Interactions between Crosstalk in Wavelength Division Multiplexing and Graded index Optical Fiber Parameters

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***Abstract*— In this paper, an interaction between multimode graded-index optical fiber parameters with crosstalk and spatial shift in Wavelength Division Multiplexing (WDM) technique is presented. Pulse spreading caused by linear effects in optical fiber due to dispersion is considered in this proposed system. Results show how channel spacing, fiber core radius and spatial shift affect on the crosstalk. Furthermore, the significance of fiber length, chirp parameter and refractive index profile parameter on crosstalk is presented and analyzed in detail.**

***Index Terms*— Crosstalk; Dispersion; Optical Fiber; WDM.**

I. INTRODUCTION

An optical fiber is an efficient way of data transmission over long distances. Fiber optic communication has appeared as the dominant technology these days due to high information carrying capacity [1], immunity to electromagnetic interference, electrical isolation, signal security, less size and weight [2]. The rapid development desired for high information carrying capacity telecommunication links and effective utilization of fiber bandwidth has resulted in a remarkable increase in the use of WDM in advanced light-wave networks [3].

WDM is the most common multiplexing technique used in optical fiber communication system that allows combining two or more optical input signals into a single fiber link using different wavelengths λ. WDM will not only lead to the increase in the transmission capacity but also the enhancement of spectrum efficiency [4]. An optical fiber has some physical limitations on its bandwidth; the most important is its dispersion [2]. At high data rate, the dispersion produces the broadening of short pulses that travels in the fiber causes crosstalk between the adjacent pulses, leading to errors when the communication distance increases [3].

Dispersion is the variation of the refractive index of a material with wavelength and causes spreading of the optical pulses when they propagate through the fiber [5]. When pulses spread or broaden, they will overlap and lead to an interference with the adjacent pulses. This interference is called Inter-Symbol Interference (ISI), and in this case, the receiver cannot distinguish the pulses as 0s or 1s, leading to errors and loss of information. There are two main categories of dispersion, intermodal and intramodal dispersion [6].

Designing optical fiber link with WDM needs attention to some parameters such as the link bandwidth, optical power requirements, performance limitations due to nonlinear effects and crosstalk between adjacent channels [7].

The channel spacing Δλ, known as the minimum wavelength separation between channels is required to ensure minimum crosstalk degradation. The value of crosstalk must be as small as possible to get a suitable system performance [8].

The narrow channel spacing in WDM links produces crosstalk, which is defined as the feedthrough of one channel's signal into another channel. Crosstalk can be introduced by almost any component in a WDM system, including optical filters, wavelength multiplexers and demultiplexers, optical switches, optical amplifiers, and the fiber itself. Fiber induced crosstalk, which arises from the nonlinear effects on the optical signal when it travels in the glass medium [9].

Optical fiber communication with Dense WDM system faces some challenges: One of these challenges is the dispersion that limits the bandwidth-distance product of the optical fiber and causes broadening of pulses used to convey information, which in turn, lead to interference between adjacent pulses. Another other challenge is the crosstalk between the adjacent channels [6]. Previous researches discussed and solved the crosstalk problem and the parameters effected on it only at the input of the optical fiber link, neglecting the fiber length and chirping effect on the pulse.

In this paper, the fiber length and chirp parameter will be taken into consideration. Moreover, the significance of these parameters on crosstalk will be covered.

The rest of the paper is organized as the following: In Section II, the proposed system is presented. In Section III, the effect of the different parameters on the crosstalk of the proposed system is discussed. The conclusions are presented in Section IV.

II. THE PROPOSED SYSTEM DESIGN AND PROCESS AND ANALYSIS

A proposed system presented in this paper is a multimode graded-index optical fiber cable of length Z with WDM technique: The cable consists of two layers, core and cladding. The core layer is doped gradually with Germanium Dioxide (GeO2) to produce a graded-index medium such that the index of refraction decreases gradually from the core to the cladding. The core layer has a refractive index $n_{1,}$ which is slightly greater than the other layer. The cladding layer is undoped pure Silica (SiO2) with refractive index n_2. The values of n_1 and n_2 depend on wavelength. The general form of the refractive index profile in the multimode graded-index fiber is given by the following equation [10]:

$$n(r) = \begin{cases} n_1[1-\Delta(r/a)^{\alpha}], & r < a \\ n_1(1-\Delta) = n_2, & r \geq a \end{cases} \tag{1}$$

$$\Delta = \frac{n_1 - n_2}{n_1} \tag{2}$$

where: Δ=The refractive index difference
α=refractive index profile parameter
n_1=Core refractive index
n_2=Clad refractive index

