A New Suppression approach of FWM Crosstalk Effect in Optical Communication Link based on Polarization combiner Method

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Abstract: To meet the growing needs of internet data, optical communication systems have become the backbone of modern communications networks. At the present time, the dense wavelength division multiplexing (DWDM) technique has been used to increase the number of channels, but the nonlinear effects have a great impact that limits the performance of doubling the DWDM system. The four wave mixing (FWM) is the most harmful and dangerous as the effect of FWM increases on the system the greater the optical connection distances. The new approach of pairing groups of different optical signals was investigated to suppress the FWM effect. The simulation was conducted for an 8-channel system with a total data rate (80Gb/s). A comparative study was conducted on the suppression of FWM by the difference in the power inputs (-0.5 to 20) dBm. The robustness of the proposed technique was examined using two forms of modulation (Carrier Suppressed Return to Zero (CSRZ) and Duo Binary Modulation class -1(DBM-1)) techniques, with optical fiber system of (1,2,5) spans, each of length 60 Km, with spacing between the channels 50GHz. The power of FWM was significantly reduced with the CSRZ & DBM-1 techniques to less than (47.97%, 41.38 %) respectively, at an input power of 12.5 dBm. The performance of the proposed system with the polarization technique was improved by the rate of the quality factor (Q-factor of (91.59%, 78.67%) for the same sequence of modulation.

Keywords: Polarization combiner, Modulation Formats, Q-Factor, FWM, Nonlinear effect, DWDM

1.Introduction

Dense wavelength division multiplexing (DWDM) techniques are an appropriate approach to meet the demands of rapid development services in fiber-optic communications systems. Because of the need to increase the capacity of the data, the transmission has been increased [1-3]. The International Telecommunication Union (ITU) developed a wavelength division multiplexing (WDM) system [4], which is doubled the largest number of channels on a single-mode fiber [4]. There are two ways to increase the channel capacity either by increase the number of channels or increase the data rate. However, this increase has limitations by the user hardware, as more channels mean less spacing between them. Furthermore when the channel spacing is reduced, known as a dense multi-wavelength system [5], the use of lower channel spacing and increase in the input energy lead to the emergence of
nonlinear effects such as FWM. As it is the basis of the Kerr effect and is the origin of nonlinearity. One of the causes of this effect is changes in the refractive index when the input power is increased [6]. The increasing demand for bandwidth is overcome by using the DWDM technique. It gives high-speed data service, but the main limitation of this system is nonlinear distortions generally and four-wave mixing particularly. By using modulation techniques, suitable parameters for simulation, appropriate techniques for reduction, chromatic dispersion, and channel spacing are simulation parameters that are used to control the effects of FWM [7-12]. Different modulation forms are used to reduce impairments of the nonlinear [13-17]. Also, for the compensation techniques where different techniques are analyzed to reduce dispersion [18], a technique of using linear polarization to set the state of polarization where adjacent channels are perpendicular and using three electrical filters at the receiver [19-22].

In this work, a new technique was presented using a Polarization combiner with two different modulation formats such as ( CSRZ, Duobinary-1) to reduce the effects of nonlinearity (FWM) under the data rate (80Gb / s). The proposed technique was examined under different transmission distances and different input signal power. Modulation forms are highly affecting the FWM in high data rates transmission system where the crosstalk will depend on the immunity of the formats. This paper consists of the following organization: Section 2 describes the traditional system (DWDM) and effects (FWM) on the system, Section 3 describes the proposed system, while Section 4 presents a discussion of the results. Finally, a conclusion is made in Section 5.

2. Wavelength division multiplexing (WDM)

To enhance the performance of optical communication systems, (WDM) is used to increase the capacity of the communication system, where in the field of optical fibers (WDM) gets great fame. Communication systems are of two types known as (DWDM) dense wavelength division multiplexing and (CWDM) coarse wavelength division multiplexing. According to the channel spacing, the two types have been classified. (WDM) It is known to be a multiplex technique in which there is more than one optical signal and the transmission takes place. With different wavelengths it is possible to transmit the signal using one way that (WDM) is another version of the frequency-division multiplexing (FDM), but the main difference between them are the wavelengths or the range in which the frequencies are used in each method. Therefore, through (WDM) different formats of digital and optical information can be sent, and bits of different formats can be received through the same optical channel.

