MSc Program
Engineering Management

An overview on the fiber optic technologies

A Master's Thesis submitted for the degree of
"Master of Science"

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Affidavit

I, **JACK TARZI BASHI**, hereby declare

1. that I am the sole author of the present Master's Thesis, "AN OVERVIEW ON THE FIBER OPTIC TECHNOLOGIES", 55 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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Chapter 1: INTRODUCTION

1.1 Abstract

Every day, people use different methods to ensure they communicate, for example, voice, images, video, and data communication. The need for more efficient forms of communication has continued to rise with the increase in technological advancements. This implies that there is a high demand for large transmissions, which require advanced forms of technology. In this context, light wave technology has been introduced to cater for high data rate requirement and larger bandwidth. When photons and glass fibers combine, they provide a tremendous improvement in the transmission capability compared to the transmission that occurs through electrons and copper wires. As a result, fiber optical transmission systems have gained wide usage as they are currently being deployed in the backbone network. Fiber optics play a fundamental role in transmitting information, and this is expected to continue as technologies continue to advance. In fact, the last three decades have seen enormous strides being made in the field of fiber optics making the notion that it is expected to remain the key communication technology for the future generations.

Fiber optics uses one major principle that involves guiding of light by refraction. It is a principle that was first demonstrated in Paris by Jacques Babinet and Daniel Colladon in the 1840s. Since then, fiber optics have been used in numerous applications that involve dentistry, image transmission through tubes, television pioneer among others. On the field of telecommunication, its usage has become possible due to its flexibility and the ability to be bundled as cables. As a result, it has become more advantageous for long distance communications as little attenuation is experienced during the propagation of light through the fiber to the electrical cables. This allows long distance coverage with few repeaters. In the light of this context, the main drive of research for this thesis is to focus on the overview of fiber optics techniques particularly on communication aspects, its overview, and applications.

1.2 Historical Brief

The history revolving around the use of fiber optics dates back to 2500 B.C when the glass was first discovered and later on drowned into fibers. Since then, a lot of creative ideas and numerous inventions have come in this direction. With a particular focus on communication, data shows that light has been used in the telecommunications since the early ages of man where there were candles between ships or huge towers with torches to depict various meanings. Nevertheless, it was not until late 18th century when Claude Chappe illustrated a more complex and practical system that used light which he referred to as semaphore system as depicted in the figure below.

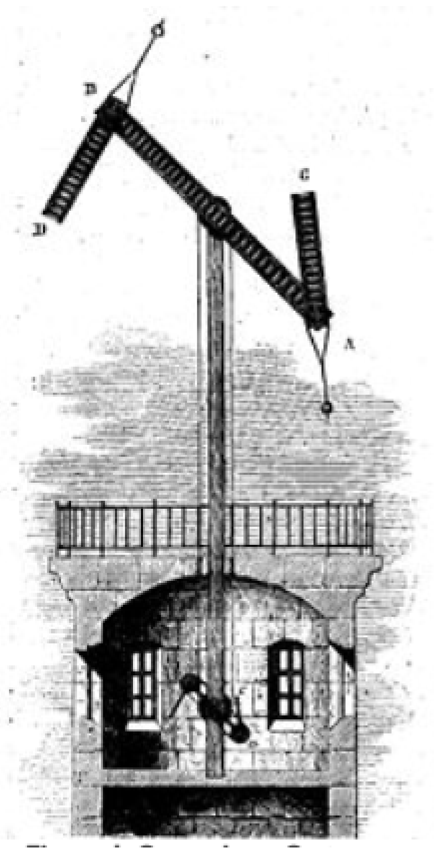

Figure 16: The Semaphore System invented by Claude Chappe

The semaphore system relied on the concept of the special towers built on their top that would assist to encode messages according to the mechanical position of the pivot and the emitted lights. This system operated with more efficiency than the postal riders where privacy and costs had become an issue of concern leading to its disadvantage.

Towards the year 1880, Alexander Graham Bell patented an optical telephone device, which he named as photo-phone although his earlier invention of the electrical telephone was cheaper and easier to implement. Bell believed that photo-phone was his greatest invention as it permitted encoded and transmission of sound signals into a beam of light with a varied intensity that represented varied tones and finally the message would be decoded as sound again.

Optical devices required a visible line of sight between the receiver and the emitter. Nevertheless, this failed miserably when attempts were made on their electrical counterparts. In the following years, research on the light subjects, for example, the phenomena of reflection and refraction were used to solve the issues. Most particularly, the knowledge of total internal reflection was used.

Total internal reflection allows the bouncing and confinement of lighting a material that is surrounded by lower refractive index (Fig. 2).

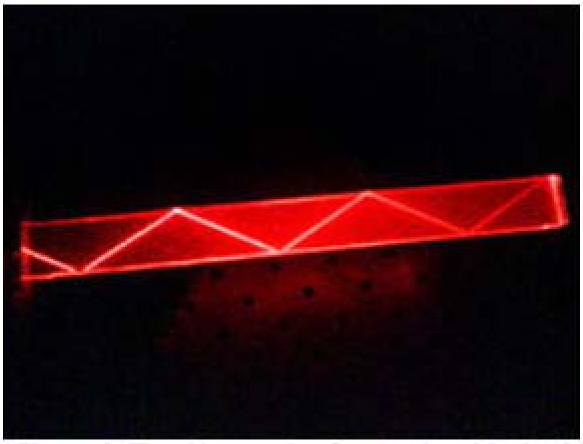

Figure 17: Laser being used to showing total internal reflection in a block of Plexiglas surrounded by air. (https://www.siyavula.com/read/science/grade-11/geometrical-optics/05-geometrical-optics-07).

Towards the beginning of the 20th century, inventors noticed that bent quartz rods had the capability of carrying light and were therefore used as illuminators in the microscope. During the first half of this century, different people attempted to explore the phenomenon of total internal reflection. The following are some of the examples.

1920: Clarenee Hansell and John Logie Baird from USA and England respectively documented the ideology of utilizing hollow pipes arrays or transparent rods to transmit images for various systems such as televisions.

1930: A Jew medical student in Munich, Heinrich Lamn reported using a short bundle to transmit the image of a light bulb filament. In fact, he is the first person known to have successfully demonstrated that images can be transmitted through fiber optic bundles.

1931: Owens-Illinois devised a technique that enabled mass production of glass fibers for fiberglass.

1939: the sales of Curvlite offered illuminated tongue depressor and dental illuminators of Lucite material, transparent plastic that Dupoint invented.

1949: Abraham C.S. Van Heel and Holger Moller Hansen of Delft and Denmark respectively began research to investigate the transmission of images through bundles of parallel glass fibers.

Inventions concerning fiber optics continued even after the first half of the 20th century. In 1954 Van Heel, Hopkins, and Kapany, increased the ability of fiber bundles to carry light further. Their innovation comprised a cladding layer (Fig. 3) that surrounded the material with a lower refractive index of the air that protected the beam of light from the noise and mitigated the cross talk between fibers.

Towards 1960, glass-clad fibers were noted to possess a typical attenuation of approximately 1dB/m, just fine for use in medicine for imaging although far too high for long distance communications.

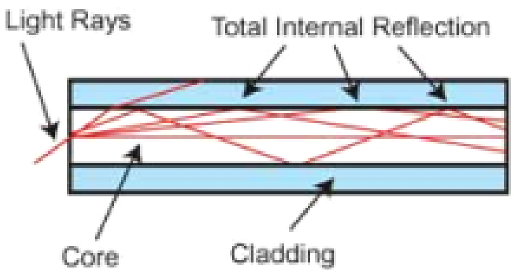

Figure 18: An illustration of basic fiber

In 1960, another breakthrough in communications revolving around fiber optics was experienced through the invention of the laser (Chapter 4 discusses this in details). This permitted the emission of light in a narrow wavelength spectrum thereby allowing the functioning at varied frequencies through utilizing the properties of light waves.

Charles K. Kao, a Shanghai engineer, researched in 1964 on different materials he was convinced that attenuation was due to impurities and that it could theoretically be reduced to about 20dB/km. Kao and colleagues presented their paper at a meeting of the IEEE in London in 1966. In the same year, there were funding from reputable sources in Britain to facilitate the study of fiber loss and attenuation. This research continued even after 1970 with more inventions being made such as semiconductor laser diodes.

Hitherto, various discoveries and inventions have been made in regards to realizing the potential of fiber optics in enhancing communication. In the process, it is worth noting that the technology of fiber optics can be utilized at different wavelengths although some factors such as material composition, the source of light, geometry among others can affect its performance.

1.2 The Significance of Fiber Optics

Kao and Hockman introduced the ideology of using glass fiber for long distance transmission of light. This realization came to take effect when low-loss glass optical fibers were fabricated for the first time in the 1970s by Corning. Almost the same time, Bell labs developed semiconductor diode lasers that could operate well at room temperatures. Later on, there was a combination of compact optical transmission and the miniature diode laser that led to the production of a series of revolutions in the communication technology affiliated with fiber optics. After 1970, telecommunication companies began embracing this technology, which has continued to gain uses in various systems of communication such as internet and cable TVs. Moreover, the demand has increased due to the need for more data with less time and long distance coverage and most importantly with less attenuation. The copper wires as already noted earlier on cannot meet the requirement of signal transmission over long distances due to limited capacity and limited speed. The optical signals in a glass medium can carry more information over long distances than electrical signals in the copper medium. After the invention of the laser in 1960, using optical systems was just possible, and the first efficient fiber optic system with law loss was developed in the 1970s, and since then the world is connected with fiber optic and slowly the copper cables are replaced or just moved out of service.

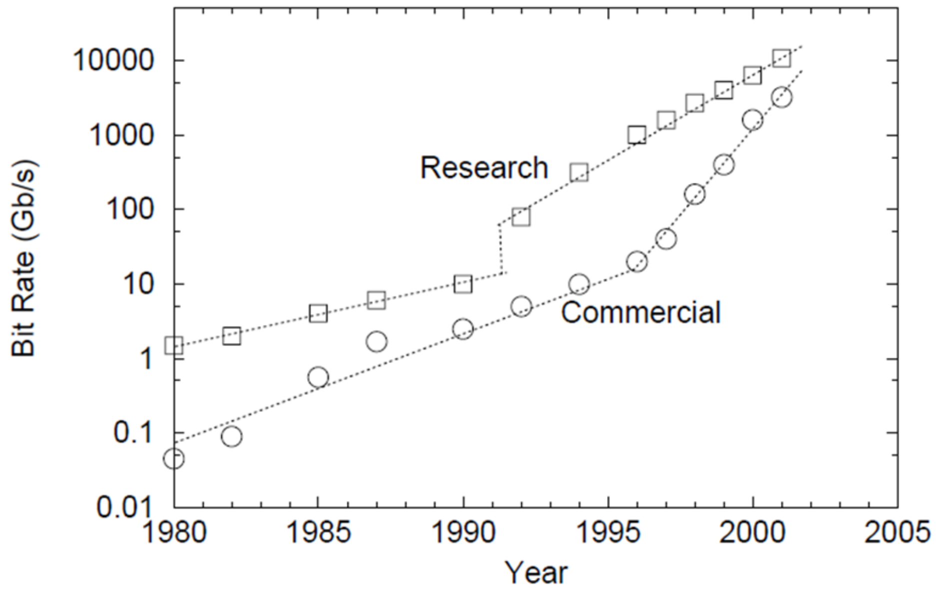

Figure 19: the increasing in the Bit rate transmitted since the 1980s that shows the needs of the bigger rate that needs to be transmitted.

(https://komunikasioptik.wordpress.com/2013/03/22/69/).

Fiber optic in the communication sector is crucial as it enables the provision of wide bandwidth costs effectively. In fact, in the modern fiber optic communication systems, the technology of dense wavelength division multiplexing (DWDM) has enabled the provision of ultra-high bandwidth communication systems.

1.3 Fiber optic communication system components

Fiber optic communication system consists of three main components: optical transmitter, fiber optic cable, and an optical receiver. ''The optical transmitter converts electrical signal to optical signal; the fiber optic cable carries the optical signal from the optical transmitter to the optical receiver, and the optical receiver reconverts the optical signal to electrical signal''. LEDs and laser diodes are semiconductor devices which are most commonly used as optical transmitters for optical systems. Photo-detector is the key part of an optical receiver. Using photo-detector effect light signal will be converted into electric signals.

As the use and demand for speed and bandwidth increase, the optical market has developed terribly fast. Now in the optical cable market, there are OS2, OM1, OM2, OM3, OM4 and OM5 fiber cable for different optical applications. Optical fibers are moved forward and being used as a standard for the telecommunication and networking field because it is flexible and can be bundled and transmit higher amount of data per second. ''It is especially advantageous for long-distance communications because light propagates through the fiber with little attenuation compared to electrical copper cables. The figure below shows that all fiber optic transmission systems use modulated light to convey information from a transmitter to a companion receiver''.

