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Four-Wave Mixing Suppression Method Based on Odd-Even Channels Arrangement Strategy

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Abstract—In this work, a new technique in suppressing the effect of four-wave mixing (FWM) by Odd-Even Channels Arrangement (OEC) is presented. The proposed technique is verified mathematically and by simulations with other recent techniques which are input power and channel spacing under the same input parameters. Simulation was done with the power variation effect, and the bit rate was 100 Gb/s. Based on theoretical and simulation analyses, FWM power was drastically reduced by more than 10 dB when OEC was conducted. In terms of system performance, OEC offered better performance than previous techniques in both theoretical and simulation analyses.

1. INTRODUCTION

Recently, the tremendous growth of the Internet and e-commerce has increased data traffic loads in optical networks. In numerous applications, such as IPTV, HDTV, and mobile broadband services, the optical bandwidth in the wavelength division multiplexing (WDM) system must be widened to cover all applications that necessitate transmission of data at a high rate of bits per second [1]. As users' data traffic increases in the fiber optic, the number of wavelengths in a dense wavelength division multiplexing (DWDM) system must be increased. When the total light power inside a fiber is increased, the nonlinear effect becomes uncontrolled and may affect signal efficiency and degrade system performance [2]. One of the major factors that possibly cause crosstalk in WDM systems, which has equally spaced channels, is the four-wave mixing (FWM) [3–11]. For optical communication systems, suppressing FWM efficiency is ideal. A few techniques have been used to suppress the effect of FWM crosstalk and to improve the signal output [12–15]. Fabrizio et al. [12] suggested a channel spacing design to suppress the FWM crosstalk defect. For a 10-channel system, choosing a suitable spaced between channels minimizes FWM crosstalk and increases the received power to 9 dBm. Nevertheless, this technique cannot decrease the FWM crosstalk outside the receiver bandwidth.

Singh et al. [13] made numerical analysis for both single and combined effects of dispersion parameters, i.e., second-, third-, fourth-, and fifth-order on FWM power at varied input power values and cross effective areas. FWM power has been suppressed by mixing the second- to fifth-order dispersion terms effects, but the weakness of this analysis is the absence consideration of dispersion compensation. Kaler et al. [14] performed a comparison for FWM using low unequal channel spacing. Increasing the channels spacing can prevent the interference between spaced channels and mitigate the FWM effect. However, decreasing the FWM crosstalk levels by using unequal channel frequency spacing will not be practical because it disallows the implementation of DWDM. According to the nonlinear effect, fiber FWM efficiency is strongly based on the polarization states of mixing channels [15].

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A previous study attempted to reduce FWM crosstalk by setting the polarization state of the channels randomly [16–18]. Random change in the state of polarization (SOP) is not guaranteed to minimize all interferences in the active channel. However, all these given techniques either are inefficient or require a complex system design. Moreover, some of these techniques can minimize the crosstalk defect but at the expense of DWDM capacity. A new suppressing approach with increased transmission capacity and simple system design has not been reported.

In this study, we have used a new FWM reduction technique by Odd-Even Channels Arrangement (OEC). By performing this approach, a significant reduction in FWM crosstalk was found, and great improvement was seen in the bit-error rate (BER).

2. SYSTEM SIMULATION DESIGN AND THEORETICAL ANALYSIS

Figures 1(a) and (b) depict the proposal scheme design of the transmitter and receiver. The laser source is obtained by an assortment of CW laser sources, in which a number of separated carriers will be emitted, which are spaced by 100 GHz. The separated carriers are linked to an extrinsic modulator which is linked to a pulse generator, and the optical signals will be modulated utilizing the formation of Return-Zero (RZ) modulation. As a result, the Mach-Zehnder modulator (MZM) will be fed by the output RZ modulation format.

