SIMULATION STUDY OF FIBER NONLINEARITY EFFECTS ON WDM SYSTEMS DESIGN

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الملخص

عند تصميم أنظمة الاتصال الضوئية متعددة إرسال دمج الأطوال الموجية بالتقسيم (WDM) وذات السعات العالية والمدى الطويل من الضروري أن نكون على بينة من القيود القائمة. من بين هذه القيود ما تسبّبه الخصائص الغير خطية لألياف التوصيل البصرية. هذه الورقة تدرس هذه الخصائص الغير خطية والقيود التي تفرضها على معلمات منظومات اتصال دمج الأطوال الموجية بالتقسيم مثل المسافة أو عدد القنوات. تشتت ريمان المستحث (SRS) وتشتت بريليون المستحث (SBS) والتضمين الذاتي للطور (SPM) والتضمين غير الذاتي (XPM) وخلط الموجات الأربع (FWM) كلها خصائص غير خطية سنتعرض لدراستها ونفحص آثارها علي منظومة اتصال دمج الأطوال الموجية بالتقسيم ذات السعة العالية والمدى الطويل (4×10 جيجابايت / ثانية) والعاملة في الإطار البصري الثالث. درسنا كذلك أثر معلمات المنظومة مثل القدرة والحيز بين القنوات ومعدل تدفق المعلومات والتشتت وأقسام المدى وعددها ونوع التضمين على الخصائص الغير خطية. تمّ رسمنا بعدها نتائج المحاكاة واستخلصنا الاستنتاجات. هذه الدراسة مهمة عند تصميم منظومات الاتصال التي يراد فيها أن يكون أثر الغير خطيات في حده الأدنى وهذا ما سنبحثه في دراسة مستقبلية.

ABSTRACT

In opticalhigh-capacity long-haul wavelength-division multiplexed (WDM) transmission systems design, it is essential to be aware of the existing limitations. Among these limitations are those introduced by nonlinearities inherent in the optical fibers. This paper presents a study of these fiber nonlinearities and limitations they impose on WDM system parameters such as distance or number of channels. The Stimulated Raman Scattering (SRS), Stimulated Brillouin Scattering (SBS), Self-Phase Modulation (SPM), Cross Phase Modulation (XPM) and Four Wave Mixing (FWM) fiber nonlinearities are introduced. Their effects on high-capacity long-haul WDM transmission systems (4 x 10 GB/s) working in the third optical window are examined. The impact of system parameters like power, channel spacing, bit-rate, dispersion, span length, number of spans, number of channels, and modulation type on fiber nonlinearities are studied. Simulation results are plotted and conclusions are drawn. This study is important when designing WDM system with minimum nonlinearity effects. This is to be our future research study.

KEYWORDS: WDM; Fiber Nonlinearities; SRS; SPM; XPM; FWM.

FIBER NONLINEARITIES IN WDM SYSTEMS

The origin of nonlinear response in optical fibers can be discussed in light of the truncated Taylor expansion relation:

$$\vec{\boldsymbol{P}} \cong \epsilon_0\left[\chi^{(1)}.\vec{\boldsymbol{E}} + \chi^{(2)}:\overrightarrow{\boldsymbol{EE}} + \chi^{(3)} : \overrightarrow{\boldsymbol{EE}}\,\vec{\boldsymbol{E}}\right] \quad (1)$$

Where $\vec{P}$ is the induced polarization in the fiber material and $\vec{E}$ is the applied electric field intensity. $\chi^{(1)}$ is the linear susceptibility resulting the fiber refractive index n. $\chi^{(2)}$ is the second-order susceptibility tensor responsible for second order harmonics generation.

In Silica fibers $\chi^{(2)}$= 0. $\chi^{(3)}$ is the susceptibility third-order tensor whose real part gives rise to Kerr effect and its imaginary part is responsible for the Raman effect. Brillouin effect on the other hand is explained by solving coupled acoustic and optical wave equations rather than relating it directly to $\chi^{(3)}$[1].

Nonlinear effects in optical fibers arise from two phenomena. One is the inelastic scattering process and the other is the change in the refractive index with optical power, which results in the Kerr effect. The inelastic scattering processes are the stimulated Raman scattering (SRS) and the stimulated Brillouin scattering (SBS). The Kerr nonlinearity on the other hand exhibits three different effects, which are self-phase modulation (SPM), cross-phase modulation (XPM or CPM), and four-wave mixing (FWM).

Stimulated Raman Scattering

SRS is due to the interaction of photons with atomic nuclei through the transition of nucleus to a vibrational excited level. If a sufficiently powerful optical wave (the pump) is launched into the fiber, a new field (the Stokes wave) of lower frequency is generated through stimulated scattering at the expense of the pump power [2]. The Stokes wave propagates in the same direction of the pump wave. If another signal is present at the Stokes wavelength, the SRS will amplify it and the pump-wavelength signal will decrease in power. SRS is a broadband phenomenon since it can transfer energy from short wavelength waves to neighboring higher-wavelength channels that are up to 15 THz (125 nm) [3].

The SRS threshold is known to be around 1W for a single-channel system. In a single-channel system, the large threshold power makes SRS a negligible effect. However, the gain bandwidth of SRS is of the order of 12THz, which is about 6 orders of magnitude greater than that of SBS. The large gain bandwidth of SRS enables it to couple different channels in a WDM system, which can cause performance degradation through cross talk [4].

In amplified systems, the effects of SRS are more subtle. Among all these effects, stimulated Raman scattering (SRS) is one of the majorlimitations of system performance [5].

