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# Effects of Residual Dispersion on Intra-Channel Cross-Phase Modulation Induced Phase Fluctuation in Dispersion Managed Line

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**ABSTRACT**

The effects of residual dispersion on intra-channel cross-phase modulation (IXPM) induced phase perturbation in optical RZ pulse propagating in a periodically dispersion managed (DM) transmission line are investigated in this work. Using perturbed variational formulation, we have obtained several ordinary differential equations for various pulse parameters. These equations have been solved to identify phase perturbation in the DM cell of the system. Full numerical simulation of the nonlinear Schrodinger equation has been employed to identify effects of phase fluctuation on pulse propagation and to investigate the intra-pulse interaction. The analytical result is verified by numerical simulation based on split-step Fourier method (SSFM). We therefore explore the effects of various parameters such as transmission distance, input power, duty cycle, and bit-rate on phase fluctuation for different transmission models having different residual dispersion. Simulation results confirm significant improvement in the phase fluctuations due to IXPM by using dispersion managed line having some residual dispersion compared to perfect dispersion compensation. The outcome of our work is to explore the performance of the DM system with respect to some residual dispersion so that the IXPM induced phase fluctuations remain low in optical fiber communication.

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## 1. INTRODUCTION

Dispersion management (variation of the chromatic dispersion along the line) is an attractive technique that can be used to enhance the performance of fiber communication links both for soliton and non-soliton transmission. Dispersion managed (DM) systems have shown great opportunity in long distance high speed optical fiber communication systems because of their superb characteristics which are not achievable in conventional systems [1]-[3]. Indeed the main limitation of high-bit rate transmission in optical fiber links is the chromatic dispersion. Other limitations are fiber loss, radiation from the pulse due to lumped amplifiers compensating the fiber loss, noise and other nonlinear effects. One of the solutions to compensate for the pulse broadening induced by dispersion is a direct dispersion compensation for linear pulse propagation [4]. In a dispersion-managed system, fiber dispersion varies alternately between anomalous and normal values. This variation is maintained periodically and the average dispersion over a period could be positive, negative or even zero [5]-[6]. A dispersion managed optical communication system is made of alternate segments of normal (positive) and anomalous (negative) dispersion fiber in a periodic manner. The combination of fiber segments with alternating normal and anomalous dispersions makes a unit cell of a DM link. Thus, in a unit cell, fiber dispersion becomes locally high, but the average dispersion of a cell remains low. It has been also established that an intra-pulse interaction can be minimized by choosing a dispersion profile and a fiber length alternating between normal and anomalous dispersions. However in any realistic optical network it is not possible every time to compensate all the dispersion in each segment. As a result there remains some residual dispersion in a dispersion managed system.

In particular, in standard single mode fiber (SSMF) the high local dispersion leads to rapid pulse broadening over several bit slots, and the overlapping neighboring pulses interact through intra-channel cross phase modulation (IXPM) and intra-channel four wave mixing (IFWM) in a single channel system [8]. Recently IXPM has drawn considerable attention as phase- modulated formats are going to be implemented in near future for optical fiber communication. IXPM is caused by the modulation of a pulse phase by nonlinear interaction with neighboring pulses within the channel. It was shown that the pulse propagation in such conditions was described by the nonlinear Schrodinger equation with a distance-varying dispersion coefficient [7]. However, the analyses of phase fluctuations due to IXPM in phase modulated signal and their impact on fiber-optic transmission system has yet to be address completely. Recently some research on IXPM have been conducting [9]-[11] but the basic study with overall performance analyses due to IXPM distortion are still under research. Most of the researches did not consider the aspect of residual dispersion and its effects on intra-channel cross-phase modulation induced phase fluctuation.

