FWM Mitigation in DWDM Optical Networks

Habib Ullah Manzoor¹, Tareq Manzoor², Ashiq Hussain³, Moustafa H. Aly⁴

¹ University of Engineering and Technology, Lahore, Pakistan, habibullahmanzoor@gmail.com
² Faculty of Engineering, COMSATS, Sahiwal, Pakistan, tareqmanzoor@hotmail.com
³ HITEC University, TaxilaCnatt, Pakistan, hafizashiq@hotmail.com
⁴ College of Engineering and Technology, Arab Academy for Science, Technology and Maritime Transport Alexandria, Egypt, Member of OSA, mosaly@aast.edu

Abstract In this paper, three optical communication systems have been proposed to mitigate Four Wave Mixing (FWM). Three techniques are used, namely: low input power with high gain amplifier, a combined Optical Time Division Multiplexing (OTDM) and Wavelength Division Multiplexing (WDM) system, and the use of alternative circular polarization. The first technique involves reduction in input power to -20 dBm and then amplifying it 20 dB before demultiplexing. The second technique divides the input signal into four time slots and then combine them with a power combiner. In the third technique, the polarization of input pulses is changed before multiplexing into right and left handed circular polarization. Exhaustive set of simulations is carried out using Optisys. The performance analysis includes Q-factor, Optical Signal to Noise Ratio (OSNR), received power, Bit Error Rate (BER) and eye diagram.

Key words: Four Wave Mixing (FWM), Optical Signal to Noise Ratio (OSNR), Optical Time Division Multiplexing (OTDM), Dense Wavelength Division Multiplexing (DWDM), Bit Error Rate (BER).

1. INTRODUCTION

Next generation optical networks will require substantial enhancements in capacity and efficiency. To increase the capacity, it is necessary to use Wavelength Division Multiplexing (WDM), where multiple wavelengths are transmitted in a single fiber. To increase capacity, channel spacing is reduced. If it is reduced to 200 GHz, then WDM becomes Dense Wavelength Division Multiplexing (DWDM). Deploying DWDM in optical networks will increase capacity. However, it has some drawbacks arising from nonlinear effects; namely, light scattering and dependence of refractive index on light intensity. The first category includes Stimulated Raman Scattering (SRS), Stimulated Brillouin Scattering (SBS). The second includes Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM) and Four Wave Mixing (FWM) [1, 2]. However, these drawbacks have some useful applications such as pulse regeneration, optical monitoring, wavelength conversion, and switching [2].

Among all nonlinearities in DWDM systems, FWM is the most prominent which creates power penalties and limitsthe input power [3]. FWM is to be avoided because new pulses produced by FWM may reduce SNR and increase BER FWM is to be avoided [4]. When two light pulses of same phase velocities are lunched intoan optical fiber, along the propagation through fiber they interact with each other and create two more pulses [2]. More input pulses produce more new pulses according to the relation [5]:

\[ \text{number of generated pulses} = \frac{n^2}{n(n-1)} \]  

where n is the number of input pulses.
Let $\lambda_i$, $\lambda_j$ and $\lambda_k$ are three different wavelengths of different channels, then, the FWM generated wavelengths, $\lambda_{ijk}$, are given [6]:

$$\lambda_{ijk} = \lambda_i \pm \lambda_j \pm \lambda_k$$  \hspace{1cm} (2)

The FWM power produced, in terms of the input powers $P_i$, $P_j$ and $P_k$ follow the expression [7]:

$$P_{ijk} = d_{ijk} \gamma L_{eff} P_i P_j P_k \eta_{ijk} e^{-\alpha L}$$  \hspace{1cm} (3)

Here, $d$ is a degeneracy factor whose value is 1 for degenerate and is 2 for non-degenerate systems. $L_{eff}$ is the fiber effective length of fiber, $\gamma$ is a nonlinear coefficient and $\eta$ is efficiency of FWM products. The parameters $\gamma$ and $\eta$ can be defined, respectively, as [7]:

$$\gamma = \frac{2\pi n_2}{A_{eff} \lambda_0}$$  \hspace{1cm} (4)

$$\eta = \frac{a^2}{a^2 + \Delta B_{ijkl}} \left[ 1 + \frac{4 e^{-az} \sin^2 \left( B_{ijkl}^2 / 2 \right)}{(1 - e^{-az})^2} \right]$$  \hspace{1cm} (5)

where $n_2$ is fiber nonlinear coefficient, $\lambda_0$ is the central wavelength, $A_{eff}$ is fiber core effective area and $B_{ijkl}$ is the phase mismatching coefficient.