2.1. Analysis for traditional multichannel DWDM systems without Polarization Combiner

Figure.1 clarifies the schematic diagram of the proposed system design. The DWDM transmitter comprises eight subsystems with the following ingredients for each one. The suggested system design can summarized as follows:

A. The transmitter part :

I. In the transmitter component the carrier signal is produced and the Array Continue Wave, (CW-laser from L1–L8) is represented by a laser diode. The laser signal is continuously wavelength so it provides a beam whose width is narrow. Also 10Gb/s Bit rate for every channel modulated.

II. Pseudo-Random-Bit-Sequence (PRBS): This portion is responsible for generating randomized binary sequence. The PRBS generator gives binary sequences (zeros and ones).

III. The Ext. modulator composed of (CSRZ and DBM-1). The transmitter system composition of each modulation employed is illustrated in Fig.2. The Mach-Zehnder modulator (MZM) is represented the intensity modulator and then is connected to the WDM-MUX.
IV. WDM-MUX transmitter system: It is used to multiplex various optical wavelengths more than one.

B. The optical link:

It includes three spans. Figure 3 shows the optical fiber channel that is used in the system simulation, where a symmetrical dispersion compensation scheme is used. It consists of three spans of single mode fiber (SMF) followed by optical fiber amplifiers Erbium-Doped Fiber Amplifier (EDFA) which have noise figure value of 6dB and gains of 5 dB followed by DCF. It is possible to use fiber DCF to mitigate the desperation in the fiber which has negative dispersion also a native dispersion slope accumulated dispersion that leads to reducing the broadening of the pulse resulting from the products of chromatic dispersion (CD).

C. The receiver part.

The receiver part composed of the following ingredients and as shown in Figure 4.

I. The last rim of the WDM-DMUX is the De-multiplexers for communication systems. It retrieves the data utilizing the technique of (Demultiplexing). In a communication system, WDM-DMUX is the last edge where the work of WDM-MUX is the opposite of the work of WDM-MUX. Independent information in addition to access protocols where the communication networks allow it to operate in a single system [17].

II. After the operation of DEMUX, the photo indication enters the optical receiver. It is composed of a PIN photodiode that is used to convert the photo signal into an electrical signal and detect it. The detected signal is applied to the second part which is named a low pass Bessel filter.

III. The low pass Bessel filter is used in the optical receiver to divide the modulated informative from the rising carrier frequency. The utilized low pass Bessel filter at cutoff frequency $0.75 \times$ data rate, also reduces the noise that results in the detection process.

IV. The 3R regenerator is the fourth part of the optical receiver that is used to produce the original sequence of bit and modulated electrical signal to be applied.

V. Eye diagram is used to show the Quality factor and Bit Error Rate is directly connected to the 3R regenerator is utilized to produce the diagram. Table (1) illustrates the system simulation parameters.

2.2 Mathematical model of FWM in Optical Link

In a fiber cable, the pulses interact with each other, so when two of them are spread, they can produce two new pulses, and this phenomenon is called four mixing waves, as well as three optical pulses, it produces nine new pulses. The occurrence depends on many factors such as the length of the transmitter in which the pulses interact, the input power, the spacing between the channels, and the dispersion in the fibers [5]. The power transferred as a result of FWM of original frequencies subsequently light has been spread in a distance in the fiber can be summarized in the Eq. (1). All parameters in Eq. (1) are defined in Table 1.

$$P_{FWM} = \frac{1024\pi^6}{n^6 \lambda^2 c^2} \left( \frac{Dx_{111} L_{eff}}{A_{eff}} \right)^2 \left( P_i P_j P_k \right) e^{-\alpha L} \frac{\alpha^2}{c \alpha^2 + 2\pi D_c (\Delta f j k)}$$ (1)
Under the effect of polarization, FWM efficiency becomes:

$$\eta_{\text{FWM (pol)}} = \frac{1}{N} \times \eta_n \times X_{i11r}^2 \tag{2}$$

$\eta_{\text{FWM (pol)}}$ is FWM efficiency attained by polarization technique.

