International Journal of Nanoelectronics and Materials
Volume 11 (Special Issue) Dec 2018 [7-16]

Phase Noise Suppression in Spatially Division Multiplexing System Based on PCTWs

Jassim K. Hmood[1*] and Safa Salam Radhi[1]

[1]*Laser and Optoelectronic Department, University of Technology, 10066 Baghdad, Iraq.*

ABSTRACT

In this paper, we investigate the phase-conjugated twin waves (PCTWs) technique in spatially division multiplexing (SDM) system for suppressing the nonlinear phase noise. Furthermore, the analytical model that describes the phase noise suppression is developed. In the proposed system, the 20 Gsymbol/s quadrature phase shift keying (QPSK) signal and its phase-conjugated copy are spatially multiplexed through two identical optical fiber channels. At receiver, they are coherently superimposed to suppress the nonlinear phase noise and maximize the signal-to-noise ratio (SNR). The analytical results show that the phase noise variance is extremely decreased when PCTWs technique is employed. In addition, the numerical results reveal that the proposed scheme improves SNR of received signal by more than 4.5 dB and extends the achievable transmission distance by 77.8% at bit error rate (BER) of 10^{-5}.

Keywords: Coherent Optical Communication Systems, Nonlinear Phase Noise Suppression, Phase-Conjugated Twin Waves, Spatially Division Multiplexing Systems.

1. INTRODUCTION

Due to the superiority of optical fiber communication systems for transmitting data around the world, they have played a key role in making the extraordinary growth in carrying the information to be possible. They have immense transmission capacities and highly immunity from the interferences that can disturb electrical telecommunication systems. However, fiber nonlinearity impairments have been considered as the main problem that limits the maximum transmission reach and reduce the capacity of optical fiber communication system [1-5]. To control signal deterioration, coherent detection has been proposed in combination with fiber compensation technicality [6, 7]. In order to overcome the capacity crunch limitations in optical fiber, physical dimensions namely polarization, space, time, and frequency are explored. Based on extensive studies of multicore fibers, many signals are spatially multiplexed by sending them through many cores or fibers. However, signals that modulated with high-order modulation formats exhibit sensitivity to phase noise due to the fiber nonlinearity and laser phase noise [8]. The phase noise due to fiber nonlinearity, such as self-phase modulation (SPM) restricts the performance of spatially division multiplexing (SDM) systems [9]. The nonlinear distortion is limited by power of optical source, transmission length, and number of amplifiers [10].

Several techniques have been reported to mitigate the fiber nonlinearity. Some of them deal with received signal in electrical domain, such as digital-back-propagation (DBP). The DBP has been investigated as an efficient nonlinearity compensation method in which the distorted signal has been inverted digitally at the receiver [11, 12]. However, as the number of spans increase; the complexity in the digital processing also increases [13]. Other techniques have been implemented in transmitter, in which the transmitted signal is modulated in way to

* Corresponding Author: *jassim_711@yahoo.com*

mitigate the nonlinear phase noise. By combining the return to zero (RZ) coding with modulation format at modulators, the nonlinear fiber impairments have been reduced [14,15].

Another efficient scheme called phase-conjugated twin waves (PCTWs) has been implemented in the optical orthogonal frequency division multiplexing (O-OFDM) and superchannel systems. In this technique the transmitted signal and its phase-conjugated wave are propagated though orthogonal dimensions. Co-propagating the signal with its phase-conjugated copy along the fiber channel can cancel the nonlinear distortions [1,3,16]. However, in PCTWs, the spectral efficiency is halved because of the 50% overhead related to transmission of the phase-conjugated copy of the signal [2,3].

In this paper, we explore nonlinearity mitigation for QPSK signals in SDM system by employing PCTWs technique. In this technique, the QPSK signal and its phase-conjugated copy are spatially transmitted through two fiber links. At the receiver, the twin waves are coherently superimposed to suppress the nonlinear phase noise and to improve the SNR. Analytical model that describe the efficiency of PCTWs technique on the nonlinear phase noise in QPSK-SDM communication system is developed. A numerical results show that the nonlinearity tolerance is improved. Furthermore, the achievable transmission distance for the proposed technique is increased by 72.4% as compared with traditional system.

The reminder of this paper is organized as follows. In Section 2, the basic principle of nonlinear phase noise suppression by employing PCTWs technique is described. The setup of the proposed QPSK-SDM system is characterized in Section 3. The results are presented in Section 4, where the transmission performance of proposed system is explored and discussed. Lastly, the final conclusions are given in Section 5.