For long fiber cable efficiency can be approximated as:

$$\eta = \frac{a^2}{a^2 + \Delta B_{ijkl}}$$  \hspace{1cm} (6)

FWM at different channel spacings has been investigated in [8-10] and is parametrically investigated in [11]. Several attempts have been proposed to reduce FWM in WDM systems. The unequal channel spacing technique was used which is uneffective for bandwidth use. Other techniques were used leading to complicated optical networks and produced unsatisfactory results [12-15]. In this paper, three systems have been proposed and analyzed to reduce FWM. The proposed systems utilize circular polarization, low input with high optical gain and system using OTDM with DWDM (DWDM/OTDM). After implementing the proposed systems, FWM is almost completely eliminated. All simulations are performed using Optysis. Spectrum, eye diagram, BER, received power and OSNR for different systems are analyzed study the effects of proposed changes in conventional optical communication systems.

2. Low Input Power With High Optical Gain System

2.1 System Design

Since, the power of the generated FWM signals is of the order three (cube) of the optical carrier power, so, a slight change in input power can result in a significant reduction in power of FWM generated signals [16].

Figure 1 shows our proposed optical communication system that consists of a 16 channels WDM transmitter at a spacing of 100 GHz with -20 dBm input power for each channel. The channels frequencies are in the range 193.1THz to 194.6THz. A NRZ modulation format is used in transmitter followed by a WDM multiplexer (MUX). The MUX is connected to a 50 km single mode fiber having a dispersion of 16.75ps/nm/km and a dispersion slope of 0.075ps/nm²/km with 0.2 dB/km material loss and 80 µm² effective area. The fiber is connected to a 10.4 km dispersion compensating fiber (DCF) of -80ps/nm/km and -0.358ps/nm²/km dispersion.
and dispersion slope, respectively, and 20µm² effective area, so that residual dispersion is zero. The DCF is followed by a 20 dB gain optical amplifier (OA) with zero noise figure. On the other side, a demultiplexer (DEMUX) is used and followed by an optical receiver with cutoff frequency of 0.75×bit rate. The system capacity is 160 Gbps (10 Gbps×16 channels).

2.2 Results and Discussion

In this system, the input power has been decreased, so, there is less power to interact and produce FWM products. After that, the use of OA will increase the output power. The obtained simulation results are displayed in Fig. 2. From Fig. 2(a), no FWM signals can be observed and the original pulses are still at -20 dBm. The thin red curve, Fig. 2(b), shows a decision instant that has the highest value at the middle of eye diagram. Some variations in the curve of decision instant of eye diagram can be observed. The red curve shows the Q-factor versus decision instant. Its highest value occurs at the highest eye opening. Moreover, all channels show eye height of more than 300µ a.u.
The obtained values of BER, Q-factor, received power and OSNR of all channels are summarized in Figs. 3 and 4, respectively.

![Figure 3](image1.png) ![Figure 4](image2.png)

Figure 3 (a) OSNR and (b) Received power, of all channels.

Figure 4 (a) BER and (b) Q-factor, of all channels.

From Fig. 3(a), the highest OSNR occurs at 193.5 THz. Figure 3(b) shows the variation in received power within all channels. The average received power is -17.8 dBm with noise power of -37.8 dBm and the average OSNR is 20.1 dB. From Figs. 4(a) and 4(b), it is observed that the Q-factor varies from 3.8 to 5.55 and the highest Q-factor is observed at 193.7 THz. Moreover, the BER varies from zero to 0.00005. So, the described technique can completely eliminate FWM products without reducing the power of input pulses. It can be seen that transmitter is producing input pulses at 20 dB and after traveling 60.46 km, and at the receiver, output pulses still have power of 20 dB without any FWM products.
3. WDM/OTDM SYSTEM

3.1 System Design

As shown in Fig. 6, the proposed system consists of 16 continuous wave (CW) laser as a transmitter spaced at 200 GHz, each with 0 dBm input power. Every CW laser is modulated using a NZR pulse generator by Mach-Zehnder Modulator (MZM). The MZM is further connected to a power splitter of the four ports, every port is connected to time delay of 1/(bit rate × i/4), where i = 1, 2, 3, 4. The channel frequencies are from 193.1THz to 195.1THz. After the time delay, all ports are combined using a power combiner which is connected to a WDM multiplexer (MUX). The MUX is connected to a single mode optical fiber and a DCF with the same specifications mentioned in the previous system. The DCF is followed by a 20 dB gain optical amplifier with zero noise figure. On the other side, the DEMUX is followed by a power splitter connected to four time delays. The time delay is further connected to an optical receiver with cutoff frequency of 0.75 × bit rate.

![Figure 6 Single transmitter (4×TDM).](image)

Here, the system capacity is 160 Gbps (10 Gbps × 16 channels). Every channel is divided in 4 parts using OTDM; if 4 users are adjusted on a single frequency, then 64 users can be accommodated by the entire system.

