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COMPARISON AMONG DIFFERENT TYPES OF ADVANCED MODULATION FORMATS UNDER FOUR WAVE MIXING EFFECTS

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Advanced modulation formats play a significant role for enhancing the bit rate in an optical transmission system. Ultra-long haul transmission distances are intensively investigated to further increase the spectral efficiency for building the next-generation optical networks. However, under a high data rate, the effects of a fiber nonlinearity such as the four-wave mixing (FWM) give a significant lower system performance. In this paper, a system simulation is performed to compare the robustness of four types of modulation formats such as Return-to-Zero Frequency Shift Keying (RZ-FSK), Non- Return-to-Zero Frequency Shift Keying (NRZ-FSK), Differential Phase Shift Keying (DPSK), and Duobinary (DB) to the FWM effect, where the performances were mainly characterized by eye opening penalties and Bit Error Rate (BER). It was found that the FWM power is the lowest with the DPSK modulation format and reaches –55 dBm, while, in the presence of RZ-FSK modulation, it reaches a maximum value and is equal to –14 dBm. In addition, the the DPSK gives a low value of BER of 4.56×10^{-68} in comparison with RZ-FSK modulation that offers BER in the range of 2.83×10^{-14}. It can be concluded that the DPSK modulation can be a crucial component to suppress the FWM effect in a wavelength division multiplexing system.

Keywords: four-wave mixing, modulation format, nonlinear effect, DPSK, RZ-FSK.

1. Introduction

Nowadays, the advanced modulation format is a right option to build modern optical transmission systems with high flexibility and effective cost [1]. The requirement for producing the ultra-high bit rate and, consequently, the enhancement of the spectral efficiency has opened the door to develop and design new modulation formats, which not only carry information in their optical amplitude, but also modulate their phases to improve the tolerant of chromatic dispersion, optical filtering, and nonlinearities [1, 2]. Under a high data rate, optical fiber systems are faced with some fatal effects that may influence the spectral efficiency and deteriorate system's performance. They are called nonlinear effects. In addition, due to the increasing demand for enhancing the channel capacity, more channels are being added to the optical fiber by reducing the spaces between channels. However, this leads to increasing the crosstalk between channels because of the interactions due to a fiber non-linearity, which can influence and limit the capacity that can be produced for a given channel spacing. The major non-linear effect responsible for this limit is called the Four-Wave Mixing (FWM) [3]. FWM effect is formed mainly as a result of changing the intensity dependence of the refractive index of an optical fiber [4–6]. Previously, the problems associated with four-wave mixing were controlled by using relatively low channel counts, wide channel spacing, and fibers with a reasonable degree of dispersion [4]. However, the dispersion causes a distortion of transmitted signals and needs to be compensated to achieve a long-haul system, and 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 and gives a negative impact on FWM suppression methods. To overcome this problem, the research direction is being done on novel ways to suppress FWM by using advanced modulation schemes. Selecting the right modulation types is an important key for reducing FWM in a fiber with advantage of a higher spectral efficiency [7–12].

Recently, a few of approaches and techniques have been developed to overcome the four-wave mixing limitation and to improve the system performance in terms of advanced modulation [13–15]. Laxman *et al.* [13] investigated the effect of FWM on BER in the presence of duobinary & binary modulations under different parameters, which are: channel spacing, input optical power, core effective area, and dispersion value for a fiber length of 100 km. The results confirmed that the duobinary modulation gives the optimum BER and a lower FWM power rather than the binary modulation (by increasing the core effective area). However, the disadvantage of this technique is the absence of calculation of the dispersion compensation.

Emdadul [14] compared the performance of NRZ-intensity modulation with that of direct modulation (IM-DD) in the presence of FWM under effect of the channel spacing, input optical power, and chromatic dispersion. DPSK modulation showed a higher tolerance to FWM than IM-DD. The main thing lacking in this approach is that, under the effect of dispersion values (0 and 17 ps/nm·km), the eye diagrams are the same.

Shao *et al.* [15] suggested an optical modulation transmitter that can transmit the RZ-FSK signal. By adjusting the frequency tone spacing (FTS) for a data rate of 40-Gb/s FSK (with two values of FTS, 100 and 60 GHz), it can improve the receiver sensitivity. The results explained that the power penalties after the transmission over 80 km SMF are 0.58 dB and 0.46 dB, respectively. The limitation of this work that no investigation of the effect of modulation format on the FWM power and the system efficiency in terms of BER were made.