The basic material for most high-quality optical fibers is SiO_2, which is in the form of fused quartz. In the proposed optical fiber, the cladding material is undoped pure silica. To produce the graded-index core material, there is a need to vary the refractive index gradually and the substantial concentrations of oxide impurities must be added to the silica. We chose GeO_2 as dopants with (13.5%GeO_2 + 86.5%SiO_2) concentrations to increase the refractive index of the core. Since the silica is a dispersive medium, its refractive index is wavelength-dependent [11].

We applied the Sellmeier equation (equation 3) to the GeO2 core to derive n_1, as given in equation (4) [12] :

$$n(\lambda) = \sqrt{1 + \sum_{i=1}^{3} A_i \cdot \frac{\lambda^2}{\lambda^2 - \lambda_i^2}} \tag{3}$$

where: A_i = oscillator strength
λ_i = resonant wavelength

Both Ai and λi are different for each material type, for the fiber type used, the core refractive index is given as:

$$n_1(\lambda) = \sqrt{1 + \frac{0.711040\,\lambda^2}{\lambda^2 - (0.064270)^2} + \frac{0.451885\,\lambda^2}{\lambda^2 - (0.129408)^2} + \frac{0.704048\,\lambda^2}{\lambda^2 - (9.425478)^2}} \tag{4}$$

n_1=1.4660 at λ=1.510 μm. It is worth mentioning that at wavelength equal to 1.510 μm, the fiber attenuation is minimum.

The proposed system suffers from the material dispersion as one of the limitations of the information carrying capacity. Material dispersion parameter D_{mat} in ps/(nm.km) is given in the following equation [13] :

$$D_{mat} = -\frac{\lambda}{c}\frac{d^2 n_1}{d\lambda^2} \tag{5}$$

where c=The velocity of light in free space.

At λ=1.510 μm, D_{mat} =10.85501 (ps/(nm.km). Group Velocity Dispersion (GVD) parameter β_2 in ps^2/km defines how much the broadening of the optical pulses when they propagate through the fiber; So GVD shows the effect of linear dispersion on a Gaussian pulse [14] and it is given in the following equation [5,15] :

$$\beta_2 = -\frac{D_{mat}}{2\pi c}\lambda^2 \tag{6}$$

At λ=1.510 μm, β_2 =-13.13055 ps^2/km. The increase in data traffic requirements requires WDM to be considered as a standard technique used in optical fiber communication systems. When the data traffic increases, a huge bandwidth is needed to cope with this rising demand for audio, video and data networks, which is known as triple play networks [16]. One of the key features of the optical fiber with WDM systems is the spatial shift Δx between successive channels, which refers to the space between the demultiplexed channels at the output of the system [17].

Spatial dispersion is defined as a change in the exit position of the light beam with the wavelength. Each wavelength component propagates into the dispersive media with different angles and velocities due to the dependence of refractive index on the wavelength; thus, each wavelength travels in a different path and spatially separated at the output [18].

An expression for the spatial shift between any successive wavelengths at the output of the optical fiber is given by [17]:

$$\Delta x(\lambda_k, \lambda_{k+1}) = \frac{2a\sin(\theta_i)}{\alpha\left(n_1(\lambda_k) - n_2(\lambda_k)\right)^{1/\alpha}} \cdot f_{\alpha}(\theta_i) \cdot \left[\left(n_1(\lambda_k)\right)^{1/\alpha} - \left(n_1(\lambda_{k+1})\right)^{1/\alpha}\right] \tag{7}$$

where $f_{\alpha}(\theta_i) = \int_1^{\sin(\theta_i)} \frac{(1-s)^{(1/\alpha)-1}}{\sqrt{s^2 - \sin^2\theta_i}} ds$,
θ_i = The incidence angle of the light ray
λ_k = The kth wavelength
λ_{k+1} = The (k+1)th wavelength

Equation (7) shows the different parameters that decide the amount of spatial shift between two adjacent wavelengths. These parameters are the radius of the core (a), the refractive index profile parameter (α), the incidence angle (θ_i), the refractive index of the core (n_1), the refractive index of the cladding (n_2) and the channel spacing between the adjacent wavelengths (Δλ). The effect of each of a, α and Δλ will be discussed on the spatial shift between adjacent wavelengths.

