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A NEW FWM REDUCTION TECHNIQUE BASED ON DAMPING SELECTIVE WAVELENGTHS

This paper proposes a new method that can suppress the four-wave mixing using an Optical Drop Multiplexing (ODM) technique. The four-wave mixing (FWM) behavior and the performance of wavelength division multiplexing (WDM) systems are investigated, using the proposed technique. It is found that the FWM power is drastically reduced to –96 dBm, when the ODM technique was used. For a WDM system at the first channel (193 THz), the suggested approach offered the bit error rate (BER) to be 1.47×10^{-27}*, in comparison with the absence of the current technique, where BER was* 2.53×10^{-17}*. Moreover, it is found that the proposed technique caused the FWM power to reduce by 28 dB.*

Keywords: four wave mixing, ODM, nonlinear effect, WDM, BER, FWM suppression methods.

1. Introduction

The wavelength division multiplexing (WDM) has played a significant role in high-channel-capacity efficient fiber-optic communication systems. The WDM permits huge amounts of data in different channels to be transferred at different wavelengths. In modern WDM systems, an optical fiber under high data rates suffers from some of the undesirable effects that degrade the system performance. This phenomenon is called nonlinear effects. The most significant drawback of nonlinear effects is that it can lower the performance of WDM optical networks, which consequently creates a probable distortion of the output signal and the channel energy waste [1, 6, 9, 11, 12]. Four-wave mixing (FWM) is the strongest detrimental effect, which is created when the refractive index inside a fiber changes with the power level [3, 10, 12]. The problems introduced by the four-wave mixing can be mitigated by few techniques such as the use of relatively low channel counts, advanced modulation format techniques, and fibers with a reasonable degree of dispersion [3, 5, 8]. However, the dispersion causes a distortion of the transmitted signals and needs to be compensated to achieve a long-haul transmission system. As the channel count increases, more channels have to be confined to the erbium-doped fiber amplifier (EDFA) gain band by reducing the channel spacing. This will increase the effects of FWM. An advanced modulation technique may also enhance the bit-error rate, but it has a little impact on the FWM power reduction. However, all these recent techniques aiming to suppress the FWM crosstalk and enhance

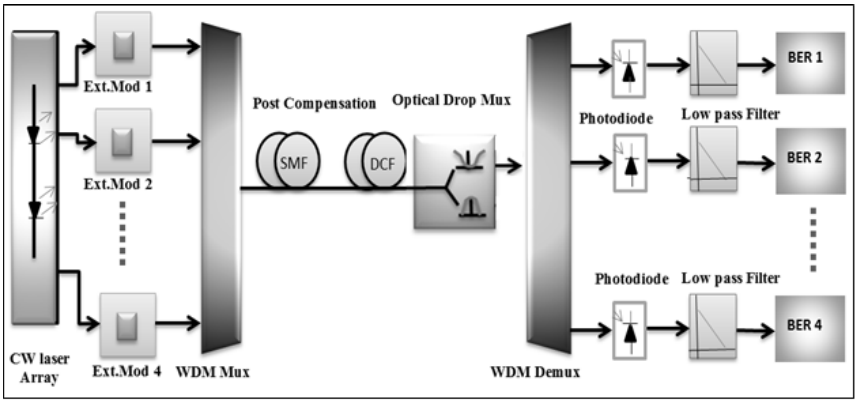

Fig. 1. The proposed system simulation configuration

the bit error rate (BER) is far from the effective solution to reduce the FWM crosstalk to a minimum value for a better bit error rate. In this paper, a new approach is proposed to suppress the FWM effect in WDM systems with the use of the ODM technique. The dramatic reduction in FWM was observed, which leads to an enhancement in the system performance. Based on the ODM approach, the FWM power was suppressed to –96 dBm, and the system BER was reduced to 1.47×10^{-27}.