; https://www.fs.com/the-advantages-and-disadvantages-of-fiber-optic-transmission-aid-431.html

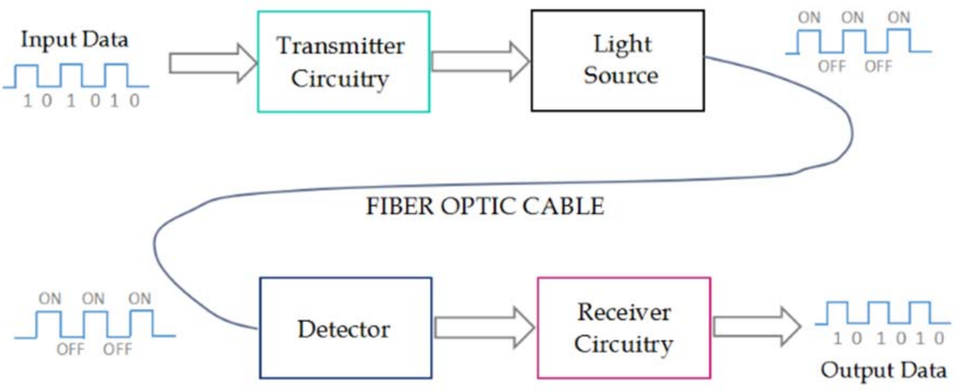

Figure 20: simplified fiber optic system where the fiber optic use modulated light to convey information from a transmitter to a companion receiver.(https://www.elprocus.com/basic-elements-of-fiber-optic-communication-system-and-its-working/) .

1.3 Advantages and disadvantages:

Advantages:

I. High Bandwidth: the fibers offer a high volume of Bandwidth, and no other cable or other signal transfer technologies can offer this Bandwidth. The fiber optic cables have the ability to transmit per unit time a far greater amount of volume data than copper cables.

II. Longer distance: in fiber optic transmission, this is only possible thanks to the law loss amount, which offered by fibers, this helps the fibers to transmit the signals over a longer distance than the copper cables.

III. Resistance to Electromagnetic Interference: In copper cables, electrical noise could affect the integrity of signals. This can also reduce the speed of transmission, and this is not possible to happen within the fibers, as it is immune to the EMI.

IV. Low-Security Risk: the growth of the fiber optic communication market is mainly driven by increasing awareness about data security concerns. Transmitted Data are converted into light signals and travel through fibers. ‘’Therefore, there is no way to detect the data being transmitted by "listening in" to the electromagnetic energy "leaking" through the cable‘’, like what we can do with the copper cables which ensures the absolute security of information.

V. Small Size: fiber optic cable has a very small diameter. Small size saves more space and makes it easier to deal with it.

Disadvantages:

I. Fragility: usually optical fiber cables are made of glass, which explains why they are more fragile than electrical wires. Also, various chemicals can affect glass, so they need more cares when deployed underground.

II. Difficult to install: it is not easy to deal technically with the fiber cable. It is hard to be spliced, and if you bend it too much, it will break. Moreover, fiber cable is critical to be damaged during installation or construction activities.

III. Attenuation & Dispersion: as transmission distance getting longer, the light will be attenuated which always required a repeater, which gives power to the pulses.

IV. Expensive: although the cost of installation for the optic systems is dropping, installing such systems and cables are still much more expensive than the copper ones.

Chapter 2: OPTICAL FIBERS AND THEIR SOURCES

2.1 Optical Fibers

Optical fibers comprise a fine cylinder of glass core, which enables the propagation of light. This core is surrounded by another layer of glass known as cladding, which is eventually wrapped by a thin plastic jacket, as shown in figure (6). The core glass exceeds the cladding glass regarding index of refraction. The ratio of these two glasses defines the critical angle θ_c:$\sin\theta_c$= n2/nl, where nl refers to the refractive index of the core and the n2 refers to the refractive index of the cladding. The total internal reflection is the major principle that enables the workability of the optic fiber. When a ray of light travels from the core to the boundary of the core-cladding at an angle that exceeds $\theta_{c,}$ the ray becomes reflected back to the core. Therefore, the signals of light can be guided within the optical fibers.

Apart from being made using of glass or polymers, most common fibers are made of Silica (Silicon Dioxide SiO_2), the fiber is made of a core in which the light guide, surrounded by a cladding which protects the core and providing the required properties, and then it can be covered by several materials for protection and several layers due to the customer needs.

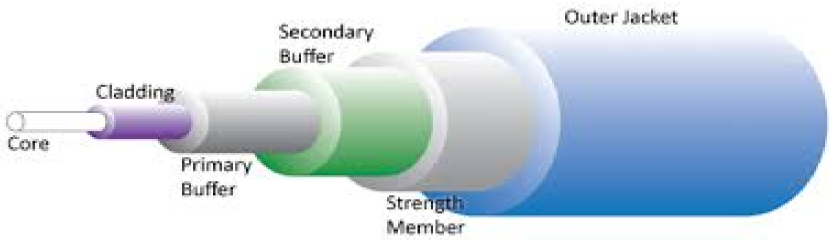

Figure 21: *fiber optic structure*. (http://www.electronicdesign.com/embedded/beyond-speed-design-tradeoffs-fiber-optic-cable) .

The core guiding structure is achieved by changing the refractive index through doping the silica glass with Germanium Oxide or with Fluorine when the first tends to raise the refractive index; the second make sure to lowers it.

To be able to guide the light and confine it in the core, the core refractive index must be higher than the claddings. Different type of fibers can be considered to achieve a waveguide structure depending on the refracting index profile (step index, graded index), or depending on the mode that can this fiber transfer (single mode, Multimode). Each fiber type has very different properties and transmission characteristics.

2.2 Types of Fibers

Telecommunications uses different types of fibers depending on their utilization and application. Most particularly, the single and multi-mode are the ones that are commonly used. These are shown together with the effect on the transmission characteristics in Fig 7.

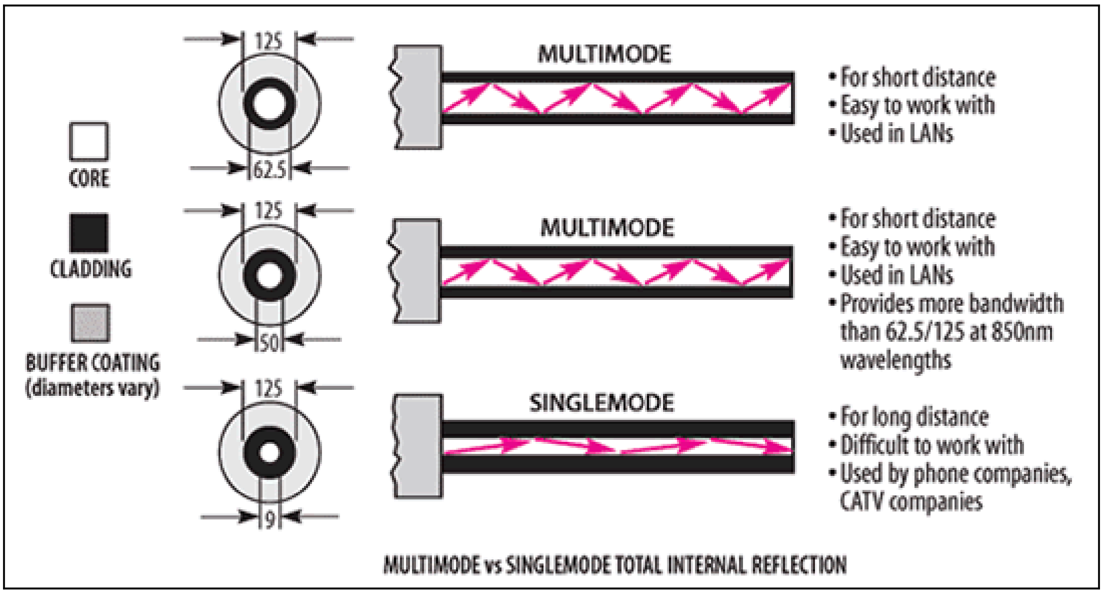

Figure 22: Optical fiber geometries.(https://www.cozlink.com/modules-a272-275-276/article-68208.html).

2.2.1 Multimode fibers:

A multimode optical fiber (MMF) is a type of optical fiber which is designed to curry multiple rays of light or multiple modes, each at a different reflection angle within the optical fiber core, are mostly used for communication over shorter distances because of the highly attenuation rate, such as within a building or a company or a campus. Typical multimode links have data rates of 10 Mbit/s over link lengths of up to 600 meters. Also, Multimode fibers normally have a core diameter of 50 to 62.5 µm. Multimode fibers divided into two types graded-index and step-index fibers.

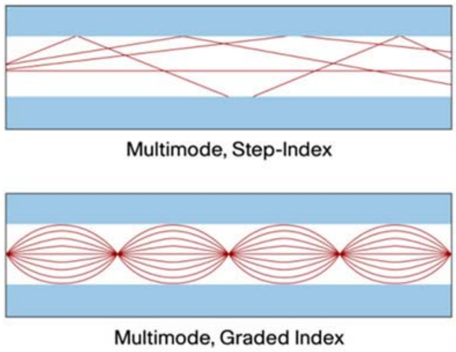

Figure 23: two kinds of the multimode fibers and how multiple light beams can travel at the same time from one side to other through the core in different angles.

2.2.1 Multimode Graded-Index Fiber

Optically the Graded-index fibers use the refractive index to guide the light and not the total internal reflection like other fibers, and the refractive index is not the same on the entire core, it decreases continually from the center to the cladding surface and dropping to the same value as the cladding. The light follows different paths in the graded-index fiber, but the light-speed changes concerning its refractive index

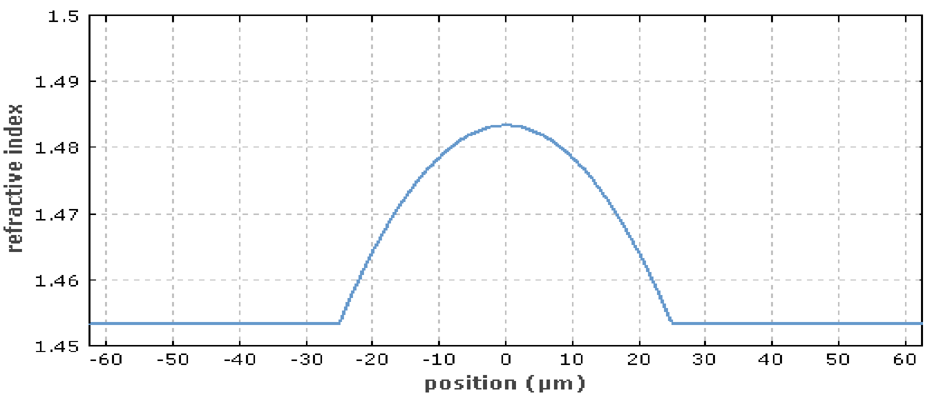

Figure 24: the difference in the refractive index of the different positions until it reaches the same cladding value. (https://www.rp-photonics.com/graded_index_fibers.html).

Thus, the closer the light travel near the core, the slower its velocity and vice versa the closer the light travel near the edge of the core, the faster its velocity. The differences between the values are not much, but it stills enough to match the longer paths of the light rays that go farthest from the axis.

The adjustment of the values of the refractive index over the core profile can influence the modal dispersion, which gives those kinds of fibers a big advantage.

Graded-index fibers are used commonly for communications as they were developed mainly for this field. Fibers of this kind may differ in the core diameters, but as standard, there are two common diameters of 50 or 62.5 µm with a uniform cladding diameter of 125 µm, although they are many that have been made with a different diameter. However, as standard and to make it easier for the market, the core with 50 µm is covered by the International Telecommunications Union (ITU) G.651 standard.

The graded-index fiber is a compromise, the big core gives the fiber the ability to collect more light than the smaller core like in the single-mode, and they can transmit the signals in higher speed in comparison with any other multimode fiber types.

A lot of researches and improvements were done on this type of fibers trying to push it forward and to get it to carry higher speed signals, but there is nothing to mention in this direction because the graded-index fibers use remain limited in small networks and domestic communication over short distances.

2.2.2The Single Mode

Also referred to as mono-mode fiber is theoretically a single strand with a diameter of approximately 8-10µm with one mode of transmission. These fibers possess a relatively low diameter, through which only one signal can propagate. Compared to multimode fiber, it has a higher bandwidth although it requires a light source with narrowed spectral width. The single mode fiber is mainly used where the applications send data in multi-frequency, for example, WDM (wave division multiplexing). As a result, only one cable is required. With single mode, it is possible to achieve a transmission rate that is about 50 times higher regarding distance than multimode. However, it is quite expensive. Regarding core, the single mode has a smaller core as compared to multi-mode. This, together with the single light wave assist in the virtual elimination of any distortion that can arise from the interfering pulses of the light thereby providing the least signal attenuation and the highest speeds in transmission in any fiber cable type.

