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The Impact Of Cross Phase Modulation Induced Crosstalk in SCM-WDM Transmission Systems With Higher-Order Dispersion

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Abstract- In this paper, the XPM-induced crosstalk has been evaluated in a SCM–WDM communication link. Results show that XPM-induced crosstalk dominates at 2OD and comparatively decreases for higher order of dispersion. The present work analyzes the individual and combined effect of second-, third-, fourth-, and fifth-order dispersion parameters on XPM at different input channel powers, transmission length. The limiting influence of XPM increases as the transmission length, modulation index and optical power increases but decreases as the core affective area of fiber increases.

Index Terms- *Sub-carrier multiplexing ; Wavelength division multiplexing ; Cross phase modulation, Higher-order dispersion ; Nonlinearity coefficient.*

1. INTRODUCTION

Due to the exponential growth of wireless communication in the past few years, the Information is a key global resource and continued growth of our global economy relies on an ever-increasing capacity to process and communicate information. Future optical networks demand high capacity optical networks in support of a variety of applications including 3-D multimedia entertainment, telemedicine, and cloud computing [1]. 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 fulfill various demands, networks operators are having great difficulty accommodating the increasing traffic because, when a high-speed optical signal is transmitted in an optical fiber, it undergoes various distortions due to the impairments caused by system noise, attenuation, fiber dispersion, and nonlinearities such as stimulated Raman scattering (SRS), four wave mixing(FWM)and cross phase modulation (XPM).

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.XPM generate significant amount of nonlinear crosstalk between very closely spaced SCM channels [2,4].

The transmission limitation of multiple narrow single-sideband subcarrier-multiplexed (SSB/SCM) signals with transport capacities of 10 or 20 Gb/s per wavelength, with a wavelength spacing of 25, 50, and 100 GHz are studied in [5]. XPM induced crosstalk was one of the major limiting factor in high capacity WDM networks with narrow channel spacing [6].A chirped fiber gratings reported as the dispersion compensating device to reduce the nonlinear dispersion and XPM-induced crosstalk for bi-directional DWDM CATV system [7]. The deviation caused by XPM-induced phase shift is inversely proportional to the channel separation for a highly dispersive RZ differential phase-shift keying transmission system was reported by [8] .

The impact of second-order dispersion (2OD) for the combined effect of SRS and XPM-induced crosstalk was evaluated and an expansion to the higher- order dispersions is essential in order to design and develop an efficient high bit rate broadband optical communication system or network that handles converging requirements for subscriber mobility and high bandwidths[9]. The analysis reported in [10] considered second order dispersion (2OD) and third-order dispersion (3OD) coefficients independently for different modulation frequencies at varied walk off parameters. This paper extends the work reported in [18] by including higher-order dispersion coefficients independently and combined at different transmission lengths, modulation index, core affective area, optical powers of optical fiber.

2. THEORY

The optical power at the fiber input is given by $P_i = P_c[1 + m\cos\omega_1 t]$ where $A_1(z,t),\ i = 1,2$ denote the slowly varying complex field envelop of

each wave, γ is nonlinearity coefficient. Therefore optical power at the input of fiber can be expressed as [10].

In this work we consider two optical waves with identical polarization, co-propagating in single mode fiber and the investigation is done for pulse of duration ≤ 0.1 ps propagating over the fiber. The coupled equation for cross phase modulation under a slowly varying envelop are given by [9, 12].

$$\frac{\partial A_1}{\partial Z}+\frac{1}{V_{g1}}\frac{\partial A_1}{\partial t}=\left(-j\gamma P_2-\frac{\alpha}{2}\right)A_1 \tag{1}$$

$$\frac{\partial A_2}{\partial Z}+\frac{1}{V_{g2}}\frac{\partial A_2}{\partial t}=\left(-j\gamma P_1-\frac{\alpha}{2}\right)A_2 \tag{2}$$