In this work, we have extended the work in [15] to compare the robustnesses of RZ-FSK with those for three types of modulations such as NRZ-FSK, DPSK, and Duobinary to FWM. The comparisons were made to improve the system performance to nonlinear effects as compared with the previous work. The FWM power has been calculated in the presence of four types of modulations. We simulate the transmitter design of each modulation at 40 Gb/s by using a simulation under the effect of pump input power. This paper is structured as follows: In Section 2, we will investigate the simulation system design for different types of modulation format. In Section 3 based on the simulation using OptisysmTM, we calculated and compared the values of BER and FWM with four types of modulation format. Finally, the conclusion of this paper is reported in Section 4.

2. System Design

The system configuration is shown in Fig. 1 [15] for a bit rate of 40 Gb/s. At the transmitter part, the system consists of two external CW laser sources. The laser sources have varied the optical power from –12 to –2 dBm with step of 2. The laser wavelengths are 1550, 1550.4 nm, respectively, with an optical line width of 10 MHz. It is feed to the wavelength division multiplexing (WDM) with two input and one output. The external modulator includes Pseudo Random Bit Sequence (PRBS), which is connected to a different pulse generator to modulate the optical signals using NRZ. Then this goes into a Mach–Zehnder delay interferometer MZDI (demodulated the signal to the intensity modulation).

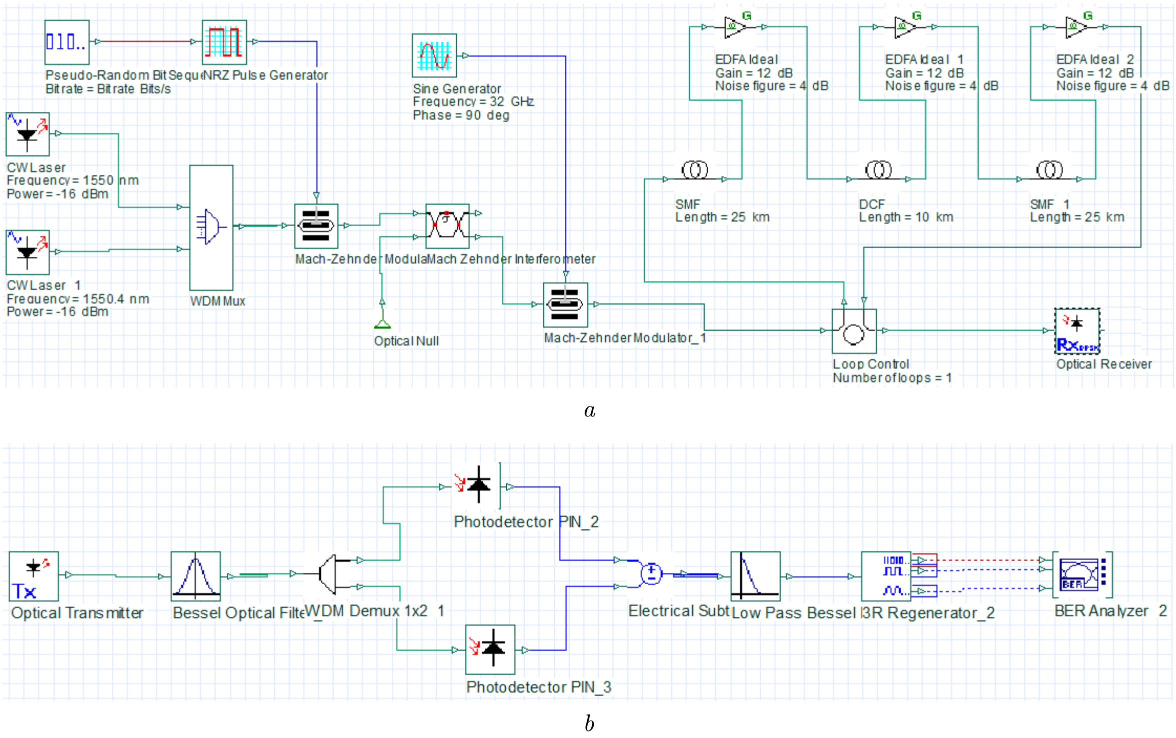


Fig. 1. System design for a RZ-FSK (*a*) transmitter and (*b*) a receiver

Table 1. **Parameter of nonlinear fiber**

Fiber type	Length (km)	$n_2(10^{-20})$ $(\mathrm{m}^2/\mathrm{w})$	Area ($\mu\mathrm{m}^2$)	Attenuation α (dB/km)	Dispersion (ps/nm·km)	Dispersion slope (ps/nm^2·km)
SMF	50	70	2.6	0.2	16.75	0.075
DCF	10	22	4	0.5	–85	–0.3

