber, waveguide dispersion is as a result of the effective refractive index of the fiber core varying with the wavelength. It should be noted that, whereas material dispersion is due to the material of the fiber optic cable, waveguide dispersion is due to the structure or geometry of the fiber optic cable.

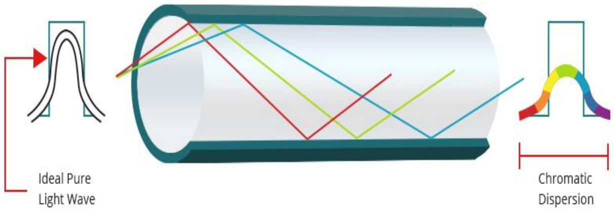


Fig 14: Chromatic (Intramodal) Dispersion

This dispersion (chromatic dispersion) is pronounced in Wavelength Division Multiplexing (WDM) systems; and used for long-haul transmission network **[29].** This defect can be mitigated by using slope compensation; this mitigating technique has the tendency of increasing nonlinear distortions **[30].** Other mitigating mechanisms such as dispersion-shifted

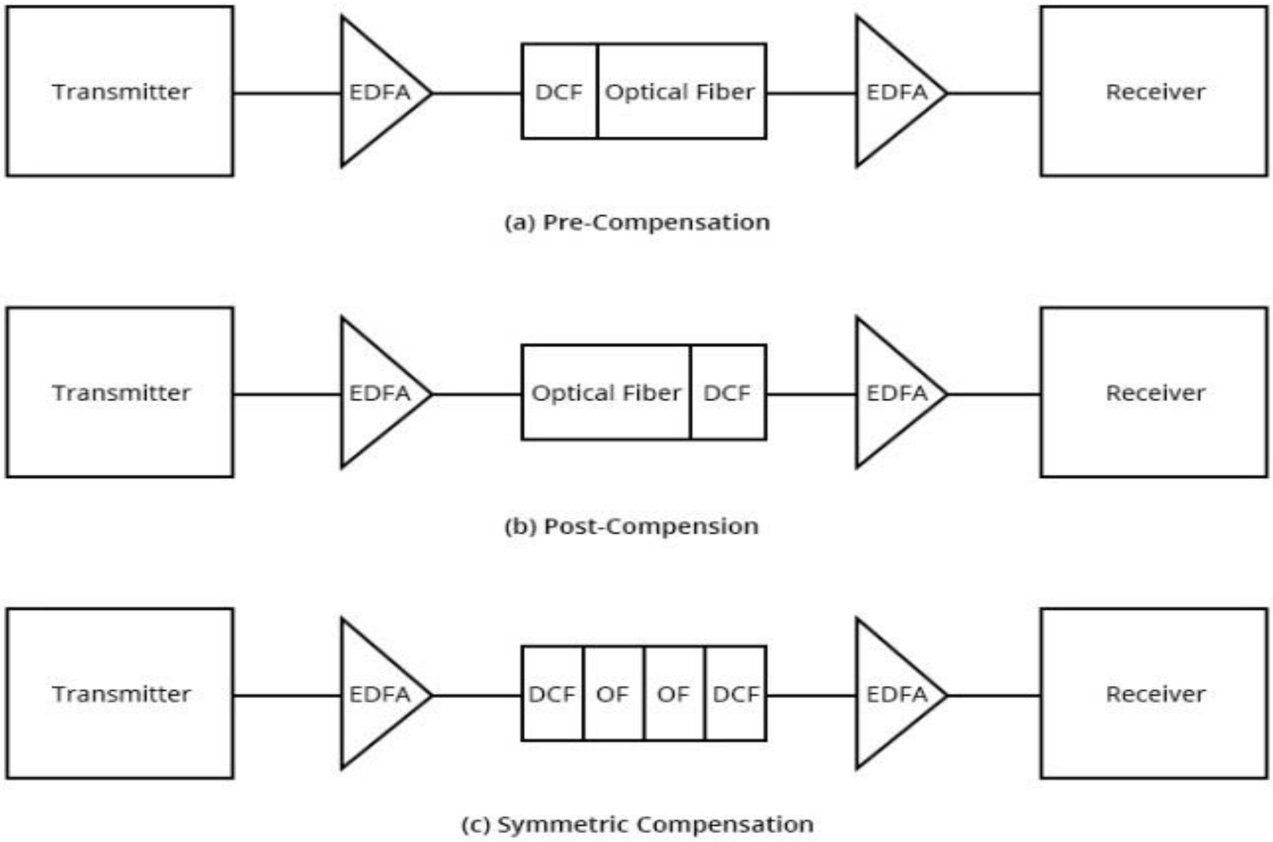


Fig. 15: Fibre Optical Network with 3 Dispersion Compensation Fibers Schemes

fibers and dispersion compensation fibers can also be employed. In the dispersion compensation fiber technique, three schemes such as pre compensation, post compensation or symmetrical compensation can be deployed as shown in figure 15**[31].**

This technique is widely used when an installed 1310nm wavelength optical fiber link needed to be upgraded to function at 1550nm for the purpose of optimization **[32].**

Intermodal or Modal Dispersion is a dispersion that occurs in multimode fiber optic cables only. In this type of dispersion, light signal can take distinct and multiple modes or paths as it propagates at different times through the fibre optic cable as depicted in figure 16. A typical multimode fiber can have up to 17 modes of light traveling along it at once **[33]**.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

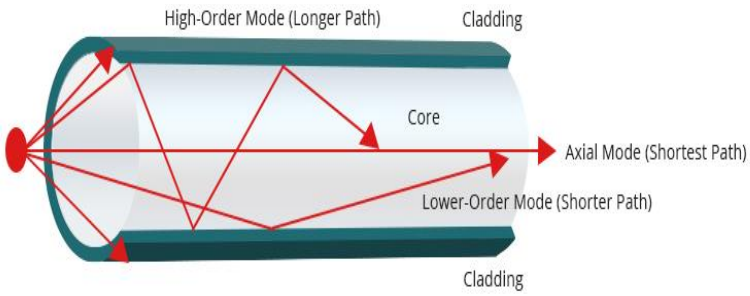


Fig 16: Intermodal Dispersion

This dispersion that is hindrance to transmission distance and bandwidth can be mitigated by using single mode fibre **[34].** Since single mode permits only one light signal to propagate through the fibre. It canalso be minimized by using mode conditioning patch cords or employing graded index fibre with a lower refractive index profile **[35].**

Polarization Mode Dispersion (PMD), this dispersion is caused by different propagation speeds of light waves with different polarization states. The difference in speed results in the delay in arrival of light signal and the broadening of the pulse at the output (receiver) as shown in figure 17. This phenomenon is due to fibre imperfection and known as birefringence. There is no problem of Polarization Mode Dispersion in perfectly uniform and symmetrical fiber optic cable.

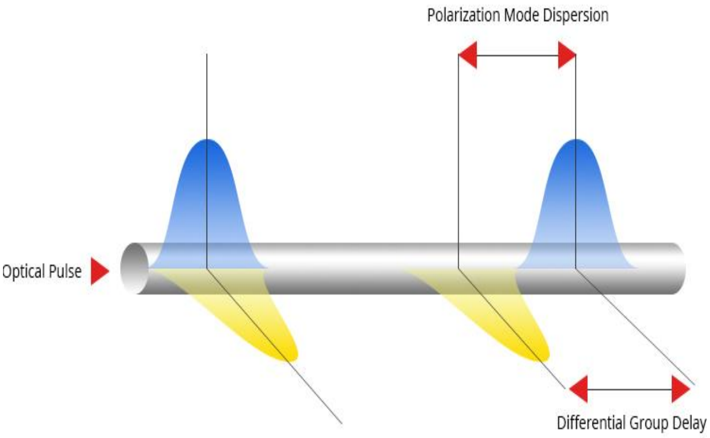


Fig 17: Polarization Mode Dispersion

However in an imperfect fiber, this dispersion can be mitigated by using polarization controllers and polarization-maintaining. Mitigation by polarization controllers can be archived by continuously regulating the state of the polarization emanating from the light signal**[36].** Polarization-maintaining fibre is a mitigation technique whereby expertly designed fibre optic cable is used to preserve the state of polarization of light signal propagating through the optical fibre**[37].**

Attenuation

Attenuation in fibre optic cable is the loss of light signal or signal strength or power during transmission between the input and the output. It is expressed as the ratio of input signal to output signal and measured in decibel (dB).This phenomenon causes the signal to be useless and unable to be recovered at the optical output or the receiver end. In this instant, the intelligence that is carried through the optical transmission signal is so degraded that voice, data or video could not be recovered. This corrupted transmission signal that has lost all detection capabilities at the receiver is in pulses and in forms of zeroes and ones (0s & 1s). There are variety of attenuations as depicted in figure 18.