This research work is intended to explore the influence of residual dispersion on IXPM induced phase fluctuation of RZ pulse in three different DM models having different residual dispersion. We have analyzed the phase shift induced by IXPM by using variational analysis [12]. Several dynamical equations are obtained for various pulse parameters. The phase fluctuation is calculated by solving these equations using Runge-Kutta method. Furthermore, we show the effect of various parameters on phase perturbation and therefore analyze the performance of the DM system with respect to random fluctuations of the dispersion. Finally split step Fourier method (SSMF) is used in some cases to validate the analytical results. This paper is organized as follows: variational analysis presuming IXPM as a perturbation has been presented in section 2. Section 3 gives the system description of different transmission models. The simulation results for different models have been highlighted in Section 4 stating the significance of various parameters that could affect IXPM. Finally the summary of work is stated in Section 5.

## 2. PROPOSED ALGORITHM

The dynamics of optical pulses in a dispersion managed optical communication system is governed by the modified nonlinear Schrodinger equation (MNLSE):

$$i\frac{\partial U_j}{\partial Z} - \frac{b}{2}\frac{\partial^2 U_j}{\partial T^2} + S(z)\left|U_j\right|^2 U_j = R_j, \tag{1}$$

Where $U\ (Z,\ T)$, $b(z)$, $S(z)$, $T$ and Z represent normalized envelop of electric field, dispersion parameter, nonlinear coefficients, normalized retarded time and propagation distance respectively. We assume that $A_j$, $p_j$ , $C_j$, $\kappa_j$, $\tau_j$ and $\theta_j$ represent the *j-th* pulse's amplitude, reciprocal of pulse width, linear chirp, central frequency, central time position and the phase of the pulse, respectively. Then the solution of Equation (1) can be approximated by a Gaussian pulse which is associated with linear chirp as:

$$U_j(Z,T) = A_j(Z)\exp\left(\frac{-\tau_j^2}{2}\right)\exp(i\phi_j),$$

Assuming IXPM as the sole perturbation, $R_j$ is can be defined as:

$$R_j = -2S(Z)\left|U_{3-j}\right|^2 U_j = -2S(Z)A_{3-j}^2 A_j\exp\left(-\tau_{3-j}^2\right)\exp\left(-\frac{\tau_j^2}{2}\right)\exp\left(i\phi_j\right)$$

The dynamical equations with perturbation can be written for two pulses ($j$ = 1, 2) as:

$$\frac{dp_j}{dZ} = b(Z)\,p_j^3 C_j + R_{p_j} \tag{2}$$

$$\frac{dC_j}{dZ} = -b(Z)\,p_j^2\left(1+C_j^2\right) - \frac{S(Z)}{\sqrt{2}}A_j^2 + R_{C_j} \tag{3}$$

$$\frac{d\kappa_j}{dZ} = R_{\kappa_j} \quad (4)$$

$$\frac{dT_j}{dZ} = b(Z)\kappa_j + R_{T_j} \quad (5)$$

$$\frac{d\theta_j}{dZ} = -\frac{b(Z)}{2}\left(\kappa_j^2 - p_j^2\right) + \frac{5S(Z)}{4\sqrt{2}}A_j^2 + R_{\theta_j} \quad (6)$$

Where:

$$R_{p_j} = \frac{p_j}{\sqrt{\pi}A_j}\int_{-\infty}^{\infty}\mathrm{Im}\left[R_j e^{-i\varphi_j}\right]\left(1-2\tau_j^2\right)\exp\left(-\frac{\tau_j^2}{2}\right)d\tau \quad (7)$$

$$R_{C_j} = \frac{2}{\sqrt{\pi}A_j}\int_{-\infty}^{\infty}\left\{\mathrm{Re}\left[R_j e^{-i\varphi_j}\right] - C_j\,\mathrm{Im}\left[R_j e^{-i\varphi_j}\right]\right\}\left(1-2\tau_j^2\right)\exp\left(-\frac{\tau_j^2}{2}\right)d\tau \quad (8)$$

$$R_{\kappa_j} = \frac{2p_j}{\sqrt{\pi}A_j}\int_{-\infty}^{\infty}\left\{\mathrm{Re}\left[R_j e^{-i\varphi_j}\right] - C_j\,\mathrm{Im}\left[R_j e^{-i\varphi_j}\right]\right\}\tau_j\exp\left(-\frac{\tau_j^2}{2}\right)d\tau \quad (9)$$