In this design, the MZM is conducted by a sinusoidal signal with a frequency of 32 GHz. After a transmitter, the optical fiber links involve the hybrid dispersion compensation, which contains two single mode fibers (SMF) and a dispersion compensation fiber (DCF) to compensate the dispersion in the link. Three optical amplifiers (EDFAs) are connected between the fiber links to amplify the optical signal. The amplifier gain and noise figures are equal to 12 dB and 4 dB, respectively. The parameter of nonlinear fibers is shown in Table 1. The FWM power was calculated by using the optical spectrum at the end of an optical fiber. The power transferred due to the FWM to new frequencies after light has been propagated within a distance L in the fiber can be estimated from the following equation [16]:

$$P_{\mathrm{FWM}} = \eta \frac{1024\pi^6}{n^4\lambda^2C^2}\left(\frac{DX_{111}L_{\mathrm{eff}}}{A_{\mathrm{eff}}}\right)^2 (P_iP_jP_k)\, e^{-\alpha L}, \quad (1)$$

where P_i, P_j, and P_k are the input powers at central frequencies f_i, f_j, and f_k, respectively, D is the degeneracy factor and is equal to 3 for two-tone and 6 for three-tone systems, X_{111} is the third-order susceptibility equal to $6 \times 10–15$ $(\mathrm{m}^3/\mathrm{w{\cdot}s})$, 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, which can be calculated by using the equation [16]

$$L_{\mathrm{eff}} = \frac{1 - e^{-\alpha l}}{\alpha}. \quad (2)$$

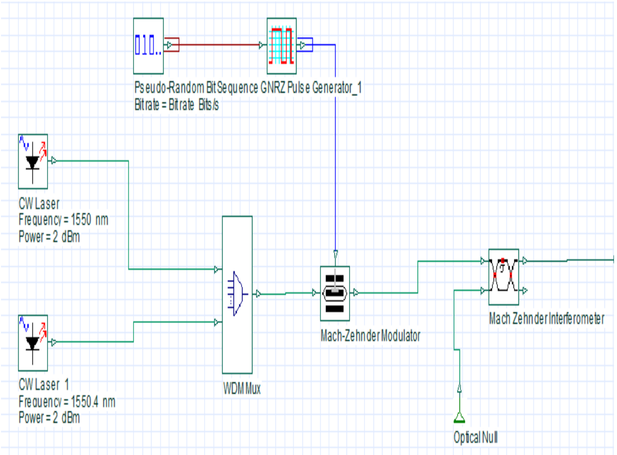


Fig. 2. Transmitter design for NRZ-FSK

The efficiency (η) of four-wave mixing is given by [17–19]

$$\eta = \frac{\alpha^2}{\alpha^2 + \Delta\beta^2}\left(1 + \frac{4e^{-\alpha L}\sin^2(\Delta\beta L/2)}{[1 - e^{-\alpha L}]^2}\right), \tag{3}$$

where $\Delta\beta$ represents the phase mismatch and can be expressed in terms of signal frequency differences [17–19]:

$$\Delta\beta = \frac{2\pi\lambda^2}{c}\,|f_i - f_k|\,|f_j - f_k -| \times$$

$$\times\left(D_C + \frac{dD}{d\lambda}\left(\frac{\lambda^2}{2c}\right)(|f_i - f_k| + |f_j - f_k|)\right), \tag{4}$$

Table 2. **Description of system simulation component abbreviations**

Abbreviations	Description
FWM	Four-Wave Mixing
BER	Bit-Error-Rate
Q	Maximum Q-factor
SNR	Signal-to-Noise-Ratio
SMF	Single Mode Fiber
DCF	Dispersion Compensation Fiber
EDFA	Erbium-Doped Fiber Amplifier
OBPF	Optical Band Pass Filter
WDM	Wavelength Division Multiplexing
MZM	Mach-Zehnder Modulator
PM	Freduency Modulator
MZDI	Mach-Zehnder Delay Interferometer
Optisys Tm	Otiwave system software