INTERNATIONAL JOURNAL OF RESEARCH AND INNOVATION IN APPLIED SCIENCE (IJRIAS)
ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

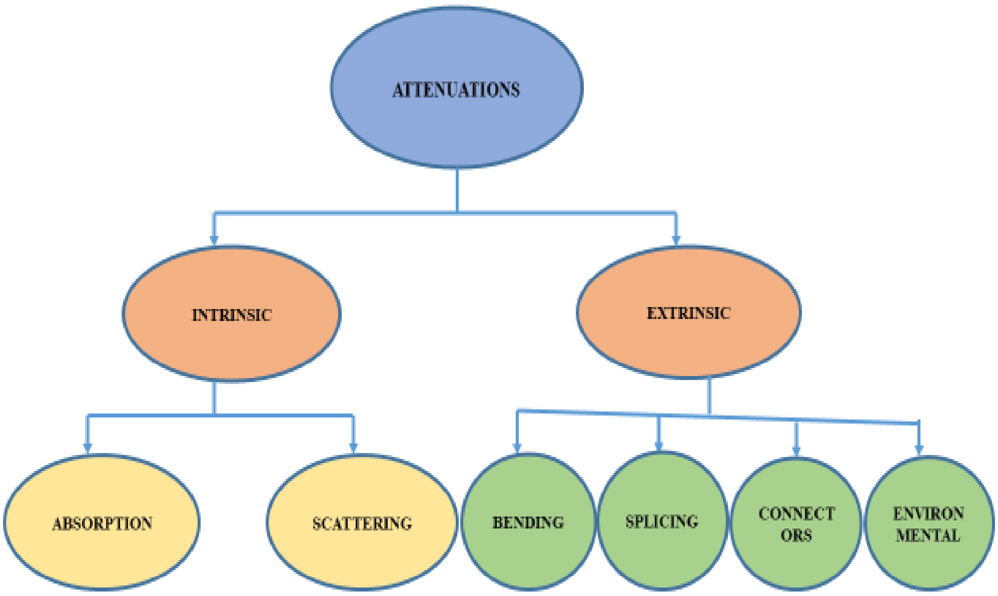


Fig 18: Types of Attenuations

Intrinsic attenuation is a loss of light signal in fibre optic cable due to the fundamental or inherent properties of the material itself. This attenuation which is also known as material attenuation is influenced by the wavelength of light signal, composition of the core and cladding of the fibre optic cable and the presence of impurities or defects in fibre. Two examples of this attenuation are absorption and scattering; they are shown in figure 19. Absorption attenuation is attenuation whereby light energy through the fibre (glass) is converted into heat by natural impurities such as molecules or hydrogen ions of the fibre material.S cattering attenuation, also referred to as Rayleigh scattering attenuation is attenuation whereby light signals deflect in diverse directions when there is interaction of waves with physical anomalies in the fibre optic cable. Here, the light waves migrating in the core are reflected into newconduit and can be lost through the cladding.

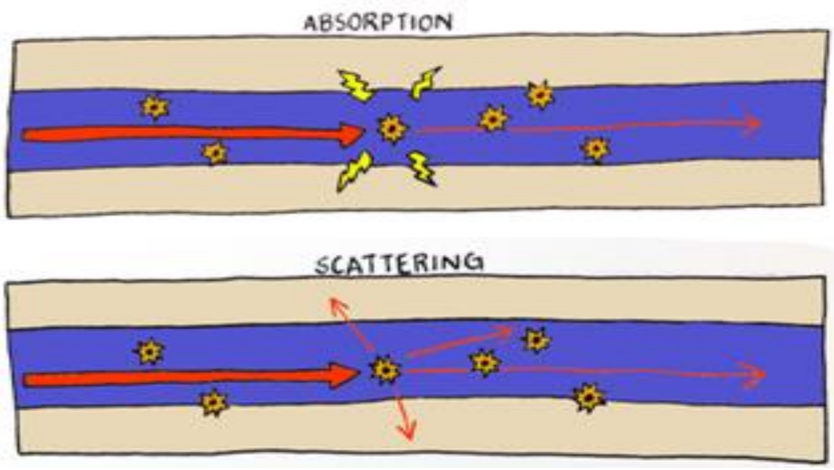


Fig 19: Absorption and Scattering Attenuations

Extrinsic attenuation is attenuation that emanates from external sources and includes: bending, splicing, fibre optic connectors and environmental losses. Extrinsic attenuation can be referred to as Return Loss or Insertion Loss depending on the loss mechanism **[38]**. Return Loss which is measured in dB is an optical power loss that is due to light signal reflecting back to the source of an optical component's boundary or interface. This attenuation is also known as reflectance and expressed as the magnitude of the reflected signal demonstrated in Equation 26:

$ReturnLoss = -10log\left(\frac{P_0}{P_1}\right)$……………………………..**(26)**

Where:

P_0= Reflected Optical Power

P_1= Incident or Input Optical Power

Insertion Loss is also measured in dB, is optical power loss and due to light signal being transmitted through component such as connector, splice, coupler or any other device that introduces an additional optical path **[39]**. It is expressedin Equation 27;

$InsertionLoss = -10log\left(\frac{P_{out}}{P_{in}}\right)$…………………………**(27)**

Where:

P_{out}= Output Optical Power

P_{in}= Input Optical Power

Bending attenuation is a loss that occurs in a fibre optic cable when the cable is sharply curved or twisted; beyond a certain limit; this defeat would cause light signals to escape or deviate from the core into the cladding or air. This attenuation comes in two mechanisms: Macro bending loss and Micro bending loss. Macro bending loss occurs in the fibre optic cable when light signal travelling through fibre is unable to make a turn and lost to the cladding. This type of attenuation is due to large-scale bending and visible to the eye **[40]**. This type of loss in fibre optic cable is shown in figure 20.

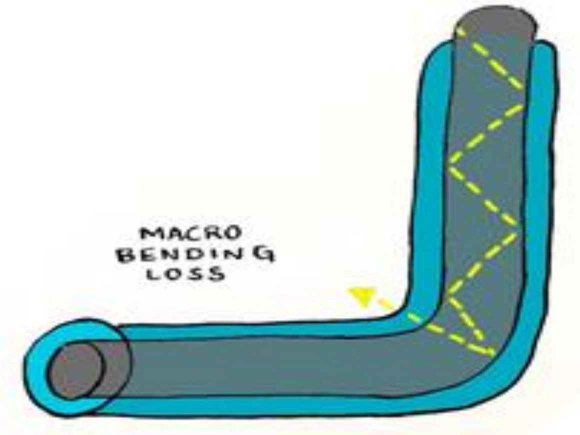


Fig 20: Macro Bending Loss

Micro bending loss is a loss in fibre optic cable due to small-scale bending in the core-cladding boundary and invisible to the naked eye**[41]**. It can occur in the manufacturing process of fibre optic cable. This loss can also occur during optical fibre deployment and may be due to temperature, tensile stress, crushing or contraction forces on the fibre. Figure 21 depicts a fibre showing micro bending loss.

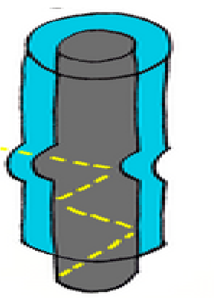


Fig 21: Micro Bending Loss

Splicing and connector attenuations, before we go further with these attenuations, we will discuss splicing and connector. Splicing is a technique used in Fibre Optic Communication to join two optical fibre cables together for permanent connection. Attenuation sets in when the end of the two fibre cables to be joined are not well aligned. A situation like this will predispose the splicing to insertion loss. This technique is mostly employed when the fibre optic cable is accidentally broken or when the cable is to be lengthened during fibre optic cable deployment. Splicing is also known as Termination or Connectorization. There are two types of splicing techniques, they are: Fusion Splicing and Mechanical Splicing. Fusion Splicing technique involves the usage of an equipment known as fusion splicer. Fusion is achieved by producing an electric arch that welds two fibre ends and thereby joining them together**[42]**.In the case of Mechanical Splicing, anadhesive gel is used to hold or secure the fibre optic cable ends one against another**[43]**. It should be noted that, this method does not use welding. Mechanical splicing is divided into two: V-grooved Splicing and Elastic-tube Splicing.

