NCC – ABU RESEARCH COLLABORATION

DESIGN, FABRCATION, AND EXPERIMENTAL CHARACTERISATION OF PLASTIC OPTICAL FIBRE CABLE AND EXPLOITATION OF ITS POTENTIALS IN THE NIGERIAN TELECOMMUNICATIONS INDUSTRY

FINAL REPORT

Submitted to Nigerian Communications Commission (NCC)

19th November, 2021

CONTACT

Engr. Dr. Suleiman Muhammad Sani

Telecommunications Engineering Department,

Ahmadu Bello Unversity, Samaru, Zaria

e-mail: smsani_2@yahoo.com; tankonbaba@gmail.com

TABLE OF CONTENT

MEMBERS OF RESEARCH TEAM

Engr. Dr. S. M. Sani:	**(Team Leader)**
Engr. Dr. A.D. Usman:	**(Member)**
Engr. Dr. A. M. S. Tekanyi:	**(Member)**
Engr. G. Danasabe:	**(Member)**
Engr. Dr. M. J. Musa	**(Member)**
Engr. Dr. A. S. Yaro	**(Member)**
Engr. I. Ya'u:	**(Member)**

LIST OF SYMBOLS

$\Delta\tau'_{\max}$	-	Maximum Differences in Time Delay (Dispersion per unit Length)
$\tau'_{slowest}$	-	Time delay of the Slowest Mode
$\tau'_{fastest}$	-	Time delay of the Fastest Mode
n_g	-	Group index
c_o	-	Speed of Light ($3x10^8$ ms^{-1})
$\vartheta_{\max}$	-	Maximum Possible Propagation Angle
NA	-	Numerical Aperture
n_{core}	-	Refractive Index of Core Material
$n_{cladding}$	-	Refractive Index of Cladding Material
L	-	Length of the Optical Fibre Cable
BW	-	Bandwith
η_c	-	Coupling Efficiency
R_f	-	Reflectivity at the fibre front end
$\min_n f(n)$	-	Minimization of $f(n)$

ABSTRACT

Optical fibre has become the preferred transport medium for broadband communications. In recent years, research and development efforts have been largely focused on how to extend broadband to the home through optical fibre. Plastic Optical Fibre (POF) is a leading contender in this regard because it is a lot cheaper than glass fibre and easier to manufacture. The main shortcoming of Step Index POF (SI-POF) is modal dispersion that limits the link bandwidth to about 40 MHz over 100 m. Consequently, a lot of research is being undertaken with a view to improving the bandwidth-length product of the cable. This work seeks to develop an improved POF cable by minimizing modal dispersion of the fibre. Optimal core and cladding materials for an improved bandwidth-length product of the cable are found through optimization by minimization of modal dispersion. The results show that the optimal core and cladding materials have refractive indices of 1.4865 and 1.4756 respectively. The minimum dispersion per unit length is found to be 36.169 ps/m. Thus, the bandwidth of 100 m length of the improved SI-POF is 121.65 MHz. This represents about 80 MHz bandwidth improvement compared with the works of Albakay & Nguyen, (2017). A standard LF-1000 980/1000 SI-POF is used to fabricate locally a small core 490/500 SI-POF using the freeform drawing process. The attenuation of the developed POF is found as 1.588 dB/m. Experimental measurements of the attenuation of the cable are carried out. The measured results indicate that the attenuation is 0.161 dB/m.

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

In recent years, telecommunications has experienced significant changes. Fibre optics are steadily substituting copper wire as a suitable means of signal transmission. A variety of optical equipment is attributing factor to the communication advancement, during which optical fibre cables are leading the way. An optical fibre is a flexible and transparent fibre made by drawing glass (silica) to a diameter slightly thicker than that of a human hair. For decades, glass (silica) optical fibre (GOF) is widely used in telecommunications offering large bandwidth, low attenuation and electromagnetic compatibility, being reliable and economical for long distance and high data rate applications worldwide.

However, GOF does not properly run for shorter distances and rugged environment. Unforeseen rapid developments in software and image technology have enabled a convergent communication set (voice, data, and video), that is pushing data rates higher and higher in application environments that are more severe and require shorter and intensive links (Iracema A et al., 2015). Therefore, in order to address the stated challenges, there is need for Plastic Optical Fibre (POF).

Plastic Optical Fibre (POF) boast of simpler and less Expensive components, as well as greater flexibility, and resiliency to bending, shock and vibration. In addition, they are lighter in weight. POFs can be handled without special tools or techniques. All these make plastic fibres a lower cost alternative to glass fibre or copper at distances ranging from 100 m to 500 m and bit rates of 10 Gbps.

POF largely comprises of PMMA (acrylic) which can be derived from petroleum products, and research shows that the raw material is abundantly in Nigeria as one of the world largest oil producers in the world. Therefore, in view of the availability of the key raw material there is great potential for synergy between the plastic industry, the academia, and the telecommunication industries in Nigeria, for the production of and further research in the use of POFs.

POF has the potential of transporting broadband services to the home over the last ‘mile’ in a very cost effective manner. This potential, and the abundant availability of the raw material in Nigeria, are the key motivators behind this research. The primary objectives of this research are to increase both the reach and the bandwidth of POF whilst reducing the limiting effect of dispersion.

POF are increasingly deployed in the following areas of application such as, Military, Automotive, Aerospace, and Medicine etc.

1.2 Plastic Optical Fibre

Plastic/polymer optical fibre or POF is an optical fibre which is made out of plastic. Traditionally, it comprises of Polymethyl methacrylate (PMMA (acrylic)) as the core (96% of the cross section in a fibre 1mm in diameter) that facilitates the transmission of light, and fluorinated polymers as the cladding material. Plastic fibre uses harmless green or red light that is easily visible to the eye. Plastic fibres can be safely installed in a home without risk to inquisitive children. But nowadays, a higher-performance plastic fibre is used based on perfluorinated polymers. Figure 1.1 shows the picture of theconstruction of POF.

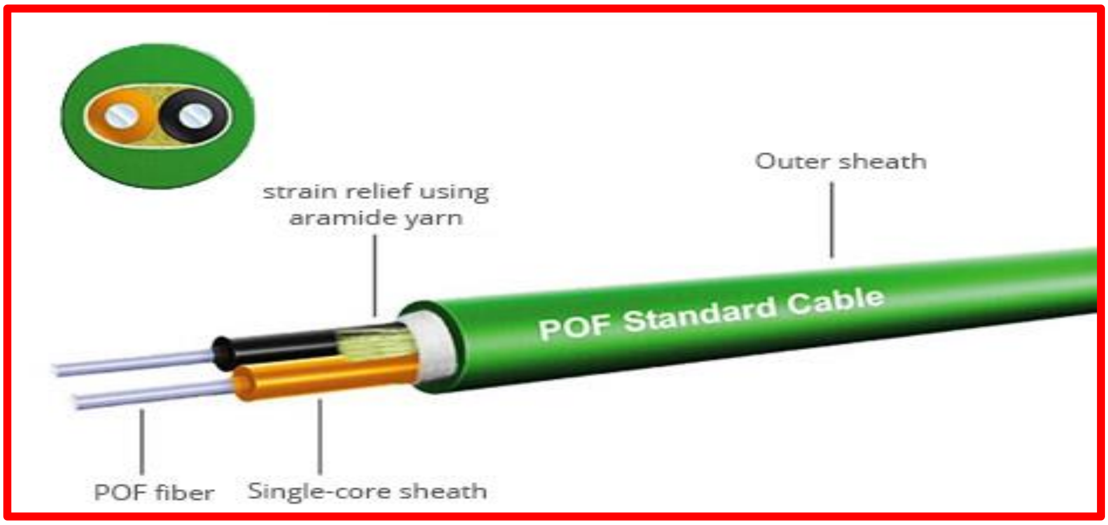

Figure 1:1 Plastic Optical Fibre(FONP/FS.com, 2017)

1.3 Glass Optical Fibre

Glass optical fibre (GOF), just as its name shows, is an optical fibre made of glass. Being a delicate type of optical fibre, it cannot be cut, spliced or repaired, less resistant to flexibility and accidental breakage. Glass fibre optic cables are extremely versatile and robust and available in a mix of configurations, end fittings and adapter types. However, this kind of optical fibre is generally not ideal for hostile environments. Even when exposed to mechanical stress, high temperatures or chemical substances, it still performs normal operation. Figure 1.2 shows the construction of GOF.

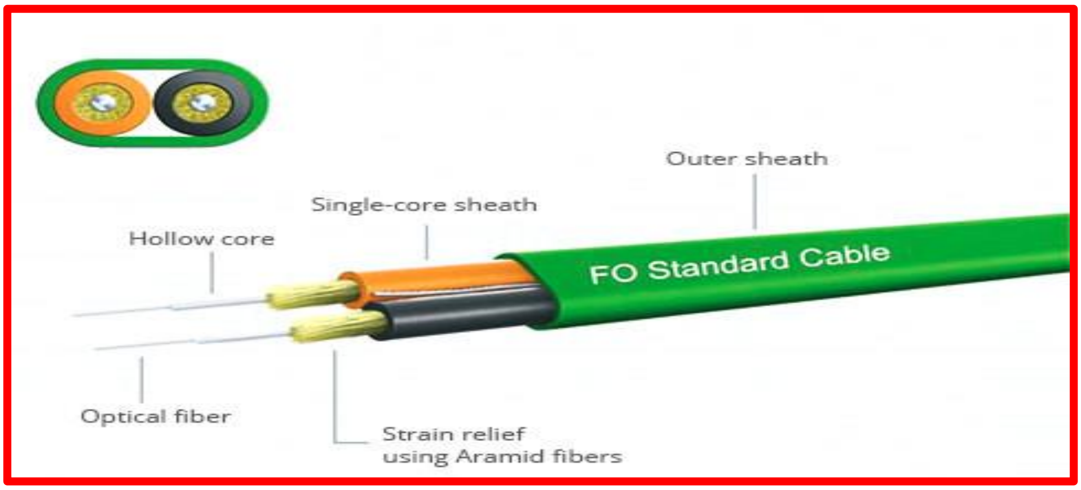

Figure 1.2: Glass Optical Fibre(FONP/FS.com, 2017)

1.4 Advantages of POF over GOF

Plastic optical fibres boast of simpler and less expensive components, as well as greater flexibility, and resiliency to bending, shock and vibration. In addition, they are lighter in weight. POFs can be handled without special tools or techniques. All these make plastic fibres a lower cost alternative to glass fibre or copper at distances ranging from 100m to 5000m (Zubia and Arrue, 2001) and bit rates of 10 Gbps. (FONP/FS.com, 2017)In contrast, GOFs are difficult to handle and more delicacy. While being mechanically well protected, GOFs have higher data transmission capacity with lower loss. Moreover, GOFs are optimized for small spaces and small targets. They can be used with both visible red and infrared light and are compatible with a long list of fibre heads.

1.5 Locally Available Raw Materials

POF largely comprises of PMMA (acrylic)can be derived from petroleum by-products, and research shows that the raw material is abundantly available in Nigeria (Solventis, 2016) as one of the world largest oil producer. Therefore, in view of the availability of the key raw material there's great potential for synergy between the plastic industry, the academia, and the telecommunications industries in Nigeria, for the production of and further research in the use of POFs.

1.6 OUTCOMES OF THE RESEARCH

The following are the expected outcome of the research:

i. Develop local competence in our polymer research institutes and plastic industries in the production of plastic optical fiber cable that can go beyond 100m
ii. Accelerate the development of broadband communications in Nigeria by extending the fiber to the home through the use of plastic optical fiber in the access segment of the network

iii. Save foreign exchange by encouraging the telecommunications companies in Nigeria to patronize the locally produced plastic optical fiber cable

iv. Encourage the telecommunications companies in Nigeria to pool resources with NCC and Universities in order to advance the frontiers of research and development in telecommunications through addressing peculiar technical challenges in the Nigerian operating environment.

v. Provide training and research opportunities to Universities by setting up a test bench on plastic optical fiber transmission system through modeling, simulation and validation on different types of polymer materials.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

This section presents the review of fundamental concepts and the review of similar research works relevant to this proposal. Under concepts, discussions will cover fundamental principles of optical fibre, Plastic/Polymer Optical Fibre (POF), cable construction as well as optical fibre link design.

2.2 REVIEW OF FUNDAMENTAL CONCEPTS

The review of fundamental concepts pertinent to this proposed work is presented. These concepts are discussed at length in order to justify the choice of design and technique used in this work.

2.2.1 Ray Theory of Light

When light propagates into a new medium, refraction occurs. Total internal reflection occurs when a ray traveling from a medium with a high refractive index, n_1 is incident on a boundary of a material having lower refractive index, n_2 at an angle greater than the critical angle as illustrated in Figure 2.1. The critical angle, θ_c is the angle of incidence in the denser medium at which the refracted ray just grazes the surface of separation of the media (Nelkon and Parker 1995).

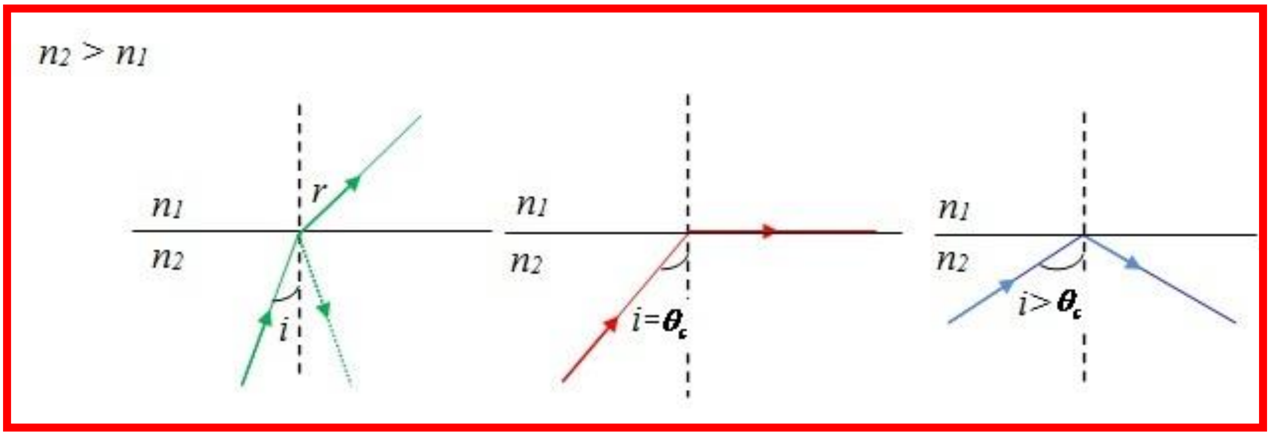

Figure 2.1: Total Internal Reflection (Nelkon and Parker 1995)

The refractive index of medium 2 with respect to medium 1 is given by Snell's law (Nelkon and Parker 1995) as

$$ {}_2n_1 = \frac{\sin i}{\sin r} \tag{2.1}$$

The critical angle of incidence, c, is given by (Nelkon and Parker 1995)

$$ \theta_c = \sin^{-1}\left(\frac{n_1}{n_2}\right) \tag{2.2}$$

Total internal reflection finds application in optical fibre transmission where light is used to convey information through an optical waveguide composed of two transparent materials having different refractive indices. This optical waveguide is called optical fibre.

