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Combating Cross Phase Modulation and its Polarisation Effects in Dense Wavelength Division Multiplexed Systems

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Abstract—Cross Phase Modulation is one of the major interchannel nonlinearity which occurs in multichannel systems. It is a nonlinear effect where the intensity of the optical signal propagating through the fiber alters the refractive index of the transmission medium through the Kerr effect. This causes phase shift between the co propagating signals and polarisation rotations even in the absence of polarisation mode dispersion. We theoretically and experimentally analyse the effects of XPM using OPTSIM simulator. A method to reimburse the effects of XPM is also proposed.

Keywords— Cross Phase Modulation, refractive index, phase shift, polarisation rotations, polarisation mode dispersion.

I. INTRODUCTION

Point to point fiber optic communication system uses only one wavelength normally. To serve today's ever increasing data traffic, more than one wavelength channels have to be sent through a single fiber. Several different wavelengths, transmitted over one single fiber at the same time is the upcoming trend to meet the customer's requirements. Channel capacity has to be increased at the lowest possible cost, this is done through the utilization of DWDM systems. In Dense Wavelength Division multiplex systems the wavelengths are closely spaced and the spacing will be 1.6 nm and less. Fiber nonlinearities present are interachannel and interchannel. The most concrete nonlinear effects are Self Phase Modulation, Cross Phase Modulation and Four Wave mixing. Cross Phase Modulation is one of the dominant degradation effects in NRZ transmission systems. When one or more signals propagate through the fiber, the change in the intensity of the optical beam produces anisotropic change in the refractive index. This causes a nonlinear polarisation dependent phase shift between the signals propagating through the same optical fiber, known as Cross Phase Modulation. XPM is a serious contender in high data rate transmission systems (i.e Gb/s, Tb/s) where the signals interact with each other. Cross Phase Modulation causes phase shift between the pulses, spectral broadening, pulse overlapping, timing jitter, amplitude distortions and polarisation rotations.

The change in the refractive index and the nonlinear phase change due to XPM in two channel WDM system is given in equation 1 and 2.

$$\Delta n_{NL} = n_2 \left(|I_1|^2 + b|I_2|^2 \right) \quad (1)$$

$$\varphi_{NL} = (2\pi L/\lambda)\, n_2[I_1(t)+bI_2(t)] \quad (2)$$

where I_1 and I_2 are the intensity of the signals, λ is the wavelength. Cross Phase Modulation in DWDM systems causes rapid changes in the state of polarisation of the signals [1]. To overcome this the transmitted bit is divided into two with the first bit transmitted at an orthogonal polarisation to the other. Due constant phase shift and polarisation rotations produced by XPM additional spectral components are generated in the optical spectra, which can be reduced by carrier suppression implemented by polarisation filtering [2]. The polarisation of the probe signal is launched at 45^0 with respect to the fiber axis. Therefore its polarisation rotates from linear to circular. The polarisation difference between the pump and probe is random, so the XPM effect reduces. XPM effect weakens when adjacent channels are transmitted at an orthogonal polarisation to each other.

II. CROSS PHASE MODULATION AND ITS POLARISATION EFFECTS

Cross Phase Modulation is described by a set of modified nonlinear Schrodinger equation as in 3 and 4.

$$\frac{\partial E1}{\partial z} + \beta_{11}\frac{\partial E1}{\partial t} + \frac{i\beta 21}{2}\frac{\partial^2 E1}{\partial t^2} + \frac{\alpha_1}{2} E_1 = i\gamma_1 [\,|E_1|^2 + \eta |E_2|^2\,]E_1 \quad (3)$$

$$\frac{\partial E2}{\partial z} + \beta_{12}\frac{\partial E2}{\partial t} + \frac{i\beta 22}{2}\frac{\partial^2 E2}{\partial t^2} + \frac{\alpha_2}{2} E_1 = i\gamma_2 [\,|E_2|^2 + \eta |E_1|^2\,]E_2 \quad (4)$$

where E_1 and E_2 are the electric fields, β_{1i} (i=1,2) and β_{2i} are the inverse group velocities and group velocity dispersion coefficients respectively. α_1, α_2 are the fiber losses. η is the XPM coefficient and it is denoted as in equation 5.

$$\eta = \frac{2}{3}(1+2\cos^2\theta) \quad (5)$$

θ is the angle between the polarisation of the two signals. Polarisation is the orientation of wave in space. Energy of the signal is divided into two polarised modes according to which polarised signals are of two types, single polarised signals and dual polarised signals. The former has horizontally polarised signals wherein the latter has both horizontal and vertically polarised signals. XPM causes polarisation rotation which induces polarisation scattering. Polarisation scattering depolarises the two polarisation components and causes crosstalk between the X and Y polarisation components. Hence it is obligatory to remove Cross Phase Modulation in Fiber Optical transmission systems.

