Novel Approaches for Suppression of Four Wave Mixing in WDM System Using Concocted Modulation Techniques

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Abstract— **The problem of four wave mixing (FWM) has become the principle focus for communication Engineers in designing a wavelength division multiplexing (WDM) system which is generated due to the optical nonlinear effect of fiber in multichannel systems. It has been observed through simulations results of different techniques that FWM effect becomes maximum when the fiber dispersion level approaches to zero. In this paper we have investigated the hybrid modulations for suppressing the FWM effect in 2.5Gbps system on OptiSystem Software and proposed the three hybrid modulators schemes depending upon the level of FWM suppression considering the results of eye diagram at different power levels. During simulation we use the default values of the parameters of modulators employed. Three schemes; High level reduction, Low level reduction and Intermediate level reduction have been implemented using combination of different modulators in this paper and their simulation results show that the Intermediate level reduction technique (Hybrid Tripely Technique) is comparatively the better one.**

Keywords-component; Four Wave Mixing(FWM); Hybrid modulation techniques;Optical Cross-talkOptical non-linearities;continuous phase frequency shift keying (CPFSK); Dual drive mach zehender(DDMZ)Modulator.

I. INTRODUCTION

In this modern era, there is an ever increasing demand for more services by users in terms of traffic. Telecommunication networking plays an important role for the rapid increase in the high data transmission. Therefore optical networks [1] have been adopted as an efficient means to accommodate this traffic increase, especially in the backbone and metro part of the network. But even then the fast grooming in communication requires having an efficient and robust optical system. Optical communication based on Wavelength-Division multiplexing (WDM) is progressing at an astonishing rate due to the possibility of high transmission capacity. In WDM systems, the entire optical bandwidth is divided into a number of channels centered at different wave- lengths that allows many light beams of distinct wave- lengths to be simultaneously sent into the core of the fiber [2]. It means that by increasing the number of carriers the optical traffic capacity can be increased as required.

To reduce the cost of system it is necessary to devise the minimum usage of optical amplifiers. It requires increasing the transmitter power to meet signal to noise ratio (SNR). While discussing WDM it was assumed that different carriers propagate along the fiber without affecting one another. This assumption is failed if the power level is increased. The high optical power level leaves the system performance more vulnerable to various nonlinear effects [3], stated as fiber non-linearity. Nonlinear distortion is one of the dominant penalty factors in dense WDM transmission systems and its suppression leads to system performance enhancement such as in the transmission distance and capacity [4, 5]. Many demonstrations for fiber nonlinearity were made but all those proposals and demonstrations [6, 7, 8, 9, 10] work partially in fighting the fiber nonlinearity. They either are specialized to only one aspect of the nonlinear effects, or fail to work in the presence of dispersion slope or higher order dispersion effects. Hence fiber nonlinearity has become one of the major limiting factors in modern optical transmission systems [11, 12].

There are several nonlinear effects in WDM systems, such as stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS), self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM) [13]. The carriers in a WDM system exchange energy at high input power through a process called four wave mixing (FWM). Among the fiber nonlinearities known to limit the throughput of the WDM transmission system employing non-zero dispersion fiber and narrow channel spacing ($\Delta fch \leq 100$GHz) four-wave mixing (FWM) is the dominant effects [14].

Many techniques have been proposed to reduce the effect of four wave mixing. To reduce the four-wave mixing (FWM) [15]–[18] effect in wavelength-division multiplexing (WDM) systems, many unequally spaced channel-allocation methods [19]–[23] are proposed. Other techniques involve polarization allocation and dispersion management.

In this paper we have implemented three hybrid modulation techniques with AM modulator and NZR pulse generator as essential part and simulation results are generated in OptiSystem. The hybrid modulation schemes are very helpful for the suppression of FWM side lobes. The results are analyzed deeply in this paper.

The paper is outlined as follows. In Section II we have discussed four wave mixing. Section III discuses the FWM reduction techniques. Our hybrid triply technique is discussed in Section IV. Section V gives the comparative analysis of all the three techniques and important results are mentioned. Conclusions are discussed in Section VI.