2. Simulation Structure and Operating Principles

Figure 1 illustrates the transmitter and receiver simulation setup of the proposed system. At the transmitter part, the system consists of an array of continuous-wave (CW) units which are the laser sources connected to an external modulator. The frequency of the first channel is set to 193 THz, and the spacing between channels is 100 GHz. The external modulator comprised a Pseudo-Random Bit Sequence (PRBS), which is connected to a pulse generator to modulate the optical signals using the Non-Return-Zero (NRZ) modulation format. It is then connected to a Mach-Zehnder modulator (MZM) as an intensity modulator. The optical link uses post dispersion compensations map to compensate the dispersion in the link. The map consists of a single mode fiber (SMF) and a dispersion compensation fiber (DCF). The ODM is placed after this map. It is used to selectively drop optical signals into a transparent WDM network [4]. ODM consists of an input port, which can receive the wavelengths of transmitted channels, and two optical output ports; one can be connected to the next component which can be used and the other is related to the optical spectrum which cannot be used. The input signal to the ODM is split into two signals, and each signal is filtered by an optical filter. The filters used are identical, but one operates as an inverse to the other. The first signal is filtered by the inverse one, and the second signal by the non-inverse one. The first signal is filtered by the inverse optical filter, and then it passes to the optical receiver, while the second signal will be not connected to the receiver but to the optical spectrum analyzer. Therefore, the BER calculation was only carried out for the first channel. The signal is detected by a PIN photodiode with responsivity (b) of 0.8 A/W and a dark current of 10 nA. It is then passed through a low-pass Bessel filter. The FWM frequencies can be predicted as a result of the interference of the original frequencies and depend on the number of channels (M). For 4 channels, if we assume that the frequencies of input channels are F_i, F_j, F_k, and F_l, the total number of FWM frequencies (n) can be found using the following equation:

$$n = \frac{M^3 - M^2}{2}, \quad (1)$$

and the frequencies can be classified into three groups;

$$2F_i - F_j, 2F_i - F_k, 2F_i - F_l, \quad (2)$$

$$2(2F_i - F_j) - F_k, 2F_l - F_k, 2F_l - F_j, \quad (3)$$

$$2(2F_l - F_k) - F_j, 2(2F_k - F_i) - F_i, 2(2F_l - F_j) - F_j, \quad (4)$$

where $i \neq j \neq k \neq l$, and i, j, k, l are channel numbers from 1 to 4.

Figure 2 illustrates the steps for our proposed technique. It determines the FWM power dropped after applying the ODM technique. The technique calculates F_{FWM}, which can be estimated from (2) to (4). The FWM frequencies dropped separately ($N_1 \to N$), and the algorithm determines the average FWM power drop for each frequency removed and compares it with the P_{FWM} threshold which is considered as a reference. The suppression in the FWM power below the P_{FWM} threshold was ignored. This process is repeated until all the FWM frequencies are removed, and the total FWM power drop is calculated. The power transferred due to FWM can be summarized in the following equation, as in [7]:

$$P_{\text{FWM}} = \eta \frac{1024\pi^6}{n^4\lambda^2 C^2}\left(\frac{D_g X_{111} L_{\text{eff}}}{A_{\text{eff}}}\right)^2 (P_i P_j P_k) e^{-\alpha l}, \quad (5)$$

where P_i, P_j, and P_k are the input powers, D_g is the degeneracy factor, X_{111} is the third-order susceptibility, A_{eff} is the effective area, C is the speed of light, λ is the laser wavelength, α is the fiber loss coefficient, L is the total fiber length, n is the refractive index of the fiber, and L_{eff} is the nonlinear effective length.

After going through the ODM, the FWM power dropped can be estimated as

$$P_{\text{FWM(drop)}N} = K \times 10^{-0.1D}, \quad (6)$$

where K is the power of four-wave mixing by the conventional method, $10^{-0.1D}$ is the FWM power reduction factor, and D is the filter depth value. It can take any value. For this work, the value chosen is 50 dB which means that the FWM signal will be attenuated by that depth value. The minus sign signifies the drop process.

The total FWM power dropped is represented by the equation

$$\text{Total FWM power drop} = \frac{P_{\text{drop}(N)}}{n}. \quad (7)$$

The system performance is represented by the calculation of Q, which is then used for the BER calculation using the equations [2]

$$Q = \frac{bP_s}{\sqrt{N_{\text{th}} + N_{\text{sh}} + N_{\text{FWM}}} + \sqrt{N_{\text{th}}}}, \quad (8)$$