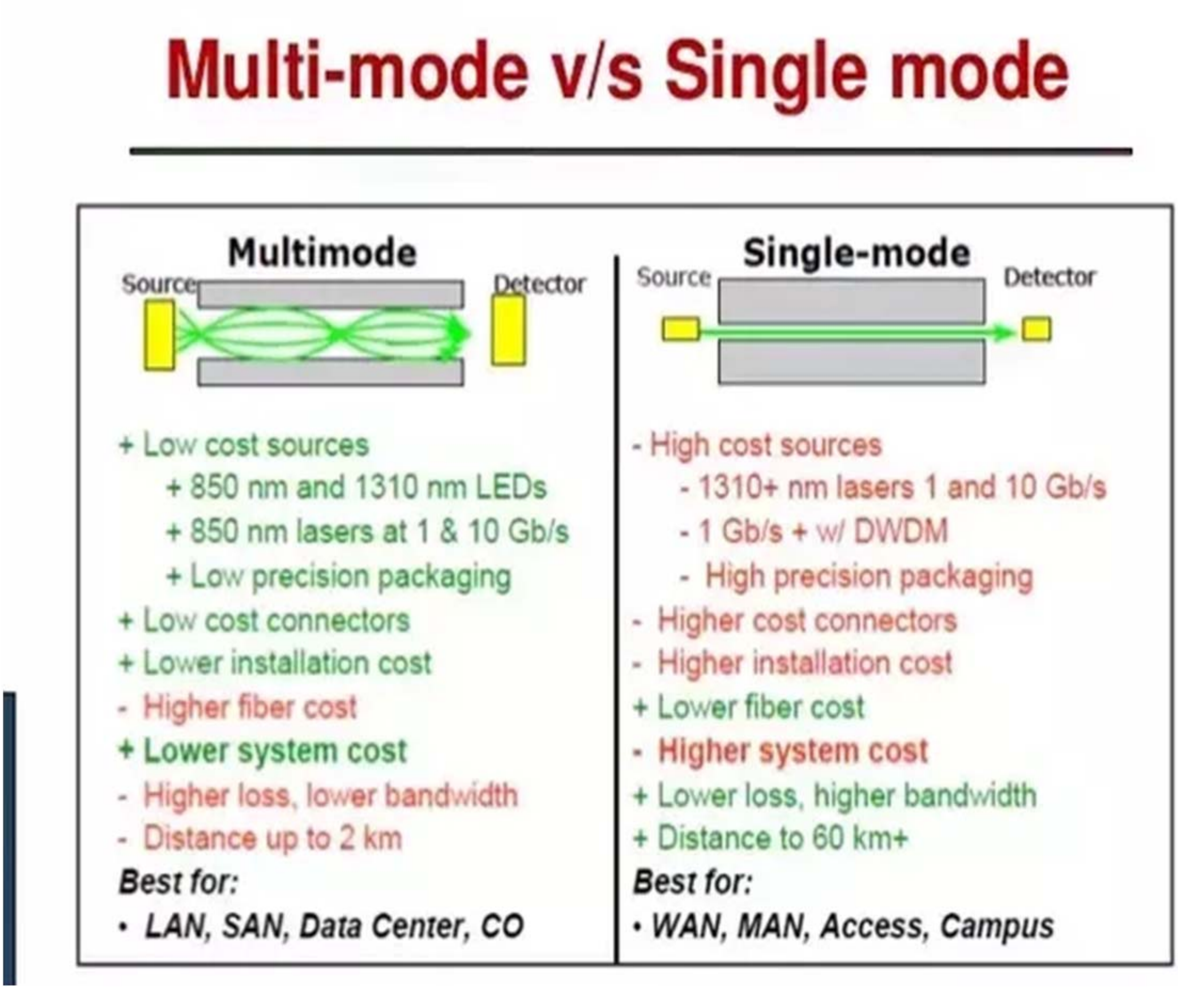

Table 2*: summary of the major differences between single and multi-mode. (https://www.quora.com/What-are-the-differences-between-single-mode-and-multi-mode-optical-fibers).*

2.3 Fiber optic splices and connectors

We may need to connect fibers to each other therefor people use connectors, or it could be done by splicing, by this, we join two or more fibers forming a continuous optical waveguide. The world accepted, and well-known splicing method is arc fusion, in which the fiber ends will be melted together with an electric arc.

An optical fiber connector allows a faster connection and disconnection than splicing. The connectors couple mechanically the two cores of the fibers, so that helps the light to pass with small losses. A good connector presses firmly the two fibers resulting a direct glass-to-glass connection avoiding any glass to air interfaces, which would be a higher rate of light losses.

A variety of optical fibers connectors are available in the market and may be selected depending on the application requirement. Examples of standard connector types are FC, SC, ST, LC, or E-2000. For single-mode fiber, ''the fiber ends are polished with a slight curvature, such that when the connectors are mated the fibers touch only at their cores''. This is known as physical contact (PC) polish. The curved surface may be polished at an angle to make an angled physical contact (APC) connection. The APC connectors have a higher loss than the PC ones, but they greatly reduced back reflection because of the angle in which the light reflected from and spread out of the core. Most sensing application based in light backscattering are sensitive to back reflection. These can be eliminated or at least greatly reduced by using angled connectors usually with 8-degree angle, which minimize the perturbation back reflection.

Figure 25: different types of connectors (http://de.flukenetworks.com/knowledge-base/dtx-efm2-fiber-adapters/fiber-optic-connector-types),.

Chapter 3: FIBER OPTICS PARAMETERS

The early theoretical studies of wave propagation in the dielectric waveguides never showed much interest in the properties of fiber optics until the surfacing of microwaves and lasers. These early studies were only concerned with the wave properties of modes that were low guided and never included the considerations of attenuation and other parameters that are significant to the transmission of information. This chapter focuses on explaining some of the progress made in the last few decades in regards improving the various parameters of fiber optics particularly in the categories of the single and multi-mode waveguide.

3.1 Basic Structural Features and Physical Parameters

Fig. 11 below displays the cross-sectional view of the refractive index distributions of single and multi-mode fiber. The crucial parameters and the typical dimensions are also provided. Multi-mode fibers possessing such specifications have been produced for commercial purposes. Nevertheless, the single mode fibers require particular specifications, which depend on the operational wavelength.

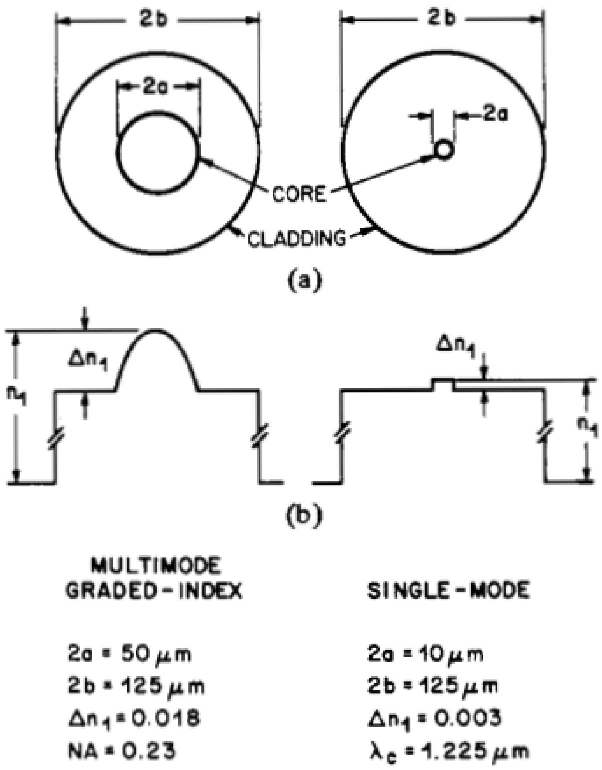

Figure 26: *Single-mode and Multi-mode structures and parameters. (a) Cross-sectional views.(b) Profiles of refractive index. (c) Typical parameters*

3.1.1Single-Mode Fiber

The focus of this part is on the step-index fiber which operates in the single mode regime if it has a *V* number of 2.405 or a normalized frequency as explained by (6 10.1109).

$$V = ka(n_1^2 - n_2^2)^{1/2} \qquad (1)$$

With:

a is the core diameter

k is 2π/λ

λ denotes the free space wavelength

n_1 and n_2 show the refractive indices of both the core and the cladding respectively.

For instance, from the single-mode fiber shown in Fig. 11 (2*a* = 10μm and $n_1 - n_2 = 0.003$), the wavelength denoting the cutoff λ_c, is 1.225 μm above which modes with the higher order cannot propagate. In the actual single mode fibers made through the process of modified chemical vapor composition (MCVD) the index, profiles tend to be graded in a way that exhibits a dip on the axis (as a result of the dopants' burn off at the center during collapsing). The impact of these perturbations is to enhance the increment of the cutoff's value of the *V* number (where n_1 now represents the maximum value of the core's refractive index according to (1) and the consequent decrement $\lambda_{c.}$ A simpler method for determining λ_c involves obtaining an effective *V* number such that:

$$V_{eff}^2 = 2k^2 \int_0^a [n^2(r) - n_2^2] r \, dr \qquad (2)$$

Where

n(r) denotes the variation of the index based on the radius

r the Radius

V_{eff}^2 = 2.405.

For example, the following case can be considered as

$$n(r) = n_1[1 - 2\Delta(r/a)^g]^{1/2} \qquad (3)$$

Where

$\Delta = (n_1^2 - n_2^2)/2n_1^2 \approx (n_1 - n_2)/n_1$

g is the coefficient of power law

so the effective *V* number is calculated as follows

$$V_{eff} = kan\sqrt{2\Delta}/\sqrt{1 + 2/g} \qquad (4)$$

The setting of V_{eff}=2.405 provides λ_c with a value that exactly concurs with that of (6) and approximately with others from (7) and (8) due to the existence of *r* in (2) the presence of central dip never seems to influence λ_c as compared to the deformation that is close to the interface of core cladding. In the perception of practice, the efficacy of single-n**o**de is always observed to be occurring at a wavelength that is somehow shorter than the one theoretically predicted since the closeness to the cutoff makes the next set of higher order modes so suffer high losses attributed to radiation from waveguide imperfections and unavoidable bends.

To select parameters with a suitable design for single mode fibers, it is important to consider the losses arising from cabling (a major source of micro-bending) and splicing. Effective calculation of these losses requires one to be well acquainted with the knowledge of modal field distribution, which requires the Gaussian function which is used to approximate the field distribution of the fundamental (HE_{11}) mode of a graded-index fiber possessing power-law profile. The approximation has been utilized in calculating the splicing loss of single-mode fibers .

Losses affiliated with micro bending rely on the parameters of the fiber in a very complicated way. Normally, field confinement that is tighter tends to mitigate losses due to micro-bending.

The findings of various scientific experiments and theoretical studies show that cabling and splicing losses are minimized in step-index fibers for *V*= 2.2 and Δ=0.002.

Since there is extension of the field of the fundamental modes into the step index (cladding) of a single mode fiber (for example 20% of the total power resides in the cladding for *V*=2.2 , the cladding must possess enough thickness to mitigate losses arising from absorption and effects of the mode stripping of the fiber jacket. Calculations have shown that when the cladding has a thickness that exceeds the core radius by ten times, then this is sufficient to ensure that only negligible losses occur.

3.1.2 Multimode Fiber

In the pursuit of meeting the requirements for telecommunications applications, multimode fibers are normally fabricated with profiles of graded-index to mitigate the intermodal dispersion. The critical parameters of the graded-index multimode fiber are the diameter of its core 2*a*, the coefficient *g* of the power law, and the numerical aperture (NA). The NA is obtained through the sine of the maximum angle (external) of the ray entering and trapped in the core and is, therefore, the measure of the light-gathering ability of the fiber. For small angles, it is approximated using

$$NA = (n_1^2 - n_2^2)^{1/2}$$

$$\cong n_1\sqrt{2\Delta} \quad (5)$$

In the case of the profiles of the power-law by (3), the efficiency pertinent to coupling η_c of a fiber butt that is coupled to LED of a similar area as the core of the fiber is estimated as

$$\eta_c = (NA)^2/(1 + 2/g) \quad (6)$$

η_c= (LED power into fiber)/ (LED power into air)

Where the fiber has a large core the area emitting LED, NC can be increased by utilizing a lens between the LED and the fiber. Based on this, another parameter of interest is total quantity of the guided modes *N* which has affiliations with *V* based on (cite 13)

$$N = V^2/2(1 + 2/g) \quad (7)$$

It is worth noting that (6) and (7) can be expressed in simple forms as

$$n_c = (NA_{eff})^2 \quad (6a)$$

and

$$N = V_{eff}^2/2 \quad (7a)$$

Where

$$NA_{eff} = V_{eff}/ka$$

and (2) defines V_{eff}.

Multimode fibers of typical graded index commercially produced have dimensions and refractive index as indicated in Fig 11. Mostly, GeO_2-P_2O_5-SiO_2 is often utilized as the constitute of the core material. The choosing of these parameters and this composition is for the provision of equilibrium among the factors that comprise transmission features, abilities of handling and splicing, physical strength, sustainability for voluminous production, and cost. An ideal graded fiber has a parameter of, 2a=50μm, Δn_1=0.018, NA=0.23, the guided modes are 192 in total at λ=1.3μm.

3.2 Dispersion

This feature dictates the upper limit of the product δ irrespective of the attenuation of the optic fiber. The term is coined to any effect of dispersion which the components of the spectrum of the signal transmitted travel at varied speeds along the fiber thereby reaching the section of the recipient at various times. This phenomenon implies that the waveform transmitted becomes subjected to progressive deformation that leads to inter-symbol interference in the reception and then the loss of power regarding the system performance

Each mode that propagates into the fiber can be defined in the perception of

- Fase speed: $v_f = \frac{c}{n_{eff}} = c\frac{k}{\beta}\, n_m \leq n_{eff} \leq n_n$ (8)
- Group speed $v_g = \frac{c}{\frac{d\beta}{dk}} = \frac{c}{n_{eff} - \lambda\left(\frac{dn_{eff}}{d\lambda}\right)}$ (9)

From the employing of β from the utilization of λ and k, it is quite clear that at different wavelengths, the components travel at varied speeds thereby leading to dispersion as Shown below.

