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Full Length Research paper

Effect of chromatic dispersion on four-wave mixing in WDM optical transmission system

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Crosstalk due to four-wave mixing (FWM) is the dominant nonlinear effect in long-haul multi-channel optical communication systems which can severely limit system performance. In this paper, we have simulated the effect of chromatic dispersion on FWM using equal and unequal channel spacing in terms of input/output spectrum, eye diagram and bit error rate. Results show that the effect of FWM reduces with the increasing dispersion coefficient but the reduction is more effective for unequal channel spacing than equal channel spacing.

Key words: Four-wave mixing, optical communication, chromatic dispersion, bit error rate, Q-factor, eye diagram.

INTRODUCTION

Very high-capacity, long-haul optical communication systems are made possible by the extremely wide bandwidth of optical fibers which is best exploited by wavelength-division multiplexing (WDM) (Agrawal, 2002). The performance of long-distance optical communication systems is limited, however, by chromatic dispersion and nonlinear effects of fiber, which interact and accumulate along the length of the optical link. Chromatic dispersion, which broadens the pulses can be reduced by using dispersion-shifted fibers (DSFs) at the 1550 nm wavelength range, but low chromatic dispersion enhances some nonlinear effects of fiber, especially four-wave mixing (FWM) (Agrawal, 2001). FWM is of a particular concern on account of its relatively low threshold power and rises very quickly as the number of channels increased. The number of FWM product with channel number is shown in Figure 1. The efficiency of FWM crosstalk generation can be reduced by increasing the frequency separation between the various channels (Waarts and Braun, 1986), increased channel separation would preclude dense WDM systems. To suppress FWM-induced crosstalk in WDM systems in dispersion-shifted fiber, the unequal channel-spacing scheme was proposed and worked quite well for most cases since it avoids generating FWM products to fall on to any channels (Shuxian, 2000; Inoue, 1994). However, the newly produced FWM products can mix with channel signals or themselves to produce higher-order FWM products which can overlap with channels and result in crosstalk (Shibata et al., 1987; Forghieri et al., 1994). In this paper, we have simulated the effect of FWM products in an intensity-modulated direct-detection (IM-DD) WDM environment by varying the chromatic dispersion parameter for equal and unequal channel spacing.

It is observed that the effect of FWM is maximum when channel of the chromatic dispersion coefficient is zero.

THEORITICAL ANALYSIS

FWM is a nonlinear process in optical fibers in which generally three signal frequencies combine and produce several mixing products. It originates from the weak dependence of the fiber refractive index on the intensity of the optical wave propagating along the fiber through

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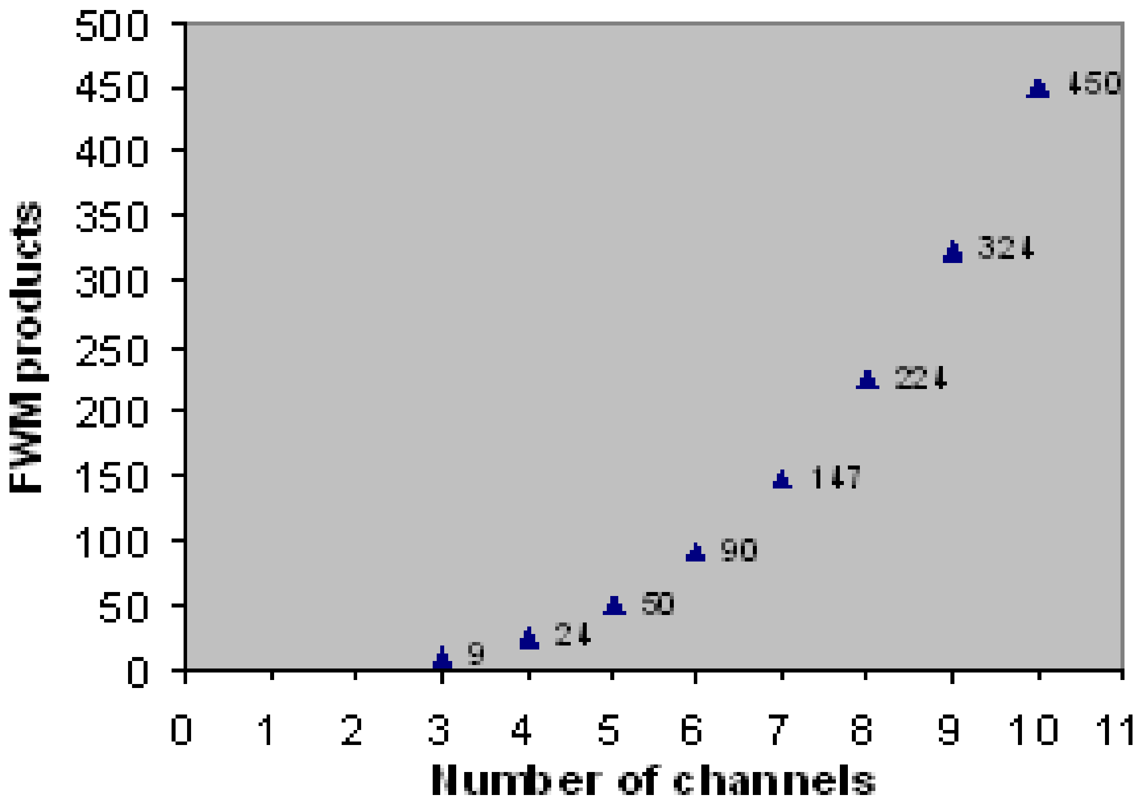

