FWM Suppression in WDM Systems Using Advanced Modulation Formats

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*Abstract*__ **In this paper, four wave mixing (FWM) and its impact on wavelength division multiplexing (WDM) is examined through a computer simulation (VPI Transmission Maker) using different advanced modulation formats. The modulation formats covered are NRZ, RZ, CRZ, CS-RZ and duobinary. The obtained results assure that the duobinary format yields the better performance corresponding to less FWM product powers of lower, upper, lowest and highest neighborhood channels.**

Index Terms— **Four-wave mixing, Nonlinear fiber optics, Wavelength division multiplexing, Advanced modulation formats, Eye diagram.**

I. Introduction

In order to increase the capacity of an optical fiber system, channels with narrow channel spacing must be used in WDM systems. The two dominant nonlinear effects; cross-phase modulation (XPM) and Four wave mixing (FWM) introduce intensity fluctuations that are dependent on the neighborhood channels, thus causing interchannel interference (ICI) at the receiver. The present study is focused on FWM.

FWM is three channels interact to transfer a fraction of their energy to a fourth one which is third-order nonlinearity analogous to intermodulation distortion in electric systems. The origin of FWM lies in the power dependence of the refractive index of the fiber. The name four-wave mixing comes from the fact that three waves of the frequencies f_i, f_j, f_k ($k \neq i, j$) give rise to a fourth wave through interaction with the third-order susceptibility [1].

Based on Ref. [2], the worst case conditions for FWM product is near zero dispersion. Recently, system operation on the zero dispersion wavelengths has become important for high-speed transmission to avoid degradation due to chromatic dispersion. It has therefore become important to study FWM using different modulation formats to depict the best one better performance of a WDM system. For a long time, the Non-Return to Zero (NRZ) format has been the dominant modulation format in IM/DD fiber-optical communication systems. There are many advantages for using NRZ in the early days of fiber-optical communication: first, it requires a relatively low electrical bandwidth for the transmitters and receivers (compared to RZ); second, it is insensitive to laser phase noise (compared to PSK); and last, it has the simplest configuration of transceivers.

In recent years, as optical communication is advancing to higher data rates, dense wavelength division multiplexing (DWDM) and long distance with optical amplifiers, the NRZ modulation format may not be the best choice for high capacity optical systems. The Return to Zero (RZ) format has two benefits: first, it is self-synchronized, and second, laser has long life time. For these reasons, RZ modulation is currently favored in submarine systems [3].

Chirped RZ (CRZ) has been shown in transmission studies to be more tolerant of fiber dispersion than regular RZ and can achieve longer transmission distance. Carrier-suppressed RZ (CS-RZ) modulation is one of the recently proposed modulation formats for high bit rate transmission systems. The major difference between a CS-RZ and a conventional RZ is that CS-RZ optical signal has a π phase shift between adjacent bits. Because of its phase alternation in the optical domain, there is no DC component for CS-RZ. As a consequence, there is no carrier component for CS-RZ in the spectrum.

Duobinary coding has been used in the radio transmission, and recently was adapted to an optical transmission system. Optical duobinary transmission can be understood as a multilevel transmission with phase encoded bits and a reduced spectral width in which the three-levels are mapped into three optical states ”1”, ”0” and ”-1” by modulating both the amplitude and the phase of the signal. Duobinary modulation produces a narrower spectrum compared to NRZ.

II. SIMULATION SCHEME AND PARAMETERS

The main idea of the present simulation is to demonstrate the influence of FWM on WDM systems, using different modulation formats. The WDM system is simulated using VPI Transmission Maker software with the block diagram shown in Fig.1 which consists of the following components:

a. Four Transmitters: Transmitter structure varies with different modulation formats and will be discussed later in details.
b. Multiplexer: The module multiplexes 4 optical WDM channels with adjustable insertion losses. One can move any channel to measure the effect of FWM product on it.
c. Fiber Section: This module solves the nonlinear Schrodinger (NLS) equation describing the propagation of linearly-polarized optical waves in fibers using the split-step Fourier method. Depending on the signal representation, different effects are represented such as length, attenuation, dispersion, nonlinear index and core area.
d. Signal Analyzer: It is used to measure the optical spectrum for both input and output signals.
e. Demultiplexer: The module demultiplexes eight WDM channels to analyze the FWM effects on the neighborhood channels.
f. Power Meters: The eight power meters are used to measure different optical signals at the output.