Solving (1) and (2) of electric envelop by neglecting γ for initial condition z = 0 and t = τ_1

$$A_1(z,t)=A_1(0,\tau_1)\exp\left(\frac{\alpha z}{2}\right) \tag{3}$$

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

$$A_2(z,t)=A_2(0,\tau_2)e^{-j\psi}e^{-(\alpha/2)z} \tag{4}$$

Where

$$\psi=-2\gamma\int_0^z P_1\left(0,\tau_2+d_{12}z\right)e^{-\alpha z}dz \tag{5}$$

And

$$\tau_1=\tau_2+d_{12}z \tag{6}$$

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

$$P_2(z,\tau_2)=P_2(0,\tau_2)\left|\begin{array}{l}\{1+j\left(\frac{\partial^2\psi}{\partial t^2}+\left(\frac{\partial\psi}{\partial t}\right)^2\right)F_1+1+\\ \left(\frac{\partial^3\psi}{\partial t^3}-3\frac{\partial^2\psi}{\partial t^2}\frac{\partial\psi}{\partial t}-j\left(\frac{\partial\psi}{\partial t}\right)^3\right)F_2+1\\ +j\left(\begin{array}{l}-j\frac{\partial^4\psi}{\partial t^4}-4\frac{\partial\psi}{\partial t}\frac{\partial^3\psi}{\partial t^3}-3\left(\frac{\partial^2\psi}{\partial t^2}\right)^2\\ +6j\frac{\partial\psi}{\partial t}\frac{\partial^2\psi}{\partial t^2}+j\left(\frac{\partial\psi}{\partial t}\right)^4\end{array}\right)F_3+\\ 1+j\left(\begin{array}{l}-j\frac{\partial^5\psi}{\partial t^5}-3\frac{\partial\psi}{\partial t}\frac{\partial^4\psi}{\partial t^4}-10\\ \frac{\partial\psi}{\partial t}\frac{\partial^3\psi}{\partial t^3}+3\frac{\partial\psi}{\partial t}\frac{\partial^2\psi}{\partial t^2}-j\left(\frac{\partial\psi}{\partial t}\right)^5\end{array}\right)F_4\}\end{array}\right|^2 \tag{7}$$

Where

$$F_1=-\beta_2\frac{z}{2},F_2=-\beta_3\frac{z}{6},F_3=-\beta_4\frac{z}{24},F_4=-\beta_5\frac{z}{120} \tag{8}$$

$$\beta_2=\frac{\partial^2\beta}{\partial\omega^2},\beta_3=\frac{\partial^3\beta}{\partial\omega^3},\beta_4=\frac{\partial^4\beta}{\partial\omega^4},\beta_5=\frac{\partial^5\beta}{\partial\omega^5} \tag{9}$$

β is the phase constant at wavelength λ_2, solving Eq. (5) we obtain

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

Neglecting the value of $\beta_2{}^2,\beta_3{}^2,\beta_4{}^2,\beta_5{}^2$, being very small,

$$P_2(z,\tau_2)=P_2(0,\tau_2)\left\{\left(\begin{array}{l}1-2F_1-6F_2\frac{\partial\psi}{\partial t}-\\ 24F_3\frac{\partial^2\psi}{\partial t^2}-120F_4\frac{\partial^3\psi}{\partial t^3}\end{array}\right)\frac{\partial^2\psi}{\partial t^2}\right\} \tag{11}$$

We define here the following dispersion parameters [17]. β_i represent i^{th} order dispersion parameter.

$$\begin{aligned}\beta_2&=\frac{\lambda^2}{2\pi c}D\\ \beta_3&=\frac{\lambda^2}{(2\pi c)^2}\left[\lambda^2D_1+2\lambda D\right]\\ \beta_4&=\frac{\lambda^3}{(2\pi c)^3}\left[\lambda^3D_2+6\lambda^2D_1+6\lambda D\right]\\ \beta_5&=\frac{\lambda^4}{(2\pi c)^4}\left[\lambda^4D_3+12\lambda^3D_2+36\lambda^2D_1+24\lambda D\right]\end{aligned} \tag{12}$$

From (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. XPM-induced crosstalk is defined due to higher order dispersion at wavelength λ_2.