The effect of the channel spacing on the spatial shift Δx for different values of α and a fixed core radius a = 5 mm is shown in Figure 1. It is clear that the spatial shift depends heavily on the channel spacing, increasing channel spacing between adjacent channels increases spatial shift which in turn minimizes the value of crosstalk between channels.

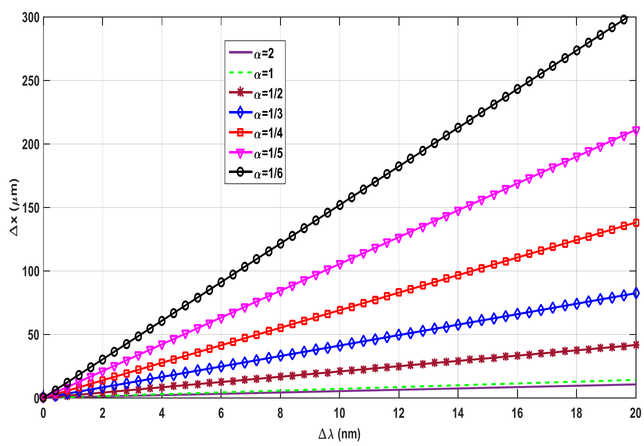

Figure 1: Spatial shift Δx versus channel spacing Δλ for different values of α and a = 5mm.

The effect of the refractive index profile parameter α on the spatial shift is shown in Figure 2. It shows the dependence of the spatial shift on the refractive index profile parameter α for different values of a and a channel spacing of 1 nm. It can be observed that spatial shift is increased by the decreasing α.

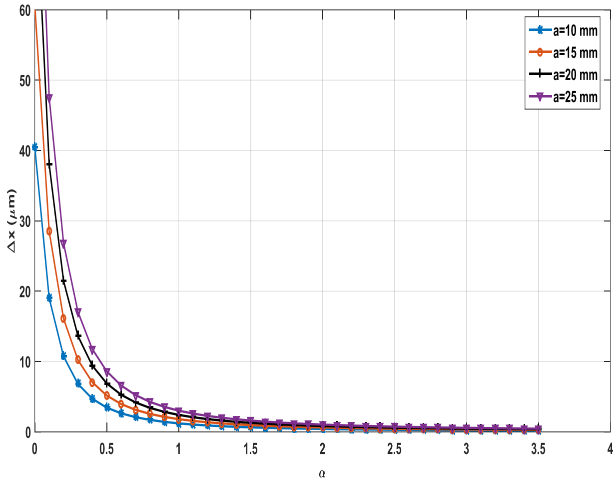

Figure 2: Spatial shift Δx as a function of α for different values of a and a channel spacing of 1nm.

Crosstalk takes place when an interfering signal comes from an adjacent channel. Moreover, crosstalk refers to how much power is present due to an adjacent channel[19].

The crosstalk from the adjacent wavelengths, which is the function of the spatial shift Δx can be calculated using the following equation [19]:

$$\mathrm{Crosstalk} = \frac{\mathrm{erf}\left(\sqrt{2}\frac{1.5\Delta x}{\omega_0}\right)}{2\mathrm{erf}\left(\sqrt{2}\frac{0.5\Delta x}{\omega_0}\right)} - 0.5 \qquad (8)$$

where erf = the error function.

Figure 3 plots the crosstalk as a function of the spatial shift for different beam spot sizes. It is obvious from this figure that the crosstalk can be reduced by either increasing the spatial shift between adjacent channels or reducing the beam spot size.

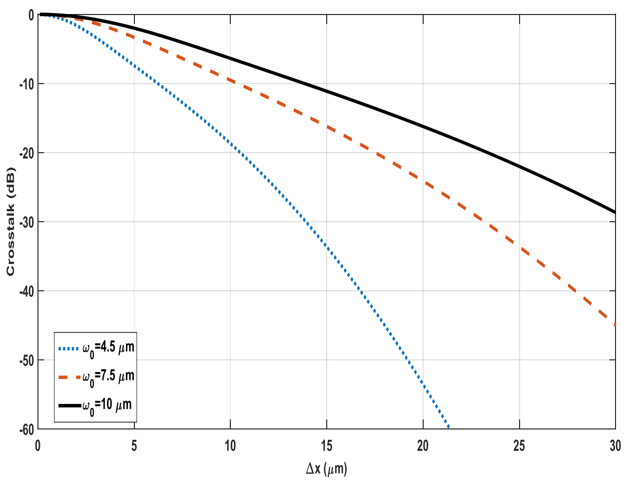

Figure 3: Crosstalk versus spatial shift Δx for different laser beam sizes ω_0.