2.2.1.1 Numerical Aperture

When light enters a material such as optical fibre at an angle θ_{max}, it is refracted at an angle α_{max} as shown in figure 2.2. The sine of the maximum incident-ray angle θ_{max} is defined as the Numerical Aperture NA. The angle θ_{max} is referred to as the acceptance angle, and twice the acceptance angle is referred to as the aperture angle.

The value for NA is obtained as (Ziemann *et al.*, 2008):

$$NA = n_{core}\sqrt{2.\Delta} \quad (2.3)$$

were Δ is the relative refractive index difference given by

$$\Delta = \frac{n_{core}^2 - n_{cladding}^2}{2.n_{core}^2} \quad (2.4)$$

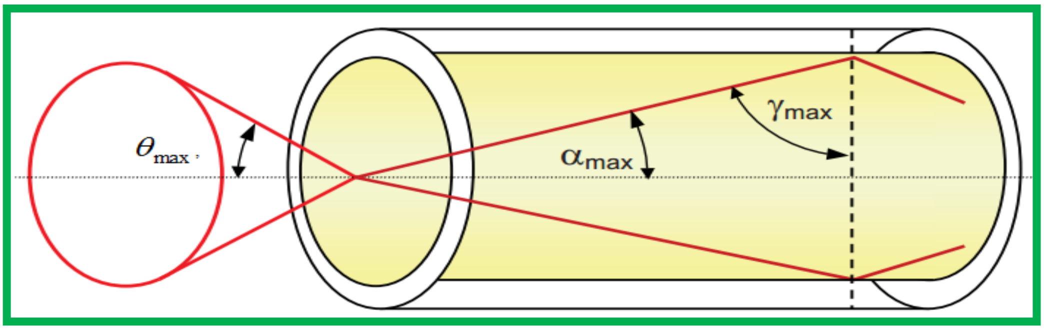

Figure 2.2: Acceptance Angle (Ziemann *et al.*, 2008)

2.2.2 Propagation of Light through an Optical Fibre

Light can propagate down an optical fibre cable by either reflection or refraction. Figure 2.3 illustrates the propagation of light ray through the fibre by principle of total internal reflection.

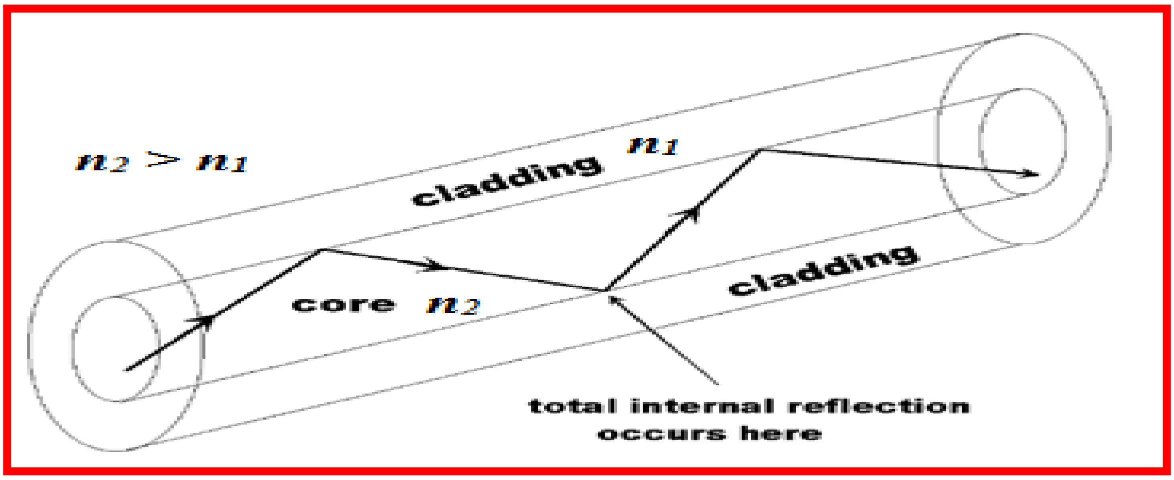

Figure 2.3: Light Propagation along Optical Fibre Cable

How the light is propagated down an optical fibre depends on the mode of propagation and the index profile.

2.2.2.1 Mode of Propagation

In fibre optic terminology, the word mode simply means path. If there is only one path for light to take down the fibre cable, it is called single Mode. If there is more than one path, it is called multimode.

2.2.2.2 Index Profile

The index profile of an optical fibre is a graphical representation of the refractive index of the core. There are two basic types of index profiles:

i. **Step index**: It has a central core with a uniform refractive index. The core is surrounded by an outside cladding with a uniform refractive index less than that of the central core as illustrated in Figure 2.4. The profile of the refractive index in the core and in the cladding is expressed as follows (Ziemann *et al.*, 2008):

$$n(r) = \begin{cases} n_{core} & for\, r \leq a \\ n_{cladding} & for\, r > a \end{cases} \tag{2.5}$$

where a is the core radius.

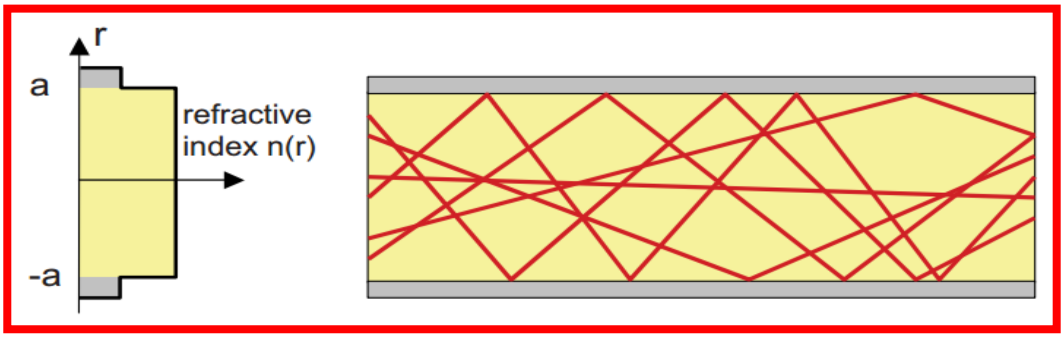

Figure 2.4: Index Profile in Step Index Fibre (Ziemann *et al.*, 2008)

ii. Graded index: the refractive index of the core is non-uniform; it is highest at the center and decreases gradually toward the outer edge as illustrated in Figure 2.5. The core therefore has a radius-dependent refractive index. The index profile is given by (Ziemann *et al.*, 2008) as

$$n^2(r) = \begin{cases} n^2_{core\_max}\left[r - \Delta\left(\frac{r}{g}\right)^g\right] & for\, r \le a \\ n^2_{cladding} & for\, r > a \end{cases} \qquad (2.6)$$

where g is the index profile exponent and Δ is the relative refractive index difference

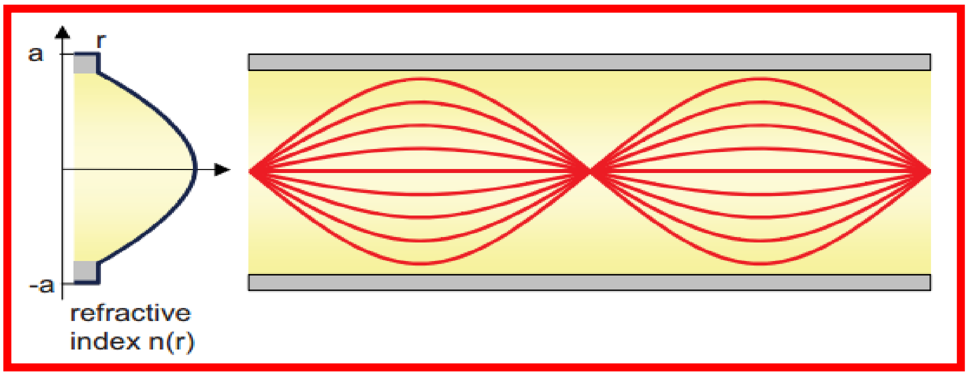

Figure 2.5: Index Profile in Graded Fibre

The characteristics of optical fibres depend on a number of possible constructive details. For instance, the choice of material primarily determines the attenuation and the thermal stability. On the other hand, the optical bandwidth, in essence the transmission capacity, is determined by the refractive index profile. Thus, the major design issues for the optical fibres are related to the refractive-index profile, the amount of dopants, and the core and cladding dimensions.

2.2.3 Optical Fibre Configurations

Figure 2.6 shows the three fibre optic configurations used in communication systems:

i. Step-index multimode

ii. Step-index single mode

iii. Graded-index

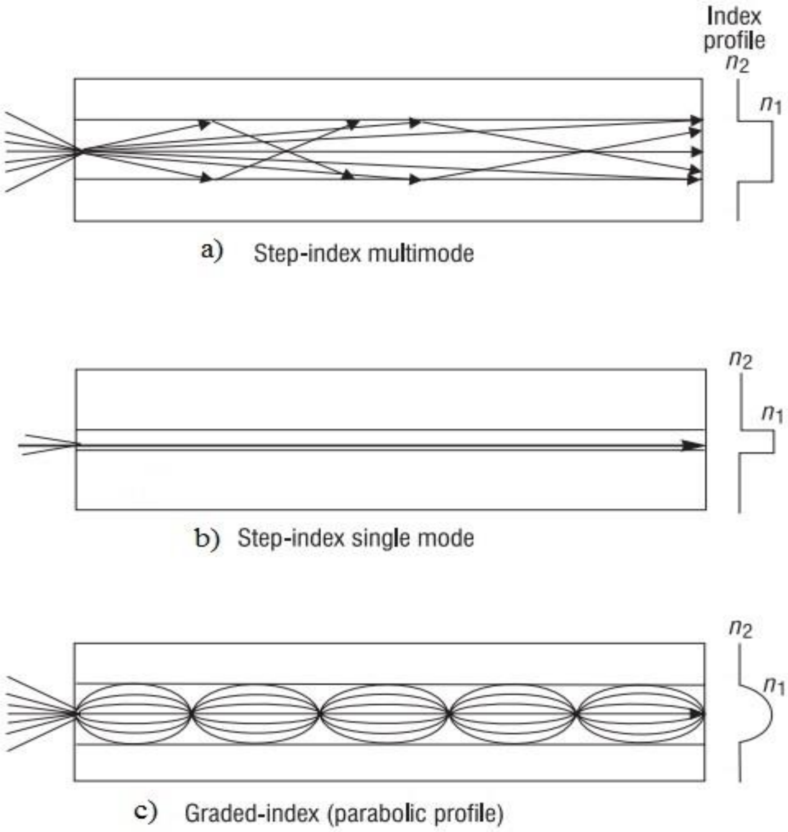

Figure 2.6: Fibre Optic Configurations (Massa, 2000)

Table 2.1 summarises the comparison between the three fibre optic configurations.

Table 2.1: Comparison of Fibre Optic Configurations

Step-index multimode	**Step-index single mode**	**Graded-index**
Large NA	Small NA	Large NA
Easy coupling	Coupling more difficult	Easy coupling
Modal dispersion	No modal dispersion	Less modal dispersion
Lower data rates	High data rates	Intermediate
Shorter distances	Long distances	Intermediate

2.2.4 Optical Fibre Cable Construction

From optical point of view, structurally, an optical fibre cable consists of two coaxial layers in cylindrical form: a core in the central part of the fibre and a cladding surrounding the core. The core is designed to have a slightly higher refractive index than the cladding. Thus, when the angle of incidence of the light input to the core is greater than the critical angle determined by Snell's law, the input light is confined to the core region and propagates a long distance through the fibre because the light is repeatedly reflected back into the core region by total internal reflection at the core–cladding interface. The structure of the optical fibre cable is shown in figure 2.7 (Zubia and Arrue, 2001).

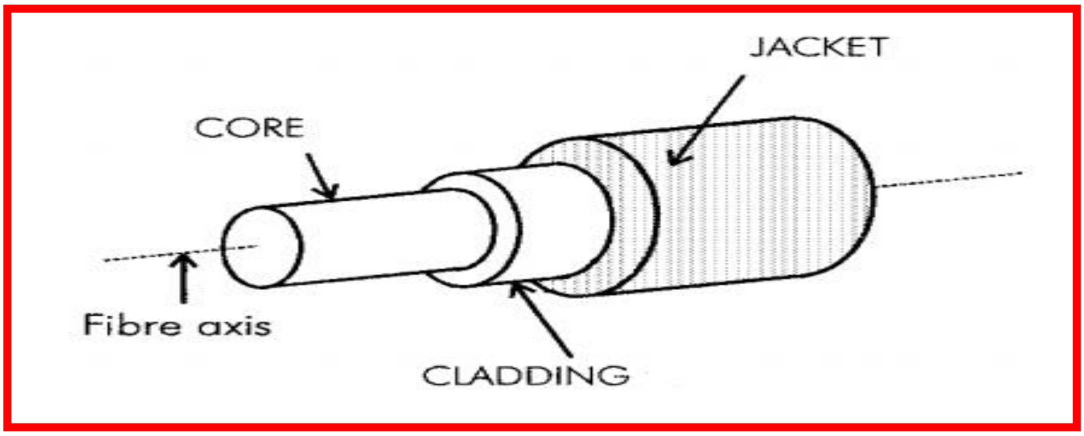

Figure 2.7: Structure of Optical Fibre Cable (Zubia and Arrue, 2001)

The core and the cladding can be made from glass (silica) or plastic (polymer). Plastic optical fibres are more cost effective than the glass counterparts. They are ideal for applications that require continuous flexing of the fibre. To provide mechanical protection, a jacket is used to cover the optical fibre. It is generally made of polyethylene, although polyvinylchloride and chlorinated polyethylene can also be used.