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

$$V=-\frac{2m\beta_3\gamma^2P_c\omega^3}{(\alpha-j\omega d_{12})^3}\left\{\begin{pmatrix}3+2\alpha L+4e^{-L\alpha}\cos(\omega d_{12}L)-\\ e^{-2\alpha L}\cos(2\omega d_{12}L)+\\ j4e^{-\alpha L}\sin(\omega d_{12}L)-2\omega d_{12}L\end{pmatrix}\right\} \quad (14)$$

$$Y=-\frac{4\beta_4\gamma^4P_c^3m^2\omega^5e^{4i\omega\tau_2}}{3(i\omega d_{12}-\alpha)^4}\begin{bmatrix}-6\alpha L+6i\omega d_{12}-\\ 18e^{(i\omega d_{12}-\alpha)L}+11+\\ 9e^{2(i\omega d_{12}-\alpha)L}-2e^{3(i\omega d_{12}-\alpha)L}\end{bmatrix} \quad (15)$$

$$Z=-\beta_5\frac{4\gamma^4P_cm^3\omega^5e^{4i\omega\tau_2}}{3(i\omega d_{12}-\alpha)^5}\begin{bmatrix}12(i\omega d_{12})L-12L\alpha-48\left(e^{(i\omega d_{12}-\alpha)L}-1\right)\\ +36\left(e^{2(i\omega d_{12}-\alpha)L}-1\right)-16\left(e^{3(i\omega d_{12}-\alpha)L}-1\right)\\ +3\left(e^{4(i\omega d_{12}-\alpha)L}-1\right)\end{bmatrix} \quad (16)$$

3. RESULT AND DISCUSION

In our calculations, we assume following parameters as given below Referring to ITU: T recommendation G.653 [ITU][18]. $D=0.5$ ps/nm/km, $D_1=0.085$ ps/nm/km, $D_2=$ 0.00025 ps/nm/km, $D_3=0.0000025$ ps/nm/km and , the channel spacing of $\Delta\lambda=4$ nm, length of fiber $L=50$ km for the graph of the XPM-induced crosstalk versus optical power , the fiber non-linear refractive index $n_2=2.68e^{-20}m^2/W$, m = 0.7, attenuation factor $\alpha=0.25$ dB/km, $\lambda_1=1542$ nm and $\lambda_2=1546$ nm.

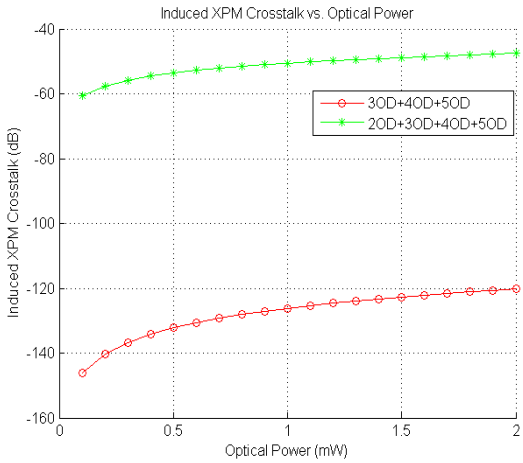

Fig. 1 Induced XPM crosstalk versus optical power at for 2OD+3OD, 3OD+ 4OD, 4OD+ 5OD

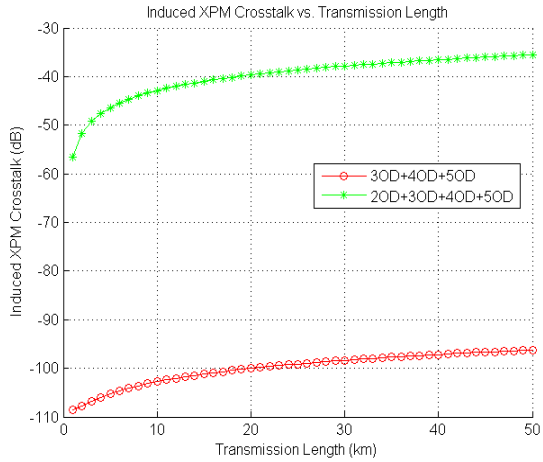

Fig. 2. Induced XPM crosstalk versus transmission length at for 2OD+3OD+4OD+5OD, 3OD+ 4OD+5OD