$$Q = \frac{b^2 P_s^2}{2b^2 P_s \frac{P_{\text{FWM}}}{8}}, \quad (9)$$

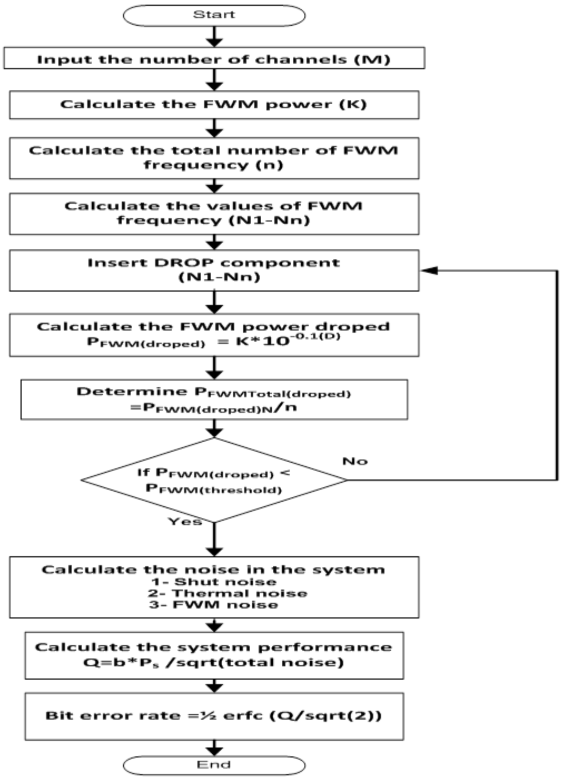

Fig. 2. The flowchart steps for the ODM technique

$$\text{BER} = 0.5 \ \text{erfc}\left[\frac{Q}{\sqrt{2}}\right], \quad (10)$$

where Q is the maximum Q factor, BER is the bit-error-rate, b is the detector responsivity, P_s is the received power, N_{FWM} is the FWM noise, N_{sh} is the shot noise, and N_{th} is the thermal noise. Equations (1) to (10) were evaluated, by using values shown in Table 1.

3. Results and Discussion

Since the chromatic dispersion greatly influences the FWM generation, the simulation was conducted by increasing the dispersion value from 0 to 18 ps/nm·km and applying the ODM method. Using (2), (3), and (4), the dominant FWM frequencies are 192.9, 192.8, 192.7, 193.4, 193.5, 193.6, 193.7, 193.8, and 193.9 THz as shown in Fig. 3, *A*. The ODM dropped each FWM frequency individually by entering each frequency to the ODM component. It is clear from Fig. 3, *A* that the FWM power was –40 dBm at a dispersion value of 0 ps/nm·km. Figure 3, *B* and *C* shows that the

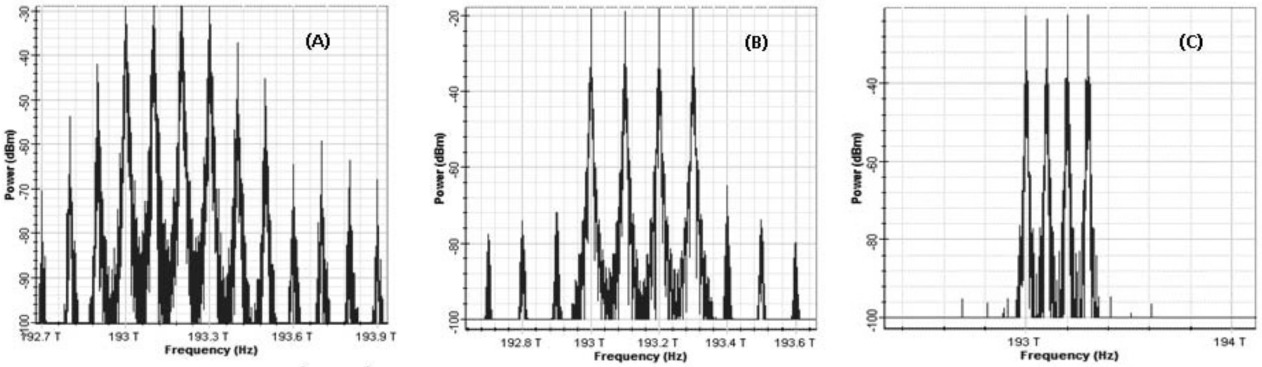

Fig. 3. Optical spectrum comparison after 60 km for the FWM power for (A) at dispersion of 0 ps/nm·km, (B) without ODM technique and at dispersion of 18 ps/nm·km and (C) with ODM technique at dispersion of 18 ps/nm·km

