

Performance Limitations of WDM Optical Transmission System Due to Cross-Phase Modulation in Presence of Chromatic Dispersion

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Abstract — With the increasing demands on the capacity of wavelength division multiplexed (WDM) systems, nonlinear effects including inter-channel crosstalk become increasingly important. One of the most significant nonlinear effects in this context is cross-phase modulation (XPM) in optical fiber and accurate determination of this effect is an important issue in the design of WDM optical system. This paper presents XPM theory in brief and simulation results for intensity fluctuation due to XPM in an intensity modulation-direct detection (IM-DD) WDM optical transmission system at a bit rate of 10 Gbit/s. The spectral characteristics have been found to be strongly dependent on channel spacing and dispersion coefficient. It is shown that the system suffers maximum penalty due to XPM effect at zero dispersion coefficient and XPM interference is linearly dependent on the optical powers of the injected signals in a very large range of system parameters. For example, the eye opening penalty is about 8.10 dB and 1.45 dB for corresponding dispersion coefficients of 0.5 ps/nm-km and 4.0 ps/nm-km respectively at a probability of 10^{-3} .

Keywords — WDM, XPM, Chromatic Dispersion, DSF, EDFA.

1. Introduction

By overcoming the attenuation limits on optical transmission distance with the advent of Erbium doped fiber amplifiers (EDFA) the field of optical communication has gained tremendous advances. But major limitations in the transmission medium are the chromatic dispersion (CD) and nonlinearities like self phase modulation cross-phase modulation (XPM) and stimulated scattering and their distribution over the propagation direction, which degrade the performance of wavelength division multiplexing (WDM) optical transmission systems [1]-[10]. In general, the nonlinear effect XPM is caused by the modulation of the nonlinear refractive index by the total optical power in the fiber. In the presence of CD this would result in the modulation of the optical phase and the intensity of various signals would be affected.

The performance degradation caused by XPM on intensity modulation-direct detection (IM-DD) WDM systems has been investigated through computer simulations [4]-[6] and experiments [7]-[8]. The extent of the intensity fluctuations caused by XPM as a function of channel separation has been investigated experimentally and numerically [9] and the

dependence of XPM-induced intensity modulation on the fiber length, channel separation and modulation frequency has been investigated theoretically and numerically in single segment fiber links [10].

In this paper, we have outlined the XPM theory and simulated the intensity fluctuation characteristics of probe signal in a 2-channel WDM transmission system due to XPM in terms of eye diagram and other related parameters in a single mode dispersion shifted fiber (DSF) in presence of CD. It is shown that at zero CD the intensity fluctuation is highest in the probe channel and injected pump or probe power maintains a linear relationship with XPM interference.

2. System model

The block diagram of a pump-probe configuration WDM system with EDFA in cascade used for theoretical analysis is shown in Fig.1. The pump and probe are multiplexed by WDM MUX and the composite signal is transmitted through a single mode DSF. To describe the effect XPM, we assume that the pump, A_1 act as channel 1, which modulates the transmitted (f_1) data from the laser diode at wavelength, λ_1 and the probe, A_2 act as channel 2, which is a low-power continuous wave (cw) at wavelength, λ_2 and frequency, f_2 . The in-line EDFA's are used in cascade to compensate the fiber losses. Finally, the composite signal is demultiplexed at WDM DEMUX and from the modulated carrier, λ_2 original signal f_2 is recovered through IM-DD method.

3. Theory

The theoretical analysis begins with the nonlinear wave propagation equation [1]. The equation of pump and probe can be written as,

$$\frac{\partial A_1(t, z)}{\partial z} = -\frac{\alpha}{2} A_1(t, z) - \beta_{11} \frac{\partial A_1}{\partial t} - i \frac{\beta_{21}}{2} \frac{\partial^2 A_1}{\partial t^2} + i \gamma_1 p_1(t, z) A_1(t, z) + 2 i \gamma_1 p_2(t - z/v_2, z) A_1(t, z) \quad (1)$$

