Gb/s Transmission Data Rates Over Graded Index Plastic Optical Fibers in Short Distance Applications

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Abstract*— The most significant features of plastic optical fibers (POFs) are investigated, including the main types of POFs, and their properties regarding bandwidth, attenuation, and influence of external parameters are analyzed over wide range of the affecting parameters. This paper has presented the transmission link by using plastic optical fibers that should be verified the following parameters for the POFs system under construction as the following: i) Minimum and maximum transmission distance to be spanned, ii) Transmission data rate, iii) Operating signal wavelengths, iv) Minimum and maximum operating temperature of a system, v) Type and properties of cable to be used, vi) Any required number of passive coupling points, if necessary. This data is the basis for planning the installation from a transmission view point. We have compared our theoretical results of different graded index plastic optical fibers with their simulation results with using perflourinated graded index plastic optical fibers as listed in the conclusion part.

***Index Terms*— POFs, System losses, Loss margin, Attenuation and dispersion plans, and Passive couplings.**

I. Introduction

Since an increase in the carrier frequency provides a larger information capacity [1], the historical trend in telecommunications systems has been to employ progressively higher frequencies. At the destination, the information is removed from the carrier wave and processed as desired. Because of its high frequencies, the optical portion of the electromagnetic spectrum is currently being used for most of the communications links by employing optical fibers as transmission media. Specifically, the well-known plastic optical fibers with poly methyl metha acrylate (PMMA) core were introduced in the 1960s, although the first optical fibers that were used as a communications channel were made of glass. In the past several decades, concurrent with the successive improvements in glass fibers, POFs have become increasingly popular, owing to their growing utility [2]. Although POFs have been available for some time, only quite recently have they found application as a high-capacity transmission medium, thanks to the successive improvements in their transparency and bandwidth [3]. At present, they are advantageously replacing copper cables in short-haul communications links by offering the advantages intrinsic to any optical fiber in relation to transmission capacity, immunity to interference and small weight. In addition, POFs serve as a complement for glass fibers in short-haul communications links because they are easy to handle, flexible, and economical, although they are not used for very long distances because of their relatively high attenuation. These characteristics make them especially suitable as a means of connection between a large net of glass optical fiber and a residential area, where distances to cover are generally less than 1 km. An example would be Internet access from home or from an office. For this purpose, POFs allowing for increasingly better features regarding distance and transmission speed have been manufactured. Nowadays, with the PMMA core optical fibers, transmissions at 156 Mbit/sec over distances up to 100 m can be carried out [4], and transmission speeds of 500 Mbit/sec over 50 m can be reached [5]. To achieve higher transmission speeds graded index POFs can be used [6]. In addition, a special type of POF made from an amorphous fluorinated polymer called cyclic transparent optical polymer (CYTOP) and developed by Koike and Asahi Glass will be soon available in the market [7]. This new fiber presents a considerably lower attenuation than the common POFs, which allows the transmission distance to be increased up to 1 km for a transmission speed of 1.2 Gb/s/km. With increasing demand to access from home or office to Internet which is the most popular network in the world, high speed data communication even in the premises area has been of great importance. The growing interests have been focused on high speed optical fiber communication. However, regarding the premises area network, since the small core (5-1 0 μm diameter) of the single-mode fiber requires highly accurate connectors, serious increase of the cost of the whole system is expected. The large core of the polymer optical fiber (POF) would make it possible to adopt injection-molded plastic connectors, which dramatically decreases the total cost of the systern without any complicated lens alignment [8].

We have deeply investigated the development and planning of plastic optical fibers to be used in short transmission link applications for different materials such as CYTOP, plastic clad silica (PCS), polycarbonate (PC), and polystyrene (PS) based optical transmission cable. As well as we have taken into account the study of system performance evaluation at different operating signal wavelengths, transmission date rates, required number of passive coupling points, different transmission link lengths, and different ambient temperatures.

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II. System Model Analysis

The total loss of a system α_{sys} comprises the cable length loss, the coupling loss at the transmitter α_{ct} and receiver α_{cr} and the coupling loss at any passive couplings α_{cp}. Together with any loss margin which must be allowed for α_{mar}. This produces the following equation:

$$\alpha_{sys} = \alpha_{cable} L + \alpha_{ct} + \alpha_{cr} + n\, \alpha_{cp} + \alpha_{mar} \qquad (1)$$

Where α_{sys} is the total system loss (attenuation) in dB, α_{cable} is the attenuation coefficient of the cable in dB/km, α_{ct} is the input coupling loss at the transmitter, α_{cr} is the input coupling loss at the receiver, α_{cp} is the coupling loss at passive coupling, α_{mar} is the loss margin (e.g. 3 dB), L is the lengths of cable in km, and n is the number of passive couplings. With most commercially available transmitters and receivers the coupling loss does not have to be considered, as the manufactures test the launch power or receiver sensitivity with the aid of connectorized plastic optical fibers. Plastic, as all organic materials absorb light in the ultraviolet spectrum region .The mechanism for the absorption depends on the electronic transitions between energy levels in molecular bonds of the material. Generally the electronic transition absorption peaks appear at wavelengths in the ultraviolet region, and their absorption tails have an influence on the POF transmission loss. According to urbach's rule, the attenuation coefficient α_e due to electronic transitions in plastic material is given by [9]. In addition, there is another type of intrinsic loss, caused by fluctuations in the density, orientation, and composition of the material, which is known as Rayleigh scattering. This phenomenon that gives rise to scattering coefficient α_R that is inversely proportional to the fourth power of the wavelength, i.e., the shorter is λ the higher the losses are. In the same way, the estimated total loss coefficient factors for different POFs based on MATLAB curve fitting program and the data clarified in Ref. [2], the obtained expressions:

$$\alpha_{cable}(PS) = 1.10\times10^{-3}\exp\left(\frac{8}{\lambda}\right) + 2.78\left(\frac{0.189}{\lambda}\right)^{6}, dB/km \qquad (2)$$

$$\alpha_{cable}(PC) = 2.45\times10^{-2}\exp\left(\frac{3.876}{\lambda}\right) + 65.98\left(\frac{89}{\lambda}\right)^{8}, dB/km \qquad (3)$$

$$\alpha_{cable}(CYTOP) = 0.845\times10^{-5}\exp\left(\frac{0.655}{\lambda}\right) + 0.3965\left(\frac{0.643}{\lambda}\right)^{3}, dB/km \qquad (4)$$

$$\alpha_{cable}(PCS) = 0.15\times10^{-5}\exp\left(\frac{0.225}{\lambda}\right) + 0.135\left(\frac{0.433}{\lambda}\right)^{3}, dB/km \qquad (5)$$

Where λ is the operating signal wavelength of the plastic material in μm. For grade index (GI) POF, the deduced equation become that [10]:

$$A^{G} = \frac{\sqrt{2\pi}\, R}{k_0\, n_{core}\, \Delta n} \qquad (GI) \quad , \qquad (6)$$

Where R is the plastic fiber core radius in μm, n_{core} is the refractive index of plastic material core fiber, Δn is the absolute refractive index difference and k_0 is the vacuum wave number in m^{-1}, and is defined by :

$$k_0 = \frac{2\pi}{\lambda_0} \quad , \qquad (7)$$

The parameters to characterize the temperature and operating signal wavelength dependence of the refractive-index from Sellmeier equation is given as by [11]:

$$n_{core} = \sqrt{1 + \frac{S_1\lambda^2}{\lambda^2 - S_2^2} + \frac{S_3\lambda^2}{\lambda^2 - S_4^2} + \frac{S_5\lambda^2}{\lambda^2 - S_6^2}} \quad , \qquad (8)$$