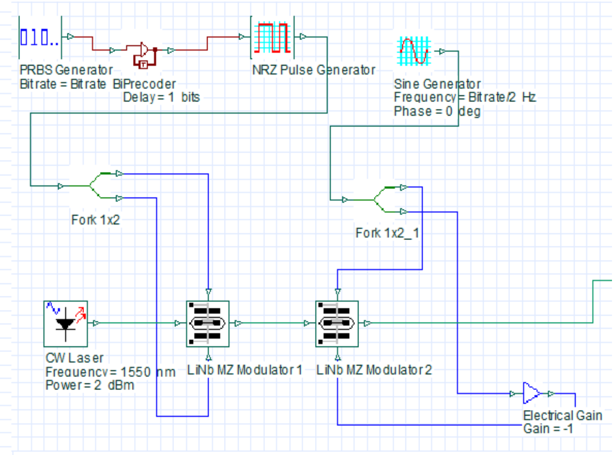


Fig. 3. Transmitter design for DPSK

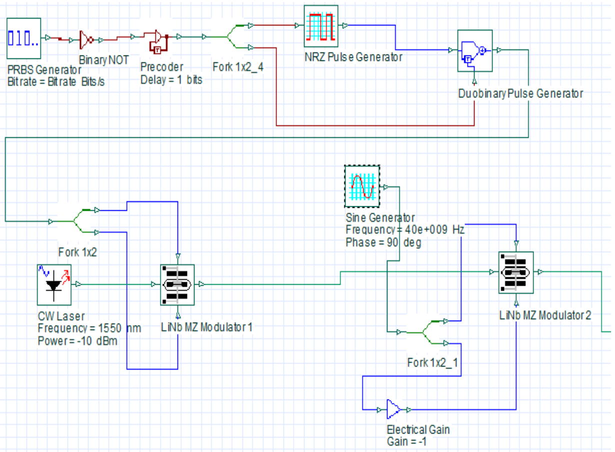


Fig. 4. Transmitter design for the duobinary modulation format

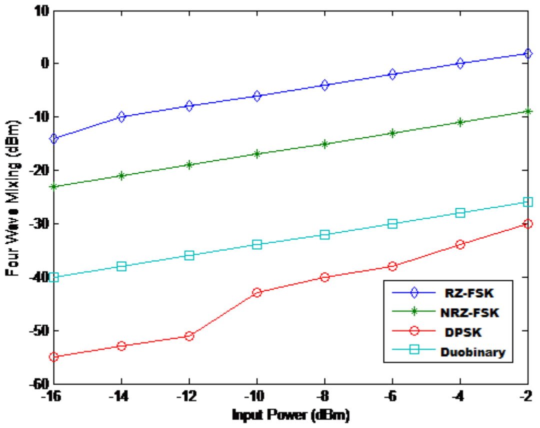
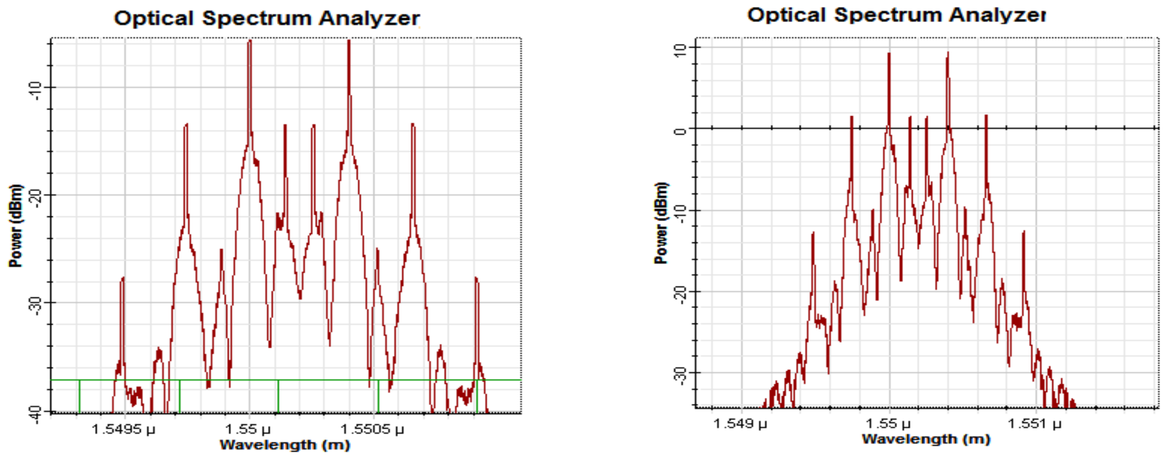
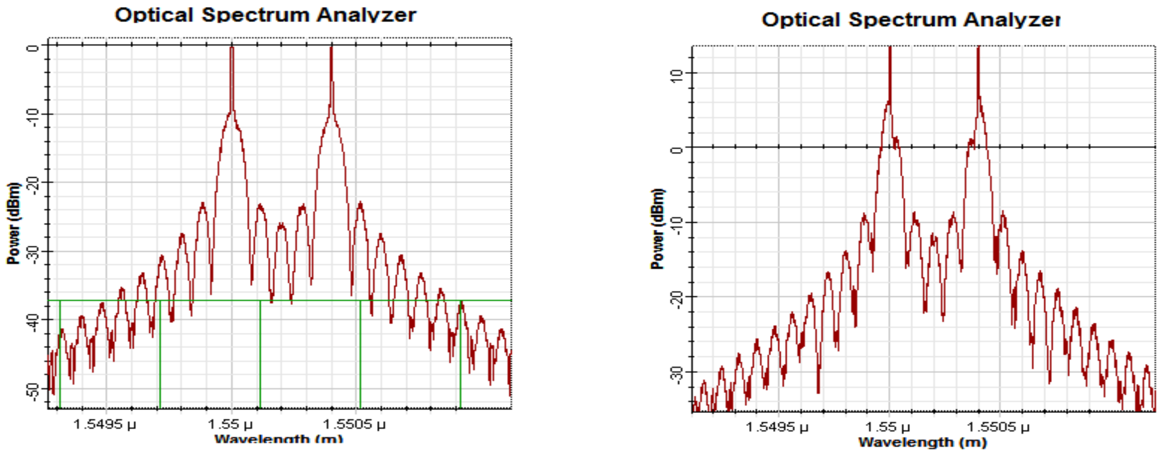