Figure 1. Number of FWM products.

the third order nonlinear susceptibility. If three signal waves three frequencies f_a, f_b and f_c are incident at the fiber input, the new waves generated whose frequencies are:

$$f_{abc} = f_a + f_b - f_c \quad \text{where, } (a,b,c = 1,2,3) \tag{1}$$

The number of the side bands use to the FWM increases geometrically, and is given by:

$$M = \left(\frac{N^3 - N^2}{2}\right) \tag{2}$$

Where, *N* is the number of channels and *M* is the number of newly generated side bands. For example, eight channels produce 224 side bands. Figure 1 shows the FWM products due to the channels increases.

If we assume that the input channels are not depleted by the generation of mixing products, the power of the new optical signal generated at frequency exiting the fiber is given by:

$$P_{FWM} = \frac{1024\pi^2}{n^4\lambda^2c^2}\left[\frac{D\chi_{111}L_{eff}}{A_{eff}}\right]^2 P_aP_bP_ce^{-\alpha L}\eta \tag{3}$$

Where *n* is refractive index, λ is the wavelength, P_a, P_b and P_c are the input power of three waves, D is the degeneracy factor. χ_{111} is nonlinear susceptibility and $\chi_{111} = 4\times10^{-15}esu$ and η is the mixing efficiency, A_{eff} is the effective area of the fiber and L_{eff} is the effective length of fiber.

The four wave mixing (FWM) efficiency η is given by:

$$\eta = \frac{\alpha^2}{\alpha^2 + \Delta\beta^2}\left(1 + \frac{4e^{-\alpha L}\sin^2(\Delta\beta/2)}{\left(1-e^{-\alpha L}\right)^2}\right) \tag{4}$$

Where α is the attenuation or loss coefficient and $\Delta\beta$ is the propagation constant difference which can be written as:

$$\Delta\beta = \beta_{abc} + \beta_c - \beta_b - \beta_a \tag{5}$$

Here, β indicates the propagation constant. Efficiency η takes the maximum value of 1 for $\Delta\beta$ = 0. In this situation, the phase matching condition is satisfied. And the probability of error or bit error rate (BER) is defined by: Where signal- to- noise ratio is:

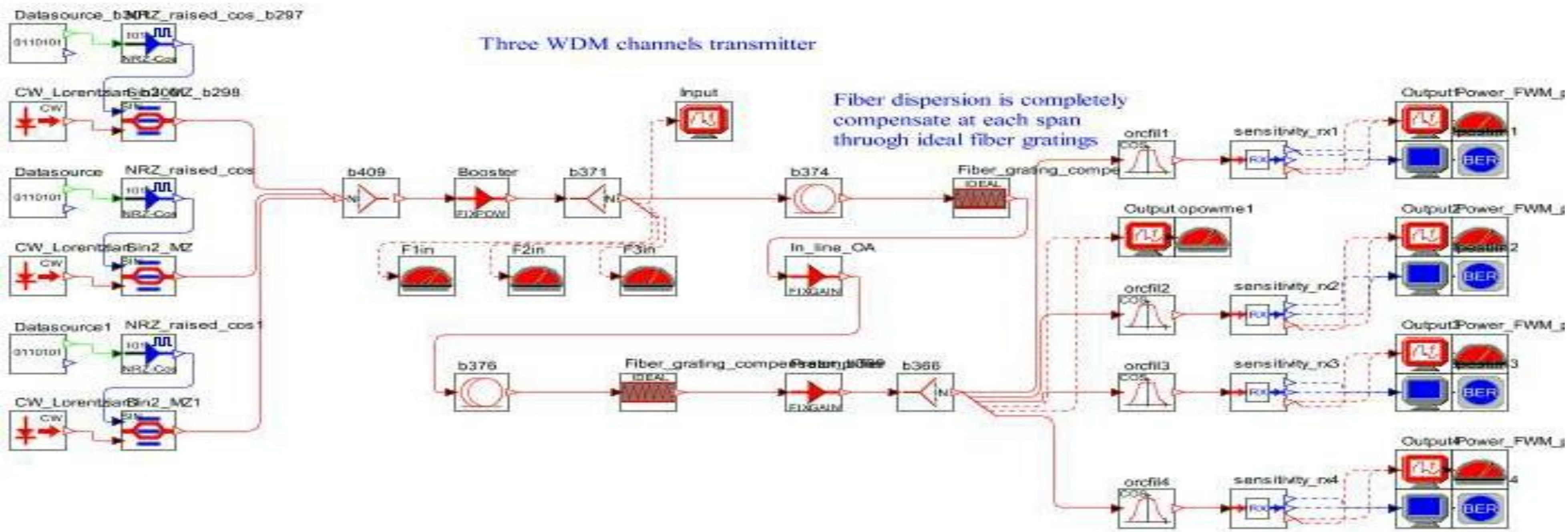

Figure 2. Simulation set up diagram of 3-channel WDM system.

$$SNR(r) = \frac{I_s}{\sigma\sqrt{2}} \tag{7}$$

Where $I_s = R_d P_s(r)$ and $\sigma = \sqrt{P_{th} + P_{shot} + P_{FWM}}$

P_{th} is the thermal noise, P_{shot} is the shot noise.

SIMULATION SETUP AND DESCRIPTION

In this work, we have used the OptSim simulator that gives us the environment almost the exact physical realization of a fiber-optic transmission 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 Figure 2. This simulation is carried out to observe the effect of FWM in a WDM configuration in presence of CD.

Transmitter section

The transmitter consists of a PRBS generator which generates pseudo random bit sequences at the rate of 10 Gbps with $2^7 - 1$ bits. This bit sequence is fed to the NRZ coder that produces an electrical NRZ coded signal. Three channels are used in this simulation.

Fiber section

The combined optical signal is fed into the fiber which is a single mode fiber. 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 FWM options. At the output of the fiber, the probe signal would have undergone the FWM effects and the waveform at the output will be distorted.

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

Table 1. Simulation parameter and their values.

Parameter (Unit)	Values
Pump frequency (THz)	193.025-193.125
Probe frequency (THz)	193.075
Channel separation (GHz)	50
Pump power (dBm)	-10 to 4
Reference bit rate (Gbit/s)	10
Attenuation (dB/km)	0.2
Fiber length (km)	100
Dispersion coefficient (ps/nm-km)	0-6
Booster amplifier gain (dBm)	6
Preamplifier gain (dB)	25