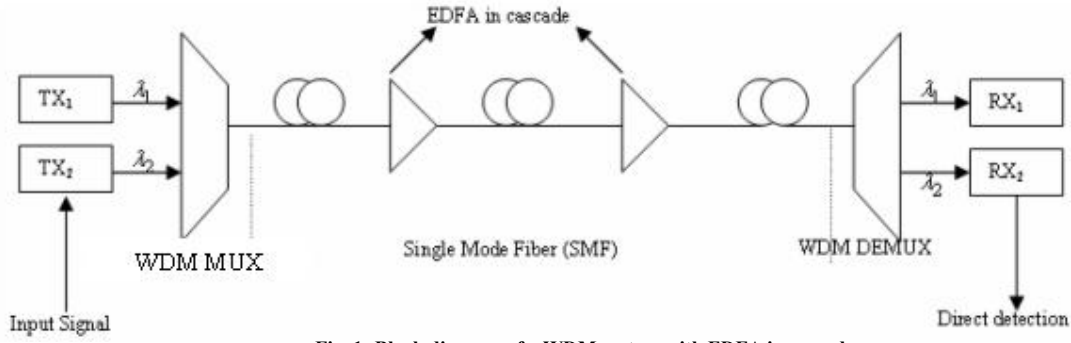


Fig. 1: Block diagram of a WDM system with EDFA in cascade

$$\frac{\partial A_2(t, z)}{\partial z} = -\frac{\alpha}{2} A_2(t, z) - \beta_{12} \frac{\partial A_2}{\partial t} - i \frac{\beta_{22}}{2} \frac{\partial^2 A_1}{\partial t^2} + i \gamma_2 p_2(t, z) A_2(t, z) + 2 i \gamma_2 p_1(t - z/v_1, z) A_2(t, z) \quad (2)$$

Where α is the attenuation coefficient of the fiber, $\beta_{2(1,2)}$ is the CD parameter, $\gamma_{1,2} = 2\pi n_2 / (\lambda_{1,2} A_{eff})$ is the nonlinear coefficient, n_2 is the nonlinear refractive index, λ_1 and λ_2 are the pump and probe signal wavelengths. A_{eff} is the fiber effective core area. $p_1 = |A_1|^2$ and $p_2 = |A_2|^2$ are optical powers of the pump and the probe respectively.

The frequency domain description of the intensity fluctuation in the probe channel caused by the intensity modulation of the pump channel according to Ref. [16] can be given by,

$$\Delta \tilde{s}_{21}(f_2, L) = 4\gamma_2 p_2(L) p_1(f_2, 0) \frac{\sin(\beta_{22} f_2^2 L / 2)}{\alpha - i f_2 d_{21}} \exp(i f_2 / v_2 L) \quad (3)$$

Equation (3) can be generalized to analyze multispan optically system, where the intensity fluctuation at the receiver is the accumulation of the XPM contributions created by each fiber span.

In the time domain, the probe output optical power with XPM-induced crosstalk is,

$$p_{21}(t, L) = p_2(L) + \Delta s_{21}(t, L) \quad (4)$$

where $\Delta s_{21}(t, L)$ is the inverse Fourier transform of $\Delta \tilde{s}_{21}(f_2, L)$ and $p_2(L)$ is the probe power output without XPM. $\Delta s_{21}(t, L)$ has a zero mean. The originally cw probe is intensity modulated by the pump through the XPM process.

After the square-law detection of a photodiode, the electrical power spectral density is the Fourier transform of the autocorrelation of the time domain optical intensity waveform. Therefore, we have,

$$p_2(f_2, L) = R_d^2 \{ p_2^2(L) \delta(f_2) + |\Delta \tilde{s}_{21}(f_2, L)|^2 \} \quad (5)$$

where δ is the Kronecker delta and R_d is the photodiode responsivity. For $f_2 > 0$, the XPM induced crosstalk in the probe channel, normalized to its power level without this effect can be expressed as,

$$\Delta p_{21}(f_2, L) = \frac{R_d^2 |\Delta \tilde{s}_{21}(f_2, L)|^2}{R_d^2 p_2^2(L)} = \left| 4\gamma_2 p_1(f_2, 0) \exp(i f_2 d_{21} L) \frac{\sin[f_2^2 \beta_{22} L / 2]}{\alpha - i f_2 d_{21}} \right|^2 \quad (6)$$

We define $\Delta p_{21}(f_2, L)$ as the normalized XPM power transfer function.

4. Simulation setup and description

In this work, we use the Rsoft OptSim simulation software that gives us the environment almost the exact physical realization of a system. OptSim provides the users with laser diodes, filters, modulators and all the components which are essential to build an optical network. The simulation setup for a pump-probe configuration for a NRZ modulated WDM system is shown in Fig. 2. This simulation is carried out to observe the effect of XPM in a pump-probe configuration in presence of CD. The different simulation parameters that are used in the simulation are shown in Table 1. The 2-WDM channels are launched over two DSF spans of 100 km each where fiber loss is totally compensated by the EDFA and CD is completely compensated at each span by the fiber Bragg grating. The interaction of XPM depends upon the fiber's CD due to walk off effects between the pump and probe. So, we varied the CD coefficient from 0 - 6 ps/nm-km and observe XPM effects on the transmission system. This system consists of three major sections, i.e., transmitter section, fiber section and receiver section.

