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XPM-induced crosstalk with higher order dispersion in SCM–WDM optical transmission link

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ABSTRACT

In this paper, the XPM-induced crosstalk has been evaluated with higher order dispersion in SCM–WDM optical transmission link at different modulation frequencies. It has been observed that there is exponent increase in XPM-induced crosstalk with the increase in modulation frequency from 0 to 3 GHz. The impact of 3OD, 4OD and 5OD is small as compared to 2OD but still contributes when the combined terms are considered. The combined effect of second, third, fourth and fifth-order dispersion parameters is that the induced crosstalk introduced by XPM increases.

1. Introduction

Due to the explosive growth of wireless communication in recent years, network operators are having great difficulty accommodating the increasing traffic. As demand on multimedia services including voice, data and video continue to grow, it is necessary to achieve a mature service with a high percentage of consumer use, lower and constant access charge, full time connectivity to service providers and higher bandwidth. In order to cope up with the various demands, future wireless communication systems require a large capacity. The converging requirements for subscriber mobility and high bandwidths have led to the proposal of micro cellular systems in which system capacity can be increased by augmenting the reuse efficiency of limited radio resources [1]. The micro cellular system poses problems, since installation of new radio base stations require time and a large investment. The combination of SCM and WDM is seen as a viable solution to the problems posed by a micro cellular system as it provides the so-called radio over fiber link using microwave photonics techniques. SCM–WDM systems however, suffer from nonlinear effects in fiber. When multiple wavelengths carrying SCM signals propagates in a single fiber, fiber nonlinearities can lead to crosstalk between subcarriers on different wavelengths. In a dispersive fiber, the dominant fiber nonlinearity that causes crosstalk is cross-phase modulation (XPM). Cross phase modulation (XPM) may generate significant amounts of nonlinear crosstalk between adjacent SCM channels because they are very closely spaced [2–4].

The transmission limitations due to XPM-induced crosstalk in SCM–dense-wavelength-division-multiplexing (DWDM) systems were studied at wavelength spacing of 50 and 100 GHz [5]. XPM was reported as a major performance-limiting effect in high-bit-rate WDM networks with narrow channel spacing [6]. A four-wavelength bi-directional DWDM CATV system used chirped fiber gratings as the dispersion compensates devices to reduce the fiber dispersion and XPM-induced crosstalk simultaneously [7]. In a highly dispersive RZ differential phase-shift keying two adjacent channel transmission system, without spectral overlap, the standard deviation of XPM-induced phase shift was reported inversely proportional to the channel separation [8].

The work reported in Ref. [9] considered the impact of second-order dispersion (2OD) only for SRS and XPM-induced crosstalk. With the advancement of communication systems, there is a trend of using higher modulation frequencies. So it is necessary to investigate the performance of optical transmission link at higher modulation frequencies including the higher-order dispersion coefficients. The work reported in Ref. [10] considered the impact of 2OD and third-order dispersion (3OD) coefficients independently at different modulation

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frequencies. This paper extends the work reported in Ref. [11] by including fourth-order dispersion (4OD) and fifth-order dispersion (5OD) coefficients independently and combined at different modulation frequencies.

After describing the introduction in Section 1, the expression for XPM-induced crosstalk has been reported in Section 2 including the impact of higher-order dispersion coefficients. The results and discussion are mention in Section 3 and concluding remarks are given in Section 4.

2. XPM-induced crosstalk

Here the analysis for XPM induced crosstalk has been reported by considering the higher-order dispersion terms. The investigation is important for pulse of duration ≤0.1 ps propagating over the fiber.