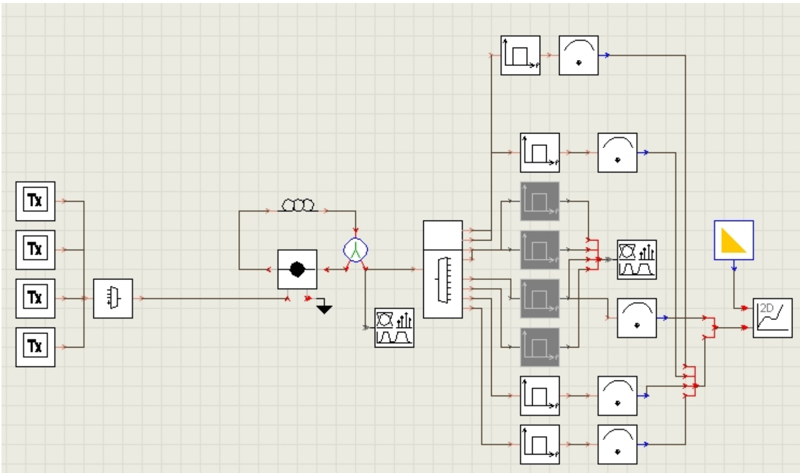


Figure 1 Block diagram of the VPI software for a WDM transmission system.

In WDM systems, an optical fiber always carries multiple channels in the same link with narrow spacing between them. For simplicity and better understanding the worst effects of FWM, one may consider only four channels launched at 193.025 THz, 193.075 THz, 193.125 THz and 193.175 THz, respectively, with a 3 mW power, so that they have uniform spacing. The neighborhood signals are studied to investigate the effect of FWM using an optical power meter. The optical spectrum and eye diagrams are obtained at the output of the fiber.

Many dispersion values are examined in the range 0 to 5 ps/nm.km. The worst case of FWM product power is found at zero dispersion, in a fair agreement with results obtained by R. S. Kaler [2]. Therefore, the zero dispersion case will be considered in the following part, for different modulation formats.

a. NRZ Modulation

The block diagram of a NRZ transmitter is shown in Fig.2. It consists of the 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, which produces an electrical NRZ coded signal. Realistic electrical pulses do not have sharp edges. The edges have a finite rise time. So, it must be fed to rise time adjustment. Rise time refers to the ratio

10% - 90% of amplitude values. Continuous wave (CW) laser is used to produce the optical signal. Time dynamics (like overshoots) and other detailed laser characteristics that can distort the optical pulses and add noise are taken into account. The modulator used here is the Mach-Zehnder modulator (MZM). It has two inputs, one for the laser diode and the other for the data from the channels. It converts the electrical signal into an optical signal form [4].

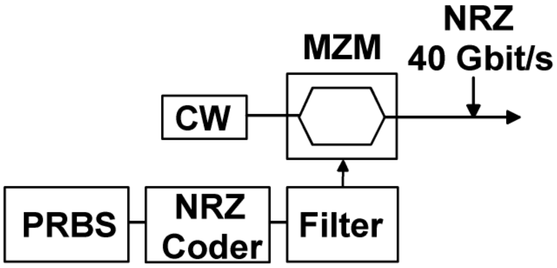


Figure 2 NRZ transmitter.

Figures 3 and 4 show, respectively, the optical spectrum with the frequency peaks generated by FWM and eye diagrams at the input and the output of a 50 km fiber for the NRZ modulation method, and at zero dispersion.

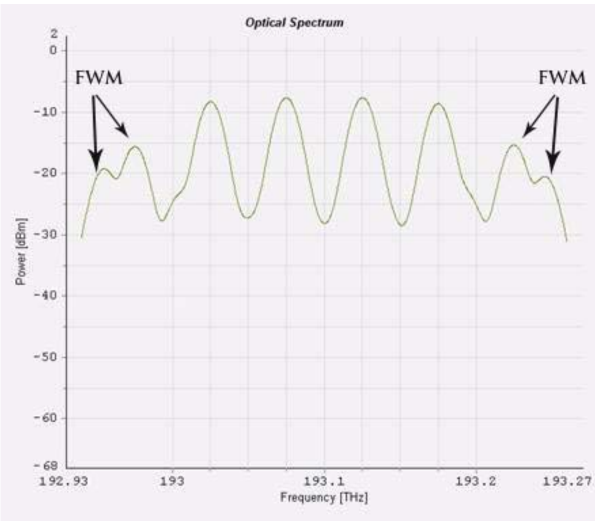
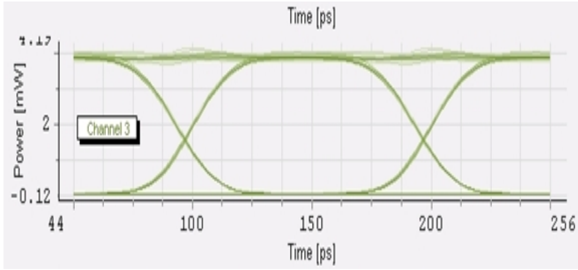
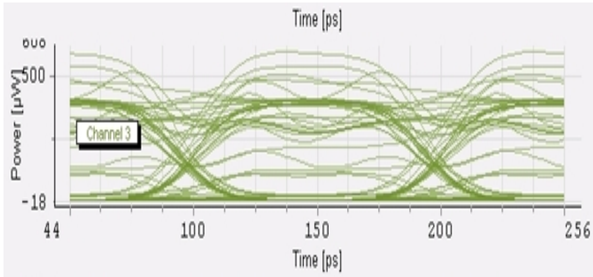