III. Design Parameters

This section presents the simulation results carried out by Matlab program. The impact of additional factors on crosstalk is investigated. These factors are the length of the fiber Z, the chirp parameter C and the refractive index profile parameter α.

At the input of the optical fiber cable Z=0, and before the pulses propagate through the fiber, the initial pulse width T_0 assumed to be 5 ps with the chirp parameter C varies from-1 to 5, then the spectral half width Δω is given by [14,20]:

$$\Delta\omega = (1 + C^2)^{1/2}/T_0 \qquad (9)$$

Thus,

$$\Delta f = \Delta\omega/2\pi \qquad (10)$$

And the channel spacing is given by the following equation [21]:

$$\Delta\lambda = \Delta f \cdot \lambda^2/c \qquad (11)$$

Using equation (7) and (8), we can calculate the spatial shift Δx and crosstalk between the adjacent wavelengths respectively at α=0.6 and α=2. Table 1 illustrates the parameters used to build the system model used to enhance its performance.

Table 1
Units for Magnetic Properties

Value	Conversion from Gaussian and CGS EMU to SI [a]
Initial pulse width (T_0)	5 ps
Beam spot size (ω_0)	4.5 μm
Refractive index profile parameter (α)	0.6 and 2
Speed of the light in free space (c)	$3 * 10^8$ m/s
Core radius(a)	**5 *mm***
Incidence angle (θ_i)	**1.21 *rad***
Wavelength (λ)	1.510 μm
GVD parameter (β_2)	$-13.13055\ ps^2/km$

After propagating a distance into the optical fiber cable, the pulse width will broaden and become T_1 that is given in equation (12) [14]:

$$T_1 = T_0\left[\left(1 + \frac{C_1\beta_2 z}{{T_0}^2}\right)^2 + \left(\frac{\beta_2 z}{{T_0}^2}\right)^2\right]^{1/2} \qquad (12)$$

Also, the chirp parameter changes to C_1 according to the following equation [14]:

$$C_1(z) = C + (1 + C^2)\left(\beta_2 z/{T_0}^2\right) \qquad (13)$$

Thus, the spectral half width changes to $\Delta\omega_1$, which is given by [14]:

$$\Delta\omega_1 = \left(1 + {C_1}^2\right)^{1/2}/T_1 \qquad (14)$$

$\Delta\omega_1$ will be used to recalculate Δf and consequently Δλ using equations 10 and 11 respectively.

Figure 4 shows the effect of the channel spacing on the spatial shift for different values of Z and α=0.6. It is clear that increasing the channel spacing between adjacent channels increases the spatial shift. Furthermore, it is obvious that the larger spatial shift has been occurred at the input of the optical fiber when Z=0 and has a value of Δx=11.739 µm, the corresponding value of channel spacing is equal to 0.001234 µm.

Also, for α=2, spatial shift increases when channel spacing between adjacent channels increases, as seen in Figure 5. The larger spatial shift has been occurred when Z=0, in which at this length the value of Δx=0.39681 µm and Δλ=0.001234 µm. It can be observed that the spatial shift is smaller than its value when α=0.6.

Figure 6 and 7 present the crosstalk as a function of the channel spacing for different fiber lengths with α=0.6 and α=2, respectively. It is obvious from these two figures that the crosstalk can be reduced by either increasing the channel spacing between adjacent channels or reducing the optical fiber length. Based on these two figures, the larger crosstalk occurred at Z=50 km and α=2.

Figure 8 illustrates the crosstalk as a function of the spatial shift for different values of fiber length and α=0.6. As can be seen from Figure 8, the crosstalk decreases when the spatial shift increases. The larger value of crosstalk is -0.0032833 dB when the fiber length equals to 50 km.