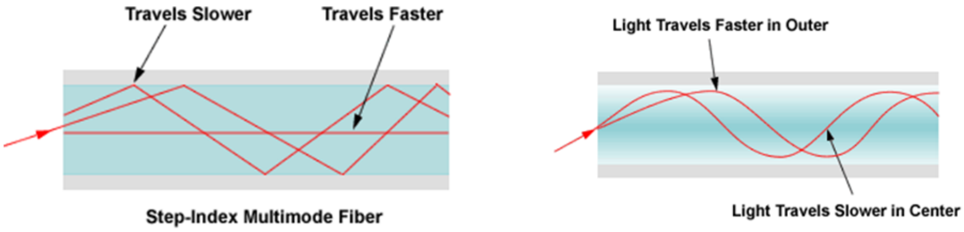

Figure 27: light travels in varied speeds leads to the dispersion.

There are two forms of dispersion:

1. Intermodal dispersion, which exists in a multimode fiber. It is caused by the modes that carry part of their energy using a particular speed. The effect can be mitigated partially through the employment of graded index fibers to reduce the differences between the 'velocity of the group' and the eliminated employing single mode fiber .
2. Intra-modal dispersion, which is noted in a single mode fiber although in a residual form. It denotes the uneven distribution of the propagated velocities for the various components of the spectrum in the electromagnetic field being propagated (cite 13). This form of dispersion is caused by two different phenomena:

a.	Material dispersion, also known as chromatic dispersion. It is linked to the index of refraction with frequency and is as a result of the occurrence of a series of resonant frequencies along the absorption spectrum characteristic of silica that corresponds to the fluctuations of their bonding electrons. For optical communications in the spectral region of interest, the wavelength leading to zero dispersion is 1276 nm .

b.	The waveguide dispersion. In this form, the constant affiliate with propagation varies non-linearity with frequency; this leads to a variation of the field confined to the nucleus. With the heightening frequency, the modal distribution to increasingly confine itself within the nucleus, taking as the index of refraction η_{eff} that denotes the efficient value of the mantle than the core. This effect has a negligible contribution to the standards of fibers and is only expressed in a slight shift of the zero chromatic dispersion towards the higher wavelengths .

That said, consider *t* to be the time taken for an impulse to travel along a stretch of fiber length *L* the group velocity dispersion will be characterized by the parameter *D* (ps/nm/km) to mean:

$$D = \frac{1}{L}\frac{d\tau}{d\lambda}$$

$$\tau = \frac{L}{v_g} = \frac{L}{c}\frac{d\beta}{dk} \qquad (10)$$

The picosecond obtains a measurement of pulse's deformation, the width of the spectral distance in nanometers and the miles traveled in kilometers. The illustration below shows the dispersion curves for the various types of fiber are illustrated in the figure below.

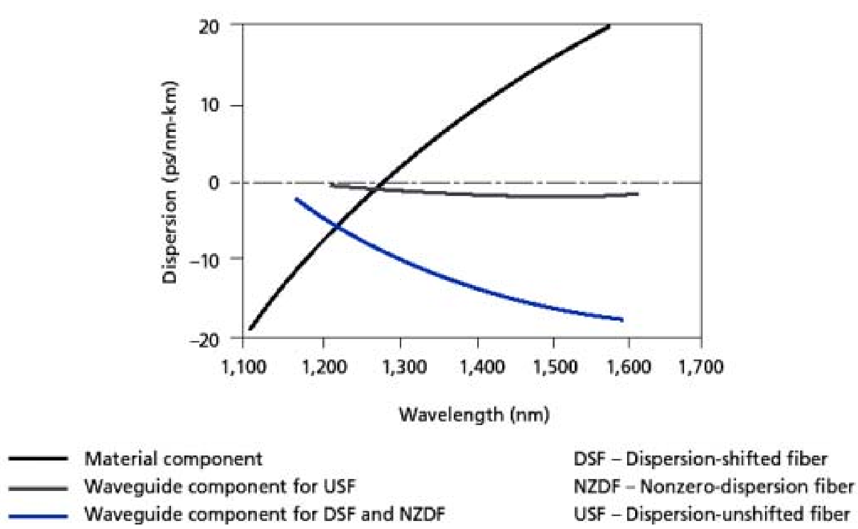

Figure 28: dispersion of various forms of fiber

Finally, there is polarization dispersion contributed to by the total dispersion (PMD, Polarization Mode Dispersion) which is responsible for the pulse broadening based on the traveled distance. The cause of this dispersion has affiliations with the fact that fiber is propagated even in the single-mode, linearly polarized, and two independent modes that are orthogonal to one another. In a situation where the fiber possesses a perfect circular cross-section symmetry, these modes seem to have a similar group velocity, in reality any factor of anisotropy whether stress or any negativity, renders the fiber birefringent. Based on this, the two states of polarization are propagated with varied speeds and can be given to a differential group delay (DGS). Agrawal (1997) denotes that such an impact is referred to as polarization dispersion.

Unlike the GVD, DGD never accumulates linearly with the distance in propagation and is therefore regarded as the random variable with the function of Maxwell probability density. In the description of the first order, PMD is characterized by assigning its coefficient, which is the average ratio between the value of DGD and the root length.

Typical value for this case are 0.1-1ps/km$^{1/2}$ or 0.05 ps/km$^{1/2}$.

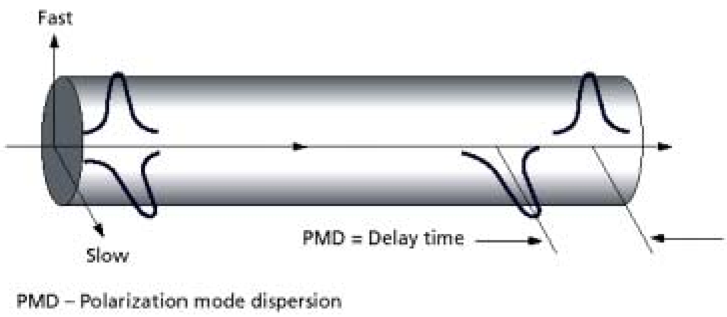

Figure 29: The polarization mode dispersion (PMD)(Agrawal, 1997)

Attenuation

The conducted analysis have depicted that attenuation has been overlooked as the possibility arising from loss during propagation in the core. Not taking into consideration that the light signal (signal attenuation), under the guidance of propagation can undergo attenuation that can be obtained using the following differential equation:

$$\frac{dP(z)}{dz} = -\alpha P(z) \quad \Rightarrow \quad P(z) = P(0)e^{-\alpha \cdot z} \qquad (11)$$

Where P (z) shows the signal strength on a nucleus' cross-section,α is the attenuation's coefficient (Agrawal, 1997). The fiber experiences an exponential decay of power with the z-axis remaining positive. For a section of fiber length, L becomes the coefficient of attenuation expressed in dB/km and can be written as:

$$\alpha = -\frac{1}{L} 10 \log \frac{P(L)}{P(0)} \tag{12}$$

The coefficient α depends on the wavelength as depicted in the following figure.

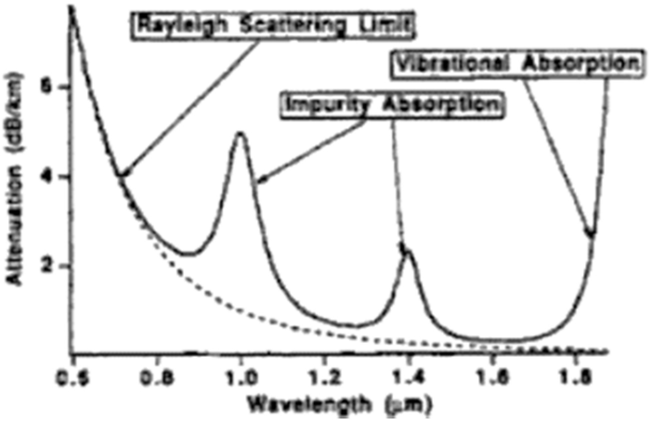

Figure 30: Attenuation characteristics of typical fiber. (http://what-when-how.com/fiber-optics/optical-fibers-and-fiber-optic-communications-part-1/).

Diverting focus to signal attenuation, it is worth mentioning that it is attributable, the various effects of materials, geometrical, joint effects, cladding and jacketing, and leaky modes.

3.2.1 Material Effects& Absorption

The loss mechanism in attenuation attributed to material effects include the light absorbing impurities such as Hydroxyl (OH) and ions of transitional metals, Rayleigh scattering through refractive index in-homogeneities frozen in the lattice of the glasses and so forth. Based on the advancements in technology for fiber fabrication, Rayleigh and infrared absorption remain the great limiters of the losses experienced . The presence of the OH – impurities in the various optical-fiber precursor materials brings about the emergence of optical losses in the fiber constituents. Deriving from the implicit research by Winch (1993), the typical precursor materials are inclusive of $SiCl_4$, $POCl_3$, and $GeCl_4$. The losses that mainly occur due to the OH - impurities/molecules are often subject to harmful effects upon wavelengths that are currently quite useful when dealing with optical communication systems.

Specifically, the occurrence of material absorption tendencies is a result of imperfections and the existence of impurities in the fiber-optic cable. According to research by Ganguly (2010), the most prevalent impurity effects occur due to the residue of hydroxyl (OH) - molecules. The residue (OH) – remnants are quite difficult to remove and thus, require the implementation of stringent production techniques that mostly correlate with the application of stain/impurity removal chemicals like chlorine and PCL_3 (Ganguly, 2010). For example, using PCl_3 or PBr_2 as a removal mechanism facilitates the reduction of the impurities to HCL and $POCL_3$, with the latter left out in the material component due to its harmless effects. The HCl is otherwise, easily removed using bromine or else, chlorine.

However, the production of optical waveguides that portrays the essential low-loss foundation to guarantee suitability for communication purposes have been necessary for most developed nations such as the United States and Europe (Xavier, da, Temporao, & von, 2011). One of the keys and effective techniques adopted into the production of OptiFiber often comprise the oxidation of the silicon tetrachloride component to necessitate the production of silica (SiO_2). Providing an inherent description of the stipulated process, the U.S Patent No. 4,217,027 ascribes towards the use of MDVD (modified chemical vapor deposition technique). From the report by Keiser (2011), the MDVD technique effectively facilitates the reduction of the harmful hydroxyl containing impurities contained in the impure liquid chlorides consisting of $SiCl_4$, $POCl_3$, and $GeCl_4$.

The efficiency of the intervention (MDVD) in reducing the amount of OH – impurities contained by chlorides of silica Optical fiber and other dopants is well exemplified by the research undertaken by Shams (2015). What is clear is that the processes (MCVD & MDVD) improve the functionality of the fiber core & cladding regions by partitioning out the impure ions under the process of oxidation. The precursor chlorides initially undergo oxidation due to the reducing capabilities of the PCL_3 or PBr_2 agents. Being the first step of the technique, the removal of the impurities is yet to be complete since the chemical components only reduce the degree of incorporation of the precursor chlorides inside the fiber cable. However, with the addition of Cl2 and BR2 chemicals, the cleaning process would be subject to completion and thus, the proper functioning/efficiency of the optical waveguide (Garg& Sharma, 2017).

3.3 Refractive Index & Fiber Optics

The composition fiber optic cables entail two major concentric layers. The two distinctive layers are; the cladding and the core. The two components have different refractive indices. The optical telecommunication fibers are mostly made of silica glasses. The purity glass is referred to as a substrate or host material. According to the research by Bourdine (2013), the silica glass is characteristic of the bulk refractive index, which normally defines the fiber cladding. As such, the addition of dopant materials onto the host material composition necessitates the foundation of the fiber core.

Facilitating the change of the refractive index of any optical fiber requires the introduction of dopants into the pure silica glass. For instance, with the addition of germanium, Winch (1993) concludes that the refractive index would be subject to increment, while the addition of fluorine will subsequently decrease the refractive index. Notably, determining the refractive indices of doped fiber optic materials calls for the use of the existing linear relationship between mole percentages and permittivity of the doped material. Developing an equation to represent the refractive index, we assume n_0 to be the initial refractive index of the host material and n_1 to be the refractive index of am_1 percentage mole of the doped material.

As such, the refractive index (n) of the m mole-percentage brought about after the introduction of the dopant material could be interpolated as follows:

$$n^2 = {n_0}^2 + \frac{m}{m_1}({n_1}^2 - {n_0}^2) \tag{13}$$

The fiber refractive index also exemplifies radial distribution characteristic, which is called index profile. The profile as indicated by the research studies by Garg& Sharma (2017) determines the essential guiding properties associated with the fiber core. The core region of any fiber cable has greater refractive index compared to the cladding region. The index profile could, however, have regions whereby the respective index is much lower than the refractive value of the cladding region. Shams (2014) insists that the modernization of various fiber designs mostly emphasizes index profiles, to ensure the attainment of quality operation under different wavelengths. An example is a multimode fiber, which comprises of a graded refractive index-profile to necessitate positive influence upon the performance of the core.

Therefore, the refractive characteristic of the core (n1) will/should always be of greater value than the respective index of the cladding (n2). In this sense, the light will be traveling through the fiber core as the external fiber cladding acts as the optical waveguide.