3.2 Results and Discussion

Based on the described system, the simulation results are shown in Fig. 7.
Figure 7 (a) Spectrum after DEMUX. (b) Eye diagram of 1\textsuperscript{st}, 6\textsuperscript{th}, 11\textsuperscript{th} and 16\textsuperscript{th} channel.

From Fig. 7(a), it can be observed that FWM products are nearly zero. At lower data rates, they completely disappear; however, original pulses are at -28 dBm. Figure 7(b) is shows the eye diagrams and the Q-factor of 1\textsuperscript{st}, 6\textsuperscript{th}, 11\textsuperscript{th} and 16\textsuperscript{th} channels. The thin red curve is the graph of decision instant VersaceQ-factor. Figure 7(b) shows 60µ a.u. average eye height.

The obtained values of BER, Q-factor, received power and OSNR of all channels are summarized in Figs. 8 and 9, respectively.

Figure 8 (a) OSNR and (b) Received power, of all channels.
Figure 9 (a) BER and (b) Q-factor, of all channels.

Figure 8(a) shows the variations in the received power from -15.57 dBm to -16.1 dBm with noise power. The highest OSNR of 22.42 dB is observed at 193.2 THz in Fig. 8(a). Figure 9(a), (b) shows the values of Q-factor and BER of all channels. The highest Q-factor was is 4.21 by 194.7 THz with BER of $8.79 \times 10^{-6}$. Again, this technique can eliminate FWM products while maintaining power of output pulses. However, OTDM is required for every channel. This system can accommodate 64 (16×4) channels which results in an increase in channel capacity upto 640 GHz ($64 \times 10$ GHz) rather than 160 GHz.

4. Alternative Circular Polarization System

4.1 System Design

In this system, circular polarization (CP) is used to reduce FWM. Our proposed system consists of a WDM transmitter containing 8 channels at a spacing of 200 GHz having -3 dBm (0.5 mW) input power. The channel frequencies are from 193.1THz to 194.5THz. RZ modulation is used in transmitter followed by circular polarizer. The CP of the right hand and left hand are used in all channels alternatively, i.e., if the first channel is connected to right hand CP, then, the second channel is connected to left hand CP. CPs are connected to MUX which is further connected to a single mode optical fiber having the same specifications of the previous systems with an effective area of 150 µm². Fiber is connected to DCF exactly like that of the previous systems. The DCF is followed by a 10 dB gain OA. This relatively lower gain helps in FWM reduction with zero noise figure. On the other side, the DEMUX is followed by the optical receiver with cutoff frequency of 0.75×bit rate. The schematic diagram of this system is shown in Fig. 10.
4.2 Results and Discussion

The above system is simulated leading to the results displayed in Fig. 11.

Figure 11 (a) Spectrum after DEMUX. (b) Eye diagram of 1st, 3rd, 5th and 8th channel.

Figure 11(a) shows the FWM generated signals at -95 dBm. They are so small that they can be ignored. The original pulses are at -27 dBm. A Q-factor of 5.2 and eye height of 83µ a.u. can be observed from Fig. 12(b).

The obtained values of BER, Q-factor, received power and OSNR of all channels are summarized in Figs. 12 and 13, respectively.

Figure 12 (a) OSNR and (b) Received power, of all channels.
Figure 12(a) displays the OSNR, where the highest OSNR is observed by the first channel while lowest OSNR is observed by last channel. The received power varies from -25.23 dBm to -25.35 dBm. Figure 13(a) is implied that worst BER is seen on 194.3 THz. The Q-factor shows a variation from 4.3 to 5.7 in Fig. 13(b). So, this technique can eliminate FWM products while providing a better received power, OSNR and Q factor.

Table I summarizes the obtained results using different techniques. It is clear that, the best one is the circular polarization system.

| Technique                                  | Avg. OSNR (dB) | Avg. Received Power (dBm) | Avg. Q factor | Avg. RER  |
|--------------------------------------------|----------------|---------------------------|---------------|-----------|
| Low input power and high optical gain      | 20.14          | -17.84                    | 4.5           | 12 × 10⁻⁸ |
| WDM/OTDM                                   | 22.05          | -15.8                     | 4             | 3 × 10⁻⁶  |
| Circular polarizers                        | 23             | -25.27                    | 5             | 7 × 10⁻⁷  |

5. Conclusion
In this paper, three systems are proposed and investigated to eliminate FWM. The three techniques are separately applied to optical communication networks; first the use of low input power with high gain optical amplifier, second is a combined use of DWDM and OTDM, and third is an alternative circular polarization. All proposed systems have shown tremendous FWM reduction, however, at the cost of system quality. By adjusting system parameters, FWM can be eliminated appreciably. Using alternative circular polarizers to suppress FWM gives the better system performance based on OSNR, received power and Q factor.

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