2. BASIC PRINCIPLES

In this section, the analytical model that best describe the nonlinearity cancellation using PCTWs is developed by twinning the signal with its phase-conjugate on two orthogonal fibers. Figure 1 illustrates the principles of PCTWs in spatially multiplexed channels where the signal $E(0,t)$ and its conjugated copy $E^{*}(0,t)$ are transmitted over two similar fiber channels. A symmetrical dispersion map is adopted to compensate dispersion. If dispersion symmetry condition is met, the two orthogonal states became anti-correlated, thus reducing the nonlinear distortion [3, 17, 18]. Two dispersion-compensating fibers (DCFs) with equal lengths are employed to perform symmetrical dispersion map [16] for totally compensating the dispersion in single mode fiber (SMF). During transmission, perturbation is added to the signal due to SPM, parametric noise amplification and amplified spontaneous emission (ASE) noise [3, 9]. At the receiver, the original signal can be recovered by coherent superposition of the two signals. In our system, the signal $E\,(\mathrm{z,t})$ and its conjugated copy $E^{*}(\mathrm{z,t})$ can be written as [9, 10]:

$$E(\mathrm{z,t})=\left[E(0,\mathrm{t})+n_1(t)\right]\exp(j\phi), \tag{1}$$

$$E^{*}(\mathrm{z,t})=\left[E^{*}(0,\mathrm{t})+n_2(t)\right]\exp(j\phi), \tag{2}$$

where $n_1(t)$ and $n_2(t)$ are the noises of Erbium-doped fiber amplifiers (EDFAs) that added to the signal and its phase conjugated copy, respectively, is the phase noise caused by linear and nonlinear distortions given by ϕ

$$\phi=\phi_L+\phi_{NL}^{n(t)}, \tag{3}$$

where ϕ_L represents the phase noise due to dispersion and $\phi_{NL}^{n(t)}$ is the phase noise due to interaction of fiber nonlinearity with ASE noises caused by optical amplifiers.

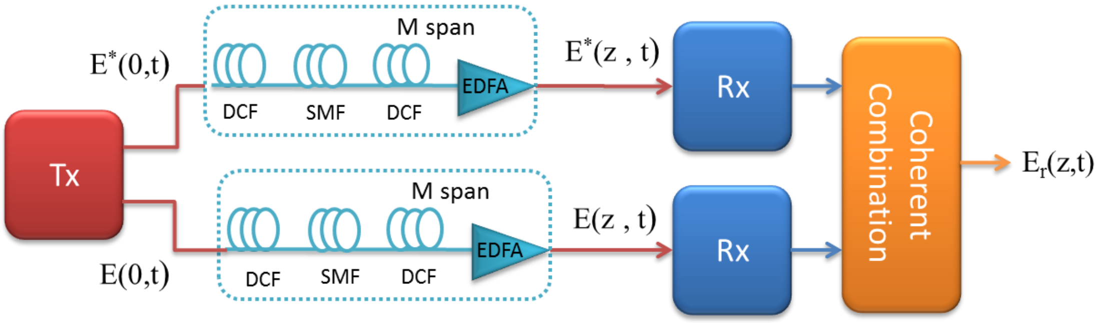

Figure 1. Basic principle of the PCTWs technique in SDM system.

At receiver, the PCTWs are coherently combined to mitigate the Kerr fiber nonlinearity. The field of combined signal can be expressed as:

$$E_r(\mathrm{z,t}) = E(\mathrm{z,t}) + \left[E^*(\mathrm{z,t})\right]^*, \tag{4}$$

where $E_r(\mathrm{z,t})$ is the optical field of received signal. By substituting Eq. (1) and Eq. (2) in Eq. (4); yields

$$E_r(\mathrm{z,t}) = E(0,\mathrm{t})\left[\exp(j\phi) + \exp(-j\phi)\right] + \left[n_1(t)\exp(j\phi) + n_2^*(t)\exp(-j\phi)\right]. \tag{5}$$

Last term represents the total noise that added by both optical amplifiers and laser sources. Let us assume it equal to n(t), then

$$E_r(\mathrm{z,t}) = 2E(0,\mathrm{t})\cos\phi + n(t). \tag{6}$$

The symmetrical dispersion map compensates the linear distortion due to dispersion. Further, the interaction between Kerr fiber nonlinearity and random noise of optical amplifier leads to deterministic as well as stochastic impairments. After averaging the received signal, the random part of the nonlinear distortion of received signal, $\delta E_r(\mathrm{z,t})$, can be written as

$$\delta E_r(\mathrm{z,t}) = E(0,\mathrm{t})\cos\phi_{NL}^{n(t)} + \frac{n(t)}{2}. \tag{7}$$

