

## Mitigating the Effect of Modal Dispersion of Plastic Optical Fibre

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### ABSTRACT

Optical fiber 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 Fiber (POF) is a leading contender in this regard because it is a lot cheaper than glass fibre and easier to install. 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 by reducing the level of modal dispersion through experimenting with different polymer materials. The objective is to find optimal core and cladding materials for an improved bandwidth-length product of the cable. 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 standard SI-POF.

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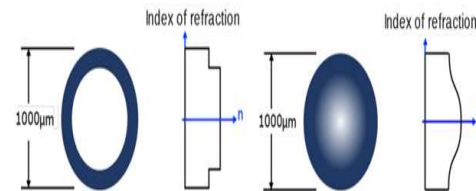
Plastic Optical Fibre, step index, modal dispersion, bandwidth and refractive index

### INTRODUCTION

Optical communications in the broad sense date back to ancient times. One of the earliest optical communication systems was the use of fire and smoke. Electrical communications started in 1837 with the invention of the telegraph by Samuel F. B. Morse. The development of electrical communication systems shifted to use progressively higher frequencies, which offered increases in bandwidth or information capacity. Optical communication was gradually becoming attractive because optical frequencies are several orders of magnitude higher than those used by electrical communication systems. Therefore, the optical carrier frequencies yield a far greater potential transmission bandwidth than electrical systems with metallic cables.

Plastic Optical Fibre (POF) is a type of fibre optic cable with its core and cladding made from polymer or plastic materials. Poly(methyl methacrylate) (PMMA) is the most commonly used material for the fabrication of POF. The use of plastic materials, as an alternative to silica, guarantees flexibility and mechanical resistance of the fibre even though it has a large diameter up to 1 mm. Figure 1.1

illustrates the relationship between refractive index and radial distance of the fibre with the core diameter making up to 95% of the fibre (Forni *et al.*, 2017).



(a) SI-POF (b) GI-POF  
Figure 1.1: POF Index Profiles (Forni *et al.*, 2017)

The large core ensures easy and low installation cost. At the same time, the high optical power loss and narrow bandwidth due to the large modal dispersion are the main disadvantages (Albakay & Nguyen, 2017). POFs have become attractive and have increasingly been installed in short-reach networks because of their large mechanical tolerance which provide easy and cost-effective installation. For instance, Local Area Networks (LANs) in homes, offices, hospitals, and vehicles, as well as very short-reach networks

such as interconnects inside computers use POF (Forni *et al.*, 2018).

## LITERATURE REVIEW

Thomas *et al.*, (2015) demonstrated experimentally the use of Plastic Optical Fibre (POF) for digitized radio-over-fibre downlink. The digitized ROF was adopted because of its capability in overcoming the effects of the non-linearity and fibre dispersion of the typical optical link between the Base Station (BS) and Radio Access Point (RAP). The effects limited both the attainable data rate as well as the employable fibre length. The transmission technique relied on Ethernet protocol where a 5 GHz RF signal was sent through the POF. The results of the experiment showed that the maximum length of the fibre for the digital optical link was found to be 143 m at a bit rate of up to 31.32 Mbps. However, the digitization of the ROF signal mitigated the fibre dispersion without improving the bandwidth length product of the fibre. Cseh *et al.*, (2016) implemented an improved scheme for broadband signals transmission in radio over fibre systems through mode filtering. The work focused on the study of large bandwidth wireless signal transmission based on a 60 GHz standard over a multimode fibre. The modal dispersion was controlled through mode filtering which allowed for the significant attenuation of the several higher order mode groups. Two forms of mode filters were used, namely; Single Mode Fibre (SMF) patch-cord and mandrel wrap. The SMF patch-cord was a short SMF fibre added between the MMF and the photodetector.

The SMF patch-cord blocked the higher order modes. However, at lower transmission power, the mandrel had no effect on the transmission. Thus, increasing the transmission power would cause transmitter saturation leading to more non-linearity behaviour. Albakay & Nguyen (2017) presented a technique that mitigated the effect of modal dispersion of a standard, 1 mm Step-Index Plastic Optical Fibre (SI-POF). The aim was to improve the data rate up to 1 Gbps. The modal dispersion was mitigated by reducing the effective numerical aperture of the optical fibre link. A spatial mode filter made of a polycarbonate capillary tube was constructed with an air gap in between the transmitter and receiver fibre. The proposed technique was

demonstrated experimentally on a 30 m link, achieving a BER of less than  $10^{-8}$  at 1 Gbps. However, considerable power penalty was incurred which limited the achievable length of fibre link between transmitter and receiver.

## METHODOLOGY

The refractive indices of core and cladding is a major design consideration in the development of an improved Plastic Optical Fibre (POF). The ability of the optical fibre to capture as more optical power as possible depends the core/cladding refractive indices. The following subsections are the step-by-step approaches adopted for the development of an improved Step-Index POF (SI-POF).