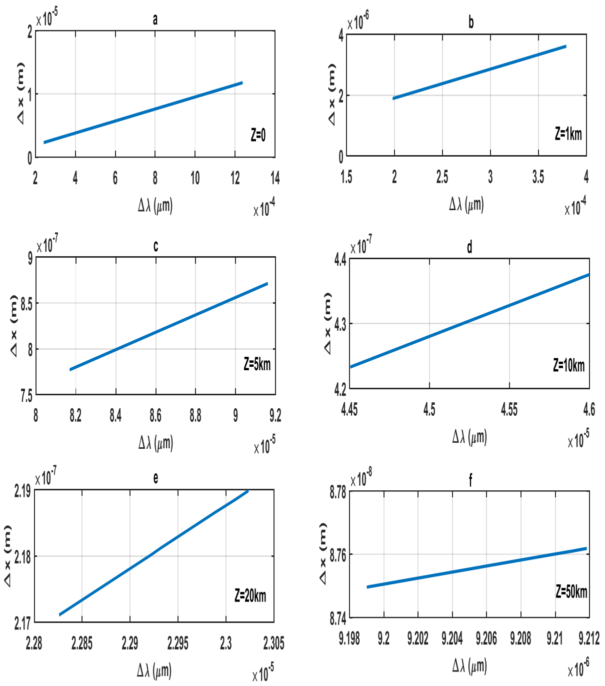

Figure 4: Spatial shift Δx versus channel spacing Δλ for different values of Z and α=0.6 (a) Z=0 (b) Z=1 km (c) Z=5 km (d) Z=10 km (e) Z=20 km and (f) Z=50 km.

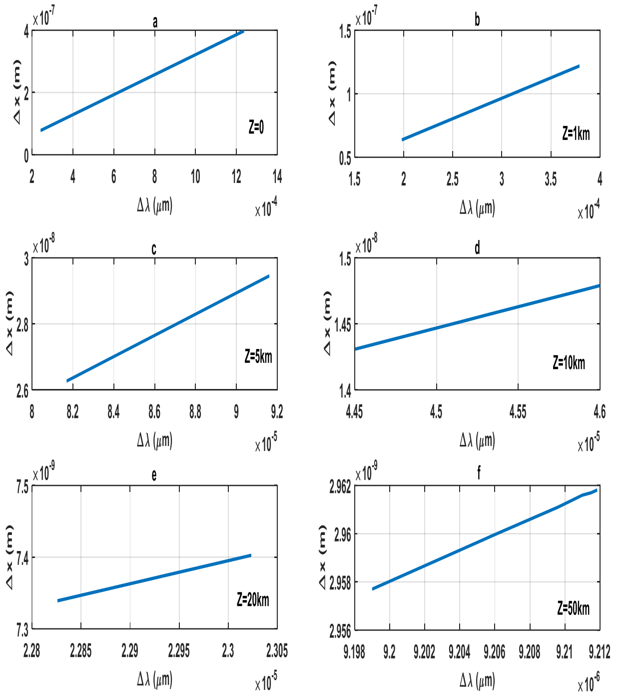

Figure 5: Spatial shift Δx versus channel spacing Δλ for different values of Z and α=2 (a) Z=0 (b) Z=1 km (c) Z=5 km (d) Z=10 km (e) Z=20 km and (f) Z=50 km.

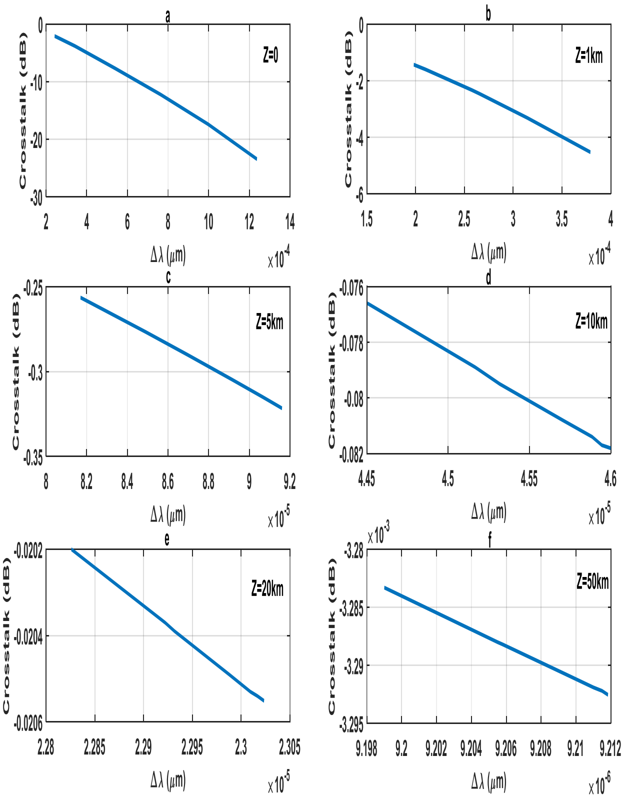

Figure 6: Crosstalk versus channel spacing Δλ for different values of Z and α=0.6 (a) Z=0 (b) Z=1 km (c) Z=5 km (d) Z=10 km (e) Z=20 km and (f) Z=50 km.