$X_{i11r}$ is a factor that presents a polarization dependency of the nonlinear effect and varied from 0 to 1 according to SOP between channels

$\eta_n$ is the normal FWM efficiency in WDM system.

FWM efficiency ($\eta_n$) can be rewritten as follows:

$$\eta_n = \frac{\alpha^2}{c\alpha^2 + 2\pi D_c (\Delta f_i k)(\Delta f_j k)} \tag{3}$$

By substituting Eq. (3) into Eq. (2), we can derive Eq. (4) as the following:

$$\eta_{\text{FWM (pol)}} = \frac{1}{N} \times \frac{X_{i11r}^2 \times \alpha^2}{c\alpha^2 + 2\pi D_c (\Delta f_i k)(\Delta f_j k)} \tag{4}$$

With the OEC effect, FWM power in Eq.(1) will be changed as follows:

$$P_{\text{FWM (pol)}} = \frac{1024 \pi^6}{n^4 \lambda^2 C^2} \left( \frac{DX_{i11r} L_{\text{eff}}}{\alpha_{\text{eff}}} \right)^2 \left( \frac{PP_{j}P_{k}}{P_{\text{FWM}}^2} \right)^n e^{-\alpha t} \times \frac{X_{i11r}^2 \times \alpha^2}{N \times (c\alpha^2 + 2\pi D_c (\Delta f_i k)(\Delta f_j k))}$$

FWM noise power NFWM is:

$$NFWM = 2b^2 P_s \left( \frac{P_{\text{FWM}}}{8} \right) \tag{5}$$

Where $b$ is the responsively of the detector, $b = (\eta e/hf)$, where $h$ is the Planck's constant, $\eta$ is the quantum efficiency of the detector, $e$ is the elementary electric charge, and $P_s$ is the signal light power at the receiver that it may be assumed. The system performance can be evaluated using Q factor as [5]

$$Q = \frac{b P_s}{\sqrt{N_{\text{th}} + N_{\text{FWM}} + \sqrt{N_{\text{th}}}}} \tag{6}$$

And the BER has been designed from the Q factor:

$$BER = 0.5 \times \text{erfc} \left( \frac{Q}{\sqrt{2}} \right) \tag{7}$$
Figure 1. System layout of transmitter and receiver of CSRZ and DBM-1

Figure 2. Simulation design of optical transmitter for (a) CSRZ, (b) DBM-1

Figure 3. Optical fiber link

Figure 4. Optical receiver
### Table 1. System parameters of Optical transmission system

| Parameter                      | Value          | unite  |
|--------------------------------|----------------|--------|
| **Optical Transmitter Parameters** |                |        |
| Input Power ($P_i$)            | -0.5-20        | dBm    |
| Input Freq.                    | 193.1-193.8    | THz    |
| Channel spacing                | 50             | GHz    |
| Line width                     | 10             | MHz    |
| No of channels ($N$)           | 8              |        |
| **Fiber Link Parameters**      |                |        |
| Length of the optical link     | 25 for SMF1, 10 for DCF, 25 for SMF2 | Km     |
| Total length ($L_{eff}$)       | 60, 120, 300   | Km     |
| Attenuation ($\alpha$)         | 0.2 for SMF and 0.5 for DCF | dB/km  |
| Dispersion parameter ($D$)     | 17 for SMF and -85 for DCF | ps/nm/km |
| Dispersion slope ($S$)         | 0.075 for SMF and -0.3 for DCF | ps/nm²/km |
| Effective area ($A_{eff}$)     | 70 for SMF and 22 for DCF | μm² |
| Differential Group Delay (DGD) | 0.2            | ps/km  |
| Nonlinear index of refraction ($n_2$) | $26 \times 10^{-21}$ | m²/W   |
| **Optical Receiver Parameters** |                |        |
| Low pass Bessel Filter         | Cut off frequency | 0.75*Bit rate |
| PIN (Photo detector) Dark current | 10               | nA     |