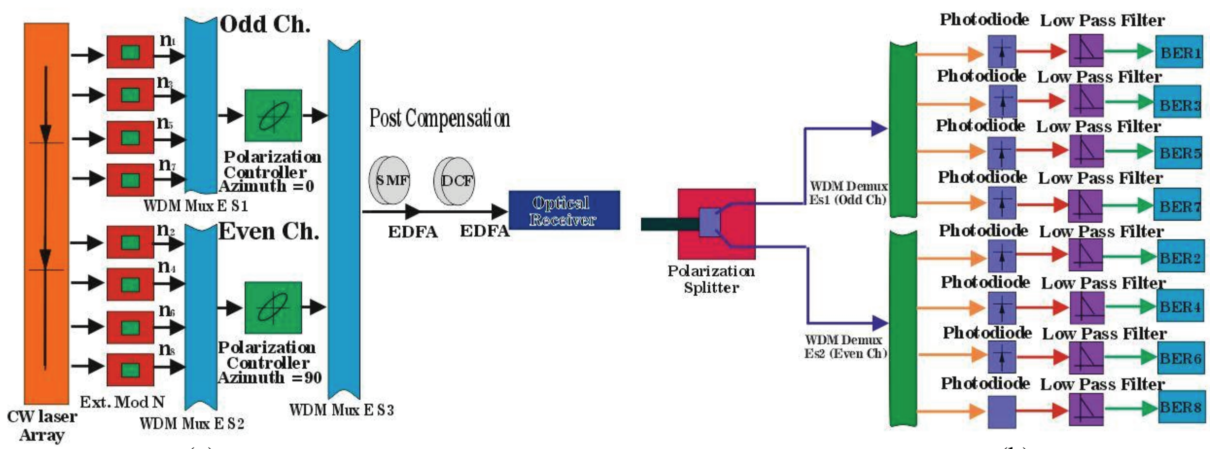

Figure 1. Optical transmission system proposed, (a) transmitter and (b) receive.

Odd-Even Channels Arrangement (OEC) scheme is implemented in designing the WDM system to minimize FWM nonlinear action and also to upgrade the capacity utilization of the WDM system. Indeed, the function of OEC scheme is to partition the whole channels (N) into two sets. The first one is an odd channel, and the other is an even channel. So the two sets are multiplexed individually. Both sets undergo various polarization states. Eight channels ($N = 8$) were utilized in the design of the system. The channels, planned as n_1, n_2, n_3, n_4, n_5, n_6, n_7, and n_8, were categorized into odd channels set (n_1, n_3, n_5, and n_7) and even channels set (n_2, n_4, n_6, and n_8). One set was supplied into a multiplexer while the other set was supplied to another multiplexer. The output of the two multiplexers was supplied into a polarization controller (PC). (PC) is an appliance in which the signal feed of SOP is changed through adjusting the azimuth and ellipticity variables. SOP of odd channels set is 0°, while that of even channels set is 90°, rendering any channel adjacently vertical. In a conventional system, the SOP of the all signals is sorted on 0°. The signals which are polarized by both multiplexers are pushed all together over the ultimate multiplexer.

The optical link involves seven spans, and every span comprises post dispersal compensation accompanied by two erbium-doped fiber amplifiers (EDFAs) in the middle of them, which have a noise figure amount of 4 dB and gains of 14 dB. When the signal is propagated through the channel of the optical fiber, the signal will be detected and collected at the receiver. The collecting received signal is divided by a polarization splitter (PS) into even- as well as odd-channel sets which are passed to the de-multiplexers. As soon as the de-multiplexers divide the channels, a photodiode (PIN) is utilized to detect them. Then, they are passed into the low-pass Bessel filter. Eventually, the signal is linked immediately to the eye illustration analyzer, so the graph is collected.

The nonlinear light amplitude E^{NL} describes the FWM light, $F_{FWM} = Fi + Fj - f_k$. The total nonlinear amplitude is [15]:

$$E^{NL} = \eta \left|E_1(0)\right| \left|E_2(0)\right| \left|E_3(0)\right| . \left(\langle S_k \mid S_j\rangle \left|S_i\right\rangle + \langle S_k \mid S_i\rangle \left|S_j\right\rangle\right) \tag{1}$$

where $|Ej(0)|$ $(j = A, B, C)$ are the amplitudes at $z = 0$, and (A, B, C) are the optical signals. Relative polarization states can be represented by normalized Jones vectors which are assumed to be maintained throughout the fiber. The OEC impact on nonlinear effect behavior can be categorized into different cases:

1. For identical signal at same polarization, $\langle S_i S_j\rangle i \neq j = 1$, the value of $X^2_{111\,r} = 1$, and Eq. (1), for i and j, can rewritten as

$$E^{NL} = 2\eta \left|E_1(0)\right| \left|E_2(0)\right| \left|E_3(0)\right| . \tag{2}$$

$$\left|E^{NL}\right|^2 = 4\eta \left|E_1(0)\right|^2 \left|E_2(0)\right|^2 \left|E_3(0)\right|^2 . \tag{3}$$

2. For the case of two waves being co-polarized and the third being orthogonally polarized $(|S_i\rangle = |S_j\rangle \perp |S_k\rangle)$, this means $\langle S_k \mid S_j\rangle = 0, \langle S_k \mid S_i\rangle = 0$, with the value of $X^2_{111r} = 0$.

