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Research Article

Performance Analysis of WDM-based Optical Communication Systems in presence of Kerr Nonlinearities

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Abstract

Kerr nonlinearities take a toll over the performance of an optical system. For a multiple channel system, i.e., a Dense Wave Division Multiplexing (DWDM) system, cross phase modulation (XPM) and four wave mixing (FWM) deteriorate the overall system performance and efficiency. In this paper, we have explained the most important linear and non linear impairments of an optical fiber and the effects of the interplay between them. We have also reviewed the mathematical analysis of these impairments to obtain a better idea of the behavior of the fiber in their presence. Further, we have simulated an optical system and observed its performance by variation in parameters such as channel spacing and dispersion. The best performance was obtained for maximum channel spacing and minimum dispersion allowed by system 1.73nm and 9.6ps/nm/km. The values were chosen so that the nonlinear effects can be analyzed.

Keywords: *Dense wave division multiplexing, bit error rate, cross phase modulation, four wave mixing, group velocity dispersion, Kerr effect*

1. Introduction

An expanding demand of high capacity optical communication systems is a consequence of the colossal development of Internet usage. The optical transmission systems offer enhanced solutions for managing increasing demands for transmission bandwidth and system capacity. In the most recent 20 years, the optical transmission systems have turned into an important communication sector, whose consistent integration with conventional system provisions and services drives a further advancement and a more extensive organization of optical systems in all telecommunication regions.

Optical transmission systems are popular for maintaining low power for short to medium range wireless communications. But for other applications where transmission distance is large, high power is required. In an optical fiber, various nonlinear effects begin to appear as the optical power level increases. Consequences of nonlinear effects include power gain or loss at different wavelengths, wavelength conversions, and crosstalk between channels in wavelength division multiplexing (WDM) system. These nonlinearities can degrade system performance and also, prove beneficial at times, if managed properly.

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Basic of nonlinear effect is the one arising from intensity-dependent variations in the refractive index of a silica fiber, termed as Kerr effects. They include self phase modulation (SPM), cross phase modulation (XPM), and four wave mixing (FWM). Kerr nonlinearities can alter the frequency spectrum of a pulse traveling through a fiber. Thus, the interplay between the linear and non linear impairments and its effect on the behavior of an optical system is a matter of great importance.

In this paper, we have simulated the optical system for nonlinear effects and analyzed the performance. To balance the nonlinearity with signal attenuation, some optimization techniques such as dispersion compensation, channel spacing has been employed.

2. Linear and Nonlinear Impairments in WDM Systems

To observe the performance of an optical system, it needs to be analyzed holistically. As WDM systems are getting more complex, taking into account the impact of different impairments such as noise, group velocity dispersion, fiber nonlinearities and polarization effects is critical.

Depending on the power level inside the fiber, linear and nonlinear effects are seen. Up to a threshold value linear effects degrade the signal, above which nonlinear effects come into picture. Linear effects consist of fiber attenuation and group velocity dispersion (GVD) whereas nonlinear effects are XPM and FWM. Linear effects such as attenuation and dispersion can be compensated by using various techniques, but nonlinear effects accumulate. They are the fundamental limiting mechanisms to the amount of data that can be transmitted in optical fiber. Because of their low threshold, the most problematic nonlinearities are those caused by the optical Kerr effect, which includes FWM, SPM and XPM between different channels. Because these effects depend either directly or indirectly on fiber dispersion, system impairments can be reduced by dispersion-management techniques (Lefrancois, *et al*, 2006), (Judy, 1997).

2.1 Fiber Attenuation

The signal propagation in an optical fiber is always accompanied by loss of the input power P (0, t). The signal power after propagation through a fiber length z is given by:

$$P(z,t) = P(0,t)\exp(-\alpha z) \quad (1)$$

The parameter α is called fiber attenuation and represents a sum of different losses in the fiber. The fiber attenuation describes the fact that optical signal power decreases exponentially when propagated in optical fiber. α derived from equation (1) is given as:

$$\alpha[dB/km] = \frac{-10}{z}\log_{10}\left(\frac{P(z,t)}{P(0,t)}\right) = 4.343\alpha \quad (2)$$

The attenuation exhibited by the optical fiber is dependent on the wavelength of the propagating signal. Figure 1 shows loss spectrum of a silica fiber which gives minimum loss of 0.2dB/km at 1550nm.

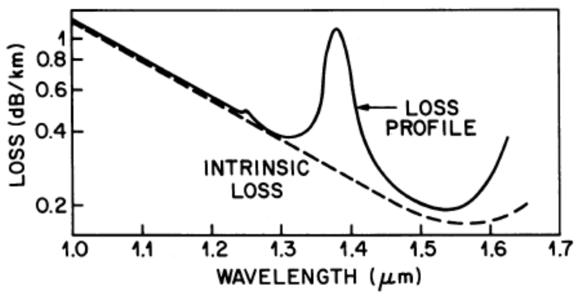

Fig. 1 Loss spectrum of single mode silica fiber (Agrawal, 2001)

As can be seen, optical fibers exhibit higher losses at shorter wavelengths, reaching a level of few db/km in visible range. The total loss is caused fundamentally by three different mechanisms: material absorption, Rayleigh scattering and waveguide imperfections (Shine, 2002).