3. Analysis of multichannel DWDM system with combiner polarizers

Figure 5 shows the proposed optical network system. Each two channels is connected to the WDM-MUX and then reached to the polarization combiner with an angle of (45°) and. The polarization combiner chooses at the input ports the appropriate polarization component of each signal and adds the polarization components selected. The polarization combiner outputs for each paired channel are connected to a third polarizer combiner with an angle of (0°) and then the signal is sent through the transmitter optical link fiber that was indicated in Fig.3. The optical link consists of (1, 2, 5) loops. Each loop has (60, 120, 300)Km fiber length respectively and then the signal passes through WDM - DMUX to the receiver where the signal is detected at PIN photo detector then to low pass Bessel filter. The signal sent to the 3R regenerator, then the signal is connected to the eye diagram tester to configure the graph, and System performance was evaluated in terms of Q-factor and BER. The effect of the polarization technique on WDM performance with regard to FWM was simulated using an optical systems simulator OptiSimTM which is adequate for this purpose as in Figure 5.
4. Obtain Results and Discussion

In this part, the polarization combiner effect on FWM power with three modulation types (CSRZ, DBM-1) was evaluated. The system perform is simulated and the Q-factor of the received signal is calculated under different input power for changing different transmission distance between the transmitter and receiver.

4.1. Effect FWM Crosstalk

The simulation of the system was done with various transmission distances (60, 120 and 300 km), i.e. three spans. Figure 6 shows a comparison of FWM effects for various forms of modulation of distance of 300 km. Figure 6(a-d) represents optical spectrum of the FWM in the traditional system (without-PC) and under proposed PC system at the same conditions. Where the transmission has been improved for the proposed system with (PC), where (47.97% at CSRZ, & 41.38% at DBM-1) is reduced according to the type of modulation compared to the traditional DWDM system. So that CSRZ is the best type to mitigate the effect of FWM crosstalk compared to the traditional one even when increased input power of the channel .
For further investigation, a work has been proposed with an input power of 2.5 dBm, the trend of the results was similar when using the condition at input power of 12.5 dBm as in Figure 7(a-d). Figure 8 explains the behavior of FWM power in the two modulations form (CSRZ and DBM-1) via increasing of the power input values from -0.5dBm to 20dBm for 300 km fiber length. Observation shows that the increasing the FWM crosstalk as a results in the increase of the input power of the signal. This leads to increase the nonlinear effects and thus affect the efficiency of the optical system.
4.2. The Quality Factor and Eye Diagram

The relationship between the quality factor and the power of the input signal under the influence of the bit rate of (80Gb/s) and with / without the proposed technique as illustrated in Figure. 9 (a-c) & Figure. 10 (a-c) at the second channel. The system was implemented for two types of modulation used and for distances of 60, 120 and 300 km respectively. It can be seen that an increase in the input power of the signal leads to improve the (Q-Factor) and a decrease in the bit error rate. For all channels the system performance was similar and it was found that (CSRZ) reveals better system performance. From the behavior of modulation with high values, it can be concluded that modulation (CSRZ) reveals the extent of diminution of nonlinear effects, especially effects of FWM, more than DBM-1.
Fig. 10 Quality factor vs input power of transmission signal for modulation CSRZ&DBM-1 at distance (a)60Km (b)120Km(c)300km

From fig. 11(a ), it shows that the optimal eye diagram for all formations used after distance (300) km is calculated in the fourth channel . CSRZ had the optimum height of the eye diagram (Q Factor=, 41.5313), the opposite with modulation of DBM-1 where we find the eye plot less clear and the height of (Q Factor=10.2552) is in the same distance(300km) as shown in Fig.11(b) Thus in the proposed system means more opening eyes diagram the system is optimized and in the successful rate of detecting (1,0) the receiving bits and no noise due to interference

Fig.11 Shown eye diagram Performance of the proposed system (a) CSRZ modulation, (b)DBM-1 modulation using (ch4) at distance 300km at 12.5 dBm input power
Figure 12  Shown eye diagram Performance of the traditional DWDM system (a) CSRZ modulation, (b) DBM-1 modulation using (ch4) at distance 300Km at 12.5 dBm input power

