FWM versus XPM in WDM Systems Using Low Dispersion Fibers

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Abstract: The influence of cross-phase modulation (XPM) and four-wave mixing (FWM) on the performance of WDM systems using dispersion-shifted fibers (DS) and non-zero dispersion shifted fibers (NZ-DS) are studied and the role of these effects in the penalty for different cases are discussed.

I. INTRODUCTION

Optical nonlinear effects can cause serious degradations in the performance of wavelength division multiplexed (WDM) systems [1]. The nonlinear effects of cross-phase modulation (XPM) and four-wave mixing (FWM) have been considered two of the most significant effects in the signal degradation for WDM systems.

In XPM, the intensity modulation of each modulated channel changes the refractive index of the fiber, which in turn modulates the phase of the other co-propagating channels. During propagation, the fiber dispersion converts this phase modulation into amplitude modulation, degrading the system performance. FWM is a nonlinear phenomenon in which 2 (or 3) photons mixes to generate a third (or fourth) at a frequency f_{fwm}. If the system employs equal channel spacing, the FWM tone may have the same frequency as one of the WDM channels. The crosstalk due to the interference between a WDM channel with the overlapping tones can significantly degrade the system performance.

Considering the FWM does not have a significant impact in WDM systems using standard fibers ($D \cong 17$ ps/km-nm) due to the low FWM efficiency caused by high dispersion, XPM is the main nonlinear effect in these systems [2]. In WDM systems using DS fibers or NZ-DS fibers the XPM and FWM have different trends depending on the characteristics of each system (e.g., channel spacing, channel power, region where the channels are allocated, etc) and the parameters of each fiber.

S. Ten et al. [3] compared FWM and XPM impairments in a WDM system trough analysis of the Q parameter. In this paper the system performance is evaluated in terms of eye diagram penalty using different mathematical models to evaluate the influence of XPM and FWM. In Section 2, the WDM system characteristics are discussed and system setup is showed. In Section 3, the numerical results of the simulations for the systems are presented.

II. THE WDM SYSTEM

The IM-DD system setup is showed in fig. 1. It consists of a set of ideal transmitters, multiplexer, single-mode fibers (DSF or NZ-DSF), ideal optical amplifiers (noiseless), demultiplexer and a set of ideal optical receivers.

A. The Transmitter

Each transmitter has a laser source that emits a noiseless 128 pseudorandom bit sequence. The optical signal is a 10 Gbps NRZ signal. The bit sequence is passed by an electrical gaussian filter with a bandwidth of 9 GHz.

B. The MUX/DEMUX

They are ideal multiplexer and demultiplexer.

C. The Single-Mode Fibers

Two single-mode fibers were used: a DS fiber and a NZ-DS fiber. The parameters of these two fibers are showed on table 1. The Nonlinear Schrödinger Equation was used for modeling the light propagation in the fiber.

D. The Optical Amplifier

The optical amplifier model is considered an ideal noiseless EDFA with constant gain. Each amplifier compensates the losses caused by the fiber attenuation.

E. The Receiver

After propagating through the optical link, the optical signal is received by an ideal PIN diode.

$$I = K \cdot \left|A(z,t)\right|^2$$

The detector responsivity, K, chosen is 1 A/W. Afterwards, the detected photocurrent is low-pass filtered by a gaussian filter with a bandwidth of 9 GHz.