Material absorption is a loss mechanism that is related to material composition and is caused due to the absorption of photons within the fiber. When optical signal is passed through a material, photons cause valence electrons to transit to higher energy levels. In doing so, photons exert their energy to electrons and transform this energy into electric potential energy. This energy can then be re-emitted or dissipated to the rest of the material. The second option where the optical energy is converted to heat dissipation within the fiber is known as material absorption loss (Fink, *et al*, 1999). There are two types of material absorption, intrinsic loss which is caused by interaction with one or more components of the glass and extrinsic loss caused by impurities within the glass. Rayleigh scattering is dominant intrinsic loss mechanism which is caused due to inhomogeneities in the glass, of a size smaller than operating wavelength. For 1550nm, the loss is approximately 0.18dB/km.

2.2 Group Velocity Dispersion (GVD)

One of the most important features of the optical transmission is the signal broadening, also known as chirping, during propagation of different spectral components in an optical fiber. This phenomenon known as chromatic dispersion refers to propagation time differences in the fiber. Chromatic dispersion represents the fact that different colors or wavelengths travel at different speeds, even within the same mode and thus arrive at different times at the fiber end. Therefore the range of arrival times at fiber end of the spectrum of wavelengths will lead to pulse spreading (Keiser, 2008). This can be understood as a frequency dependence of the refractive mode index that causes different spectral components of the pulse to propagate at different group velocities. Accordingly, chromatic dispersion is known as group-velocity dispersion (GVD). The consequence of chromatic dispersion is the broadening of the single pulse and interference between adjacent pulses known as inter-symbol-interference (ISI).

The evolution of an optical pulse propagating through a nonlinear dispersive medium is given by Nonlinear Schrödinger equation as follows (Ghatak, *et al*, 2002):

$$-i\left(\frac{\partial f}{\partial z} + \frac{1}{v_g}\frac{\partial f}{\partial t}\right) - \frac{1}{2}\alpha\frac{\partial^2 f}{\partial t^2} + \Gamma|f|^2 f = 0 \quad (3)$$

First term on the LHS represents wave travelling through dispersive medium. Second term is proportional to and is a dispersion term and the last term represents nonlinearity.

In the absence of nonlinearity, this equation will only represent GVD and chirping due to GVD. Thus modifying the equation for dispersive effects

$$-i\left(\frac{\partial f(z,T)}{\partial z}\right) - \frac{1}{2}\alpha\frac{\partial^2 f(z,T)}{\partial t^2} = 0 \quad (4)$$

Using the method of separation of variables, general solution of above equation is given as

$$f(z,T)=\int A(\Omega)e^{i(\Omega T-\frac{1}{2}\alpha\Omega^2 z)}d\Omega \quad (5)$$

Equation (5) represents frequency spectrum of the input pulse. Due to dispersion, pulse experiences chirping. In the linear approximation, the envelope propagates with the group velocity remaining unchanged in shape. But in the quadratic approximation it spreads and reduces in amplitude with distance and it chirps as shown in figure 2.

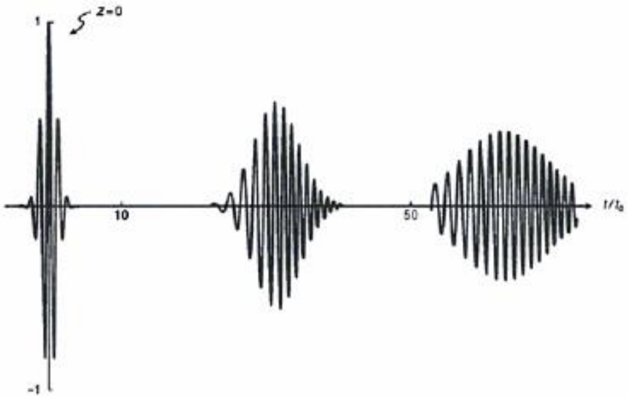

Fig. 2 Pulse spreading and chirping due to GVD

The dispersion in optical fibers is strongly influenced by the dispersion in material itself. Figure 3 shows variation of GVD with wavelengths.

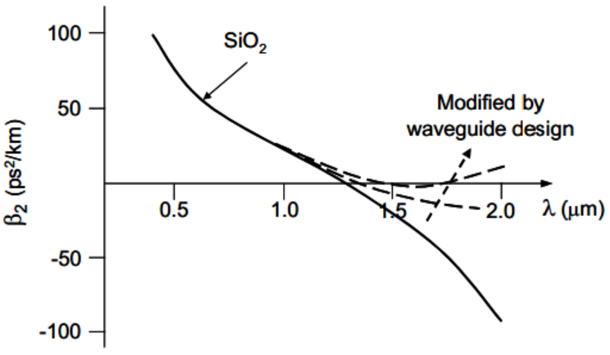

Fig. 3 GVD in optical fiber v/s wavelengths

The solid line in figure 3 is the GVD for fused silica (SiO_2) glass material by itself. It has a value of zero dispersion at 1310nm. With the introduction of erbium-doped fiber amplifiers (EDFA) operating at 1550nm, the zero GVD point was shifted to that wavelength (Saleh, *et al*, 1991). Modern fiber-optic communication systems operating near 1550nm reduce the GVD effects using dispersion-shifted fibers (DSF) designed such that the minimum-loss wavelengths and the zero-dispersion wavelengths nearly coincide.