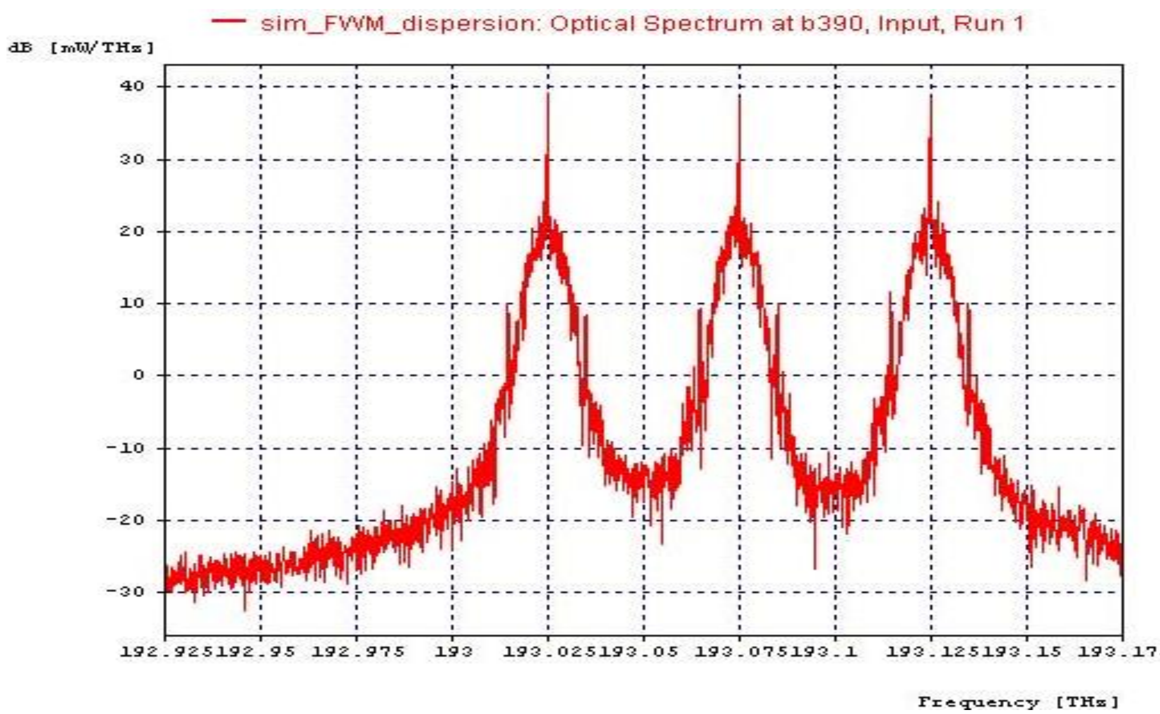

Figure 3. Input signals of 3-channels with equal channel spacing.

display and BER estimation features. If the eye opening is very wide means that there is no crosstalk. Eye diagrams can be used to effectively analyze the performance of an optical system.

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 0.4 nm, the distance between the in-line optical EDFA fiber amplifiers is 100 km (span length). The fiber dispersion value is varied from 0 to 6 ps/nm-km through several parametric runs. The three signals are launched at 193.025, 193.075 and 193.125 THz respectively, so that they have 0.05 THz uniform spacing. The fourth signal FWM is studied to investigate the effect of FWM using optical power meter with a center frequency, estimated in equation-1 (192.975 THz). The simulation parameters are given in Table 1. The optical spectrum for input signals shown is in Figure 3. The output spectrum of the signals for D = 0 and 6.0 ps/nm-km are shown in Figures 4 and 5, respectively. The output signal spectra show that with the increase of dispersion, the peak of the FWM effect decreases. For example, at zero dispersion co-efficient, the effect becomes significant and it generated other wavelengths of significant amplitude which are taking power from its parent signal. On the other hand, at Figure 5, at dispersion co-efficient of 6