Figure 3 Optical spectrum of NRZ modulation after 50 km with zero dispersion.



4.a



4.b

Figure 4 Eye diagram at the a) input and b) output of a 50 km fiber for the NRZ modulation.

In Fig. 4-a, undistorted eye diagram looks nearly square in shape; the eye opening will be wide opened at the input of fiber. But, in Fig. 4-b, the eye diagram becomes distorted and the size of the eye opening reduces both horizontally and vertically due to the effect of FWM and other nonlinearity impairments such as cross phase modulation (XPM).

In order to further illustrate the effect of FWM, the optical signal is detected by four power meters tuned at eight frequencies (4 input and 4 FWM neighborhood channels). The power in dBm measured at the output is displayed in Fig. 5.

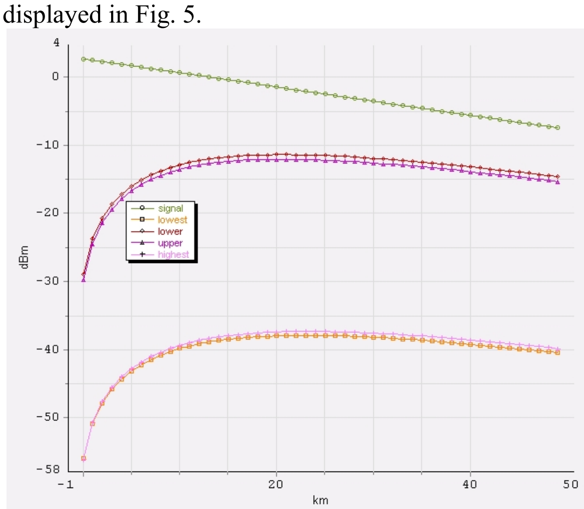


Figure 5 The FWM product power at neighborhood channels versus fiber length with zero dispersion.

The corresponding optical spectrum, eye diagrams and FWM product power for the other modulation formats can be obtained using the same procedure as in the NRZ modulation.

b. RZ Modulation

The RZ transmitter is exactly the same as NRZ but replacing the NRZ coder with a RZ coder, Fig. 6.

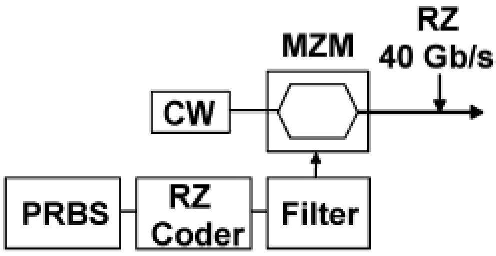
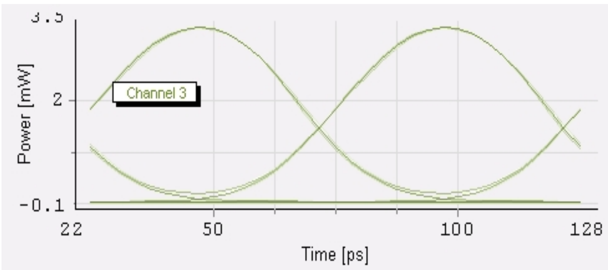
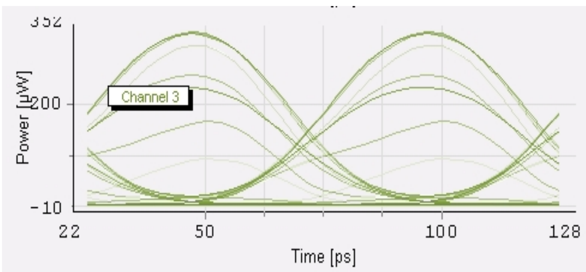


Figure 6 RZ transmitter.

