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Compensation of The Nonlinear Impairments in All-Optical OFDM Systems Based on The Optical Phase Conjugation (OPC) Module

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***Abstract*— This study presents a nonlinearity mitigation technique for achieving high performance in the All-Optical Orthogonal Frequency Division Multiplexing (AO-OFDM) transmission systems. Therefore, the Optical Phase Conjugation (OPC) technique has been employed for mitigating the Nonlinear Phase Noise (NLPN) in the AO-OFDM transmission systems. The NLPN has been mitigated in the AO-OFDM transmission system by utilizing the proposed OPC at the middle point of the transmission link. The proposed system is numerically simulated by Virtual Photonics Integrated (VPI) Transmission Maker 9.0 at a symbol rate of 25 Gsymbol/s. During the simulation, 29 subcarriers were generated by Optical Frequency Comb Generator (OFCG) and modulated by 4-array Quadrature Amplitude Modulator (4-QAM). The generated signals are transmitted over 580 km fiber link and received by the coherent receiver. The transmission link contains 4 spans before and 4 spans after OPC module. Each span comprises the Standard Single-Mode Fiber (SSMF) and an EDFA (noise figure = 6 dB) to compensate for the fiber loss. The length of each span is fixed at 70 km in the system simulation. In addition, a 20 km Dispersion Compensation Fiber (DCF) has been used just before the OPC module to compensate for accumulated fiber dispersion. The Signal-to-Noise Ratio (SNR) and Error Vector Magnitude (EVM) have been used to certify the feasibility of the proposed technique. The results reveal that by employing the proposed OPC module, the SNR is improved by ~3.4 dB, and the EVMs are substantially reduced.**

***Keywords*— Optical phase conjugation; fiber nonlinearities; all-optical OFDM.**

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I. Introduction

The system vendors and network operators are trying to increase the Spectral Efficiency (SE), channel capacity, and flexibility of the optical networks to produce high-speed transmission applications. Recently, the All-Optical Orthogonal Frequency Division Multiplexing (AO-OFDM) technique has been proposed to use in high-speed optical communication systems and attracted significant attention from the optical communication community. In the AO-OFDM transmission systems, the subcarriers are generated and modulated in the optical domain.

Therefore, the AO-OFDM systems can dominate the electronics speed limitation and achieve a higher data rate than other transmission systems such as Optical Orthogonal Frequency Division Multiplexing (O-OFDM) systems. In addition, the AO-OFDM systems have a high tolerance towards the linear fiber impairments such as Chromatic Dispersion (CD), Polarization Mode Dispersion (PMD), and Inter-Symbol Interference (ISI). Although the AO-OFDM systems have several advantages for high-speed optical data transmission, they suffer from non-linear impairments such as the Nonlinear Phase Noise (NLPN). Various techniques have been reported to mitigate the non-linear impairments in the AO-OFDM systems, such as the receiver-based electronic phase rotation, transmitter-based electronic pre-compensation [1], and Digital-Back-Propagation (DBP) techniques [2]. In this study, an Optical Phase Conjugation (OPC) technique is employed to mitigate the nonlinearity in the AO-OFDM systems.

This technique has been used to compensate for the non-linear fiber impairments in the coherent optical OFDM transmission systems [3]. While, to the best of our knowledge, the OPC has not been used in the AO-OFDM transmission systems. The proposed OPC is employed in the AO-OFDM system for the first time and improves the transmission system's performance.

II. MATERIALS AND METHOD

All AO-OFDM is a technique of realizing the OFDM super-channel without using Digital Signal Processing (DSP). This technique employs an optical multicarrier source and performs the Fourier transforms all optically without needing the high bandwidth [4]. In the AO-OFDM systems, subcarriers are generated all-optically while they are precisely orthogonal to each other. An optical splitter separates the generated subcarriers, and then each subcarrier is modulated individually. Afterward, the modulated subcarriers are combined to generate the AO-OFDM signal [5].

In recent years, many schemes have been reported for the AO-OFDM systems such as Fiber Bragg Gratings (FBGs) [6], Array Waveguide Gratings (AWGs) [7], Wavelength Selective Switch (WSS) [8], and Delay Interferometers (DI) [9]. Various configurations have been designed by combining several phase shifters, time delayers, and optical splitters [10]. So far, two methods have been reported to design the AO-OFDM transmitters [11]. In the first method, the optical subcarriers are generated in the transmitter by employing an optical multicarrier source such as the Optical Frequency Comb Generator (OFCG) [12]. In the second method, the transmitter is designed by utilizing the Optical Inverse Fast Fourier Transform (OIFFT) in order to transform the input optical signals to the OFDM symbol [13]. In other words, the OIFFT and Optical Fast Fourier Transform (OFFT) have been implemented in the optical domain in order to achieve the high processing speed in the high bit rate transmission systems [14].