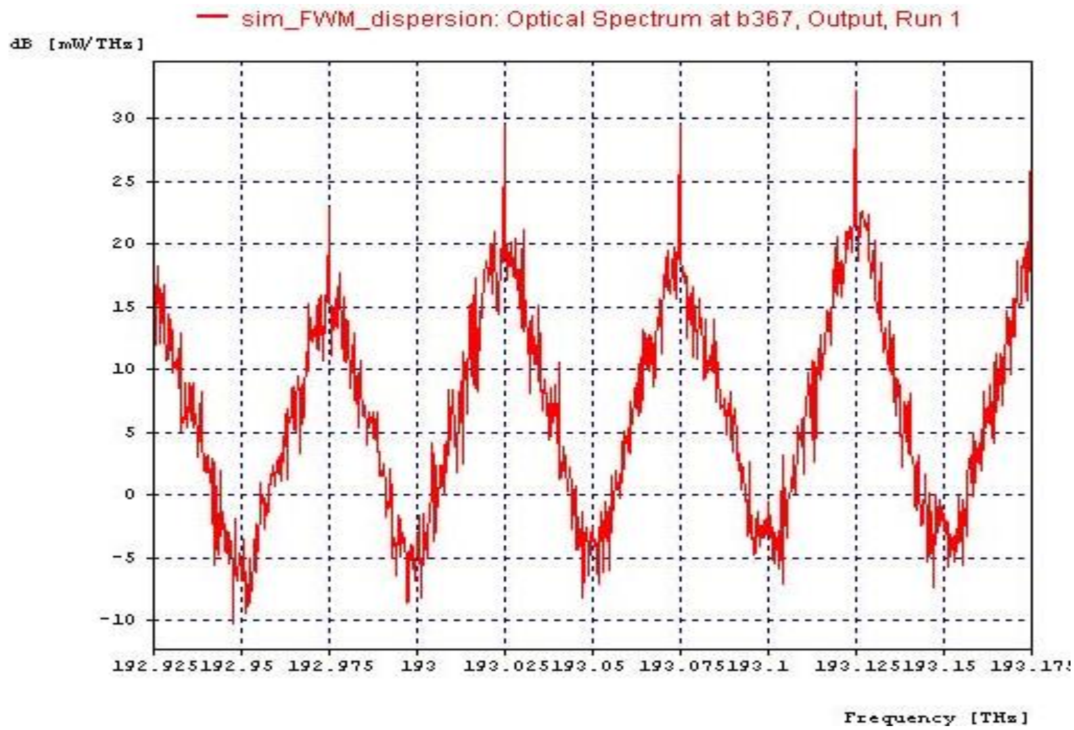

Figure 4. Output spectrum of 3-chs. with equal channel spacing (D = 0).