III. PROPOSED COMPENSATION METHOD

XPM decorrelates the polarisation signal and also causes phase shift between the propagating signals. The phase shift can be compensated by introducing an instantaneous phase shift contrary to the phase shift produced by XPM. This is done by using a phase modulator. The proposed method is used to compensate XPM that uses mixed modulation DWDM network.

The optical signal after the fiber is split into single polarised and dual polarised signals using polarisation beam splitter (PBS). DGD module receives the dual polarised signals and it applies walk off to the polarisation components of the dual polarised signals (DP), there is no polarisation rotation in SP signals.

Parts of single polarised signals (SP) may also go through the DGD module.

IV. SIMULATION SETUP

The simulation setup in figure 1 shows a DWDM network which has mixed modulation transmitters. The DWDM system has N transmitters with the first few set of channels using on-off keying (OOK) modulation that produces single polarised signals and the second set of channels uses dual polarised quadrature phase shift keying (DP-QPSK) modulation which produces dual polarised signals. The wavelength channels are combined using wavelength division multiplexer and it is transmitted through the optical fiber. The other nonlinearities in the fiber are turned off to analyse the effects of XPM clearly. The PMD of the fiber is maintained low to examine the XPM effects on polarisation of the signal. Small amount of chromatic dispersion (1-2 ps/nm/km) in the system changes the propagation constant of the signals causing walk away phenomenon. This prevents interaction between the propagating signals thus reducing XPM, as interaction is the major cause for Cross Phase Modulation. The signal after the fiber is split into SP and DP signals. The DP signal is sent to the polarisation controller which is used set the state of polarisation of the signal at 45^0 to yield the splitting of the signal into X component and Y component inside the DGD module. DGD is any suitable component configured to introduce delay between the different polarisations of a dual polarised signal. Knowledge of the transmitted signals is necessary to eliminate XPM in the transmission system this is done by the photodetector. It detects the XPM across its neighbouring channels by detecting the low frequency fluctuations across them.

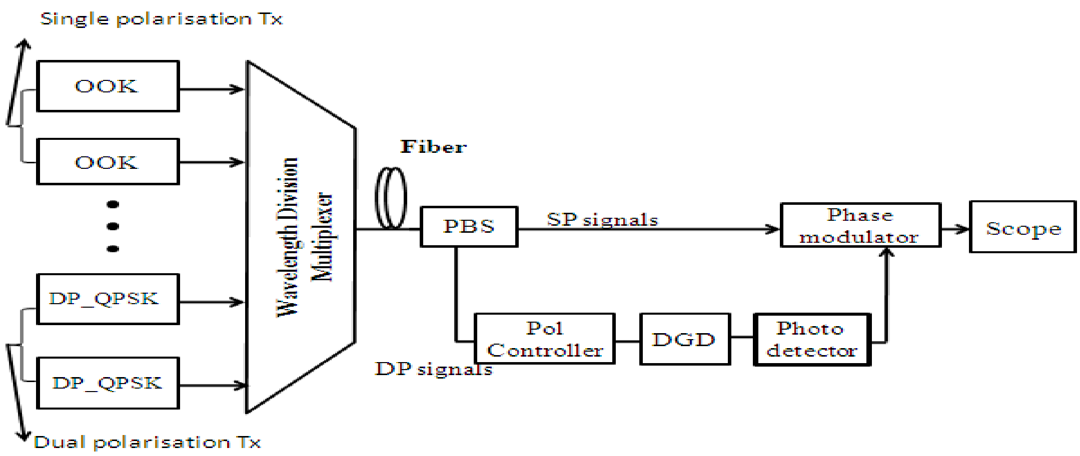

Fig 1 Block diagram for the proposed XPM compensation method

The phase modulator modulates the phase of the SP signals with respect to the electrical signal thereby eliminating the phase errors caused by Cross Phase Modulation. The resulting signal is analysed using a scope. The system specifications are shown in table 1.