### Modelling Modal Dispersion in Optical Fibre

The objective of the link modelling is to optimize the bandwidth by minimizing the dispersion of a standard SI-POF by finding the optimal core/cladding materials. The modal dispersion in an SI fibre is quite large. The reason being that the modes/rays that propagate under a large angle  $\mathcal{G}_{\max}$  regarding the fibre axis is assumed to take a longer distance than the fundamental mode that just follows the axis at an angle of  $\mathcal{G}_{\max}$ . The maximum mode delay differences per unit length  $\Delta\tau'_{\max}$  is given in Saleh & Teich (1991) as:

$$\Delta\tau'_{\max} = \frac{n_g}{c_o} \left( \frac{1}{\cos \mathcal{G}_{\max}} - 1 \right) \quad (1)$$

with  $\mathcal{G}_{\max}$  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,  $\tau'_{\text{slowest}}$  is the time delay of the slowest mode and  $\tau'_{\text{fastest}}$  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 (1) is then simplified to:

$$\Delta \tau'_{\max} \approx \frac{NA^2}{2c_o n_{core}} \quad (2)$$

where  $n_{core}$  is the refractive index of core material and  $NA$  is the numerical aperture given by equation (3) as follows:

$$NA = \sqrt{n_{core}^2 - n_{cladding}^2} \quad (3)$$

For an SI-POF with the length,  $L$ , the total dispersion is estimated as shown in equation (4)

$$\Delta \tau'_{\max} \approx \frac{LNA^2}{2c_o n_{core}} \quad (4)$$

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

$$BW = \frac{0.44}{\Delta \tau'_{\max}} \quad (5)$$

Substituting equation (4) into equation (5) yields:

$$BW = \frac{0.88c_o n_{core}}{LNA^2} \quad (6)$$

From equation (6), the bandwidth is inversely proportional to the length of the fibre, hence, the quality of the fibre can be characterized by the bandwidth-length product and presented as follows:

$$BW \times L = \frac{0.88c_o n_{core}}{NA^2} \quad (7)$$

Equations (4) and (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  $\eta_c$ , given by Agrawal, (2002) as:

$$\eta_c = (1 - R_f) NA^2 \quad (8)$$

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 (2). This leads to the optimization problem of equation (9) subject to the constraints of equations (10) to (12).

$$\min_n f(n) \equiv \frac{n_{core}^2 - n_{cladding}^2}{2c_o n_{core}} \quad (9)$$

Subject to:

$$\eta_c = (1 - R_f)(n_{core}^2 - n_{clad}^2) = 3\% \quad (10)$$

$$n_{core}, n_{cladding} \geq 1.3 \quad (11)$$

$$n_{core}, n_{cladding} \leq 1.6 \quad (12)$$

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 (9) are to be obtained, subject to the constraints in equations (10) to (12) being satisfied.

To solve this problem, the *fmincon* function provided in MATLAB is used. The optimal design variables  $n_{core}$  and  $n_{clad}$  are obtained as 1.4865 and 1.4756, respectively. The minimum dispersion per unit length is 36.169 ps/m.

Using equation (5), the bandwidth of 100m

length of SI-POF is obtained as

$$BW = 44/(100 \text{ * fopt}) = 121.65 \text{ MHz}$$

### Obtaining the Optimal Core and Cladding Material for the Cable

Since the first POF was invented in the mid-1960s, considerable efforts have been made to develop materials in order to enhance its performance. One of the fundamental requirements for choosing or designing materials for POF fabrication is that the polymer should be of low refractive index (Koike, 2015). The Refractive Index (RI) is a fundamental physical quantity of materials. It describes how light or electromagnetic waves propagate through an optical medium.

Recall that, the optimal values of the refractive indices of the core and cladding materials of the proposed step-index POF are 1.4865 and 1.4756, respectively. One way to obtain polymer materials with these values of indices of refraction is to tune the permittivity of some existing polymers.

Fabrication of polymer based composites is an effective method of modifying the refractive index of polymers (Švorčík *et al.*, 2005). Sometimes a material that has some of the properties of one polymer and some of the properties of another is desired. Instead of going back into the lab and try to synthesize a brand new polymer with all the properties, a mix

of two polymers is explored to form a blend that hopefully has 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):

$$\frac{n_c^2 - 1}{n_c^2 + 2} = Q_1 \times \frac{n_1^2 - 1}{n_1^2 + 2} + (1 - Q_1) \times \frac{n_2^2 - 1}{n_2^2 + 2} \quad (13)$$

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.

It is quite challenging to make two different polymers miscible. This is due to differences in their entropy. Table 3.1 shows pairs of polymer that have been found to be miscible (Pslc, 2019).