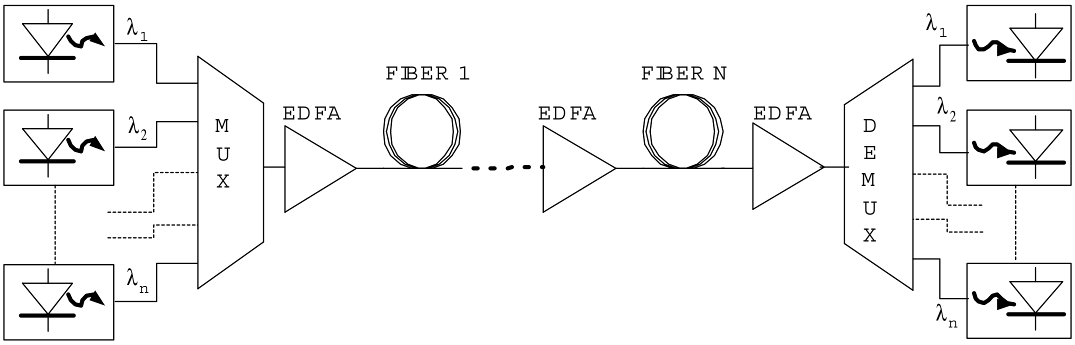


Figure 1 - System configuration

TABLE 1
CHARACTERISTICS OF THE FIBERS

	DSF	NZ-DSF
Attenuation Coefficient (dB/km)	0.24	0.25
Effective Area (μm^2)	52	72
Dispersion Slope ($ps/nm^2/km$)	0.075	0.1143
Chromatic Dispersion* (ps/nm/km)	0.6	4.2857
Zero Dispersion wavelength (nm)	1550	≈1512.5

* In a specific wavelength, DSF: λ= 1558 nm; NZDSF: λ= 1550 nm

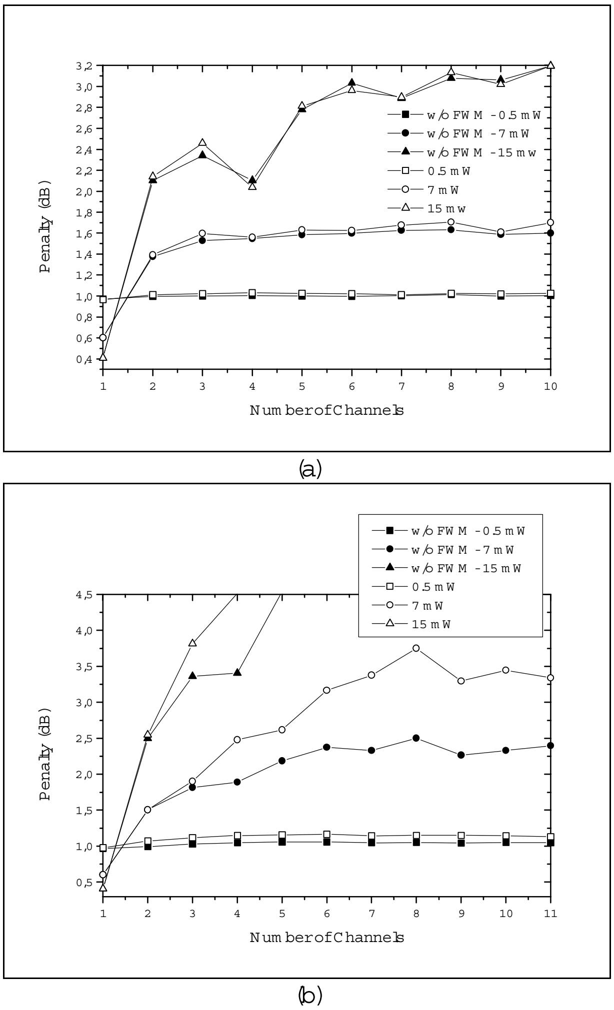
III. NUMERICAL RESULTS

The split-step Fourier method is used to simulated WDM signal propagation in the optical fibers. Two different approaches are used in the simulations to study the influences of XPM and FWM in the signal degradation. One approach considers all Kerr effects (SPM, XPM and FWM), and another neglects the FWM effect. In this way, the role of XPM and FWM nonlinear effects in the WDM systems may be analyzed. Although, the Stimulated Raman Scattering effect is not include in the models simulated, the results showed here do not suffer considerably difference if the SRS were included [4,5].

The system performance analysis is based on measuring the eye diagram closure compared to a back-to-back situation.