Fig. 5. Relationship between the FWM power and the input power at different modulation formats



a *b*

Fig. 6. Optical spectrum after 60 km for (*a*) RZ-FSK at Pin = −16 and (*b*) Pin = −2 dBm



a *b*

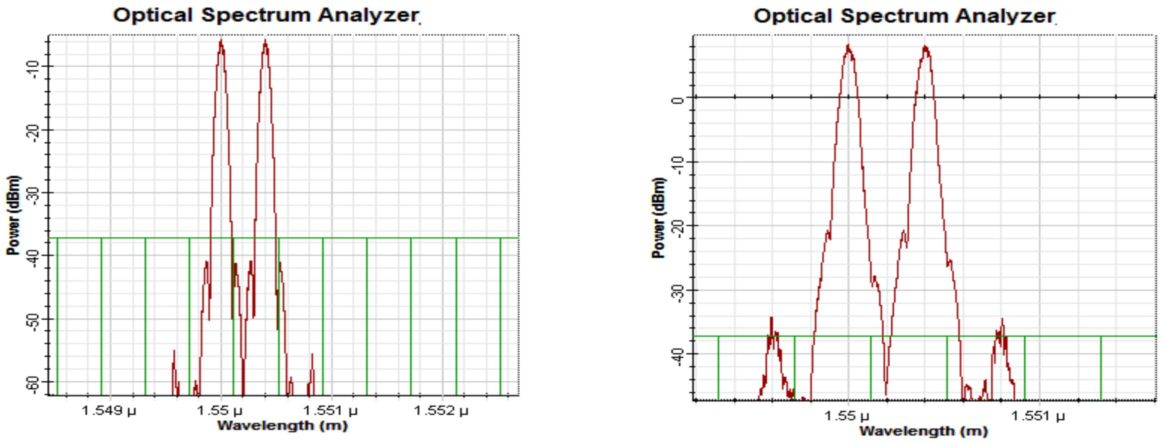
Fig. 7. Optical spectrum after 60 km for (*a*) NRZ-FSK at Pin = −16 and (*b*) Pin = −2 dBm

Table 3. **FWM and system performance for different modulation formats**

Type of Modulation Formats	Minimum FWM Power (dBm)	Maximum Received Power (dBm)	Minimum BER	Maximum Q Factor
RZ-FSK	–14	–9.5	2.83×10^{-18}	8.69
NRZ-FSK	–23	–5.27	5.94×10^{-19}	8.77
Duobinary	–40	0.815	2.51×10^{-21}	9.41
DPSK	–55	7.13	4.56×10^{-68}	17.3

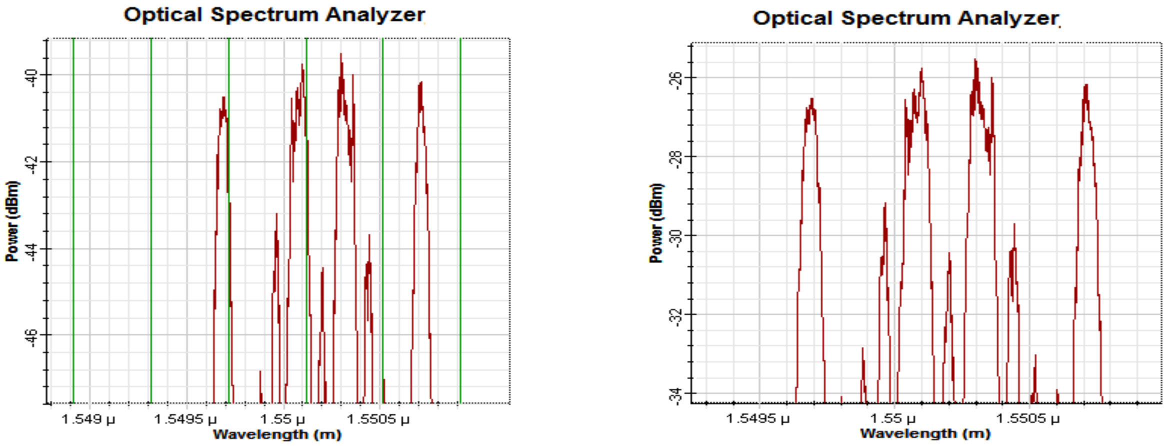
where D_c is the fiber chromatic dispersion, and $dD/d\lambda$ is a derivative dispersion coefficient of the optical fiber.