Fibre Optic Connectors are coupling devices used to join optical fibre cables. They facilitate and maximize efficient transmission of optical power between linked optical fibre cables. Connectors are used where fast connection and disconnection are required in linked optical fibre optic. They mechanically orientate the fibre cores enabling light signals to traverse the fibre optic cables without disruptions. Connectors are supposed to be precisely or well aligned to the core of the fibre optic cables; anything short of this, insertion loss will arise. The fibre optic connectors that are employed in optical Fibre Communication Systems include: ST (Straight Tip) Connector, SC (Square Connector), FC (Ferrule Connector), LC (Lucent Connector) and MTP (Multiple-fiber Pull-off). These connectors are shown in figure 22.

Fig 22: Fibre Optic Connectors

Both splicing and connectors losses emanate from misalignment, reflection or dirt.While splicing attenuation happens at the location where two or more fibre optic cables are joined together, connector attenuation occurs where two or more fibre optic cables are linked or connected to other devices. In both situations, some of the light signals are scattered or lost to the cladding. Connectorization loss may also be due to dissimilar optical fibre cable segments being spliced. Air gaps and surface roughness of connectors can also be a source of light signal lost in the fibre optic cables.

Environmental attenuation is due to imperfect surroundings of the fibre optic cables. This attenuation is influenced by external characteristics such as: stress, vibration, temperature and humidity on the fibre.

Reduction or mitigation of attenuation in fibre optic communication system is archived through various means including enhancing fibre optic materials and system components. Laying high quality fibre optic cable and handling it in the right manner during installation will mitigate signal losses. Good maintenance of fibre connectors and splice areas such as cleaning and removal of dust will reduce the effect of signal loss. The use of optical amplifier which will eliminate electrical conversion of signal and repeaters to boost signal at regenerative points can help strengthen signal level**[44].**

Emerging Mitigation Mechanism of Dispersion and Attenuation in Fibre Optic Systems

These researchers wish to bring to the fore some of the recent trends of dispersion and attenuation mitigation techniques discussed and implemented by experts in the Telecommunication Industry.

Dispersion Mitigation Techniques

Nonlinear Fiber Designs are modern effective methods by which dispersion in fibre optic communication systems can be compensated. This fibre design has the ability to neutralize dispersion in the fibre optic cable and thereby increase signal performance in terms of reliability and integrity **[45].** Digital Signal Processing (DSP) has the ability to mitigate dispersion in fibre optic communication systems by enhancing signal performance and integrity thus reducing pulse broadening and distortion**.** DSP techniques include Electronic Dispersion Compensation (EDC) and Adaptive Equalisation**[46]**. EDC has two procedures; pre-distortion and post-compensation. In the pre-distortion procedure, anti-dispersion properties are added to the signal before propagation so as to pre-recompense any anticipated dispersion; whereas in the post-compensation procedure, digital filters are used at the output or receiver to correct dispersion-induced distortions**.** Adaptive Equalisation is dispersion technique that has the ability to adjust filter factors in order to compensate for unpredictable dispersion effects in fibre optic communication systems**.**

Attenuation Mitigation Techniques

Ultra-Low-Loss Fiber is a type of fiber that is manufactured from exceedingly highly pure materials, this improvement in the manufacture leads to substantial reduction of intrinsic losses. This new technique in fibre manufacturing has gone a long way to minimize micro bending and macro bending losses **[47].** Ultra-Low-Loss Fiber has its excellent performance in high altitude areas and long haul transmission **[48].** Hollow-Core Fibre is a fibre manufactured with a hollow central air-filled core channel rather than a solid glass core **[49].** This innovative idea emanated from the fact that light propagates faster through air than glass and thereby reducing losses. Even though this innovation is at the embryos stage, its potential cannot be over emphasized. Hollow-Core Fibre has impressive characteristics that include: low latency, negligible optical nonlinearity, wide low-loss spectrum, ability to carry high power and potentially lower loss than solid-core single-mode fibre (SMFs) **[50].**

Hybrid Amplifier is also another emerging technique of mitigating the effect of attenuation in fibre optic communication systems. This technique is a combination of Erbium-Doped Fibre Amplifier (EDFA) and Raman Amplifier. EDFA is built from erbium-doped optical fibre and the most essential loss mitigating amplifier for long haul transmission in optical fibre communication systems **[51].** Raman Amplifier loss mitigation prowess also occurs in long distance transmission systems. In this compensation mechanism, the amplification process boosts the strength of the optical signals by using stimulated Raman scattering within the fibre optic cable **[52].** While the operation ofErbium-Doped Fibre Amplifier is in 1500 nm wavelength region that of Raman Amplifier ranges between 1550nm to 1600nm.

Impact of Fiber Optic Communication Systems in Today's Digital Age

There are so many factors that make fiber optic communication systems the first choice in every endeavour in the fields of Telecommunications, Broadcasting and Security. Data is propagated through optical fibre cable almost at the speed of light in space or vacuum ($3*10^8$ m/s); in fact it is approximately 70 percent. This percentage is as a result of refractive index of glass. Quantifying the 70% of $3*10^8$ m/s, indicates that the speed of light signal travelling through fibre optic cable is 210,000 kilometer per second. Another factor wealth discussing is the bandwidth; a single optical fibre cable has a bandwidth that goes beyond 60 terabits per second (Tbps). This gargantuan bandwidth enables optical fibre cables to simultaneously transmit huge volume of data. Fibre optic cables are very important in Global Communication Networks, in that, they enable international connectivity which are seamless between countries and continents. They also aid in long distance, high-speed and reliable intercontinental data transfer via the Submarine Communication Systems **[53]**. Some of the links carried by the Submarine Communication Networks are the Trans-Pacific Express and Europe-Asia-Connect and the Marea cable with a distance of more than 6,600 kilometers running through the Atlantic Ocean, United States and Europe carrying huge amount of data for global internet traffic. Others are South Atlantic 3/ West African Submarine Cable/South Africa Far East (SAT- 3/WASC/SAFE) and the South-East Asia- Middle East-Western Europe 3 (SEA-ME-WE 3); this cable spans approximately 39,000 kilometers connecting 33 countries and territories providing fast, reliable data propagation across continents. Fibre optic cables also play significant role in the deployment of 5G infrastructure in that, they aid in higher bandwidth and faster data communication speeds.

The significance of fiber optic systems will be better appreciated if its factors and parameters are compared with its counterpart data transmission system- copper cables. Fiber optic cable systems consume power more efficiently as compared to copper cable systems. While a total of 1 Watt is consumed by fibre optic network (light beams) over a distance of 300 meters, copper network (electrical signal) consumes 3.5 Watts per 100 meters **[54].** Fibre optic cables have lower signal amplification needs, for this reason, they can undergo long distance transmission with lower signal loss as compared to copper-based cables. The necessity for regeneration stations or repeater stations are few; devices at these stations are energy-intensive ones, making the overall energy consumption in optical fibre network more efficient. The reliability of fibre optic networks can never be compared with that of copper networks; since they have fewer failures, fewer service interruptions and lower maintenance expenditures. More comparison of parameters of fibre optic and copper cables or networks are as depicted in table 2.

Table2: Comparison between Fibre Optic Cable and Copper Cable

Parameters	Fibre optic	Copper
Noise	Immune	Susceptible to EMI/RFI, Crosstalk, Voltage Surge
Security	Nearly Impossible to tap	Susceptible to tapping
Handling	Lightweight, Thin Diameter, Strong Pulling Strength	Heavy, Thicker Diameter, Strict Pulling Specifications
Life Span	30-50 Years	5-15 Years
Bandwidth	60 Terabits per Second (Tbps) +	10 Gigabit per Second (Gbps)
Durability	Not affected by Corrosion & Rust	Affected by Corrosion & Rust
Weight per 305 m	2 kg	18 kg
Tensile Strength	91 kg	11 kg
Loses	3% of its Transmission Signal per 100 Meters	90% of its Transmission Signal per 100 Meters
Distance	19 km+ @ 10 Gbps	91m @ 1 Gbps
Technology	Less Likely to become Outdated because of Technology	Easily Subject to becoming Outdated because of Technological Advances

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

METHODOLOGY

The researchers demonstrated the consequences of dispersion and attenuation in fibre optic communication systems by delving into material dispersion, waveguide dispersion and attenuation coefficients. This section of the work is limited to chromatic dispersion.

Material Dispersion Coefficient

Material dispersion coefficient (D_m), is a factor that enumerates dispersion of light in a form of pulse

broadening in an optical fibre which is due to the features of the material of the fibre in question. It can be determined using expression in equation 28**[55].**It can be said to be the parameter used to evaluate the group velocity of light as it changes with respect to wavelength due to the material properties of the fibre optic cable. It is measured in picoseconds per kilometer per nanometer (ps/km.nm).