Then the first and second differentiation with respect to operating signal wavelength λ yields:

$$\frac{dn_{core}}{d\lambda} = -\left(\frac{\lambda}{n_{core}}\right)\cdot\left(\frac{S_1S_2^2}{\left(\lambda^2 - S_2^2\right)^2} + \frac{S_3S_4^2}{\left(\lambda^2 - S_4^2\right)^2} + \frac{S_5S_6^2}{\left(\lambda^2 - S_6^2\right)^2}\right), \qquad (9)$$

$$\frac{d^2n_{core}}{d\lambda^2} = -\left(\frac{1}{n_{core}}\right)\cdot\left(\frac{S_1S_2^2\left(3\lambda^2 + S_2^2\right)}{\left(\lambda^2 - S_2^2\right)^3} + \frac{S_3S_4^2\left(3\lambda^2 + S_4^2\right)}{\left(\lambda^2 - S_4^2\right)^3} + \frac{S_5S_6^2\left(3\lambda^2 + S_6^2\right)}{\left(\lambda^2 - S_6^2\right)^3}\right) - \left(\frac{dn_{core}}{d\lambda}\right)^2, \qquad (10)$$

As well as $\lambda = \lambda_s$, and the coefficients of the polymeric materials such as CYTOP, PS, PC, and PCS are listed in Table 1

Table 1. Coefficients of different materials based optical cable of POFs [10, 12].

	CYTOP	PS	PC	PCS
S_1	0.6749	0.79	0.78	0.7246
S_2	0.9472 (T/T_0)	1.107 (T/T_0)	1.1 (T/T_0)	1.0167 (T/T_0)
S_3	0.4383	0.512	0.5	0.47
S_4	0.9764 (T/T_0)	1.1416 (T/T_0)	1.134 (T/T_0)	0.1.048 (T/T_0)
S_5	0.1596	0.1866	0.185	0.1714
S_6	12.56 (T/T_0)	14.868 (T/T_0)	14.6 (T/T_0)	13.48 (T/T_0)

Where T and T_0 are the ambient temperature and room temperature along POF media link and measured both in K. One often very useful measure of a fiber is usually called the "V". In some texts it is called the "normalized frequency" and in others just the "dimensionless fiber parameter". V summarizes all of the important characteristics of a fiber in a single number. It can be used directly to determine if the fiber will be single-mode or not at a particular wavelength and also to calculate the number of possible bound modes. In addition, it can be used to calculate the spot size, the cutoff wavelength and even chromatic dispersion. However, it is important to note that V incorporates the wavelength that we are using on the fiber and so to some extent it is a measure of a fiber within the context of a system rather than the fiber alone [10, 12]:

$$V = \frac{6.28\, R}{\lambda_s}\sqrt{n_{core}^2 - n_{clad}^2} = \frac{6.28\, R}{\lambda_s} NA \quad , \qquad (11)$$

Where NA is the numerical aperture, R is the POF core radius. It can be proved that the behavior of graded index fibers within multimode, for large values of V, the number of propagation modes in a step index and graded index fiber is given, according to the electromagnetic theory, by the following expression [13]:

$$M(Graded\ index) = \frac{V^2}{2}\left(\frac{g}{g+2}\right), \qquad (12)$$

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The output pulse width from the POF was calculated by the solution of WKB method in which both modal and material dispersions were taken into account as shown in the following expressions [14, 15]:

$$\sigma_{modal} = \frac{LN_1\Delta n}{2c} A_1 A_2 \left(C_1^2 + A_3 + A_4\right)^{0.5}, \quad (13)$$

With A_1=g/g+1, A_2=$(g+2/3g+2)^{0.5}$, A_3=$4C_1C_2\Delta n(g+1)/2g+1$, c is the speed of light and A_4=$4\Delta n^2 C_2(2g+2)^2/(5g+2)(3g+2)$.

$$\sigma_{chromatic} = \frac{\sigma_s L}{\lambda}\left(A_5^2 + A_6 A_7 + A_8 A_9\right), \quad (14)$$

With A_5=$-\lambda^2 d^2n/d\lambda^2$, A_6=$-2\,\lambda^2 d^2n/d\lambda^2(N_1\Delta n)$, A_7=$C_1(g/g+1)$, A_8=$(N_1\Delta n)^2(g-2-\varepsilon)/g+2$, and A_9=2g/3g+2. Where σ_s is the root mean square spectral width of the light source in nm, g is the index exponent, L is the polymer fiber cable length in km, N_1, ε are the group refractive index, profile dispersion parameter and can be:

$$N_1 = n_{core} - \lambda_s \frac{dn_{core}}{d\lambda}, \quad (15)$$

$$\varepsilon = \frac{-2\,n_{core}}{N_1}\frac{\lambda_s}{\Delta n}\frac{d\Delta n}{d\lambda}, \quad (16)$$

With the constants C_1=g-2-ε/g+2, and C_2=3g-2-2ε/2(g+2). Then the total root mean square pulse width can be:

$$\sigma_{total} = \sigma_{modal} + \sigma_{chromatic}, \quad (17)$$

The transmitted signal bandwidth within POFs can be expressed as [16-18]:

$$B.W_{Sig.} = \frac{0.44}{\sigma_{total}\,L}, \quad (18)$$

Moreover the optical signal to noise ratio (OSNR) of the plastic optic fibers system can be [19-21]:

$$OSNR = \frac{0.5\,P_{Budget}\,\lambda_s}{h\,c\,B.W_{Sig.}}, \quad (19)$$

Where P_{Budget} is the total budget power per channel in Watts, h is the Planck's constant (6.02 x10^{-34} J.sec), c is the speed of light (3x10^8 m/sec), λ_s is the operating signal wavelength in μm, $BW_{sig.}$ is the transmitted signal bandwidth. According to modified Shannon theorem, the maximum bit rate per optical channel, or the maximum capacity of the channel for maximum subscribers is given by [22]:

$$B_{Sh} = 3.3119\,BW_{sig.}\log_{10}\left(1 + OSNR\right), \quad (20)$$

The thermal-dependent spectral losses, α_{sys}, are processed based on the models of Ref. [23]. The multi-limitations bit rate (dispersion, losses, and depth) is calculated based on the same spirit of the model of Ref. [23], where it is:

$$B_r = 2.828\,BW_{Sig.}\sqrt{Log\frac{B_u}{B_r}e^{-(\alpha_{sys}L+\alpha_{mar})}} \quad (21)$$

Where B_u is the Ultimate bit-rate (limitations-free). The calculation of the power budget of the POFs system is [24]:

$$P_{Budget} = P_{T(min)} - P_{R(min)} \quad (22)$$

Where $P_{T(min)}$ is the minimum transmit power in mWatt, and $P_{R(min)}$ is the receiver sensitivity in mWatt. In order that the overall system functions when the longest cable is being used, the following condition must be met:

$$\alpha_{sys} \le P_{Budget} \quad (23)$$

The change in the optical output power and the receiver sensitivity can be estimated as follows:

$$P_{R(min)}(T) = P_{R(min)}(T_0) + \frac{\Delta P_R}{\Delta T}\left(T - T_0\right), \quad (24)$$

The maximum transmission link distance can be estimated by the following equation [23, 24]:

$$L_m = \frac{P_{budget} - \alpha_{mar}}{\alpha_{cable}}, \quad (25)$$

III. Simulation Results and Performance Evaluation

We have investigated the development POFs system for Giga bit per second system operation in short transmission applications under the assumed set of parameters ranges of operation are: operating signal wavelength, $0.6 \le \lambda_s$, μm ≤ 1.6, number of passive couplings n=1, root mean square spectral linewidth of the optical source σ_s=0.1 nm, center wavelength λ_0=1.3 μm, ambient temperature 300 ≤ T, K ≤ 340 K, change in receiving power ΔP_R=0.0035 μWatt/K, room temperature T_0=300 K, minimum transmitter power, 0.25 ≤ $P_{T(min)}$, mWatt ≤ 0.5 at T_0, minimum receiver power, 1.5 ≤ $P_{R(min)}$, μWatt ≤ 5 at T_0,, system marginal loss, α_{mar}=3 dB, ultimate bit rate B_u=1 Gb/s, polymer fiber cable length, 0.01 ≤ L, km ≤ 0.1, and index exponent g=2.