Consider two optical waves with identical polarization, co-propagating in single mode fiber and take two coupled equation describing XPM under a slowly varying envelop are given by [9,12]

$$\frac{\partial A_1}{\partial Z} + \frac{1}{V_{g_1}}\frac{\partial A_1}{\partial t} = \left(-j\gamma P_2 - \frac{\alpha}{2}\right) A_1 \tag{1}$$

$$\frac{\partial A_2}{\partial Z} + \frac{1}{V_{g_2}}\frac{\partial A_2}{\partial t} = \left(-j\gamma P_1 - \frac{\alpha}{2}\right) A_2 \tag{2}$$

where $A_1\,(z,t)$, $i=1,2$ denote the slowly varying complex field envelop of each wave, γ = nonlinearity coefficient. Therefore optical power at the input of fiber can be expressed as [10]

$$P_i = P_c[1 + m\cos\omega_1 t] \tag{3}$$

where $i=1(\lambda_1)$ or $2(\lambda_2)$ and $\lambda_1 > \lambda_2$, P_c is the average optical power, m is the modulation index, $\cos\omega t$ is the modulation signal, ω is the angular frequency.

Solving Eqs. (1) and (2) of electric envelop by neglecting γ for initial condition $z=0$ and $t=\tau_1$

$$A_1\,(z,t) = A_1\,(0,\tau_1)\exp\left(\frac{\alpha z}{2}\right) \tag{4}$$

By substituting the result of $A_1\,(z,t)$ in the second coupled equation

$$A_2\,(z,t) = A_2\,(0,\tau_2)\,e^{-j\psi}e^{-(\alpha/2)z} \tag{5}$$

where

$$\psi = -2\gamma\int_0^z P_1\,(0,\tau_2 + d_{12}z)\,e^{-\alpha z}dz \tag{6}$$

and

$$\tau_1 = \tau_2 + d_{12}z \tag{7}$$

Considering group velocity dispersion and higher order dispersion can be converted into intensity modulation via relation [13–16]

$$\begin{aligned} P_2(z,\tau_2) = P_2(0,\tau_2)\Bigg|\Bigg\{ & 1 + j\left(\frac{\partial^2\psi}{\partial t^2} + j\left(\frac{\partial\psi}{\partial t}\right)^2\right)F_1 + 1 + \left(\frac{\partial^3\psi}{\partial t^3} - 3\frac{\partial^2\psi}{\partial t^2}\frac{\partial\psi}{\partial t} - j\left(\frac{\partial\psi}{\partial t}\right)^3\right)F_2 + 1 \\ & + j\left(-j\frac{\partial^4\psi}{\partial t^4} - 4\frac{\partial\psi}{\partial t}\frac{\partial^3\psi}{\partial t^3} - 3\left(\frac{\partial^2\psi}{\partial t^2}\right)^2 + 6j\frac{\partial\psi}{\partial t}\frac{\partial^2\psi}{\partial t^2} + j\left(\frac{\partial\psi}{\partial t}\right)^4\right)F_3 + 1 \\ & + j\left(-j\frac{\partial^5\psi}{\partial t^5} - 3\frac{\partial\psi}{\partial t}\frac{\partial^4\psi}{\partial t^4} - 10\frac{\partial\psi}{\partial t}\frac{\partial^3\psi}{\partial t^3} + 3\frac{\partial\psi}{\partial t}\frac{\partial^2\psi}{\partial t^2} - j\left(\frac{\partial\psi}{\partial t}\right)^5\right)F_4\Bigg\}\Bigg|^2 \end{aligned} \tag{8}$$

where

$$F_1 = -\beta_2\frac{z}{2}, F_2 = -\beta_3\frac{z}{6}, F_3 = -\beta_4\frac{z}{24}, F_4 = -\beta_5\frac{z}{120} \text{ and}$$

$$\beta_2 = \frac{\partial^2\beta}{\partial\omega^2}, \beta_3 = \frac{\partial^3\beta}{\partial\omega^3}, \beta_4 = \frac{\partial^4\beta}{\partial\omega^4}, \beta_5 = \frac{\partial^5\beta}{\partial\omega^5}$$

β is the phase constant at wavelength λ, solving Eq. (5) we obtain

$$P_2(z,\tau_2) = P_2(0,\tau_2)\left\{\left(1 - 2F_1 - 6F_2\frac{\partial\psi}{\partial t} - 24F_3\frac{\partial^2\psi}{\partial t^2} - 120F_4\frac{\partial^3\psi}{\partial t^3}\right)\frac{\partial^2\psi}{\partial t^2}\right\} \tag{9}$$