Stimulated Brillouin Scattering

The second form of inelastic scattering nonlinearity is SBS which arises when light waves interaction and scattering from acoustic waves. The scattered wave propagates backwards in single-mode fibers and experiences a gain from forward-propagating signals, resulting in a depletion of the signal power [6].The frequency of the scattered light experiences a Doppler shift. The scattered light is shifted to a lower frequency by an amount $\nu_B = 2nV_S/\lambda$ and$\nu_B \approx$ 11 GHz for silica glasses where$V_S$the velocity of longitudinal sound waves and λ isthe operating wavelength. This gives rise to crosstalk in WDM systems. In silica, this interaction occurs over a very narrow Brillouin linewidth of $\Delta\nu_B$=20 MHz at 1550 nm and $\Delta\nu_B$ varies as $1/\lambda^2$.

For a nearly monochromatic transmitter (linewidth ≤ 50 MHz), SBS is the most important nonlinear process; threshold power is only about 10 mW. Maximum SBS gain will occur for pump lasers with linewidths less than 20 MHz. For lasers with linewidths $\Delta\nu_L$ much larger than 20 MHz, SBS gain decreases as the ratio $\Delta\nu_B/\Delta\nu_L$. The peak SBS gain coefficient in single-mode fibers is over two orders of magnitude larger ($g_B \approx$ 4 × 10–9 cm/W) than the gain coefficient for SRS and it is approximately wavelength independent [3].

Brillouin gain spectrum is much narrower (bandwidth < 100 MHz) in comparison with the Raman-gain spectrum (20-30 THz). SBS effects can be reduced by careful design; placingoptical isolators at the transmitters; and using special modulation schemes. [7].

It should be mentioned that SRS becomes more important for shorter pulses (larger bandwidth) unlike SBS which nearly ceases to occur for pulses shorter than 10 ns [8].

Self-Phase Modulation

The presence of $\chi^{(3)}$ in equation (1) implies that the refractive index of the fiber material depends on the field intensity and in accordance depends the phase of the optical propagating signalφ:

$$\varphi = (n_0 z + \varphi_0) + \frac{2\pi}{\lambda} n_2\, I(t)\, z \tag{2}$$

Where$\varphi_0$is the initial phase (at $z = 0$).n_0 and $n_2$are the linear and nonlinear refractive indices respectively. I is the optical signal intensity and z is distance along fiber. This Kerr effect here gives rise to the self-phase modulation (SPM) in single-wavelength links. SPM converts optical fluctuations in a propagating light wave to phase fluctuations in the same wave [6].In phase-shift keying (PSK) systems; SPM may lead to a degradation of the system performance since the receiver relies on the phase information [9].The temporally varying index change results in a temporally varying phase change. Thus, the instantaneous optical frequency differs from its initial valueν_0 across the pulse and different parts of the pulse undergo different phase shifts. This leads to frequency chirping [6, 9]. SPM is more severe for higher-intensity pulses and when combined with fiber dispersion, it can be significant limitation in very long transmission links [6].For very short pulses, the additional frequency components generated by SPM combined with the effects of material dispersion will also lead to spreading or compression of the pulse in the time domain, affecting the maximum bit rate and the BER. Interacting with fiber dispersion, the SPM can cause temporal pulse broadening (in normal dispersion regime ($\beta_2 > 0$)), or pulse compression (in anomalous dispersion regime ($\beta_2 < 0$). The well-known interaction of SPM with anomalous dispersion is the formation of solutions [10]. β_2 is the second order derivation of the optical wave propagation constant β. The accumulated dispersion along the fiber leads to waveform distortion in those channels due to the interplay with SPM and the distortion becomes more significant with channel bit rate [11].

Cross-Phase Modulation

Similar to the SPM, cross-phase modulation is due to the nonlinear behavior of the refractive index on the optical intensity. However, in this case the total nonlinear phase shift on a given channel is due to the combined intensities of all transmitted channels, which can result in cross talk among WDM channels. When N channels are transmitted in a single optical fiber, the nonlinear phase shift on the jth channel is governed by [12].

$$\varphi_j(z,t) = \frac{2\pi n_0 z}{\lambda} + \frac{2\pi n_2 z_{eff}}{\lambda}\left[I_j(t) + 2\sum_{m\neq j}^{N} I_m(t)\right] \quad (3)$$

Where $I_m(t)$ is the optical intensity of the mth channel, z_{eff} is the effective transmission distance, n_0 is the linear refractive index of the material and n_2 is the nonlinear refractive index. The first term in the parentheses on the right hand side of (3) corresponds to SPM whereas the second term is responsible for XPM. The factor of 2 in (3) suggests that the effect of XPM from a neighboring channel is two times stronger than that caused by SPM itself.

In WDM, XPM affects only the phase of optical signals. Consequently angle-modulated systems will be affected most by this nonlinearity. XPM can be a significant problem in WDM links operating at 10 Gb/s and higher over DCF and like SPM when combined with fiber dispersion, it can also be a limiting factor in very long transmission links [6].The dispersion-induced chirp is positive for negative accumulated dispersion, while XPM induced chirp is always positive [13].

XPM can also lead to asymmetric spectral broadening, and combined with SPM and dispersion may also affect the pulse shape in the time domain [9]. When all channels are located on one side of the zero-dispersion wavelength, the dominant degradation factors is the interplay between XPM and dispersion [14].

