Optimization Techniques for 160 GBPS WDM Optical Links to Minimize Nonlinear Effects

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Abstract

Increased channel capacity of optical transmission system is obtained by either increasing the bit rate of transmission or by using the technique of Wavelength Division Multiplexing (WDM). In long distance communication, higher launched power is required to achieve the required signal-to-noise ratio (SNR) but with increased launched optical powers, rates and the number of wavelength channels, nonlinear optical effects have been increased. DWDM (Dense Wavelength Division Multiplexing) Systems facilitate the maximum channelization of the huge bandwidth offered by Optical Systems. The paper recognizes Cross Phase Modulation (XPM) and Four Wave Mixing (FWM) as major performance limitations for DWDM Systems. We have optimized the 160 GBPS, 16 channel optical link and have observed the optimization by variation of parameters like Dispersion, Channel Spacing and Pulse Width alongside NZDSF (Non-Zero Dispersion Shifted Fiber) and DCF (Dispersion Compensated Fiber) have been employed to further optimize the system performance. System parameters have been proposed for optimum performance yielding a Q –factor value of 34.89 dB and BER (Bit Error Rate) value of the order of $10^{-26}$.

Keywords

Cross phase modulation; Four wave mixing; Optimization; Channel spacing; Nonlinear effects; Q factor

Introduction

During the early days of communication system, low frequency domain was used mainly due to its applications in telephony and related areas. In order to incorporate large number of telephone networks and improve the capacity of system, the focus was shifted to high frequency domain. This led to the development and deployment of microwave communication system. It found applications in radio frequency (RF) and microwave devices and also mobile phones. With the advent of digital communication where voice and data are transmitted digitally, a measure of system capacity played pivotal role. The need for higher bit rate demanded more bandwidth. To increase the channel bandwidth, it was necessary to increase the carrier frequency and this directed the communication technology to enter into the optical domain.

The capacity of optical communication system is up to 50 TBPS due to large frequencies associated with the optical carrier. The earlier optical system which provided loss of 1000 dB/km evolved to system giving loss of 0.2 dB/km\cite{1}. With the advances in optical amplifiers, a significant improvement in the bit rate-repeater spacing product became practically possible. The huge amount of bandwidth offered by optical fibers can be completely utilized by employing Wavelength Division Multiplexing (WDM). It is a scheme in which multiple optical carriers at different wavelengths are modulated and sent over same fiber. Instead of using single channel system which is limited in terms of bit rate, usage of multiple channels multiplexed together was found to improve system performance. In long distance communication, high launched power is required to achieve the required signal to noise ratio. But with the increased launched optical powers, bit rates and the number of wavelength channels, the nonlinear optical effects have been increased. Also, at high bit rate, attenuation and group velocity dispersion (GVD) limits the transmission distance. The use of WDM and optical amplification as a method of increasing the information capacity and/or reach in optical fiber systems has led to significant propagation impairments as a result of fiber nonlinearity. Important nonlinear effects causing interchannel crosstalk in WDM systems are four-wave mixing (FWM) and cross phase modulation (XPM).

XPM is an important nonlinear impairment that causes interference through intensity-dependent phase shifts between two optical fields in optical networks using WDM. This effect limits the allowable input optical power and system capacity.

The XPM effect with Self Phase Modulation (SPM) and GVD degrade the system performances significantly. In FWM, optical signals at different wavelengths are mixed together to generate new optical signals at new wavelengths; hence, the signal power of the main wavelengths is depleted and transferred to newly generated wavelengths\cite{2-4}.

To have increased data rate and high signal-to-noise ratio, the system should be optimized for the distortion and nonlinear effects such as XPM and FWM. This paper particularly deals with effects on optical system for bit rate as high as 160 GBPS and various optimization techniques.

Cross Phase Modulation (XPM)

XPM is an important nonlinear impairment limiting the length of fiber and system capacity. During the transmission of optical pulse, the leading edge of the pulse increases refractive index and the trailing edge reduces it, due to the dependence of refractive index on power. This causes leading edge of the pulse to shift toward the longer wavelengths and trailing edge towards the shorter wavelengths\cite{5}. This is known as Self Phase Modulation (SPM). The same phenomenon extended in case of multiple channels is known as Cross Phase Modulation (XPM). The XPM is always accompanied by SPM and can also occur between two optical fields of different wavelengths.

