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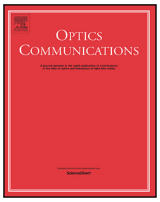

SPM and XPM crosstalk in WDM systems with DRA: Channel spacing and attenuation effects

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ABSTRACT

This paper presents a theoretical analysis of a closed formula for nonlinear crosstalk due to self-phase modulation (SPM) and cross phase modulation (XPM) in wavelength division multiplexing (WDM) systems. The influence of channel spacing and attenuation on the system behavior is modeled and investigated. The system under consideration is a standard single-mode fiber (SSMF) with a single-span distributed Raman amplifier (DRA) and is operating at 100 Gbps.

1. Introduction

Nonlinear fiber optics plays an increasingly important role in the design of such high-capacity WDM systems [1]. As a matter of fact, understanding various nonlinear effects occurring inside optical fibers is almost a prerequisite for a lightwave-system designer. However, it is limited by various factors such as channel spacing, attenuation and dispersion. A Raman amplification capability is to provide distributed amplification. The major advantage for the Distributed Raman Amplifiers (DRA) is that the gain is distributed throughout the entire fiber span which is specific and unique to Raman amplification [2].

In a previous work [3,4], we introduced a detailed discussion of SPM and XPM induced inter-crosstalk with respect to bit rate (B_T) at 25, 10, 40, 50 and 100 Gbps. OOK, DPSK, DBPSK and DQPSK modulation formulas were performed in multi-pumping DRA (forward, backward and bi-directional pumping) based on the theoretical model in Refs. [5,6]. It has been obtained that 100 Gbps RZ-DPSK signal with 33% duty cycle for backward pumped RA achieved the most dramatically decrease in the nonlinear crosstalk values at a constant channel spacing of 0.8 nm and a constant attenuation coefficient (α) of 0.2 dB/km neglecting their direct effects on the system performance.

Different 2D (time and wavelength) discrete time input output models for single channel multi-span WDM systems were developed in Refs. [7–9], based on Volterra series transfer function (VSTF). The well-known trip integral problem was overcome by reducing it into a simple integral using the split-step Fourier (SSF).

In the present work, we analyzed the effect of crosstalk at high bit rates in a single span WDM system based on the closed loop formula for pseudorandom process using the Fourier transform (FT). The infinite integration is overcome by using algebraic manipulation to achieve the minimum crosstalk. We also illustrated the effect of channel spacing and attenuation at 100 Gbps bit rate (B_T), based on the statistical theory in Refs. [5,6]. Attenuation in practical systems is not always constant ($\alpha = 0.2$ dB/km) as ITU-T recommendation because of the occurrence of many cable cuts leading to splicing loss along the transmission line. So, the net span loss will increase. In addition, the channel spacing is performed according to the bit rate of each channel with sufficient use for bandwidth.

The paper is organized as follows. The analytical model of a single span WDM DRA is explained in Section 2. It is divided in two subsections; the power spectral density (PSD) parameters that have a direct impact on the performance of SPM and XPM induced crosstalk and the modulation techniques that are used in the WDM transmission system. Then, the obtained results are presented and discussed in Section 3. Section 4 is devoted for the main conclusions.

2. Analytical model

In an N-channel of WDM system, the phase modulation in bidirectional DRA between two adjacent channels ith and jth can be represented as [5]

$$q_{ij}(t) = 2\gamma \int_0^L P\left(0, t - d_{ij} z'\right) e^{-\alpha z'} G_F\left(z'\right) G_B\left(z'\right) dz \tag{1}$$

where γ is the nonlinear coefficient, $P\left(0, t - d_{ij} z'\right)$ is the transmitted signal power at distance ($z = 0$) and time duration t, $d_{ij} = 1/v_i - 1/v_j$ is