2.3 Cross Phase Modulation (XPM)

Cross-phase modulation (XPM) is a multi-channel effect, where the intensity modulation of one carrier modulates the phases of other co-propagating carriers. Fiber dispersion, fiber length, channel spacing and bit rate are the parameters on which the magnitude of XPM is dependent.

The phase is converted to intensity noise due to fiber dispersion leading to nonlinear interaction between the optical carriers. The impact of XPM can be minimized by employing proper dispersion management techniques. The XPM effect is always accompanied by the SPM effect. For separation of XPM from SPM, an efficient method is the pump-probe method, in which an intensity modulated channel (pump) with a large channel power distorts a continuous wave (CW)-probe channel.

Optical pulse propagation in a fiber governed by the nonlinear Schrödinger equation (NLSE) is described as:

$$i\frac{\partial U}{\partial z}-\frac{b(z)}{2}\frac{\partial^2 U}{\partial T^2}+S(Z)|U|^2 U=R \quad (6)$$

where U, Z, T are normalized amplitude of pulse envelope, distance and retarded time, respectively. b(Z) stands for fiber dispersion, S(Z) represents the effective fiber nonlinearity which includes the effect of nonlinearity, fiber loss and periodic gain by optical amplifier, and R denotes perturbation. For a constant normalized nonlinear coefficient of S_0 and loss coefficient Γ, the expression for S(Z) is:

$$S(Z)=S_0\frac{2\Gamma Z_a}{1-\exp(2\Gamma Z_a)}\exp\{-2\Gamma(Z-nZ_a)\} \quad (7)$$

where $nZ_a \le Z \le (n+1)Z_a$ and Z_a is amplifier spacing. For a two-channel WDM system, we consider RZ pulse U_j(Z, T) (j = 1, 2) where two pulses U_1 and U_2 interact each other through the XPM effect only. Assuming XPM as a perturbation, NLSE can be separated to the equations for U_1 and U_2 as

$$i\frac{\partial U_j}{\partial Z}-\frac{b(Z)}{2}\frac{\partial^2 U_j}{\partial T^2}+S(Z)|U_j|^2 U_j=R_j \quad (8)$$

where $R_j=-2S(Z)|U_{3-j}|^2 U_j$. We assume that U_j has a Gaussian waveform with linear chirp.

$$U_j(Z,T)=A_j\exp\left[-\frac{p_j^2}{2}(1-iC_j)(T-T_j)^2-ik_j(T-T_j)+i\theta_j\right] \quad (9)$$

where A_j(Z), p_j(Z),C_j(Z), κ_j(Z), T_j(Z) and θ_j(Z) are the pulse parameters representing the amplitude, the inverse of pulse width, the linear chirp, the central frequency, the central time position and the phase of the pulse, respectively. Applying variational method to

(9), the dynamical equations of these parameters under perturbation can be derived as:

$$\frac{dp_j}{dZ} = b(Z)p_j^3 C_j \tag{10}$$

$$\frac{dC_j}{dZ} = -b(Z)\,p_j^2\left(1 + C_j^2\right) - S(Z)\frac{E_j}{\sqrt{2\pi}}\,p_j - 4S(Z)\frac{E_{3-j}}{\sqrt{\pi}}\frac{p_j p_{3-j}^3}{P^5}\{P^2 - 2(\Delta\tau)^2\,F \tag{11}$$

$$\frac{d\theta_j}{dZ} = -\frac{b(Z)}{2}\left(k_j^2 - p_j^2\right) + S(Z)\frac{5E_j}{4\sqrt{2\pi}}p_j + S(Z)\frac{E_{3-j}}{\sqrt{\pi}}\frac{p_1 p_2}{P^5} \times \left\{P^2\left(2P^2 + p_{3-j}^2\right) - 2p_{3-j}^2(\Delta\tau)^2\right\}F \tag{12}$$

$$\frac{d(\Delta k)}{dZ} = 4S(Z)\frac{E_1 + E_2}{\sqrt{\pi}}\frac{p_1^2 p_2^2 \Delta\tau}{P^3}\,F \tag{13}$$

$$\frac{d(\Delta\tau)}{dZ} = b(Z)\{(p_1^2 C_1 + p_2^2 C_2)\Delta\tau + p_1 p_2 \Delta k\} \tag{14}$$

where $\Delta k(Z) = k_1(Z) - k_2(Z)$ (15)