A. Transmitter section

The transmitter consists of a PRBS generator, which generates pseudo random bit sequences at the rate of 10 Gbit/s with $2^7 - 1$ bits. This bit sequence is fed to the NRZ

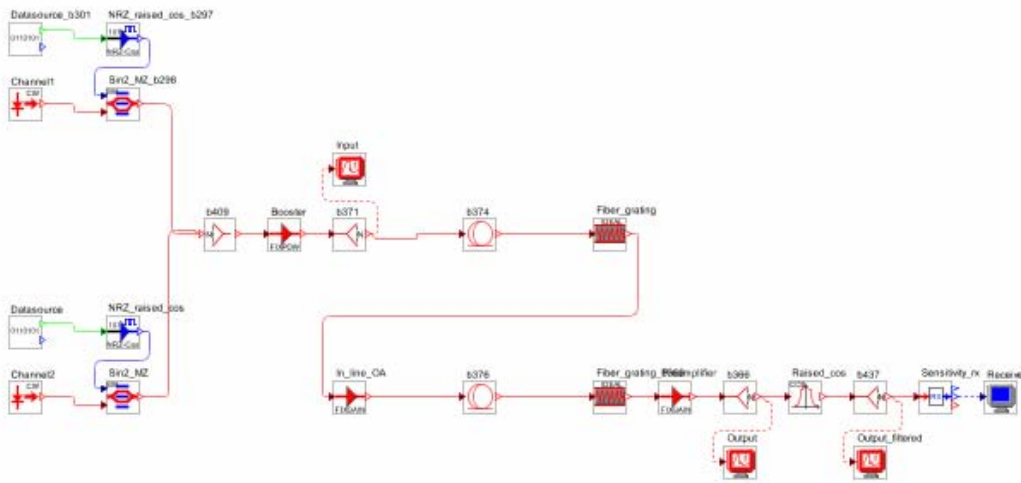


Fig. 2: Setup of the system simulation model for pump-probe WDM/ IM-DD transmission system

coder that produces an electrical NRZ coded signal. Two channels are used in this simulation. One is the pump signal which has higher power and produces phase modulation of the neighbouring channel. This pump channel operates at the frequency of 193.075 THz which is equivalent to 1552.725 nm wavelength channel. The probe channel operates at 193.025 THz which is equivalent to 1553.127 nm wavelength channel. The modulator used here is the Mach-Zehnder modulator. It has two inputs, one for the laser diode and the other for the data from the channels. There are two Mach-Zehnder modulators used, one for pump channel and one for probe channel. It converts the electrical signal into optical signal form.

B. Fiber section

The combined optical signal is fed into the fiber which is a single mode DSF. The fiber model in OptSim takes into account the unidirectional signal flow, stimulated and spontaneous Raman scattering, Kerr nonlinearity and dispersion. Here, we can set the length, dispersion parameters, attenuation, nonlinear index, core area of the fiber and XPM options. The parameters are adjusted according to the simulation environment and given in Table 1. At the output of the fiber, the probe signal would have undergone the XPM effects and the waveform at the output will be distorted.

C. Receiver section

At the output of the trapezoidal optical filter (for the probe channel), a photodiode converts the optical signal into an electrical signal. An electrical low pass Bessel filter follows the avalanche photodiode. This has a cut-off frequency determined by the type of the waveform used for modulation and in our case 193.125 THz. Finally at the output of the low pass filter, OptSim provides a visualization tool called *Scope*. It is an optical or electrical oscilloscope with numerous data processing options, eye display and BER estimation features. If the eye opening is very wide and there is no crosstalk. Eye diagrams can be

used to effectively analyze the performance of an optical system. Eye diagrams clearly depict the data handling capacity of an optical transmission system. The more the eye is open, the more efficient the system. Performance degradation will directly affect the eye diagrams which in turn results in reduced eye opening and time jitter at the edges.

5. Results and discussion

Here, we investigate the effect of XPM on WDM optical transmission system in terms of eye diagram, BER, input pump and probe power etc. The channels are modulated at 10 Gbit/s data rate using NRZ format and separated by 0.8 nm, the distance between the in-line optical EDFA fiber amplifiers is 100 km (span length).

The input and output optical spectrum of the pump and probe are shown in Fig. 3 and Fig. 4 respectively. It is noticed that optical signal after propagating 200 km fiber link, the output optical spectrum is distorted and two new frequencies are generated due to fiber nonlinearity.