Four-Wave Mixing

FWM is a third-order nonlinearity in silica fibers that is analogous to intermodulation distortion in electrical systems.FWM is a nonlinear effect arising from a third-order optical nonlinearity described by $\chi^{(3)}$.When channels are located near the zero-dispersion point, three optical frequencies (ν_i, ν_j, ν_k) will mix and produce a fourth intermodulation product ν_{ijk} given by:

$$\nu_{ijk} = \nu_i + \nu_j - \nu_k \text{ With } i, j \neq k \quad (4)$$

When this frequency falls in the transmission window of the original frequencies, it can cause severe crosstalk. The power of FWM light depends on the power on the input lights and FWM efficiency η.η is known to take the maximum value of 1 when the following phase matching condition is satisfied [15]:

$$\Delta\beta = \beta(f_i) + \beta(f_j) - \beta(f_k) - \beta(f_{ijk}) = 0 \quad (5)$$

The efficiency of the FWM generation is a function of the channel separation. The smaller separation causes the larger efficiency. The efficiency of the FWM generation is high when phase matching is satisfied, and it becomes low when the signals are out of phase. As the phase of the signal lights changes in random due to the fiber birefringence, the efficiency of the FWM generation also changes in random. This causes additional fluctuations in the system performance. The small walk-off ensures phase matching conditions for FWM even though the operating wavelengths are separated by more than several tens of nanometers [14].The limitation on transmitted optical power due to the FWM strongly depends upon channel frequency allocation and total number of channels [16].

It is interesting to note that this nonlinearity does not introduce any SNR degradation when the transmission fiber has normal GVD, but it does so with the zero-dispersion fiber or the anomalous GVD fiber, through which solutions can pass. This is explained by the fact that, because of the nonlinear-index change due to the light power inside the fiber, the phase matching condition necessary for the parametric process is fulfilled in the anomalous GVD region, but it is not fulfilled in the case of the normal GVD region [6].

SYSTEM SIMULATION AND RESULTS

In this section we run a simulation study of the effects of nonlinearities on a (4 × 10 Gb/s), 500-km WDM system shown in Figure (1). The VPI transmission Maker™WDM simulation software is used. Detailed information of software features, theory and applications can be found at the producing company website http://www.vpiphotonics.com/.This software calculates the evolution of the optical signals as they propagate through the fiber by solving the nonlinear Schrödinger equation employing split-step Fourier method (SSFM) [17].

Even though SBS nonlinearity has the lowest threshold power, its effects on WDM systems are not investigated in this study. This is because SBS has an extremely narrow band. The effects of SRS, SPM, XPM and FWM are accordingly of prime concern in WDM systems. These processes arise from the interaction between two or more WDM channels [13]. To show the power of simulation study of effects of WDM parameters on different nonlinearities, we will only consider samples from the high number of simulation results.

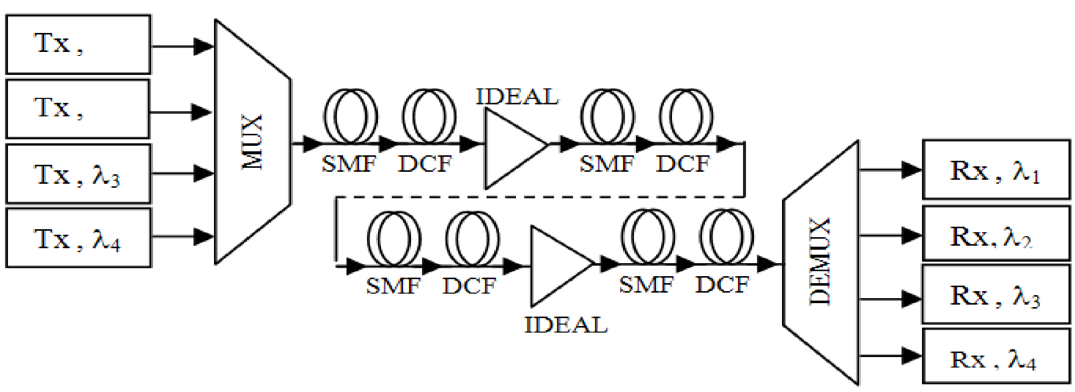


Figure 1: WDM system

The SRS case

Effect of channel power on SRS

For a channel spacing of 200 GHz (1.6 nm) and values of power/channel running from 0 to 12 dBm, Figure (2) indicates the bit error rate (BER) versus average channel power for this nonlinearity.

From Figure (2), we observe that for the average channel power of 12 dBm, the BER is in the order of 10−11 (Typical error rates for optical fiber telecommunication systems range from 10-9 to 10-12). It is reported in literature that SRS becomes severely effective when average channel power exceeds the threshold value of 12 dBm [5].

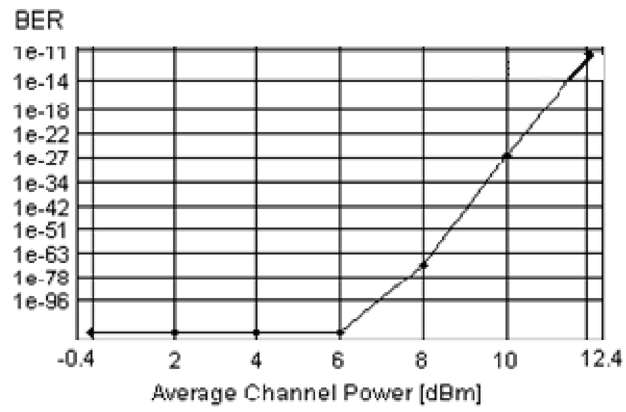


Figure 2: the effect of power on SRS

Effect of channel spacing on SRS

Since dispersion slope value is set to zero, channels do not suffer from residual dispersion. A relation of BER values versus channel spacing is given in Figure (3a).

For the channel spacing of 3200 GHz, Figure (3b) shows the Raman tilt in power spectrum. This is a typical SRS effect. Eye patterns of channel 4 for channel spacing of 100 and 400 GHz are given in Figure (3c) and d respectively. These results confirm that as channel spacing value exceeds 400 GHz, the effect of SRS becomes more pronounced [18].