$$\Delta\tau = p_1 p_2 (T_1 - T_2) \tag{16}$$

$$P = \sqrt{{p_1}^2 + {p_2}^2} \tag{17}$$

$$F = \exp\left\{-\left(\frac{\Delta\tau}{P}\right)^2\right\} \tag{18}$$

and $E_j = \int_{\infty}^{\infty} |U_j|^2\,dT = \sqrt{\pi}\,A_j^2/p_j$ which represents constant pulse energy of U_j. Momentum conservation law represented by $E_1 k_1(Z) + E_2 k_2(Z) = E_1 k_1(0) + E_2 k_2(0)$ is satisfied for any Z. Eq. (15) indicates the frequency separation of the two channels. Eq. (16) is related to pulse widths and time difference $\Delta T(Z) = T_1(Z) - T_2(Z)$ between inter-channel pulses, and at Z = 0, $\Delta T(0)$ gives the initial pulse spacing. By integrating Eq. (12), the pulse phase can be written as

$$\theta_j(Z) = \theta_j(0) + \theta_{Disp}(Z) + \theta_{SPM}(Z) + \theta_{XPM}(Z) \tag{19}$$

where
$$\theta_{Disp}(Z) = -\frac{1}{2}\int_0^Z b(\zeta)\{k_j^2(\zeta) - p_j^2(\zeta)\}d\zeta \tag{20}$$

$$\theta_{SPM}(Z) = \frac{5E_j}{4\sqrt{2\pi}}\int_0^z S(\zeta)p_j(\zeta)d\zeta \tag{21}$$

$$\theta_{XPM}(Z) = \frac{E_{3-j}}{\sqrt{\pi}}\int_0^z S(\zeta)\frac{p_1 p_2}{P^5}\{P^2(2P^2 + p_{3-j}^2(\Delta\tau)^2\} \times F(\zeta)d\zeta \tag{22}$$

Here $\theta_j(0)$ indicates the initial pulse phase θ_{Disp}, θ_{SPM} *and* θ_{XPM} terms imply the contributions from dispersion, SPM, and XPM, respectively. The phase shift observed at any channel is deduced as

$$\delta\theta = \theta_{2ch} - \theta_{1ch} = \delta\theta_{Disp} + \delta\theta_{SPM} + \delta\theta_{XPM} \tag{23}$$

where θ_{2ch} is the phase observed at one channel when both channels carry signals and θ_{1ch} is the phase of the pulse for a single-channel system.

2.3.1 Concept of Walk-off length

There are two length scales known as the walk off length and the dispersion length. XPM couples two pulses; in its absence the two overlapping pulses would have co-propagated without affecting each other (Agrawal, *et al*, 1989). However the XPM-induced mutual coupling may affect both the shape and spectrum of the pulse. The important point is that such a coupling can occur irrespective of the wavelength of the two pulses. GVD can influence XPM in two ways. First, it is responsible for a mismatch between the group velocities associated with the two pulses. As a result, the two pulses walk off from each other as they propagate along the fiber (Schadt, *et al*, 1987), (Kim, *et al*, 2005), (Yaman, *et al*, 2005). The XPM interaction ceases to occur when the pulses are physically separated from each other. For a pulse width of T_o, walk-off length can be defined as,

$$L_W = \frac{T_o}{|v_{g_1}^{-1} - v_{g_2}^{-1}|} \tag{24}$$

XPM occurs only over distances $\sim L_W$ irrespective of the actual fiber length. L_W depends on the relative wavelengths and decreases as the wavelength difference Δλ increases. Typically $L_W \sim$1m in the visible region for T_o=10 ps and Δλ=10-20 nm. Since different spectral components of a pulse travel at different speeds, the pulse shape and the spectrum acquire new features when SPM and XPM occur together with GVD. The relative importance of such GVD is governed by the dispersion length defined by:

$$L_D = T_o^2/|\beta_1| \tag{25}$$

For a 10ps pulse, L_D>1km. If the fiber length is L<<L_D, GVD effects are negligible. In the case of XPM, L_W governs the distance over which two pulses interact with each other. The GVD effects are most dominant when L_W and L_D are comparable. This can occur for T_o< 1ps.

2.4 Four Wave Mixing (FWM)

Four-wave mixing (FWM) is a parametric process in which different frequencies interact and by frequency mixing generate new spectral components. It is a phenomenon that occurs in the case of WDM systems in which the wavelength channel spacing are very close to each other. This effect is generated by the third order distortion that creates third order harmonics. These cross products interfere with the original wavelength and cause the mixing. In fact, these spurious signals fall right on the original wavelength which results in difficulty in filtering them out. In case of 3 channel system, there will be 9 cross products, where 3 of them will be on the original wavelength. This is caused by the channel spacing and fiber dispersion. If the channel spacing is too close, then FWM occurs.

If the dispersion is lesser, then FWM is higher since dispersion is inversely proportional to mixing efficiency.