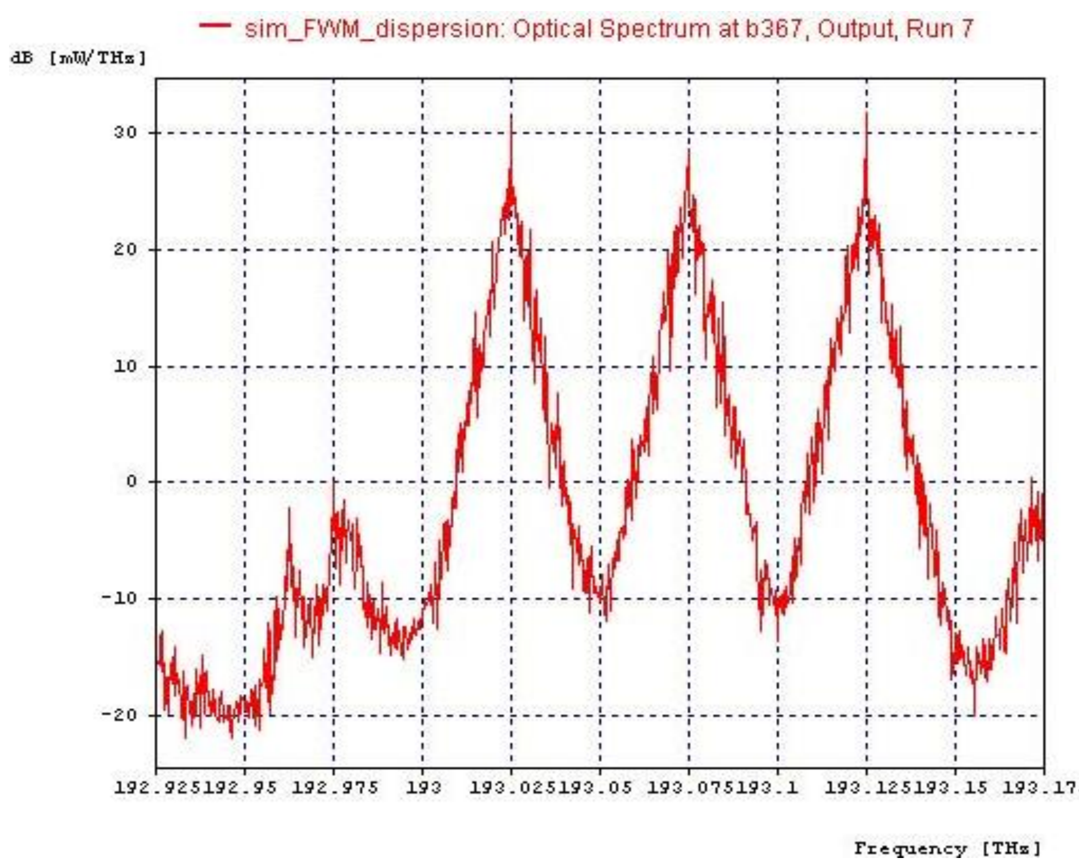

Figure 5. Output spectrum of 3-chs. with equal channel spacing (D = 6).

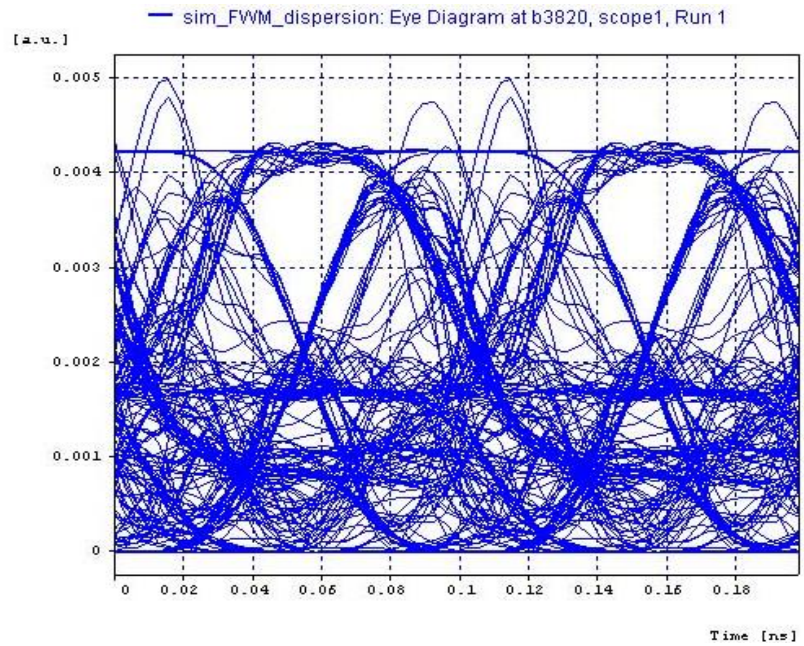

Figure 6. Eye diagram for equal channel spacing at D = 0.