After doing some approximating, the variance of the phase noise of both random noise of amplifier and its interaction with fiber Kerr nonlinearity can be written as:

$$\sigma^2_{n(t)-PCTW} = \frac{\sigma_{n(t)}^{\ 2}}{2} \; and \;\; \sigma^2_{NL-PCTW} \cong \frac{\sigma_{NL}^{\ 2}}{4}; \tag{8}$$

respectively. In rest of this section, we discuss the nonlinear phase noise in proposed system when the signal and its phase-conjugated are modulated with high-order modulation formats. The optical fields of the signal and it phase-conjugated copy can be described as:

$$E(0,\mathrm{t}) = \sqrt{\frac{P}{2}} A \cdot rect\left[\frac{t - T_s}{T_s}\right] \exp\left(j2\pi f_s t\right), \tag{9}$$

$$E^*(0,\mathrm{t}) = \sqrt{\frac{P}{2}} A^* \cdot rect\left[\frac{t - T_s}{T_s}\right] \exp\left(j2\pi f_s t\right), \tag{10}$$

respectively, where P is the optical power, f_s is the symbol frequency, $T_s = 1/f_s$, A is the complex values corresponding to constellation of signal and *rect (t)* is rectangular function.

In long-haul optical communication systems, once the optical signal propagates through the optical fiber channel, it is affected by linear and nonlinear distortions. With spatially multiplexing, both the signal and the phase-conjugated copy are transferred over similar fiber cores. In proposed technique, the nonlinear phase noise is mainly originated in proposed system due to SPM and its interaction with ASE noise caused by optical amplifiers. The nonlinear phase noise of the signal can be expressed as [9]:

$$\phi_{SPM}(ML) = \gamma L_{eff} \sum_{m=1}^{M} \left| E(0,\mathrm{t}) + \sum_{\mu=1}^{m} n_\mu(t) \right|^2 , \tag{11}$$

where γ is the nonlinear coefficient and $L_{eff} = \left[1 - \exp(-\alpha L)\right]/\alpha$ with α attenuation coefficient. Here, $n_\mu(t)$ is the complex noise that added in μ^{th} span. The last term of the equation represents the accumulated noises of amplifiers. By doing some algebra, the nonlinear phase noise variance of the signal due to interaction SPM with ASE noise can be written as :

$$\sigma^2_{SPM}(ML) = \frac{1}{2} M\,(M+1)\gamma^2 L^2_{eff}\, P\,|A|^2\, \sigma^2_{ASE}. \tag{12}$$

Similarly, we find the nonlinear phase noise variances of phase-conjugated wave and the signal are equal because the nonlinear phase noise variances are governed by the amplitude of launched power. In order to determine the phase noise variance due to accumulated ASE noises only, the deviation of optical field that represented in last term of Eq. (11) is considered. Then, the phase noise can be defined as:

$$\phi_{n(t)}(ML,t) \cong \frac{\sum_{\mu=1}^{M} n_\mu(t) n^*_\mu(t)}{\left|E(0,t)\right|}. \tag{13}$$

The phase noise variance can be expressed by:

$$\sigma^2_{n(t)}(ML) = \frac{2M\sigma^4_{ASE}}{P|A|^2} \tag{14}$$

By substituting Eqs. (12) and (14) in Eq. (8), the phase noise variance of superimposed signal can be expressed as:

$$\sigma^2_{E_r(ML,t)} = \frac{1}{8} M(M+1)\gamma^2 L^2_{eff} P|A|^2 \sigma^2_{ASE} + \frac{M\sigma^4_{ASE}}{P|A|^2} \quad (15)$$

First term of Eq. (15) represents the phase noise variance of interaction the SPM with amplifier noises. The expected value of phase noise variance in proposed system is highly reduced since signal to noise ratio is maximized by coherently adding PCTWs.