$$R_{T_j} = \frac{2}{\sqrt{\pi}A_j p_j}\int_{-\infty}^{\infty}\mathrm{Im}\left[\mathrm{R}_j e^{-i\varphi_j}\right]\tau_j\exp\left(-\frac{\tau_j^2}{2}\right)d\tau \quad (10)$$

$$R_{\theta_j} = -\frac{1}{2\sqrt{\pi}A_j p_j}\int_{-\infty}^{\infty}\left\{p_j\,\mathrm{Re}\left[R_j e^{-i\varphi_j}\right]\left(3-2\tau_j^2\right) + 4\kappa_j\,\mathrm{Im}\left[R_j e^{-i\varphi_j}\right]\tau_j\right\}\exp\left(-\frac{\tau_j^2}{2}\right)d\tau\,. \quad (11)$$

Here $\mathrm{Re}\left[R_j e^{-i\varphi_j}\right]$ and $\mathrm{Im}\left[R_j e^{-i\varphi_j}\right]$ represent the real and imaginary parts of $R_j e^{-i\varphi_j}$, respectively, and can given as:

$$\mathrm{Re}\left[R_j e^{-i\varphi_j}\right] = -2S(Z)A_{3-j}^2 A_j\exp\left(-\tau_{3-j}^2\right)\exp\left(-\frac{\tau_j^2}{2}\right)$$

$$\mathrm{Im}\left[R_j e^{-i\varphi_j}\right] = 0.$$

Now applying variational method and $E_j = \int_{\infty}^{\infty}\left|U_j\right|^2 dT = \sqrt{\pi}\,A_j^2/p_j$ which represents constant pulse energy of $U_j$, Equation (2)–(6) can be deduced as:

$$\frac{dp_j}{dZ} = b(Z)p_j^3 C_j \quad (12)$$

$$\frac{dC_j}{dZ} = -b(Z)p_j^2(1+C_j^2) - S(Z)\frac{E_j p_j}{\sqrt{2\pi}} - 4E_{3-j}p_{3-j}^2\left\{P^2 - 2(\Delta\tau)^2\right\}K \quad (13)$$

$$\frac{d(\Delta\kappa)}{dZ} = 4(E_1 + E_2)p_1 p_2 P^2(\Delta\tau)K \quad (14)$$

$$\frac{d(\Delta\tau)}{dZ} = b(Z)\{\Delta\tau\sum_{j=1}^{2}p_j^2 C_j + p_1 p_2\Delta\kappa\} \quad (15)$$

$$\frac{d\theta_j}{dZ} = \frac{-b(Z)}{2}\left(\kappa_j^2 - p_j^2\right) + S(Z)\frac{5E_j}{4\sqrt{2\pi}}p_j + E_{3-j}\left[2P^4 + p_{3-j}^2\left\{P^2 - 2(\Delta\tau)^2\right\}\right]K \quad (16)$$

Where $\Delta\kappa = \kappa_1 - \kappa_2$ , $P = \sqrt{(p_1^2 + p_2^2)}$

$K = \frac{S(Z)}{\sqrt{\pi}} \frac{p_1 p_2}{P^5} \exp\left\{ -\left(\frac{\Delta\tau}{P}\right)^2 \right\}$ and $\kappa_1(0) = \kappa_2(0) = 0$ . The pulse phase is evaluated by:

$$\theta_j(Z) = \theta_j(0) + \frac{5E_j}{4\sqrt{2\pi}} \int_0^z S(\zeta) p_j d\zeta - \int_0^Z b(\zeta)(\kappa_j^2 - p_j^2) d\zeta +$$
$$E_{3-j} \int_0^Z \left[2P^4 + p_{3-j}^2 \left\{P^2 - 2(\Delta\tau)^2\right\}\right] K(\zeta) d\zeta \qquad (17)$$

The phase shift observed at any pulse is deduced as $\Delta\theta = \theta_2 - \theta_1$, here $\theta_2$ is the observed phase when two pulses are transmitted and $\theta_1$ is the phase when single pulse is transmitted. Applying Runge-Kutta method, we can evaluate phase shift due to IXPM using (12) to (17).