At the receiver part, a selected optical band pass filter (OBPF) is used as a frequency to demultiplexing the received FSK signal. The signal is fur-



a *b*

Fig. 8. Optical spectrum after 60 km for (*a*) DPSK at Pin = −16 and (*b*) Pin = −2 dBm



a *b*

Fig. 9. Optical spectrum after 60 km for (*a*) Duobinary at Pin = −16 and (*b*) Pin = −2 dBm

ther amplified, and it is detected by a PIN photodiode. PIN has a responsiveness ($\Re$) of 1 AW^{-1} and a dark current of 10 nA shown in Table 2. Then it passed through a low-pass Bessel filter with the 3-dB cut-off frequency = 0.75 × bit rate. The BER tester is used to generate graphs and figured the system performance. The BER was calculated under the effect of four types of noises, which are the most dominant in a optical fiber: thermal noise due to an electric filter (N_{th}), shot noise due to a photodetectot (N_{sh}), amplifier noise due to an amplifier (N_{amp}), and FWM crosstalk noise due to the interference of different wavelengths (N_{FWM}). The maximum Q factor in term of noise is as follows [12]:

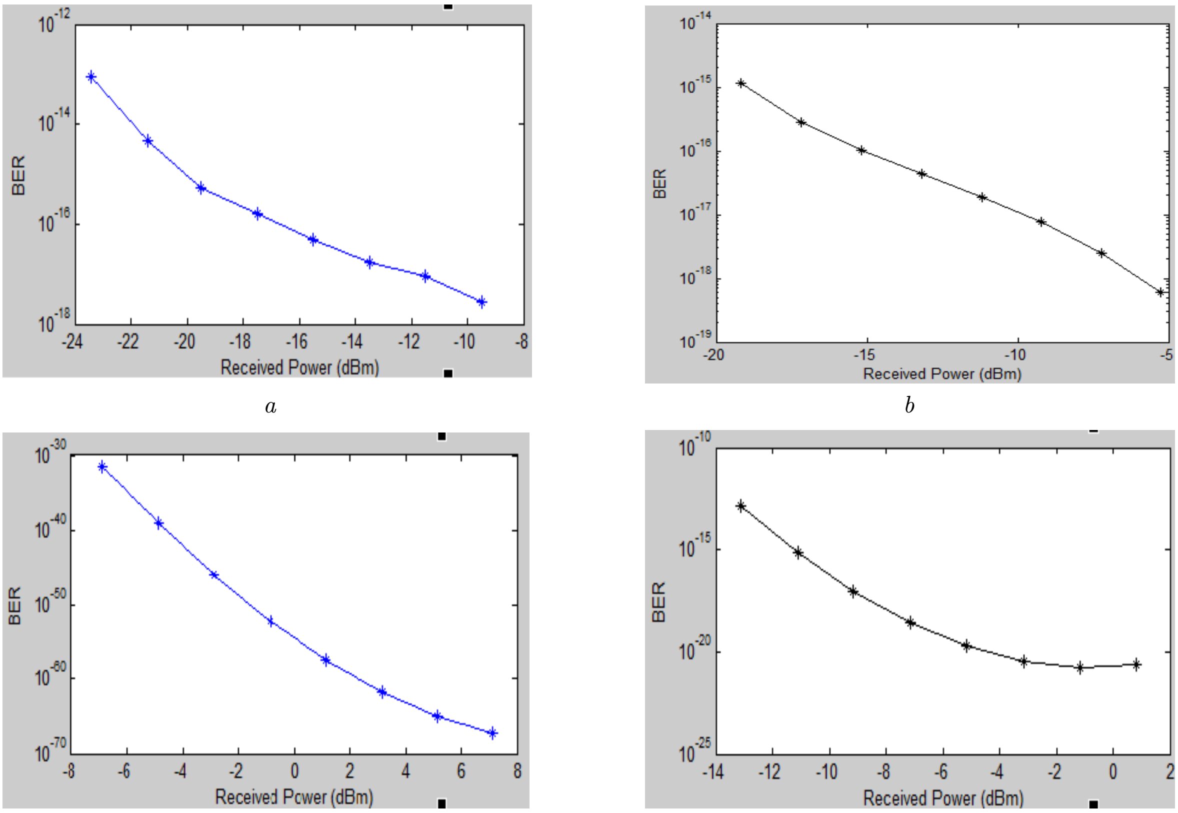
$$Q = \frac{\Re \times P_3}{\sqrt{N_{\text{sh}} + N_{\text{th}} + N_{\text{amp}} + N_{\text{fwm}}} + \sqrt{N_{\text{th}}}}, \tag{5}$$

where P_s is the received power (W). The BER equation [12] reads

$$\text{BER} = \left[1 - \operatorname{erf}\left(\frac{Q}{\sqrt{2}}\right)\right]. \tag{6}$$