2.2.5 Transmission Windows

Optical fibre transmission uses wavelengths that are in the near-infrared portion of the spectrum, just above the visible, and thus undetectable to the unaided eye. Typical optical transmission wavelengths are 850 nm, 1310 nm, and 1550 nm. Both lasers and LEDs are used to transmit light through optical fibre. Lasers are usually used for 1310- or 1550-nm single-mode applications. LEDs are used for 850- or 1300-nm multimode applications. There are ranges of wavelengths at which the fibre operates best. Each range is known as an operating window as shown in Figure 2.8 (Binh, 2015).

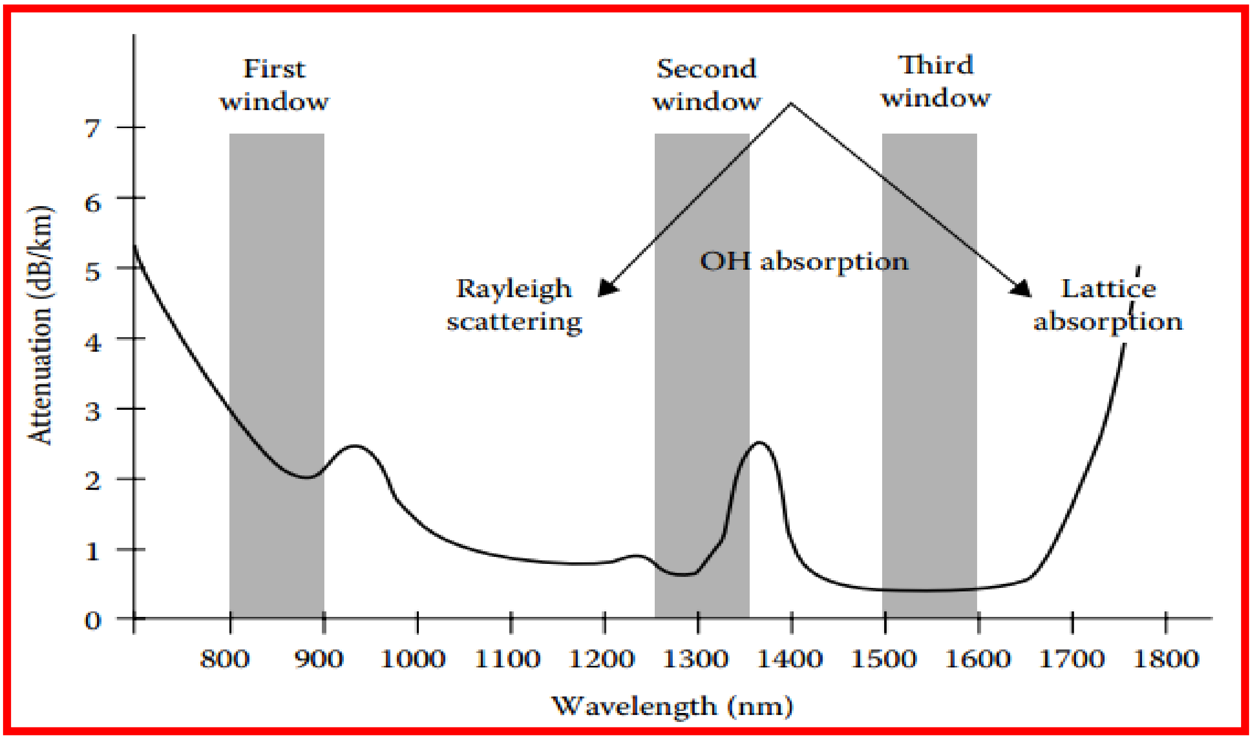

Figure 2.8: Optical Fibre Transmission Windows (Binh, 2015)

Each window is centered on the typical operational wavelength, as shown in Table 2.2

Table 2.2: Fibre Optic Transmission Windows

Window	Operating Wavelength
800 – 900 nm	850 nm
1250 – 1350 nm	1310 nm
1500 – 1600 nm	1550 nm

2.2.6 Losses in Optical Fibre Cable

Losses in the optical fibre cable result in a reduction in the light power, thus reducing the system bandwidth, information transmission rate, efficiency, and overall system capacity.

The predominant fibre losses are:

i. Absorption losses; caused by ultraviolet absorption, infrared absorption, ion resonance absorption. Typical absorption losses are between 1 and 1000 dB/km. When passing through an optical fibre of the length L, the power of the light decreases due to absorption form P_o to P_L as shown in figure 2.9 (Ziemann *et al.*, 2008).

Figure 2.9: Optical Attenuation (Ziemann *et al.*, 2008)

The following equation gives the optical power P_L as:

$$P_L = P_o e^{-\alpha' L} \qquad (2.7)$$

were α' is the attenuation coefficient in km^{-1}

To make it easier to work, it is usual to express attenuation logarithmically. Thus, the attenuation coefficient is expressed as α in dB/km as:

$$\alpha = \frac{10}{L} \log\left(\frac{P_o}{P_L}\right) \qquad (2.8)$$

ii. Material and Rayleigh Scattering losses: caused by sub-microscopic irregularities which are permanently formed in the fibre during the manufacturing process. Light rays are diffracted by these irregularities. The Rayleigh scattering loss, L_R, of the material, is given by (Binh, 2015) as

$$L_R = (0.75 + 4.5\Delta)\lambda^{-6} \qquad \text{dB/km} \qquad (2.9)$$

where Δ is the relative index difference and λ is the wavelength in μm.

iii. Chromatic or Wavelength Dispersion: Each wavelength within the composite light signal travels at different velocity arriving at the receiver at different times and phase. This leads to a distorted received signal.

iv. Radiation Losses: Caused by small bends and kinks in the fibre.

v. Modal Dispersion or Pulse Spreading: Caused by the difference in the propagation times of light rays that take different paths down a fibre. This occurs only in multimode fibres. This leads to pulse spreading or pulse-width dispersion as illustrated in Figure 2.10. In digital transmission, it causes error in the form of Inter Symbol Interference (ISI).

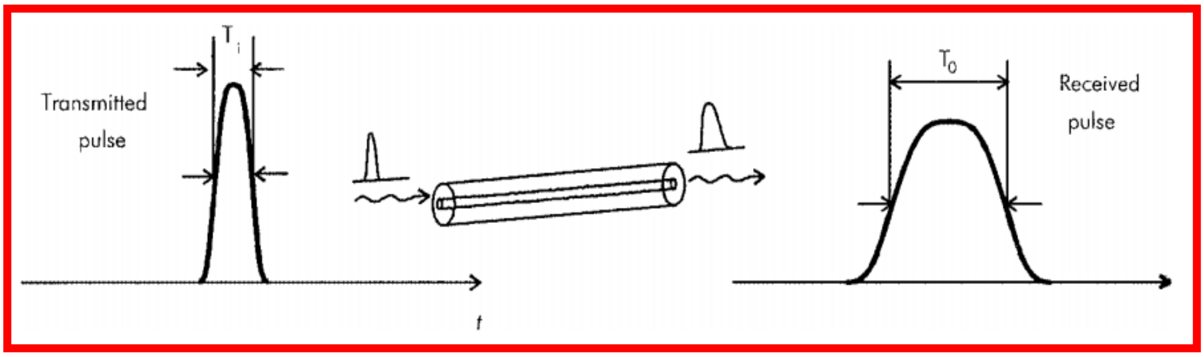

Figure 2.10: Dispersion in Optical Fibre (Zubia and Arrue, 2001)

2.2.7 Optical Fibre Link Design

The purpose of the optical fibre link design is to ensure that information can be transmitted satisfactorily. The satisfactoriness of the transmission can be defined in terms of some characteristic parameters.

A simple point-to-point optical link is illustrated in Figure 2.11

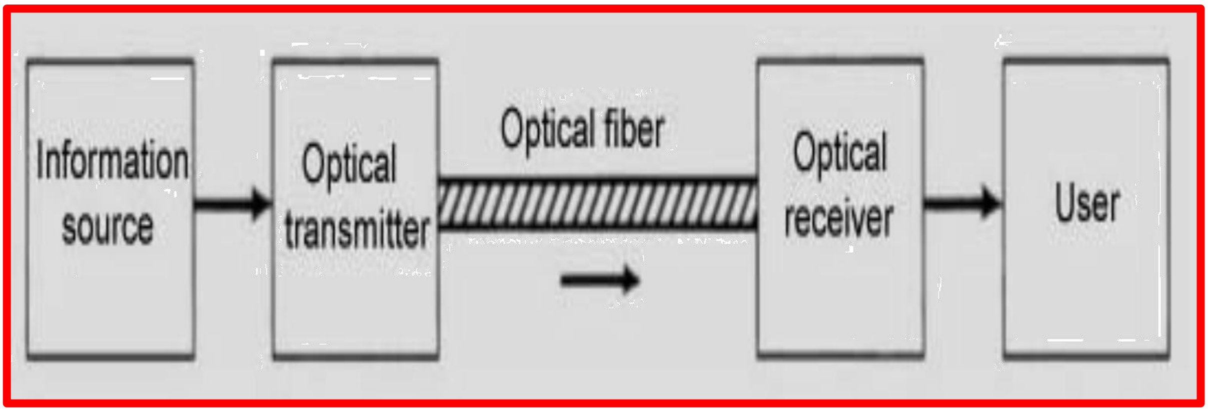

Figure 2.11: A simple point-to-point Optical Fibre Link

The key design parameters are:

(i) Data Rate

(ii) Link length

(iii) Modulation format

(iv) System fidelity: BER, SNR

(v) Cost: Components, installation, maintenance

(vi) Upgradeability

Two calculations are carried out in the link design:

(i) The power loss budget

(ii) The power link budget

The power loss model of an optical fibre link is Figure 2.12

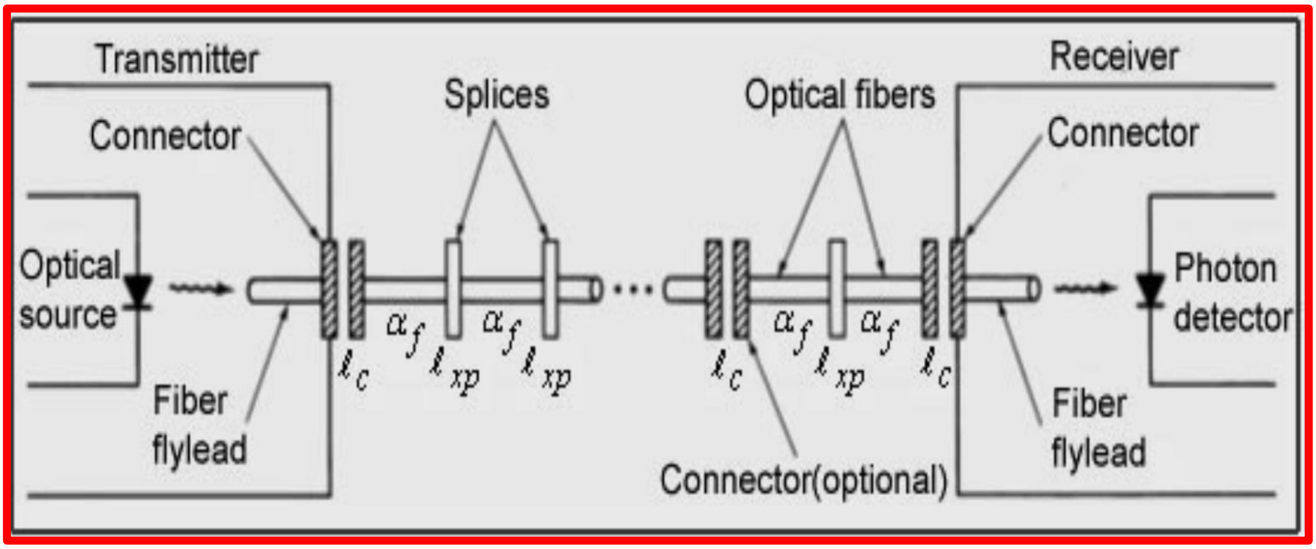

Figure 2.12: Power Loss Model

2.2.7.1 Power Budget Calculations

P_s = Power from the Transmitter in dBm

P_r = Sensitivity of receiver in dBm for given BER

Maximum permissible loss = $\alpha_{max} = P_s - P_r$

$$\alpha_{max} = \alpha_{fiber} + \alpha_{conn} + \alpha_{splice} + \alpha_{system}$$

$$\Rightarrow \quad \alpha_{fiber} = \alpha_{max} - (\alpha_{conn} + \alpha_{splice} + \alpha_{system}) \qquad (2.10)$$

Power limited Link Length $(L_{P_{max}}) = \frac{\alpha_{fiber}}{Loss/km}$ (2.11)

Beyond this distance, the SNR is below the acceptable limit

2.2.7.2 System Margin

System margin is generally taken to be 6 dB to accommodate deterioration of components.