## 3. SYSTEM DESCRIPTION

In the present investigation, we consider the case where Gaussian pulses are launched in a DM system. A long-haul single channel fiber-optic transmission line is considered for 1000km propagation. We have considered RZ signal format over NRZ because RZ pulse is significantly superior to NRZ when the intra-channel nonlinear effects are considered. Transmission line with highly dispersive fibers like standard single mode fiber (SSMF) and dispersion compensating fiber (DCF) is used to control the total residual dispersion. The fiber parameters for SSMF are taken as dispersion 17ps/nm/km, effective core area 80 μm², nonlinear index coefficient $2.5\times10^{-20}$ m²/W, and loss 0.21 dB/km when these are -100ps/nm.km, 20 μm², nonlinear index coefficient $3\times10^{-20}$ m²/W, and 0.5 dB/km for DCF. We have three different models, Model (A), Model (B) and Model (C) considering zero, positive and negative residual dispersion respectively. We vary the residual dispersion by changing the length $L_2$ of DCF segment keeping other variables constant. Typical dispersion managed transmission line models are shown in Figure 1.

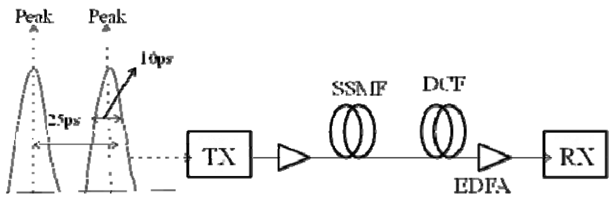


Figure 1. Transmission line models for a DM system

In Model (A) the residual dispersion is kept 0ps/nm per span. Here SSMF is followed by DCF in each period where length of SSMF is $L_1$= 43km and length of DCF is $L_2$=7.31km. The length of DCF is chosen such that it satisfies the equation $L_1D_1+ L_2D_2$=0 for zero residual dispersion at the end of each period where $D_1$ and $D_2$ are dispersion parameters of SSMF and DCF. In Model (B), 43km SSMF is followed by 7.21km DCF and in Model (C) 43km SSMF is followed by 7.41km DCF. The residual dispersion is +10ps/nm per span and -10ps/nm per span for Model (B) and Model (C) respectively. For both models the input pulse is operated at 40 Gb/s and the carrier wavelength is 1550nm. The minimum pulse width (FWHM) is taken as 10ps and the pulses have a difference in time domain of 25ps. Amplifiers are assumed to be noise free in our studies, as we focus on perturbations by nonlinear intra-channel effects only.

## 4. RESULTS AND DISCUSSION

Under the influence of dispersion and nonlinearities, the typical variation of the pulse shape within a single DM cell has been depicted in Figure 2.We numerically simulate the Gaussian pulse evolution in DM transmission system for the total transmission length of 1000 km. The numerical simulations have been carried out by directly solving Equation (1) using split-step Fourier method (SSFM). We observe a stationary pulse propagation in a dispersion managed system which is enviable for long haul transmission system.

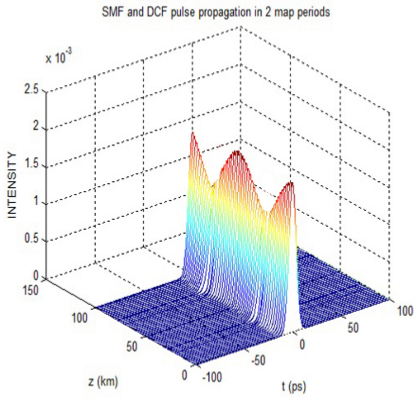


Figure 2. Single Pulse dynamics within the DM system with full numerical simulation

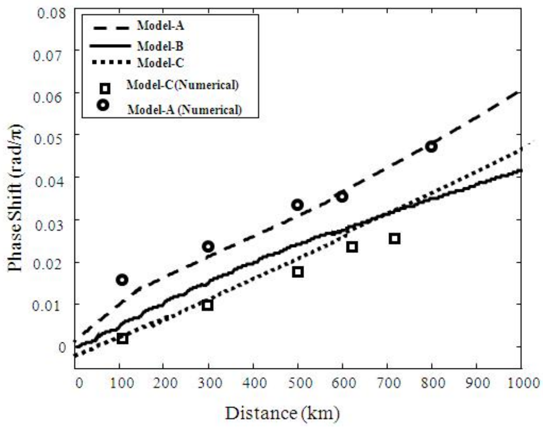


Figure 3. Phase fluctuation against transmission distance for different residual dispersion.