3. In the case of $|S_i\rangle = |S_k\rangle \perp |S_j\rangle$, $\langle S_k \mid S_j\rangle = 1, \langle S_k \mid S_i\rangle = 0$, in this case the value of $X^2_{111r} = 1/4$, and the nonlinear amplitude square becomes:

$$\left|E^{NL}\right|^2 = \eta \left|E_1(0)\right|^2 \left|E_2(0)\right|^2 \left|E_3(0)\right| .^2 \tag{4}$$

4. If the case $|S_i\rangle = |S_j\rangle \perp |S_k\rangle$, FWM efficiency will also become 1/4, but the output polarization of the generated wave will be $|S_B\rangle$ instead of $|S_A\rangle$. This case is similar to case 2 that has the value of $X^2_{111r} = \frac{1}{4}$.

In WDM system, the power of the generated frequency due to FWM after light propagation within a distance L in the fiber can be estimated using Eq. (1),

$$P_{FWM} = \eta_n \times \frac{1024\pi^6}{n_r^4 \lambda^2 C^2} \left(\frac{D X_{111} L_{eff}}{A_{eff}}\right)^2 \left(P_i P_j P_k\right) e^{-\alpha L} \tag{5}$$

where Pi, Pj, and P_k are the input power values at central frequencies f_i, f_j, and f_k, respectively. D is the degeneracy factor equal to 3 for two-tone and 6 for three-tone systems, X_{111} the third-order susceptibility equal to 6×10^{-15} (m3/w.s), A_{eff} the effective area, C the speed of light, λ the laser wavelength, α the fiber loss coefficient, L the total fiber length, n_r the refractive index of the fiber, and L_{eff} the nonlinear effective length that can be calculated using the following equation:

$$L_{eff} = \frac{1 - e^{-\alpha L}}{\alpha} \tag{6}$$

The efficiency (η) of four-wave mixing is given by [3]

$$\eta = \frac{\alpha^2}{\alpha^2 + \Delta\beta^2} \left(1 + \frac{4e^{-\alpha L} \sin^2\left(\Delta\beta L/2\right)}{\left[1 - e^{-\alpha L}\right]^2}\right) \tag{7}$$

where $\Delta\beta$ represents the phase mismatch and may be expressed in terms of signal frequency differences.

$$\Delta\beta = \frac{2\pi\lambda^2}{c} |f_i - f_k||f_j - f_k| \left(D_c + \frac{dD}{d\lambda}\left(\frac{\lambda^2}{2c}\right)\left(|f_i - f_k||f_j - f_k|\right)\right) \tag{8}$$

where f_i, f_j, and f_k are the light frequencies of the signals; Dc is the fiber chromatic dispersion; $dD/d\lambda$ is a derivative dispersion coefficient of the optical fiber. The right term of Eqs. (7) and (8) has small and negligible values. By substitute Eqs. (7) and (8) in Eq. (5), the modified formula of FWM power can be written as follows:

$$P_{FWM} = \frac{1024\pi^6}{n^4\lambda^2C^2}\left(\frac{D_g X_{111} L_{eff}}{A_{eff}}\right)^2 (P_i P_j P_k)\, e^{-\alpha L} \frac{\alpha^2}{c\alpha^2 + 2\pi D_c(\Delta fik)(\Delta fjk)} \tag{9}$$

where P_{FWM} at the FWM crosstalk is generated by the optical channels (or signals) at frequencies f_i, f_j, and f_k, from a frequency combination satisfying $f_i + f_j - f_k = f_s$ where $f_k = f_s$.

$(\Delta fik, \Delta fjk)$ are the channel spacing.

Under the effect of OEC, FWM efficiency becomes

$$\eta_{FWM(OEC)} = \frac{1}{N} \times \eta_n \times X_{111r}^2 \tag{10}$$

$\eta_{FWM(OEC)}$ is the FWM efficiency attained by OEC technique.

X_{1111r} is a factor that presents a polarization dependency of the nonlinear effect and varied from 0 to 1 according to SOP between channels, as shown in Eqs. (1) to (4).