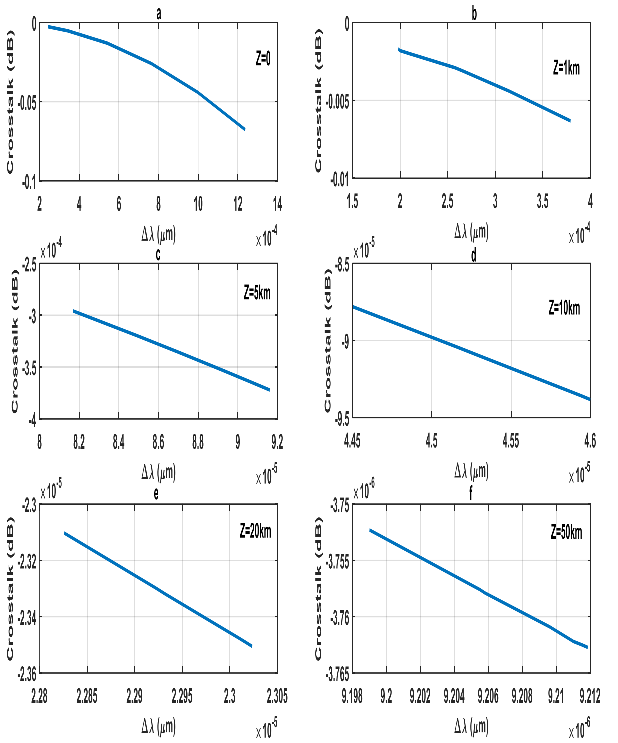

Figure7: Crosstalk versus channel spacing Δλ for different values of Z and α=2 (a) Z=0 (b) Z=1 km (c) Z=5 km (d) Z=10 km (e) Z=20 km and (f) Z=50 km.

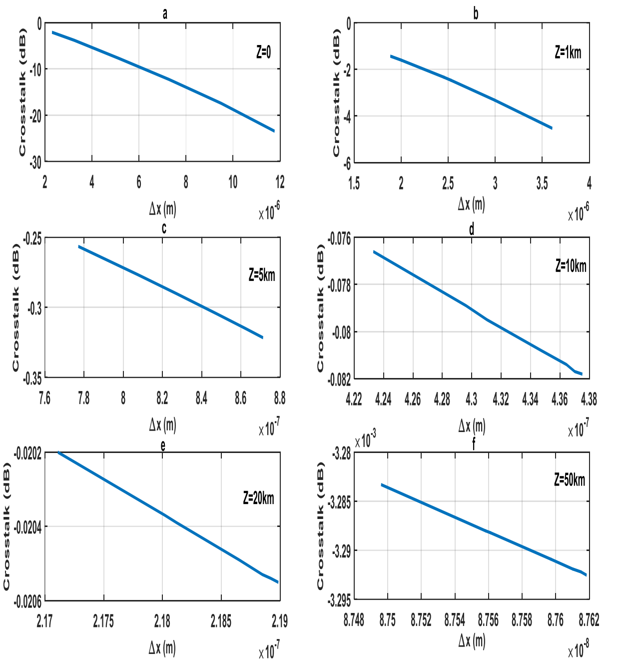

Figure 8: Crosstalk versus spatial shift Δx for different values of Z and α=0.6 (a) Z=0 (b) Z=1 km (c) Z=5 km (d) Z=10 km (e) Z=20 km and (f) Z=50 km.

Consequently, Figure 9 explains the dependency of the crosstalk on the spatial shift for different values of fiber length and α=2. In this case, the larger value of crosstalk is -0.0000037523 dB when Z=50 km, thus it is a very large and undesirable value. This would be the worst case scenario in the system design. When we compared this value with the value obtained with α=0.6, it was found that the crosstalk improved as α decreased.