First we have focused our attention to the effects of residual dispersion on IXPM induced phase fluctuation with respect to transmission distance. Figure 3 shows maximum phase fluctuation versus transmission distance for three types of DM Models both analytically and numerically for 1000km propagation. The simulation is done at 40% duty cycle with a peak power of 1mW. Phase fluctuation increases linearly with the transmission distance which is shown in Figure 3. It is evident from the figure that different models give different amount of phase shift. But Model (B) and Model (C) have shown better performance compared to Model (A). The disagreement between the theoretical predictions and the numerical values are quite negligible.

Figure 4 depicts the phase shift behavior with initial peak power. In this section we have varied peak power and plotted the IXPM induced phase perturbation for all three models. It shows phase fluctuation is sensitive to residual dispersion. Every model experiences higher phase shift with greater input power. We notice Model (B) and Model (C) gives almost the similar result. Like the previous case Model (A) shows higher phase fluctuation.

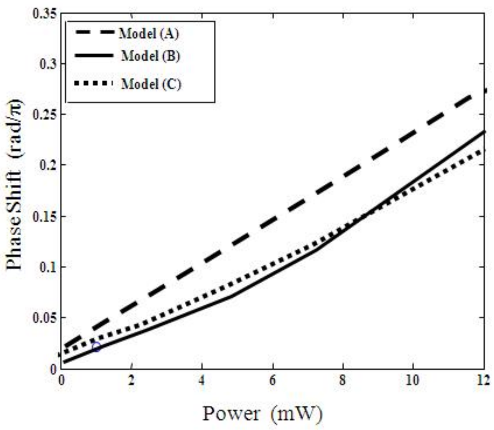


Figure 4. Phase perturbation is plotted as a function of initial peak power

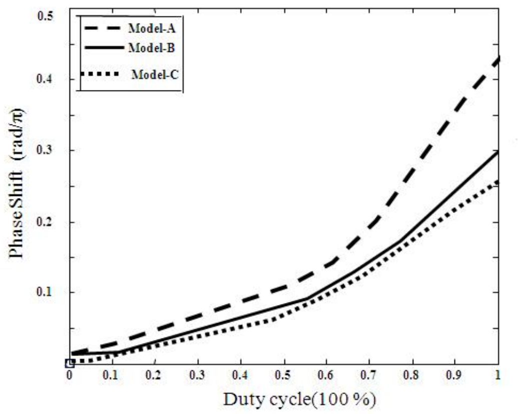


Figure 5. Effect of duty cycle on IXPM induced phase fluctuation for three models

Figure 5 illustrates the behavior of IXPM induced phase fluctuation with the change of duty cycle $d$ for 40 Gb/s system with a peak power of 1mW. We can see from Figure 5 when duty cycle $d \ll 1$, no pulses overlap and the phase shift is less for all three models. As duty cycle $d$ is increased, pulse broadens and the phase shift increases. Here the effect of IXPM depends on two factors: the level of pulse overlap and the intensity derivative in this context means the first derivative of pulse intensity. As interacting pulses are dispersed during propagation, their intensity derivatives are decreased while the pulse overlap region is increased. Therefore, when pulses strongly overlap each other, the intensity derivative of the pulses involved in the IXPM process is small due to the pulses being severely dispersed. On the other hand, the intensity derivative of the pulses is strong when the pulse overlap is small ($d$<<1). Hence, the IXPM is strongest when pulses partially overlap ($d \approx 1$) due to the compromise between the intensity derivatives of the interacting pulses and the level of overlap. Again we can say the models with some normal or anomalous residual dispersion show better performances.