Table 2. Operating parameters of different materials based POFs [10].

Materials based POFs	Operating parameters of POFs		
	NA	R	Δn
CYTOP	0.32	65-250 μm	0.013
PS	0.73	250 -750 μm	0.176
PC	0.78	250-500 μm	0.277
PCS	0.4	55-250 μm	0.05

Based on specially designed software, and the assumed set of the series of the above operating parameters are listed in Table 2 with set of controlling affecting parameters listed above, the following facts as shown in the series of Figs. (1-19) are assured the clarified results:

i) Figs. (1-3) have demonstrated that as both transmission cable length and ambient temperature decreases, and optical signal wavelength increases, this results in decreasing of total pulse broadening through different materials based fiber cable. We have observed that PCS and CYTOP materials have presented lower total pulse broadening compared to other materials based fiber cable.

ii) As shown in the series of Figs. (4-6) have proved that as both transmission cable length and ambient temperature decreases, and optical signal wavelength increases, this results in increasing of total transmitted signal bandwidth through different materials based fiber cable. As well as we have observed that PCS and CYTOP materials have presented higher total signal bandwidth compared to other materials based fiber cable.

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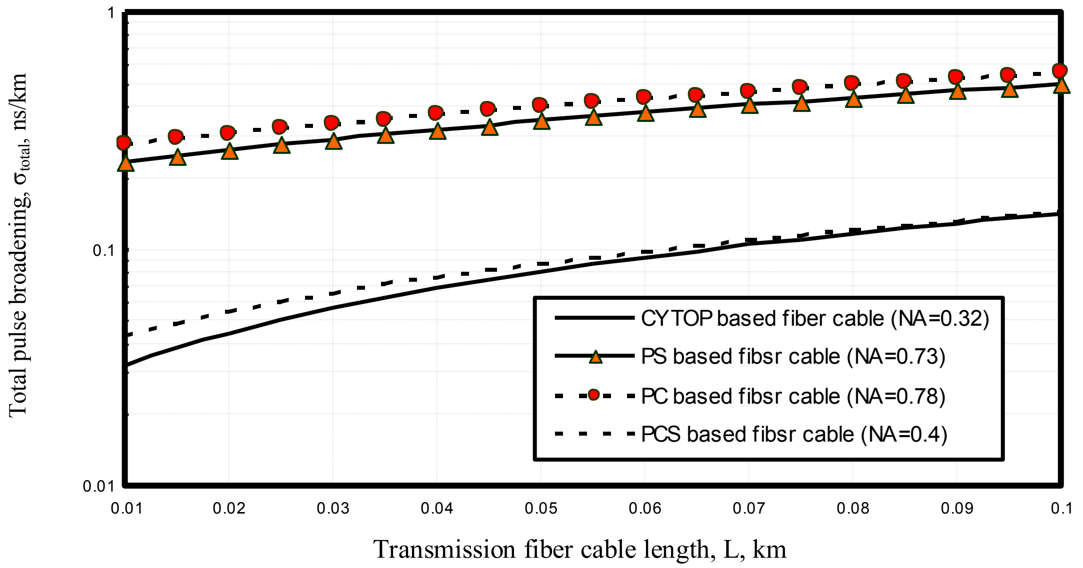

Fig. 1. Variations of total pulse broadening versus transmission fiber cable length at the assumed set of parameters.

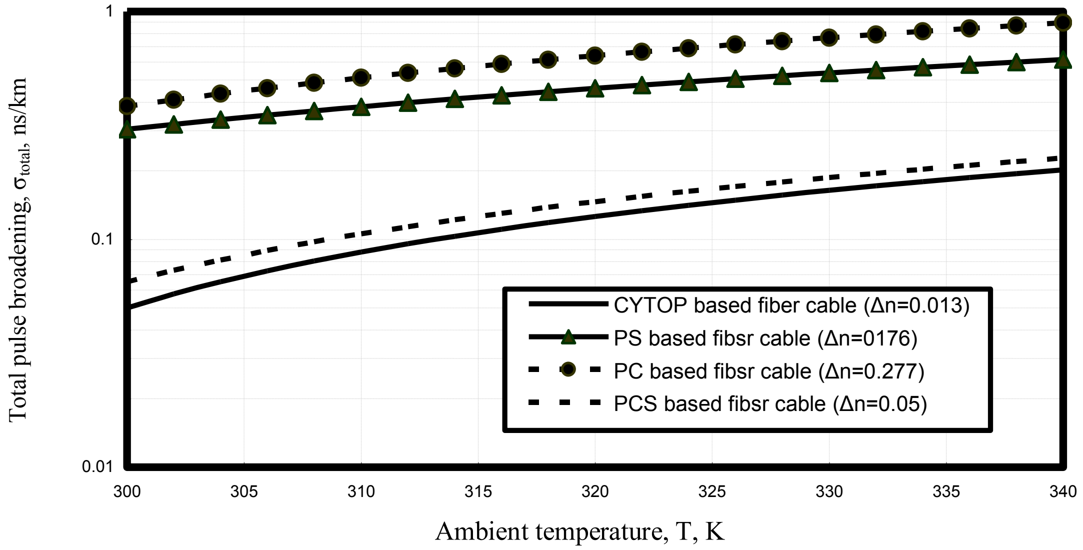

Fig. 2. Variations of total pulse broadening versus ambient temperature at the assumed set of operating parameters.

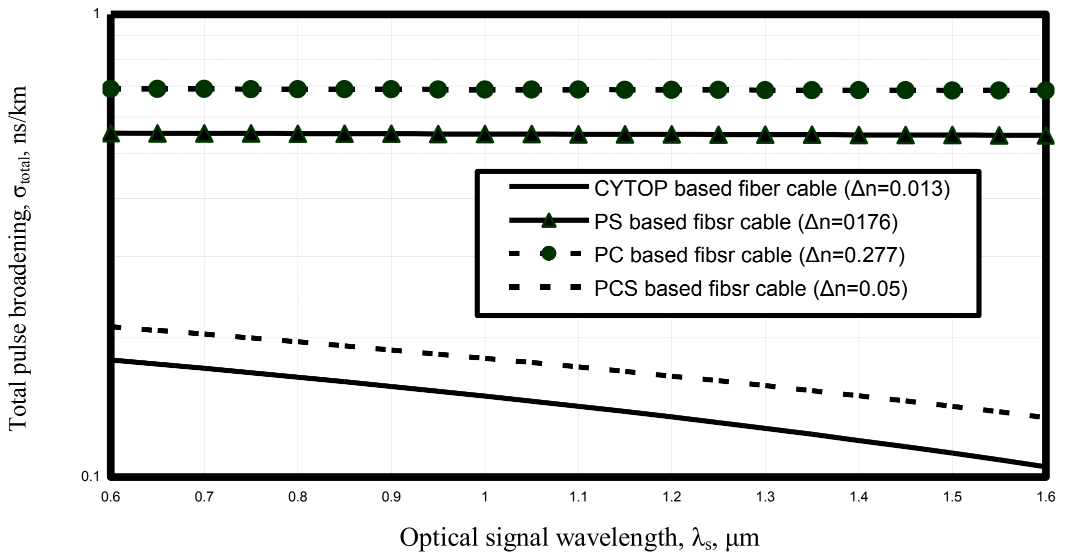

Fig. 3. Variations of total pulse broadening versus optical signal wavelength at the assumed set of operating parameters.