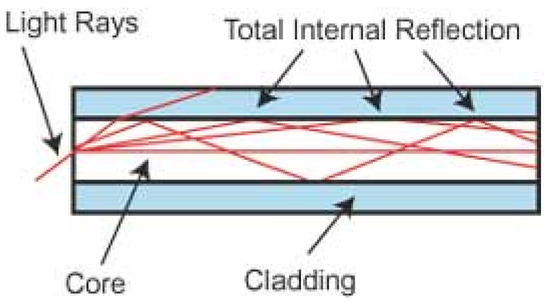

Figure 16: Representation of light propagation through a fiber optic under the principle of total internal reflection. (Poli et al.,2007)

Figure 16 above; is a representation of light propagation through a fiber optic under the principle of total internal reflection (Poli, Cucinotta, &Selleri, 2007). As indicated, light rays pass through the fiber-optic cable, and in the case, the ray of light strikes the cladding-to-core interface at angles greater than the critical angle (this is concerning normal axis), the eventual reflection of the light will be towards the core. Recognizing the “principle of total internal reflection,” the angle of incidence is always equal to the angle of reflection. As such, the lights reflected into the core by the cladding will continually experience reflection throughout its wavelength such that, it continues to bounce down the entire length of the cable. The measurement of the critical angle will be subject to the consideration of the cylindrical and normal axis of the core. For instance, if n1 were 1.557, while n2 is an equivalent of the refractive index of 1.343, then the critical angle would be 30.39 degrees (Allen, & University of California, Barbara, 2009).

3.4 Index of Refraction

The assessment of propagation of multimode signals raises essential concerns regarding the design of the optical fiber components because of the critical nature that many elements influence signal propagation.In this sense, the step index, which is the earliest designs of optical fibers, constructed with an in-built uniform index of refraction (Sillard&Molin, 2017). As such, with the inbuilt and uniform index, all energized light paths irrespective of being propagated at the core or the cladding edge were subject to traveling at the same equal speeds. Therefore, the undesired results, especially over long distance transmissions, were that the energized modes/paths in the step index fiber become supportive of different path lengths. The subsequent output pulse also experience lowered amplitude and widening of the spread (long duration of transmission). Making a comparison between the output and input pulse, there are considerably adverse effects brought about by the faster and otherwise, slower light paths (Beas, Castañón, Orozco, Aldaya, Aragón, &Campuzano, 2015).

Presenting the issue, Beas et al. (2015) insist that modal dispersion (describes the degree at which output pulses are spread in comparison to input pulse) effectively brings about the limiting of bandwidth or bit rate in the step index fiber to around 20 million signal circles. The speculated perspective hinders the effective transmission of the light in the optical fiber over distances more than a kilometer. Therefore, to enable the compensation of the above phenomenon (experienced in step index optical fibers), the graded index optical fibers are more efficient especially considering the integration of a refraction index that gradually experiences changes. The gradual change in the index is from a maximum level (at the center and brings forth a “slowing down” effect) to the minimum, which is near the cladding edge. At the minimum level, the light signals will experience a “speeding up” effect.

The gradual changes in the refractive index location as such facilitates the increment in the bandwidth of the graded-index fiber to guarantee the attainment of speeds greater than 1 billion cycles per second of transmission (1 GHz km). All the multimode fibers under use in the current tech. Telecommunication systems implement the use of the graded index. The fact that modal dispersion is of minimal concern in single-mode optical fibers, the use of graded-index is unnecessary. According to Djordjevic (2018), the improvement of the transmission capacity or efficiency of multimode fibers could as well involve the optimization of the media to be supportive of VCSEL light source. Particularly, the LED source aperture exceeds the largest optical fibers' diameter (that is optical fibers used in telecommunication links, diameter= 62.5 μm) it is a necessity to ensure that all multimode fibers are subject to energizing procedures. The above notion in essence guarantees that the pulse output can easily be of control using the graded index optical fiber. The source aperture of VCSEL source is lesser than that of the smallest optical fiber used in telecommunication transmissions (50 μm). Hence just a portion of transmission paths of the multimode fiber would be subject to energizing.

3.5 Refractive Index Profile

To facilitate the current Opti-Fiber geometry, two applicable methods could be useful to ascertain the material composition: The processes entail, direct definition of refractive index profile and the definition of 'dopant concentration profile.' Using the first method, "defining refractive index profile," abscissa values n(x) are critical to the formulation of the necessary formulae (Raisinghani&Ghanem, 2009). In essence, the abscissa values facilitate the direct interpretation of refractive index by the user's specific wavelength. Whenever necessary, the concentration of the dopant is each specified region is subject to internal calculations derived through the interpolation of given values that emanate between the separate values of the two materials ("Dopant +" and "Dopant -)." Essentially, the generation of the necessary refractive index values through the numeric formula propagated in "Dopant Materials."

Using the specified method “refractive index profiling,” Morelli et al. (2009) exclaim that the profile dispersion and material dispersion would be necessarily calculated using the known ‘Sell Meier coefficients’ that refer the articulations of “Dopant + & Dopant -.” In this case, developing the material parameters “Dopant +” and “Dopant –“could either be extendable and from internal materials in OptiFiber library or else, from the end-users specifications (Daum, Krauser, Zamzow, &Ziemann, 2002). The method is clearly of convenience when the refractive index distribution quality and wavelength are present after experimental estimations and measurements.

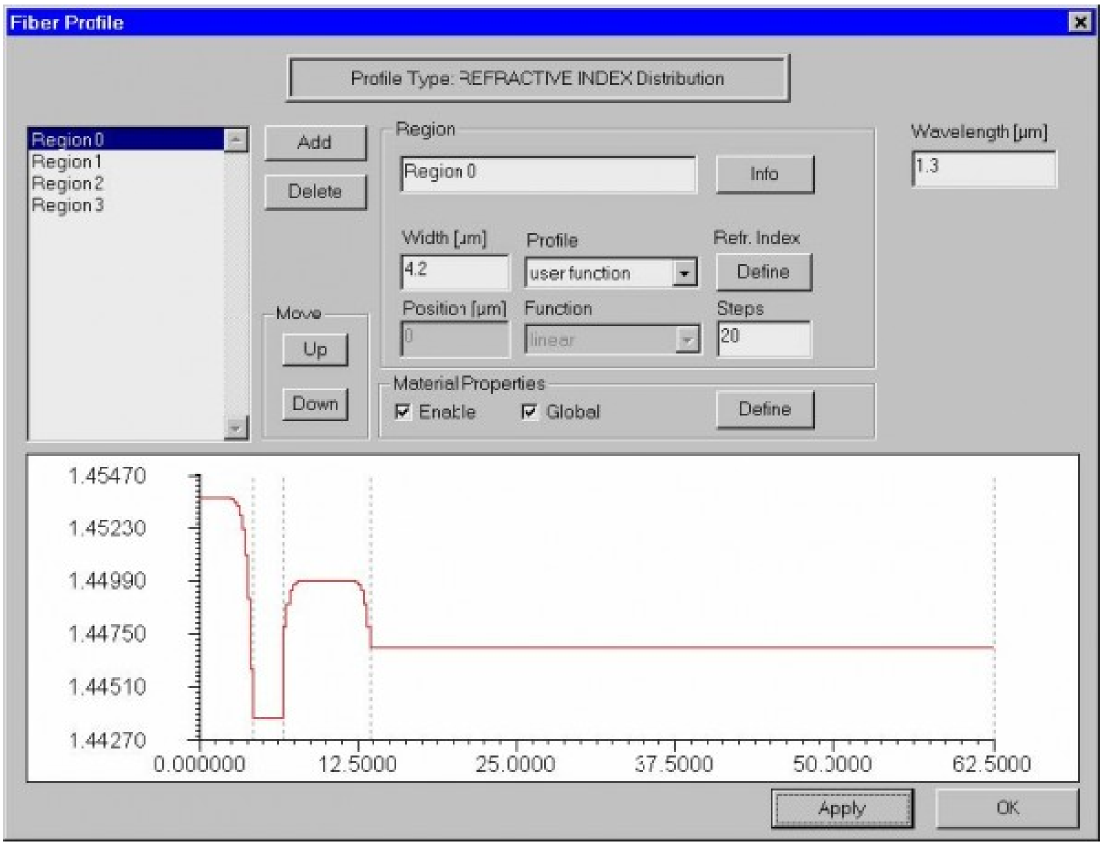

Figure 17: Refractive index profiling

With OptiFiber, “regions” facilitate a definitive and rational understanding of the symmetric fiber profile. From the figure above, the fiber profile, represent the composition of four distinctive regions. Notably, each specific region as portrayed has its distinct profile and dimension (width). Just to review the regional profiling in the fiber optic system, whereby *x* represents the coordinate of the region’s locality and *w* being an indication of the width; the following formulas (calculations) are quite evident:

Constant Profile:

$$n(x) = const \tag{14}$$

Linear Profile

$$n(x) = n(0) + x \cdot \frac{n(w) - n(0)}{w} \tag{15}$$

Parabolic Profile:

$$n(x) = [n(w) - n(0)] \cdot \left(\frac{x}{w}\right)^2 + n(0) \tag{16}$$

Exponential Profile

$$n(x) = [n(0) - n(w)] \cdot \frac{e}{e-1} \cdot \exp\left(-\frac{x}{w}\right) + \frac{e \cdot n(w) - n(0)}{e-1} \tag{17}$$

Making reference to the listed refractive index and profiling equations, n(0), n(w) delineate the refractive indices at; x=w and x=0.

The second method, which is quite simple and fundamentally used in defining and thus, the evaluation of refractive index and profile, relates to the definition of dopant concentration (Louvros, 2008). Particularly, the process involves the use of the abscissa values n(*x)* when interpreting the formulae of molar concentrations at a specified dopant point. In this sense, the calculation of the dopants' known Sell Meier coefficients is characteristic of the profile dispersion and material dispersion. The acquisition of the dopants' coefficients could be from an extendable OptiFiber material library or else, from the specific requirements suggested by the users. According to Djordjevic (2018), the stipulated method (dopant concentration profiling method) is of convenience only when there is sufficient accuracy regarding the distribution of the 'dopant concentration' in the fiber optic core/cable.

3.6 Attenuation & Wavelength

The aspect of attenuation provides a linear correlation regarding various characteristics that are mostly inclusive of chromatic dispersion (CD), PMD (polarization mode dispersion), and OSNR (refers to; optical signal-to-noise ratio). According to Dodd (2012), several factors that are often diverse bring about attenuation. The categorical dissemination of attenuation could essentially be under either extrinsic or intrinsic factor. The causes of intrinsic attenuation are subject to inherent substances present in the fiber optics constituents. Equally, extrinsic attenuation occurs due to external causes/forces like bending. Stating the attenuation coefficients *α,* the expression as brought forth by Mohammad (2009) is always under decibels per kilometer (the coefficients in this sense provides an explicit representation of the loss per each kilometer of the optical fiber in decibels).

3.6.1 Intrinsic Attenuation

The emergence of intrinsic attenuation is subject to causes emanating from the materials used when developing the fiber cable. In this case, the causes are mainly impurities and dopant residue deposits left out during the manufacturing processes. Irrespective of the precision used during the manufacturing process, Tychopoulos&Koufopavlou (2004) insist that at times, it is quite difficult for the producers to guarantee the satisfactory elimination of all the impurities. Therefore, when light traveling through the waveguide hits any impurity at their intensity and speed, two aspects are likely to occur; the impurities scatter all around the fiber optic or else, the material composition of the optical fiber necessitates the absorption of the impure components. The categorical classification of intrinsic loss could as well be under the following components: Material absorption & Rayleigh scattering (Poli, Cucinotta, &Selleri, 2007).

3.6.2 Extrinsic Attenuation

Extrinsic attenuation is subject to two causal mechanisms that are often external: macro-bending or micro bending. The specified perspectives eventually bring forth the reduction the optical power (Sillard&Molin, 2017). With the imposition of a bend in an optical fiber, the eventual placement of a strain on the fiber mainly occurs near the region of the bent. The bending strain as indicated through the research by Allen (2009)affects the refractive index and otherwise, the critical angle concerning the ray of light traveling inside a specified area. The occurrence of loss is characteristic of the refraction of light out of the core.

A macro-bend is quite visible because it is a large-scale bend, and the losses generally, are reversible after the rectifications of the bends. To necessitate the prevention of macro-bends, all optical fibers should entail specification that limits the bend radius to a minimum that should never exceed. The specified restriction as indicated by Shams (2014) determines how a bend existing in any fiber could withstand before the experience of problems relating to optical performance as well as mechanical reliability.

The second cause relating to extrinsic attenuation is the aspect of micro-bend. Micro bending is subject to arise due to imperfections inside the cylindrical geometry of the fiber throughout the manufacturing processes. Micro bending relates to tensile stress, temperature, or crushing force. Like macro-bending, the perspective of micro-bending facilitates the reduction of optical power inside the glass optical fiber. Micro bending is often localized in nature, and the occurrence of a bend might and will always be visible upon inspection. According to Raisinghani&Ghanem (2009), with usage of bare fiber, the micro bending effect could be reversible.

3.7 Rayleigh scattering

Light traveling in the core, interacts with silica molecules that exist in the core. Rayleigh scattering as such is the result of the elastic collisions emanating between the silica molecules and the light waves inside the fiber. Rayleigh scattering specifically accounts for at least 96 percent of attenuation in various optical fibers. In the case that the scattered light maintains the angle that supports forward travel within the core, the occurrence of attenuation would be minimal (Poli, Cucinotta, &Selleri, 2007). ‘’If the light is scattered at an angle that does not support continued forward travel, however, the light would be subject to diversion out from the core and thus, the occurrence of attenuation‘’.