A. Non-Zero Dispersion Shifted Fiber

The first IM-DD system studied utilizes NZ-DS fiber. This system consists of 3 spans of 80 km, forming a 240-km optical link. Initially, the penalty in the channel 1 as function of the variation in the number of channels in the WDM system is analyzed. In the case showed in Fig. 2, the number of channels in the system was varied from 1 to 10 (11, Fig. 2b), and the channel spacing is 100 GHz (Fig. 2a) and 50 GHz (Fig. 2b). The simulated procedure consisted of propagating a single channel initially; this channel was located in the 1550 nm wavelength. After this propagation, another channel is added with a frequency separation of 100 GHz (2a), or 50 GHz (2b), and the simulation is repeated. This procedure continues until the system reaches 10 (11) channels, being channel 1 a central channel.



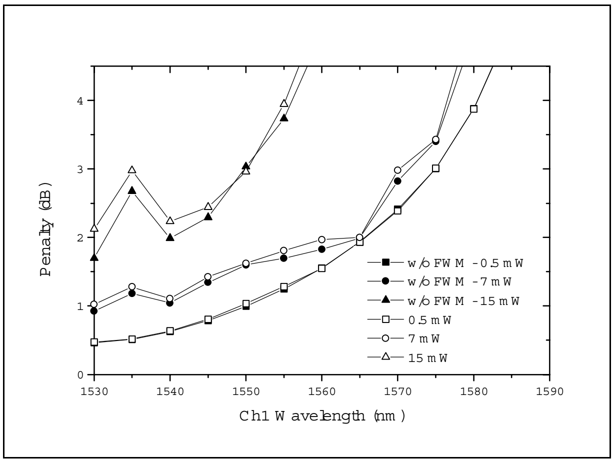
(a)

(b)

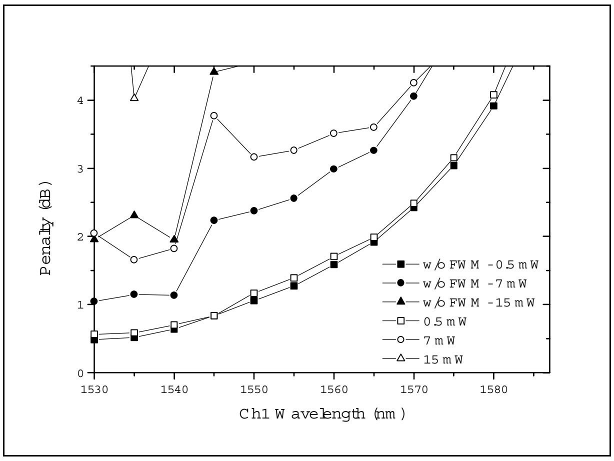
Figure 2 - Penalty in the channel 1 (central) as a function of the number of channels in a 240-km WDM transmission system with FWM (open symbols) and without FWM (solid) for a channel spacing of (a) 100 GHz, (b) 50 GHz.

In the Fig. 2.a for 100 GHz spacing, is possible to see that the FWM influence in the penalty of channel 1 could be negligible without losing the accuracy for the three different peak powers simulated. What means that the XPM is the main nonlinear effect to influence the signal degradation in this system. In the other way, when the channel spacing is decreased to 50 GHz, Fig. 2.b shows a great difference among the results with and without FWM for optical peak powers where the nonlinear penalties become significant (7 mW and 15 mW). The lower channel spacing increases both the influence of XPM and FWM effects. The FWM mixing efficiency becomes so important that is not possible to neglect this effect like in Fig. 2.a. Another important feature observed in the two graphs is the penalty saturation when increasing the number of channels. The number of channels in which this saturation is verified depends on how strong is the nonlinear effect.