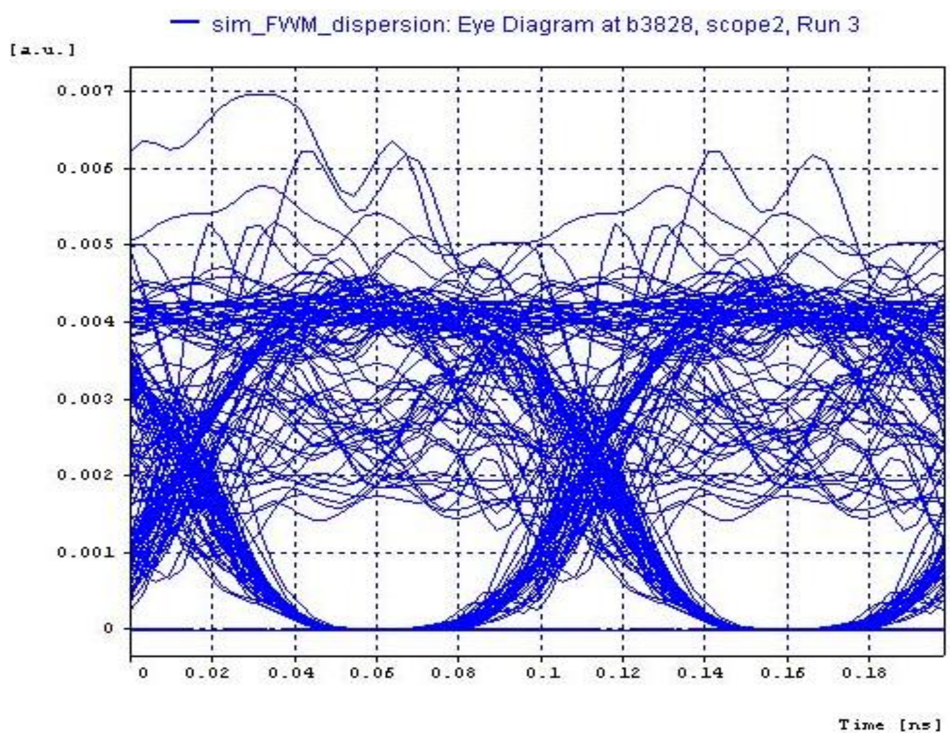

Figure 7. Eye diagram for unequal channel spacing at D = 0.

ps/nm-km, FWM generates other wavelengths with amplitude significantly small. The performance of the probe channel is also monitored at the receiver end by observing the eye diagram formation for equal as well as unequal channel spacing by varying the dispersion parameter. Figures 6 and 7 shows the effect of zero dispersion for equal and unequal channel spacing respectively. We found that the link performance of

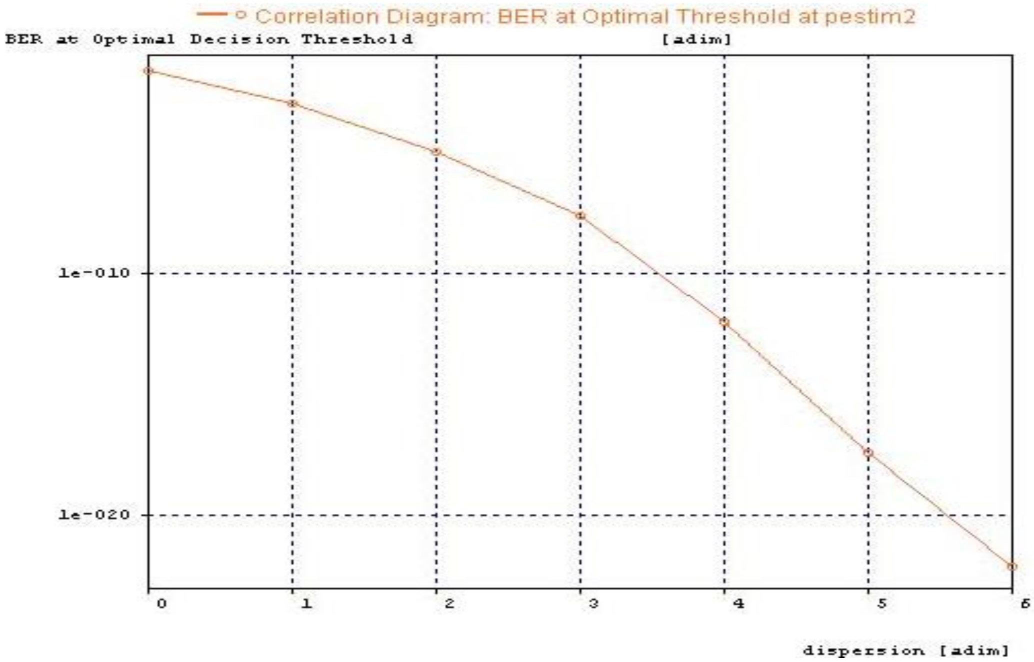

Figure 8. BER versus dispersion coefficient for equal ch. spacing.