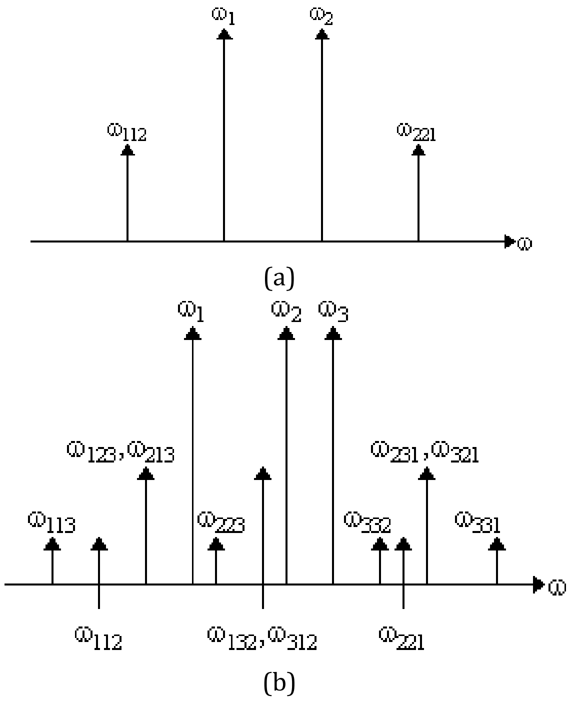

Fig 4 (a) two input signals ω1 and ω2 (b) three input signalsω_1, ω_2 and ω_3 and the arising new frequency components due to FWM

It can be seen that three of the interfering products fall right on top of the original three signals and the remaining six products fall outside of the original three signals. These six wavelengths can be optically filtered out. The three interfering products that fall on top of the original signals are mixed together and cannot be removed by any means. Fig. 4 shows results graphically. The three tall solid bars are the three original signals.

The shorter bars represent the nine interfering products. The number of the interfering products increases as $(N^3 - N^2)/2$ where N is the number of signals.

The magnitude of FWM efficiency depends on channel power, channel spacing and fiber dispersion but is independent of the bit rate. FWM efficiency is also a function of signal polarization. It can be seen that low dispersion fiber have a higher FWM efficiency than high dispersion fibers and efficiency decreases with increase in channel spacing.

Fiber suppliers now manufacture nonzero dispersion-shifted fiber (NZDSF), which is dispersion shifted but has a finite dispersion in the EDFA transmission window, to minimize FWM. Its main features can be understood by considering the third-order polarization term

$$P_{NL} = \varepsilon_0 \, \chi^{(3)} \vdots EEE \tag{26}$$

where E is the electric field
P_{NL} is the induced nonlinear polarization
ε_0 is the vacuum permittivity

Consider four optical waves oscillating at frequencies ω_1, ω_2, ω_3, and ω_4 and linearly polarized along the same axis x. The total electric field can be written as

$$E = \frac{1}{2}\hat{x}\sum_{1}^{4} E_j \exp\left[i(k_j z - \omega_j t)\right] \tag{27}$$

where the propagation constant $k_j = n_j\omega_j$=c, n_j is the refractive index, and all four waves are assumed to be propagating in the same direction. If we substitute Eq. (27) in Eq. (26) and express P_{NL} in the same form as E using

$$P_{NL} = \frac{1}{2}\hat{x}\sum_{1}^{4} P_j \exp\left[i(k_j z - \omega_j t)\right] \tag{28}$$

we find that Pj (j =1 to 4) consists of a large number of terms involving the products of three electric fields. For example, P4 can be expressed as

$$P_4 = \frac{3\varepsilon_0}{4}\chi^{(3)}_{xxxx}\begin{bmatrix} |E_4|^2 E_4 + 2\left(|E_1|^2 + |E_2|^2 + |E_3|^2\right)E_4 \\ + 2E_1E_2E_3\exp(i\theta_+) \\ + 2E_1E_2E_3^*\exp(i\theta_-) + \dots \end{bmatrix} \tag{29}$$

where θ_+ and θ_- are defined as

$$\begin{aligned} \theta_+ &= (k_1 + k_2 + k_3 - k_4)z - (\omega_1 + \omega_2 + \omega_3 - \omega_4)t \\ \theta_- &= (k_1 + k_2 - k_3 - k_4)z - (\omega_1 + \omega_2 - \omega_3 - \omega_4)t \end{aligned} \tag{30}$$

The first four terms containing E_4 in Eq. (29) are responsible for the SPM and XPM effects. The remaining terms result from FWM. There are two types of FWM terms in Eq. (29). The term containing θ_+ corresponds to the case in which three photons transfer their energy to a single photon at the frequency $\omega_4 = \omega_1 + \omega_2 + \omega_3$. This term is responsible for the phenomena such as third-harmonic generation ($\omega_1 = \omega_2 = \omega_3$), or frequency conversion when $\omega_1 = \omega_2$ 6= ω_3. In general, it is difficult to satisfy the phase-matching condition for such processes to occur in optical fibers with high efficiencies. The term containing θ_- in Eq. (29) corresponds to the case in which two photons at frequencies ω_1 and ω_2 are annihilated with simultaneous creation of two photons at frequencies ω_3 and ω_4 such that

$$\omega_3 + \omega_4 = \omega_1 + \omega_2 \quad (31)$$

3. Simulation

RSoft Optsim was used to simulate a 10Gbps optical system consisting of a two-channel pump-probe configuration with probe power of 0.001mW and pump power of 0.1mW.

The channel spacing (in nm) between the pump-probe and the value of dispersion (in ps/nm/km) of the fiber were the two parameters that were varied. The system performance was observed using the eye diagrams at the receiver.