Depending on the incident angle, some part of the light travels forward through the core to the other side, and the other portion deviates out of the propagation path and run off from the fiber core. Some scattered light mostly reflects back toward the light source. This property is useful in the “optical time domain reflectometer” (OTDR) testing fibers. The same principle is applicable during the analysis of loss associated with the localized events that often emanate from the fiber-like splices. The short wavelengths are subject to more scattering compared with longer wavelengths. As resented by Bourdine (2013) any wavelength below 800 nm will eventually be characteristic of lesser usability for optical communication because of the issue of attenuation associating high Rayleigh scattering. Otherwise, propagation that is above 1700 nm would be impossible due to extensively high losses that are mainly the results of infrared absorption (Allen, & University of California, Barbara, 2009).

3.8 Chromatic Dispersion

Chromatic dispersion entails the spread of light pulses as it travels up and down the fiber optic cable. Light under its dual nature ought to be subject to considerations/assessments from electromagnetic wavelengths as well as quantum perspectives. As indicated by Hioki (1998), this enables businesses/individuals to quantify the light as waves and as quantum particles. During the light propagation, all the spectral components ought to be characteristic of effective propagation. ‘’These spectral components travel at different group velocities that lead to dispersion called *group velocity dispersion (GVD)* ‘’. The dispersion brought forth due to GVD is otherwise, referred *chromatic dispersion* due to the wavelength dependence. The effects of chromatic dispersion as presented throughout the research by Clarke,& Poole (2013) are the pulse spread.

As the pulses diffuse, or broaden, they lean to overlap and are no more detectable by the receiver as 0s and 1s. ‘’Light pulses launched close together (high data rates) that spread too much (high dispersion) result in errors and loss of information‘’ (Tychopoulos & Koufopavlou, 2004). Chromatic dispersion occurs because of the range of wavelengths present in the light source. Light which is generated from LEDs or lasers and includes range of wavelengths, each of those wavelengths travels at a different speed. Over distance, the light pulse would spread in time because of the different in the wavelength speeds. This is of most importance in single-mode applications (Xavier, Temporão, & von, et al. 2011).

Modal dispersion is of significant value in the multimode applications. According to Keiser (2011), the stipulated perspective is mainly referable to the various light traveling modes traveling down the fiber arrive at the receiver under different wavelengths and intensities thus, causing a spreading effect. Chromatic dispersion commonly occurs under major bit rates. Chromatic dispersion can be compensated for or mitigated using dispersion-shifted fiber (DSF). ‘’DSF is fiber doped with impurities that have negative dispersion characteristics‘’. The measurement of Chromatic dispersion is in ps/nm-km. A 1-dB power margin is typically subject to reversals to enable accountability for the various effects that emanate because of chromatic dispersion (Frisken, Clarke, & Poole, 2013).

3.9 Optical Signal-to-Noise Ratio

The optical signal-to-noise ratio (OSNR) puts forth the specifications on the ratio associating with net signal power and further, net noise power. The specifications as such facilitate the identification of signal quality. The compensation of attenuation can necessarily be with the amplification of the optical signal. The optical amplifiers, however, amplify both the signal and the noise (Raisinghani&Ghanem, 2009). The loss of the signal will occur over distance when the receivers fail to distinguish between the signal and the noise.

According to the research by Morelli (2009) regeneration would be of essence to mitigate the undesirable effects before rendering the system unusable and further, ensure better signal detection by the receiver. The optical amplifiers in any sense facilitate the addition of certain noise amounts to the channel. Further, active devices like lasers will also add noise to the optical fiber. Passive devices, which are inclusive of taps and fiberglass, might also bring about the addition of noise components. With any system design, optical amplifier noise is often subject to explicit considerations as the predominant source for OSNR degradation and penalty (Tychopoulos et al. 2004).

OSNR is important and is fundamental to the system design. The parameter that is put into consideration by most designers entails the Q-factor. The Q-factor, as functionality of OSNR, facilitates the provision of qualitative description and essentially influences the receiver performances. The Q-factor suggests that the minimum signal-to-noise ratio (SNR) necessarily affects the specific BER for the given signal. The measurement of OSNR is in decibels. In this sense, the higher the bit rates, the higher the OSNR ratio requirements. Providing an example, Willner et al. (2013) exclaim that for OC-192 transmissions, OSNR should be between 27 and 31 dB while for OC-48 the OSNR ought to be 18 to 21 dB.

3.10 Signal Interference

Light signals that are traveling through a fiber-optic cable are often immune from electromagnetic (EMI) and “radio-frequency interference” (RFI). There is also minimal interference from lightning and high-voltage current. Fiber networking is best under conditions whereby EMI, as well as RFI interference, is heavy and characteristic of safe operation, which ought to be free from sparks and static interferences (Ivan William, &Bane, 2010). The desirable and otherwise specified property influencing fiber-optic cable essentially makes it the medium best suitable and of choice for bio-medical and industrial networks. There is also a better possibility of placing fiber cable into the various natural-gas lines with this the pipelines would be useful conduits.

3.11 Polarization Mode Dispersion

Polarization mode dispersion (PMD) occurs due to asymmetric distortions of the fiber that results in the imperfection of the cylindrical geometry. The fiber is nota cylindrical waveguide, but its description could be thought as an imperfect cylinder due to its physical dimensions that are perfectly constant. The mechanical stress exerted upon the fiber is characteristic of the extrinsically induced stresses, and bends that are in essence brought about by cabling, splicing, and deployment, as well as the various imperfections from the manufacturing process in means and reasoning behind the variations that exist in the cylindrical geometry.

Single-mode optical components and fiber are supportive of one fundamental mode, which consist of orthogonal polarization modes. The asymmetry facilitates the introduction of small refractive index differentials for the two polarization states. This characteristic is well-renowned as birefringence. Birefringence in this sense causes a specific polarization mode to necessitate light to travel faster, thus resulting in differences in propagation time. The stipulated aspect is understood to be differential group delay (DGD).

DGD as a unit of measurement facilitates the description of PMD. DGD measurements are always in picoseconds. When a fiber acquiresbirefringence, the effects entail the emergence of a propagating pulse that facilitates loses in the balance between the different polarizations components. According to the research by Allen (2009), the issue above leads to a stage whereby different polarization components that are traveling at different velocities, create pulse spread. The classification of PMD could be as first-order PMD, also called DGD, and the second alternative order PMD (SOPMD). In this case, the SOPMD emanates due to a dispersion that mainly occurs due to signal's spectral width and wavelength dependence.

PMD issues are quite minimal at low bit rates, but Raisinghani&Ghanem (2009) insists that the aspect will be impactful on the optical fiber at bit rates in excess of 5 Gbps. PMD is well noticeable under high rates its significance is well pronounced as the source of impairment when dealing with ultra-long-haul systems.

The achievement of PMD compensation is mainly through use ofPMD compensators, which contain dispersion maintenance fibers that present high degrees of birefringence (Drake & Photonics 40, 1985). The introduction of birefringence will essentially negate the effects generated from PMD over the entire length of the transmission waveguide. The creation of error-free transmission as such requires the implementation ofPMD compensation, which is quite useful as a technique for long-haul networking.Particularly, ‘’the PMD value of the fiber is the mean value about time as well as the frequency of DGD and well denoted as ps/ km‘’.

3.12 Performance Considerations

The light entering into the core is subject to external acceptance angle, which is directly proportional to the fiber-optic cable efficiency. In this sense, the greater the light amount coupled into the core, the impact entails lower bit error rate (BER). According to Ganguly (2010), the specified aspect is due to the fact that much of the light would reach the end receiver. Notably, the attenuation experience by the light rays during the propagation down the core has an inverse proportionality with the efficiency of the optical cable used. In essence, with a lower attenuation of the core, there will be a lower BER. What is also clear is that the lesser the chromatic dispersion in the propagation of the ray down the core, the signaling rate would be faster and thus, the higher end-to-end data transmission from source. Therefore, the major factors that are impactful on performance considerations of any optical fiber entail; the fiber size, composition elements of fiber, and mode used in the propagation of light.

3.13 Self-Phase & Cross-Phase Modulation

The issue of phase modulation in the optical signal is made reference by Louvros (2008) as self-phase modulation (SPM). In this case, SPM primarily occurs due to self-modulation that occurs in pulses. The emergence of SPM is mainly under single-wavelength systems. With high bit rates, SPM often necessitates the cancelation of dispersion. As indicated by the research by Garg& Sharma (2017), SPM will always increase with every increment in signal power levels. Fiber plant designs bring about strong input signals that enable the transmission fibers to overcome the perspective of linear attenuation and losses incurred due to dispersion.

However, there is a need to be considerate of the receiver saturation and thus, nonlinear effects like SPM, to enable the eventual realization of proper functionality of the optical fiber. SPM results in phase shift and a nonlinear pulse spread. As the pulses spread, they tend to overlap and are no longer distinguishable by the receiver. The acceptable form with system designs' and capability to counter SPM effect dictates we take account power penalty, which should keenly be undertaken as an equivalent of the negative effects imposed by XPM. Particularly, a 0.5-dB power margin should be put to the reservation to ensure accountability for the effects relating to SPM under high power levels and bit rates.

Cross-phase modulation (XPM) is nonlinear and mainly affects else limits the system performance throughout wavelength-division multiplexed systems (WDM). XPM, in this case, is the phase modulations that often arise with adjacent signal interferences within same fiber. From the research by Hioki (1998), XPM provides an implicit correlation of the combination that exists between dispersion and signal transmissions in effective regions of the cable cladding.

CPM originates from different carrier frequencies that exist in independent channeling systems and is inclusive of associated phase shifts that eventually cause interferences between the signals. The phase shift is mainly characterized by the *walkover* effect, such that two pulses under different bit rates and differentiated group velocities interfere with each other's wavelengths. As a result, slower pulses experience the walkover and essentially induce the limiting phase shift effects. The total phase shift affected by the net power of all the channels and the amount of bits in the output of those channels.

XPM can be subject to mitigation, but this requires careful selection of the unequal bit rates to enable the attainment of the necessary adjacency in the WDM channels. Particularly, XPM severity in the long-haul WDM networking and acceptable norm under the system design facilitates the counteraction of this effect by taking into account the aspect of power penalty that is always equivalent to the negative effect imposed by the XPM notion.

3.14 Intensity & Fiber Displacement Sensors

The angular displacement sensor is well structured as presented in the figure below. The sensor is characteristic of the composition of double circle-coaxial fiber bundles that are perpendicular to the plane, and another left optical bundle fiber as well as the right "optical fiber bundle."

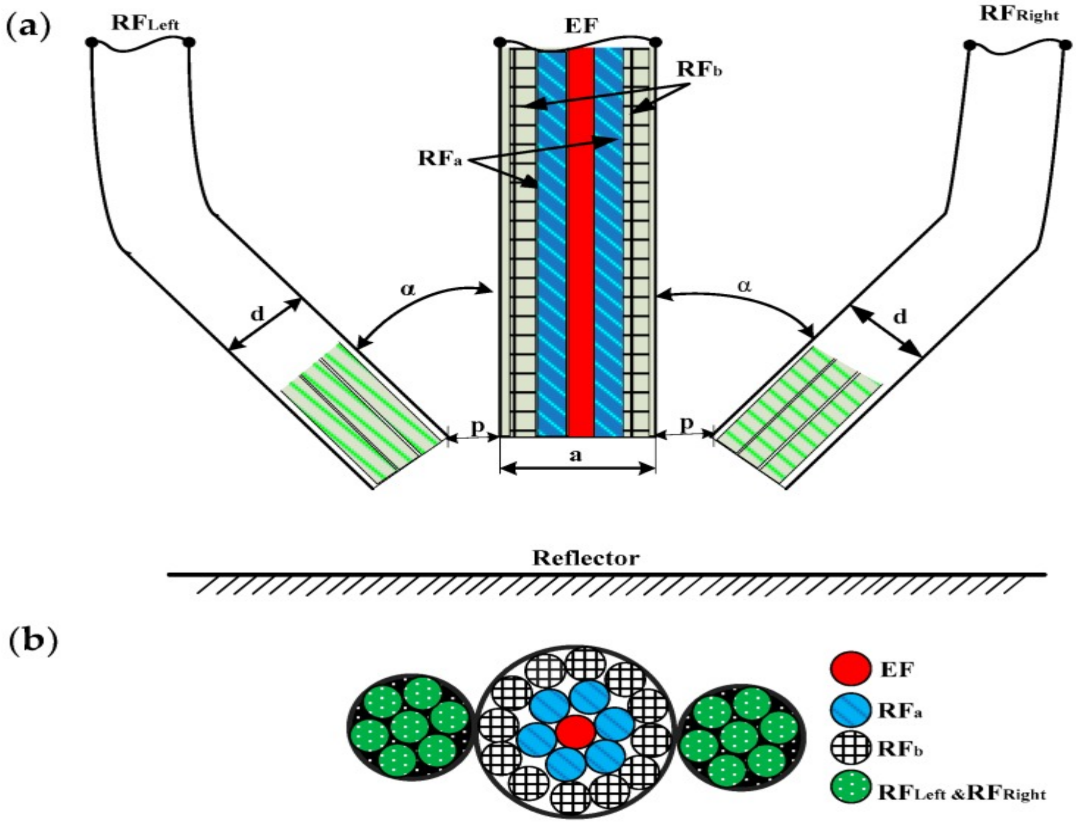

Figure 18: An Angular displacement sensor

In this sense, RF_{Left} refers to the left optical fiber bundle while the right fiber bundle is RF_{Right}. The angular displacement constituents bring about the existing correlations of the angle *α* concerning the circle coaxial fiber optical bundle. According to aspects of the light intensity distribution in the optical fiber ends, geometric distribution of the fiber emission intensity is essentially subject to the influence of sensor radius, numerical aperture, and distances between the reflector planes.