$D_m = \frac{\Delta_t}{L\Delta\lambda} = -\frac{\lambda d^2\mu}{cd\lambda^2}$...28

Where:

$\Delta_t =$ Spread in Arrival Time for different Wavelength Components

$L = Length\ of\ Fibre\ Optic\ Cable, in\ km$

$\Delta\lambda = \Delta\boldsymbol{\lambda_o} =$Spectral Width for different Wavelength Components

c = Speed of Light in Vacuum in m/s

$\frac{d^2\mu}{d\lambda^2}$= Material Property

$\lambda =$ Wavelength in nm

If D_m is negative, it implies that longer wavelengths have a shorter arrival time, that is, their travelling time is faster.

If D_m is positive, it implies that longer wavelengths have a longer arrival time, that is, their travelling time is slower.

For negative D_m,$\lambda < \lambda_0$ and for positive,$\lambda > \lambda_0$, where λ_0 =1300nm in silica glass**[56].** This is evident in table 3**[57]** where wavelengths less than 1300nm gave negative D_m and wavelengths equal to1300nm or more, gave positive D_m. The experiment in the table also factored the refractive index (μ) and group index $(\mu_g)$for various wavelengths λ_o. The group index which has a value slightly larger than the refractive index is obtained from equation 29.

$\mu_g = \frac{c}{V_g}$ 29

Group refractive index can also be determined using the expression depicted in equation 30.

$\mu_g = \mu - \lambda\frac{d\mu}{d\lambda}$...30

Where:

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

V_g = Group Velocity in m/s which is the velocity as the pulse propagates through the fiber and can be determined using the expression in equation 31.

$V_g = \frac{c}{\mu - \lambda\frac{d\mu}{d\lambda}}$……………………………………………………..31

Table 4: Pulse Widths Estimated at the various Material Dispersion Coefficients

$\lambda_o(nm)$	D_m(ps/km.nm)	τ_m(ns)
700	-172.902	21.6128
750	-135.313	16.9141
800	-106.609	13.3261
850	-84.2077	10.5260
900	-66.383	8.2979
950	-51.9441	6.4930
1000	-40.0577	5.0072
1050	-30.1214	3.7652
1100	-21.6951	2.7119
1150	-14.4511	1.8064
1200	-8.14213	1.0178
1250	-2.57872	0.3223
1300	2.38579	0.2982
1350	6.86631	0.8583
1400	10.9539	1.3692
1450	14.7211	1.8401
1500	18.2268	2.2784
1550	21.5187	2.6898
1600	24.6358	3.0795

The Pulse Width (τ_m) measured in picoseconds (ps) shows how broadened or spread out light pulses propagating through the fibre will look like at the output or the receiver end. This phenomenon is estimated using equation 32.

$\tau_m = D_m * L * \Delta\lambda_o$……………………………………………...32.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

The Pulse Width for the various wavelengths in table 3 can be estimated assuming the length of the fiber and spectral width being 5 km and 25 nm respectively. The result of this experiment is found in table 4.

Waveguide Dispersion Coefficient

Table 3: Values for Refractive Index, Group Refractive Index and Material Dispersion Coefficient at various Wavelengths

$\lambda_o(nm)$	μ	μ_g	D_m(ps/km.nm)
700	1.45561	1.47154	-172.902
750	1.45456	1.46924	-135.313
800	1.45364	1.46744	-106.609
850	1.45282	1.46601	-84.2077
900	1.45208	1.46489	-66.383
950	1.45139	1.46401	-51.9441
1000	1.45075	1.46332	-40.0577
1050	1.45013	1.46279	-30.1214
1100	1.44954	1.46241	-21.6951
1150	1.44896	1.46214	-14.4511
1200	1.44839	1.46197	-8.14213
1250	1.44783	1.46189	-2.57872
1300	1.44726	1.46189	2.38579
1350	1.44670	1.46196	6.86631
1400	1.44613	1.46209	10.9539
1450	1.44556	1.46229	14.7211
1500	1.44498	1.46253	18.2268
1550	1.44439	1.46283	21.5187
1600	1.44379	1.46318	24.6358

Waveguide dispersion coefficient (D_w) is a factor that enumerates dispersion of light in an optical fibre which is due to the structure of the waveguide in question. It can be said to be the parameter used to evaluate the group velocity of light as it changes with respect to wavelength due to the waveguide structure of the fibre

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

optic cable.It is also measured in picoseconds per kilometer per nanometer (ps/km.nm) and assessed using equation 33 **[58].**

$$D_w = -\Delta \frac{\mu_2}{c\lambda_o} V \frac{d^2(bV)}{dV^2} \quad \textbf{33}$$

Where:

Δ=Fractional Refractive Index

b= Normalized Propagation Constant

$V =$ Normalized Frequency or V-Number

μ_2 =Refractive Index attributed to the cladding

From empirical formula adapted from **[59],** the normalized propagation constant and the normalized frequency is given by equation 34.

$$V \frac{d^2(bV)}{dV^2} = 0.080 + 0.549(2.834 - V)^2 \quad \textbf{34}$$

For conventional single-mode fiber also adapted from **[60],** $\Delta = 0.27\% = 0.0027$, $\mu_2 = 1.446918$ and $V = \frac{2746.3nm}{\lambda_o}$

In this experiment, the researchers adopted the same values for refractive index (μ_2) and fractional refractive index(Δ); evaluated the normalized propagation constant and normalized frequency $\left(V \frac{d^2(bV)}{dV^2}\right)$to estimate the waveguide dispersion coefficient (D_w) at different wavelengths as shown in table 5.

Table 5: Values of Refractive Index, Fractional Refractive Index, Normalized Propagation Constant, Normalized Frequency and Waveguide Dispersion Coefficient at various Wavelengths

$\lambda_o(nm)$	μ_2	Δ	$\left(V\frac{d^2(bV)}{dV^2}\right)$	D_w(ps/km.nm)
700	1.446918	0.0027	3.923	-13.5757
750	1.446918	0.0027	3.662	-7.9040
800	1.446918	0.0027	3.432	-4.4850
850	1.446918	0.0027	3.231	-2.5541
900	1.446918	0.0027	3.051	-1.5311
950	1.446918	0.0027	2.890	-1.1221
1000	1.446918	0.0027	2.746	-1.0920
1050	1.446918	0.0027	2.616	-1.287
1100	1.446918	0.0027	2.497	-1.6781

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

1150	1.446918	0.0027	2.388	-2.1365
1200	1.446918	0.0027	2.289	-2.6325
1250	1.446918	0.0027	2.197	-3.1512
1300	1.446918	0.0027	2.113	-3.65
1350	1.446918	0.0027	2.034	-4.1504
1400	1.446918	0.0027	1.962	-4.615
1450	1.446918	0.0027	1.894	-5.0655
1500	1.446918	0.0027	1.831	-5.4773
1550	1.446918	0.0027	1.772	-5.8626
1600	1.446918	0.0027	1.716	-6.2234

The Pulse Width or the Time Taken by the pulse to traverse the length, L of the fiber optic cable is given by equation 35 **[61].**

$$\tau_w = \frac{L}{V_g} \approx \frac{L\mu_2}{c}\left[1 + \Delta\ \frac{d\ (bV)}{dV}\right] \therefore \tau_w = \frac{L\mu_2}{c}\left[1 + \Delta\ \frac{d\ (bV)}{dV}\right] \ldots\ldots \mathbf{35}$$

The empirical formula for $\frac{d\ (bV)}{dV}$ is as depicted in equation 36 **[62].**

$$\frac{d\ (bV)}{dV} = A^2 - \frac{B}{V^2} \ldots\ldots \mathbf{36}$$

Where:

A and B are Sellemeier Coefficients with the following constantsA=1.1428 and B= 0.996 obtained from **[63].**

The Pulse Width or Delay Time for the various wavelengths are as shown in table 6, the researchers adopted the length of the fibre to be 5 km.