3. SDM SYSTEM SETUP

The schematic of single channel spatially multiplexing PCTWs system is depicted in Figure 2. The system consists of a transmitter, two identical multi span fiber links and a coherent receiver. On the transmitter side, a laser beam, which is generated by a continuous wave (CW) laser sources operates at 1553 nm wavelength with linewidth of 10^5 HZ, is halved. Each halve is fed to complex optical modulator that consists of two Mach-Zehnder modulators (MZMs). QPSK signal and its phase conjugated copy are generated from a pseudo-random binary sequence (PRBS) where they are coded into imaginary and quadrature components. To generate optical QPSK signal, the imaginary and quadrature components of QPSK symbols are directly fed to the upper and lower MZMs; respectively. Similarly, to originate the phase-conjugated copy, the imaginary component is directly supplied to the upper MZM, while the quadrature component derives the lower MZM after inverting its phase. The output signals are then launched into transmission channel.

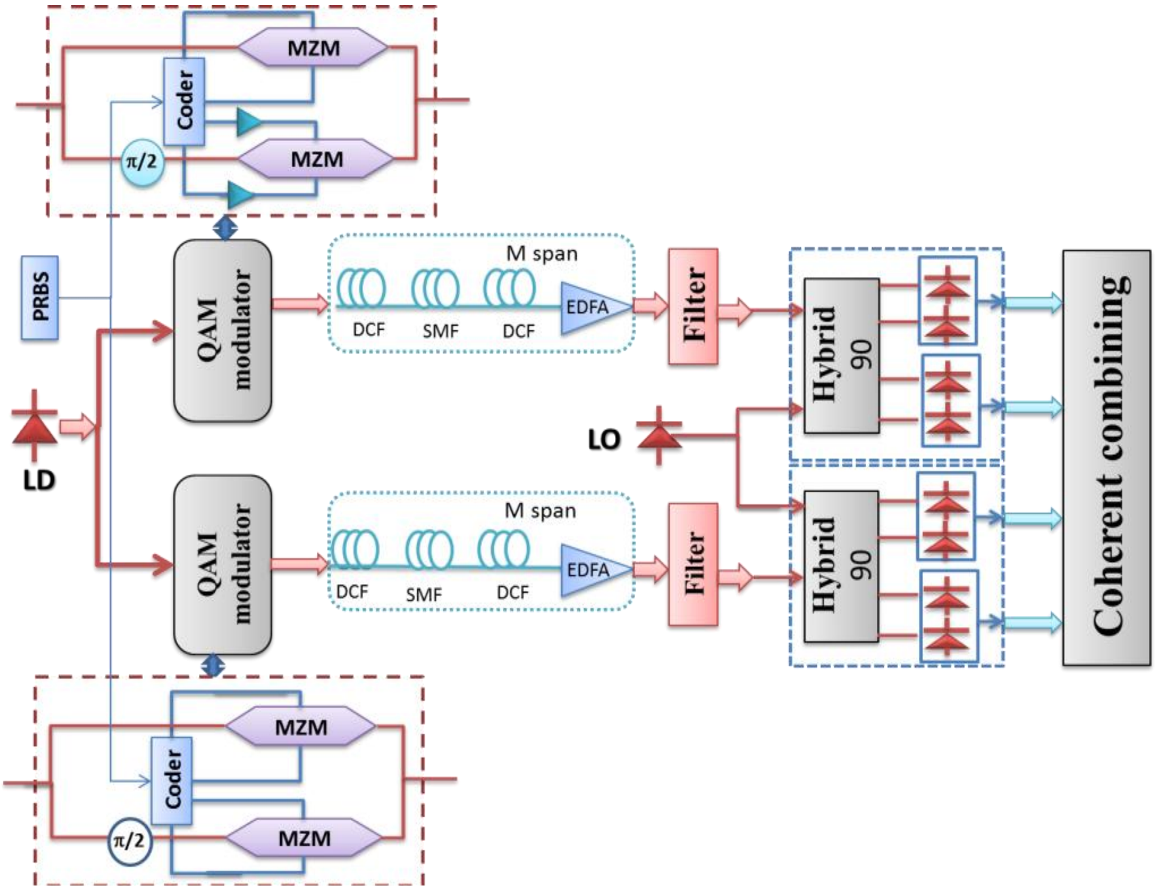

Figure 2. The schematic diagram of a spatially multiplexed single channel system based on PCTWs technique.