η_n is the normal FWM efficiency in WDM system.

Using Eq. (9), FWM efficiency (ηn) can be rewritten as follows:

$$\eta_n = \frac{\alpha^2}{c\alpha^2 + 2\pi D_c(\Delta fik)(\Delta fjk)} \tag{11}$$

By substituting Eq. (11) into Eq. (10), we can derive Eq. (12) as follows:

$$\eta_{FWM(OEC)} = \frac{1}{N} \times \frac{X_{111r}^2 \times \alpha^2}{c\alpha^2 + 2\pi D_c(\Delta fik)(\Delta fjk)} \tag{12}$$

With the OEC effect, FWM power in Eq. (9) will be changed as follows:

$$P_{FWM(OEC)} = \frac{1024\pi^6}{n^4\lambda^2C^2}\left(\frac{D X_{111} L_{eff}}{A_{eff}}\right)^2 (P_i P_j P_k)^N\, e^{-\alpha L} \times \frac{X_{111r}^2 \times \alpha^2}{N \times (c\alpha^2 + 2\pi D_c(\Delta fik)(\Delta fjk))} \tag{13}$$

In the Gaussian approximation [16, 17], error probability is written as

$$P_e = \frac{1}{\sqrt{2\pi}} \int_Q^\infty \exp\left[-\frac{t^2}{2}\right] dt \tag{14}$$

To calculate system performance under the effect of FWM, shot, and thermal noises, we use the following equations:

$$Q = \frac{KP_S}{\sqrt{N_{th} + N_{sh} + 2K^2 Ps^2 C_{IM}^{(m)}} + \sqrt{N_{th}}} \tag{15}$$

$$C_{IM}^{(m)} = \frac{1}{8}\sum_I \frac{P_{ijk}}{P_s} + \frac{1}{4}\sum_{III} \frac{P_{iik}}{P_s} \tag{16}$$

where Q is the Q factor, $C_{IM}^{(m)}$ the FWM crosstalk effective in intensity modulation-direct modulation (IM-DD) transmission, P_{ijk} the FWM power generated at frequency f_s from a frequency combination satisfying $f_i + f_j - f_k = f_s$, $(f_k = f_s)$, P_{iik} the FWM power at identical i and j $(i = j \neq k)$, K the detector responsivity, Ps the power received at the receiver, e the electron charge $(1.6 \times 10^{-19}\text{C})$, N_{th} the thermal noise, and N_{sh} the shot noise.

To obtain the received power and achieve a given BER $= 10^{-9}$, $Q = 6$, without FWM, and $C_{IM}^{(m)} = 0$, Eq. (15) is modified as follows:

$$2K^2 P_s^2 C_{IM}^{(m)} + N_{th} + N_{sh} = \frac{K^2 P_s^2}{Q^2} - 2\sqrt{N_{th}}\frac{KP_s}{Q} + N_{th} \tag{17}$$

$$P_{S0} = \frac{Q^2}{K}\left[2Be + 2\frac{\sqrt{N_{th}}}{Q}\right] \tag{18}$$

The effect of shot and thermal noises can be ignored as these noises have lower values than those of FWM noise. Q can be modified using Eq. (15) as follows:

$$Q = \frac{KP_S}{\sqrt{2K^2Ps^2C_{IM}^{(m)}}} \quad (19)$$

$$Q^2 = \frac{K^2P_S^2}{2K^2Ps^2C_{(IM)}^{(m)}} = \frac{1}{2C_{(IM)}^{(m)}} \quad (20)$$

$$Q = \sqrt{\frac{1}{2C_{(IM)}^{(m)}}} \quad (21)$$

3. RESULTS AND DISCUSSIONS

3.1. Theoretical Result

The performance of the OEC technique has been compared mathematically with recent techniques, such as channel spacing and input power, under the same input parameters. The system simulation parameters are listed in Table 1 (the simulation parameters according to ITU-T recommendations).

Table 1. System design parameters.