The electric field can be written as follows to separate the rapidly varying parts of it:

$$E(r,t) = \frac{1}{2} \chi \left[ E_1 \exp(-i\omega_1 t) + E_2 \exp(-i\omega_2 t) \right]$$

(1)
Where \( \mathbf{e}_j \) is the polarization unit vector, \( \omega_1 \) and \( \omega_2 \) are the carrier frequencies of the two pulses, and the corresponding amplitudes \( E_1 \) and \( E_2 \) are assumed to be slowly varying functions of time compared with an optical period. This assumption is equivalent to assuming that the spectral width of each pulse satisfies the condition \( \Delta \omega << \omega \) (j=1,2), and holds quite well for pulse widths >0.1ps. Evolution of the slowly varying amplitudes \( E_1 \) and \( E_2 \) is governed by following wave equation:

\[
\nabla^2 E - \frac{1}{c^2} \frac{\partial^2 E}{\partial t^2} = \mu_0 \frac{\partial^2 P_{NL}}{\partial t^2} + \mu_0 \frac{\partial^2 P_{NL}}{\partial t^2}
\]

To see the origin of XPM, we substitute equation (1) in following equation of nonlinear part of the induced polarization:

\[
P_{NL}(r,t) = \mathcal{E}_0 \mathcal{X}^{(3)} \Phi(r,t) E(r,t) E(r,t)
\]

Thus we get following nonlinear polarization:

\[
P_{NL}(r,t) = \frac{1}{2} \sum \left[ P_{NL}(\omega_1) \exp(-i\omega_1 t) + P_{NL}(\omega_2) \exp(-i\omega_2 t) + P_{NL}(2\omega_1 - \omega_2) \exp[-i(2\omega_1 - \omega_2) t] + P_{NL}(2\omega_2 - \omega_1) \exp[-i(2\omega_2 - \omega_1) t] \right]
\]

Where the four terms depend on E1 and E2 as

\[
P_{NL}(\omega_1) = \mathcal{X}_{eff}(\omega_1) \left( E_1^2 + 2|E_2|^2 \right) E_1
\]

\[
P_{NL}(\omega_2) = \mathcal{X}_{eff}(\omega_2) \left( E_2^2 + 2|E_1|^2 \right) E_2
\]

\[
P_{NL}(2\omega_1 - \omega_2) = \mathcal{X}_{eff}(E_1^2 E_2^*)
\]

\[
P_{NL}(2\omega_2 - \omega_1) = \mathcal{X}_{eff}(E_2^2 E_1^*)
\]

With \( \mathcal{X}_{eff} = (3\mathcal{X}_0/4)\mathcal{X}_{max}^{(3)} \) acting as an effective nonlinear parameter.

The induced nonlinear polarization in Eq. (2) has terms oscillating at the new frequencies \( 2\omega - \omega_1 \) and \( 2\omega - \omega_2 \). The remaining two terms provide a nonlinear contribution to the refractive index. This can be seen writing \( P_{NL}(\omega) \) in the form (j=1,2)

\[
P_{NL}(\omega_j) = \mathcal{E}_0 \mathcal{E}_{NL} E_j
\]

And combining it with the linear part so that the total induced polarization is given by

\[
P(\omega_j) = \mathcal{E}_0 \mathcal{E}_j E_j
\]

Where \( \mathcal{E}_j = \mathcal{E}_j^L + \mathcal{E}_j^{NL} \), \( \mathcal{E}_j^{NL} = (n_j + \Delta n_j)^2 \)

\( n_j \) is the linear part of the refractive index and \( \Delta n \) is the change induced by the third-order nonlinear effects. Using the approximation \( \Delta n << n_j \), the nonlinear part of the refractive index is given by ( j=1,2)

\[
\Delta n_j = n_j^{NL} \approx 2n_j \approx n_j \left( E_j^2 + 2|E_j|^2 \right)
\]

Where \( n_j^{NL} \approx n_j \) has been assumed.