978-0-7695-4927-9/12 $26.00 © 2012 IEEE
DOI 10.1109/FIT.2012.19

II. FOUR WAVE MIXING

Four-wave mixing (FWM) also known as four photon mixing (FPM) is a parametric process in which different frequencies interact and by frequency mixing generate new spectral components [24]. The magnitude of FWM efficiency depends on channel power, channel spacing and fiber dispersion but is independent of the bit rate [25].Four-Wave Mixing (FWM) is one of the nonlinear effects, also known as Kerr effects. It originates from nonlinear refraction which is a phenomenon that refers to the intensity dependence of the refractive index. FWM is the third-order nonlinear polarization process in which three waves of frequencies f_i, f_j, and f_k $(k \neq i, j)$ interact through the third order electric susceptibility of the optical fiber to generate a wave of frequency [26].

$$f_{ijk} = f_i + f_j - f_k \tag{1}$$

Thus, three co propagating waves give rise, by FWM, to nine new optical waves [27]. The output power P_{pqr} of the FWM product is given by [28]:

$$P_{pqr} = \frac{\gamma^2}{9} d_{pqr}^2 P_p P_q P_r e^{-\alpha L} L_{eff}^2 \eta \tag{2}$$

Where:

P_{pqr} is the output power of the FWM product.

γ is the non-linear co-efficient of the fiber.

d_{pqr} is the degeneracy factor.

α is the fiber loss co-efficient.

L_{eff} is the effective length of the fiber.

η is the mixing efficiency.

In a WDM system, this is because of every possible choice of the three channel waves.

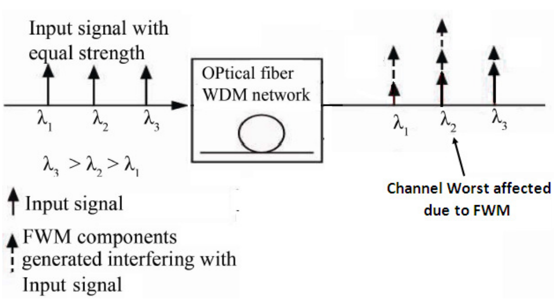


Figure 1. FWM effect in an optical WDM network

- It was experimentally observed that four wave mixing reaches to its maximum value when the chromatic dispersion of the fiber is zero.
- The FWM products are inversely proportional to the phase mismatch i.e. decreasing the phase coherence also decreases the FWM products. The phase mismatch can be employed by using Cascading intensity and phase modulators or using dispersion-compensating devices like chirped fiber gratings and DCFs.

The figure shown above elaborates the signal degradation in an optical WDM system due to Four Wave Mixing (FWM) effect. FWM no doubt increase the power level of the host channel but it degrades the voice security factor by inducing cross talk in that channel. Crosstalk is the main performance evaluation parameter for these devices. Crosstalk can be of two types:

- **Heterodyne** crosstalk derives from interferences of small power levels that appear outside the bandwidth of the channel, causing bit error rate increases when detecting the other channels (inter channel crosstalk);
- **Homodyne** crosstalk results from interferences inside the channel's bandwidth (intra channel crosstalk) [29].

In this way FWM has been a very serious issue and a major limitizing factor. This non-linear factor should be removed to provide a reliable fiber optical communication network.

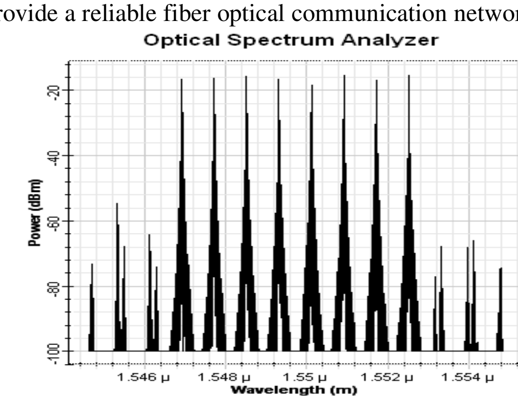


Figure 2. FWM in 8-channel WDM system.