Fig. 1 illustrates the XPM-induced crosstalk versus transmission length in the presence of all combined higher dispersion order 3OD + 4OD + 5OD and 2OD + 3OD + 4OD + 5OD that lies in the range of (−108.5to−96.2) and (−56 to−35.5) dB at 3 GHz modulation frequency respectively. Similar result have been reported for XPM-induced crosstalk versus optical power in the presence of all combined higher dispersion order 3OD + 4OD + 5OD and 2OD + 3OD + 4OD + 5OD in Fig. 2, but it lies in the range of (−146 to−120.2) and (−60 to−47.5) dB at 3 GHz modulation frequency respectively.

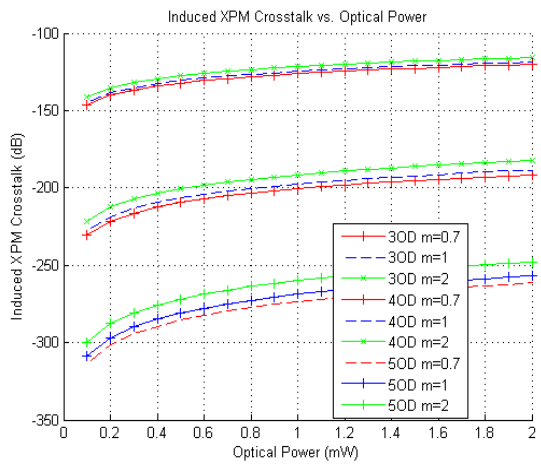

Fig. 3 Induced XPM crosstalk versus optical power at for 3OD, 4OD, 5OD at different values of m

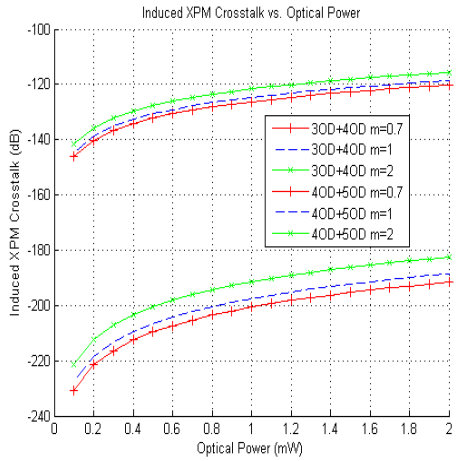

Fig. 4. . Induced XPM crosstalk versus optical power at for 3OD+ 4OD, 4OD+ 5OD at different values of m

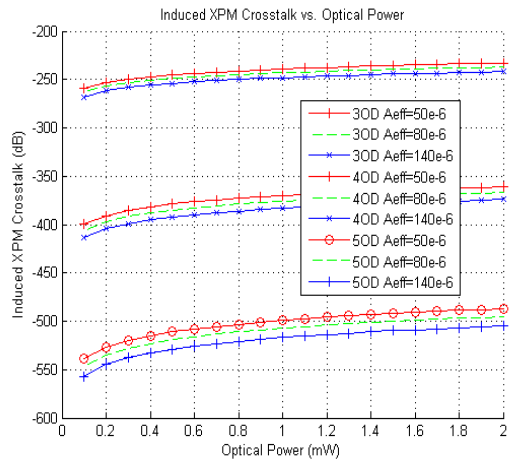

Fig. 5. Induced XPM crosstalk versus optical power at for 3OD, 4OD, 5OD at different values of core affective area