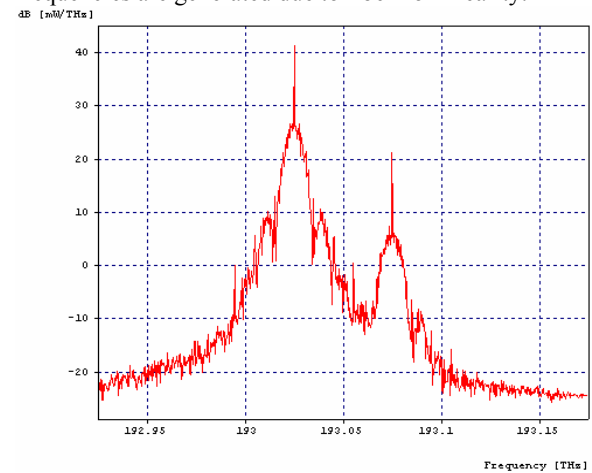


Fig. 3: pump and probe optical spectrum at the input

To assess the impact of XPM on the transmission system in electrical domain we monitor the probe signal eye diagram at the input (back-to-back) as well as at the output for a receiver sensitivity of -24 dBm (at a BER of 10^{-9}). Fig. 5 shows the eye diagrams at the input and output of the fiber link of probe channel for different dispersion coefficient. It is observed that for a fixed channel spacing (50 GHz in this case) probe channel eye diagram deteriorates more at lower values of dispersion.

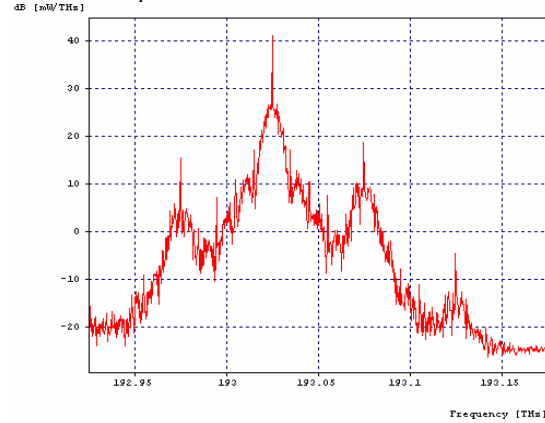


Fig. 4: pump and probe optical spectrum at the output

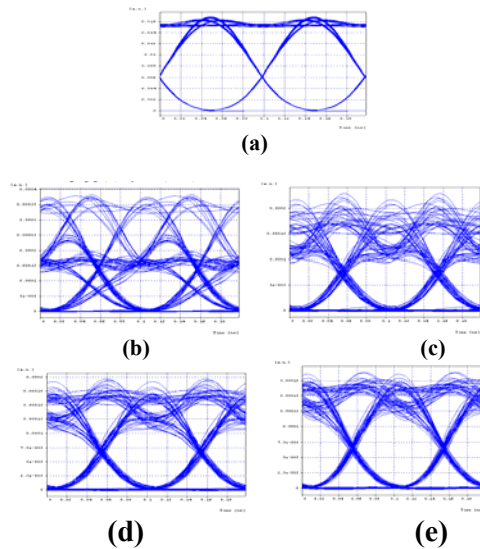


Fig. 5: (a) Base line eye diagram (back-to-back), (b) output eye diagram for $D= 0$ ps/nm-km (c) output eye diagram for $D= 1$ ps/nm-km (d) output eye diagram for $D= 2$ ps/nm-km (e) output eye diagram for $D= 3$ ps/nm-km and (f) output eye diagram for $D= 4$ ps/nm-km of probe signal

The plots of BER vs. input pump power and BER vs. input probe power are shown in Fig.6 and Fig.7 for various values of dispersion coefficient. It is observed (Fig. 6) that the XPM impact is maximum at zero dispersion coefficient *i.e.*, the BER is significantly higher and it is about 10^{-2} and as the dispersion coefficient increases the effect becomes less due to the walk-off phenomenon. On the other hand, as pumps power increases the BER decreases due to the larger effect of XPM on the probe signal. From Fig. 7, it is found

that at zero dispersion the BER is very high when the probe power varies from -30dBm to -20dBm. For higher values of dispersion coefficient, input probe power has little impact on the BER performance. Here, we also notice that dependence of the XPM interference on the pump or probe powers are almost linear in a very large range of parameters, although XPM effect itself is highly nonlinear.