3.1 Channel Spacing

With the below-mentioned specifications, the following results were obtained when the channel spacing was varied from 0.8nm to 1.73 nm. Cases of dispersion coefficients as 0 and 16 were considered. For figures 5.1-5.6, the dispersion is 0ps/nm/km and for figures 6.1-6.6, it is 16ps/nm/km. Tables I and II are for first case and tables III and IV are for second case.

Table 1 Specifications

Probe wavelength	1552.72541nm
Probe power	0.001mW
Pump power	0.1mW
Dispersion	0ps/nm/km
Data Rate	10Gbps per channel

Table 2 System performance with variation in channcel spacing for dispersion = 0ps/Nm/Km

Spacing (nm)	Eye opening (au)	BER	Q value (dB)
0.8	10.05 e-5	1.47302 e-10	15.970755
1	10.313 e-5	9.25824 e-11	16.047841
1.73	15.0038 e-5	e-40	28.24486

It can be observed that as the channel spacing increases, eye opening as well as the Q value increases. Increasing the distance between two adjacent channels reduces their crosstalk and thus the BER also reduces. Therefore, the overall optical performance is found to be improved by increasing the channel spacing.

A similar simulation with dispersion of 16ps/nm/km was performed and the following results were obtained.

Table 3 Specifications

Probe wavelength	1552.72541nm
Probe power	0.001mW
Pump power	0.1mW
Dispersion	16ps/nm/km
Data Rate	10Gbps per channel

Table 4 System performance with variation in channcel spacing for dispersion = 16ps/nm/km

Spacing (nm)	Eye opening (au)	BER	Q value (dB)
0.8	0.0115477	0.0227501	6.02
1	0.0115477	0.0227501	6.02
1.73	0.595644	1 e-40	27.401013

It can be noted that a similar observation is obtained in this case too, i.e, increasing the channel spacing enhances the overall system performance.

3.2 Dispersion

The following results with the mentioned specifications were obtained when the dispersion was varied from 9.6 to 12.8ps/nm/km and eye diagrams were recorded as shown in figures 7.1-7.3. Tables V and VI provide specifications and tabulated results respectively. The channel spacing was kept 4.9nm. Figures 7.4-7.6 graphically describe the obtained results.

Table 5 Specifications

Probe wavelength	1549.5001 nm
Pump wavelength	1554.45638 nm
Probe power	0.001mW
Pump power	0.1mW
Data Rate	10Gbps per channel

Table 6 System performance with variation in GVD

GVD (ps/nm/km)	Eye opening (au)	BER	Q value (dB)
9.6	5.39826e-5	0.0456228	10.404866
11.2	1.78342e-6	0.0173199	2.19595
12.8	7.5754 e-6	0.0227501	6.0206

For the variation in dispersion, although the eye opening and the Q value take a dip for the value of 11.2ps/nm/km, the bit error rate also reduces for the same. Thus in such a case, optimization can be performed as per the desired parameter and its effect in the application. For a greater eye opening and Q value, a value of 9.6ps/nm/km gives the best performance but for reduced bit error rate a value of 11.2ps/nm/km can serve the purpose.

Conclusions

Analysis of the WDM system in the presence of Kerr nonlinearities recognizes the undesired effects on its performance. Simulation of a 10Gbps optical system was performed to observe its nature under different values of parameters such as channel spacing and dispersion. In general, the higher the channel spacing, the better is the system performance. Optimizing the system performance for varying values of dispersion illustrated that the optimized value of dispersion is different for different parameters namely eye opening, BER and Q value and thus, the desired application of the system decides the dispersion value to be chosen.

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Appendix I Results obtained for dispersion = 0ps/Nm/Km