Parameter	Unit	Values
Fiber length, L	Km	70 for SMF and 14 for DCF
Number of span	-	7
Input power, Pi	dBm	-12 to 0
Input frequency	THz	191.5 to 192.2
Channel spacing, Δf	GHz	100
Dispersion, Dc	ps/nm·km	17 for SMF and -85 for DCF
Cross effective area, A_{eff}	μm^2	70 for SMF and 22 for DCF
Degeneracy factor, Dg	-	6
Third order Susceptibility, X_{1110}	m^3/w.s	6×10^{-15}
Refractive index, n	-	1.48
Attenuation factor,	(dB/km)	0.2 for SMF and 0.5 for DCF
Number of channel, N	-	8
Detector responsivity K	A/W	0.8

Figure 2 shows the relation between input and FWM power values for different channel spacing values using Eqs. (9) and (13). FWM power is reduced significantly by the OEC technique for both 50 and 100 GHz channel spacings. At a power input of 0 dBm, with the conduct of the OEC technique, FWM power values of -65 and -70 dBm were obtained at 50 and 100 GHz, respectively. Without OEC, FWM power values were -45 and -60 dBm at the same input power and spaced channel values. The channel spacing effect on FWM power was also investigated by performing the OEC technique.

Figure 3 illustrates the relation between channel spacing and FWM power for 0 and -2 dBm input power values. The channel spacings were 40, 50, 60, 70, 80, 90, and 100 GHz. As shown in Fig. 3, at channel spacing of 40 GHz, without the conduct of the OEC technique, FWM power values were -41 and -45 dBm, with a power feeder of 0 and -2 dBm, respectively. FWM power is considerably minimized to -63 and -66 dBm at the same channel array and input power magnitudes as a result of the OEC technique. The system achievement evaluation represented by BER depend upon power feeder

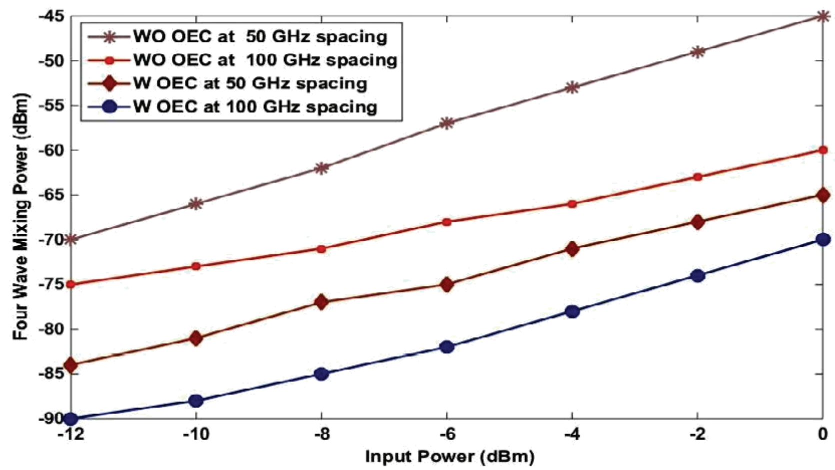

Figure 2. Input power against FWM power values with and without OEC technique for various channel spacing.

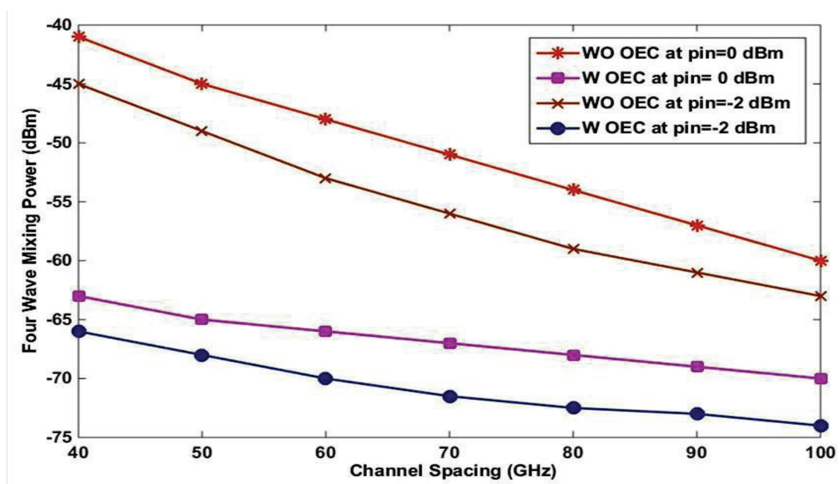

Figure 3. Channel spacing against FWM power with and without OEC technique for various input power.

effect, using Eqs. (15) to (22). Fig. 4 shows that BER values are improved as a result of OEC unlike those without OEC for both 50 and 100 GHz channel spacings. The BER magnitudes were 5×1^{-11} and 6×1^{-14} at a channel array in which each channel is 50 and 100 GHz spaced from each other, respectively, with -14 dBm received power. However, the performance indicated low BER magnitudes of 4.7×1^{-13} and 7×1^{-18} at the same channel spacing and received power in the exits of the OEC.