Equation (8) shows that the refractive index seen by an optical field inside an optical fiber depends not only on the intensity of that

field but also on the intensity of other co-propagating fields [6-9]. As the optical field propagates inside the fiber, it acquires an intensity-dependent nonlinear phase shift

\[
\phi_j^{NL}(z) = \frac{\omega_0}{c} \Delta n_j z = n_j \left( \frac{4\pi}{\lambda} \right) \left( E_j^2 + 2|E_j|^2 \right) z
\]

Where j=1 or 2. The first term is responsible for SPM. The second term results from phase modulation of one wave by the co-propagating wave and is responsible for XPM. The factor of 2 on the right-hand side of Eq. (9) shows that XPM is twice as effective as SPM for the same intensity [10].

**Mathematical Model XPM Induced Crosstalk**

Consider two optical waves having same polarization, propagating in a single mode fiber as before. Let \( A_j(z,t) \) be the slowly varying complex field envelope of each wave, normalized so that \( |A_j|^2 = P_j \). The coupled equations that describe XPM under the slowly varying envelope approximation are as follows [6]:

\[
\frac{\partial A_j}{\partial z} + \frac{1}{V_{P_j}} \frac{\partial A_j}{\partial t} = (2\gamma P_j - \alpha / 2) A_j
\]

\[
\Delta A_j + \frac{1}{V_{P_j}} \frac{\partial A_j}{\partial t} = (2\gamma P_j - \alpha / 2) A_j
\]

With the same initial condition as that of SRS at the fiber input, it is obtained.

\[
A_j(z,\tau) = A_j(0,\tau) \exp(-\alpha z / 2)
\]

\[
\times \exp[-i\gamma \int_0^z P_j(0,\tau + d_\tau) dz]
\]

Where, \( \gamma \) is nonlinear coefficient.

At this point, crosstalk is entirely in the phase 2 \( \phi \), which equal to

\[
\phi_\tau = -2\gamma \int_0^z P_j(0,\tau + d_\tau) e^{-\alpha z} dz
\]

However through Group Velocity Dispersion (GVD), the phase modulation is converted to intensity modulation via the relation,

\[
\frac{dP_j(z,\tau)}{dz} = \beta_\tau P_j(0,\tau) e^{-\alpha z} \frac{d^2 \phi_\tau(z,\tau)}{d\tau^2}
\]

Where, \( \beta = d^2 \beta_\tau / d\omega^2 \) and \( \beta_\tau \) is the phase constant of \( \Lambda_\tau \). This is the incremental change in power over a small segment \( \Delta z \). Over the length L, of the fibre, this incremental modulation will be attenuated by \( e^{-\alpha L / 2} \) due to fibre loss. The modulation at the end of the fibre is found by integrating

\[
\int_0^L \frac{dP_j(z,\tau)}{dz} e^{-\alpha(z-L)} dz
\]

To find XPM crosstalk, it is normalized by the magnitude of the modulation on \( \Lambda_\tau \approx m_{\tau} \exp(-\alpha L) \) and expressed crosstalk in phasor notation as

\[
X_{cros} = -2\Omega L P_j \beta_\tau \left[ \sin(\Omega L L - (1 + \alpha L)) \right]
\]

A similar expression can be obtained for crosstalk at \( \Lambda_\tau \)

\[
X_{cros} = -2\Omega L P_j \beta_\tau \left[ \sin(\Omega L L - (1 + \alpha L)) \right]
\]
Four Wave Mixing (FWM)

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

\[ P_{NL} = e_0 \chi^{(3)} : E E E \]  

(17)

Where \( E \) is the electric field, \( P_{NL} \) is the induced nonlinear polarization, and \( e_0 \) is the vacuum permittivity. Consider four optical waves oscillating at frequencies \( \omega_1, \omega_2, \omega_3, \) and \( \omega_4 \) and linearly polarized along the same axis \( x \). The total electric field can be written as

\[ E = \frac{1}{2} \sum_i^n E_i \exp[i(k_i z - \omega_i t)] \]  

(18)

Where the propagation constant \( k_i = n_i \omega_i / c \), \( n_i \) is the refractive index, and all four waves are assumed to be propagating in the same direction. If we substitute Eq. (18) in Eq. (17) and express \( P_{NL} \) in the same form as \( E \) using

\[ P_{NL} = \frac{1}{2} \sum_i^n P_{NL_i} \exp[i(k_i z - \omega_i t)] \]  