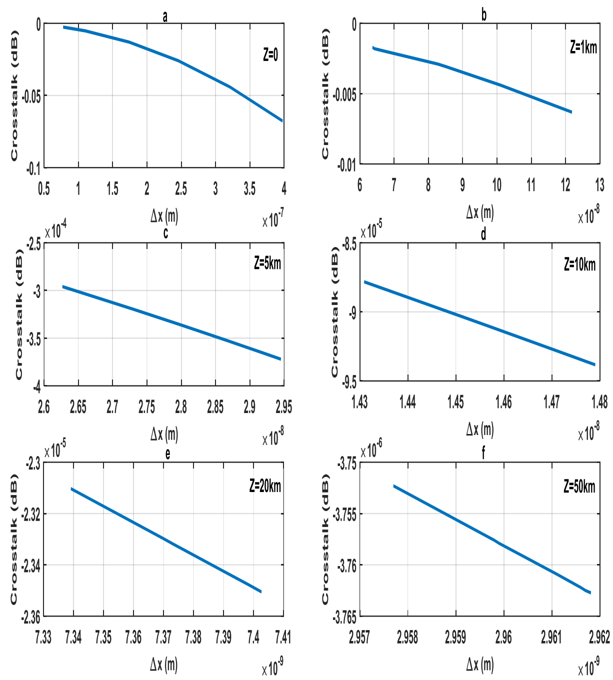

Figure 9: Crosstalk versus spatial shift Δx for different values of Z and α=2 (a) Z=0 (b) Z=1 km (c) Z=5 km (d) Z=10 km (e) Z=20 km and (f) Z=50 km.

The optical fiber length is an important parameter that affects the crosstalk between channels. The dependence of the crosstalk on the fiber length for different values of C when α=0.6 and α=2 is shown in Figure 10 and 11, respectively. It can be noticed that the crosstalk increases when the fiber length increases. Also, after fiber length is greater than 5 km, the crosstalk becomes very large and approaching to zero. For this reason, the fiber length has not been taken after 6 km in the plotted figures. This would be the worst case scenario in the system design.

Further, it can be seen from Figure 10 and 11, in which at a specific fiber length, the crosstalk increases as the chirp parameter decreases. It is worth mentioning that the chirp parameter C_1 is related to fiber length Z as in equation (13). Through our observation to these two figures, the crosstalk increased by α.

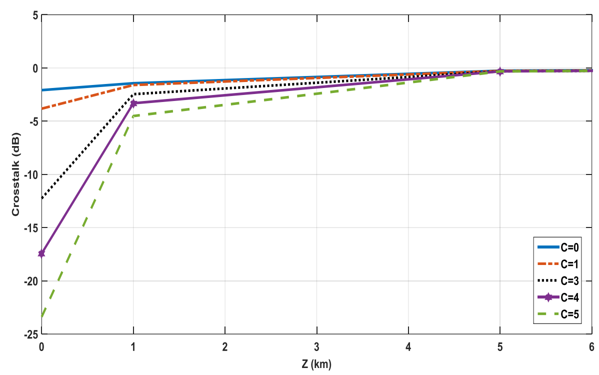

Figure 10: Crosstalk versus fiber length Z for different values of C and α=0.6.

In order to investigate the impact of the chirp parameter C on crosstalk, Figure 12 and 13 show the relation between crosstalk and C for different optical fiber length when α=0.6 and α=2, respectively. It is clear that the crosstalk decreases as the chirp parameter increases. Moreover, at a given value of C, the crosstalk increases as the fiber length increases. After Z=5 km, the crosstalk becomes very large and approaches to zero. At the same values of C and Z as shown in Figure 12 and 13, the crosstalk is smaller when α=0.6. As expected, these results are consistent with the results obtained from Figure 10 and 11.

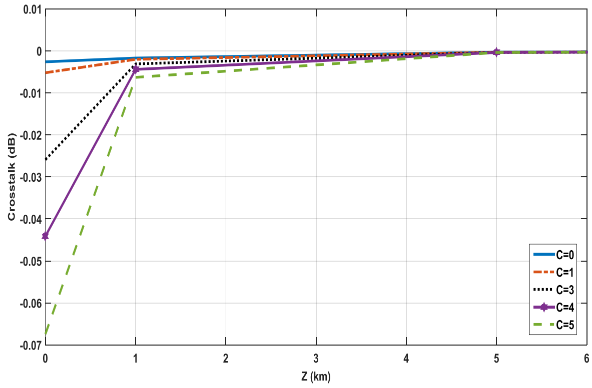

Figure 11: Crosstalk versus fiber length Z for different values of C and α=2.