In order to prove the efficiency of proposed technique, the transmission link comprises two identical multi-span fiber links. Each span consists of standard single mode fiber (SSMF, two dispersions compensating fiber (DCFs) and an Erbium doped fiber amplifier (EDFA) as depicted in Figure 2. The SSMF is modelled with an attenuation coefficient of 0.2 dB/km, a dispersion coefficient of 16 ps/(nm km), an effective core area of 80 μm^2, nonlinearity coefficient of γ of 1.3 W^{-1} km^{-1} and fiber length of 60 km. In order to compensate the losses of optical signal when it propagates through SSMF and DCFs, a single EDFA with a noise figure of 4 dB are employed at end of each span. The dispersion is fully compensated by adopting symmetrical dispersion map where two DCFs are placed before and after the SSMF. Each DCF have dispersion coefficient of -160 ps/(nm km) and length of 3 km.

The receiver is comprised of two coherent demodulators and coherent combing circuit. In each coherent modulator, the received signal is firstly filtered by bandpass filter that has bandwidth of 30 GHZ centered at 1553.5 nm. Consequentially, the filtered signals are mixed with the local oscillator in a 90° optical hybrid circuit where the imaginary and quadrature components are recovered by balanced photodiode detectors. After that, the received PCTWs are coherently superimposed in order to increase the signal to noise ratio [19].

4. RESULTS AND DISCUSSION

In this section, we numerically demonstrate the effectiveness of optical phase-conjugated twin waves (PCTWs) technique in performance of spatially multiplexing communication system that employed QPSK modulation format.

First, we evaluate our analytical model numerically based on the proposed system. Next, the analytical results of the all-optical OFDM system are demonstrated and compared with numerical simulation results. Moreover, to explore the impact of PCTWs technique on the phase noise suppression, the results are obtained for QPSK modulation format at a symbol rate of 20 Gsymbol/s. The performances of the proposed system and traditional QPSK system are compared in order to quantify the efficiency of the proposed scheme.

Figure 3 shows the variance of nonlinear phase noise as a function of the launch power for a QPSK SDM system with and without employing PCTWs technique. The fiber length is set at 1800 km (30 spans × 60 km). The analytical results are calculated at dispersion value of 16 ps/nm/km. It can be observed that the variance of the phase noise is initially decreased with increasing the launch power since the phase noise due to ASE noise is dominant at low launch powers. However, the variance of phase noise starts to increase, when the launch power increases beyond −1 dBm, since the nonlinear phase noise due to the interaction of SPM with ASE noise becomes dominant at higher powers. Furthermore, it is clear that the degradation due to nonlinearity is significantly compensated by coherently superimposed the twin waves where the phase noise variance is decreased by 72% as compared with traditional QAM system. This totally agrees with Eq. (15).

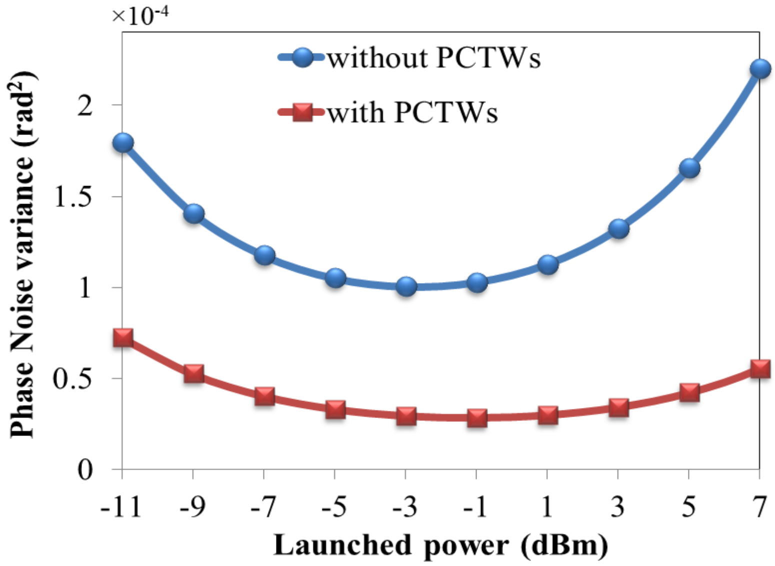

Figure 3. Influence of employing PCTWs technique on the phase noise in QPSK communication system.