(19)

We find that \( P_{NL} \) (j=1 to 4) consists of a large number of terms involving the products of three electric fields. For example, \( P_4 \) can be expressed as

\[ P_4 = \frac{3e_0}{4} \left[ E_1^4 + 2 \left( E_1^2 E_2^2 + E_1^2 E_3^2 + E_2^2 E_3^2 \right) E_4 \right] \]  

\[ + 2E_1 E_2 E_3 \exp(i\theta_+ ) \]  

\[ + 2E_1 E_2 E_3 \exp(i\theta_- ) + \ldots \]  

(20)

where \( \theta_+ \) and \( \theta_- \) are defined as

\[ \theta_+ = (k_1 + k_2 + k_3 - k_4)z - (\omega_1 + \omega_2 + \omega_3 - \omega_4)t \]  

\[ \theta_- = (k_1 + k_2 - k_3 - k_4)z - (\omega_1 + \omega_2 - \omega_3 - \omega_4)t \]  

(21)

The first four terms containing \( E_j \) in Eq. (20) are responsible for the SPM and XPM effects. The remaining terms result from FWM. There are two types of FWM terms in Eq. (20). The term containing \( \theta_+ \) corresponds to the case in which three photons transfer their energy to a single photon at the frequency \( \omega = \omega_1 + \omega_2 + \omega_3 \). This term is responsible for the phenomena such as third-harmonic generation (\( \omega = \omega_3 \)), or frequency conversion when \( \omega = \omega_2 \neq \omega_3 \). 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 \( \theta_- \) in Eq. (20) corresponds to the case in which two photons at frequencies \( \omega_1 \) and \( \omega_2 \) are annihilated with simultaneous creation of two photons at frequencies \( \omega_3 \) and \( \omega_4 \) such that

\[ \omega_3 + \omega_4 = \omega_1 + \omega_2 \]  

(22)

Need for Optimization

In long haul DWDM optical systems, the system performance is limited by Non-linear effects like XPM and FWM as explained above. As shown in the Figure 2a,b, the values of Q-factor increase and BER exponentially decay as a function of length of the optical link. In order to ensure optimum performance with values of Q-factor above 7dB and minimum BER below the order of 10^-9 it is important to optimize

Optimization Techniques for XPM and FWM

Nonlinear optical distortions limit the performance of wavelength-division multiplexed (WDM) transmission systems. As the effect of XPM and FWM depends on fiber dispersion, dispersion management is one of the optimization techniques. Different types of fibers can be employed for this purpose. In another method, the channel spacing...
can be optimized to balance with the distortion to get high bit rate. Variation in duty cycle for RZ type of modulation format is also one of the solutions for optimization. In this paper all the methods were used on the system having 16 channels, each with data rate of 10GBPS, giving total bit rate of 160GBPS.

**Dispersion compensation**

Various dispersion management schemes can be applied for the compensation with XPM. They mainly focus on usage of dispersion compensated fibers (DCF), non-zero dispersion shifted fibers (NZ-DSF) and various parameters related to it such as its length and placement.

Standard optical fibers exhibit zero chromatic dispersion in the 1.3 μm wavelength region. This was convenient for early optical fiber communications systems, which often operated around 1310 nm. However, the 1.5 μm region later became more important, due to the lower fiber losses. In this wavelength region, however, standard single-mode fibers (SMF) exhibit significant anomalous dispersion. For linear transmission, this can be a problem, because it leads to significant dispersive pulse broadening, limiting the achievable transmission rates or distances. Therefore, dispersion compensating fibers (DCF) have been developed, which possess large negative dispersion so as to optimize the fiber performance in the 1.5 μm region [11]. This is achieved by modifying the refractive index profile of the core and cladding.