The above figure shows the FWM induced in an 8-channel WDM system. This FWM phenomenon is observed for a fiber length of 50 Km having dispersion value of 16.75 *ps/nm/km* and the input power of 0 dBm is applied while the system is operating at 2.5 Gbps. The above figure shows that the FWM products have approximately half the power as the power of the channels.

III. FWM REDUCTION TECHNIQUES

Many reduction techniques for FWM have been proposed since now. These techniques include the generation of pre-chirped signals, unequal channel spacing, dispersion management (using DCF or FBG) and wavelength shift keying etc. These techniques however proved successful to some extent with some draw backs as well. The unequal channel spacing techniques resulted in an increase of bandwidth requirement, compared with equally spaced channel allocation. This is due to the constraint of the minimum channel spacing between each channel, and that the difference in the channel spacing between any two channels must be assigned to be distinct. As the number of channels increases, the bandwidth for the unequally spaced channel-allocation methods increases in proportion. The dispersion compensation technique on the other hand is a linear phenomenon whereas FWM is a non-linear effect. Therefore dispersion compensation techniques have very small effect on FWM. On the contrary hybrid modulation techniques prove very fruitful in reducing the effect of FWM in WDM system.

A. System Design:

The block diagram of general hybrid Modulated 8-channel WDM system is shown in the fig. 4.

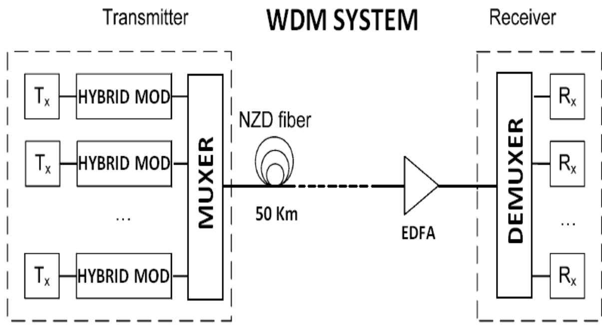


Figure 3. Block Diagram for Hybrid Modulated System

The above system is an 8-channel 2.5 Gbps WDM system and its simulation window's parameters are as follows: sample rate of 160 GHz, sequence length of 128 bits, 64 samples per bit and a bit rate of 2.5 Gbps, operating at normal mode. In this paper we have used NRZ pulse generator with our hybrid modulation schemes. The fiber used in our system is non-zero dispersion fiber with length of 50-130 Km, dispersion value of 16.75 ps/nm/km and a reference wavelength of 1550 nm. The optical amplifier used is EDFA with operating wavelength of 1550 nm. The filter used on the receiving side is a Low Pass Bessel Filter with a cut-off frequency of 0.75*Bit rate.

These hybrid modulation techniques reduce FWM products to small levels, intermediate levels and large levels. On the basis of the reduction level of FWM products as a result of these hybrid models we have categorized our results into three stages.

B. Low level FWM reduction:

In this stage the hybrid modulator portion is the combination of optical PM modulator followed by an optical AM modulator. The power level is set to zero. The optical PM modulator introduces the phase mismatch in each wavelength which then adds constructively or destructively by the AM modulator. The simulation results for different input power levels shows that the BER decreases to zero, Q-factor increases as the input power varies from -10dBm to 20dBm with a fiber length of 50km with dispersion 16.75ps/nm/km.

The variations in different parameters with respect to power are given in the table I. The FWM products have power level of -62 dBm with received optical power of 8.9284 dBm and OSNR value of 43 dB for input power of zero dBm.

TABLE I.

Input Power (dBm)	Factors affected by Input Power		
	BER (dBm)	*Quality Factor (dBm)*	*FWM Products (dBm)*
-10	0	85.8174	-86
0	0	105.205	-62
5	0	117.293	-59
10	0	135.322	-60
15	0	72.0217	-44
20	7.3876e-24	9.96448	-27

1) Drawbacks:

With low level FWM reduction scheme the FWM products reduces at lower levels but the BER analyzer parameters give efficient results i.e. Min BER decreases, eye height increases and quality factor also increases.