From Figure 12, we notice the distortion occurring in the system through the eye chart, where it shows the amount of the quality factor for the modification shapes, where the values of the Q factor (3.49364, 2.18746) for the modulation were (CSRZ, DBM-1) at fiber length 300Km, and input power 12.5dBm so the amount of improvement in the proposed system appears compared to the traditional system. The all significant results are summarized as in Table 2. Comparison between 8-channels traditional DWDM system and 8-channels with polarization combiner system at different transmission lengths, at input power (12.5 dBm) for two types of Ext. Mod. A comparison of the modulation types used as a function of the system's performance for 300km distance can be statistically described as in Figure.13.

Table 2: Results summery of system performance under PC technique

| Length | Ext. Mod | Q- Factor | Improving % | Bit Error Rate |
|--------|----------|-----------|-------------|----------------|
|        |          |           | With PC     | Without PC     |                 |
|        |          |           | With PC     | Without PC     |                 |
| 60Km   | CSRZ     | 72.0328   | 26.6611     | 62.99%         | 0.416229×10⁻¹³⁷ |
|        | DBM-1    | 21.377    | 9.0896      | 57.48%         | 1.68529×10⁻¹⁰¹ |
| 120Km  | CSRZ     | 57.7655   | 18.9943     | 67.12%         | 5.63298×10⁻³¹  |
|        | DBM-1    | 17.5484   | 5.87814     | 66.50%         | 5.167×10⁻⁸⁷   |
| 300Km  | CSRZ     | 41.5313   | 3.49364     | 91.59%         | 5.08994×10⁻¹⁷⁴ |
|        | DBM-1    | 10.2552   | 2.18746     | 78.67%         | 0.00730178     |
5. Conclusion
Four wave mixing is one of the obstacles to optical transmission and its effect increases with the length of the transmission distance as the effect of FWM on the system increases. This work presents a new technique to mitigate the FWM crosstalk based on pairing groups of different optical signals. The proposed system was conducted for an 8-channel and total data rate of (80Gb/s) and 50 GHz channel spacing. The reliability of the proposed technique was tested with two kinds of modulation techniques which are (CSRZ) and (DBM-1) and different transmission distance. The power of FWM was significantly suppressed with the CSRZ & DBM-1 techniques to less than (47.97%, 41.38 %) respectively, at an input power of 12.5 dBm. In term of Quality factor, the performance of the proposed system with the polarization technique offered an improvement around (91.59%, 78.67%) for the same sequence of modulation.

REFERENCES
[1] Mulvad, H. C. H., Galili, M., Oxenløwe, L. K., Hu, H., Clausen, A. T., Jensen, J. B., ... & Jeppesen, P. (2010). Demonstration of 5.1 Tbit/s data capacity on a single-wavelength channel. Optics Express, 18(2), 1438-1443.
[2] Mulvad, H. H., Oxenlowe, L. K., Galili, M., Clausen, A. T., Gruner-Nielsen, L., & Jeppesen, P. (2009). 1.28 Tbit/s single-polarisation serial OOK optical data generation and demultiplexing. Electronics Letters, 45(5), 280-281.
[3] Haider, J. Abd, Sabah A. Gitaffa, Mohammed G. Al-Hamiri , Impact of optimized pulse shaping on optical transmission performance in the availability of different dispersion maps , Optik - International Journal for Light and Electron Optics 241 (2021) 167006
[4] Rasheed, I., Abdullah, M., Mehmood, S., & Chaudhary, M. (2012, October). Analyzing the non-linear effects at various power levels and channel counts on the performance of DWDM based optical fiber communication system. In 2012 International Conference on Emerging Technologies (pp. 1-5). IEEE.
[5] Sabapathi, T., & Sundararadvivelu, S. (2011). Analysis of bottlenecks in DWDM fiber optic communication system. Optik, 122(16), 1453-1457.
[6] Desurvire, E. B. (2006). Capacity demand and technology challenges for lightwave systems in the next two decades, Journal of Lightwave Technology, 24(12), 4697-4710.
[7] Singh, M. (2015). Analyzing the effect of channel spacing and chromatic dispersion coefficient on FWM in optical WDM system. International Journal of Signal Processing, Image Processing and Pattern Recognition, 8(11), 99-110.
[8] Deshmukh, G., & Jagtap, S. (2013). Four wave mixing in DWDM optical
system. *International Journal of Computational Engineering Research, 3*(6).