To analyze the behavior of WDM systems in different regions of the fiber bandwidth, a six-channel (240 km) WDM system was simulated and the results are showed in Fig. 3. The wavelength of channel 1 has varied (wavelength range is 1530 nm to 1590 nm), although the relative position among the channels has been kept constant (λ_1, $\lambda_2 = \lambda_1+\lambda_s$, $\lambda_3 = \lambda_1-\lambda_S$, $\lambda_4 = \lambda_1+2\lambda_S$, $\lambda_5 = \lambda_1-2\lambda_S$, $\lambda_6 = \lambda_1+3\lambda_S$). The channel spacing utilized were 100 GHz (3.a) and 50 GHz (3.b).



(a)



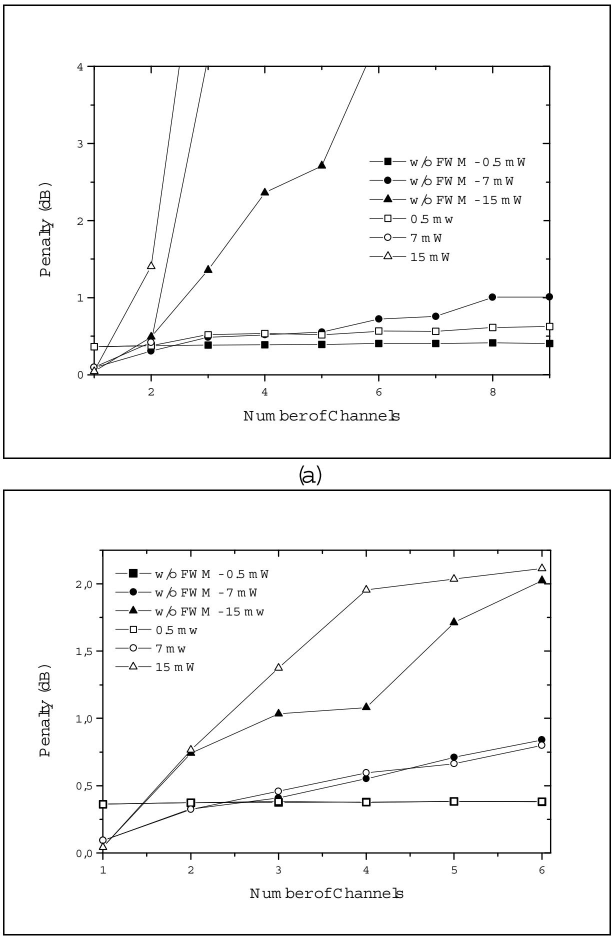
(b)

Figure 3 - Penalty in the channel 1 as a function of its wavelength in a 240 km - 6 channels WDM transmission system with FWM (open symbols) and without FWM (solid) for a channel spacing of (a) 100 GHz, (b) 50 GHz.

Fig. 3.a shows a good agreement among the results with and without FWM. However, this difference could be increased whether the ch1 wavelength becomes lower than 1530 nm, causing a lower dispersion and consequently a better FWM efficiency. If the peak power become higher than 15 mW the difference among the results will tend to increase too. For the situation showed in Fig. 3.a, FWM could be neglected. In Fig. 3.b, for a channel spacing of 50 GHz, there are great differences in the results when the peak power is over 0.5 mW (approximately a linear system). The FWM effect becomes strong and influences greatly the system penalty, but the FWM tends to diminish, as the ch1 wavelength tends to increase, due to a higher dispersion. The increasing in the FWM efficiency due the channel spacing causes these differences.

B. Dispersion Shifted Fiber

In the second part, systems using DS fiber have been studied. This system consists of 6 spans of 80 km forming a 480-km optical link. The procedure used to obtain the penalty in the channel 1 as function of the number of channels in the system is the same utilized in the last section (A), but now the channel spacing is 100 GHz (Fig. 4.a) and 200 GHz (Fig. 4.b). The first channel was allocated in 1558 nm, and the number of channels was varied from 1 to 9, Fig. 4.a, and from 1 to 6, Fig. 4.b.