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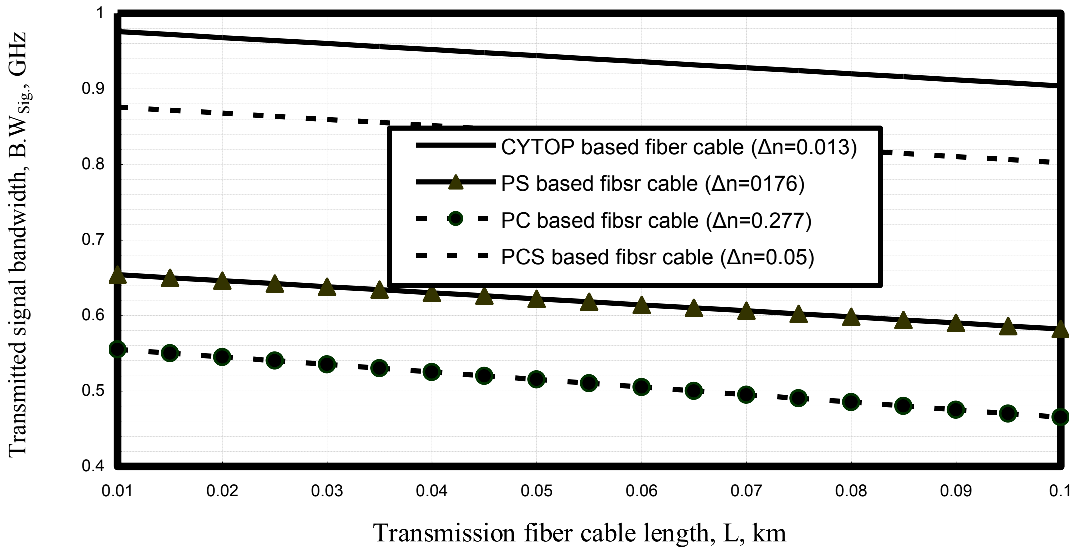

Fig. 4. Variations of transmitted signal bandwidth versus transmission fiber cable length at the assumed set of parameters.

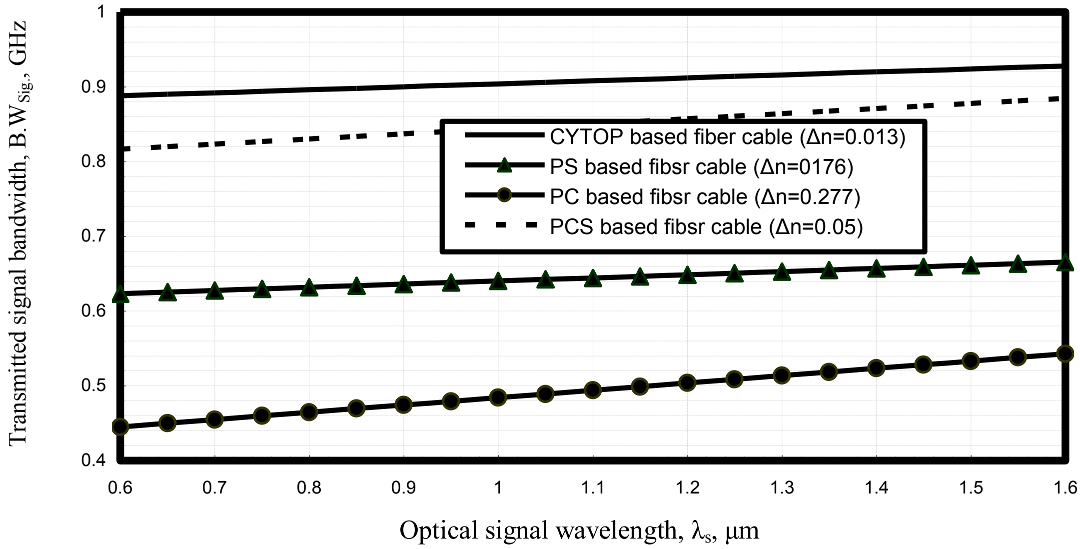

Fig. 5. Variations of transmitted signal bandwidth versus optical signal wavelength at the assumed set of parameters.

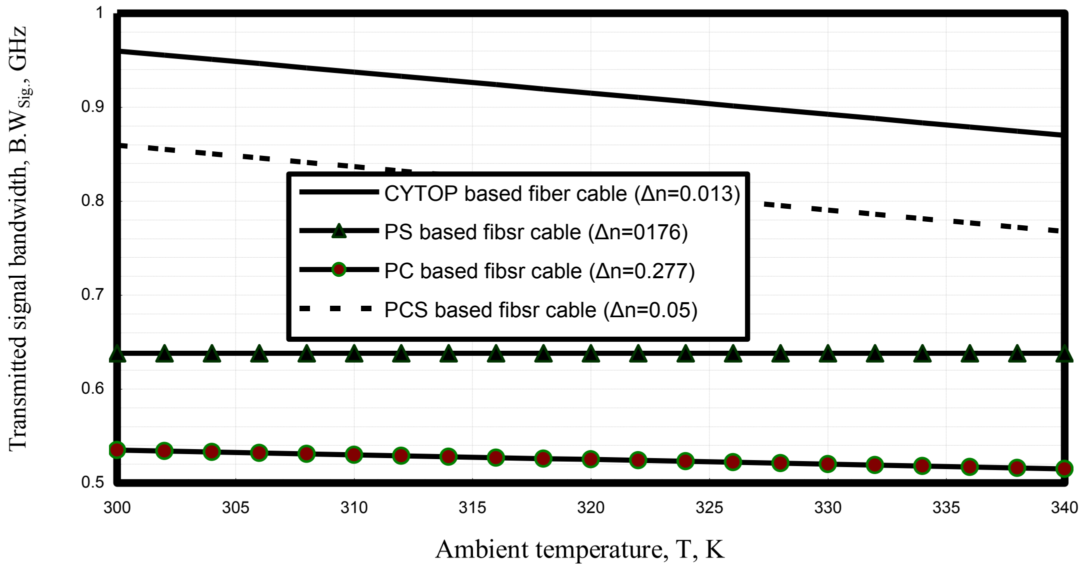

Fig. 6. Variations of transmitted signal bandwidth versus ambient temperature at the assumed set of operating parameters.