Neglecting the value of β_2^2, β_3^2, β_4^2 and β_5^2, being very small

$$P_2(z,\tau_2) = P_2(0,\tau_2)\left\{1 - 2F_1 - 6F_2\frac{\partial\psi}{\partial t} - 24F_3\frac{\partial^2\psi}{\partial t^2} - 120F_4\frac{\partial^3\psi}{\partial t^3}\right\}\frac{\partial^2\psi}{\partial t^2} \tag{10}$$

$$P_2(z,\tau_2) = P_2(z,\tau_2)e^{-\alpha z}\left[\beta_2 + \beta_3\frac{\partial\psi}{\partial t} + \beta_4\frac{\partial^2\psi}{\partial t^2} + \beta_5\frac{\partial^3\psi}{\partial t^3}\right]\frac{\partial^2\psi}{\partial t^2}. \tag{11}$$

We define here the following dispersion parameters [17]

$$\beta_2 = \frac{\lambda_2}{2\pi c}D$$

is the second-order dispersion parameter.

$$\beta_3 = \frac{\lambda^2}{(2\pi c)^2}\left[\lambda^2 D_1 + 2\lambda D\right]$$

is the third-order dispersion parameter.

$$\beta_4 = \frac{\lambda^3}{(2\pi c)^3}\left[\lambda^3 D_2 + 6\lambda^2 D_1 + 6\lambda D\right]$$

is the fourth-order dispersion parameter and

$$\beta_5 = \frac{\lambda^4}{(2\pi c)^4}\left[\lambda^4 D_3 + 12\lambda^3 D_2 + 36\lambda^2 D_1 + 24\lambda D\right]$$

is the fifth–order dispersion parameter.

From Eq. (11) the effect of β_2 in $\partial P_2(z,\tau_2)/\partial z$ is given by U and the effect of β_3 in $\partial P_2(z,\tau_2)/\partial z$ is given by V, β_4 in $\partial P_2(z,\tau_2)/\partial z$ is given by Y and the effect of β_5 in $\partial P_2(z,\tau_2)/\partial z$ is given by Z.

2.1. Case-1 (XPM-induced crosstalk with 2OD)

The XPM-induced crosstalk due to 2OD coefficient is given by

$$U = -\beta_2 P_c e^{-\alpha z}\frac{\partial^2\psi}{\partial\tau_2^2} \tag{12}$$

XPM-induced crosstalk due to 2OD at wavelength λ_2 is given by [5,17]

$$U = -\frac{2\gamma P_c\omega^2\beta_2}{(i\omega d_{12}-\alpha)^2}\left[(\alpha L - 1) + \cos(\omega d_{12}L)e^{-\alpha L} + j\left\{\sin(\omega d_{12}L)e^{-\alpha L} - (\omega d_{12}L)\right\}\right]. \tag{13}$$

2.2. Case-2 (XPM-induced crosstalk with 3OD)

The XPM-induced crosstalk due to 3OD coefficient is given by

$$V = -\beta_3 P_c e^{-\alpha z}\left[\frac{\partial\psi}{\partial\tau_2}\frac{\partial^2\psi}{\partial\tau_2^2}\right] \tag{14}$$

XPM-induced crosstalk due to 3OD at wavelength λ_2 is given by

$$V = -\frac{2m\beta_3\gamma^2 P_c\omega^3}{(\alpha - j\omega d_{12})^3}(3 + 2\alpha L + 4e^{-L\alpha}e^{j\omega d_{12}L} - e^{-2L\alpha}e^{j\omega d_{12}L} - 2j\omega d_{12}L) \tag{15}$$

$$V = -\frac{2m\beta_3\gamma^2 P_c\omega^3}{(\alpha - j\omega d_{12})^3}\left\{(3 + 2\alpha L + 4e^{-\alpha L}\cos(\omega d_{12}L) - e^{-2\alpha L}\cos(2\omega d_{12}L) + j4e^{-\alpha L}\sin(\omega d_{12}L) - e^{-2\alpha L}\sin(2\omega d_{12}L) - 2\omega d_{12}L)\right\} \tag{16}$$