The influence of PCTWs technique on phase noise suppression is also numerically demonstrated by drawing the signal to noise ratio (SNR) of received signal against launched power as shown in Figure 4. The results are obtained at transmission distance of 1800 km and the power of laser source is varied from -11 to 7 dBm. It can be seen from Figure 4, the SNRs of both proposed and traditional systems are nonlinearly raised with increasing power of the transmitter until they reach their maximum values at about -1 dBm. With increasing power beyond -1 dBm, the SNR is decreased. This phenomenon is due to the SNR is low at lower signal power and it is also low at high signal power since the SPM is dramatically rising with higher light intensity. A highest SNR is occurred at the optimum power of -1 dBm. In addition, as expected, the proposed system can transmit the optical signal with higher SNR than that for original system over entire launched power range. The SNR of proposed system is about 5 dB higher than SNR of traditional QPSK system at optimum power. This phenomenon is due to coherently superimposing the PCTWs that maximizes the received power and minimize the effect of phase noise.

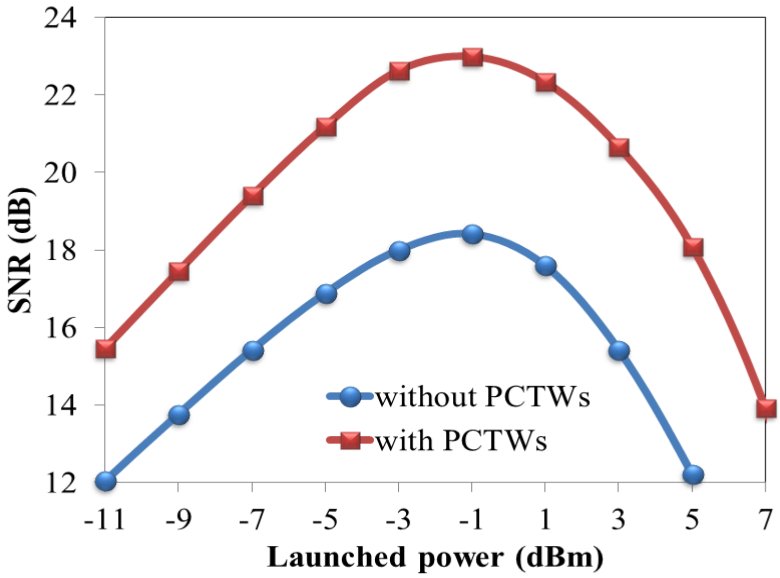

Figure 4. SNR versus launched power for QPSK optical fiber communication system with and without employing PCTWs technique.

To explore the advantages of PCTWs technique, Figure 5 shows the BER versus transmission distance. The proposed system is superior to the traditional QPSK system along transmission distance. The launch power is set to -1 dBm. It can be observed that the transmission distance is limited to 4500 km at BER of 10^{-5} using single channel communication that can be extended to 8000 km using proposed technique at the same BER level, representing a 77.8% increase in achievable transmission distance.

Figures 6(a) and (b) show the constellation diagrams of the QPSK signals with and without using PCTWs technique, respectively. Here, both constellation diagrams are obtained for the transmission distance of 6720 km at optimum power. It can be noted that, the PCTWs scheme provided a more squeezed constellation diagram as compared to that of the traditional system. Interestingly, using proposed system, the variation of the constellation points around ideal constellation points is significantly reduced as well as the constellation points in each quarter stay away from I and Q axes as compared with that of the traditional QPSK system. Accordingly, the BER in proposed system is highly reduced and the achievable transmission distance is dramatically extended.

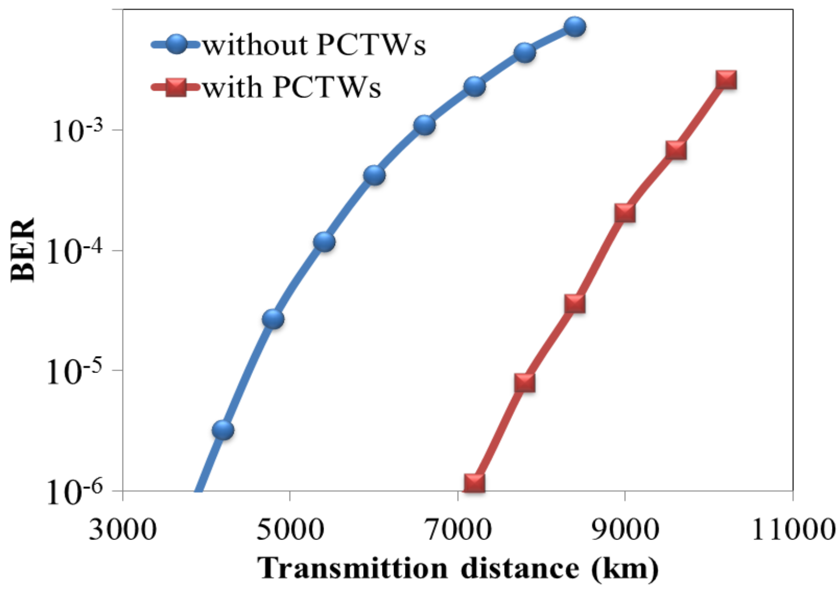

Figure 5. BER as a function of transmission distance at optimum power for single channel QPSK system with and without using PCTWs technique.