The eye diagram for the RZ modulation before and after transmission is displayed in Fig.7, showing a better than that of the NRZ modulation.



7.a



7.b

Figure 7 Eye diagram at the a) input and b) output of a 50 km fiber for the RZ modulation.

c. CRZ Modulation

The CRZ transmitter consists of a CW laser modulated with a conventional data stream in order to generate a NRZ signal. The CRZ signal is formed by re-modulating the NRZ signal amplitude and phase with a sinusoidal electrical drive into an amplitude MZM and PM as shown in Fig. 8 [5]. The corresponding eye diagrams are shown in Fig. 9.

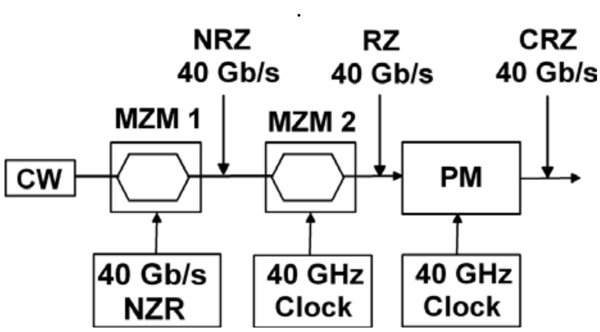
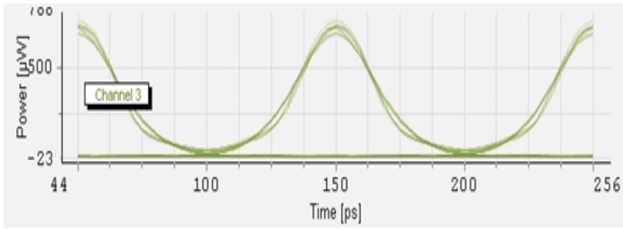
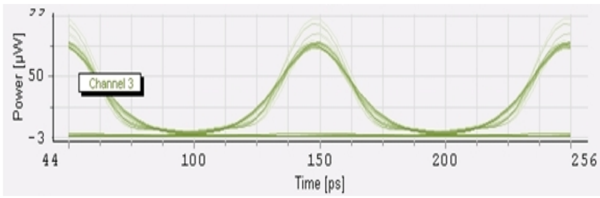


Figure 8 CRZ transmitter.



9.a



9.b

Figure 7 Eye diagram at the a) input and b) output of a 50 km fiber for the CRZ modulation.

d. CS-RZ Modulation

Figure 10 shows a block diagram of the CS-RZ transmitter. The first intensity modulator encodes the NRZ data. The generated NRZ optical signal is then modulated by the second intensity modulator to generate a CS-RZ optical signal. The second intensity modulator is biased at the minimum power transmission point and is driven by a sinusoidal clock at the half data rate of the electrical signal [6]. The obtained eye diagrams are shown in Fig. 11 for this modulation format. It is easy to notice that the eye diagrams are similar to that obtained for the CRZ format but widely opened. Both eye diagrams of the CRZ and CS-RZ formats are much better than the corresponding diagrams of the RZ format.

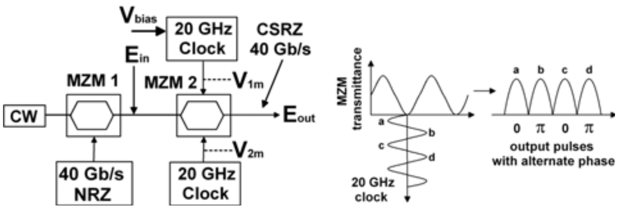
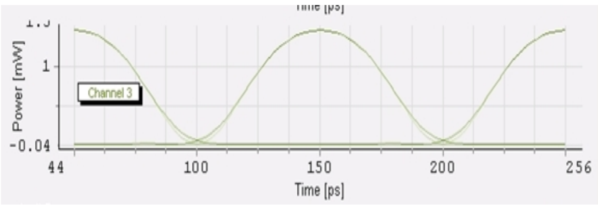
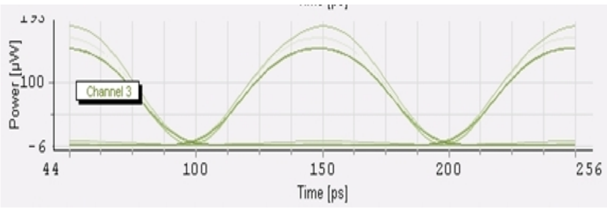


Figure 10 CS-RZ transmitter.