The ends of RF_a and RF_b were all subject to coverage by the reflected light spot mainly because the middle fiber bundle was characteristic of close packaging of the double coaxial circle structured arrangements.Otherwise, the changes in the reflector angular have minimal effects on the respective axial displacement measurements and results. The structure introduced in the research by Tafur et al. (2003) facilitates the identification of axial displacement concerning the alternate reflection surface. In this case, to improve RF_{Right} and RF_{Left} and thus, their light-receiving efficiency, the composition of the RF_{Left} and RF_{Right} fiber bundles ought to entail six fibers that have similar fiber structural parameters.

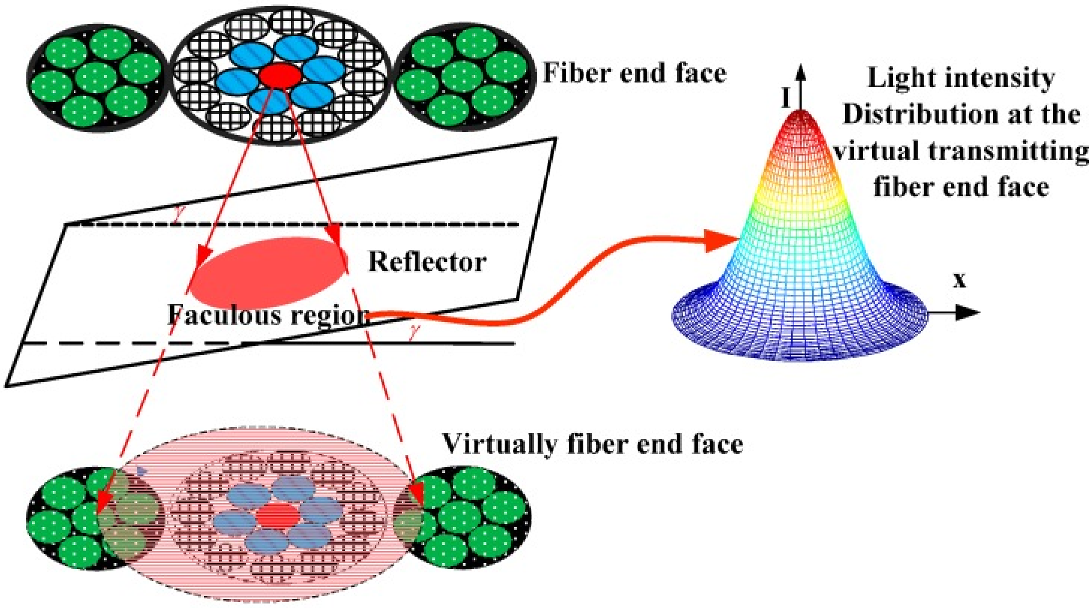

Figure 19: Identification of axial displacement concerning the alternate reflection surface. (Tafur et al., 2003)

3.14.1 Measuring Intensity

The transfer of light by optical fibers always occurs under specific intensities and wavelengths. According to Frisken, Clarke, & Poole (2013), the capability of an optical fiber to facilitate efficiency in the transfer of light is dependent upon the fibers attenuation coefficients in the specific/particular wavelength. The following figure provides a clear representation of the transmission window of the optical waveguide.

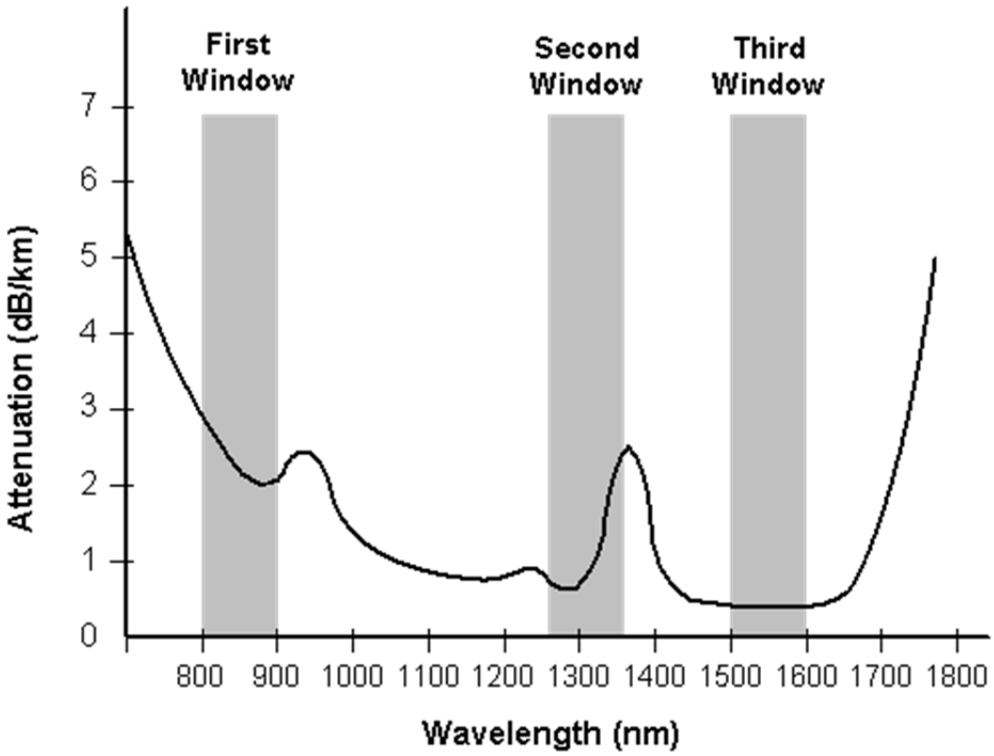

Figure 20: Representation of the transmission window of the optical waveguide. (Frisken et al.,2013)

The figure, in essence, brings forth a figurative or else graphical representation of the attenuation effects occurring under differential wavelength regions. For example, the lowest attenuation band occurs in the regions of 1300 and further between 1500 and 1600nm. As such, the regions of 1310 and 1550nm are the most preferential optical communication or band wavelengths.

Optical losses are probably the most limiting issues experienced through light transmissions (in this sense, optical loss is responsible for the issue of light attenuation across the entire fiber waveguide). The other impairment correlates with fiber dispersion – an issue associated with the effective nature of the refractive index (the combination of both waveguide and critical elements pertaining material dispersion), which varies with wavelength. According to the research by Dodd (2012), the stipulated aspect results in the travel of different wavelengths along the fiber at slightly different speeds.

Why the issue above considered as being impairment? If an individual wants to send information, the essentially need to facilitate the modulation of light, which facilitates the realization of a finite bandwidth for the transmission signal. This implies the signal exuberate multiple frequencies and otherwise, wavelength components, whereby each component is traveling at slightly differentiated speeds. Therefore, the pulses of light (created due to modulation) undergo critical spreading out resulting to overlapping of the various neighboring pulses (Sillard&Molin, 2017). As such, the detector will be unable to distinguish the pulses. In essence, there is need of management of the dispersion and similarly, the regeneration of the signal pulses to assure effective detection, and thus, the retransmission.

3.14.2 Quantifying Light & Reflective Intensity

Most specifications of lighting fall under the three categories that entail: reflected value, emitted value, and transmitted value. To ensure meaningful accountability of the light intensity, all the specified values must be subject to consideration from a definite direction, area/region, and further, at a well-known distance. The quantification of the stipulated values is otherwise, generated using the following two systems, Radiometric and Photometric (Severin&Poulain, 2007). The photometric values (determining the Luminous intensity), provide the representation of visible light (380-770nm), which are in any case-weighted using the visual sensitivity of the human eye, while the respective radiometric values will comprise of entirely electromagnetic outputs. The radiometric sources are inclusive of UV and IR units that are characteristic of power density hence lacking weighting.

Irrespective of its application, most engineers are often mistaken during the measurement of the luminous flux originating from a specified source, which is in essence, the total photometric power.The value is an equivalent of the total energy output originating from the luminous lamp. Because the vast majority of the applications facilitate the usage of light from a defined area/region, specific distance and direction, the lighting designers should often be trained with skills that will necessitate the quantification of the uniformity and the intensity of any energy beam at a point in the specific space. As such, the lumen value is quite insignificant compared with the illuminance value, which facilitates the measure of light intensity originating from a particular direction.

To illustrate the above issue, consider the scenarioio below concerning a fiber optical application: An EKE lamp has a luminous flux of 80 lumens. In this case, increasing efficiency requires some of the energy is subject to re-direction and implicit focus using a reflector, in the bundle fiber. Putting aside the reflection losses, the entry of the light into the fiber bundle will not be entirely complete. This is because some of the light is lost due to elements pertaining the fact that it misses the fiber interface. The loss of light rays might also be characteristic of restrictions brought about by the Numerical Aperture of the fiber. Additionally, more light rays could experience losses due to other factors that influence transmission efficiency.

The factors as indicated by Sharma et al. (2017), are inclusive of core and clad ratio, packaging density, Fresnel losses, and aspects associated with the final polish. The factors specified above are often changing hence; the eventual usable power is subject to fluctuations from one lamp to another, which will essentially affect the fiber optic components (Raisinghani&Ghanem, 2009). The variables above specifically differ by the lighting technology employed, such that each technology exuberate different set of variables that the optical engineer needs to account for. In the case that the illuminance value is specific, the designer of the lighting would be well aware of the application engineer’s requirements when factoring out the variables and thus, facilitate the provision of net power values needed at the interest field.

CHAPTER 4: FIBER OPTIC COMMUNICATION

4.1 Optical Sources of Light

Optical lighting sources play an integral role in the vast and ever-growing applications of fiber optical systems. A common fiber system comprises an optical fiber, transmitter, and the receiver. In this sense, as an important transmitter component, the fiber optic source of light is subject to modulations using a suitable driving circuit, which is with respect to the transmitted signals. The optical light sources as well necessitate the undertaking of efficiency and performance tests throughout the fiber optic networking system. Using optical light sources, designers or optical engineers can measure and thus, determine the fiber optic losses that might have emerged in the specific cable plant. The light sources are characteristic of different sourcing that include; LED, laser, and halogen. The laser and LED light sources are the commonly used types as they are also semiconductor sources of light (Daum andKrauser et al. 2002).

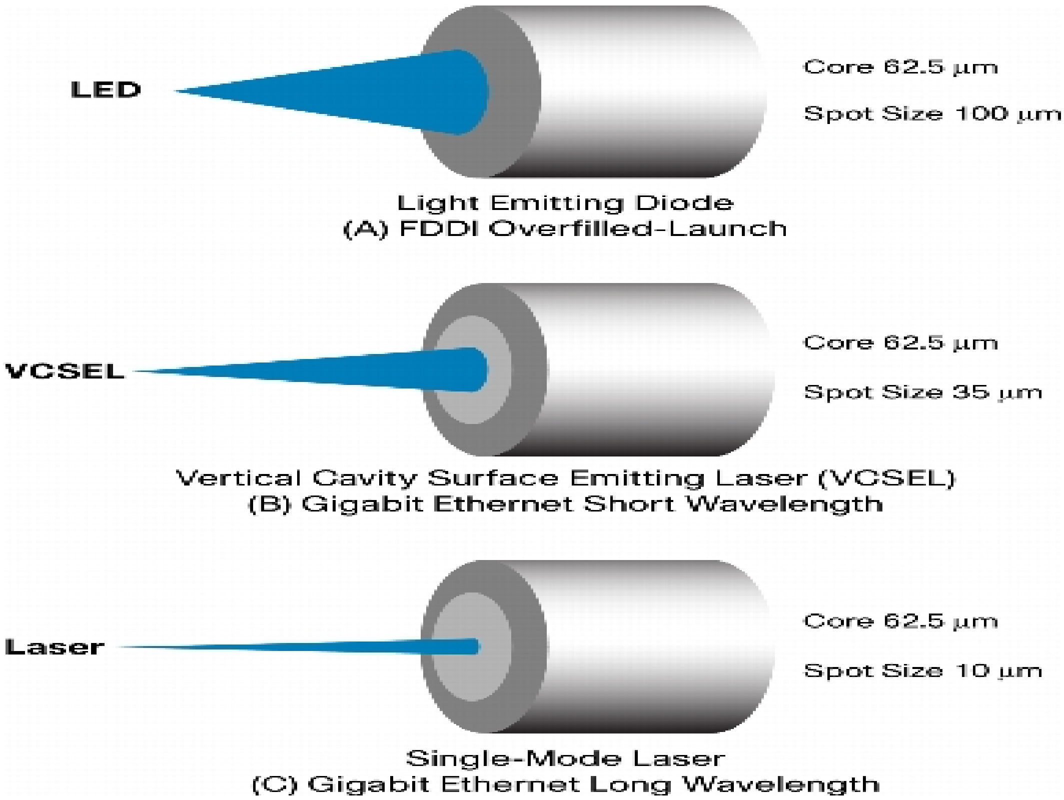

Figure 21: Various constituents of the light sources. (Dorosz&Romaniuk et al.,2011)

The figures above provide an overview of the various constituents of the light sources (Dorosz&Romaniuk et al. 2011). The light sources presented must always have the ability to turn on or off millions, if not billions of times in a single second of projection. By doing so, the light sourcing will be able to facilitate the projection of the near-microscopic light beam into the optical fiber cable. Through the working process and the transmission of the optical signals, rapid and accurate on and off switching is a necessity to guarantee effective transmission of the signals.