3.2. Simulation Results

The effect of OEC technique on WDM performance concerning FWM has been studied by applying optical systems simulator. System mechanism was carried out by raising the power feeder from -12 dBm to 0 dBm. As expressed in Fig. 5, when power feeder was increased, FWM power was jointly raised in both performing cases, the suggested OEC technique and the conventional method. The suggested technique decreased FWM power more than that by the conventional one at given time points. When the input power was -12 dBm, with the OEC technique performing, FWM power result was -82 dBm, while without using the technique, FWM power result at the same input power was -79 dBm. Similarly, as stated in Figs. 6(a), (b), by applying the OEC technique, the FWM behavior introduces a dramatic

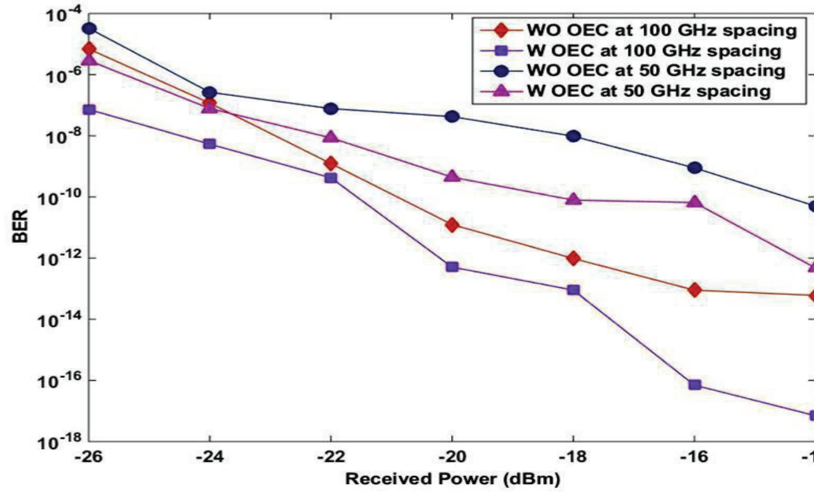

Figure 4. BER against received power with and without OEC technique for various channel spacing.

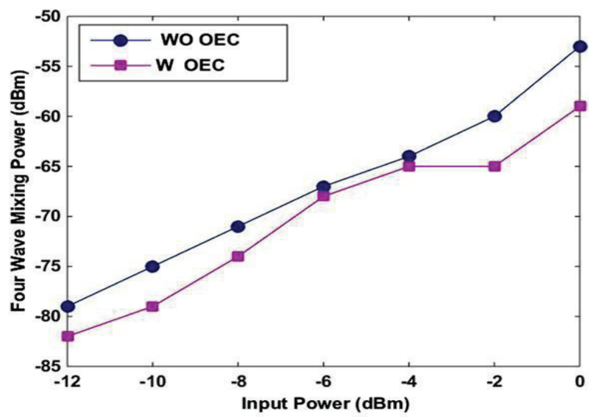

Figure 5. FWM power against power feeder with and without OEC technique.