Table 1. **System simulation parameters**

Parameter	Unit	Values
Fiber length, L	km	50 for SMF and 10 for DCF
Input power, P_i	dBm	5
Input frequency	THz	193:0.1:193.3
Channel spacing, f	GHz	100
Dispersion, D_c	ps/nm·km	(0–18) for SMF and –85 for DCF
Cross effective area, A_{eff}	m^2	70 for SMF and 22 for DCF
Degeneracy factor, D_g	–	6
Third-order susceptibility, X_{111}	$m^3/w.s$	6 10–15
Refractive index, n	–	1.48
Speed of light, c	(m/s)	3 108
Operating wavelength, λ	(nm)	1550
Attenuation factor, α	(dB/ km)	0.2
Number of channel	–	4
Depth value, D	dB	50
Detector responsivity, b	A/W	0.8
P_{FWM} threshold	dBm	–70
Received power, P_s	dBm	–14 to –16
Data Rate	Gb/s	40

FWM power was –68 dBm at a dispersion value of 18 ps/nm·km; while, in the presence of the ODM technique at same dispersion value, the FWM power was dropped to –96 dBm. The reduction in the FWM power was from –68 dBm to –96 dBm at the dispersion value of 18 ps/nm·km. Thus, the FWM reduction is 28 dB.

Figure 4 shows the relationship between the dispersion and BER in the system with ODM technique and without using it at the first channel (193 THz) and the fourth channel (193.3 THz). Observation of the results shows that the increased dispersion will reduce the BER in both channels. At the first channel, using the ODM technique reduces the BER to 1.47×10^{-27} at a dispersion of 18 ps/nm·km. When the ODM is not used, the BER of the system is 2.53×10^{-17} at the same dispersion value. The same case happened at the fourth channel, where the BER was 1.5×10^{-27} for the system using ODM and 1.39×10^{-16} for the system without it. Even at 18 ps/nm·km dispersion value, the FWM signal is reduced significantly with ODM, which is translated into a lower BER value, by improving the system performance.

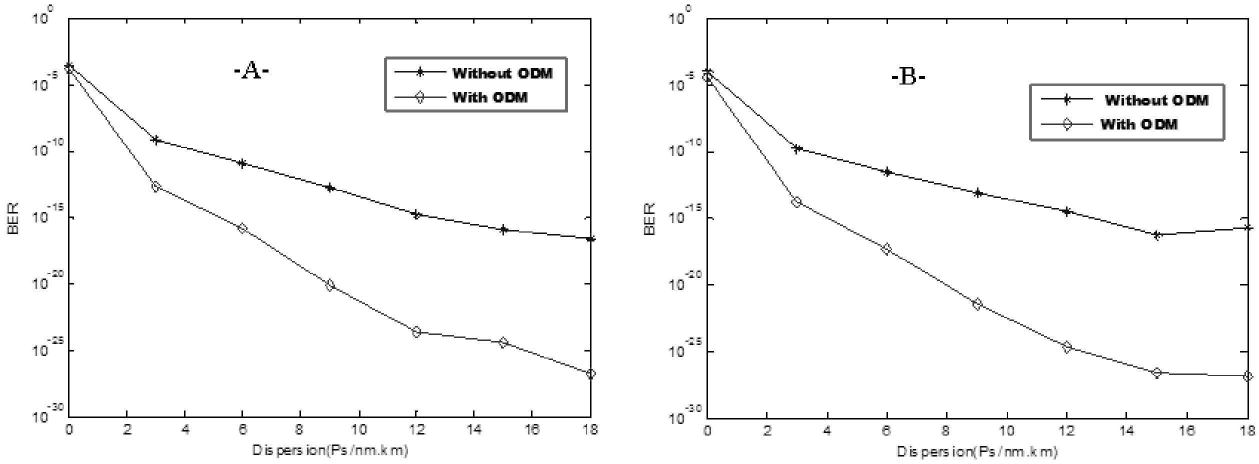

Fig. 4. Relation between the dispersion and BER in the presence and the absence of the ODM technique at the first channel (193 THz) (A)and at the fourth channel (of 193.3 THz) (B)