This is illustrated in Figure 2.13

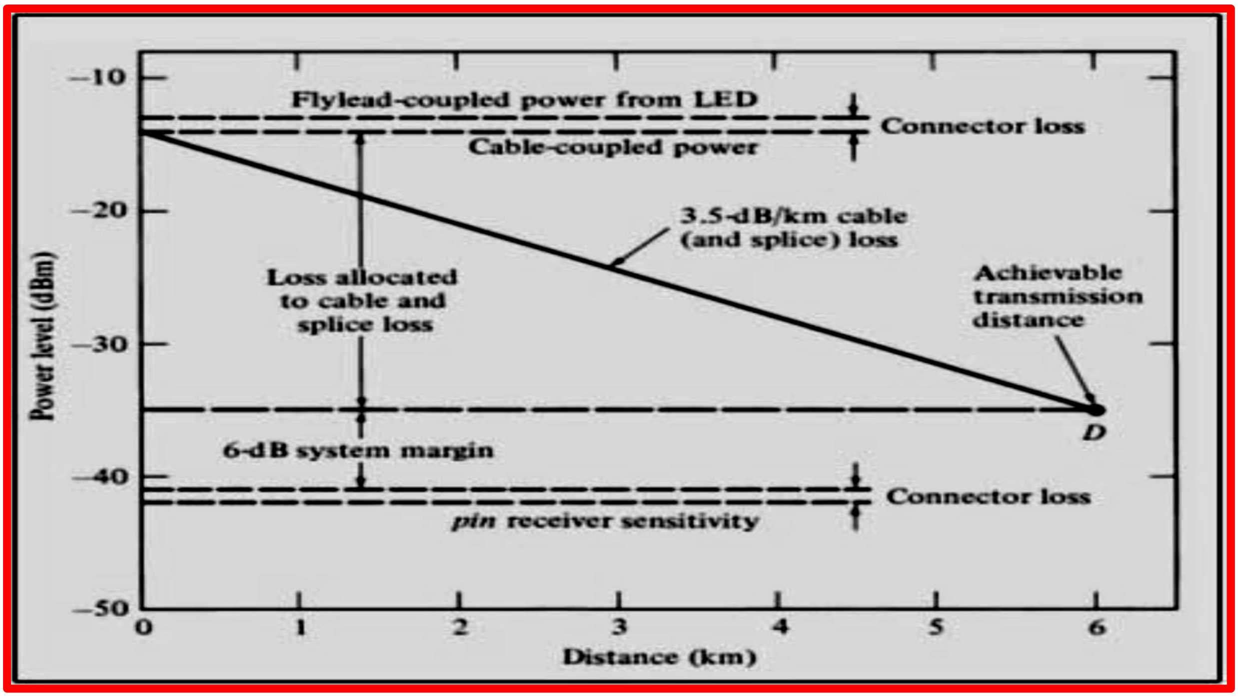

Figure 2.13: System Margin

2.2.8 Rise Time Budget Calculation

Rise time analysis gives effective bandwidth of the link (t_{sys}) **as:**

$$t_{sys} = \left[t_{tx}^2 + D^2\,\sigma_\lambda^2\,L^2 + t_{rx}^2\right]^{1/2} \qquad \textbf{(2.12)}$$

For satisfactory operation of the link [ ];

$$t_{sys} \le 0.7\;T_b \qquad \textbf{(2.13)}$$

Rise time-limited link length can be expressed as:

$$L_{RT\,max} = \frac{1}{D\,\sigma_\lambda}\left[(0.7\;T_b)^2 - \left(t_{tx}^2 + t_{rx}^2\right)\right]^{1/2} \qquad \textbf{(2.14)}$$

Beyond this distance the signal distortion is unacceptable

Where:

t_{sys} = Total system rise time.

t_{tx} = Transmitter rise time

t_{rx} = Receiver rise time.

D = Dispersion of the fibre

σ_λ = Spectral width of the transmitter

L = Length

T_b = Data bit duration

In the link design two lengths are calculated:

(i) the power budget length, ($L_{p\,max}$)

(ii) the rise time budget (L_{RTmax})

The repeater has to be installed at a minimum distance equal to;

$$L_{p\,max} - L_{RT\,max}$$

Generally, the links are power limited and the repeaters are installed at $L_{p\,max}$. Typical repeater length is about 50-60 km in practice.

2.3 REVIEW OF SIMILAR WORKS

A lot of work has been carried out regarding Plastic Optical Fibre (POF). This subsection presents the review of recent similar works. The review shows the extent of work done in POF. It also provides basis for the proposed work.

Albakay and Nguyen, (2015) proposed a technique to mitigate the effect of modal dispersion by controlling the effective Numerical Aperture (NA) of a Plastic Optical Fibre (POF) link. Higher-order modes in Step Index POF (SI-POF) usually propagate at steeper angles than the lower-order modes. The lower-order modes therefore exit the fibre before the higher-order modes as a result of the differential path lengths which caused modal dispersion. In addressing this issue, a spatial mode filtering technique was used to mitigate the modal dispersion. The results experimentally demonstrated the improved performance of the link over a 30 m, achieving a bit error rate of 10^{-8} at 1 Gbps. This approach provided a simple and a cost effective solution to deliver Gigabit Ethernet using NRZ signalling over short range POF networks employing standard 1 mm SI-POF.

López *et al*., (2016) worked on experimental characterization of transmission properties in multi-core Plastic Optical Fibres (POF). The work characterized experimentally the transmission properties of multi-core POF and compared the result with those obtained from several single-core POFs under the same condition. Measurements were carried out on the frequency response, attenuation, and angular output power distribution as functions of fibre length under different configurations. The experimental result helped in the understanding the behavior of transmission properties of multicore POFs by exploiting the mechanism that effect light propagation in different types of fibres. The comparative analysis of the results established that the attenuation slopes of MC-POFs were similar to those of SC-POFs at the same wavelength test, while bandwidths of MC-POFs longer than 25 meters were higher than those of SC–POFs under the same launching conditions and experimental setup.

Woyessa *et al*., (2017) developed and characterized a polycarbonate based Polymer Optical Fibre (POF) with reduced attenuation loss. The POF preform was made using an improved casting method. The casting procedure was optimized through a two-phase approach: drying and melting phases. In the drying phase, an oven with enhanced air circulation was used which achieved a better water removal. Thus, the water trapped inside the plastic pellets diffused out easily during the drying, thereby improving the overall quality of the casting process. The melting phase was extended to remove any possible micro-sized residuals of crystals left in the final preform. Indeed, the incomplete melting due to insufficient time led to the presence of micro-crystals in the core of the cast preform, which resulted in higher scattering loss. The minimum fibre propagation loss was found to be 4.06 dB/m at 819 nm and at this wavelength the material loss was 3.58 dB/m. The fibre loss was reduced by a factor of two compared to the previously fabricated POF.

CHAPTER TWO

METHODOLOGY

3.1 INTRODUCTION

Some of the major design considerations in SI-POF are the relative core and cladding refractive indices as well as their diameters because these elements play a very important role in giving optical fibre the ability to capture light. In this section, item (i) of the methodology which is on link modeling and simulation of the optical fibre cable is presented. The following is the adopted methodology for the design and fabrication of the SI-POF.

i. Link modelling and simulation.
ii. Cable construction.
iii. Testing and measurements.
iv. Analysis of results and submission of final report and prototype to the Nigerian Communications Commission.

3.2 LINK MODELING AND SIMULATION

The objective of the link modeling and simulation is to optimize the bandwidth by minimizing the dispersion of a standard Step-index POF by finding the optimal core/cladding materials.

2.3.1 Dispersion in Optical Fibres

Distortions due to delay differences of the optical modes are generally called dispersion effect. In an optical fibre, there exits three main types of dispersion with additive effect:

i. Material dispersion.
ii. Waveguide dispersion.
iii. Modal dispersion.

Modal dispersion is the main shortcoming of SI-POF which largely limits the link bandwidth to about 40 MHz over a 100 m fibre cable (Albakay & Nguyen, 2017).

3.2.1.1 Model Equations

The modal dispersion in an SI fibre is quite large. The reason being that the modes/rays that propagate under a large angle $\vartheta_{\max}$ regarding the fibre axis is assumed to take a longer distance than the fundamental mode that just follows the axis at an angle of $\vartheta_{\max}$. The maximum mode delay differences per unit length $\Delta\tau'_{\max}$ is given in Saleh & Teich (1991) as:

$$\Delta\tau'_{\max} = \tau'_{slowest} - \tau'_{fastest} = \frac{n_g}{c_o \cdot \cos\vartheta_{\max}} - \frac{n_g}{c_o} = \frac{n_g}{c_o}\left(\frac{1}{\cos\vartheta_{\max}} - 1\right) \tag{3.1}$$

with $\vartheta_{\max}$ being the maximum possible propagation angle regarding the fibre axis within the fibre, the group index n_g, c_o is the speed of light, $\tau'_{slowest}$ is the time delay of the slowest mode and $\tau'_{fastest}$ is the time delay of the fastest mode.

Substituting cosine term by the Taylor-series expansion $\cos x \approx 1 - \frac{x^2}{2}$ and introducing an approximation for $\frac{1}{1+x} = 1 - x$, equation (3.1) is then simplified to:

$$\Delta\tau'_{\max} \approx \frac{NA^2}{2c_o n_{core}} \tag{3.2}$$

where n_{core} is the refractive index of core material and *NA* is the numerical aperture given by equation (3.3) as follows:

$$NA = \sqrt{n_{core}^2 - n_{cladding}^2} \tag{3.3}$$

where $n_{cladding}$ is the refractive index of the cladding material.

For an SI-POF with the length, *L*, the total dispersion is estimated as shown in equation (3.4).

$$\Delta\tau'_{\max} \approx \frac{LNA^2}{2c_o n_{core}} \tag{3.4}$$

where L is the length of the optical fibre cable.

The bandwidth is estimated (Saleh & Teich 1991) as follows:

$$BW = \frac{0.44}{\Delta\tau'_{\max}} \tag{3.5}$$

where BW represents the bandwidth of the fibre cable.

Substituting equation (3.4) into equation (3.5) yields:

$$BW = \frac{0.88 c_o n_{core}}{LNA^2} \tag{3.6}$$

From equation (3.6), the bandwidth is inversely proportional to the length of the fibre, hence, the quality of the fibre can be characterised by the bandwidth-length product and presented as follows:

$$BW \times L = \frac{0.88 c_o n_{core}}{NA^2} \tag{3.7}$$

Equations (3.4) and (3.7) show that reducing *NA* by a factor of two, in turn reduces the dispersion by a factor of four and improves the bandwidth-length product by the same factor.

If the difference between the core and cladding materials refractive indices is decreased, the *NA* decreases as well. Lower *NA* leads to a higher bandwidth-length product. While this increase of the bandwidth-length product is highly welcomed, it also has the drawback of a smaller acceptance angle and tighter requirements on the coupling and adjustment of the fibre as well as potentially higher sensitivity to bending losses. The smaller acceptance angle translates to low coupling efficiency η_c, given by Agrawal, (2002) as:

$$\eta_c = (1 - R_f) NA^2 \tag{3.8}$$

where R_f is the reflectivity at the fibre front end.

The reflectivity of Poly (methyl methacrylate) (PMMA) is about 7% (Gutierrez & Zohdi, 2014). The coupling efficiency is about 1% in the case of a surface-emitting LED and roughly 10% for an edge-emitting LED (Agrawal, 2002).

The bandwidth-length product can be improved by minimizing the modal dispersion per unit length of equation (3.2). This leads to the optimization problem of equation (3.9) subject to the constraints of equations (3.10) to (3.12).

$$\min_{n} \; f(n) \equiv \frac{n_{core}^2 - n_{cladding}^2}{2c_o n_{core}} \tag{3.9}$$

Provided that:

$$\eta_c = (1 - R_f)(n_{core}^2 - n_{clad}^2) = 3\% \tag{3.10}$$

$$n_{core}, n_{cladding} \geq 1.3 \tag{3.11}$$

$$n_{core}, n_{cladding} \leq 1.6 \tag{3.12}$$

where reflectivity, R_f is taken as 10% which is considered to be the worst case scenario of the polymer. The choice of 3% coupling efficiency is because LED is used as the optical source in order to have a cost effective system. The refractive indices, n of materials used for the fabrication of polymer optical fibre ranges from 1.3 to 1.6 (Bunge, *et al.* 2016)

The optimum values of the design variables, n_{core} and $n_{cladding}$ that minimize the objective function $f(n)$ in equation (3.9) are to be obtained, subject to the constraints in equations (3.10) to (3.12) being satisfied.

To solve this problem, the *fmincon* function provided in MATLAB is used. The syntax of the function is as follows.

[nopt, fopt] = fmincon('fun', x0, A, b, Aeq, beq, LB, UB, 'nonlcon')

where *x0, A, b, Aeq, beq, LB*, and *UB* are the input variables that need to be defined before calling *fmincon*. '*fun*' is the name of the function file containing the definition of f(x), and '*nonlcon*' is the name of the function file containing the nonlinear constraints. The variables *xopt* and *fopt* are the outputs of *fmincon*, where *nopt* is the optimum vector of variables [n1,n2] and *fopt* is the minimum value of the objective function f.

3.2.2 Attenuation of the Developed POF Cable

Attenuation of fibre mainly determines the maximum transmission distance of optical communication systems without amplifiers or repeaters, as well as the maximum output power from the light source and the minimum receiver sensitivity. The attenuation is mainly caused by absorption and scattering of optical power. Attenuation, or transmission loss is defined as the ratio of input and output powers and expressed by linearly adding the losses due to the individual components in units of decibel. Optical power decreases exponentially with distance as light travels along a fibre. Thus, attenuation of optical fibre cable is typically described in dB/km. From the definition, the total attenuation, α in dB/km is expressed mathematically as Koike & Gaudino, (2013):

$$\alpha = -\frac{10}{L}\log_{10}\left(\frac{P_{out}}{P_{in}}\right) \tag{3.13}$$

where P_{out} is the power received at output of an optical fibre of length, L with input power of P_{in}.

The total intrinsic attenuation is mainly due to absorption and scattering losses largely due to the nature of material and the fabrication process of the cable. When each component of the fibre is expressed in dB, the resultant is obtained by linearly adding up all the components as follows (Koike & Gaudino, 2013).

$$\alpha = \alpha_a + \alpha_s \tag{3.14}$$

where α_a is the absorption loss and α_s is scattering loss.

For transparent polymer blends, the absorption coefficient, α_a is given by Song *et al*., (2013) as

$$\alpha_a = 10\log(e) 2\pi^3 \left(\frac{\Delta n}{n_1}\right)^2 \left(\frac{V^2 v_s}{\lambda^4}\right) \tag{3.15}$$

where $\Delta n = n_2 - n_1$, n_1 is the refractive index of PMMA, n_2 is the refractive index of PVDF, V is volume of PVDF, v is the volume ratio of PVDF to PMMA, and λ is the wavelength.