Table 6: Pulse Widths Estimated at the various Waveguide Dispersion Coefficients

$\lambda_o(nm)$	D_w**(ps/km.nm)**	τ_w **(ns)**
700	-13.5757	2.4202
750	-7.9040	2.4200
800	-4.4850	2.4200

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

850	-2.5541	2.4200
900	-1.5311	2.4197
950	-1.1221	2.4197
1000	-1.0920	2.4197
1050	-1.287	2.4195
1100	-1.6781	2.4195
1150	-2.1365	2.4195
1200	-2.6325	2.4192
1250	-3.1512	2.4192
1300	-3.65	2.4190
1350	-4.1504	2.4190
1400	-4.615	2.4188
1450	-5.0655	2.4188
1500	-5.4773	2.4185
1550	-5.8626	2.4185
1600	-6.2234	2.4183

Attenuation Coefficient

Attenuation coefficient (α) in optical fibre is the degree at which signal strength diminishes as it transmits through fibre optic cable. It is also said to be the measure at which signal power in fibre optic cable is lost over a distance and mathematically expressed as shown in equation 37**.**

$\alpha = \frac{-10}{L} log_{10}\left(\frac{P_{out}}{P_{in}}\right)$, in dβ/km …………………………...**(37)**

Where:

α = Attenuation Coefficient

L= Length if the fibre Optic Cable, in kM

P_{out} = Power Output, in Watt

P_{in} = Power Input, in Watt

Attenuation Coefficients as depicted in table 7, is determined using the expression in equation 37. These typical attenuation coefficients and their corresponding wavelengths were adopted from **[64] [65].**

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

Table 7: Typical Attenuation Coefficients and their Corresponding Wavelengths

$\lambda(nm)$	α (dB/km)
1260	0.57
1 271	0.473
1 291	0.447
1 300	0.5
1 331	0.425
1 431	0.438
1 491	0.303
1 511	0.290
1550	0.21
1625	0.35

3.4 Total Attenuation

Total attenuation (A) is the sum of all the losses in fibre optic communication system and can be mathematically defined as shown in equation 38:

$A = \alpha L + \alpha_s x + \alpha_c y$ ………………………………………..38

Where:

$\alpha =$ Typical Attenuation Coefficient of the Fibre Optic Cable in the Link in dB/km

$\alpha_s =$ Mean Splice Loss in dB

$\alpha_c =$ Mean Connector Loss in dB

$x =$ Number of Splices in the Link

$y =$ Number of Connectors in the Link

$L =$ The Length of the Link in km

The Output Power from equation 37 can also be evaluated using equation 39

$P_{out} = P_{in} - A$……………………………………………..39

The researchers exemplified the scenario with the following project designs. The project specifications among others has attenuation coefficient of 0.3dB/km at 1550nm wavelength.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

Design a 100 km-distance Fibre Optic Communication Systems from Accra to Cape Coast and from Accra to Sogakope all in Ghana. Identical single mode fibre optic cable of light wavelength of 1550 nm is to be used in both projects. The refractive indices of the core and the cladding are respectively 1.46 and 1.44; estimate the values of the numerical aperture and the normalized frequency if the core diameter is 80μm. The optical power launched into the fibres is 160 mW, determine the receiving power in each scenario if:

a) The Accra to Cape Coast link has attenuation coefficient of 0.3dB/km, connection loss of 0.6 dB per each of the 10 connectors and 15 splices with one fusion splice loss of 0.05dB.
b) The Accra to Sogakope link has the same characteristics, in addition to 10 splices due to breakages as a result of road construction. Assuming safety margin of 2dB is admitted in both scenarios

- **Data**

L = 100 km

λ = 1550 nm = 1550 * 10^{-9} m

μ_1 = 1.46

μ_2 = 1.44

d = 80 μm = 80 * 10^{-6} m

P_{in}= 160 mW

α_{fibre} = 0.3 dB/km

$\alpha_{connection}$ = 0.6 dB * 10 Connectors

$\alpha_{splicing}$ = 0.05 dB * 15 Splice

Additional $\alpha_{splicing}$ = 0.05 dB * 10 Splice on Accra to Sogakope link

Safety margin = 2 dB

NA=?

V =?

P_{out} on Accra to Cape Coast link =?

P_{out} on Accra to Sogakope link =?

- **Solution**

NA $=\sqrt{\mu_1{}^2-\mu_2{}^2}=\sqrt{(1.46)^2-(1.44)^2}=$ **0.241**

V $=\frac{2\pi a\mu_{1\sqrt{2\Delta}}}{\lambda}\,\Delta=?$

But $\Delta=\frac{\mu_1-\mu_2}{\mu_1}=\frac{1.46-1.44}{1.46}=\frac{0.02}{1.46}=$**0.0137**

Also, 2a = diameter = 80*10^{-6}m

V $=\frac{80*10^{-6}*3.142*1.46*\sqrt{2*0.0137}}{1550*10^{-9}}=\frac{366.986*0.166*10^{-6+9}}{1550}=\frac{60{,}919.676}{1550}=$ V = **39.303**

❖ **Converting 160mW into dBm**

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

P_{in} in dBm= $10log_{10}\left(\frac{P_{in}}{mW}\right)$=$10log_{10}\left(\frac{160 * 10^{-3}}{1*10^{-3}}\right)$= **22.041 dBm**

Total Losses (A) for Accra-Cape Coast Link

(A) = α_{fibre} *Length + $\alpha_{\text{connection}}$ * Connectors + α_{splicing} * Splicing + Safety Margin

(A) = 0.3dB/km * 100 km + 0.6dB *10 + 0.05 dB *15 + 2dB

= 30dB + 6dB + 0.75dB + 2dB

(A) **= 38.75dB**

- **Total Losses (A) for Accra-Sogakope Link**

(A) = 0.3dB/km * 100 km + 0.6dB *10 + 0.05 dB *25 + 2dB

= 30dB + 6dB + 1.25dB + 2dB

(A) **= 39.25dB**

a)

P_{out} = P_{in} − A= 22.041 dBm − 38.75dB

P_{out} **= − 16.709 dBm**

- **Converting − 16.709 dBm into W**

− 16.709 = $10log_{10}$ $P_{out}*10^3$

$10^{-1.671}$ = $P_{out}*10^3$

$0.021*10^{-3}$= P_{out}

P_{out} = **21μW**

b)

P_{out} = P_{in}−A= 22.041 dBm − 39.25dB

P_{out} **= − 17.209 dBm**

- **Converting − 17.209 dBm into W**

− 17.209 = $10\log_{10}$ $P_{out}*10^3$

$10^{-1.721}$ = $P_{out}*10^3$

$0.019*10^{-3}$= P_{out}

P_{out} = **19µW**

As can be observed from the scenarios, the total loss on the link from Accra to Cape Coast was 38.75dB and that from Accra to Sogakope was 39.25dB. The output power for the respective links were 21µW and 19µW. The link from Accra to Sogakope had additional splicing loss of 0.5 dB emanating from fibre cuts due to road construction. This loss reduced its output power by a colossal 2 µW. This clearly shows the effect of attenuation on fibre optic communication system.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

The researchers, using table 7 without altering any of the design specifications, estimated the values of the total attenuations (A) and their corresponding output powers to tabulate tables 8 and 9.

Table 8: Total Signal Losses and Output Powers for Accra to Cape Coast Link

λ (nm)	**α (dB/km)**	**A (dB)**	**P_{out} (dBm)**	**P_{out} (μW)**
1260	0.57	65.75	-43.709	0.043
1 271	0.473	56.05	-34.009	0.397
1 291	0.447	53.45	-31.409	0.723
1 300	0.5	58.75	-36.709	0.213
1 331	0.425	51.25	-29.209	1.2
1 431	0.438	52.55	-30.509	0.889
1 491	0.303	39.05	-17.009	19.907
1 511	0.290	37.75	-15.709	26.853
1530	0.275	36.25	-14.209	37.932
1550	**0.3**	**38.75**	**-16.709**	**21.33**
1625	0.35	43.75	-21.709	6.745

Table 9: Total Signal Losses and Output Powers for Accra to Sogakope Link

λ (nm)	**α (dB/km)**	**A (dB)**	**P_{out} (dBm)**	**P_{out} (μW)**
1260	0.57	66.25	-44.209	0.038
1 271	0.473	56.55	-34.509	0.354
1 291	0.447	53.95	-31.090	0.776
1 300	0.5	59.25	-37,209	0.190
1 331	0.425	51.75	-29.709	1.069
1 431	0.438	53.05	-31.009	0.792
1 491	0.303	39.55	-17.509	17.742
1 511	0.290	38.25	-16.209	23.933
1530	0.275	36.75	-14.709	33.806
1550	**0.3**	**39.25**	**-17.209**	**19.011**

INTERNATIONAL JOURNAL OF RESEARCH AND INNOVATION IN APPLIED SCIENCE (IJRIAS)
ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

1625	0.35	44.25	-22.209	6.012

RESULTS AND DISCUSSIONS

The goal of this experiment is to design a practical optical fibre communication system where the zero dispersion wavelength of the material dispersion coefficient (D_m) is shifted between 1350 and 1550 nm. In between these wavelengths especially 1550 nm, optimized signal propagation will be achievedand optical amplifiers work effectively. Zero dispersion wavelength is a specific wavelength where material dispersion is negligible; increase in dispersion will occur at wavelengths longer or shorter than this specific wavelength.