To calculate the BER under different modulation format types [20], we have

$$\text{BER}_{\text{Modulation}} =$$
$$= \frac{2}{\operatorname{Log}_2 M}\left(1 - \frac{1}{\sqrt{M}}\right) \operatorname{erfc}\left(\sqrt{\frac{3SNR_{\text{FWM}}}{2(M-1)}}\right), \tag{7}$$



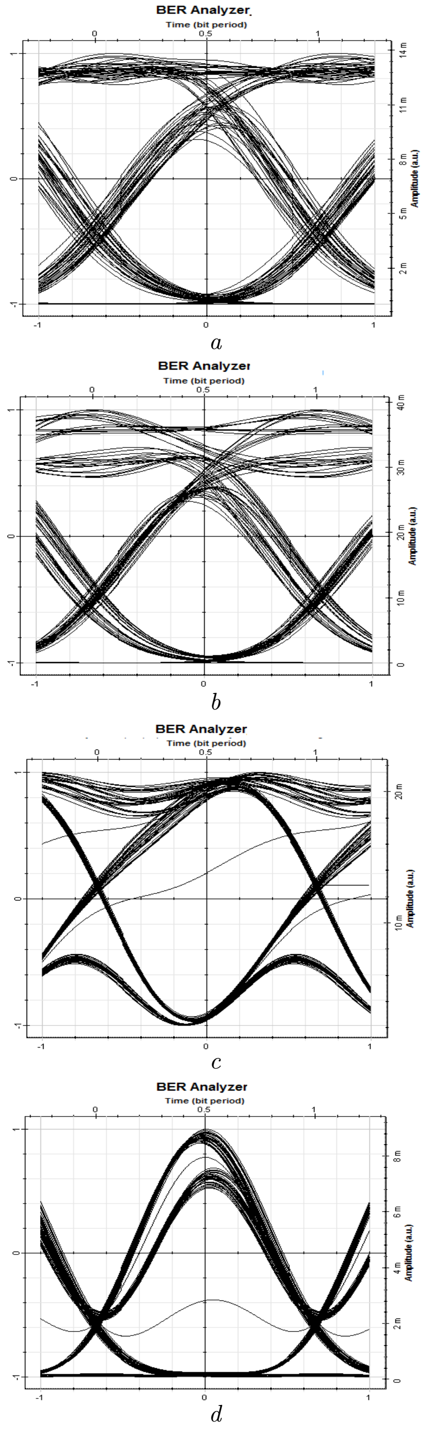
a *b* *c* *d*

Fig. 10. BER as a function of the received power: RZ-FSK (*a*), NRZ-FSK (*b*), DPSK (*c*) and Duobinary (*d*)

where M is the modulation index, and SNR is the Signal-to-Noise Ratio. Details of the transmitter system design configuration with its component in Figs. 2-4 are explained in Ref. [21]. The all abbreviations of components that are used in the system simulation are showed in Table 2.

3. Simulation Results and Discussion

In this section, the tolerance of the advanced modulation format to the FWM has been evaluated for 40 Gbps, and the system simulation was performed by the eye opening diagram and BER values. The simulation results are structuralized as the following. Figure 5 shows the relation between the FWM power and the input power as a function of different types of modulation formats such as RZ-FSK, NRZ-FSK, DPSK, and DB. It is clearly seen from the figure that a decrease of the pump input power can decrease the FWM effects for all types of modulation. More importantly, the behavior of the FWM power is different for each type of modulation. The FWM power is maximum for the RZ-FSK modulation, where the FWM power was –14 dBm for an input power equal –16 dBm, while the FWM power for DPSK is dropped under –55 dBm, for same input power. For NRZ-FSK and Duobinary, the FWM power values were –23 and –40 dBm, respectively. This meant that the DPSK modulation format gives a higher resistance to the four-wave mixing power in comparing with other types, while RZ-FSK offers a less robustness to the FWM power. Figures 6–9 show the optical spectrum after 60 km for each modulation. It is observed that the FWM is high when the input power was maximum at –2 dBm. Inversely, when the input power was minimum (–16 dBm), the FWM was low. In the case of the system performance, it can be observed from Fig. 10 that an increase in the received power can improve the BER. DPSK intro-