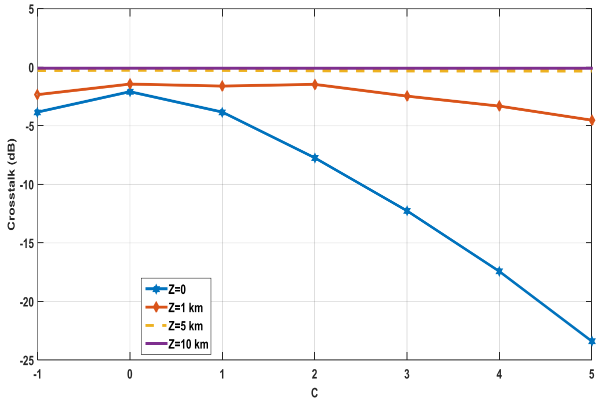

Figure 12: Crosstalk versus chirp parameter C for different values of Z and α=0.6.

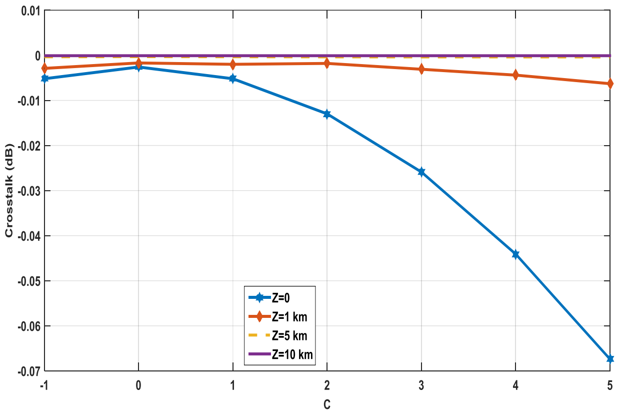

Figure 13: Crosstalk versus chirp parameter C for different values of Z and α=2.

From figure 14, it can be seen that the crosstalk is significantly affected by α. However, the crosstalk increases as α increases. Also, at a given value of α crosstalk increases, the fiber length increases. It can be observed that the best value for the crosstalk was -121 dB which is occurred at α=0.3333 and Z=1 km. We can conclude that the system performance - in terms of reducing crosstalk - improves when α is reduced. Moreover, when Z=50 km, there is a noticeable decrease in the crosstalk for α <0.3

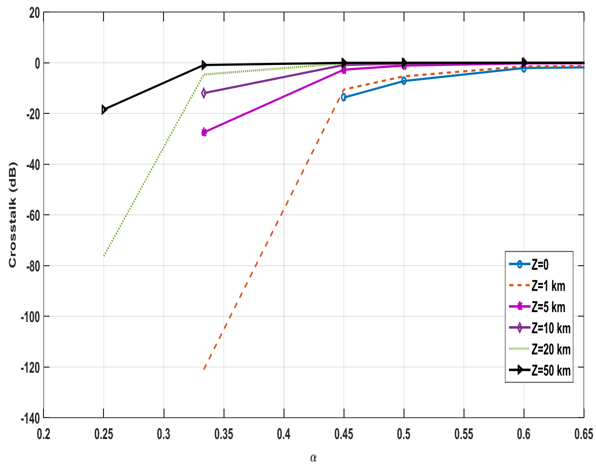

Figure 14. Crosstalk versus α for different values of Z and C=0.

IV. Conclusion

In this paper, graded index optical fiber cable of length Z with WDM system has been studied and investigated. Furthermore, some characteristics of this system have been studied, including the fiber chirp. The most important of these characteristics are the D_{mat} and the GVD parameter. Further, the effect of β_2 on the pulse, which propagates through the optical fiber (Z >0) with WDM system is very important and can alter the chirp value and the channel spacing.

Moreover, there are many factors that give impact on the crosstalk between the channels in WDM system such as the channel spacing, refractive index profile parameter, core radius and spatial shift: As the spatial shift increases, the crosstalk decreases, leading to performance improvement.

The significance of fiber length, chirp parameter and refractive index profile parameter on the crosstalk has been analyzed and evaluated. It has been concluded that crosstalk increases with the fiber length and refractive index profile parameter but decreases with the chirp parameter. The impact of decreasing α below 0.3 can lead to a possibility for increasing the fiber length up to 50 km, while keeping the crosstalk below -20 dB level.

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