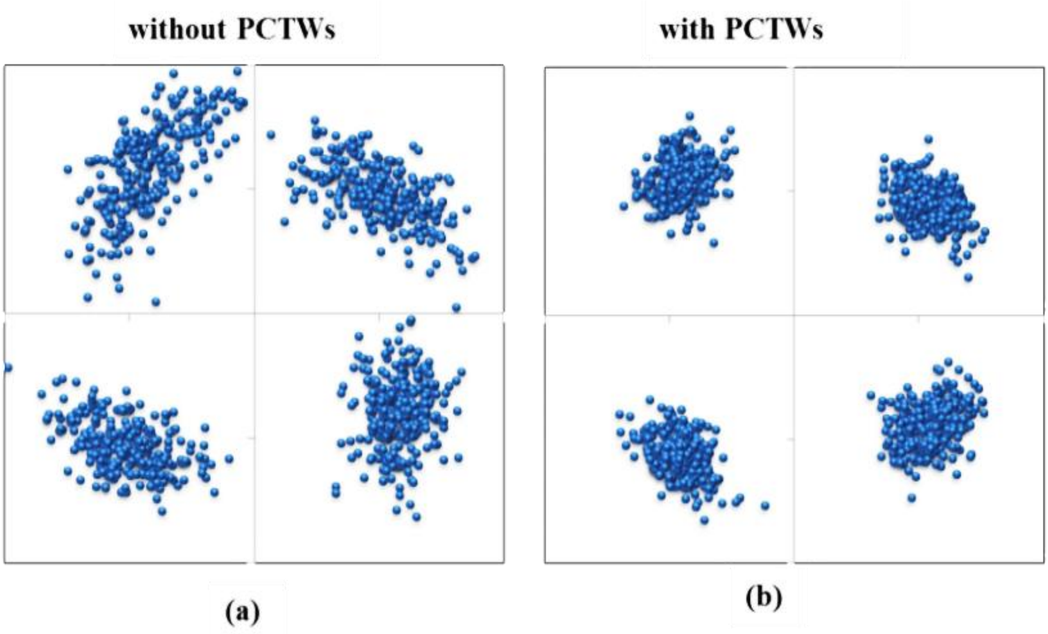

Figure 6. The constellation diagrams of the received signal at transmission distance of 6720 km for (a) the traditional system, (b) the system using PCTWs technique.

Finally, to explore the BER performance improvement, the BER as a function of optical signal-to-noise ratio (OSNR) are depicted for both proposed and conventional systems in Figure 7. For a transmission distance of 1800 km, the required OSNR for proposed system at BER $=10^{-5}$ is about 7 dB, while the required OSNR for the traditional system is about 11 dB at same BER. The results clearly confirm that the system sensitivity is enhanced by 4 dB with employing the PCTWs technique. This phenomenon is due to coherently adding twin waves, leading to double the received power of signal and to reduce the nonlinear phase noise (cf. Eqs. (6) and (15)).

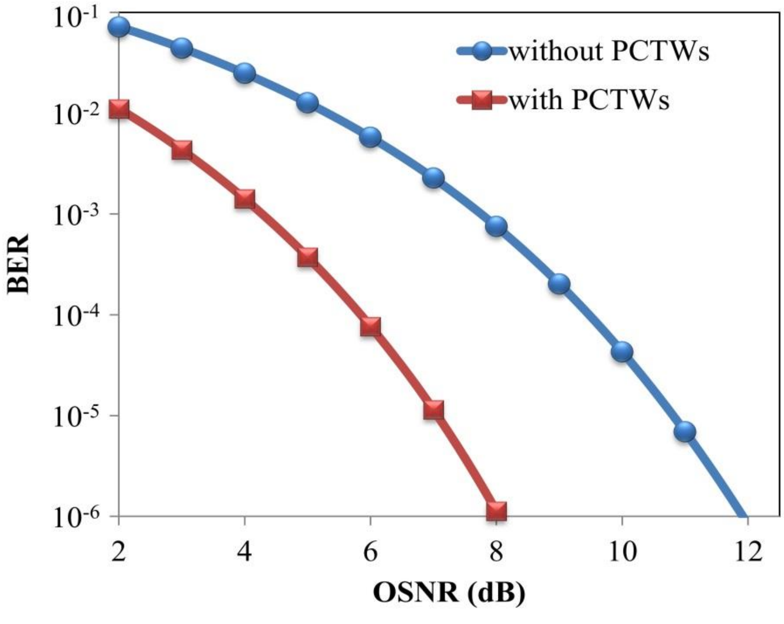

Figure 7. BER versus optical signal-to-noise ratio at transmission distance of 1800 km and -1 dBm lunching power.