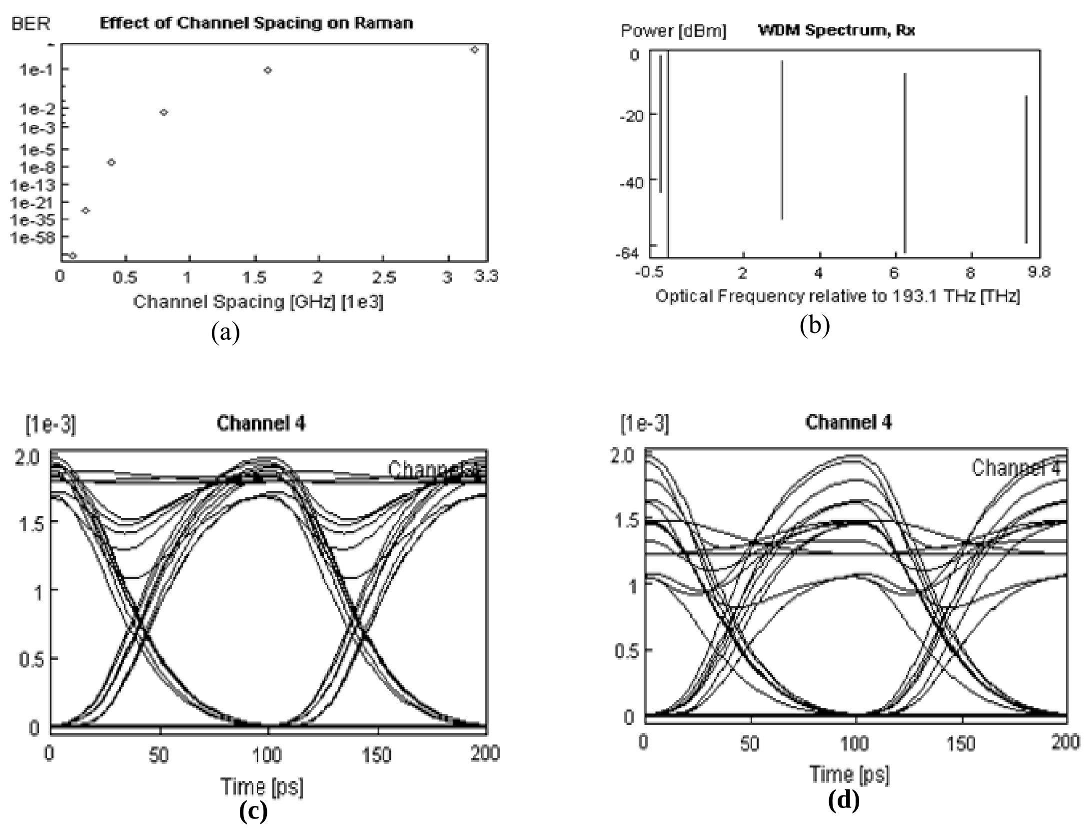


Figure 3: the effect of channel spacing on SRS

Effect of number of spans on SRS

Figure (4) gives the simulation result of how the BER of channel 4 changes with number of amplifier spans. We see that as the number of spans increases, the effect of SRS increases. This result was reported by Zou et al in 1996 [13].

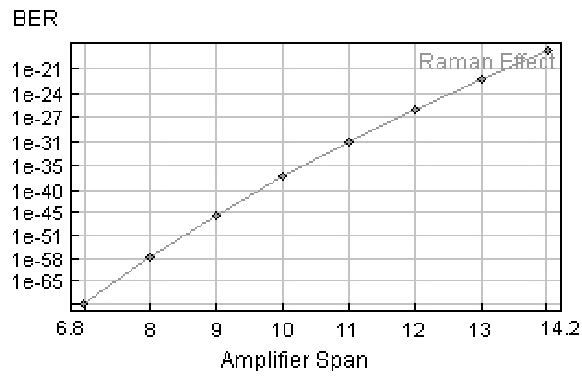
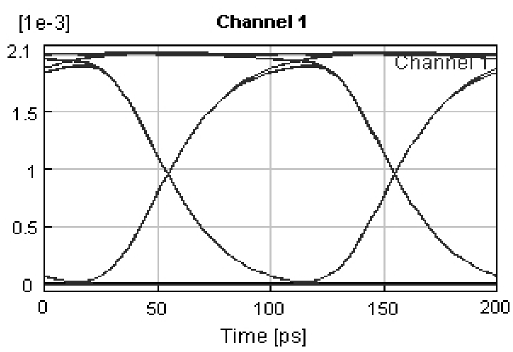


Figure 4: Effect of number of amplifier spans on SRS

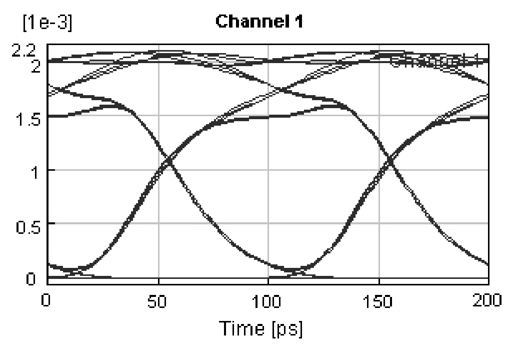
The SPM case

Effect of Channel Power on SPM

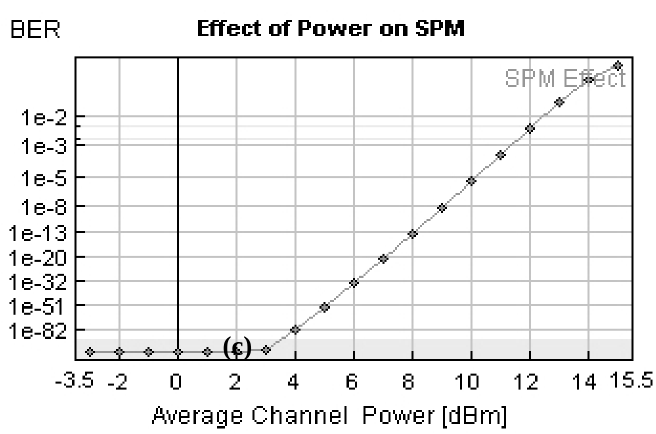
In channel 1 and for power levels of 0 and 8 dBm, Figure (3 a & b) show here the effect of SPM on different channel eye patterns respectively. Figure (5c) on the other hand presents the BER values versus average channel 1 average power.