The WDM system consisted of single mode fiber (SMF) of length 60km with dispersion of 16.75ps/nm/km. From the eye diagram in Figure 3a and parameter values, effect of XPM and FWM can be clearly seen. To compensate the distortion by XPM, a DCF of length 10 km was added after an SMF of length of 50 km over 4 spans to provide total transmission distance of 240 km. The Q factor for this is increased compared to previous system (Figure 3b). Effect of FWM was compensated by XPM when only SMF of length 60 km was maintained at dispersion of 4 ps/nm/km (Figure 3c). Table 2 gives values of various parameters for SMF and DCF.

**Channel spacing**

We examined the effect of channel spacing on phase fluctuations stimulated by XPM. The Q factor and eye opening was observed for different channel spacings after transmission of 160 GBPS over the length of 240 km. The system performance was checked for four different channels spacings-30 GHz, 50 GHz, 150 GHz and 200 GHZ. The eye digrams for these are shown in Figure 4 and various parameters are tabulated in Table 3.

From Figure 5 a,b, it can be noted that as channel spacing is increased, Q factor and eye opening increases. More spacing between channels reduces effective amount of interchannel XPM and gives better results. Thus bit error rate (BER) also decreases Figure 5c.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starting frequency</td>
<td>193.1 THZ</td>
</tr>
<tr>
<td>Frequency spacing</td>
<td>200 GHz</td>
</tr>
<tr>
<td>Power</td>
<td>-1 dBm</td>
</tr>
<tr>
<td>Modulation format</td>
<td>RZ (40% duty cycle)</td>
</tr>
<tr>
<td>Number of channels</td>
<td>16</td>
</tr>
<tr>
<td>Data rate (per channel)</td>
<td>10 GBPS</td>
</tr>
</tbody>
</table>

**Table 1:** General Specification. It contains general simulation parameters unless specified.
Non-Zero Dispersion Shifted Fiber (NZ-DSF)

While designing a fiber to operate over an extended wavelength range it is important to minimize the effect of Raman scattering and avoid having a zero dispersion wavelength within the desired operating bandwidth to avoid effect of FWM [12]. This can be accomplished by having non-zero dispersion shifted to large positive values, known as non-zero dispersion shifted fiber (NZ-DSF). From the results in Figure 6, it can be seen that FWM gets compensated after shifting dispersion value by using NZ-DSF of length 240 km, effective core area of 70 and dispersion of 2 ps/nm/km.

Variation in duty cycle

In Return-to-Zero (RZ) modulation format the constant power is transmitted only for a fraction of the bit period. Duty cycle of a single pulse is the ratio of signal pulse width to bit duration. When a channel is intensity modulated with bit rate R=1/T and the symbols are transmitted using rectangular pulses with duration ρT. The parameters ρ, 0<ρ ≤ 1, is the duty cycle. The peak power of each pulse is Pp=P/ρ, where P is the average power transmitted over one bit.

Effect of chromatic dispersion is to introduce a delay among the spectral components of the signal. Because the lower the duty cycle ρ, the higher the bandwidth, it is expected that the effect of dispersion is larger for smaller ρ. From Figure 7, it can be seen that as duty cycle is increased, the Q factor increases but after attaining a peak at 70% duty cycle, it decreases. Thus it can be said that for a particular value of duty cycle, the Q factor is maximum and reduces on both the sides of it. The values of Q factor and BER are tabulated in Table 4.

Conclusion

The degrading effects of XPM and FWM on system performance were analyzed by simulating a model optical system for data rate of 160 GBPS and mathematical model for crosstalk due to XPM was presented. Various optimization techniques were employed to minimize these nonlinear effects such as usage of various fibers and variation in channel spacing. It was also seen that optical fibers- SMF,
DCF, NZ-DSF- react differently when exposed to same optical network status. Combination of them can be used as one of the dispersion compensation technique. The result can be generalized for various types of fiber. The effect of FWM as one of the influential factor in WDM has been studied by simulating a model for the same. From the results obtained it can be seen that FWM effect was significant at high data rate of 160GBPS in SMF. It was compensated by XPM by varying dispersion and by using NZ-DSF in another method. After comparing various values of Q factors generated by different methods, it can be seen that dispersion compensation of FWM by XPM gives highest Q factor of 54.58 dB and better eye opening. Though NZ-DSF proves effective in suppressing the FWM, large core area of 70 µm² provides steep dispersion slope which adds to nonlinearity.
References


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