**Table 3.1:** 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 (13) 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 3.2.

**Table 3.2:** 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, 2014), where the upper bound of the property of the blend,  $P_b$  is given by Fried, (2014):

$$P_b = Q_1 P_1 + Q_2 P_2 \quad (14)$$

Also, the lower bound equation is:

$$\frac{1}{P_b} = \frac{Q_1}{P_1} + \frac{Q_2}{P_2} \quad (15)$$

### Attenuation of the Developed SI-POF

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,  $\alpha$  in dB/km is expressed mathematically as Koike & Gaudino, (2013):

$$\alpha = -\frac{10}{L} \log_{10} \left( \frac{P_{out}}{P_{in}} \right) \quad (16)$$

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).

$$\alpha = \alpha_a + \alpha_s \quad (17)$$

where  $\alpha_a$  is the absorption loss and  $\alpha_s$  is scattering loss. For transparent polymer blends, the absorption coefficient,  $\alpha_a$  is given by Song *et al.*, (2013) as

$$\alpha_a = 10 \log(e) 2\pi^3 \left( \frac{\Delta n}{n_1} \right)^2 \left( \frac{V^2 v_s}{\lambda^4} \right) \quad (18)$$

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  $\lambda$  is the wavelength.

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

$$\alpha_s = 10 \log(e) \left( \frac{8\pi^3}{3\lambda^4} \right) n^8 p^2 k_B T_f \beta_T \quad (19)$$

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,  $\beta_T$  is isothermal compressibility of the optical fibre cable.

### RESULTS AND DISCUSSION

Equations (14) and (15) are used to obtain the range of values of important mechanical properties such as Young's modulus, tensile strength and glass transition temperature of the blend for the improved SI-POF.

The PS/PVME blend was found to very low glass transition temperature, thereby making it not appropriate for the intended application. PMMA/PVDF, on the other hand, was found to be a very suitable candidate. The technical specifications for the improved SI-POF based on PMMA/PVDF are given in Tables 4.1.

**Table 4.1:** 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, $\mu\text{m}$	980	1000
5	Young's modulus, Mpa	2433 – 2435	2388 – 2393
6	Tensile strength, Mpa	61.4 – 61.5	59.8 – 60.0
7	Glass transition temperature $T_g$ , °C	92.6 – 96.8	62.2 – 74.1



Figure 4.1 shows the variation of bandwidth-length product with NA of an optical fibre for RI of the core from 1.3 to 1.6.

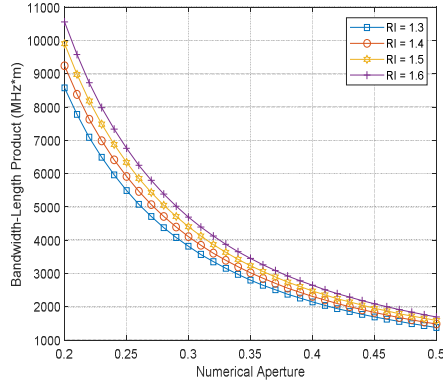


Figure 4.1: Bandwidth-Length Product versus NA at Different Optical Fibre Core RI Values

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.

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 4.2.

**Table 4.2:** 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

POF are generally operated between wavelengths of 360nm and 700nm (visible light, from violet to red) with transmission windows occurring at 570nm and 650nm. However, optical sources at 570nm are not available. Thus, it is only practical to use the 650nm window (Zubia, & Arrue, 2001). Figure 4.2 shows the variation of the attenuation of the developed SI-POF with operating wavelength. The attenuation decreases exponentially with increasing wavelength. It is found that the attenuation of the developed SI-POF at the operating wavelength of 650 nm is 0.589 dB/m.

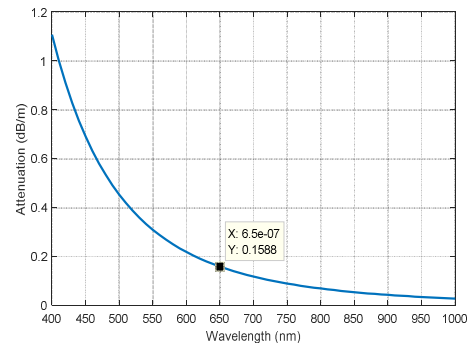


Figure 4.2: Variation of Attenuation of the SI-POF with Wavelength



## CONCLUSION

The link modelling of the SI-POF has been carried out with the aim of finding the optimal core and cladding materials for an improved bandwidth of the optical fiber. 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 was found to be 36.169 ps/m. Thus, the bandwidth of 100 m length of the designed SI-POF was achieved as 121.65 MHz. This represent about 81 MHz bandwidth improvement when compared to that of the Albakay & Nguyen, (2017). The bandwidth of the access backhaul link has been improved by minimizing the modal dispersion of the cable.

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