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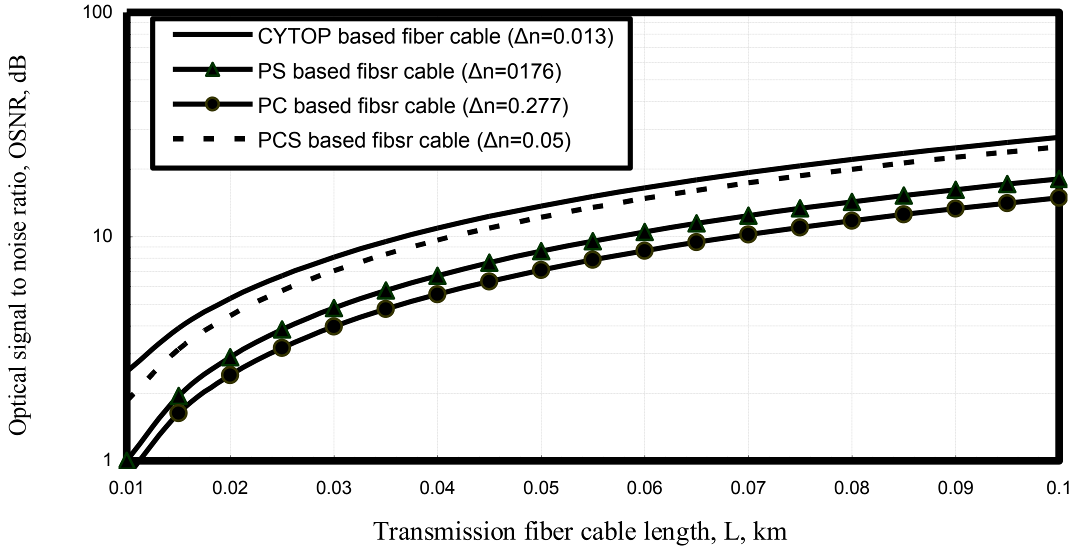

Fig. 7. Variations of optical signal to noise ratio versus transmission fiber cable length at the assumed set of parameters.

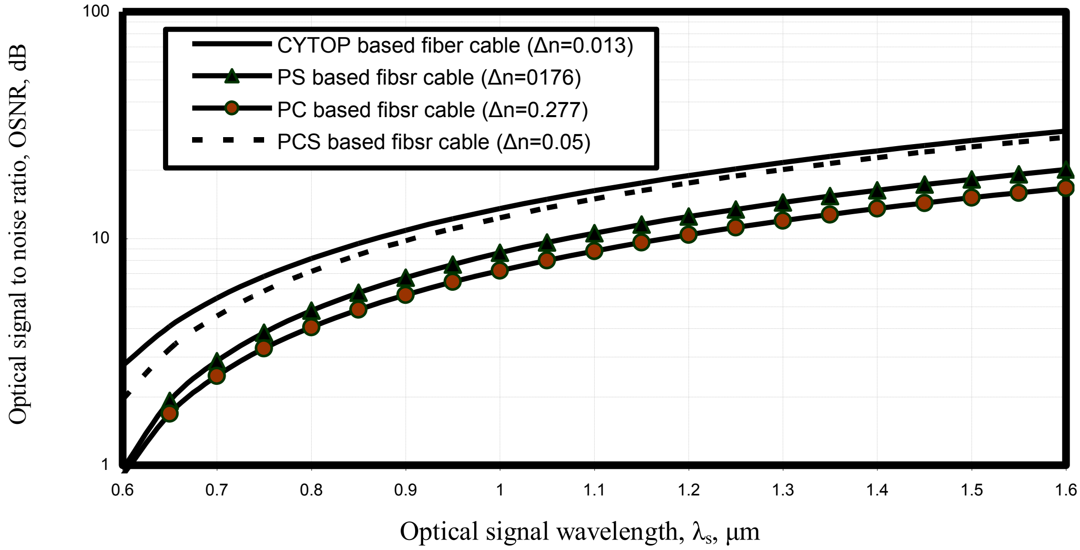

Fig. 8. Variations of optical signal to noise ratio versus optical signal wavelength at the assumed set of parameters.

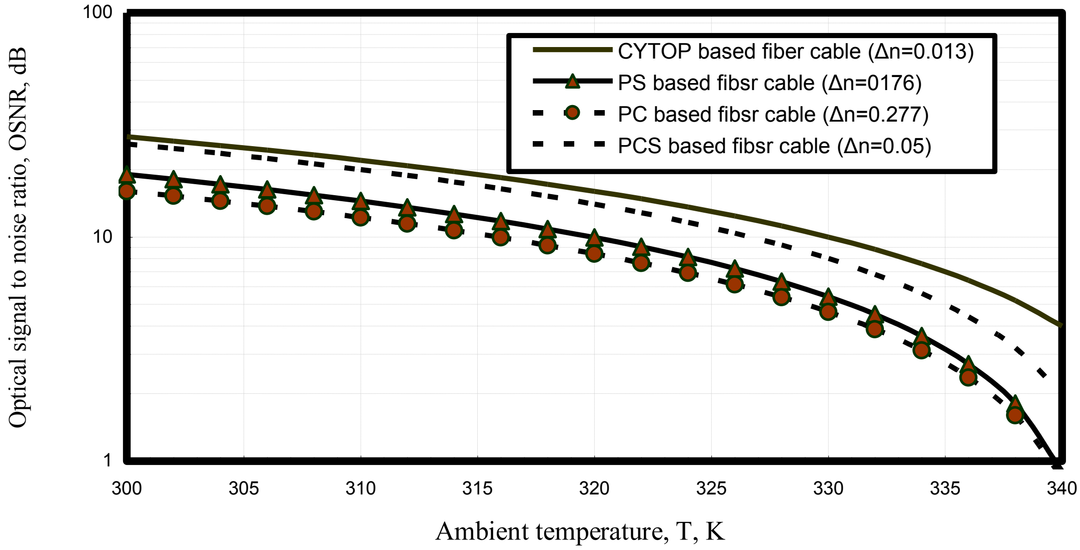

Fig. 9. Variations of optical signal to noise ratio against ambient temperature at the assumed set of operating parameters.

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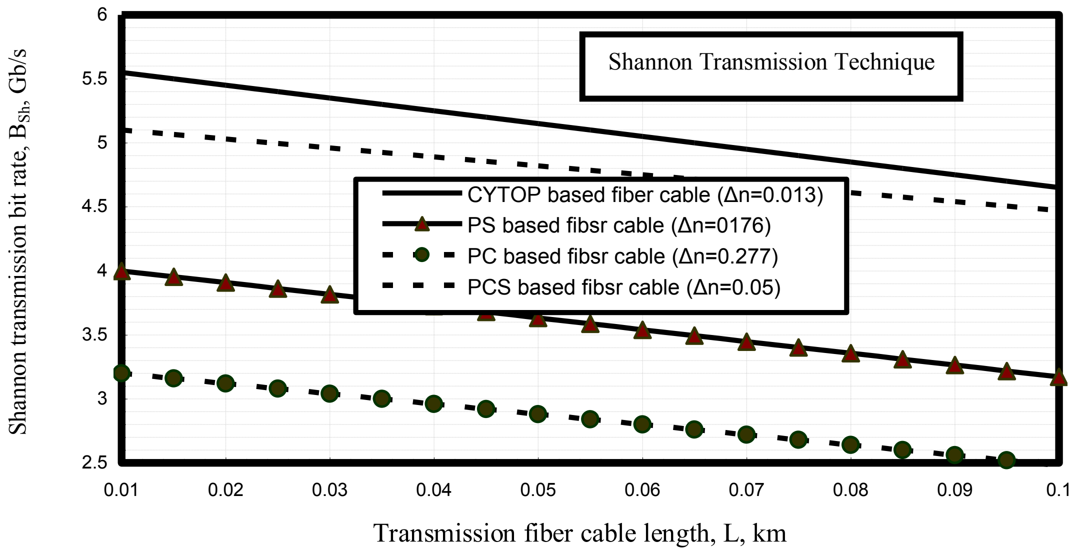

Fig. 10. Variations of Shannon transmission bit rate versus transmission fiber cable length at the assumed set of parameters.