(a)

(b)

Figure 4 - Penalty in the channel 1 as a function of the number of channels in a 480-km WDM transmission system with FWM (open symbols) and without FWM (solid), for a channel spacing of (a) 100 GHz and (b) 200 GHz.

Fig. 4a (channel spacing of 100 GHz), shows great differences in the results with and without FWM for peak powers higher than 0.5 mW. The strong FWM effect causes the eye close with as few channels as showed in Fig. 4a. For systems with two and three channels the eye diagram closes almost completely for peak powers of 7 mW and 15 mW, respectively. These results show how strong FWM is in a system using DSF and 100 GHz channel spacing, and it is possible to conclude that FWM is the dominant nonlinear effect in this system. In Fig. 4b for a channel spacing of 200 GHz the results are really different of Fig. 4a. In this case the increase in the channel spacing yield a lower influence of FWM in the system penalty. Only for a peak power of 15 mW there is considerably differences in the results. The higher channel spacing caused a decrease in the FWM efficiency.

To analyze the behavior of a WDM system using DSF in different regions of the fiber bandwidth, a four-channel WDM system is simulated and the results are showed in Fig. 5. The wavelength of channel 1 was varied (wavelength range is 1530 nm to 1590 nm), although the relative position among the channels has been kept constant (λ_1, $\lambda_2 = \lambda_1+\lambda_s$, $\lambda_3 = \lambda_1-\lambda_S$, $\lambda_4 = \lambda_1+2\lambda_S$). The channel spacing utilized is f_S = 200 GHz (3 a).

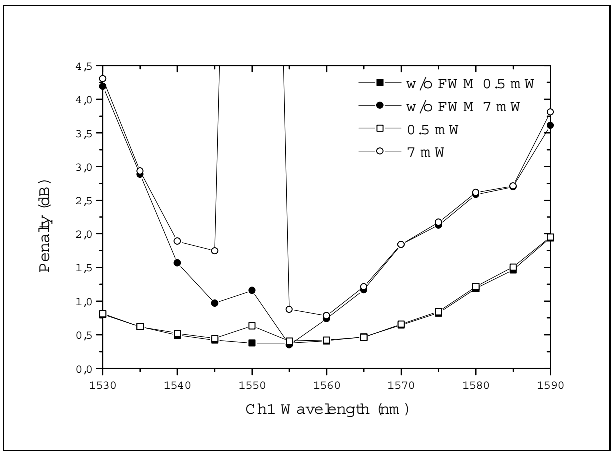


Figure 5 - Penalty in the channel 1 as a function of its wavelength in a 480 km - 4 channels WDM transmission system with FWM (open symbols) and without FWM (solid) for a channel spacing of 200GHz.

In Fig. 5 is possible to see a great difference in the results with and without FWM in the region near 1550 nm. It is because 1550 nm is the wavelength of zero dispersion in the DS fiber (table 1) and near this point the FWM efficiency is very high due a low dispersion. When the channel 1 wavelength get away of this region the two approaches have the same results.

IV. CONCLUSION

We studied numerically the influence of XPM and FWM in 10 Gbps WDM systems using two different fiber types, NZDS and DS fibers.

In the NZDS fiber, the simulations have shown that for channel spacings larger than 50 GHz, FWM could be neglected without loss of accuracy, i. e., XPM is the dominant nonlinear effect in the NZDS fiber systems to degrade the signals in the C and L band, even with high optical powers. However, for channel spacings of 50 GHz or lower, the FWM influence become higher and could not be neglected.

With DS fiber, the FWM effect was the strongest effect to degrade the system performance in the region near the zero-dispersion point due to the good phase match. However, in regions far from this point, L band for example, the FWM influence drops drastically, and the XPM may becomes the main nonlinear effect. For channel spacing of 200 GHz, FWM was the main effect to degrade the signal in a region between 1540 nm and 1560 nm, but outside this region XPM became the main nonlinear effect and FWM could be neglected.

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