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the propagation time difference between the two different channels (i) and (j) and $G_F\left(z'\right)$, $G_B\left(z'\right)$ is the forward and backward Raman gain, respectively, which given as [5,10]

$$G_F\left(z'\right) = \exp\left(\frac{g_R\left(\sum \frac{\lambda_s}{\lambda_p} P_{S0} + P_{P0}\right)}{A_{eff}\alpha}\left(1 - e^{-\alpha z'}\right)\right) \tag{2}$$

$$G_B(z') = \exp\left(\frac{g_R\left(\sum \frac{\lambda_s}{\lambda_p} P_{S0} + P_{PL}\right)}{A_{eff}\alpha}\left(e^{-\alpha(z' - L)} - 1\right)\right) \tag{3}$$

where g_R is the Raman peak gain which is equal to 6.5 × 1014 m/W. P_{S0} and P_{P0} are the initial signal and pump powers, respectively. λ_s and λ_p are signal and pump wavelengths, respectively. α is the attenuation coefficient and P_{PL} is the initial backward pump power at distance L between the two RAs.

Variance crosstalk, $\sigma_x^2(i,j)$, can be calculated through [10,11] as

$$\sigma_x^2(i,j) = \frac{1}{8\pi T}\int_{-\infty}^{\infty}\left|Q_{ij}(\omega)\right|^2 d\omega \tag{4}$$

where $Q_{ij}(\omega)$ is the Fourier transform of $q_{ij}(t)$ defined in Eq. (4), and is given by [4]

$$\begin{aligned} Q_{ij}(\omega) = {} & 2\gamma P(\omega)\left[\frac{1 - e^{-\left(\alpha + jd_{ij}\omega\right)L}}{\alpha + jd_{ij}\omega}\right] \\ & - 2\gamma A' P(\omega)\left[\frac{1 - e^{-\left(2\alpha + jd_{ij}\omega\right)L}}{2\alpha + jd_{ij}\omega}\right] \\ & + 2\gamma A'' P(\omega) e^{-\alpha L}\left[\frac{1 - e^{-\left(jd_{ij}\omega\right)L}}{jd_{ij}\omega}\right]. \end{aligned} \tag{5}$$

Let

$$A' = \frac{g_R\left(\sum \frac{\lambda_s}{\lambda_p} P_{S0} + P_{P0}\right)}{A_{eff}\alpha} \tag{6}$$

$$A'' = \frac{g_R\left(\sum \frac{\lambda_s}{\lambda_p} P_{S0} + P_{PL}\right)}{A_{eff}\alpha}. \tag{7}$$

2.1. *The power spectral density for WDM channels*

The power spectral of WDM depends on the original signal spectrum, SPM from the channel itself and XPM from all other WDM successive channels. Applying PSD needs the FT of the auto-correlation function of the input pseudorandom process [4]. Let $S_{\phi_{ij}}(\omega)$ denote the power spectral density of the output random process $q_{ij}(t)$, $S_{P_{ij}}(\omega)$ is the power spectral density obtained by passing the random process $P_n(0, t)$ through a linear filter of frequency response $H_{ij}(\omega)$.

$$S_{Q_{ij}}(\omega) = S_{P_{ij}}(\omega)\left|H_{ij}(\omega)\right|^2. \tag{8}$$

A starting point, one can considers a rectangular NRZ pulse shape $p(t)$ at time period T in the time domain, which will convert to $P(\omega)$ in the frequency domain using FT which given as follow [4]

$$P(\omega) = 2P_0 T \operatorname{sinc}\left(\frac{\omega T}{2}\right). \tag{9}$$

The general form of $S_{P_{ij}}(\omega)$ can be written as

$$S_{P_{ij}}(\omega) = \frac{1}{4T}|P(\omega)|^2 + \frac{1}{4T^2}\sum_{k=-\infty}^{\infty}\left|P\left(\frac{k}{T}\right)\right|^2 \delta\left(\omega - \frac{k}{T}\right) \tag{10}$$

where $P(\omega)$ is the FT of rectangular pulse in Eq. (9), the second term will be neglected due to its small value for rectangular and non-rectangular pulse shape [6]. The transfer function $H_{ij}(\omega)$ can be written from Eq. (5) as follows