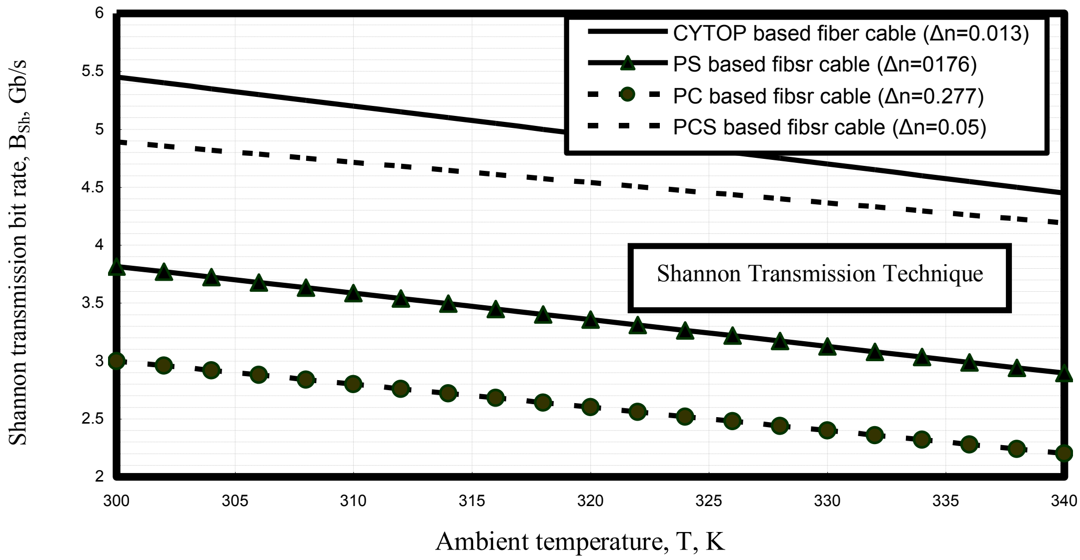

Fig. 11. Variations of Shannon transmission bit rate against ambient temperature at the assumed set of operating parameters.

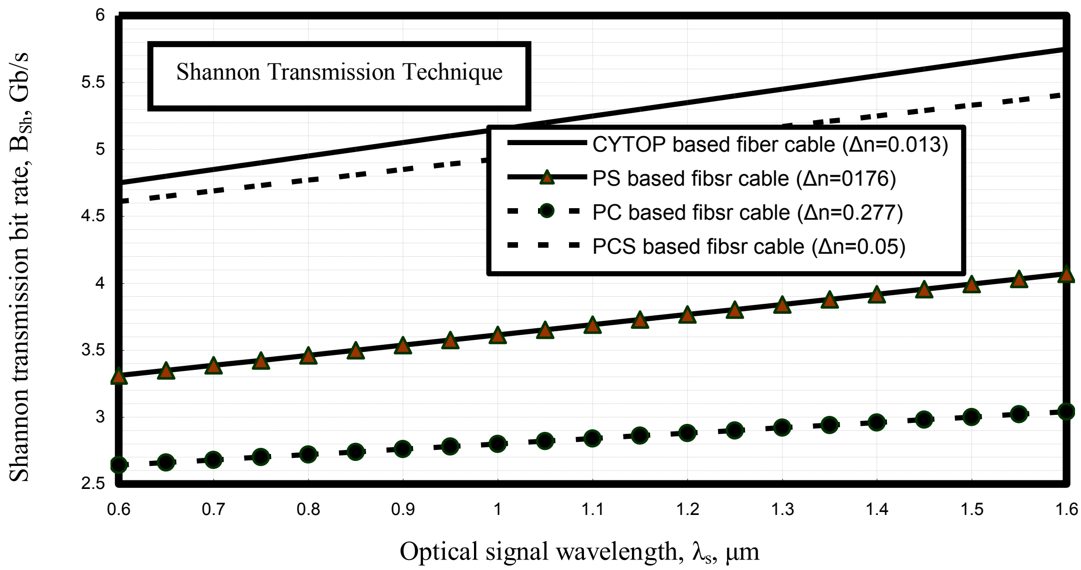

Fig. 12. Variations of Shannon transmission bit rate versus optical signal wavelength at the assumed set of parameters.

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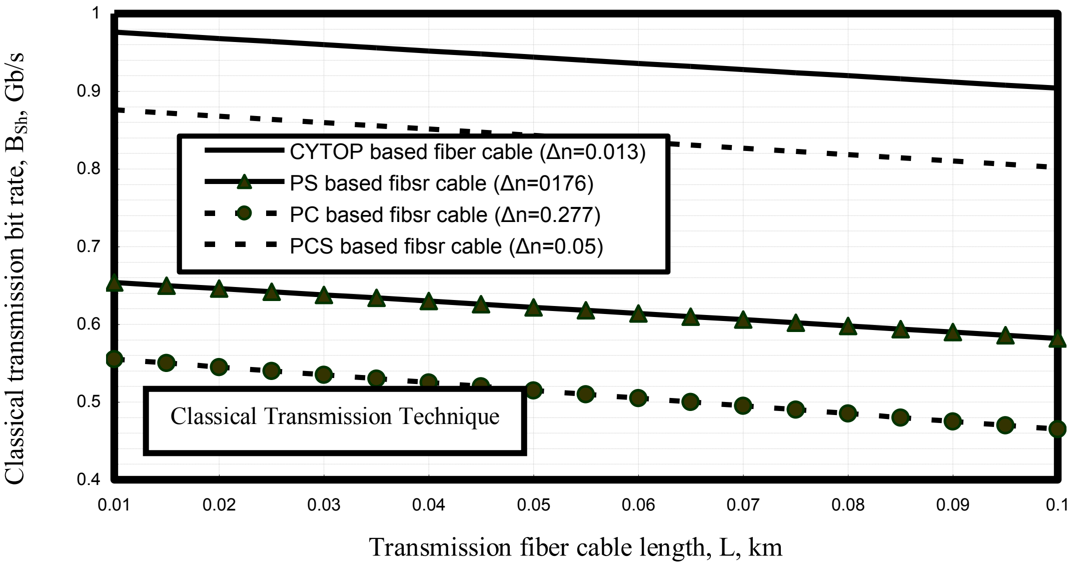

Fig. 13. Variations of Classical transmission bit rate versus transmission fiber cable length at the assumed set of parameters.

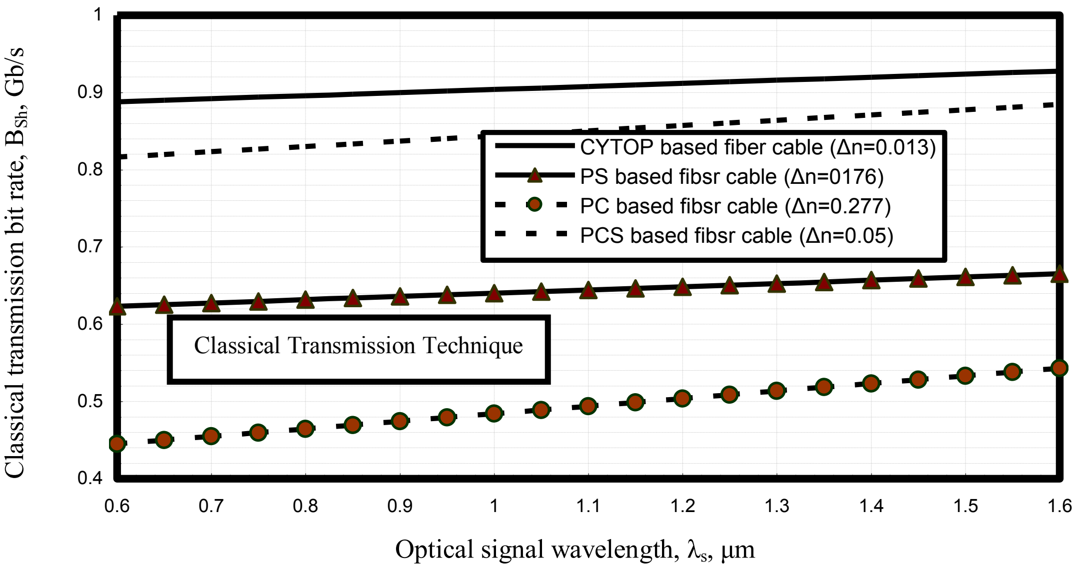

Fig. 14. Variations of Classical transmission bit rate versus optical signal wavelength at the assumed set of parameters.