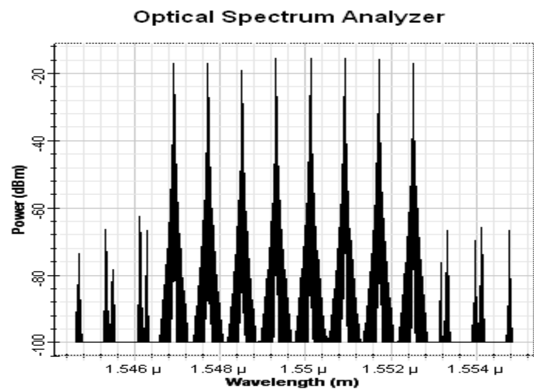


Figure 4. Low Level FWM reduction

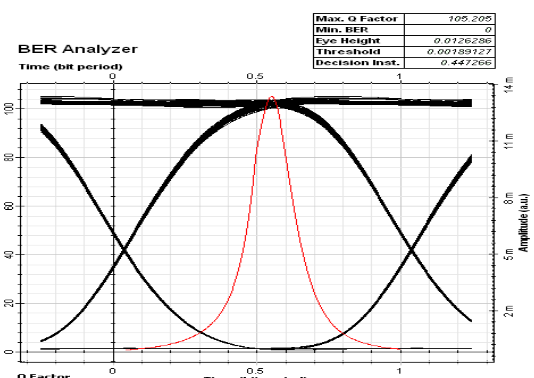


Figure 5. Low Level FWM reduction eye Diagram

C. High Level FWM Reduction:

The high level FWM reduction method uses the hybrid combination of one electrical and three optical modulators. The electrical modulator is CPFSK whose output is connected with optical Dual Port Dual Drive Mach Zehnder modulator followed by Dual Drive Mach Zehnder and AM optical modulators respectively. The simulation results shows that the minimum BER increases and Quality factor decreases with the increase of input power from -10dBm to 20dBm with a fiber length of 50km with dispersion 16.75ps/nm/km. The FWM products have power level of -94 dBm with received optical power of 4.9179968 dBm and OSNR value of 41 dB at zero dBm input power. The electrical CPFSK modulator is responsible for generating the distortion in the signal as shown in eye diagram. The height of eye is decreased due to which the quality of the signal is reduced. These distortions will wrap the eye if the power is further increased to 20dBm or 25 dBm. So this technique can be employed for short distances and low power consuming systems.

TABLE II.

Input Power (dBm)	**Factors affected by Input Power**		
	BER (dBm)	***Quality Factor (dBm)***	***FWM Products (dBm)***
-10	0.000216774	3.38719	0
0	0.000167307	3.45011	-94
5	0.000169625	3.44637	-82
10	0.000171007	3.4442	-72
15	0.000169014	3.44744	-64
20	0.000178058	3.43286	-62

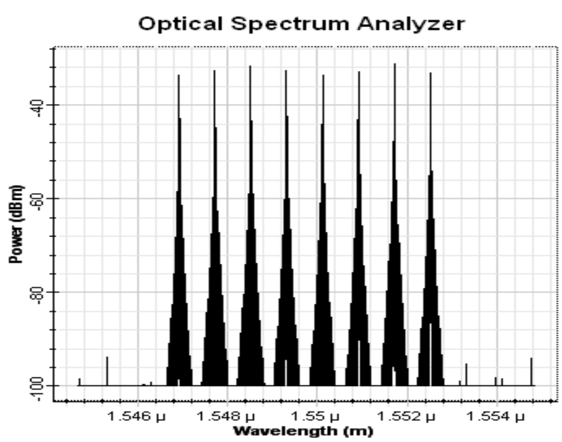


Figure 6. High Level FWM reduction

The optical spectrum analyzer shows the efficient reduction of four waves mixing in WDM system when continuous phase frequency shift keying modulator is employed with other optical modulators. The CPFSK modulator provides a high sensitivity for detection and a good tolerance to nonlinearity of transmission lines. CPFSK has good spectral efficiency and suppression of higher order side lobes.