2.3. Case-3 (XPM-induced crosstalk with 4OD)

The XPM-induced crosstalk due to 4OD coefficient is given by

$$Y = -\beta_4 P_c e^{-\alpha z}\frac{\partial^2\psi}{\partial\tau_2^2}\frac{\partial^2\psi}{\partial\tau_2^2}. \tag{17}$$

$$Y = -\beta_4 P_c e^{-\alpha z}\left[\frac{2\gamma P_c m}{(\alpha - i\omega d_{12})}\right]^3\omega^4 e^{3i\omega\tau_2}[1 - e^{(i\omega d_{12}-\alpha)z}]^3$$

Because of attenuation this incremental change is attenuated by a factor $e^{-\alpha(L-Z)}$. The modulation is obtained at the end of the fiber by integrating attenuated power over a length of fiber L.

$$\int_0^L dP_2(z,\tau_2)e^{-\alpha(L-z)} \tag{18}$$

Effect on modulation due to β_4 is given by

$$Y=-\beta_4 P_c e^{-\alpha L}\frac{4\gamma^3P_c^3m^3\omega^4e^{3i\omega\tau_2}}{3(i\omega d_{12}-\alpha)^4}[-6\alpha L+6i\omega d_{12}-18e^{(i\omega d_{12}-\alpha)L}+11+9e^{2(i\omega d_{12}-\alpha)L}-2e^{3(i\omega d_{12}-\alpha)L}] \tag{19}$$

The crosstalk in phasor form is obtained by normalizing expression in Eq. (23) by $P_c me^{-\alpha L}$.

The XPM crosstalk due to 5OD parameter at λ_2 is given by

$$\begin{aligned} XT_{XPM_5} &= -\beta_5\frac{4\gamma^4P_c^4m^3\omega^5e^{4i\omega\tau_2}}{3(i\omega d_{12}-\alpha)^5}[-12\alpha L+25-48e^{-\alpha L}\cos\omega d_{12}L \\ &\quad +36e^{-2\alpha L}\cos(2\omega d_{12}L)-16e^{-3\alpha L}\cos(3\omega d_{12}L)+3e^{-4\alpha L}\cos(4\omega d_{12}L)+j\{-48e^{-\alpha L}\sin(\omega d_{12}L) \\ &\quad +36e^{-2\alpha L}\sin(2\omega d_{12}L)-18e^{-3\alpha L}\sin(3\omega d_{12}L)+3e^{-4\alpha L}\sin(4\omega d_{12}L)\}] \end{aligned} \tag{20}$$

2.4. Case-4 (XPM-induced crosstalk with 5OD)

The XPM-induced crosstalk due to 5OD coefficient is given by

$$Z=\beta_5P_ce^{-\alpha z}\frac{\partial^3\psi}{\partial\tau_2^3}\frac{\partial^2\psi}{\partial\tau_2^2}$$

$$Z=\beta_5P_ce^{-\alpha z}\left(\frac{2\gamma P_c m e^{i\omega\tau_2}}{(\alpha-i\omega d_{12})}\right)^4\omega^5[1-e^{(i\omega d_{12}-\alpha)z}]^4 \tag{21}$$

Because of attenuation, this incremental change is attenuated by a factor $e^{-\alpha(L-z)}$. The modulation is obtained at the end of fiber by integrating attenuated power over a length of fiber L

$$\int_0^L dP_2(z,\tau_2)e^{-\alpha(L-z)} \tag{22}$$

Effect on modulation due to β_5 is given by

$$\begin{aligned} Z &= \beta_5P_ce^{-\alpha z}\left(\frac{2\gamma P_c m}{(\alpha-i\omega d_{12})}\right)^4\omega^5\frac{e^{4i\omega\tau_2}}{12(i\omega d_{12}-\alpha)}[12(i\omega d_{12})L-12L\alpha-48(e^{(i\omega d_{12}-\alpha)L}-1)+36(e^{2(i\omega d_{12}-\alpha)L}-1)-16(e^{3(i\omega d_{12}-\alpha)L}-1) \\ &\quad +3(e^{4(i\omega d_{12}-\alpha)L}-1)] \end{aligned} \tag{23}$$

The crosstalk in phasor from is obtained by normalizing expression in Eq. (23) by $mP_ce^{-L\alpha}$.