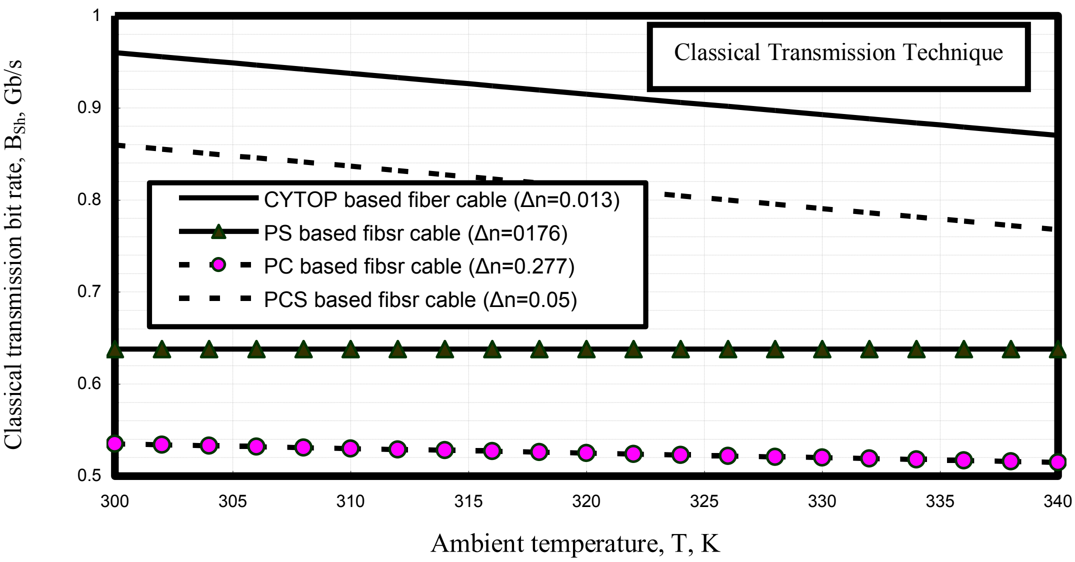

Fig. 15. Variations of Classical transmission bit rate against ambient temperature at the assumed set of operating parameters.

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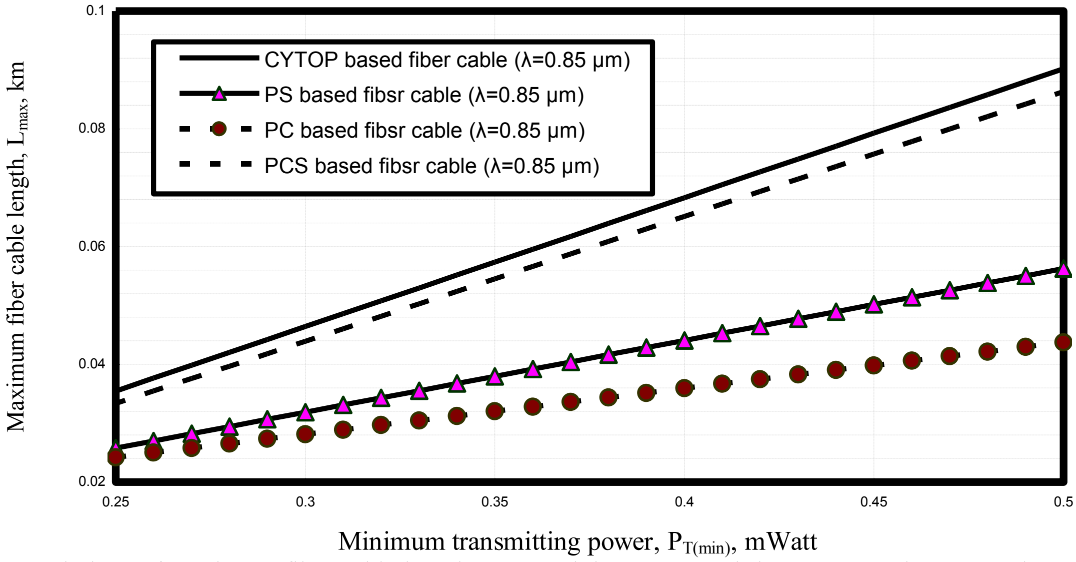

Fig. 16. Variations of maximum fiber cable length versus minimum transmitting power at the assumed set of parameters.

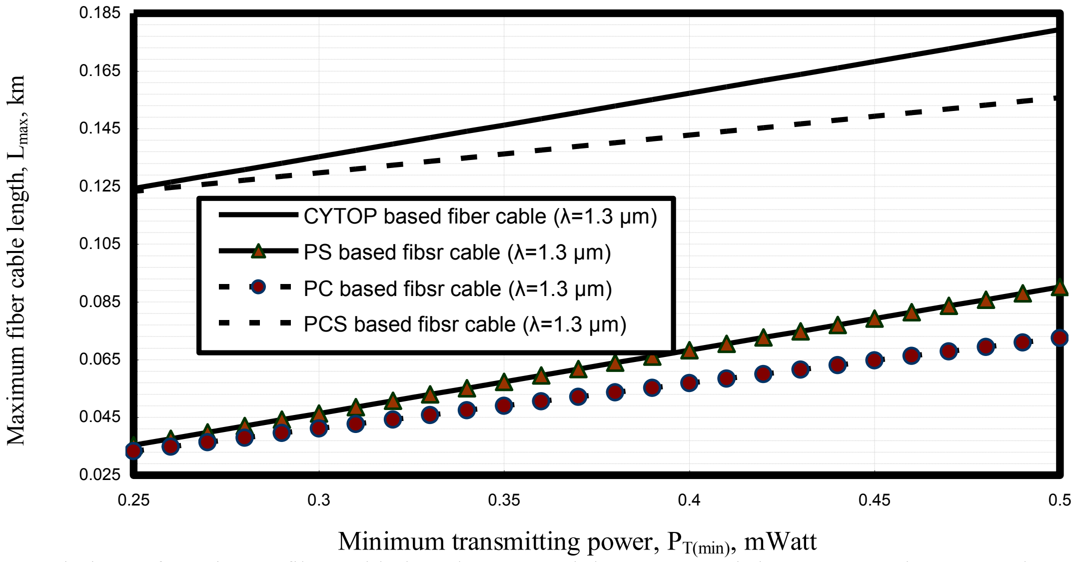

Fig. 17. Variations of maximum fiber cable length versus minimum transmitting power at the assumed set of parameters.