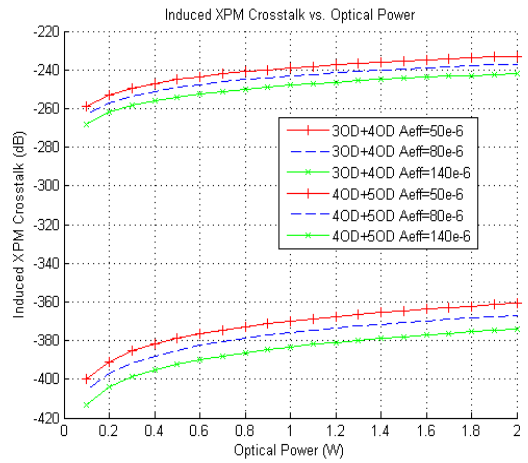

Fig. 6. Induced XPM crosstalk versus optical power at for 3OD+4OD, 4OD+5OD at different values of core affective area

TABLE I. XPM-induced crosstalk (in dB) at 2mW at various values of Modulation Index

m	*3OD*	*4OD*	*5OD*	*3OD+4OD*	*4OD+5OD*
0.7	(-141 to -120.2)	(-230.6 to -191.6)	(-313.5 to -261.4)	(-146.2 to -120.2)	(-230.6 to -191.6)
1	(-144.7 to -118.6)	(-227.5 to -188.5)	(-308.8 to -256.8)	(-144.7 to -118.6)	(-227.5 to -118.5)
2	(-141.7 to -115.6)	(-221.5 to -182.5)	(-299.8 to -247.8)	(-141.7 to -115.6)	(-221.5 to -182.5)

TABLE II. XPM-induced crosstalk (in dB) at 2mW at various values of Modulation Index

A_{eff}	*3OD*	*4OD*	*5OD*	*3OD+4OD*	*4OD+5OD*
50e-6	(-141.7 to -120.2)	(-230.6 to -191.6)	(-313.5 to -261.4)	(-146.2 to -120.2)	(-230.6 to -191.6)
80e-6	(-144.7 to -118.6)	(-227.5 to -188.5)	(-308.8 to -256.8)	(-144.7 to -118.6)	(-227.5 to -118.5)
140e-6	(-141.7 to -115.6)	(-221.5 to -182.5)	(-299.8 to -247.8)	(-141.7 to -115.6)	(-221.5 to -182.5)

The comparison of XPM-induced crosstalk reduction due to individual and different combination of higher order dispersion is given in table I .These values are calculated for different values of modulation index (m=0.7, 1, 2) at fiber length 50km. Fig. 3 depicts the XPM-induced crosstalk versus optical power at varied higher order dispersion and shows that the XPM induced in the presence of 3OD, 4OD and 5OD at3 GHz modulation frequency. Fig. 4 depicts the exponential growth in the XPM-induced crosstalk versus transmission length at varied different combined dispersion order and in the presence of combined dispersion order like 3OD + 4OD and 4OD + 5OD at 3 GHz modulation frequency.

Table II shows the variation of XPM-induced crosstalk reduction due to individual and different combination of higher order dispersion for different affective core area A_{eff} of optical fiber at length of 50km.The Fig. 5 indicates the graph of the XPM-induced crosstalk versus optical power at varied higher order dispersion and shows that the XPM induced crosstalk in the presence of 2OD, 3OD, 4OD and 5OD at3 GHz modulation frequency. Further, in Fig. 6 we calculated the XPM-induced crosstalk in the presence of combined dispersion order like 2OD + 3OD, 3OD + 4OD and 4OD + 5OD at 3 GHz modulation frequency.

4. CONCLUSION

From the above result, it is clear that the impact of 3OD, 4OD and 5OD is small as compared to with 2OD but still contributes when the combined terms are considered, for Fig. 1 to 3 the XPM-induced crosstalk more effective in the first 15 km of optical fiber after that it experiences very low variations. It is also observed that the higher-order dispersion term

has significant impact on XPM-induced crosstalk. The effect of XPM-induced crosstalk at different values of input channel powers can be observed Fig. 4 to 6. The effect of XPM-induced crosstalk increases exponentially with optical power. It is evaluated that XPM-induced crosstalk increases for the m = 1 and m = 2 as compared to m=07. Moreover it is investigated that as core effective area increases XPM-induced crosstalk decreases. Fig. 5 and 6 shows the impact of core effective area (A_{eff}) when length of fiber is constant .it is observed as core effective area increases XPM-induced crosstalk decreases.

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