(a)



(b)



(c)

Figure 5: Effect of Power on SPM

We see that the BER values fall below 10^{-9} for the value of power/channel greater than 8 dBm. This result is a confirmation of research conducted in 1990 [16].

Effect of dispersion on SPM

To study the effect of dispersion variations on SPM, we considered the following dispersion values for the SMF transmission fiber 0.5, 1.0, 2.0, 4.0, 8.0, 16.0 and 32.0 ps/(nm·km) with corresponding DCF fiber dispersion values: -2.5, -5.0, -10.0, -20.0, -40.0, -80.0, -160.0 ps/(nm·km) respectively. This is done for purpose of dispersion compensation. Figure (6a), (6b) and (6c) are channel 1 eye patterns for the 0.1, 8.0 and 16.0 ps/(nm·km) dispersion values respectively. Figure (6d) represents how BER values in different channels vary with dispersion when SPM effects are considered. As expected from earlier research work, increasing dispersion strongly intensify the effect of SPM especially at the value of 8 ps/nm/km or greater [19].

Effect of number of spans on SPM

This is studied by choosing number of amplifier spans ranging from 7 to 14 and observing the channels BER values due to SPM. For channel 1 this is given in Figure (7). It is seen that for span numbers of 8 and higher the effect of SPM becomes stronger. Such conclusion is reported by Keiser [6].

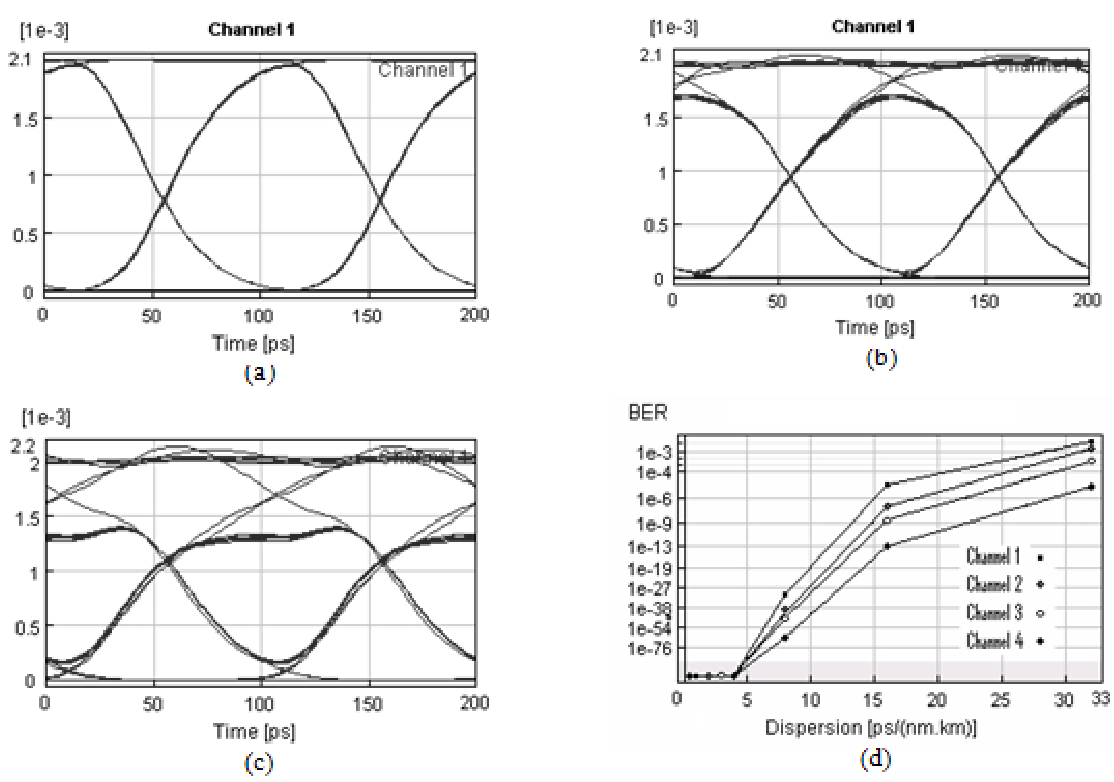


Figure 6: Effect of dispersion on SPM

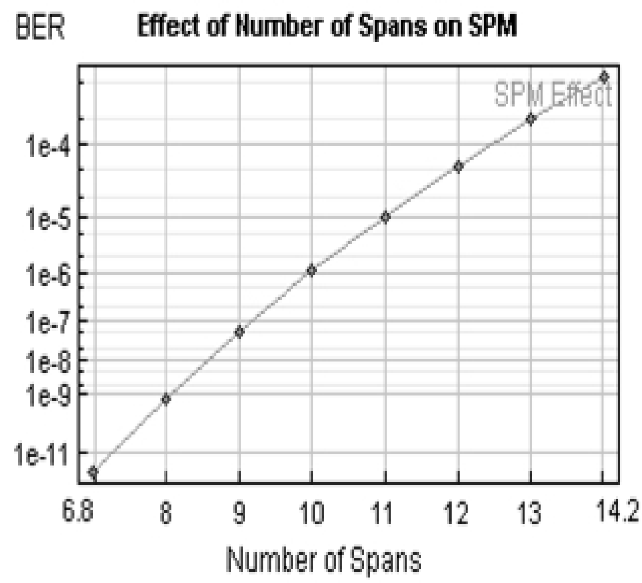


Figure 7: Effect of number of amplifier spans on SPM

The effect of modulation on SPM

The effect of modulation (coding) schemes RZ and NRZ on SPM are also investigated in this study. We observed BER versus modulation type for channel 1. Simulation results are shown in Figure (8). We see that RZ modulation is superior to NRZ modulation when SPM is only nonlinearity considered. This conclusion can be found in Ian none et al [20].