The crosstalk due to 5OD coefficient at λ_2 is given by

$$\begin{aligned} XT_{XPM_5} &= -\beta_5\frac{4\gamma^4P_c^4m^3\omega^5e^{4i\omega\tau_2}}{3(i\omega d_{12}-\alpha)^5}[-12\alpha L+25-48e^{-\alpha L}\cos\omega d_{12}L+36e^{-2\alpha L}\cos(2\omega d_{12}L)-16e^{-3\alpha L}\cos(3\omega d_{12}L) \\ &\quad +3e^{-4\alpha L}\cos(4\omega d_{12}L)+j\{-48e^{-\alpha L}\sin(\omega d_{12}L)+36e^{-2\alpha L}\sin(2\omega d_{12}L)-18e^{-3\alpha L}\sin(3\omega d_{12}L)+3e^{-4\alpha L}\sin(4\omega d_{12}L)\}] \end{aligned} \tag{24}$$

$$\begin{aligned} \mathrm{XT}_{\mathrm{XPM}_5} &= -\beta_5\frac{4\gamma^4P_c^4m^3\omega^5e^{4i\omega\tau_2}}{3(i\omega d_{12}-\alpha)^5}[-12\alpha L+25-48e^{-\alpha L}\cos\omega d_{12}L+36e^{-2\alpha L}\cos(2\omega d_{12}L) \\ &\quad -16e^{-3\alpha L}\cos(3\omega d_{12}L)+3e^{-4\alpha L}\cos(4\omega d_{12}L)+j\{-48e^{-\alpha L}\sin(\omega d_{12}L)+36e^{-2\alpha L}\sin(2\omega d_{12}L) \\ &\quad -18e^{-3\alpha L}\sin(3\omega d_{12}L)+3e^{-4\alpha L}\sin(4\omega d_{12}L)\}. \end{aligned} \tag{25}$$

3. Results and discussion

Here, the results have been obtained for XPM-induced crosstalk at various modulation frequencies in the presence of 2OD, 3OD, 4OD and 5OD. An effort has been made for the exhaustive investigation to ascertain the impact of HOD coefficients on non-linear crosstalk in SCM–WDM communication systems. The results have been reported by taking values of the various parameters like: $\Delta\lambda$ = 4 nm, L = 50 km, n_2 = 2.68 e^{-20} m^2/W, m = 0.7, $\gamma=2\pi n_2/\lambda_2 A_{\mathrm{eff}}$, α = 0.25 dB/km, λ_1 = 1542 nm and λ_2 = 1546 nm and the values of D = 0.5 ps/nm/km, D_1 = 0.085 ps/nm/km, D_2 = 0.00025 ps/nm/km, D_3 = 0.0000025 ps/nm/km. In this paper, we have investigated theoretically, the crosstalk mechanisms in SCM–WDM communication systems with XPM-induced crosstalk versus modulation frequency in the presence of higher dispersion order.

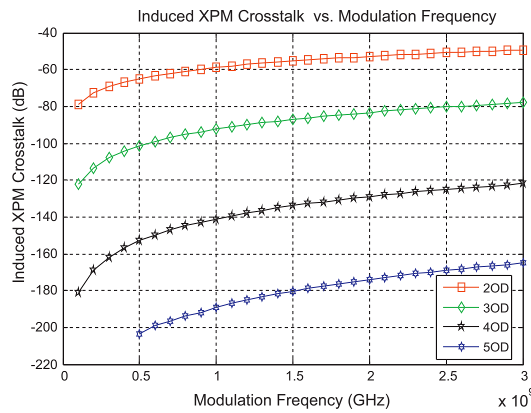

Fig. 1. The graph between induced XPM crosstalk versus modulation frequency at different Dispersion order.