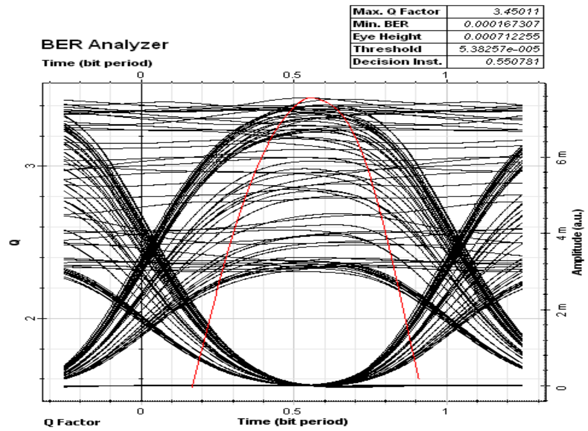


Figure 7. High Level FWM reduction eye Diagram

The eye diagram shows the variations in the BER readings for power at zero dBm. It is right that CPFSK offers less side lobes but on the other hand it also introduces the distortions in the signal.

1) Drawbacks:

The FWM products are greatly reduced with this scheme up to -89dBm but the results of BER analyzer are not satisfactory i.e. there are distortions in the eye diagram. So we need some intermediate scheme which fulfills both the demands.

IV. HYBRID TRIPELY TECHNIQUE

The drawbacks mentioned in the above two schemes (i.e Low and High Level FWM reduction) are tried to be controlled in hybrid triply technique by providing the intermediate scheme between the above mentioned techniques. This technique utilized three optical modulators PM, Dual Drive Mach Zehnder (DDMZ) and AM modulators respectively. Here the function of DDMZ is of considerable importance for polishing this technique. The 10 Gbps DDMZ modulator has matching electro-optic amplitude and phase responses, low differential drive voltages usually 2V, single sided electrical input and a wide optical bandwidth compatible with full band tunable lasers useful for active dispersion compensation.

TABLE III.

Input Power (dBm)	**Factors affected by Input Power**		
	BER (dBm)	***Quality Factor (dBm)***	***FWM Products (dBm)***
-10	1.21543e-156	26.6267	0
0	0	79.7791	-89
5	0	107.912	-80
10	0	99.3787	-67
15	0	118.936	-64
20	0	134.184	-60

The above table shows the readings of BER, Q-Factor and FWM products power level for different input power values. It is evident from these values that for negative power values the BER has some value and quality factor is low but the FWM is zero. But as the input power is increased FWM products power is increased at lower rates. On the other hand quality factor also increases but the BER remains at zero.

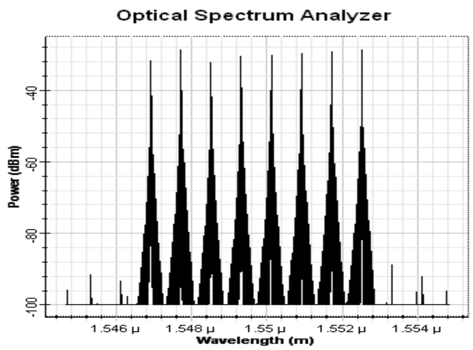
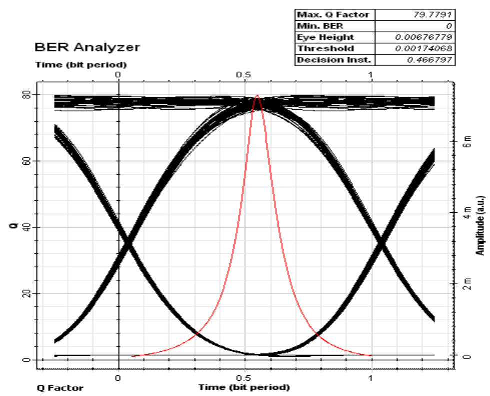


Figure 8. Intermediate Level FWM reduction eye Diagram



V. COMPARITIVE ANALYSIS

In this section we have deeply analyzed the simulation results of our three hybrid modulation scheme i.e. High level reduction, Low level reduction and Intermediate level reduction on an 8-channel WDM system operating at 2.5 Gbps. The high level reduction decreases the FWM products to minimum level hence inducing very limited cross-talk but it results in high distortion and non-negligible BER. This causes a limitation to the length of fiber. Also the quality factor is not too good for long distance communication. On the contrary, the low level reduction technique partially affects the FWM products but promises good quality factors and low dispersion effects. Also the BER is approximately zero. Hence this technique is more suitable for long distance data transfer using longer lengths of fibers. On the other hand the intermediate level reduction scheme is of great importance as this scheme removes the drawbacks introduced by the high level reduction scheme and the low level reduction technique while maintaining their advantages. This technique reduces the FWM products nearly to a negligible value hence avoiding cross-talk effect. Also this technique provides considerable value for Q-factor with zero BER. One big advantage of this scheme is that it retains its qualities even with increasing input signal values. The following graphs were developed after analyzing the effect of increasing input power on the three techniques.