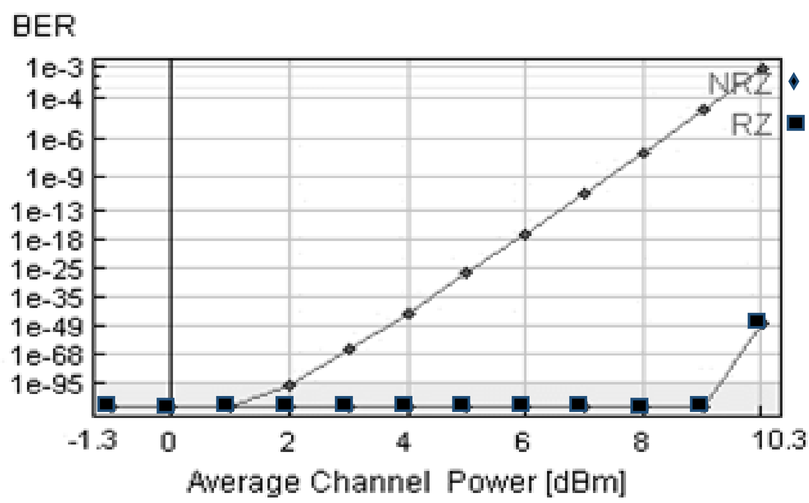


Figure 8: Effect of modulation type on SPM

The XPM case

The effect of power on XPM

Figure (9) confirms Chraplyvy conclusions in 1990 that: as channel power increases, XPM effects become severe, especially for power values of 7 dBm and higher [3].

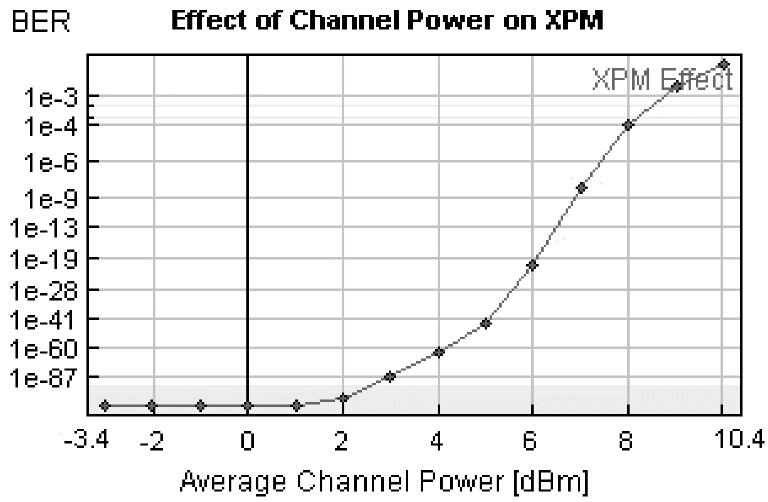


Figure 9: Effect of channel power on XPM

Effect of Dispersion on XPM

For different values of dispersion figure of the transmission fiber simulations are carried out. The dispersion value of SMF has the values of 0.5, 1.0, 2.0, 4.0, 8.0 ps/(nm·km). The dispersion figure of DCF was adjusted to (SMF dispersion) × (−50/3) so that the dispersion compensation is fulfilled. Figure (10) depicts the BER vs. dispersion of SMF for all channels. We see that as the dispersion increases, the XPM effect is suppressed [13].

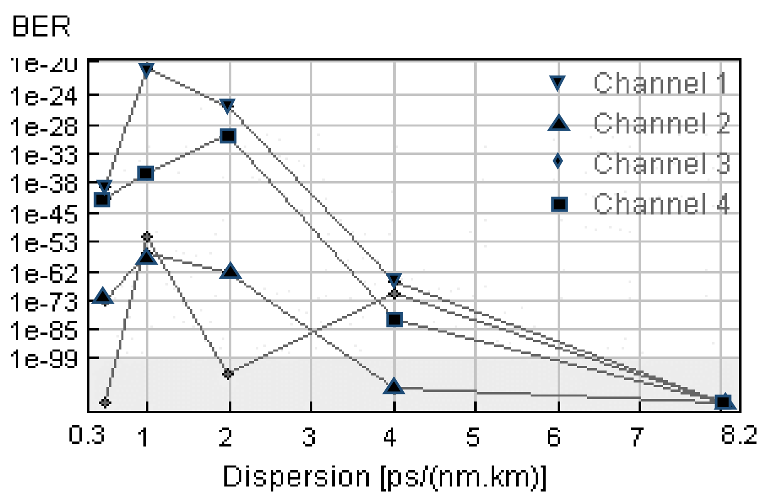


Figure 10: Effect of dispersion on XPM

The Effect of Span Length on XPM

The length of SMF is swept from 20 to 150 km and that of DCF is adjusted as (SMF length) × 0.06 to make dispersion compensation properly. The change in BER with respect to span length is indicated in Figure (11). This is confirmed in literature [21].