Table1
Specifications of DWDM

Parameter	**Range**
Fiber Length	100 km and above
Attenuation	0.25 dB/km
Data rate	100 Gb/s and above
Number of Channels	More than 360
Wavelength range	1450-1650 nm covering C,L and S bands

The system parameters are set and XPM is analysed by varying the dispersion coefficients. System performance is analysed using eye diagrams because they clearly represent the data handling capacity of the system. Width of the eye opening explains the distortions in the amplitude of the received signal. Higher the width of the eye opening lesser is the amplitude distortions which shows that the efficiency of the system is more. In the eye diagram intensity distortion manifests itself as broadening of the horizontal rails, phase errors on the other hand appears as broadening of the edges. Performance measure is done by calculating the Q factor. It is calculated using mean and standard deviation of the signal samples taken at the optimum sampling instant and considering the optimum decision threshold, i.e., using equation 6

$$Q = \frac{m_1 - m_0}{\sigma_1 + \sigma_0} \quad (6)$$

where m_1, m_0, σ_1, σ_0 are the mean and standard deviation of the signal samples when a "1" or a "0" is received. Q factor can be obtained by using Q estimator present in the OPTSIM simulator.
The eye diagram obtained from the analysis before and after compensation is shown in figure 2,3,4,5.

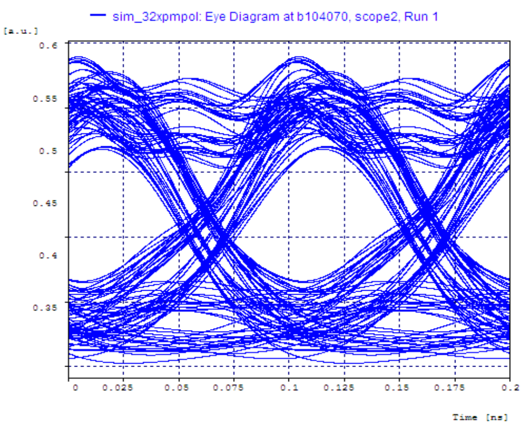

Fig 2 Eye Diagram obtained before XPM compensation in 32 channel DWDM system.

In figure 2 and 4, the width of the eye opening is less and the edges are also broadened, this shows that intensity distortions and phase errors are present in the transmission system. In figure 3 and 5 the distortions in the eye diagram is less, this shows that errors due to XPM is compensated.

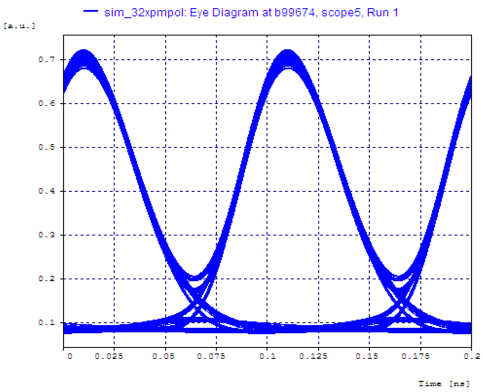

Fig 3 Eye Diagram obtained after XPM compensation in 32 channel DWDM system.

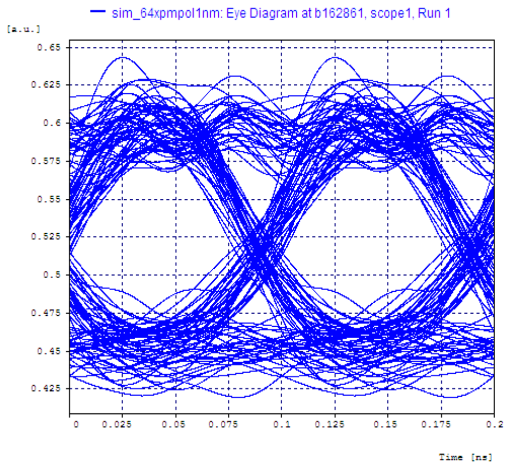

Fig 4 Eye Diagram obtained before XPM compensation in 64 channel DWDM system.