5. CONCLUSION

The effectiveness of phase conjugated twin wave (PCTWs) technique on the mitigation of fiber nonlinearity for single channel system has been analytically modeled and numerically demonstrated. In proposed system, the QPSK signal and its phase-conjugated copy have been simultaneously propagated over two similar fiber channels. The two signals are coherently added at the receiver to eliminate the nonlinear phase distortions and to increase the signal to noise ratio (SNR). The results show a significant improvement in the system performance where the SNR has been raised by more than 5 dB at 1800 km. In addition, the achievable transmission distance has been increased by 77.8% to obtain BER of 10^{-5}.

ACKNOWLEDGMENT

This work was supported by Laser and Optoelectronic Engineering Department, University of Technology, Baghdad, Iraq.

REFERENCES

[1] X. Liu, S. Chandrasekhar, P. Winzer, R. Tkach & A. Chraplyvy, Journal of Lightwave Technology 32 (2014) 766-775.
[2] S. Le, M. McCarthy, S. Turitsyn, I. Phillips, D. Lavery, T. Xu, *et al.*, in Opto-Electronics and Communications Conference (OECC), (2015) 1-3.
[3] T. Yoshida, T. Sugihara, K. Ishida & T. Mizuochi, in Optical Fiber Communication Conference, (2014) M3C. 6.
[4] Y. Yu, W. Wang, P. D. Townsend & J. Zhao, in Optical Communication (ECOC), 2015 European Conference on (2015) 1-3.
[5] X. Liu, A. Chraplyvy, P. Winzer, R. Tkach & S. Chandrasekhar, Nature Photonics **7** (2013) 560-568.
[6] Z. Zheng, X. Lv, F. Zhang, D. Wang, E. Sun, Y. Zhu, *et al.*, Journal of Lightwave Technology **34** (2016) 2182-2187.
[7] A. Ellis, S. Le, M. Al-Khateeb, S. Turitsyn, G. Liga, D. Lavery, *et al.,* in Summer Topicals Meeting Series (SUM), (2015) 209-210.
[8] D. T. Pham, M.-K. Hong, J.-M. Joo, E.-S. Nam & S.-K. Han, Optical Fiber Technology **17** (2011) 252-257.
[9] J. K. Hmood, S. W. Harun, S. D. Emami, A. Khodaei, K. A. Noordin, H. Ahmad, *et al*., Optics express **23** (2015) 3886-3900.
[10] X. Zhu & S. Kumar, Optics express **18** (2010) 7347-7360.
[11] D. Rafique, J. Zhao & A. D. Ellis, Optics Express **19** (2011) 5219-5224.
[12] E. Ip & J. M. Kahn, Journal of Lightwave Technology **26** (2008) 3416-3425.
[13] S. Le, E. Giacoumidis, N. Doran, A. Ellis & S. Turitsyn, in Optical Communication (ECOC), 2014 European Conference on, (2014) 1-3.
[14] J. Hmood, K. Noordin, H. Ahmad & S. Harun, J. Optoelectron. Adv. Mater **17** (2015) 33-38.
[15] J. K. Hmood, K. A. Noordin, S. W. Harun & H. M. Shalaby, Optics Communications **355** (2015) 313-320.
[16] J. K. Hmood, K. A. Noordin & S. W. Harun, Optical Fiber Technology **30** (2016) 147-152.
[17] X. Liu, Journal of Lightwave Technology **33** (2015) 1037-1043.
[18] X. Liu, S. Chandrasekhar & P. J. Winzer, in Photonics Society Summer Topical Meeting Series, 2014 IEEE, (2014) 134-135.
[19] M. Nakazawa, T. Hirooka, M. Yoshida & K. Kasai, Extremely higher-order modulation formats, Optical Fiber Telecommunications VIB, six ed., Academic Press, (2013) 297-336.