In this experiment as shown in figure 23,the material dispersion coefficient (D_m) did notapproach zero at wavelength between 1350 and 1550 nm, which would have been ideal situation for us but around 1300 nm specifically 1280 nm. This indicated that the zero dispersion wavelength approximately fell on 1280 nm. This also showed that the fibre optic cable was a pure silica. Zero dispersion wavelength at around1550 nm wouldbe obtained if dispersion-shifted fibre is deployed in this project.

The waveguide dispersion coefficient (D_w) is below the zero mark thus a non-zero. Addition or combination of these two dispersion coefficients that is total dispersion coefficient (D_{Total}) have their zero dispersion wavelength approximately falling on 1320 nm. It should be noted that, the modification from 1280 nm to 1320 nm was contingent on the magnitude and sign of material dispersion in relation to waveguide dispersion. However, at this zero dispersion wavelength, chromatic dispersion is reduced and signal is propagated through the system with minimal distortion.

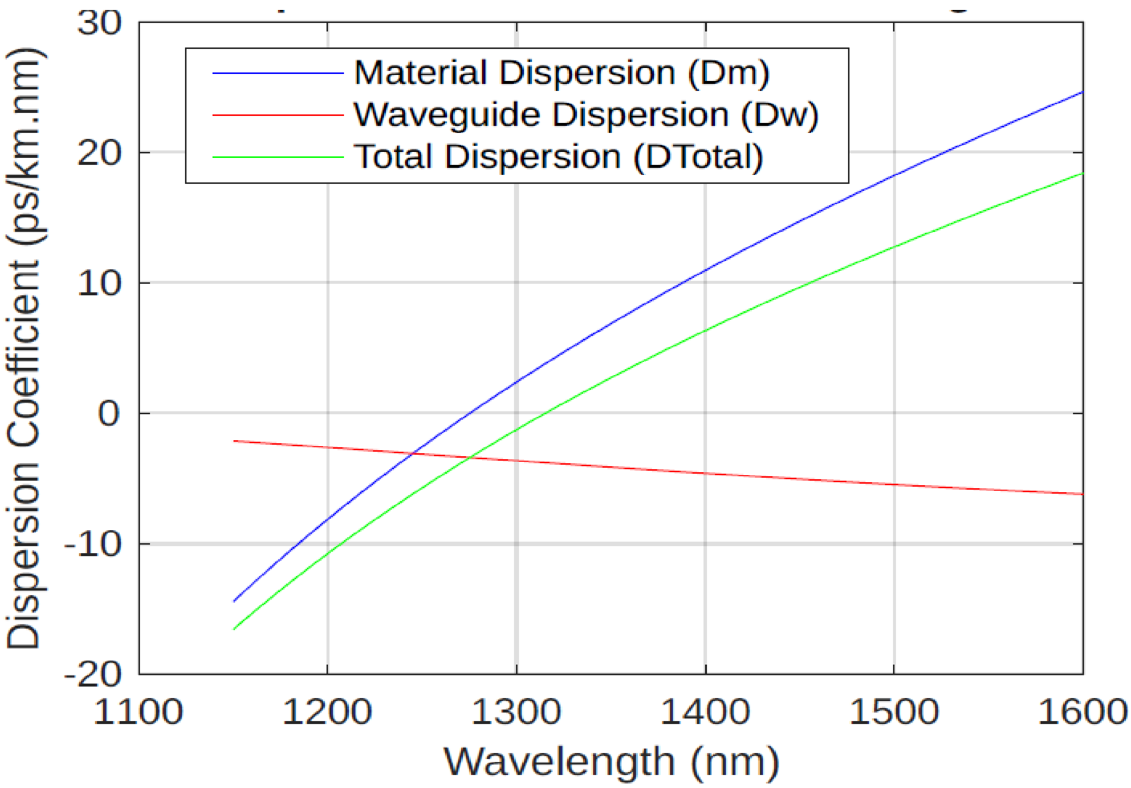


Fig 23: Dispersion Coefficients Relative to Wavelengths

Figure 24 depicted variation of pulse widths attributed to material dispersion (τ_m), waveguide dispersion (τ_w) and total dispersion (τ_{total}), with wavelengths. Even though, pulse width mainly depends on the length of fibre optic cable, however, we are analyzing the pulse widths with respect to the wavelengths. As indicated

INTERNATIONAL JOURNAL OF RESEARCH AND INNOVATION IN APPLIED SCIENCE (IJRIAS)
ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

earlier, the length of fibre cable used in this experiment was 5km. From the graph, pulse width at about2.7119 ns ascribed to material dispersion intercept pulse width at 2.4195 ns attributed to waveguide dispersion at 1125 nm and 1525 nm wavelengths respectively.

The resultant of pulse width attributed to both material dispersion and waveguide dispersion has the shortestpulse width at 2.7172 ns and the longest at 5.4978 ns. The shortest pulse width was attained at a wavelength of 1300 nm whilst the longest at 1600 nm.

Longer pulse width carries more energy than shorter pulse width this intern will enable long-haul transmission link to carry large signal with sufficient energy. Whenever the right pulse width is applied, there is improvement in the signal to noise ratio of the fibre optic system.

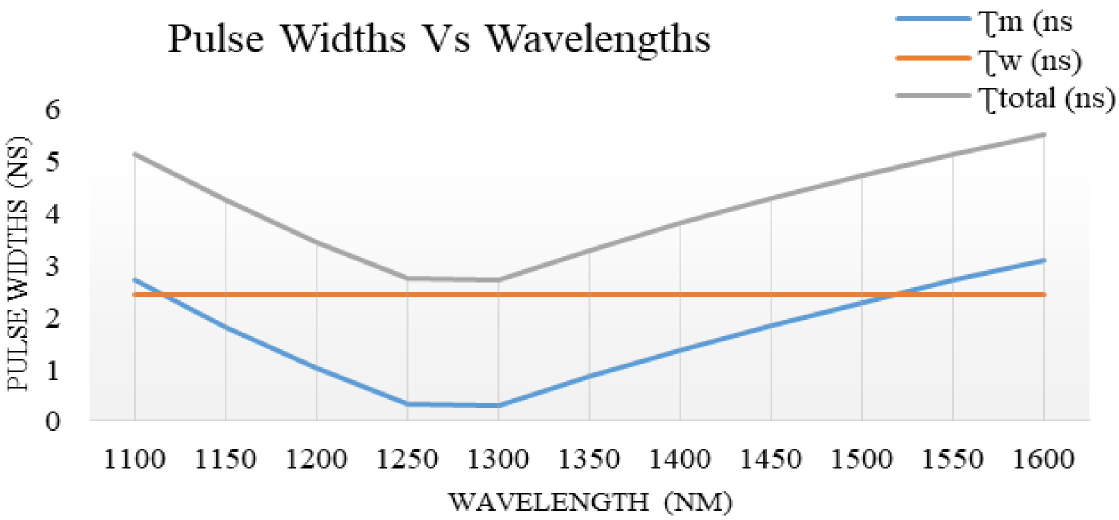


Fig 24: Pulse Widths in Relation to Wavelengths

Output power in optical fibre communication network hinges on attenuation in the course of signal propagation through the system. The higher the attenuation, the lower the output power and the lower the attenuation, the higher the output power. This accession is evident in figure 25; where the highest attenuation of 66.25 dB on the link from Accra to Sogakopegave an output power of $0.38*10^{-5}$ W (0.038 µW); the lowest attenuation of 36.75 dB gave an output power of $3.38*10^{-5}$ W (33.8 µW). The highest attenuation on the link from Accra to Cape coast was 65.75 dB, this attenuation gave an output power signal of $0.43*10^{-5}$ W (0.043 µW). Its lowest attenuation of 36.25 dB gave a receiving power of $3.79*10^{-5}$ W (37.9 µW).