11.a



11.b

Figure 11 Eye diagram at the a) input and b) output of a 50 km fiber for the CS-RZ modulation.

e. Duobinary Modulation

As shown in Fig.12, the duobinary signal is generated by adding one-bit delayed data to the present data. A three-level data labeled 1, 0, - 1 is obtained after a narrow low pass filter. The levels 1 and -1 have the same optical intensity but with an opposite phase [6]. The corresponding eye diagrams are displayed in Fig. 13, showing the three levels and best performance.

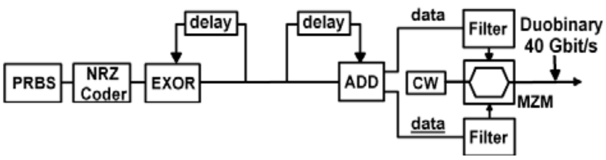
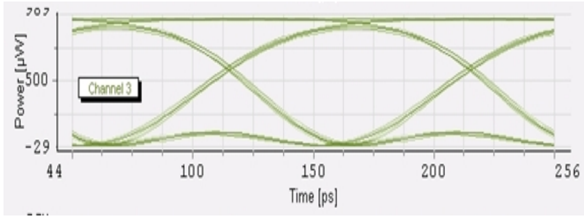


Figure 12 Duobinary transmitter.



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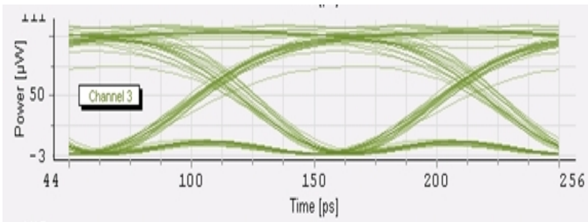

13.b

Figure 13 Eye diagram at the a) input and b) output of a 50 km fiber for the duobinary modulation.

III. RESULTS

In Figs. 14 and 15, a comparison is given for the FWM product powers of lower, upper, lowest and highest neighborhood channels, respectively, using the different modulation formats. It is clear that the doubinary modulation format has the best performance (corresponding to less power) concerning the reduction the effect of FWM product power.

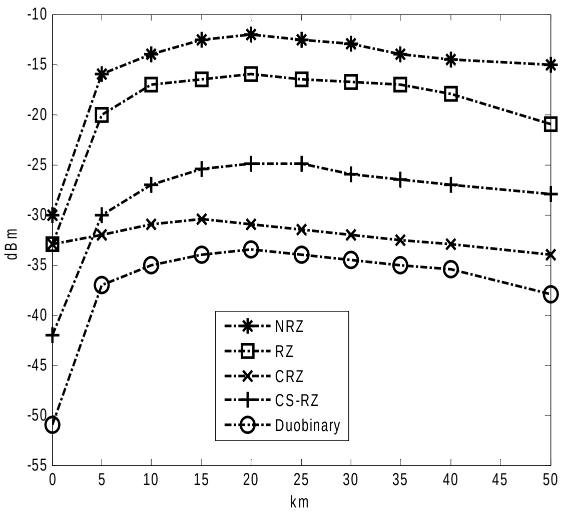

Figure 14 The FWM product power in lower and upper channels using NRZ, RZ, CRZ, CS-RZ and duobinary modulation formats.

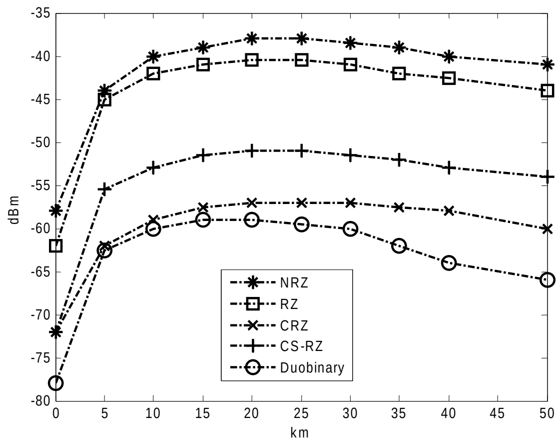

Figure 15 The FWM product power in lowest and highest channels on NRZ, RZ, CRZ, CS-RZ and duobinary modulation formats.

IV. Conclusion

In this paper, the WDM systems performance using five different modulation formats is studied to suppress the effect of FWM products. The doubinary modulation format has the best performance in reducing the effect of FWM product power. Also, the worst obtained performance correspomds to the NRZ modulation format near zero dispersion. Therefore, one may recommend a wide use of duobinary modulation technique in WDM systems in the future because of its benefits.

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