The scattering loss, α_s of optical fibre cable is given by Koike & Gaudino, (2013) as:

$$\alpha_s = 10\log(e) \left(\frac{8\pi^3}{3\lambda^4}\right) n^8 p^2 k_B T_f \beta_T \tag{3.16}$$

where n is the resultant core refractive index, p is photoelastic coefficient, k_B is the Boltzmann's constant, T_f is the fictive temperature and, β_T is isothermal compressibility of the optical fibre cable.

$$\alpha = 10\log(e) \left(2\pi^3 \left(\frac{\Delta n}{n_1}\right)^2 \left(\frac{V^2 v_s}{\lambda^4}\right) + \left(\frac{8\pi^3}{3\lambda^4}\right) n^8 p^2 k_B T_f \beta_T \right) \tag{3.17}$$

3.3 CABLE CONSTRUCTION

This section presents the development of technical specification of the Plastic Optical Fibre (POF) cable as well as the manufacture of the developed POF.

3.3.1 POF Material

Since the first POF (Plastic Optical Fibre) was invented in the mid-1960s, considerable efforts have been made to develop materials in order to enhance POF's performance. The fundamental requirements for choosing or designing materials for POF fabrication are that the polymer should be (Koike, 2015)

i. completely transparent,

ii. resistant to high temperatures,

iii. able to be drawn into a fibre, and

iv. mechanically flexible.

v. low refractive index, and

vi. low material dispersion.

The Refractive Index (RI) of the polymer material is its fundamental physical quantity. It describes how light or electromagnetic waves propagate through an optical medium. It is defined as

$$n = \frac{v}{c} \tag{3.18}$$

where v is the phase velocity of light in the optical medium, c is the speed of light in vacuum.

If a material absorbs light, the refractive index equation can be modified using a complex term (Rawle, 2017):

$$N = n + ik \tag{3.19}$$

where N is the complex refractive index, n is the real refractive index, k is the extinction coefficient, which relates to the amount of light that is absorbed.

RI is indirectly linked to a number of other fundamental physical properties; one such properties is the relative permittivity, ε_r given by (Johannes *et al.*, 2004)

$$n = \sqrt{\varepsilon_r} \tag{3.20}$$

The Lorentz–Lorenz equation defines a term known as the molecular refractivity or molar refraction, [R] as (Rawle, 2017)

$$[R] = \frac{n^2 - 1}{n^2 + 2} \times \frac{M}{\rho} \tag{3.21}$$

where M is the molecular mass of the material and ρ the density.

Equation (3.21) could be used to predict the RI of a material based on the structure of its molecule.

The refractive indices of colorless, transparent polymer such as poly methyl methacrylate (PMMA) and polyethylene terephthalate (PET) usually range from 1.30 to 1.60 as shown in table 1.

Table 1: Refractive indices of polymeric materials.

Polymeric Materials	**Refractive Index**
Poly (N-Vinylcarbazole)	1.68
Poly ether ether ketone	1.65
Poly (p-xylylene)	1.67
Polystyrene	1.59
Poly (vinyl chloride)	1.53
Polyethylene terephthalate	1.58
Polyethylene	1.51
Poly (methyl methacrylate)	1.49
Poly (dimethyl siloxane)	1.40
Poly (tetrafluoroethylene)	1.35

The optimal values of the refractive indices of the core and cladding materials of the proposed step-index POF are found to be 1.4865 and 1.4756 respectively.

Permittivity (and by extension refractive index) of polymers can be modified in different ways, such as (Švorčík *et al.,* 2005)

i. **Using High Energetic Processes**

This processes involve using ionizing radiations to modify the structure and properties of polymer (Clough, 2001). Radiation-processing techniques may be applied for cross-linking of plastics and rubbers, curing of coatings and inks, heat-shrink products, fibre-matrix composites, and etc.

ii. Copolymerization with Polar Monomers

Copolymerization is a general method of modifying the physical properties in order to meet specific needs; however, it can result in high light scattering losses. Indeed, the number of ideal random copolymer and alternating copolymer combinations is severely limited. Furthermore, an accurate prediction of the monomer reactivity ratio is also quite difficult without performing the reaction. However, this method, which inhibits the excess scattering loss by adjusting the refractive index of each component, is more realistic and relatively easy.

iii. Fabrication of Polymer Based Composites

Sometimes a material is desired to have some of the properties of one polymer, and some of the properties of another. Instead of going back into the lab and trying to synthesize a brand new polymer with all the desired properties, two polymers are mixed together to form a blend that will hopefully have some properties of both in the right combination.

Nanocomposites are materials consisting at least two constituents. Through the concept of effective medium theory, several equations have been developed to calculate the refractive index of nanocomposites. One of the most frequently used equations for binary component nanocomposites is derived from the Lorentz-Lorenz relationship (Li, 2016):

$$\frac{n_c^2 - 1}{n_c^2 + 2} = Q_1 \times \frac{n_1^2 - 1}{n_1^2 + 2} + (1 - Q_1) \times \frac{n_2^2 - 1}{n_2^2 + 2} \tag{3.22}$$

where n_c is the effective refractive index of the composite, n_1 the refractive index of component 1, n_2 the refractive index of component 2, Q_1 the volume fraction of component 1.

The various economic and property advantages accomplished by blending are (Aid *et al.*, 2019):

i. The opportunity to develop or improve on properties to meet specific customer needs
ii. The capability to reduce material cost with or without little sacrifice in properties
iii. Permit the much more rapid development of modified polymeric materials to meet emerging needs by by-passing the polymerization step
iv. Extended service temperature range
v. Light weight
vi. The ability to improve the processability of materials which are otherwise limited in their ability to be transformed into finished products
vii. Increased toughening
viii. Enhanced ozone resistance
ix. Improved modulus and hardness
x. Improved barrier property and flame retardant property
xi. Improved impact and environmental stress cracking resistance, etc.

It is quite challenging to make two different polymers miscible. This is due to differences in their entropy. Table 2 shows pairs of polymer that have been found to miscible (Pslc, 2019).

Table 2: Pairs of Miscible polymers

S/N	Polymer	Refractive Index (n)	Polymer	Refractive Index (n)
1	Poly(methyl methacrylate), PMMA	1.491	poly(vinylidene fluoride) PVDF	1.426
2	Polystyrene, PS	1.589	Poly(vinyl methyl ether) PVME	1.467

Equation (5) is used to obtain the volume ratios of the pairs of materials to produce the core and cladding blends with the desired refractive indices of 1.487 and 1.476 respectively. This is shown in table 3.

Table 3: Volume ratios of constituent polymers

S/N	Polymer Blend	Core Volume Ratio (%)	Cladding Volume Ratio (%)
1	PMMA/PVDF	94.0/6.0	77.3/22.7
2	PS/PVME	17.0/83.0	7.7/92.3

It is important to predict the properties of polymer blend as function of the composition. An easy approach is to use the simple law of mixture (Fried. 2005), where the upper bound of a property of the blend, P_b, is given by (Fried. 2005)

$$P_b = Q_1 P_1 + Q_2 P_2 \qquad (3.23)$$

and the lower bound equation is

$$\frac{1}{P_b} = \frac{Q_1}{P_1} + \frac{Q_2}{P_2} \qquad (3.24)$$

Equations (2.23) and (3.24) are used to obtain the range of values of Young's modulus, Tensile strength and Glass transition temperature of the blend that will be used to fabricate the SI-POF. The technical specifications for the fabrication of the SI-POF from different combinations of materials are given in Table 4.

Table 4: Specification of PMMA/PVDF SI-POF

S/N	**Parameter/unit**	**Core**	**Cladding**
1	Material	PMMA/PVDC	PMMA/PVDC
2	Material Volume Ratio (%)	94.0/6.0	77.3/22.7
3	Refractive Index	1.487	1.476
4	Diameter, µm	980	1000
5	Young's modulus, MPa	2433 – 2435	2388 – 2393
6	Tensile strength, MPa	61.41 – 61.49	59.84 – 60.07
7	Glass transition temperature $T_{g,}$ °C	92.67 – 96.84	62.23 – 74.13

3.3.2 POF CABLE FABRICATION

Fabrication processes of Plastic Optical Fibres (POFs), regardless of their Step-Index (SI) or Graded-Index (GI) profiles, are divided into two main categories:

i. a preform-drawing process, and
ii. an extrusion process.

The preform-drawing method enables a precise control of the fabrication process of rather complicated refractive index profiles

The preform-drawing method is a batch process where a polymeric preform is fabricated first, which is then followed by thermal drawing of the preform into the fibre. A schematic diagram of the process is shown in Figure 1. In this method, a cylindrical polymer rod consisting of a core and cladding layers is positioned vertically in the middle of the furnace where its lower portion is heated locally to the drawing temperature.

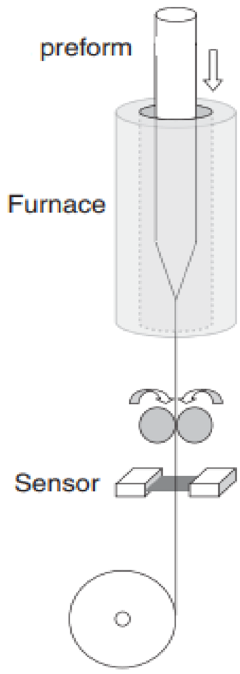

Figure 1: Preform-Drawing Process

3.3.2.1 Search for Local Fibre Cable Manufacturers

Based on the developed specifications as shown in Table 4, fifteen (15) potential cable manufacturers in Nigeria were identified and contacted in Nigeria. After much persistence, only a company in Lagos; Datacomm Express; responded partially to our request stating that although they did not have the capacity to manufacture optical fibre cables of any type, they could serve as an interface between us and a cable manufacturer in China. It was thus resolved at an emergency meeting of the research team on 5th November, 2019 that: (i) The Tender document be finalised within one week. (ii) the research team should meet with Datacomm Express in their company for exploratory discussion based on the tender document. A letter dated 7th November, 2019 was written to the company by the research team affirming the date and time for the meeting. A member of the team represented the research team at the meeting that took place on 15th November, 2019 at the Datacomm Express office in Lagos.

A tender document was presented to the company during the meeting. After studying the tender document carefully, the two parties discussed at length before reaching a conclusion. The conclusion was that the company could not manufacture optical fibre cable but could serve as a Nigerian agent in finding a foreign manufacturer. The company therefore requested one month within which they would inform us on how they could collaborate with us on the project.

Several reminders were sent to Datacomm Express but at end they reneged on the agreement reached by simply ignoring any further communication with the research team.

3.3.2.2 Search for Foreign Fibre Cable Manufacturers

Consequently, the research team decided to search for a foreign optical fibre cable manufacturer directly. Several foreign companies were contacted.

Eventually, we found and negotiated with a cable manufacture in China; Messrs Bones Electronics Company Limited, to manufacture the cable for us as specified. Shortly after effecting payment in March, the company suspended operations due to the COVID-19 lockdown in China. It was not until November, 2020 when the cable was shipped to us. The technical specifications of the manufactured cable as well as the procurement invoice are shown in Table 5 and Figure 1 respectively.

Table 5 Technical Specifications of the Manufactured Cable

项目(Item)		技术参数(Technical Parameters)	单 位 (Unit)
塑料光纤 Plastic Optical Fibre	纤芯材料(Core Material)	聚甲基丙烯酸甲酯(Polymetyl-methacrylate)	—
	包层材料(Clad dingMaterial)	氟树脂 (Fluorinated Polymer)	—
	纤芯折射率 (Core Refractive Index)	1.491	—
	包层折射率 (Cladding Reflective Index)	1.41	—
	折射率类型(Refractive Index Profile)	阶跃型(Step Index)	—
	数值孔径(Numerical Aperture)	0.50±0.15	—
	纤芯直径(Core Diameter)	980±45	Mm
	包层直径(Cladding Diameter)	1000±45	Mm
单位重量 (Unit weight)		1	g/m

BEC **Bones Industry Co., Ltd**

Add: Chongzhou Industrial Development Zone, Chengdu, Sichuan 611230 P.R., China
Tel: +86-28-8220 0303 Fax: +86-28-8220 0304 Email: salse@bones-electronics.com

PROFORMA INVOICE

No.: PI-A20021908-NG
Date: February 19, 2020

Invoiced To: Ahmadu Bello University
Samaru Campus, Zaria,
Kaduna State,
Nigeria

Price Term: FCA Door To Door
Payment Term: 100% T/T in advance
Lead Time: Within 10 working days after deposit received.

Product	Description	Unit Price (USD/Roll)	Q.T.Y (Rolls)	Amount (USD)
Plastic Optical Fiber	P/N: LF-1000 Core Diameter: 980mm Cladding Diameter: 1000mm Spool Length: 1500m	85.00	4	340.00
Freight cost	By DHL			160.00
	Total Amount			500.00

Total Say: US Dollars Five Hundred Only.

Paypal account: 519624541@qq.com

The Buyer:

For and on behalf of
BONES INDUSTRY CO., LTD
The Seller:
Archor Lam
Authorized Signature(s)

Figure 1 Proforma Invoice

Plate 1 shows the procured plastic optical fibre cable in four spools of 1.5km length each. This represents a total cable length of six (6) km.

Plate 1   Procured Plastic Optical Fibre Cable

3.3.2.3 Fabrication of Small Core Diameter POF

Step-Index POF fibres are available in sizes of 500, 750 and 1000 µm total diameter with up to 98% core diameter.

As a proof of concept, we applied a preform-drawing process as depicted in figure 1 on the 980/1000 µm LF-1000 SI-POF in order to produce a 490/500 µm SI-POF. The LF-1000 is considered to be the preform. Plate 2 shows the locally fabricated 490/500 µm SI-POF.

Plate 2: Locally Fabricated 490/500 µm SI-POF

3.4 FIBER OPTIC TESTING

Test measurements are carried out in order to evaluate the performance of the plastic optical fiber cable. Figure 2 shows a general measurement set up. Components such as, connectors, LEDs, detectors, signal generators and analyzers are used.