a

b

c

d

Fig. 11. Optimum eye diagram performance at 40 Gbps for 4 types of modulation formats at RZ-FSK (at BER = $= 2.83\times10^{-18}$) (*a*), NRZ-FSK (at BER = 5.94×10^{-19}) (*b*), DPSK (at BER = 4.56×10^{-68}) (*c*) and Duobinary (at BER = $= 2.51\times10^{-21}$) (*d*)

duces the minimum BER equal to 4.56×10^{-68} at a received power of 7.13 dBm, while RZ-FSK has the maximum BER equal to 2.83×10^{-18} at a received power of –9.5 dBm. Furthermore, for the NRZ-FSK and Duobinary, the BERs are 5.94×10^{-19} and 2.51×10^{-21} at a received power of –5.27 and 0.815 dBm, respectively. Figure 11 presents the eye-diagrams for all types of modulation for minimum BER values for each of the modulation types. Figure (11,*c*) illustrates that the DPSK gives a higher and better eye diagram which has BER equal to 4.56×10^{-68}. More opening eyes diagram means that the receiving bits (1 and 0) are properly detected at a receiver without any interference or noise. More closer eyes diagram means that the received bits (1 and 0) interfered with each of the other bits (interference). However, the eye diagram was worse and unclear in the case of RZ-FSK, where the BER was 2.83×10^{-18}, which reflects the significant effect of noise on the detected signal. The behavior of DPSK modulation format gives an impression that the differential phase modulation is more tolerant and suitable to the nonlinear effect and a better receiver sensitivity in comparison with intensity modulation and frequency modulation. Table 3 summarizes the FWM power and the system performance for all modulation formats which are used in this work.

4. Conclusion

The advanced modulation format has been used to limit the nonlinear effect in an optical transmission system. In this paper, the system performance was analyzed to compare the performances of 4 types of modulation to the FWM effects, which are NRZ-FSK, RZ-FSK, DPSK, and DB. The simulation results proved that the DPSK modulation provides the lowest FWM power equal to –55 dBm, while the RZ-FSK modulation gives the maximum value that reaches –14 dBm (i.e., DPSK has more tolerance for the FWM suppression). In addition, the DPSK gives a low value of BER which was equal to 4.56×10^{-68} in comparison with RZ-FSK which introduces BER equal to 2.83×10^{-14}. It is found that the FWM effects are drastically reduced in the DPSK scheme. Finally, it can be predicted that the DPSK modulation format is an active approach to suppress the effect of FWM in a modern optical transmission systems.

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ПОРІВНЯННЯ ПЕРЕДОВИХ ФОРМАТІВ МОДУЛЯЦІЇ РІЗНИХ ТИПІВ ЗА ЕФЕКТУ ЧОТИРИХВИЛЬОВОГО ЗМІШУВАННЯ

Резюме

Останнім часом істотну роль в підвищенні швидкості передачі двійкових даних в оптичних системах відіграють передові формати модуляції, які розглядаються як один з перспективних напрямків в додатках. Способи передачі сигналів на наддовгі відстані інтенсивно досліджуються з метою подальшого збільшення спектральної ефективності при розробці оптичних мереж наступного покоління. Однак при високих швидкостях передачі нелінійні ефекти у волокнах, такі як чотирихвильове змішування (ЧХЗ), істотно погіршують характеристики системи. У даній роботі шляхом моделювання ми порівняли робастність форматів модуляції чотирьох типів, таких як частотна маніпуляція з поверненням до нуля (RZ-FSK), частотна маніпуляція без повернення до нуля (NRZ-FSK), диференціальна фазова маніпуляція (DPSK) і ефект дуобінарний (DB) до ЧХЗ, де характеристики залежать, в основному, від помилок, пов'язаних з відкриванням ока, і також від коефіцієнта однобітових помилок (BER). Знайдено, що потужність ЧХЗ низька для формату модуляції DPSK, яка досягає –55 dBm, тоді як при RZ-FSK модуляції вона максимальна і дорівнює –14 dBm. Для NRZ-FSK і DB, потужність ЧХЗ дорівнює –23 і –40 dBm відповідно. Крім того, RZ-FSK дає значення BER рівне $2{,}83\cdot10^{-14}$, високе в порівнянні із значенням для формату модуляції DPSK, де BER дорівнює $4{,}56\cdot10^{-68}$. Можна зробити висновок, що DPSK модуляція є істотним способом придушення ефекту ЧХЗ в мультиплексних системах з розподілом довжин хвиль.