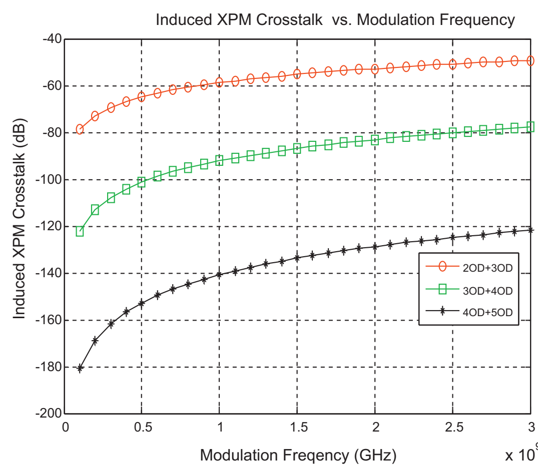

Fig. 2. The graph between induced XPM crosstalk versus modulation frequency at different combined dispersion order.

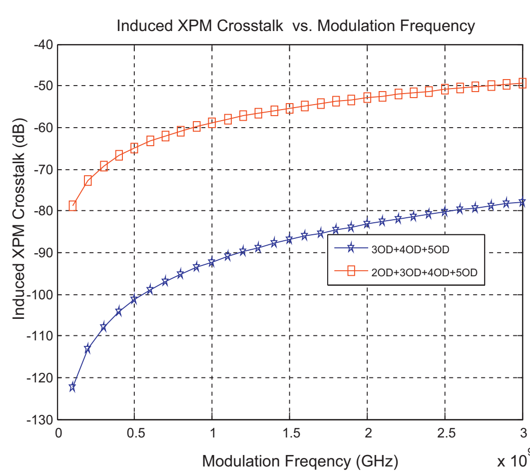

Fig. 3. The graph between induced XPM crosstalk versus modulation frequency at all combined dispersion order.

Fig. 1 depicts the XPM-induced crosstalk versus modulation frequency at varied higher order dispersion and shows that the XPM-induced crosstalk is (−80 to −50), (−122 to −78), (−180 to −122) and (−202 to −162) dB in the presence of 2OD, 3OD, 4OD and 5OD at 3 GHz modulation frequency.

Furthermore Fig. 2 illustrates the exponential growth in the XPM-induced crosstalk versus modulation frequency at varied different combined dispersion order and shows that the XPM-induced crosstalk is (−78 to −50), (−120 to −80) and (−180 to −120) dB in the presence of combined dispersion order like 2OD + 3OD, 3OD + 4OD and 4OD + 5OD at 3 GHz modulation frequency.

Similar result have been reported for XPM-induced crosstalk versus modulation frequency in the presence of all combined higher dispersion order 3OD + 4OD + 5OD and 2OD + 3OD + 4OD + 5OD in Fig. 3, but it lies in the range of (−122 to −78) and (−80 to −50) dB at 3 GHz modulation frequency respectively.

4. Conclusion

This paper presents the detailed theoretical analysis the influence of higher-order dispersion effect 2OD, 3OD, 4OD and 5OD on XPM-induced crosstalk. It is also observed that the higher-order dispersion term has significant impact on XPM-induced crosstalk. The impact decreases as the order of dispersion term increases. At modulation frequency of 2 GHz, XPM-induced crosstalk for 2OD is −58 dB, for 3OD is −84 dB, for 4OD it is −128 dB and −169 dB for fifth order. The impact of 3OD, 4OD and 5OD is small as compared to 2OD but still contributes when the combined terms are considered. At modulation frequency of 2 GHz, XPM-induced crosstalk for 2OD + 3OD is −57 dB, 3OD + 4OD is −83 dB, 4OD + 5OD is −127 dB, similarly combined effect of third, fourth and fifth-order dispersion is −82 dB and all combined effect of dispersion order is −55 dB at 2 GHz modulation frequency It is therefore concluded that under the combined effect of second, third, fourth and fifth-order dispersion parameters is that the induced crosstalk introduced by XPM increases.

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