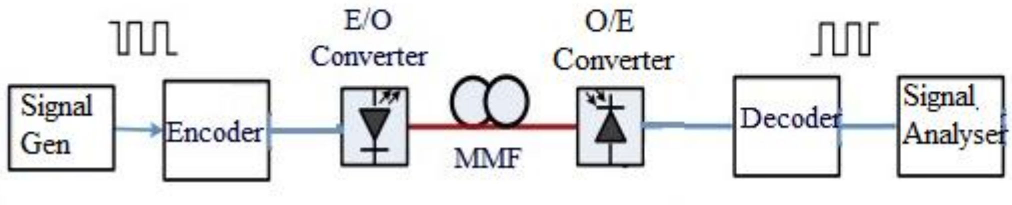

Figure 2: General Measurement Test Bed

3.4.1 Fiber Optic Testing Requirements

Table 6 shows the required instruments for various test measurements.

Table 6: Optical Fiber Test Instrument

Test Parameter	**Instrument**
Optical Power (Source Output, Receiver Signal Level)	Fiber Optic Power Meter
Attenuation or Loss of Fibers, Cables & Connectors (Insertion Loss)	FO Power Meter & Source or OLTS (optical loss test set)
Source Wavelength, Spectral Width	FO Spectrum Analyzer
Backscatter For Loss, Length and Fault Location)	Optical Time Domain Reflectometer (OTDR)
Bandwidth / Dispersion	Dedicated Bandwidth Testers Optical Sampling Oscilloscope

3.4.2 Intermodal Dispersion Measurement

Intermodal dispersion measurement can be carried out in either time domain or frequency domain. The time domain method uses the sampling oscilloscope while a spectrum analyser is used for the frequency domain method. Figures 3 and 4 illustrate time domain and frequency domain measurement of intermodal dispersion respectively.

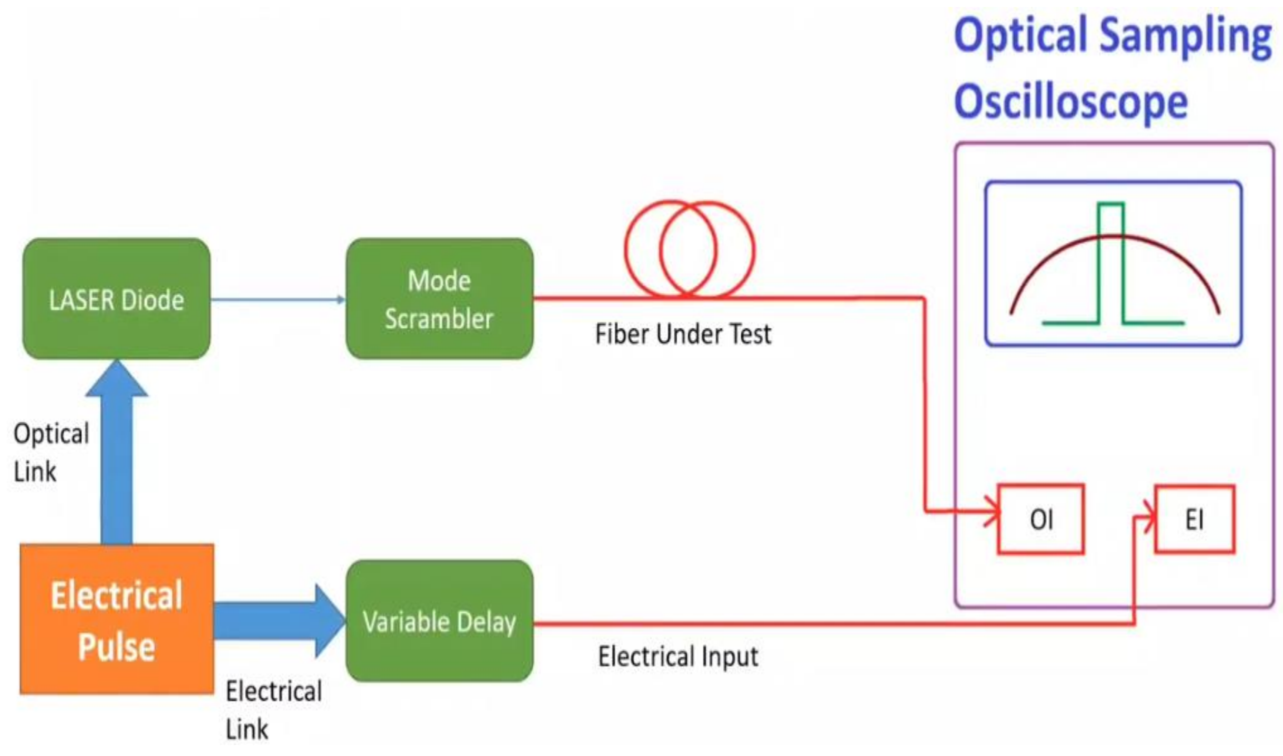

Figure 3: Time Domain Measurement of Intermodal Dispersion

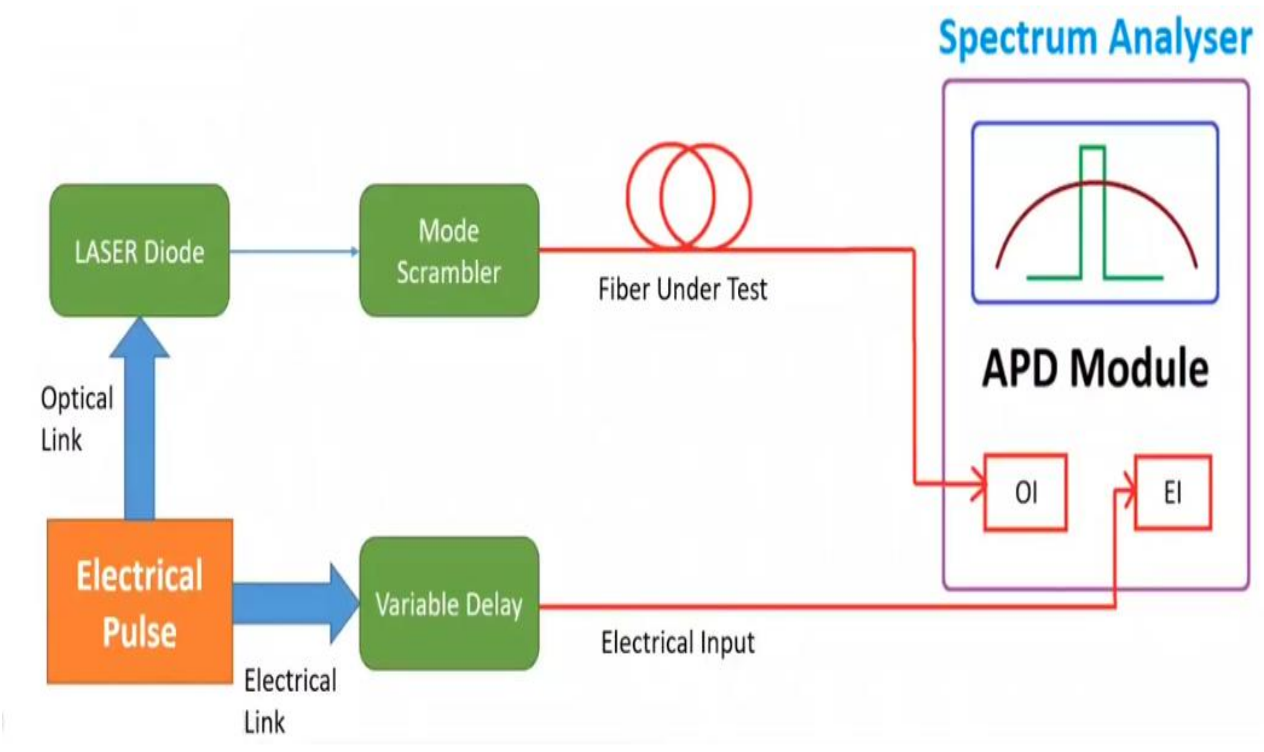

Figure 4: Frequency Domain Measurement of Intermodal Dispersion

3.4.3 Attenuation Measurement

Figure 5 illustrates optical power loss measurement

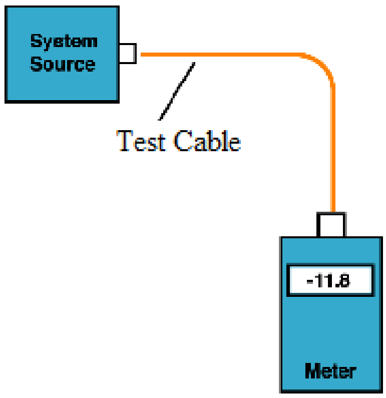

Figure 5: Optical Power Loss Measurement

3.4.4 Laboratory Test Measuerement

The attenuation and dispersion are the two major transmission charateristics of an optical fiber cable. The dispersion of the developed SI optical fibre cable is 36.167 ps/m. About 1 THz signal generator and 1 THz oscilloscope is reqired for dispersion measurement. Due to financial limitation, measurement on dispersion could not be carried out. This is because the cost of optical sampling oscillocope ($ 31,662.00) is more than what the research grant can accommodate. Attenuation measurement was succesfully carried out on the developed 490/500µm SI-POF.

3.4.5 Attenuation Measurement

The block diagram for the attenuation measurement is shown in figure 6.

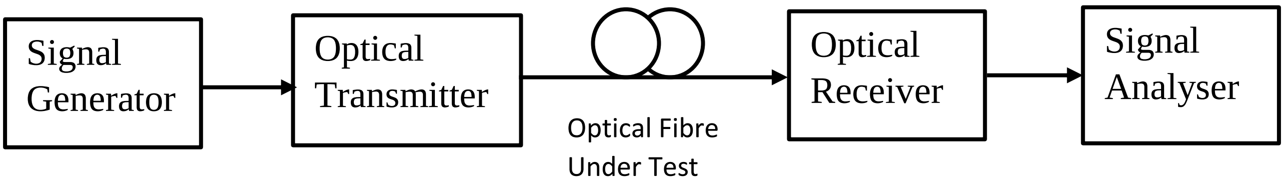

Figure 6: Attenuation Measurement

The optical transmitter and receiver are constructed locally and the circuit diagrams are shown in Figures 7 and 8 respectively.

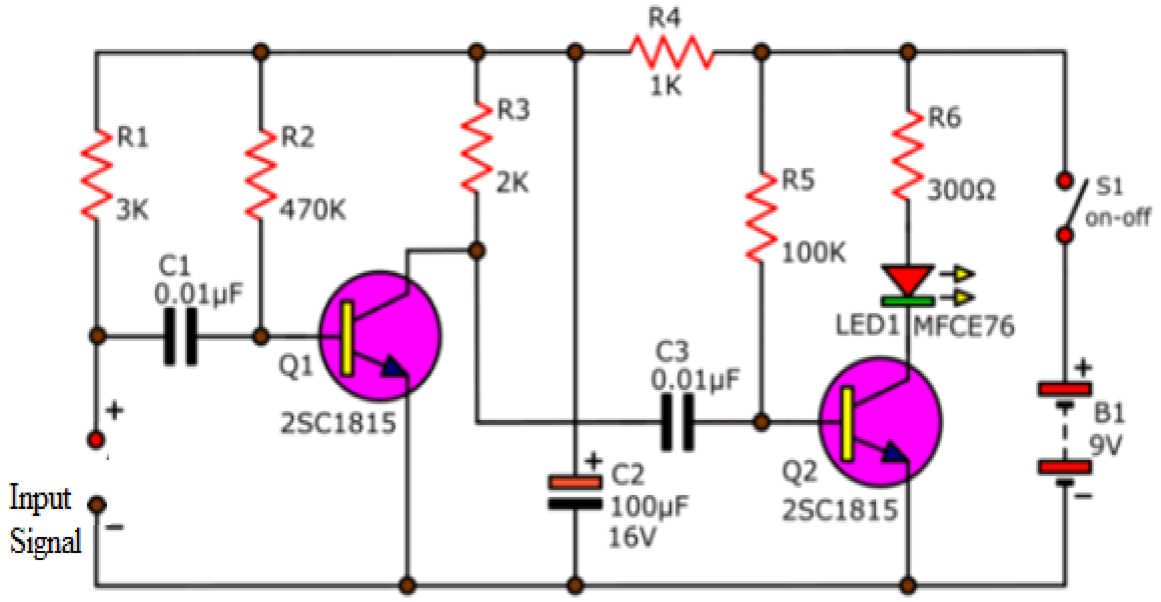

Figure 7: Optical Transmitter Circuit

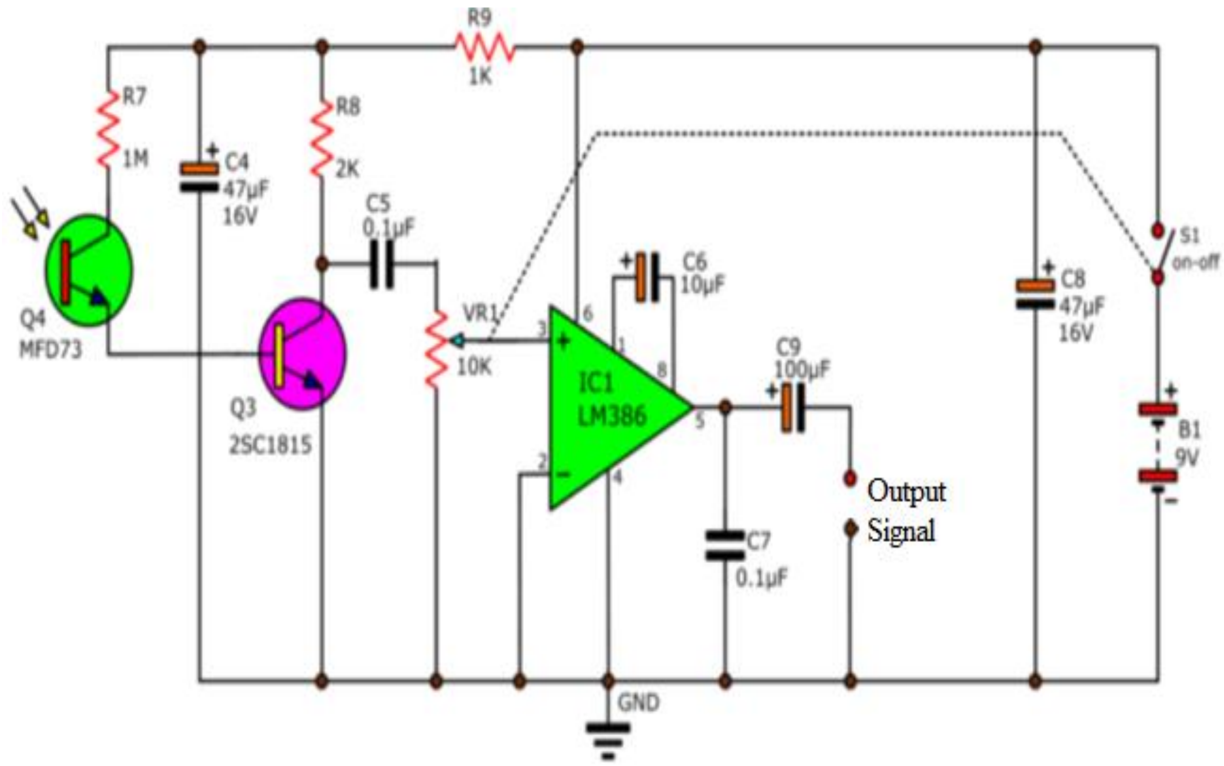

Figure 8: Optical Receiver Circuit

Plate 3 shows the laboratory test measurement setup.