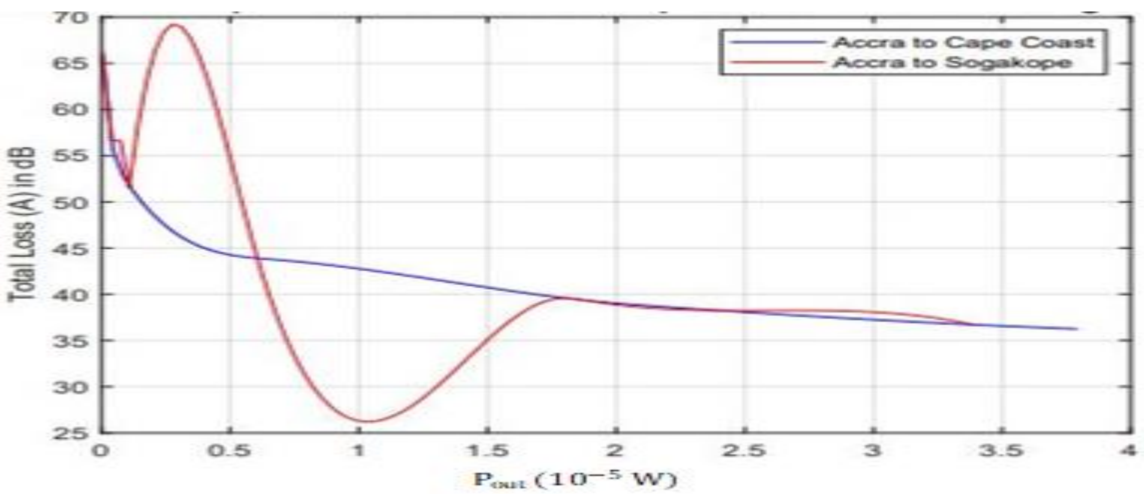


Fig 25: Total Loss Vs Output Power for Accra to Cape Coast and Accra to Sogakope Links

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

Figure 26 demonstrated compaison of output power of transmission links between Accra to Cape Coast and Accra to Sogakope. Both Accra to Cape Coast and Accra to Sogakope had their highest power outputs at 1530 nm wavelength. These power outputs were 37.93µW and 33.81 µW respectively, with a difference of 4.12 µW between them. Their lowest output powers of 0.043 µW and 0.038 µW respectively were obtained at 1260 nm wavelength. The difference between these was 0.005 µW.

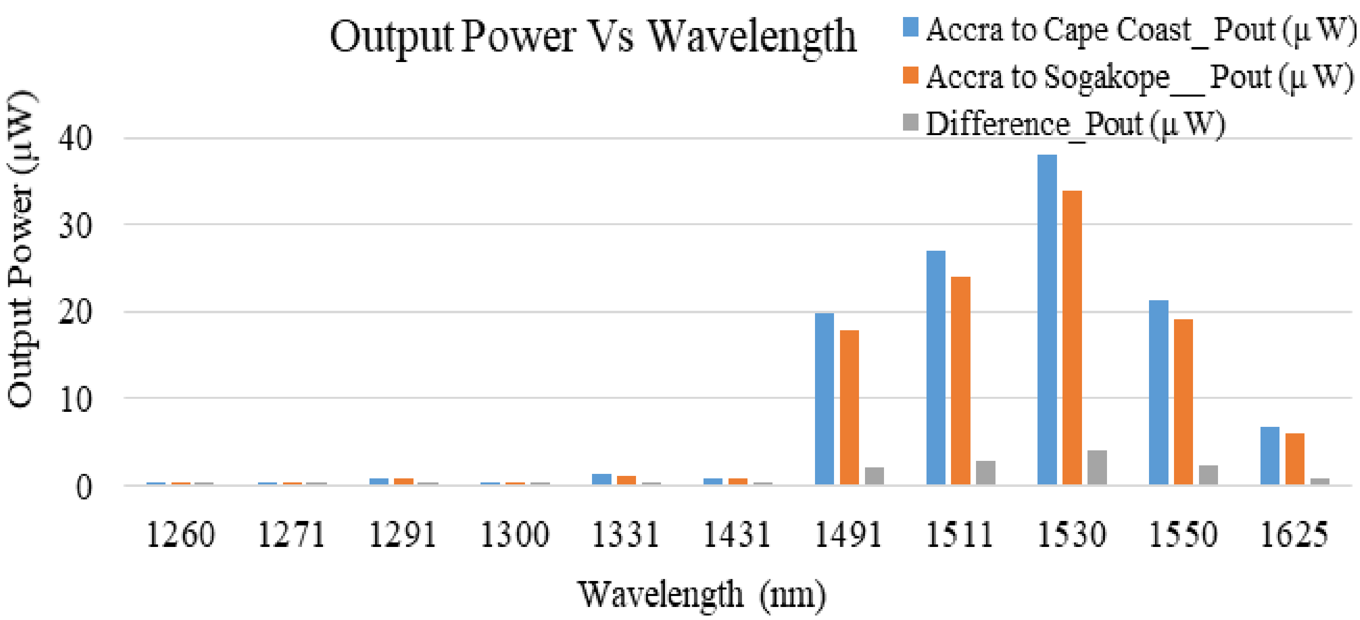


Fig 26: Comparison of Output Powers for Accra to Cape Coast and Accra to Sogakope Links with respect to Wavalength

CONCLUSION

A major component in contemporary propagation of signal infrastructure is fibre optic cable. Signal transmission in telecommunications and broadcasting have been revolutionized since the inception of this cable. Some of the factors militating against fibre optic network are dispersion and attenuation. Dispersion and attenuation cannot be completely eradicated from optical fibre communication systems; it can only be minimized. To minimize its impact on systems, designers and network engineers must adopt dispersion and attenuation standards that fall within acceptable limit.

Dispersion, though indispensable in fibre optic systems, reduces bandwidth and signal capacity. This effect can be curtailed by adopting reduction mechanism such as using single-mode fibers, dispersion-shifted fibers and signal processing techniques among others. Attenuation is also indispensable in optical network, however, standards such as connector losses between 0.25 dB to 0.75 dB and splicing losses between 0.05 dB to 0.30 dB among others will help lessen this menace.

ACKNOWLEDMENT

We are grateful to the Almighty God for the knowledge, wisdom, good hearth and insightfulness given us to write this article.

REFERENCES

1. HFCL, Optical Fiber Communication: The Science behind It, Apr 08, 2023, Available: https://www.hfcl.com › blog › optical-fiber-communication, [Accessed: May 25, 2024].

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

2. Soueid, A., Teague, E. C., & Murday, J. EMI/RFI: Electromagnetic and Radio-Frequency Interference. Buildings for Advanced Technology, pg.93-114, 2015.
3. Gupta, S.C., Textbook on optical fiber communication and its applications. PHI Learning Pvt. Ltd, 2018.
4. Mohan, S., Arjunan, V., & Jose, S. P. Fiber Optics and Optoelectronic Devices. MJP Publisher, 2014.
5. PuneMirror Bureau, Unlocking the Power of Optical Fibre Transformation in last 50 years, Apr 21, 2023, Available: https://punemirror.com/pune/others/unlocking-the-power-of-optical-fibre-transformation-in-last-50-years/cid1682122383.htm, [Accessed: Jan 24, 2024].
6. Aravind Shaji, Optical Fiber Communication, Jan 31, 2016 Available: https://www.slideshare.net/slideshow/optical-fiber-communiction-57694588/57694588 [Accessed: May 25, 2024].
7. One Monroe Titan, Fiber Optic Cable Jacket Colors Explained, Mar 9, 2022, Available: https://titanwnc.com/2022/03/fiber-optic-cable-jacket-colors-explained/ [Accessed: Jan 29, 2024].
8. Masatoshi Kagawa, Hitoshi Murai, OKI Technical Review: Multi-format all-optical-3R-regeneration Technology, Apr 2012, Available: https://www.oki.com/en/otr/2012/n219/pdf/otr-219-R11.pdf[Accessed: May 26, 2024].
9. Sabapathi.T, Chennai Rakshana, Analysis of Repeaters in Fiber Optic Communication, Mar 6, 2023 Available: DOI: https://doi.org/10.21203/rs.3.rs-2632980/v1, [Accessed: Feb 14, 2024].
10. Horvath, T., Radil, J., Munster, P. and Bao, N.H., Optical Amplifiers for Access and Passive Optical Networks: A Tutorial. Applied Sciences, 10(17), pg.5912, 2020.
11. Geeks for Geeks, Fiber Optics and Types, Sept4, 2023. Available: https://www.geeksforgeeks.org/fiber-optics-and-types/, [Accessed: Feb 20, 2024].
12. BYJU'S, Definition and Types of Optical Fiber, Sept 17, 2020, Available:https://byjus.com/physics/what-is-optical-fiber/, [Accessed: Mar 12, 2024].
13. Kuzyk, M. G. Polymer Fiber Optics: Materials, Physics, and Applications. CRC Press, 2018.
14. Mohan, S., Arjunan, V. and Jose, S.P., Fiber Optics and Optoelectronic Devices. MJP Publisher, 2014.
15. Nitin Abbey, Single & Multimode Fiber Optic Cable: What's the Difference?
16. Jan 04, 2023, Available:https://stl.tech/blog/single-multimode-fiber-optic-cable-whats-the-difference/, [Accessed: May 26, 2024].
17. 17. John, FS Community, the Advantages and Disadvantages of Optical Fiber, Dec 22, 2021, Available:https://community.fs.com › article › the-advantages-and- [Accessed: Mar 13, 2024].
18. Tutorialspoint, Difference between Step-Index Fiber and Graded-Index Fiber, Jul 17, 2023, Available: https://www.tutorialspoint.com › difference-between-ste... [Accessed: Mar 13, 2024].
19. Christian-Alexander Bunge, Thomas Gries & Markus Beckers, Polymer Optical Fibre: Fibre Types, Materials, Fabrication, Characterization and Applications, Bk. 2017.
20. Moris, Comparison of Two Optical Fibers: Glass Optical Fiber vs Plastic Optical Fiber, May 8, 2020
21. Available: https://community.fs.com/article/glass-optical-fiber-vs-plastic-optical-fibers.html, [Accessed: May 27, 2024].
22. Huawei, Plastic Optical Fiber (POF), Aug 16, 2021, Available:https://forum.huawei.com/enterprise/en/access-network-class-october-21th-community-learning-week-phase-[Accessed: Mar 13, 2024].
23. Lazzaroni, M. and Zocchi, F.E., Optical coupling from plane wave to step-index single-mode fiber. Optics communications, 237(1-3), pg.37-43, 2004.
24. Larry,Step-Index Multimode Fiber vs Graded-Index Multimode Fiber, Available:
25. https://community.fs.com/article/step-index-multimode-fiber-vs-graded-index-multimode-fiber.html[Accessed: Mar 19, 2024].
26. CBO - Connecting Technology, Multimode Fibers: Step-Index vs. Graded Index, Dec14, 2020, Available: https://www.cbo-it.de › Homepage › News, [Accessed: Mar 13, 2024].
27. S. Mohan, Fiber Optics and Laser Instrumentation: (For EEE, EI, Electronics, Computer Science & Engineering, Physics and Materials Science Students in Indian Universities), MJP Publisher – Technology & Engineering, pg. 17, Jun 6, 2019.