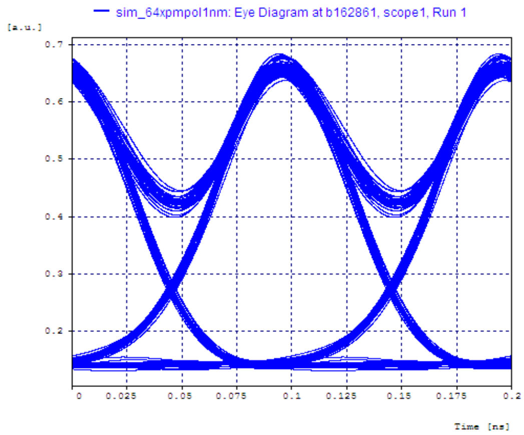

Fig 5 Eye Diagram obtained after XPM compensation in 64 channel DWDM system.

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The Q factor obtained in a 32 channel DWDM system before compensating XPM is 17.435 dB and eye opening obtained is 0.5108 ns. After compensating Cross Phase modulation the Q value obtained is 32.931 dB and eye opening is 0.59927 ns. Similarly Q value for 64 channel DWDM system before and after compensation is 15.731 dB and 30.578 dB respectively. The eye opening before and after compensation is 0.5235 ns and 0.58562 ns. XPM is also investigated by varying the channel spacings.

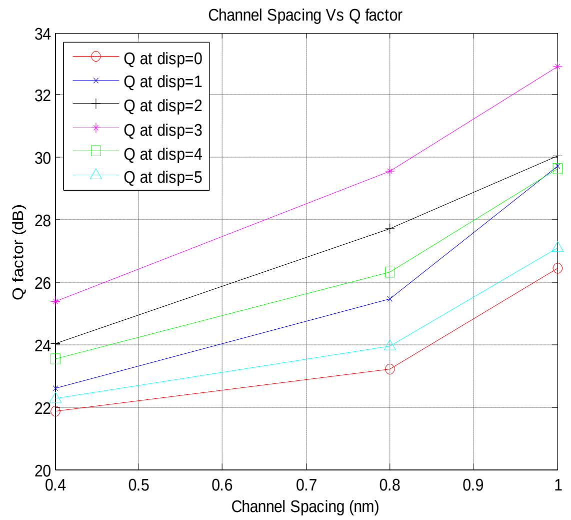

Fig 6 Q factor Vs Channel Spacing for Dispersion coefficient, D=0-5 ps/nm/km

Figure 6 shows the Q factor values for different dispersion coefficients. Dispersion in small amount reduces XPM. Q value is very less for zero dispersion because of maximum interaction (no walk off effect for zero dispersion). For very large dispersion coefficients degradation of the system is found to occur.

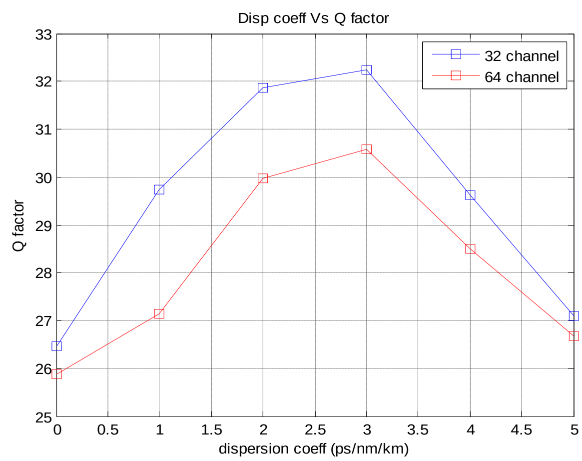

Fig 7 Q factor Vs Dispersion coefficient

From figure 7, it is observed that interaction between the individual channel increases as the number of channel increases, therefore the Q value is found to decrease with increase in the number of channels.

IV. RESULTS AND CONCLUSION

A system that reduces Cross Phase Modulation and the polarisation scattering caused by it has been proposed. The system uses only low bandwidth components like phase modulator, photodetector and DGD module. Phase errors, polarisation scattering and pulse broadening induced by XPM is analysed for various dispersion coefficients. Analysis shows that maximum interaction occurs at zero dispersion coefficient and as the dispersion coefficient increases, interaction among the channel reduces due to the walk off phenomenon. This method can also work well in DWDM system with more than 400 channels but for easy interpretation channels upto 64 is shown.

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