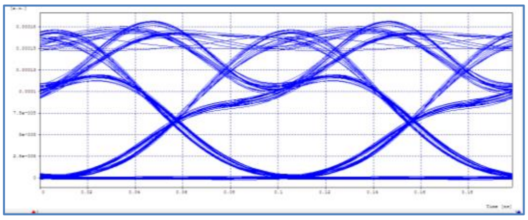

Fig 5.1 Eye diagram for channel spacing of 0.8nm

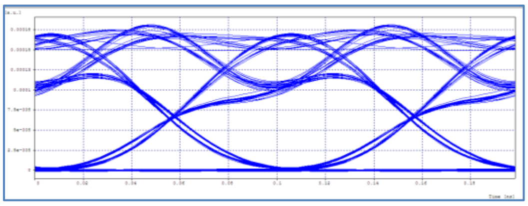

Fig 5.2 Eye diagram for channel spacing of 1.0nm

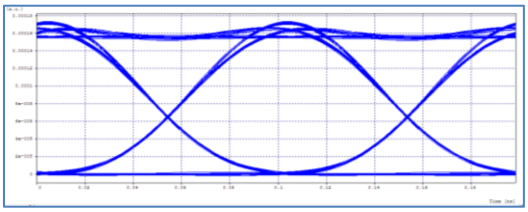

Fig 5.3 Eye diagram for channel spacing of 1.73nm

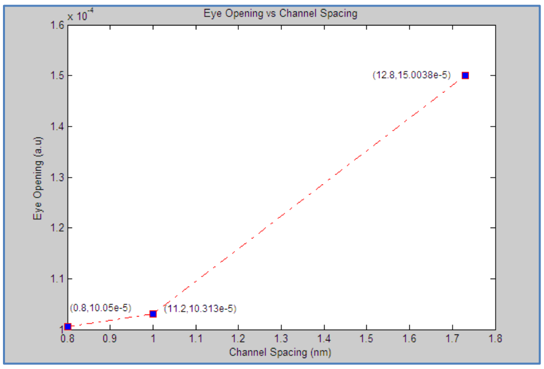

Fig 5.4 Eye opening vs channel spacing

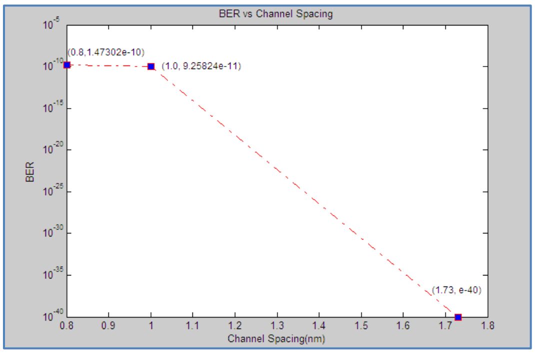

Fig 5.5 BER vs channel spacing

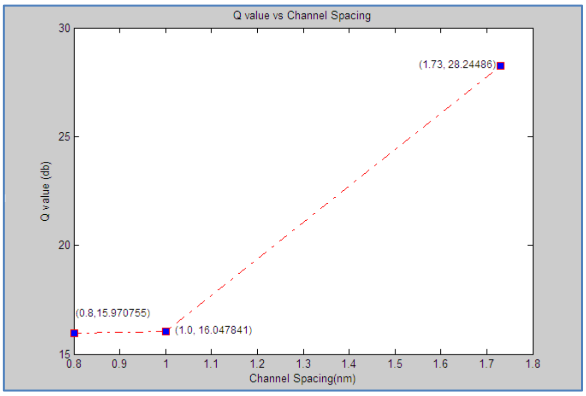

Fig 5.6 Q value vs channel spacing

Appendix II Results obtained for dispersion = 16ps/nm/km

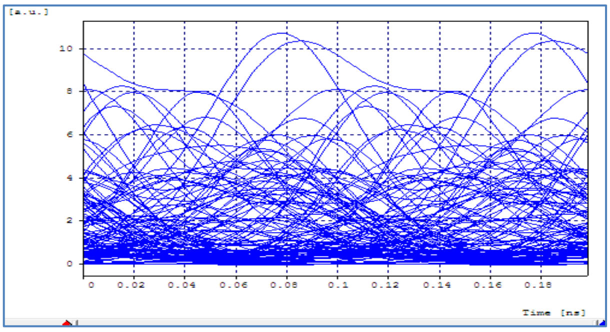

Fig 6.1 Eye diagram for channel spacing of 0.8nm

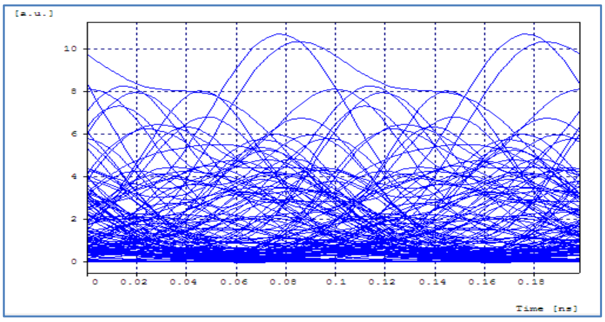

Fig 6.2 Eye diagram for channel spacing of 1.0nm

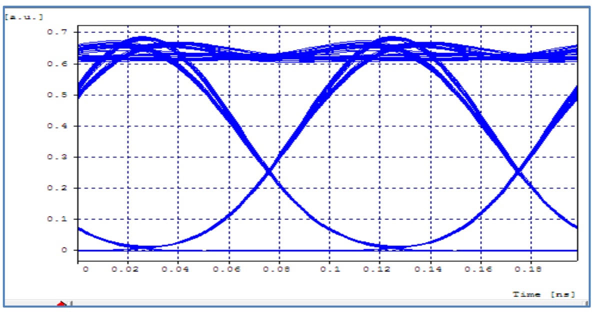