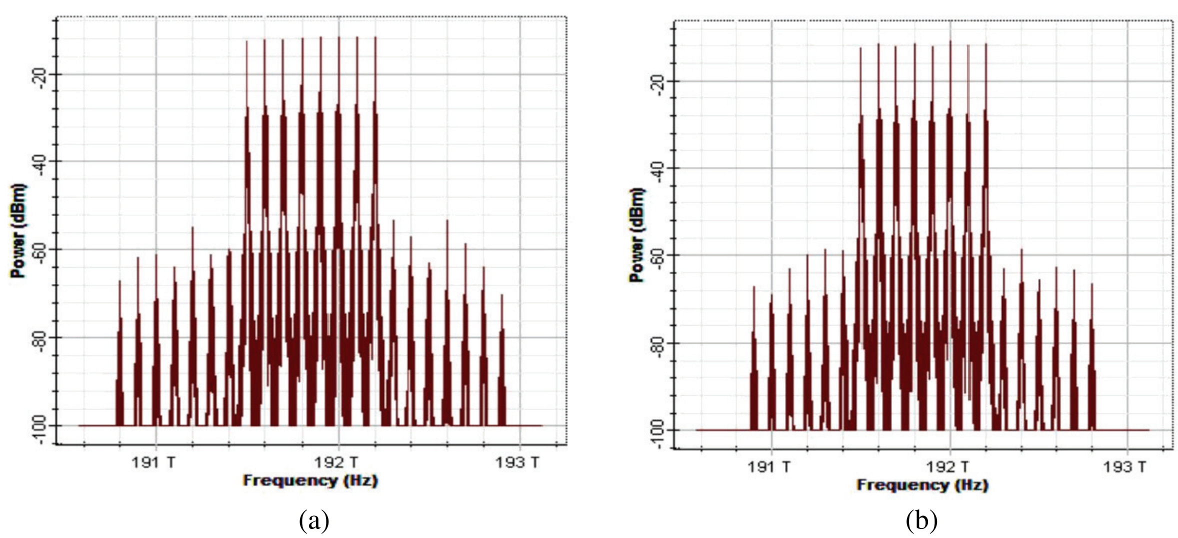

Figure 6. Optical spectrum analyzer after 490 km distance (a) without OEC technique (b) with OEC technique, both at 0 dBm power feeder.

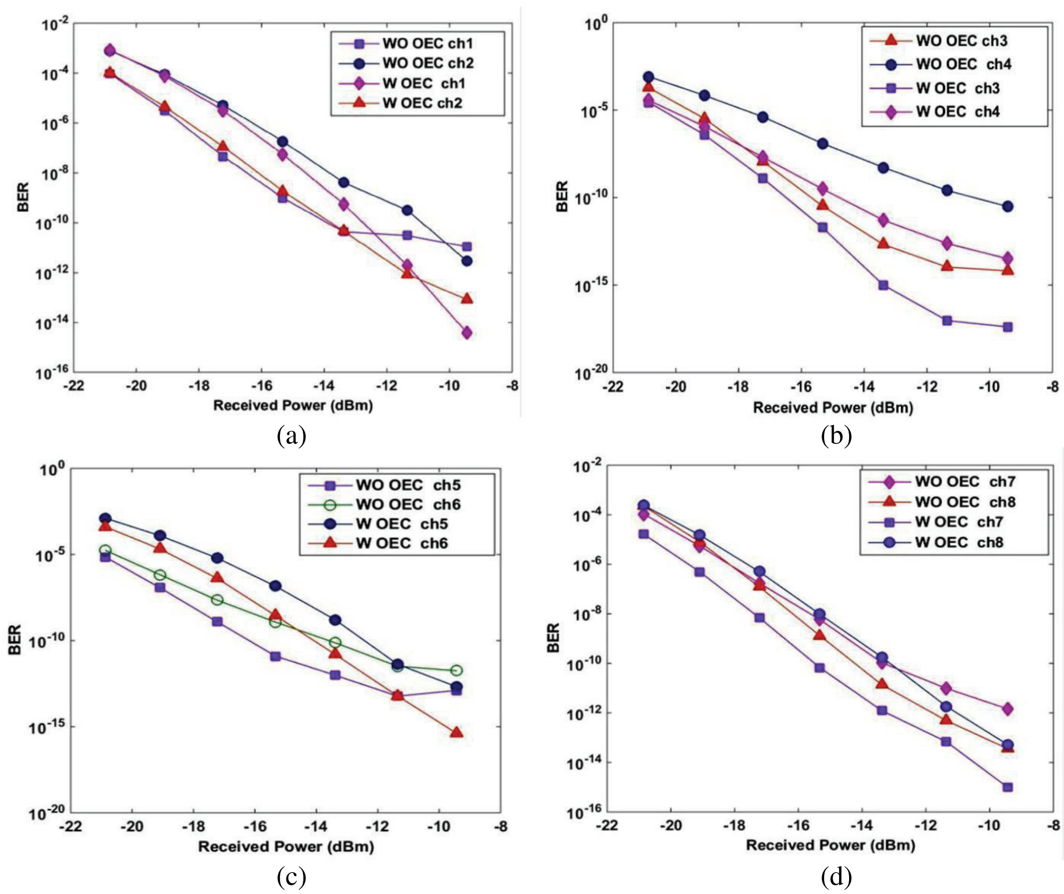

Figure 7. BER against received optical power with and without of OEC technique of (a) ch1 & 2, (b) ch3 & 4, (c) ch5 & 6, and (d) ch7 & 8.