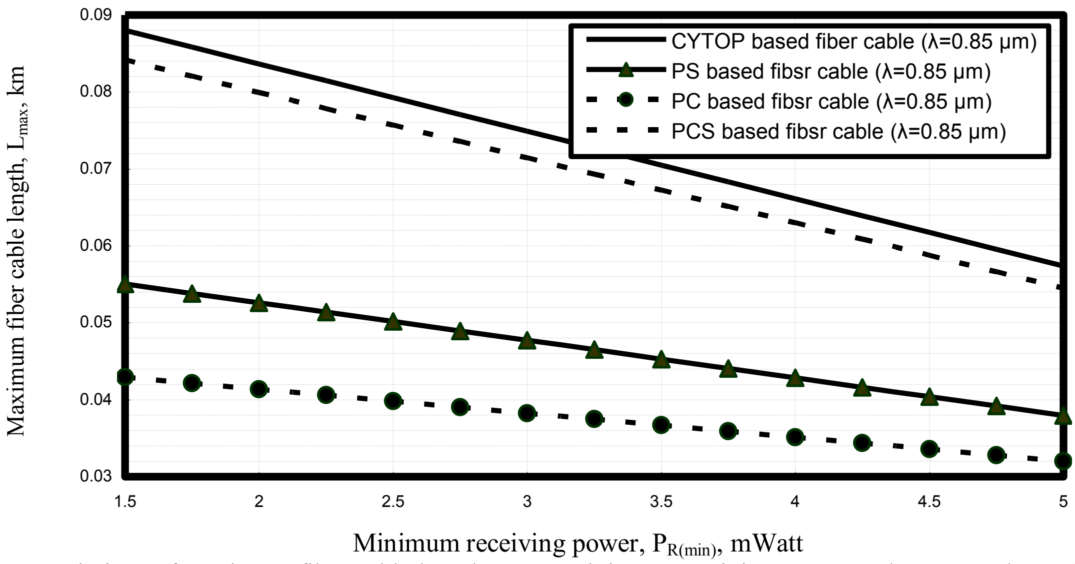

Fig. 18. Variations of maximum fiber cable length versus minimum receiving power at the assumed set of parameters.

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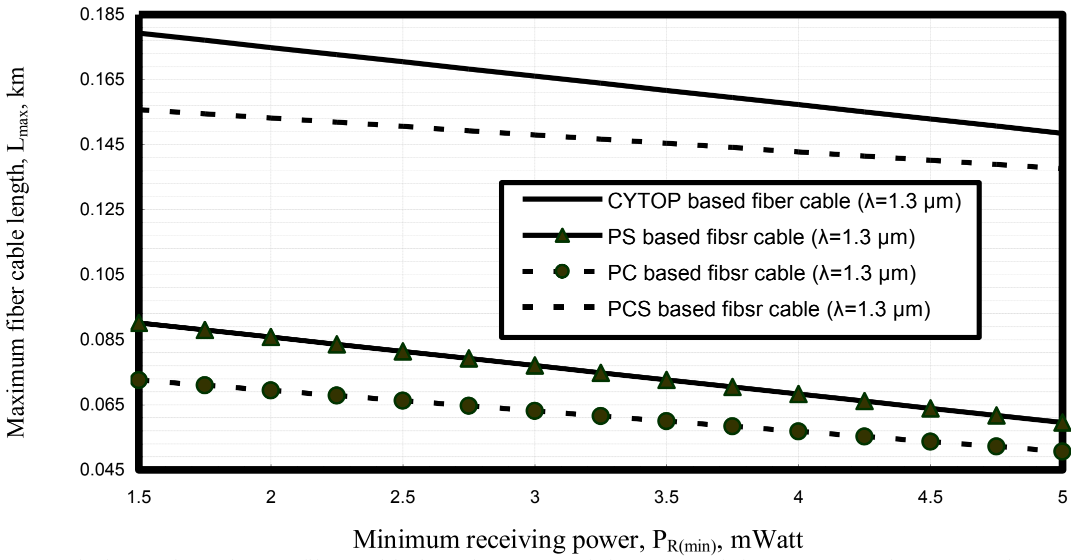

Fig. 19. Variations of maximum fiber cable length versus minimum receiving power at the assumed set of parameters.

iii) Figs. (7-9) have demonstrated that as both transmission cable length and ambient temperature decreases, and optical signal wavelength increases, this results in increasing of optical signal to noise ratio through different materials based fiber cable. As well as we have observed that PCS and CYTOP materials have presented higher optical signal to noise ratio compared to other materials based fiber cable.

iv) As shown in the series of Figs. (10-15) have assured that as both transmission cable length and ambient temperature decreases, and optical signal wavelength increases, this results in increasing of transmission bit rates by using both classical and Shannon transmission techniques through different materials based fiber cable. As well as we have observed that PCS and CYTOP materials have presented higher transmission bit rates compared to other materials based fiber cable. Shannon transmission technique has presented higher transmission bit rate compared to classical transmission technique.

v) Figs. (16-19) have indicated that as minimum transmitting power increases, minimum receiving power decreases, and operating optical signal wavelength increases, this leads to increase in maximum transmission cable length for different materials based fiber cable. Moreover we have indicated that PCS and CYTOP materials have presented maximum transmission cable lengths compared to other materials based fiber cable.

IV. Conclusions

POFs characteristics make them especially suitable for short haul telecommunications links. To improve the maximum transmission distance and speed, graded index POFs can be used, especially those made from an amorphous fluorinated polymer called CYTOP and the second made of PCS. The success of POFs arises from their easiness to use and the fact that POF production techniques have advanced as much as to enable the manufacture of inexpensive high quality low loss POFs. POFs attenuation depends on the core diameter and on the numerical aperture of the light source. The basic attenuation mechanisms in a POF can be classified into two big groups: intrinsic and extrinsic. Among the intrinsic losses we have the absorption of the constituent material and the Rayleigh scattering. Both contributions depend on the composition of the optical fiber and, therefore, they cannot be eliminated. The maximum transmission distance through a POF not only depends on the fiber's attenuation, but also depends on the waveform distortion due to intermodal and intramodal dispersion as well as to the differential mode attenuation. Although those fibers with a higher numerical aperture can accept more light, there are also POFs with a reduced numerical aperture, which are used to achieve higher transmission speeds. It is evident that PCS and CYTOP plastic materials based fiber cable links have presented lower total pulse broadening, higher both transmitted signal bandwidth and optical signal to noise ratio compared to other materials under study and under same operating conditions. Moreover PCS and CYTOP plastic materials based fiber cable have presented higher transmission bit rates within two transmission techniques namely Shannon and classical method compared to other materials under study. As well as it is theoretically found that PCS and CYTOP plastic materials based fiber cable have presented maximum transmission fiber cable lengths compared to other materials based fiber cable under the same affecting parameters. We have compared our theoretical results with their simulation results with perflourinated graded index plastic optical fibers [25, 26] under the same operating conditions.

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Table 3: Compared our theoretical results with their measured results for perflourinated plastic optical fibers.

Performance parameters	Room temperature (T_0=300 k), λ=0.85 μm, transmission distance=100 m				
	Plastic materials Based graded index optical fibers				Perflourinared graded index plastic optical fibers [25, 26]
	CYTOP	PC	PS	PCS	
Total pulse broadening, ns/km	0.12	0.7	0.665	0.125	0.4025
Transmitted bandwidth, GHz	0.9	0.45	0.55	0.8	0.675
OSNR, dB	20	12	13	18	15.75
Classical bit rate, Gb/s	0.93	0.485	0.665	0.87	0.7375
Shannon bit rate, Gb/s	4.7	2.5	3.2	4.5	3.725

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