4.1.1 Choosing Fiber Optic Transmitters

The various fiber optic transmitters have different aspects that ought to put under consideration before application. As indicated by Pipelines Conference and Najafi (2004), the differences in specifications call for close examination to ensure the particular optical fiber transmitter of choice meet all the requirements. A major and thus critical aspect of any optical fiber transmitter associates with the power level. In this case, the transmitter should necessarily be characteristic of sufficient power and high light outputs to be able to guarantee the transmission of the light beams from one optical end to the destination. Fiber optical lengths are quite varied with some being a few meters in length while others might be quite extensive with coverage going for kilometers. As such, the consideration of the transmitters' power is of greater importance especially with fiber cables that are extensive in length.

The light types produced during transmission are also important. The categories of light transmitted by most optical fiber cables are incoherent and coherent lights. Coherent lights preferentially contain a single frequency, while the opposite is with incoherent light sources, which contain a variety of packets of light that differ from each other since the all contain different frequencies. According to Iannone (2012), the transmission of the incoherent light packets could be subject to limiting difficulties since there is lack of a single and unanimous frequency.

Another important component that ought to be put into consideration when selecting a transmitter correlates with the frequency or wavelength. Fiber optic systems selectively operate fluently at a specific wavelength. Finally, before selecting the transmitter, it is of great essence to consider the transmitters' rate of modulation. Particularly, the rate of modulation affects the overall transmission of the data (Mbps). For example, low rated systems only necessitate the transmission of few/minimal data, but with telecommunication systems/links, it is necessary for data transmission to be under high rates (Gbps) to assure efficiency.

4.1.2 The Types of Transmitters

The two main semiconductor technology used in fiber optical transmission are; light emitting diodes (LED) and laser diodes. According to Kaminow, Li, &Willner (2013), the semi-conducting transmitters have numerous advantages. In this sense, the diodes are convenient, small in size, and their reliability is quite high compared with halogens. Nonetheless, the specified semiconductor diodes portray different properties that make the application for transmission of signals quite diverse.

LED Transmitters

The LED optical fiber transmitters exuberates high reliability and are cheap. In essence, the generation of the light is from the method called spontaneous emission. Thus the transmitters only emit incoherent light. The light is characteristic of the relatively wide spectrum. According to the research by Raisinghani et al. (2009), the typical LED, which is useful for optical communications provides light output that normally ranges between 30 to 60 nm. As such, the signal transmitted would be subject to the issue of chromatic dispersion, which will essentially limit the distance that the data transmission could cover. The light emission from LED is further characteristic of no particular direction; therefore, transmission of the light will only be possible under multimode fiber. The efficiency of the overall data transmission is also low considering not all the light would necessarily be coupled into the optical fiber cable.

The significant advantages of LED as fiber optic transmitters are mainly pronounced in relations to aspects of cost, availability, and lifetime accessibility/use. The LED diodes are vastly subject to extensive production because the technology used through its production is simpler and straightforward thus limiting on costs incurred. Other characteristics that make the tech. Much favorable as transmitters entail; their small size, their possession of high radiance (emission of a lot of light even in small region/area), the modulation of the light source can occur at high speeds. Another preferable characteristic of LED transmitters correlate to their durability and the fact that the emission area is small thus, comparable to dimensions of optical fibers.

Laser Diode Transmitters

The laser transmitters are very expensive, and their use often tends to be as telecommunication links, whereby the cost sensitivity is not an issue. Light outputs realized with the use of laser diode are higher compared to the transmission light generated by LED diodes irrespective of the increasing power of LEDs. In this case, laser transmitters often generate a light output that ranges in the region of about 100mW. The generation of the light by the transmitters above arises from stimulated emission and thus, facilitates the creation of coherent light (Dorosz&Romaniuk et al. 2011). The light output is much more directional bias compared to the light generated by using LEDs. The perspective of light direction and coherence in frequencies enables the attainment of greater coupling efficiencies in the fiber optical cable network. As such, the transmissions of data using laser diodes realize greater/extensive distances due to the possibility of using single-mode fiber (this element relates to the coherent frequency of light produced).

The coherent nature of the light output also brings about another advantage with using laser transmitters. In this case, the light is nominally under single frequency, therein, modal dispersion is lesser in comparison to when using LEDs. Laser diodes also necessitate direct modulation to allow high data transmission rates (rates ranging from Gbps). However, there are some drawbacks associated with the use of laser diodes in data transmission activities. For example, lasers are very expensive if compared with the other semiconductor transmitters. The stability of laser diodes is also subject to questioning since their sensitivity to high temperatures often limits their transmission and optimum performance levels. The durability of laser diodes is minimal beyond the lifespan of LEDs.

4.1.3 Summary of Fiber Optic Transmitters

With a view of the differentiated characteristics possessed by the laser diode and LED optical transmitters, there use also varies concerning applications. The table below provides an explicit summary and comparison of the characteristics;

Characteristic	**LED**	**Laser Diodes**
Cost	Low	High
Distance Covered	Short	Low
Data Rate	Low	High
Type of Fiber	Multimode fiber	Multimode & single fiber
Lifetime (durability)	High	Low
Sensitivity to temperature fluctuations	Minor	Significant

Table 2: Summary of Fiber Optic Transmitters

The useful nature of LEDs tends to lean towards cost sensitive systems or applications. The efficiency of the transmitters is often subject to lower rates data transmissions with the requirements being associated with shorter distances. For long distance, fiber optic telecommunication links that are characteristic of transfer of Gbps data rates, expensive laser diodes are necessary for efficiency in transmissions.

4.2 Performance of Receiver

The photo-detector in the fiber optic receiver is a major or else, critical element in the transmission of data. However, other aspects necessitate the essential functionality of the entire unit. For example, upon the reception of the light by the fiber optic receiver, the conversion process (from light rays into electronic pulses) is facilitated by electronics existing in the receiver itself. The process of amplification as well occurs inside the receiver through the limiting amplifier. As such, through the processes inside the receiver, the signal undergoes the necessary translation into a square wave, which will essentially undergo conversion in any logical circuitry. In the required digital format, the signal received will as well be through further signal processing in the form of clock recovery.

Diode Performance

The functionality of the entire fiber optic receiver is also subject to the influence brought about by the photodiode itself. In this case, the responsive nature and time of each diode necessitate the governance of the data speeds undergoing recovery process. The avalanche diodes might provide the required speeds to process the data recovery process, but they are noisy and often require sufficiently higher levels of signal transmission to overcome this notion. The commonly used diode type in the receiver is a p-i-n diode. In this sense, the stipulated type of diode brings about better conversion levels/rates compared to the straight p-n diode. This is because the light conversion at the regional junction is firstly into carriers existing between the p and n regions. The existence of the aforementioned intrinsic region facilitates the increment of the area of conversion thus the efficiency of light signal change into data.

4.3 Fiber Optics & Next Gen. Applications

With the consideration of the next generation applicability of telecommunication transmission possibilities, it is quite evident that systems would implement the use of complex transmission schemes, which might bring about the transmission of more than one wavelength under a single fiber optic. The aspect might be inferred as “wavelength division multiplexing.” As such, the current innovation measures engineered by designers ought to lay implicit emphasis upon the smoothening of the attenuation profile for the various types of optical fibers to accommodate the possibility of transmitting various ranges of transmission wavelengths. The particular concern about attenuation correlates to increases above 1360- to 1480-nm (this range is known as “E-Band” or else, “water peak).” The emergence of the detrimental changes/increase is subject to effects generated due to hydroxyl ions absorbed into the single-mode fiber optics during the production processes.

In this sense, LWP single mode fibers can be necessarily subject to increased performance through implementing an additional manufacturing step/process, which will facilitate the reversal and thus, elimination of the absorbed water molecules. Through the process, Mohammad (2009) articulates that the fiber optics would be able to realize near to zero attenuation effects. With ZWP (zero water peak) fibers, there is need to implement a much complex procedure when seeking the elimination of the losses arising due to OH -.

Outlook and summary

The thesis has presented valuable information on fiber optics and their value in communication. Taking into consideration the fact that there is need to develop efficient systems for data communication. This has led to the development of large forms of transmission using light wave technology such as fiber optics. Fiber optics have taken the communication industry at large by providing high-speed communication with a large bandwidth. The fact that a combination of photons and glass fiber improve the rate transmission of signals has contributed to the adoption of fiber optics in communication. This thesis has pointed out some issues regarding the current and future state of fiber optics. It has elaborated tremendous reasons for using fiber optics in communication and how they have improved the efficiency and speed. Fiber optics uses one major principle that involves guiding of light by refraction. It is a principle that was first demonstrated in Paris by Jacques Babinet and Daniel Colladon in the 1840s. Since then, fiber optics have been used in numerous applications that involve dentistry, image transmission through tubes, television pioneer among others. On the field of telecommunication, its usage has become possible due to its flexibility and the ability to be bundled as cables. As a result, it has become more advantageous for long distance communications as little attenuation is experienced during the propagation of light through the fiber to the electrical cables. This allows long distance coverage with few repeaters.

In less than a decade since the earliest explanation of a quantum interface between light and Materials, the light-matter quantum interface in nowadays one of the milestone in the field of quantum information processing and communication, and one of the most important topic in the research and development field. After a lot of Labor work und a lot of tests that led the scientists to a new physical processes of controlling quantum coherence and entanglement, experts reveals that the results were promising, revealing various paths in direction of improving quantum networks. ‘’Despite the remarkable advances, the current state of the art is still primitive relative to that required for the robust and scalable implementation of sophisticated network protocols‘’. Achieving a large-scale quantum network is still challenging in the unfavorable laboratory scalability for free-space ensemble-based approaches. ‘’Indeed, an important drawback of the current experiments in this thesis is the tremendous technical complexities required to implement even the rudimentary quantum information operations with sufficient fidelities for quantum error-corrections. this brings a very pragmatic opportunity for us to transit from the present free-space quantum optical laboratory to Nano-integrated systems comprised of ultra-cold atomic ensembles and solid-state spin ensembles interacting on a photonic waveguide circuit‘’.

Summary

This section provides a summary of fiber optics and their wide range of applications in communication. It is vital to look back into different chapters of the thesis and provide a summary of the same for a better understanding of the work.

In chapter 1, the background and significance of fiber optics in modern communication systems have been highlighted, from this chapter, it is notable that fiber optic in the communication sector is crucial as it enables the provision of wide bandwidth costs effectively. In fact, in the modern fiber optic communication systems, the technology of dense wavelength division multiplexing (DWDM) has enabled the provision of ultra-high bandwidth communication systems. The same chapter highlights the different components of fiber optics which include; an optical transmitter, fiber optic cable, and an optical receiver.

Some of the main advantages of fiber optics include long-distance transmission where it is used to transmit signals over long distances at high speed. Also, it has resistance to Electromagnetic Interference: In copper cables, electrical noises have a big influence on the integrity of the signal. This can also reduce the speed of transmission, and this is not possible to happen within the fibers, as it is immune to the EMI. Also, it has Low-Security Risk, as the costumers are more aware and they demand high security data transmission, therefore fiber optic communication market has grown. Data or signals are transmitted via light in fiber optic transmission. Therefore, ‘’there is no way to detect the data being transmitted by "listening in" to the electromagnetic energy "leaking" through the cable‘’, like what we can do with the copper cables which ensures the absolute security of information.

‘’Fiber optics have become the industry standard for the terrestrial transmission of telecommunication information. Fiber optics will continue to be a major player in the delivery of broadband services. Carriers use optical fiber to carry POTS service across their nationwide networks. Today more than 80 percent of the world's long-distance traffic is carried over optical-fiber cables‘’. Telecommunications applications of fiber-optic technologies are widely deployed, ranging from worldwide networks to personal computers and mobile phones. ‘’These involve the transmission of voice, data, and video over distances of less than a meter to hundreds of kilometers, using one of a few standard fiber designs in one of several cable designs‘’. Carriers use optical fiber to carry analog phone service. Cable television companies also use fibers for improving the quality of the digital video services. Biomedical and Intelligent transportation industry are also using fiber-optic systems. Nowadays for subterranean and submarine transmission are the Optical cables as standard defined.

‘’The principle of total internal reflection is used to propagate light signals‘’. The core guides the light through, and the fiber seems to acts like an optical waveguide. SMF and MMF cables are constructed differently. Single mode fibers have a smaller core diameter as compared to Multi mode fibers. There are two kinds of propagation for fiber-optic cable: single mode or multimode. These modes perform differently concerning both attenuation and time dispersion. SMF cables perform better than MMF cable. The three primary propagation modes include multimode step index, single-mode step index, and multimode graded index propagation.

Chapter 3 and four deals with light propagation in optical fibers. Using a ray-optics description the Multi-mode fibers (MMFs) and single-mode fibers (SMFs) are discussed. A rigorous solution of wave equations is derived, followed by a display of a wave-optics description of the SM and MM fibers. Next, the chapter discusses the propagation of pulses in SMFs, and then compares the SMFs and MMFs. Finally, the chapter concentrates on the design of SMFs. With step-index optical fiber, we can't optimize all the important parameters for the design of an SMF. Therefore, the refractive index profile is chosen so that the design parameters are optimum for a specific application. For long-haul and high-bit-rate optical communication systems, The expansion of the pulse due to dispersion within the range leads to inter symbol interference, which degrades transmission performance. Pulse expansion can be compensated using dispersion-compensating fiber (DCF).

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