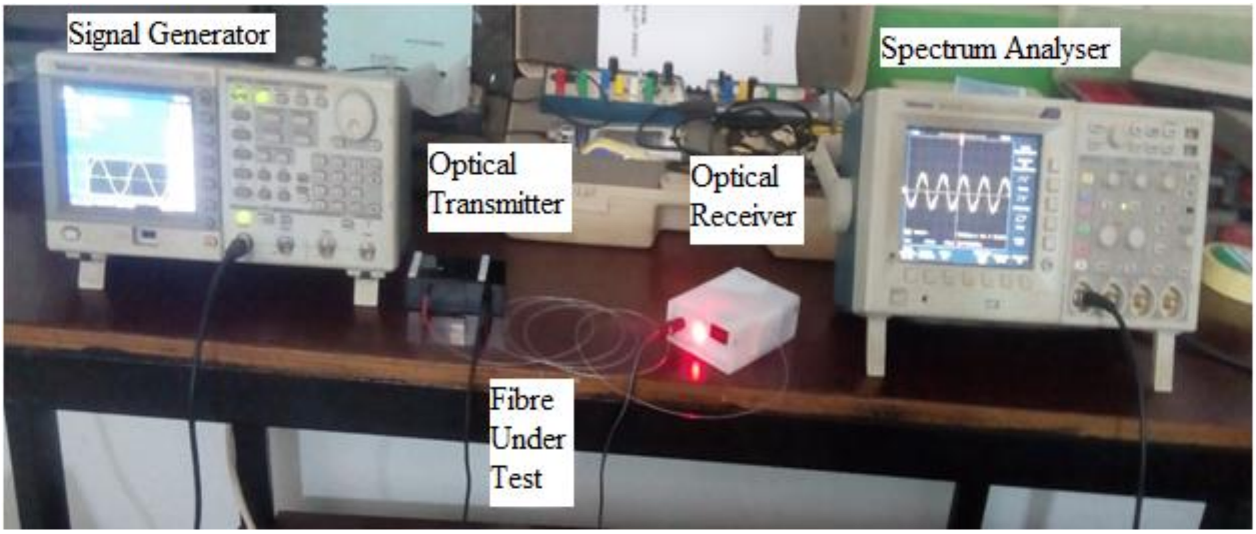

Plate 3: Laboratory Test Measurement Setup

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This section presents the results of the link modelling of the SI-POF. The relationships between the different parameters used to characterise optical fibre cable are illustrated in various plots contained in this chapter for clarity and ease of explanation. The results of the optimization of the bandwith-length product is presented.

4.2 Plots of Optical Fibre Parameters

Figure 4.1 illustrates the variation of NA of an optical fibre with the refractive index of the core for Relative Refractive Index (RRI) differences of 0.01, 0.02, and 0.03.

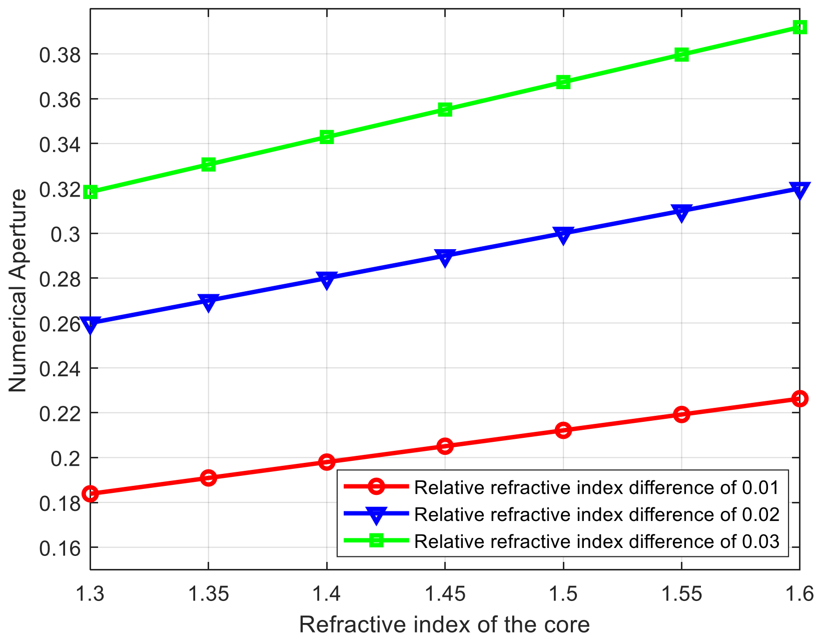

Figure 4.1: NA versus RI of the Core at Different RRI Difference Values

It can be seen that irrespective of the RRI difference value, the NA increases with an increase in the RI of the optical fibre from 1.3 to 1.6. At a fixed value of RI, the NA value is low for low RRI difference value. For instance, at RI values of 1.4, the NA for RRI differences of 0.01, 0.02, and 0.03 are 0.2, 0.28, and 0.34, respectively. This means that low RRI difference value results in low NA values. Low NA values translate to small angle of acceptance of the optical fibre, which subsequently results in low coupling efficiency.

Figure 4.2 shows the variation of bandwidth-length product with NA of an optical fibre for RI of the core from 1.3 to 1.6. Irrespective of the core RI value, the bandwidth-length product decrease exponentially with an increase in NA from 0.2 to 0.5. At fix NA value, the bandwidth-length product is higher for higher values of core RI values. For instance, at NA value of 0.3, the bandwidth-length products for core RI values of 1.3, 1.4, 1.5, and 1.6 are 3,813 MHzm, 4,107 MHzm, 4,400 MHzm, and 4,693, MHzm respectively. This means that an optical fibre fabricated using a polymer with high RI values has a high bandwidth length product value.

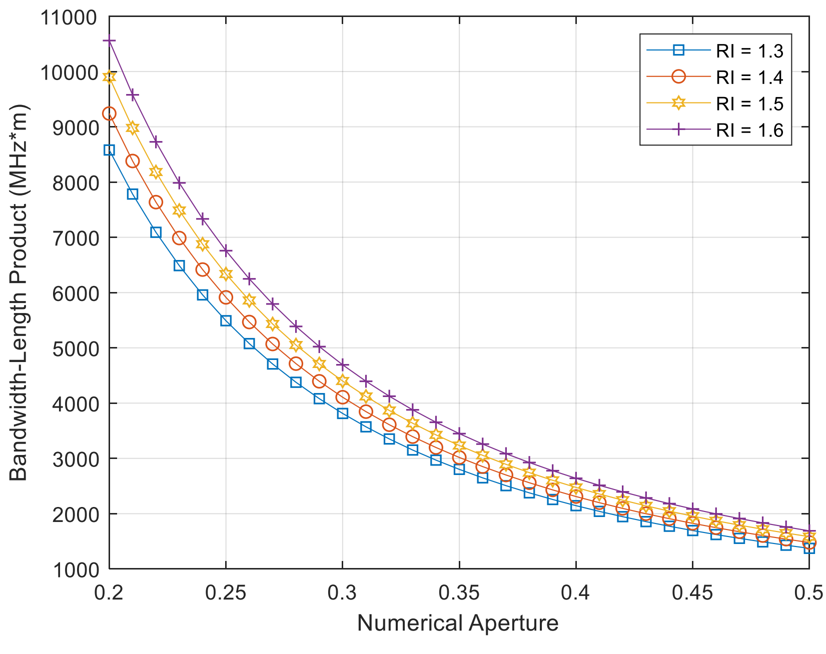

Figure 4.2: Bandwidth-Length Product versus NA

Figure 4.3 shows the variation of optical fibre cable length with the NA for different core RI values from 1.3 to 1.6 at bandwidth of 40 MHz and 50 MHz. The optical fibre cable length decreases exponentially with an increase in the NA values from 0.1 to 0.5. At fixed NA value, low RI values results in low optical fibre cable length. However, for a core RI value range of

0.1 to 0.3, there is a significant difference in the optical cable length at a fixed NA value. On the other hand, at a core RI value range of 0.3 to 0.5, the difference in the optical cable length at fixed a NA value is insignificant. For instance, using an optical fibre bandwidth of 40 MHz and at the NA value of 0.2, the optical fibre cable lengths at core RI values of 1.3, 1.4, 1.5, and 1.6 are 214 m, 231 m, 248 m, 264 m, respectively. At the NA value of 0.4, still using the same optical fibre bandwidth of 40 MHz, the cable lengths are 53 m, 57 m, 61 m, and 66 m, respectively.

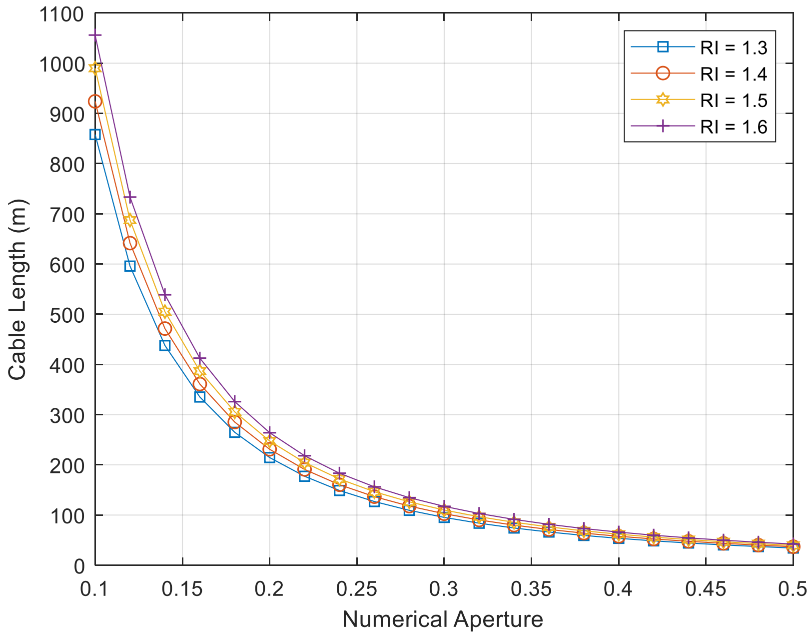

Figure 4.3: Optical Fibre Cable length versus NA at Bandwidth of 40 MHz

Extending the analysis to 50 MHz optical fibre bandwidth, the same conclusion is arrived at as with that of the 40 MHz optical fibre bandwidth as shown in Figure 4.4. Comparison between the 50 MHz and 40 MHz bandwidth shows that at fixed NA and core RI values, the optical cable length is lower for the 50 MHz bandwidth which is clearly illustrated by Table 4.1.

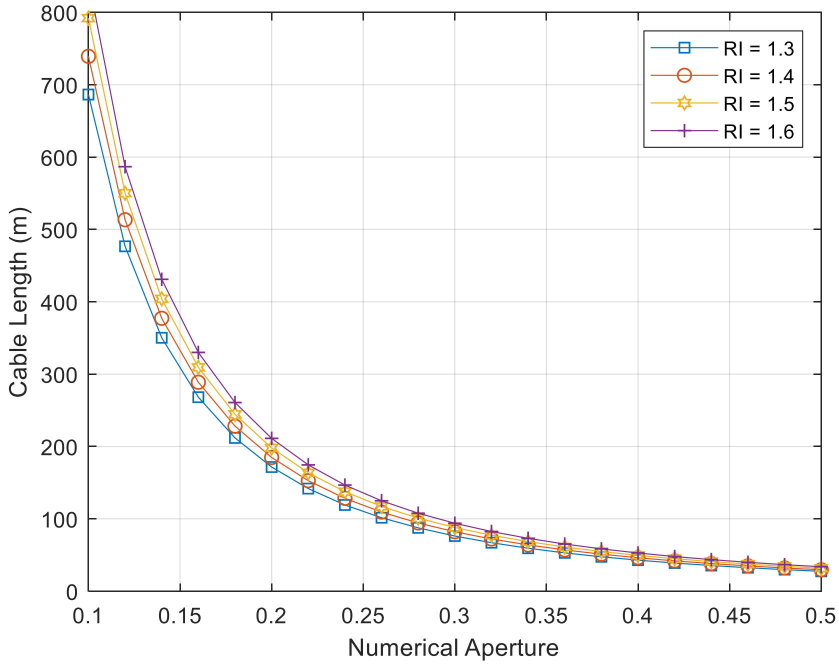

Figure 4.4: Optical Fibre Cable length versus NA at Bandwidth of 50 MHz

Table 4.1: Optical Fibre Cable Length and Numerical Aperture Comparison at Different Core RI Value and Bandwidth

Numerical Aperture	Core refractive index of 1.3		Core refractive index of 1.5		Core refractive index of 1.6	
	Length (m) at 40 MHz	Length (m) at 50 MHz	Length (m) at 40 MHz	Length (m) at 50 MHz	Length (m) at 40 MHz	Length (m) at 50 MHz
0.1	858	686	990	792	1050	844
0.2	214	171	248	198	264	211
0.3	95	76	110	88	117	93
0.4	53	42	61	59	66	53
0.5	34	25	40	30	42	34

Figure 4.5 shows the variation of coupling efficiency with the NA for different reflectivity value of the fibre end. The coupling efficiency increases slightly exponentially with the NA values from 0.2 to 0.5, irrespective of the reflectively value. For a particular value of NA, the coupling efficiency decreases slightly with an increase in the reflectivity of the fibre end. Thus, it is observed that the coupling efficiency depends significantly on the NA value.