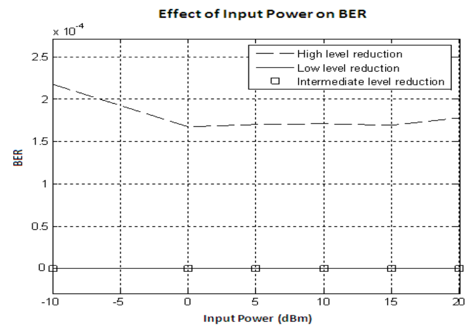


Figure 9. BER vs. Input Power

The above figure shows the behavior of BER for the three techniques as we increases the value of input power. It is observed that the BER of high level reduction have maximum level while low level reduction and intermediate reduction level have approximately the same results.

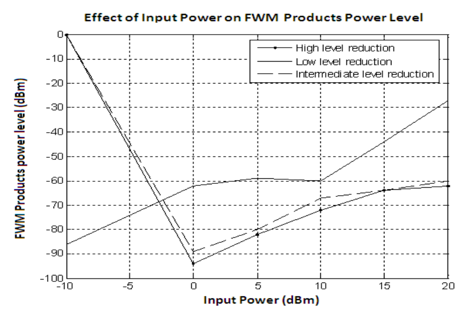


Figure 10. FWM products vs. Input Power

The above figure shows that the FWM products for low level reduction technique increases for negative values of input power and then becomes nearly constant till the input power level reaches 10 dBm and then increases rapidly. While for high and intermediate reduction techniques FWM products have approximately the same behavior.

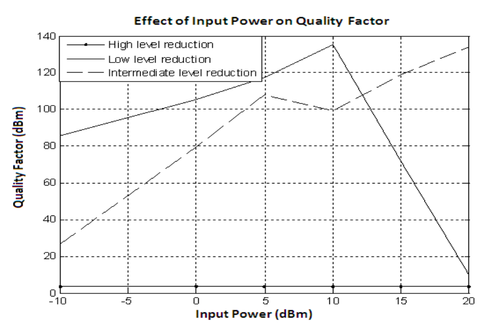


Figure 11. Quality factor vs. Input Power

The above graph shows the effect of input power on the quality factor behavior. By increasing the value of input power from -10 dBm to 10 dBm the quality factor of low level reduction technique gradually increases while there is a sudden decrease onwards as we increase the input power further from 10 dBm to 20 dBm. The quality factor for high level reduction nearly remains constant as we increase the value of input power from -10 dBm to 20 dBm. On the other hand the value of intermediate reduction technique causes the quality factor to increase from 26.62 dBm to 107.912 dBm as we increase the input power from -10 dBm to 5 dBm. It then decreases to 99.37 dBm as we further increase input power from 5 dBm to 10 dBm. Finally it starts increasing again as we further increase the value of input power from 10 dBm to 20 dBm.

VI. CONCLUSION

This paper demonstrates the effective results of three implemented hybrid modulation schemes for the suppression of FWM side lobes. The readings observed for 8-channel 2.5 Gbps WDM system for input power of 20 dBm are as follows: the received output power is 9.0911931 dBm with OSNR value of 50.555711 dB. The corresponding Q-Factor value is 134.184 with Min. BER of zero value. These readings are obtained from proposed intermediate level FWM reduction method. Similarly the comparison of readings from table I, II and III shows that the intermediate level FWM reduction scheme is more efficient than Low and High level FWM reduction schemes. As the length of the fiber is increased from 50 Km to 150 Km the FWM side lobes are removed completely but the distortion in the eye-diagram increases.

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