28. Siyavula, Critical Angles and Total Internal Reflection, Available: https://www.siyavula.com/read/za/physical-sciences/grade-11/geometrical-optics/05-geometrical-optics-07, [Accessed: Mar 14, 2024].
29. Paschotta, R, Acceptance Angle in Fibre Optics in the RP Photonics Encyclopedia, Available: https://www.rp-photonics.com/acceptance_angle_in_fiber_optics.html, [Accessed: Mar 19, 2024].
30. Circuit Globe, Numerical Aperture of Optical Fiber,Available: https://circuitglobe.com/numerical-aperture-of-optical-fiber.html, [Accessed: Mar 14, 2024].
31. Charlet, G.; Pecci, P. Ultra-long haul submarine transmission. In Undersea Fiber Communication Systems, 2nd ed.; ScienceDirect Academic Press: Cambridge, MA, USA, pp. 165–235, 2016;
32. Hui, R.; O'Sullivan, M. Optical System Performance Measurements. In Fiber Optic Measurement Techniques; Elsevier Academic Press: Cambridge, MA, USA, 2009.
33. Manpreet, Kaur, Sarangal, Himali, Bagga, Parveen, Dispersion Compensation with Dispersion Compensating Fibers (DCF), Feb 28, 2015.
34. Liyakat, Kazi Sultanabanu Sayyad, and Kazi Kutubuddin Sayyad Liyakat. "Dispersion Compensation in Optical Fiber: A Review." Journal of Telecommunication Study 8, No. 3 Pg.14-19, 2023.
35. Rahman, B., Loterie, D., Konstantinou, G., Psaltis, D., & Moser, C. Multimode Optical Fiber Transmission with a Deep Learning Network. Light: Science & Applications, 7(1), 69. 2018.
36. Larry, Types of Optical Fiber Dispersion and Compensation Strategies, Dec 22, 2021, Available: https://community.fs.com › article › types-of-optical-fibe...[Accessed: Mar 24, 2024].
37. Vázquez García, Carmen, and David Sanchez Montero, "Chapter Multimode Graded-Index Optical Fibers for Next-Generation Broadband Access.", 2013.
38. Steve Yao Polarization in Fiber Systems: Squeezing out More Bandwidth, 2003
39. Paschotta, R, Polarization-maintaining Fibers, Apr 07, 2024 Available: https://www.rp-photonics.com/polarization_maintaining_fibers.html, [Accessed: Mar 24, 2024].
40. Technopediasite, Type of Optical Fiber Losses, May 31, 2020, Available:https://www.technopediasite.com › optical fiber loss, [Accessed: Mar 20, 2024].
41. Linkwell Telecom (Shanghai) Co., Ltd., Insertion Loss (IL) and Return Loss (RL) for Fiber Connectors, May 31,
42. 2023, Available:https://www.linkedin.com/pulse/insertion-loss-il-return-rl-fiber-connectors[Accessed: Apr 02, 2024].
43. AFL HYPERSCALE, Microbending & Macrobending Power Losses in Optical Fibers, Ver 1.0 Feb 02, 2011, Available: https://www.aflhyperscale.com/wp-content/uploads/2020/06/AFLHS-Application-Note-Microbending-Macrobending-v2.pdf, [Accessed: May 27, 2024].
44. Cameron Smith, Mechanical Splicing and Fusion Splicing, Apr 2, 2022, Available: https://www.tlnetworx.com/blogs/news/mechanical-splicing-vs-fusion-splicing[Accessed: May 27, 2024].
45. Yuki Kawaguchi*, Yoshiaki Tamura, Tetsuya Haruna, Yoshinori Yamamoto and Masaaki Hirano,Ultra Low-loss Pure Silica Core Fiber, 2015.
46. Sakthivel, S., Mansoor Alam, M., Abu Bakar Sajak, A., Mohd Su'ud, M. and Riyaz Belgaum, M., Review of Compensation and Dispersion Techniques for Fiber Optic Light Path Networks. International Journal of Computing and Digital Systems, 16(1), pg.753-767, 2024.
47. Zaher Al Barakeh, Abdullah S. Karar, Raymond Ghandour, Wael Hosny Fouad Aly, Zeynep Nilhan Gürkan, Bilel Neji, Samer AlKork, Julien Moussa H. Barakat, Electronic Dispersion Compensation and Functional Link Neural Network Equalization for IM/DD links, May 1, 2023.
48. A .Ghatak & Thyagarajan, Introduction to Fiber Optic, Cambridge University Press 1979.
49. Ziru Cui, Chaowei Yuan, Chunsheng Li, The Effect of Fusion Current on Thermally Diffused Expanded Core of Splicing Ultra-Low Loss Fiber and Traditional Single-Mode Fiber, May 2021.
50. Krzysztof Borzycki, Tomasz Osuch, Hollow-Core Optical Fibers for Telecommunications and Data Transmission, Sept 26, 2023.
51. Krzysztof Borzycki, Tomasz Osuch Hollow-Core Optical Fibers for Telecommunications and Data Transmission, Sept 26, 2023.
52. Dr. Rudiger Paschotta, Erbium-doped Fiber Amplifiers, Apr 07, 2024, Available: https://www.rp-photonics.com/erbium_doped_fiber_amplifiers.html, [Accessed: May 27, 2024].

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume IX Issue VIII August 2024

53. GoPhotonics, What is Raman Amplifier?,Sep 27, 2023, Available: https://www.gophotonics.com › Technical Articles, [Accessed: May 27, 2024].
54. MEGNET-Knowledge Center, Fibre Optic Patch Leads vs. Copper Cables: A Comparison of Speed, Distance, and Reliability, Jun 20, 2023 Available: https://medium.com/@marketing.megnet.co.uk/fibre-optic-patch-leads-vs-copper-cables-a-comparison-of-speed-distance-and-reliability, [Accessed: July 24, 2024].
55. Furukawa Solutions,Energy Efficiency Day: Fiber OpticInfrastructure That Reduces Environmental Impact, Mar 5, 2023Available: https://furukawasolutions.com › knowledge Base, [Accessed: July 24, 2024].
56. M.A. Mansouri-Birjandi, Dispersion in Optical Fibers, Department of Electrical and Computer Engineering, University of Sistan and Baluchistan (USB), Zahedan, Iran.
57. W. Wang, Losses and Dispersion in Waveguides, Wei-Chih Wang Southern Taiwan University of Technology, Taiwan
58. Dr. Vipul Rastogi, Fiber Optics: Waveguide Dispersion, Department of Physics Indian Institute of Technology, Roorkee, Indian pg 6-9
59. A .Ghatak & Thyagarajan, Introduction to Fiber Optic Cambridge University Press 1979
60. ITU-T Manual 2009, International Telecommunication Union Optical Fibres Cables and Systems, ITU, 2010.
61. ITU-T G.652, Telecommunication Standardization Sector of ITU Characteristics of a Single-Mode Optical Fibre and Cable, Nov 2009.