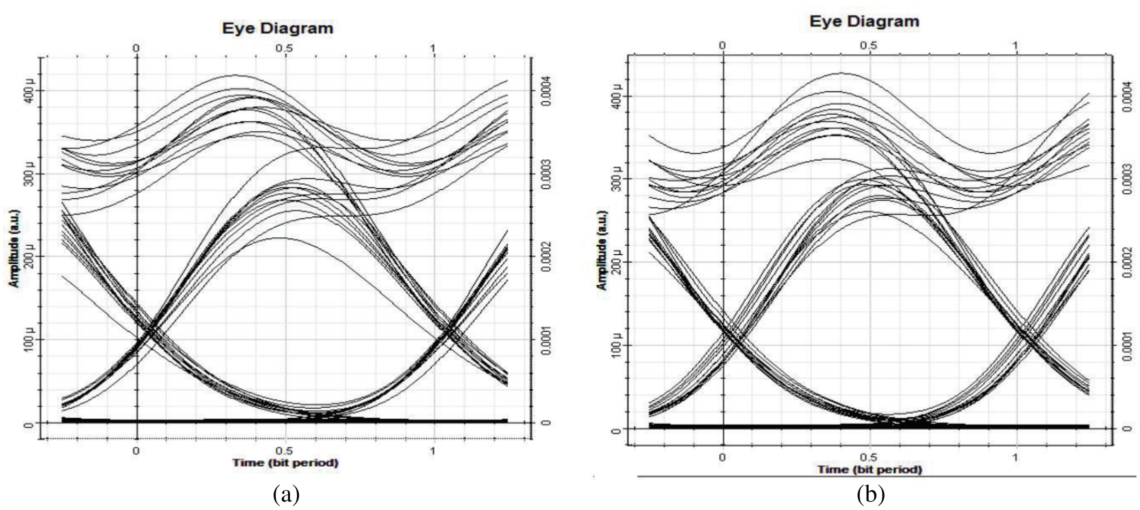

Figure 8. Performance of eye diagram, (a) without OEC technique at Pin = 0 dBm and using (ch3) and (b) with OEC technique at Pin = 0 dBm and using (ch3).

reduction in the values of FWM power. FWM power was reduced to less than −59 dBm at power feeder equal to 0 dBm due to the OEC approach, whereas without applying the OEC, FWM power was −53 dBm.

Figure 7 shows BER versus the collected power at the receiver with the suggested OEC for channels 1, 2, 3, 4, 5, 6, 7, and 8. As shown in Figs. 7(a)–(d), BERs in all channels were improved compared with those in channels in which OEC was not conducted. Without the conduct of the OEC technique, BERs in channels from n_1 to n_8 were 6.6×10^{-11}, 2.8×10^{-12}, 6.4×10^{-15}, 3.1×10^{-11}, 2×10^{-13}, 1.78×10^{-12}, 1.45×10^{-12}, and 3.6×10^{-14} at received power values of -9.43 dBm.

With the conduct of OEC technique, system performance offers low BERs, such as 3.7×10^{-15}, 8.1×10^{-14}, 4.0×10^{-18}, 3.1×10^{-14}, 1.2×10^{-13}, 4.1×10^{-16}, 9.9×10^{-16}, and 5.2×10^{-14}, at the same channels and the same collected power value at the receiver. The data obtained reveal that the third channel (n_3) has efficient BER due to the effect of OEC compared with that in other channels.

Figure 8 shows an eye diagram for the OEC technique and that without OEC. With the suggested approach, the eye style seems considerably higher and more obvious than that without using OEC. In ch3, at Pin = 0 dBm, the eye diagram has a more open BER (4.06×10^{-18}) than that in the case when OEC technique was not conducted (BER of 6.47×10^{-15}).

4. CONCLUSION

In this work, we have derived an effective solution to reduce the FWM effect by OEC. Analytical results showed that FWM power was reduced by more than 10 dB by performing the proposed OEC approach. Moreover, the simulation analysis confirmed that the proposed technique brought a considerable suppression in both the number of FWM generated and amplitude values compared with those by recent techniques at the same parameters. The OEC technique has displayed progress in improving system performance from the theoretical and simulation analyses. The finding in this study proves that the OEC solution improves the optical transmission systems efficiency.

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