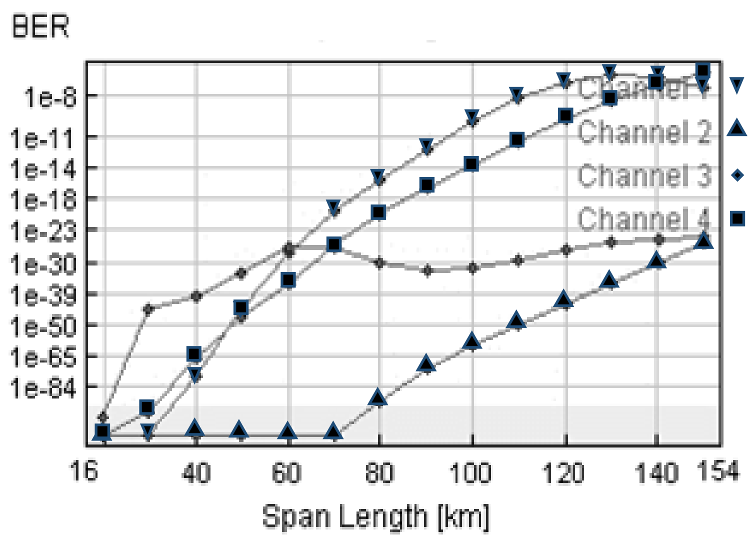


Figure 11: As the span length increases, XPM becomes more severe.

The Effect of Number of Channels on XPM

The number of channels was varied as 2, 4, 8 and 16 and simulations were performed for these values. We observed channel 1 for 4-channel case, channel 3 (but it is named as channel 1) for 8-channel case because of their similar dispersion mapping. We see from Figure (12), which is BER versus number of channels for channel 1 that as the number of channels increase, the effect of XPM becomes more severe. This is confirmed in [22].

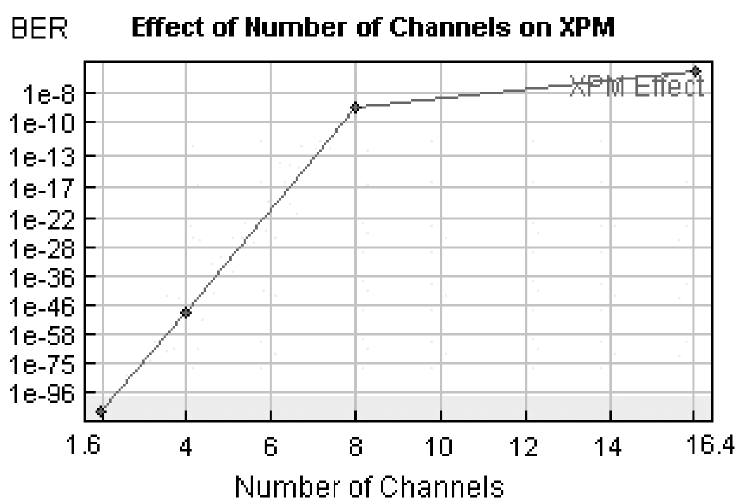
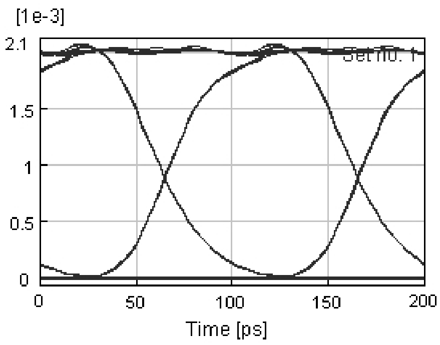


Figure 12: Effect of number of channels on XPM

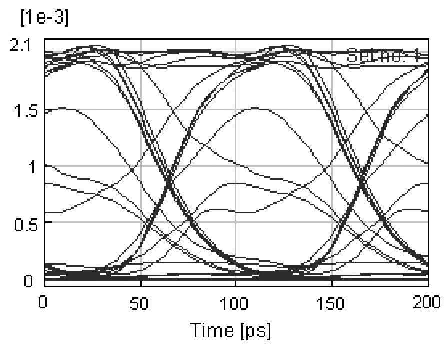
The FWM case

Effect of power on FWM

Here we observed the effect of changing the average channel power on FWM impact through observing the eye patterns of channel 1. Figure (13a) and (13b) show the simulation results for 0-dBm power per channel when FWM effect is not present and when it is present respectively. It is clear that as channel power increases the FWM effect becomes more pronounced as found by Chraplyvy [3].



(a)



(b)

Figure13: Effect of power on FWM

Effect of channel spacing on FWM

Figure (14) illustrates how channel 1 BER changes with varying channel spacing. It is clear that FWM is more effective for small spacing and it is practically zero for values of 200 GHz and larger. This result is a confirmation of results arrived at by Chraplyvy and Tkach [23]. They reported that for channel spacing of less than 100 GHz, FWM is very strong and for the value of 200 GHz FWM is almost suppressed. This is clear from Figure (14).

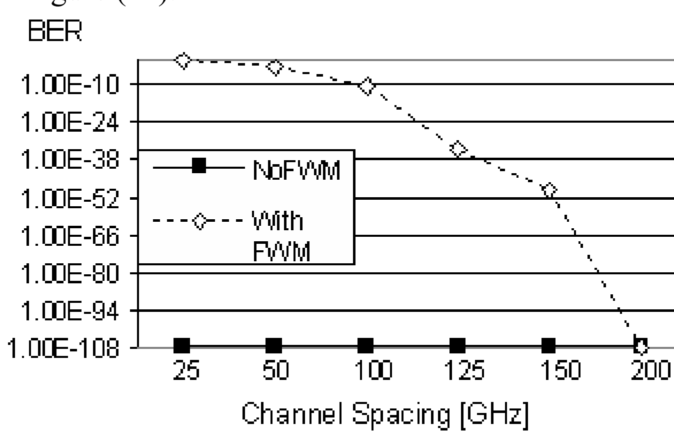


Figure 14: Effect of channel spacing on FWM

Effect of dispersion on FWM

The effect of dispersion on FWM is studied for dispersion values of 0.1, 0.3, 0.9, 1.5, 2.0, 3.0, 6.0, 10.0 ps/(nm·km) for the SMF transmission fiber. The DCF dispersion values are set to (SMF dispersion) × (-50/3)) for dispersion compensation. Figure (15a), b and c are channel 1 eye diagrams for dispersion values of 0.1, 3.0 and 6.0 ps/(nm·km) respectively. It is clear that as dispersion increases FWM has less effect.