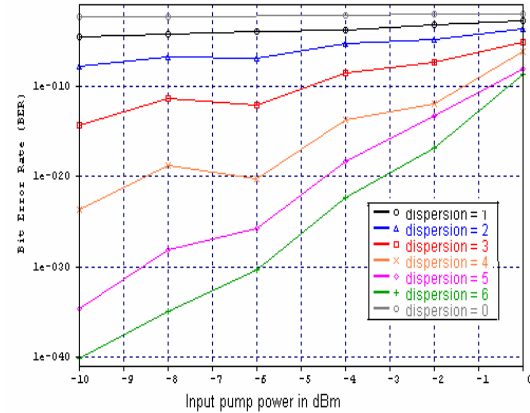


Fig.6: BER vs. pump power in dBm for different chromatic dispersion coefficient (probe power = -30 dBm)

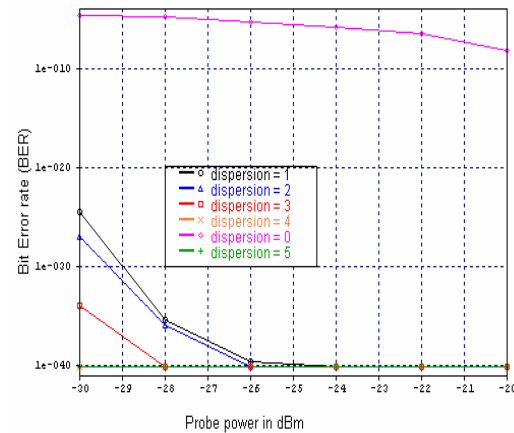


Fig. 7: BER vs. probe power in dBm for different chromatic dispersion coefficient (pump power = -10 dBm)

We may calculate the average eye-opening penalty (EOP) due to XPM for the probe signal. Here, we define the parameter of the eye-opening penalty (EOP) as,

$$EOP = -20 \log \left(\frac{B}{B_0} \right) \quad (1)$$

Where, B is the eye opening without XPM effect and B_0 is the eye-opening with XPM in the probe. From Fig.8, it is observed that the EOP is highest at zero dispersion and becomes lower as the dispersion coefficient increases. For example, at dispersion 0.5 ps/nm-km the EOP is about 8.10 dB and at 4 ps/nm-km it is 1.45 dB. So, at higher dispersion the transmission system is less affected by the XPM.

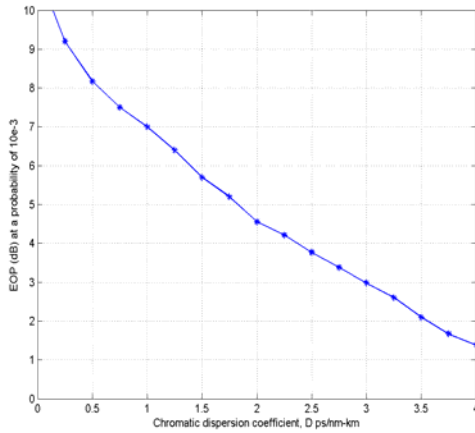


Fig.: 8: Eye opening penalty (EOP) at a probability of 10^{-3} in the dependence of chromatic dispersion for 2-channel WDM transmission system

Parameter (unit)	Values
Pump wavelength(nm)	1552.7254
Probe wavelength (nm)	1553.127
Channel separation (GHz)	50
Pump power (dBm)	-10 to 4
Probe power (dBm)	-30 to -20
Reference bit rate (Gbit/s)	10
Attenuation (dB/km)	0.2
Fiber length (km)	200
Dispersion coefficient (ps/nm-km)	2.158
Booster amplifier gain (dBm)	6
Preamplifier gain (dB)	25

Table 1: different simulation parameters

6. Conclusion

A detailed simulation is carried out to evaluate the performance limitations of a WDM transmission system due to XPM at 10 Gbit/s bit rate using single mode DSF. XPM is the most serious effect that limits the allowable input power and system capacity by generating intensity modulated power causing more noise at the receiver in long haul WDM transmission system. We analyzed to quantify the XPM effect in terms of realizable parameters in a 2-channel WDM system. Performance criteria are expressed in terms of BER and EOP. The effect of XPM in IM-DD WDM system is expected to be smaller in systems operating at lower bit rates and higher dispersion coefficients. We have shown that the XPM effect is highly dependent on dispersion coefficient of the fiber and the dependence of nonlinear XPM interference on the optical powers of the injected signal is almost linear in a very large range of parameters. This property is very useful in scaling the impairments caused by XPM with signal powers.

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