[9] Singh, N., & Goel, A. K. (2016). Analysis of four wave mixing effect at different channel spacing in DWDM systems using edfa with single pump source. *An International J Eng Sci, 17*, 382-389.

[10] Thing, V. L., Shum, P., & Rao, M. K. (2004). Bandwidth-efficient WDM channel allocation for four-wave mixing-effect minimization. *IEEE Transactions on Communications, 52*(12), 2184-2189.

[11] Bogoni, A., & Poti, L. (2004). Effective channel allocation to reduce inband FWM crosstalk in DWDM transmission systems. IEEE Journal of selected topics in Quantum Electronics, 10(2), 387-392.

[12] Sabapathi, T., & Sundaravadivelu, S. (2007, December). Capacity Improvement in Dispersive, Non-Linear Optical Fiber. In International Conference on Computational Intelligence and Multimedia Applications (ICCIMA 2007) (Vol. 4, pp. 412-416). IEEE.

[13] Sabapathi, T., & Poovitha, R. (2017, February). Combating the effect of nonlinearities in DWDM system. In 2017 4th International Conference on Electronics and Communication Systems (ICECS) (pp. 38-42). IEEE.

[14] Kaur, G., & Aggarwal, M. (2017). Simulation comparison of different dispersion compensation techniques in single channel optical fiber using Optisystem. *Int J Adv Res Electr Electron Instrum Eng, 6*, 5131-7.

[15] H.J. Abd, M.H. Al-Mansoori, N.M. Din, F. Abdullah, H.A. Fadhil, Four-wave mixing eduction technique based on smart filter approach, *Int. J. Electron.* 102 (6) (2015) 1056–1070.

[16] H.J. Abed, N.M. Din, M.H. Al-Mansoori, H.A. Fadhil, F. Abdullah, Recent four-wave mixing suppression methods, *Optik* 124 (2013) 2214–2218.

[17] H.J. Abd, M.H. Al-Mansoori, N.M. Din, F. Abdullah, H.A. Fadhil, Priority-based parameter optimization strategy for reducing the effects of four-wave mixing on WDM system, *Optik* 125 (2014) 25–30.

[18] KALER, R., & KAUR, G. (2021). Mitigation of PMD over DWDM system using polarization interleaving. *Optoelectronics and Advanced Materials-Rapid Communications, 15*(January-February 2021), 49-54.

[19] H. Abd, N.M. Din, M.H. Al-Mansoori, F. Abdullah, H.A. Fadhil, Four-wave mixing crosstalk suppression based on the pairing combinations of differently linear-polarized optical signals, *Sci. World J.* 2014 (2014) 1–10. Article ID 243795, 1, 2014

[20] Habib Ullah Manzoor, Muhammad Zafar, Sana Ullah Manzoor, Talha Khan, Songzuo Liu, Tareq Manzoor, Saqib Saleem, Woo Young Kim, Muddassir Ali, Improving FWM efficiency in bi-directional ultra DWDM-APON networking centered light source by using PMD emulator, *Results Phys. 16* (2020), 102922

[21] Habib Ullah Manzoor, Abaid Ullah Salfiy, Tayyab Mehmoodz and Tareq Manzoor, “Reduction of four wave mixing by employing circular polarizers in DWDM Optical Networks,” in Proceedings of 12th International Bhurban Conference on Applied Sciences & Technology ,IBCAST,2015, pp. 637-640.

[22] J. Šajgalíková, J. Litvik and M. Dado, “Simulation of FWM effects in WDM systems with various modulation formats,” 2016 ELEKTRO, Strbske Pleso, 2016, pp. 92-95.