Figure (15d) depicts variations of the channel 1 BER as a function of the various dispersion values.We note that for dispersion values of 6.0 ps/(nm·km) or higher FWM effect is almost suppressed. This is in agreement with published research in [13].

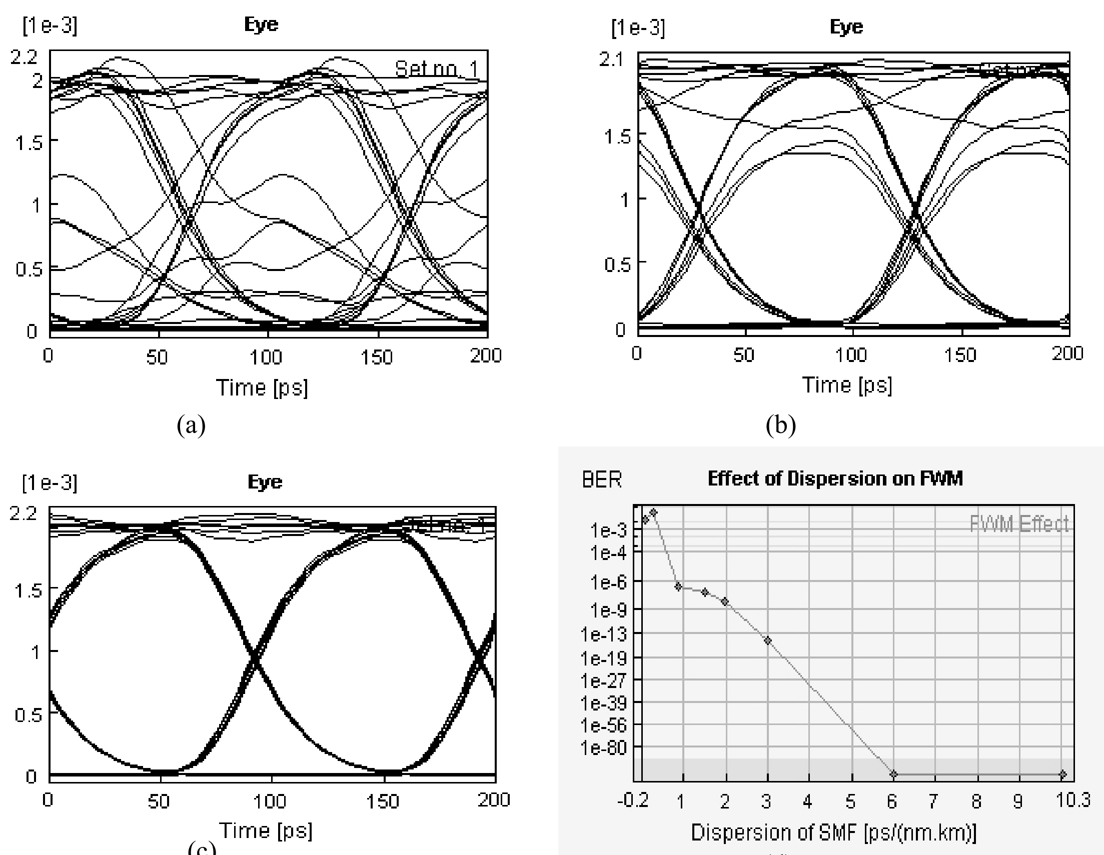


Figure 15: Effect of dispersion on FWM

Effect of unequal spacing on FWM

We studied the effect of channel allocation on FWM by comparing the 100-GHz equal-separation case to the unequal-separation between channels (125, 75, 100 GHz). Figure (16) depicts the channel 1 BER versus average channel power for equal and unequal channel spacing. It is observed that FWM effect can be suppressed by unequally allocating channels. This is confirmed in earlier research results [24].

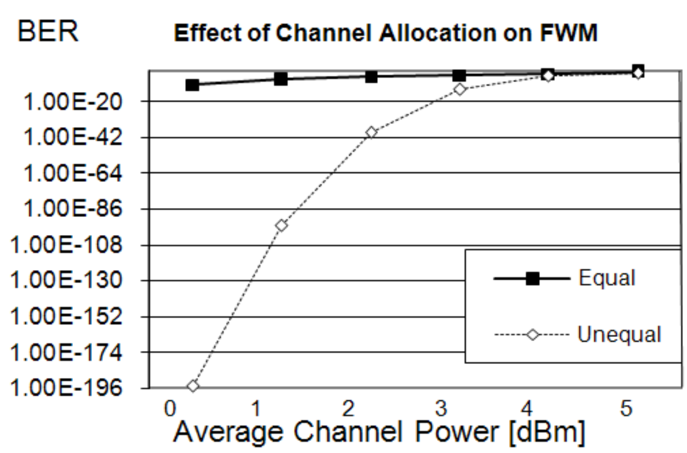


Figure 16: Effect of channel allocation on FWM

CONCLUSIONS AND FUTURE WORK

A survey of nonlinearities inherent in optical fibers is accomplished. The effect of these nonlinearities on WDM performance is studied. The *VP* Itransmission Maker™WDM simulation software is used to demonstrate these effects. Simulation results are compared to relevant literature throughout this study. Good agreements are obtained. We see that use of the powerful simulation software packages present a good alternative over involved theoretical analysis in WDM design as number of system variables goes large. This work will be used in a future work to design long haul, broadband WDM systems.

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