$$\begin{aligned} H_{ij}(\omega) = {} & 2\gamma\left[\frac{1 - e^{-\left(\alpha + jd_{ij}\omega\right)L}}{\alpha + jd_{ij}\omega}\right] \\ & - 2\gamma A'\left[\frac{1 - e^{-\left(2\alpha + jd_{ij}\omega\right)L}}{2\alpha + jd_{ij}\omega}\right] \\ & + 2\gamma A'' e^{-\alpha L}\left[\frac{1 - e^{-\left(jd_{ij}\omega\right)L}}{jd_{ij}\omega}\right]. \end{aligned} \tag{11}$$

The modulation techniques are the last stage before transmitter in the linear crosstalk Eq. (4). As it will be represented as [6]

$$\sigma_x^2(i,j) = \frac{1}{8\pi T}\int_{-\infty}^{\infty} S_{Q_{ij}}(\omega)\, d\omega. \tag{12}$$

2.2. *Modulation schemes*

The simplest and most widely used modulation scheme in optical communication is OOK, by taking $Tb = T$ as one symbol duration [12]. The nonlinear phase shift $\Delta Q_{ij}(L, t)$. On the other hand, DPSK as it is an example of non-coherent orthogonal modulation [13], by considering $T_b = 2T$ and the nonlinear phase shift

$$\Delta Q_{ij}(L, t) = 4\, S_{P_{ij}}(\omega)|H_{ij}(\omega)|^2 \sin 2(\omega T/2). \tag{13}$$

This will be added respectively to Eq. (8) as follow

$$S_{\Delta\varphi_{ij}}(\omega)\,|_{\mathrm{OOK}} = S_{P_{ij}}(\omega)\left|H_{ij}(\omega)\right|^2 \tag{14}$$

$$S_{\Delta\varphi_{ij}}(\omega)\,|_{\mathrm{DPSK}} = 4S_{P_{ij}}(\omega)\left|H_{ij}(\omega)\right|^2 \sin 2\left(\omega T/2\right). \tag{15}$$

Consequently, the variance of XPM crosstalk will be [4]

$$\sigma_{\mathrm{XPM}}^2 = \frac{1}{8\pi T}\int_{-\infty}^{\infty} S_{\Delta\varphi_{ij}}(\omega)\, d\omega. \tag{16}$$

The variance SPM induced in crosstalk is calculated by taking the inter-channel separation ($\delta\lambda$) equal to zero in the variance expression of XPM [11], therefore

$$\sigma_{\mathrm{SPM}}^2 = \left(\frac{1}{2}\right)^2 \sigma_{\mathrm{XPM}}^2. \tag{17}$$

The factor 1/2 comes from the fact that the phase shift due to the XPM is twice as large as SPM [1].

3. Results and discussion

Considering a WDM system as shown in Fig. 1 with a bidirectional multi-pumped DRA, with pump wavelength in the range 1420–1470 nm at 10 nm spacing. The multi-pumping is used to accomplish wideband amplifications required for WDM systems. N is number of channels which is equal to 60 channels starting with 1514 nm with a channel spacing of 0.2, 0.4, 0.8 and 1.6 nm which is equivalent to 25, 50, 100 and 200 GHz, respectively, according to ITU-T recommendation. These channels are multiplexing on a single DRA span of length L with input signal power range of 0–18 dBm at standard single mode fiber (SMF). The influence of dispersion is taken into account. We performed our study at the zero dispersion wavelengths. The parameters used in calculations are given in Table 1. Each channel in the network is amplified by the DRA and is then demultiplexed at the receiver end. Matlab version (R2009b) is used to perform all the simulations and calculations.

The variance crosstalk standard deviation for both SPM and XPM induced crosstalk with the input signal power for B_T of 100 Gbps at 33.3% RZ-OOK in backward pumping DRA case is shown in Fig. 2. The induced nonlinear crosstalk decreases with the channel spacing, because the probability of interference between the adjacent channels will decrease.