Fig 6.3 Eye diagram for channel spacing of 1.73nm

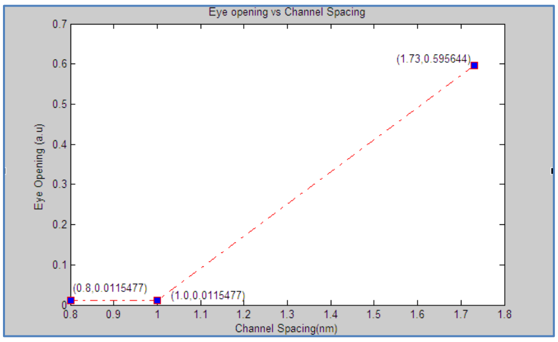

Fig 6.4 Eye opening vs channel spacing

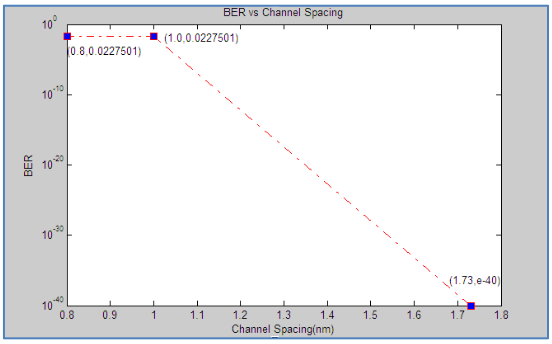

Fig 6.5 BER vs channel spacing

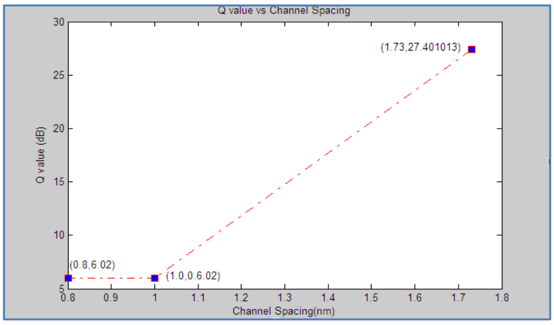

Fig 6.6 Q value vs channel spacing

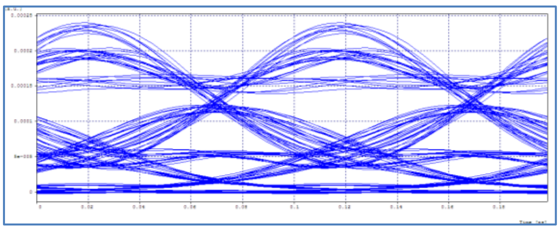

Fig 7.1 Eye diagram for dispersion of 9.6ps/nm/km

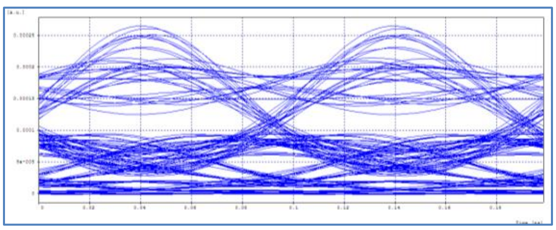

Fig 7.2 Eye diagram for dispersion of 11.2ps/nm/km

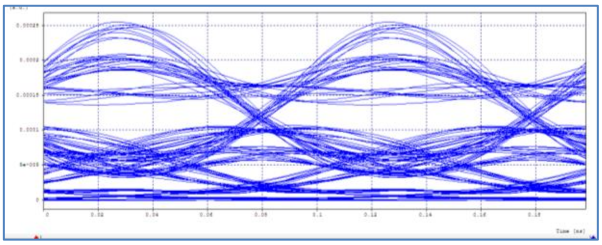

Fig 7.3 Eye diagram for dispersion of 12.8ps/nm/km

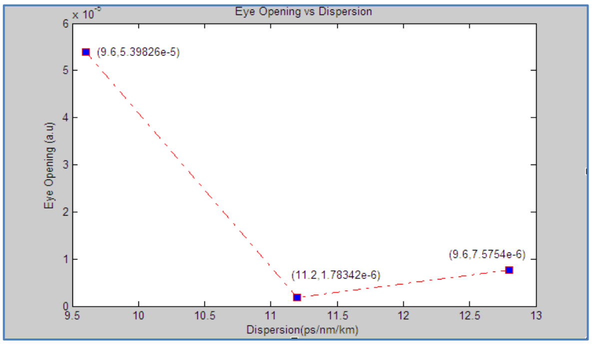

Fig 7.4 Eye opening vs dispersion

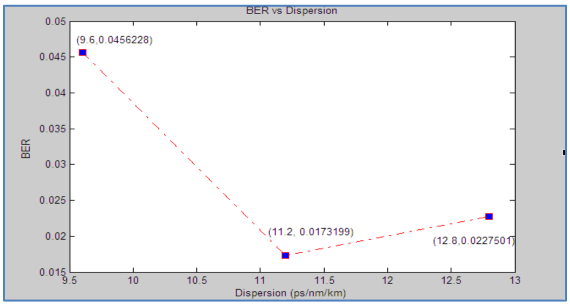

Fig 7.5 BER vs dispersion

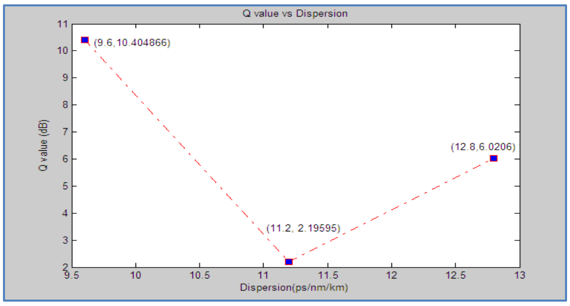

Fig 7.6 Q value vs dispersion