Next we investigate the effect of bit rate on phase perturbation for 1000km propagation in Fig. 6. The system is operated at 50% duty cycle with a peak power of 2mW. The influence of IXPM is dominant at bit rate 40Gb/s and above. A continuous increase in phase shift is observed with increasing bit rate because pulse-to-pulse interaction increases with higher bit rates. Like the previous case Model (B) and Model (C) show lower phase fluctuation and their performance is comparable.

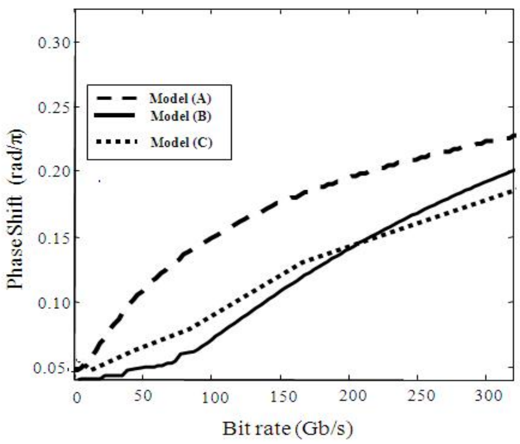


Figure 6. IXPM induced Phase fluctuation as a function of bit rate for three models

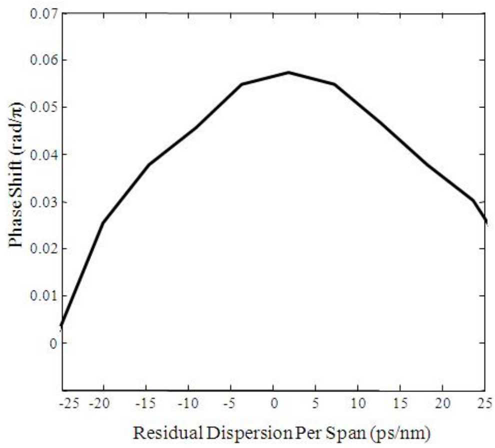


Figure 7. Phase shift versus residual dispersion per span for dispersion managed system

In Figure 7 we will check the impact of different normal and anomalous residual dispersion on IXPM induced phase fluctuation for a dispersion managed system. The amount of residual dispersion is varied up to ±25 ps/nm by changing the fiber length of DCF with a peak power of 1mW and 40% duty cycle. This result also suggests that some amount of positive or negative residual dispersion could be effective to suppress IXPM.

Finally we can say maintaining some residual dispersion is better than perfect dispersion compensation in order to obtain low phase fluctuation which is evident from above results.

## 5. CONCLUSION

In this paper impact of different residual dispersion on IXPM induced phase fluctuation has been investigated for long-haul fiber-optic transmission systems. The analytical model is based on variational method and we have obtained several ordinary differential equations for various pulse parameters. These equations have been solved by Runge-Kutta method to identify launching criteria of the system and its dynamical behavior in the nonlinear medium is also numerically simulated using the spilt-step Fourier method. Next nonlinear phase perturbation is ascertained for three different models with taking into account of the effects of IXPM only. We have considered the perfect dispersion compensation at the end of each period, i.e., there is no residual dispersion at the receiver end for Model (A). We have also considered two different models Model (B) and Model (C) considering positive and negative residual dispersion respectively. The influences of various parameters (such as transmission distance, input power, and duty cycle and bit rate) on IXPM induced phase shift have been explored for all models. It is clear from all results that a small amount of positive or negative residual dispersion offer lower phase fluctuation compared to perfect dispersion compensation. It can be said that residual dispersion per span will be beneficial to reduce nonlinear phase perturbation and a small anomalous residual dispersion is necessary to improve the transmission performance. Further DM modeling could be checked to attain lower IXPM-induced phase shift. Fiber Bragg gratings can also be considered for DM system instead of DCF. In order to obtain a complete real picture, experimental investigation can be done taking the combined effect of all other major effects including ASE noise, IFWM, stimulated Raman scattering and amplifier noise.

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