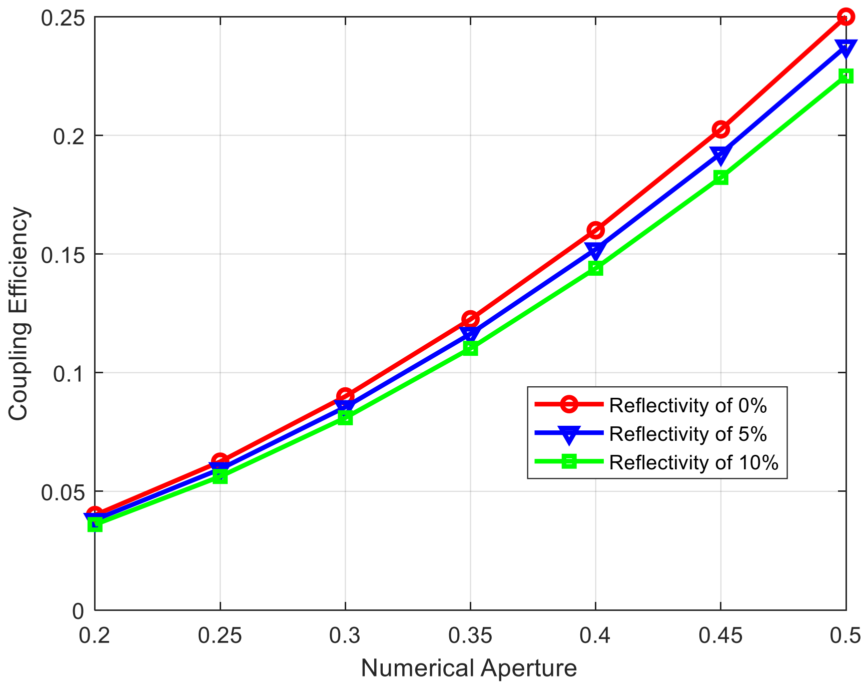

Figure 4.5: Coupling Efficiency versus NA

Figure 4.6 shows the attenuation of the developed POF against wavelength. It is observed that the attenuation decreases with increase in the operating wavelength of the propagating optical signal. One of the attraction of POF for data communication is that low cost optical sources could be used to transmit the optical pulses. Light Emitting Diodes (LEDs) are low cost devices that operates in the visible light region from 400 nm to 700 nm. The red LED operates at 650 nm and is used as optical source for this work. From Figure 4.6 the attenuation of the developed POF at 650 nm is found to be 1.588 dB/m.

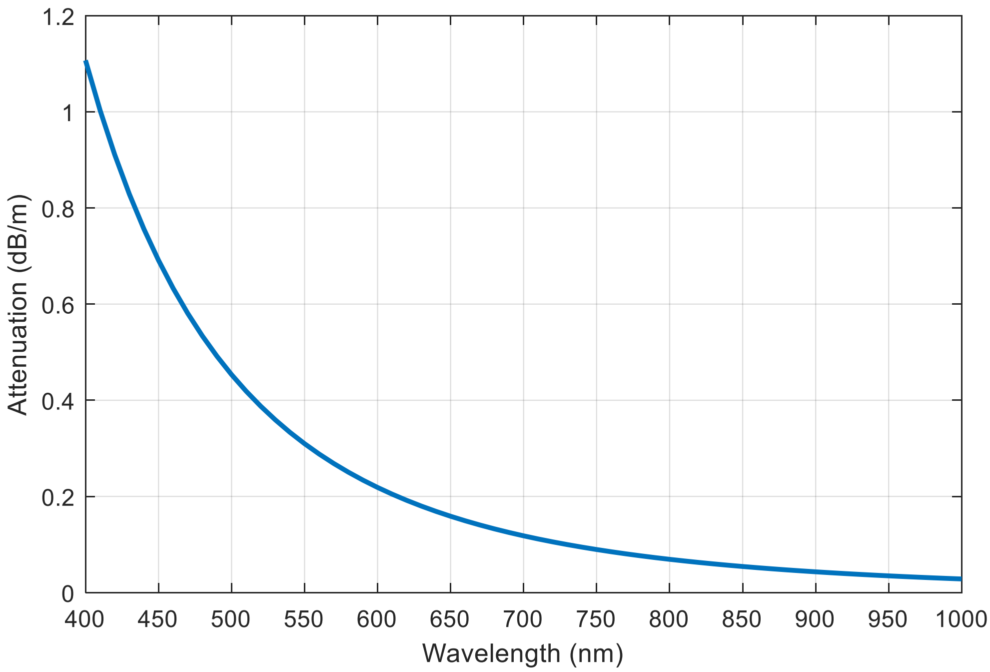

Figure 4.6: Attenuation of the Developed POF against Wavelength

4.3 SOLUTION TO THE OPTIMIZATION PROBLEM OF EQUATIONS 9 – 12

After all the variables and function files were defined, the *fmincon* function was called, and the following outputs were obtained.

nopt = [1.4865 1.4756] *fopt* = 3.6169e-11

The solver located a point that seems to be a *local* minimum, since the point is feasible (satisfies constraints within the *Constraint Tolerance*) and the *first-order optimality measure* is less than the *Optimality Tolerance*.

Thus, the optimal design variables n_{core} and n_{clad} were obtained respectively as 1.4865 and 1.4756. The minimum dispersion per unit length is 36.169 ps/m.

Using equation (5), the bandwidth of 100 m length of SI-POF is obtained as

BW = 44/(100 x fopt) = 121.65 MHz

4.4 Results of the Experimental Characterisation of the POF

Figure 4.7 shows the plot of received optical against the optical fibre cable length. The measured data is given in appendix 1. From the figure, it is observed that the received optical power decreases linearly the optical fibre cable length.

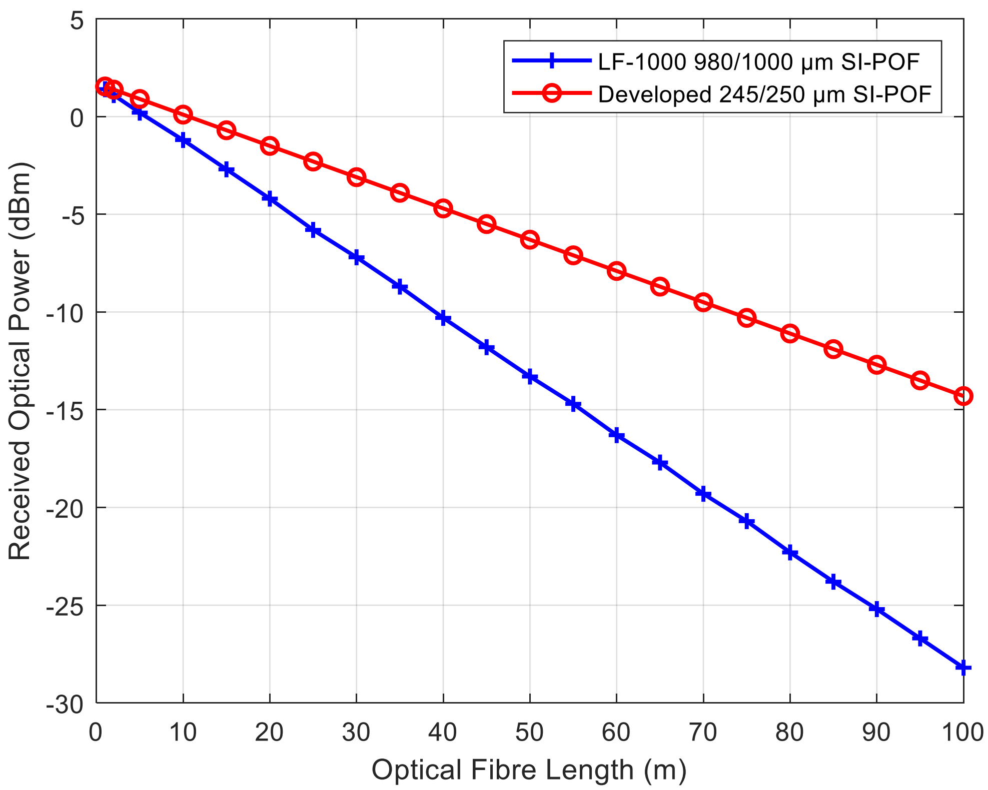

Figure 4.7: Optical Power against Optical Fibre Length

The attenuation, α of the cable is found using the equation given by Koike & Gaudino, (2013) as;

$$\alpha = \frac{10}{L}\log_{10}\left(\frac{P_1}{P_2}\right) \tag{4.1}$$

Where P_1 and P_2 are the optical power in watts at points 1 and 2 respectively and L is the distance between the two points.

Equation (4.11) can be written as

$$\alpha = \frac{P_{1(dB)} - P_{2(dB)}}{L} \tag{4.2}$$

The equation of the line of the plot in Figure (4.14) is written as

$$P_{2(dB)} = -\alpha L + P_{1(dB)} \tag{4.3}$$

From equation (4.3), α is the slope of the graph which is calculated to be 0.161 dB/m. The attenuation of the LF-1000 980/1000 µm SI-POF used as the preform is 0.3 dB/m as contained in the manufacturer's data sheet (see Appendix 4). Thus, the fabricated 490/500 µm SI-POF has lower attenuation as the LF-1000 980/1000 µm SI-POF used as the preform.

CHAPTER FIVE

CONCLUSSION

This work seeks to develop an improved POF cable by minimizing modal dispersion of the fibre. Optimal core and cladding materials for an improved bandwidth-length product of the cable are found through optimization by minimization of modal dispersion. The results show that the optimal core and cladding materials have refractive indices of 1.4865 and 1.4756 respectively. The minimum dispersion per unit length is found to be 36.169 ps/m. Thus, the bandwidth of 100 m length of the improved SI-POF is 121.65 MHz. This represents about 80 MHz bandwidth improvement compared with the works of Albakay & Nguyen, (2017). A standard LF-1000 980/1000 SI-POF is used to fabricate locally a small core 490/500 SI-POF using the freeform drawing process. The attenuation of the developed POF is found as 1.588 dB/m. Experimental measurements of the attenuation of the cable are carried out. The measured results indicate that the attenuation is 0.161 dB/m.

REFERENCES

Agrawal, G. P. (2002). *Fibre-optic communication systems*. John Wiley & Sons, Inc.

Albakay, N. A., & Nguyen, L. (2017). Achieving 1 Gbps Over Step-Index Plastic Optical Fibre Using Spatial Mode Air-Gap Filter. *IEEE Photonics Technology Letters*, *29*(8), 655-658.

Bunge, C. A., Beckers, M., & Gries, T. (Eds.). (2016). *Polymer Optical Fibres: Fibre Types, Materials, Fabrication, Characterisation and Applications*. Woodhead Publishing.

Binh, L. N. (2015). *Optical fiber communication systems with Matlab and Simulink models*. CRC Press.

Beckers, M., Schlüter, T., Vad, T., Gries, T., & Bunge, C. A. (2015). An overview on fabrication methods for polymer optical fibers. *Polymer International, 64*(1), 25-36.

Beckers, M., Vad, T., Mohr, B., Weise, B., Steinmann, W., Gries, T., . . . Bunge, C.-A. (2017). Novel Melt-Spun Polymer-Optical Poly (methyl methacrylate) Fibers Studied by Small-Angle X-ray Scattering. *Polymers*, *9*(2), 60.

Gutierrez, M. P., & Zohdi, T. I. (2014). Effective reflectivity and heat generation in sucrose and PMMA mixtures. *Energy and Buildings*, *71*, 95-103.

López, A., Ramón, S., Chueca, M., Losada, M. Á., Domínguez-Chapman, F. A., & Mateo, J. (2016). Experimental characterization of transmission properties in multi-core plastic optical fibers. In *Transparent Optical Networks (ICTON), 2016 18th International Conference on* (pp. 1-4). IEEE.

Matsuoka, T., Ito, T., & Kaino, T. (2000). First plastic optical fibre transmission experiment using 520 nm LEDs with intensity modulation/direct detection. *Electronics Letters, 36*(22), 1836-1837.

Méndez, A., & Morse, T. F. (2011). *Specialty optical fibers handbook*: Academic Press.

Massa, N. (2000). Fiber optic telecommunication. *Fundamentals of Photonics. University of Conneticut*.

Nelkon, M., & Parker, P. (1995). Advanced Level Physics. *Heinemann Publishers (Oxford) ltd. U.K*, *16*(9), 659-660.

Oliveira, I., & Bonfim, M. (2003). *Plastic optical fibers in telecommunications: analysis, comparison and applications.* Paper presented at the Microwave and Optoelectronics Conference, 2003. IMOC 2003. Proceedings of the 2003 SBMO/IEEE MTT-S International.

Saleh B.E., Teich M.C. (1991) Fundamentals of Photonics, vol. 22, Wiley, New York.

Woyessa, G., Fasano, A., Markos, C., Rasmussen, H. K., & Bang, O. (2017). Low Loss Polycarbonate Polymer Optical Fiber for High Temperature FBG Humidity Sensing. *IEEE Photonics Technology Letters*, *29*(7), 575-578.

Ziemann, O., Krauser, J., Zamzow, P. E., & Daum, W. (2008). *POF handbook: optical short range transmission systems*: Springer Science & Business Media.

Zubia, J., & Arrue, J. (2001). Plastic optical fibers: An introduction to their technological processes and applications. *Optical Fiber Technology*, *7*(2), 101-140.