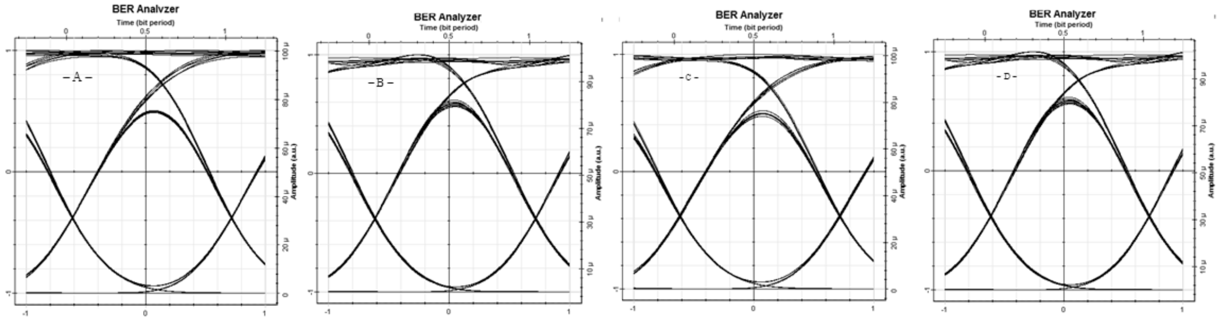

Fig. 5. Optimum eye diagram performance (A) without ODM technique at D_c=18 ps/nm·km and using (ch1), (B) with ODM technique at $D_c = 18$ ps/nm·km and using (ch1), (C) without ODM technique at $D_c = 18$ ps/nm·km and using (ch4), (D) with ODM technique at $D_c = 18$ ps/nm·km and using (ch4)

Table 2. **Summary of system simulation results**

Sequence	Technique name	Minimum PFWM(dBm)	Maximum received optical power (dBm)	Optimum minimum BER at ch1	Optimum minimum BER at ch4
1	Using dispersion parameters at $D_c = 0$ Ps /nm·km	–40	–15.198	0.000155	0.000302
2	Using dispersion parameters at $D_c = 18$ Ps /nm·km	–68	–14.84	2.53×10^{-17}	1.93×10^{-16}
3	Using ODM+dispersion parameters at $D_c = 18$ Ps /nm·km	–96	–14.76	1.47×10^{-27}	1.5×10^{-27}

Figure 5 shows the eye diagram for the proposed technique in comparison with the absence of it. The eye height of system with ODM is higher than the the system without ODM for both channels 1 and 4. It is evidence of that, with a wider eye opening resulting from a higher eye height, BER of the system improves. Table 2 summarized the simulation results.

4. Conclusion

In this paper, we suggested a new technique to reduce the transmission impairment due to FWM in the WDM system by utilizing the Optical Dropped Multiplexing technique. The WDM system performance has been evaluated under the proposed technique. It was found that the FWM power was reduced to –96 dBm in the presence of this approach; while, in the case where the proposed technique was not used, the FWM power was –68 dBm. The new method ensured the enhancement to BER in the range of 1.47×10^{-27}.

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НОВИЙ МЕТОД ЗМЕНШЕННЯ ЧОТИРИХВИЛЬОВОГО ЗМІШУВАННЯ, ЗАСНОВАНИЙ НА ПОСЛАБЛЕННІ НА ОКРЕМИХ ДОВЖИНАХ ХВИЛЬ

Резюме

Запропоновано новий метод зменшення чотирихвильового змішування (ЧХЗ) на основі техніки редукції оптичного мультиплексування (РОМ). Цим методом досліджено чотирихвильове змішування і характеристики систем мультиплексування з розділенням довжин хвиль (МРДХ). Знайдено, що потужність чотирихвильового змішування сильно падає до –96 дБм з використанням техніки РОМ. Для МРДВ системи на першому каналі 193 ТГц, пропонований метод дає $1{,}47 \cdot 10^{-27}$ для частоти появи помилкових символів, тоді як зазвичай ця частота дорівнює $2{,}53 \cdot 10^{-17}$. Знайдено, що запропонований метод зменшує потужність ЧХЗ на 28 дБ.

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НОВЫЙ МЕТОД УМЕНЬШЕНИЯ ЧЕТЫРЕХВОЛНОВОГО СМЕШИВАНИЯ, ОСНОВАННЫЙ НА ПОДАВЛЕНИИ НА ОТДЕЛЬНЫХ ДЛИНАХ ВОЛН

Резюме

Предложен новый метод подавления четырехволнового смешивания (ЧВС) на основе техники редукции оптического мультиплексирования (РОМ). Этим методом исследованы четырехволновое смешивание и характеристики систем мультиплексирования с разделением длин волн (МРДВ). Найдено, что мощность четырехволнового смешивания сильно падает до –96 дБм с использованием техники РОМ. Для МРДВ системы на первом канале 193 ТГц, предлагаемый метод дает $1{,}47 \cdot 10^{-27}$ для частоты появления ошибочных символов, тогда как обычно эта частота равна $2{,}53 \cdot 10^{-17}$. Найдено, что предложенный метод уменьшает мощность ЧВС на 28 дБ.