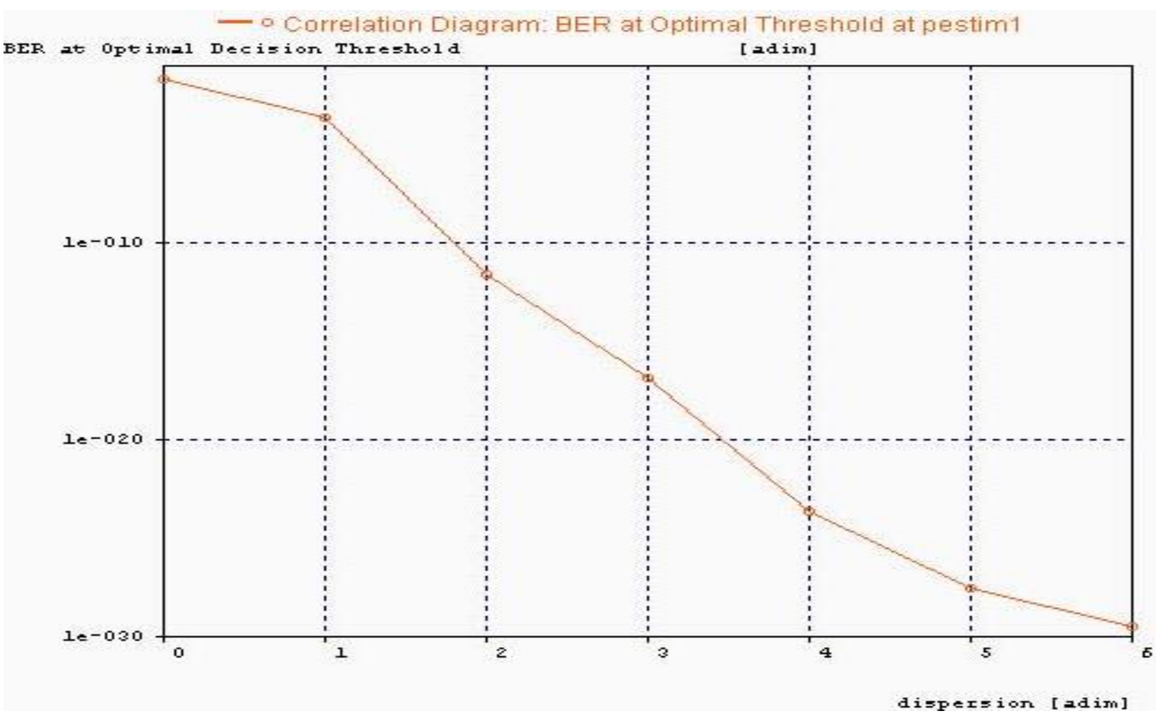

Figure 9. BER versus dispersion coefficient for unequal ch. spacing.

unequal channel spacing is better than equal channel spacing. Bit error rate (BER) is a more accurate metric to evaluate the performance of an optical transmission system. We have observed BER performance of both equal and unequal channel spacing by varying the dispersion coefficient.

The plots of BER versus chromatic dispersion are presented in Figures 8 and 9 for equal and unequal channel spacing, respectively. From Figure 8, it is seen that, at D = 3.5 ps/nm-km the BER is about 10-10 for equal channel spacing on the contrary; from Figure 9 BER is about 10-20 for the same of dispersion coefficient. Thus, we can say that the fibers which have higher dispersion are good enough than the zero dispersion fiber for a WDM fiber-optic transmission system.

Conclusion

In this paper we have demonstrated the impact of dispersion coefficient on FWM in a WDM system for equal and unequal channel spacing for 3-copropagrting channel at a bit rate of 10 Gbps. We studied that FWM crosstalk generation and its effect is maximum at zero dispersion. The results of our simulation have important consequences for understanding multi-channel WDM systems that suffer signal degradation by FWM or use FWM for wavelength conversion.

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