Two techniques have been reported in the AO-OFDM transmission systems to detect the transmitted signals at the receiver side. The first technique is called direct-detection [15], and the second one is called coherent detection [16]. These approaches are suitable for various types of optical transmission systems based on the system requirements such as the transmission distance and data rate. Normally, coherent and direct detection techniques have been employed to detect the transmitted signals in long-haul and short distance transmission systems. The direct detection receivers require the guard band to avoid inter-modulation impairments. While the coherent receivers do not require the guard band and have high tolerance toward the linear impairments. Due to the guard band requirements in the direct detection technique, the direct detection receivers require high bandwidth, limiting the transmission system's SE. Although the longer transmission distances can be achieved by employing the coherent detection technique, the implementations of the coherent receivers are more complicated than the direct detection receivers. Due to the high number of utilized components in the coherent receivers, the power consumption and the implementation cost of these receivers are higher than the direct detection receivers.

In this study, each signal is transmitted over a distance of 580 km and detected by the coherent technique at the receiver side. In the AO-OFDM transmission systems, several impairments occur during the signal transmission process, which degrades the performance of the transmission system. One of the major impairments that restrict the performance of the AO-OFDM system is NLPN. The NLPN can be caused by non-linear fiber impairments such as the Four-Wave Mixing (FWM), Self-Phase Modulation (SPM), and Cross-Phase Modulation (XPM). The number of subcarriers, number of amplifiers, power of subcarrier, and transmission length determine the NLPN in the optical transmission system. In the AO-OFDM system, the produced NLPN is added to the transmitted signal and degrades the quality of the received signal. In the AO-OFDM systems, the phase noise generates a Phase Rotation Term (PRT) on each subcarrier and destroys the orthogonally between subcarriers. Due to the lack of orthogonally between the subcarriers, the Inter-Carrier Interference (ICI) can be occurred, which corrupts the phase of the received signal and severely degrades the transmission performance.

In order to transmit data over long distances, the NLPN must be mitigated. Several techniques have been presented to mitigate the impacts of the non-linear impairments on the performance of the optical transmission systems, such as optical phase conjugation [17], receiver-based electronic phase rotation [18], Phase-Conjugated Twin Waves (PCTWs) [19], transmitter-based electronic pre-compensation [20], and DBP [21]. Combining the coherent receiver with DSP is another technique to compensate the linear and non-linear impairments in the AO-OFDM systems.

In this study, the OPC module is proposed and inserted at the middle point of the transmission link in order to compensate the effect of the fiber non-linear impairments in the AO-OFDM transmission system. The employed OPC conjugates the transmitted signal phase in the first segment of the transmission link to cancel the non-linear phase shift in the second segment of the transmission link, as shown in Fig. 1.

This study investigates the impact of the middle link OPC on the performance of the 4-array Quadrature Amplitude Modulation (4-QAM) AO-OFDM system. To verify the efficiency of the proposed technique, the simulation results are achieved before and after employing the middle link OPC.

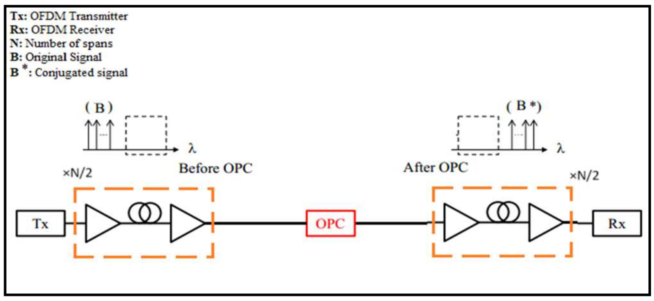

Fig. 1 Middle link OPC

The structure of the proposed OPC module is shown in Fig. 2. It can be seen that an Erbium-Doped Fiber Amplifier (EDFA) and a Band-Pass Filter (BPF) are employed just before the OPC module to boost the input power and filter the input signal, respectively. A BPF filters the resulted signal from the EDFA with 2nm bandwidth. Subsequently, the filtered signal is combined with a Continuous Wave (CW) pump and passed through the Highly Non-Linear Fiber (HNLF). The transmitted signal is filtered again and amplified by another EDFA. Then, the resulted signal is passed to the second half of the transmission link.

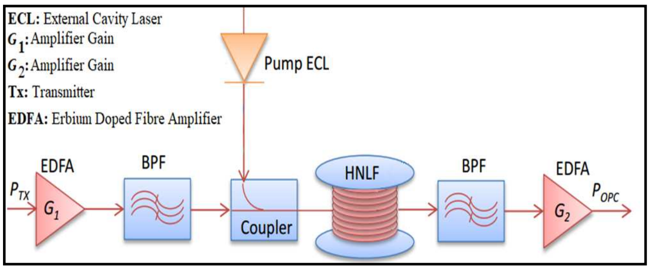

Fig. 2 The OPC module

In order to provide a fundamental understanding of how the proposed OPC works, Fig. 3 demonstrates the functionality of the proposed OPC module. It can be seen that both the optical input signal and pump signal are given as the inputs of the OPC module. These signals are combined by a 3 dB coupler and fed into a non-linear element such as HNLF.

The output of the HNLF is passed through a BPF to remove both the input and pump signals, but leave the OPC signal. Afterwards, the obtained OPC signal is amplified before passing to the second half of the transmission system.

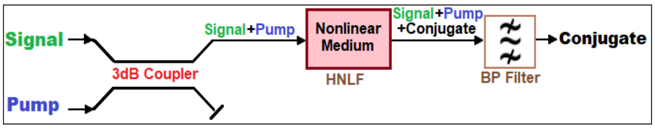

Fig. 3 Schematic diagram of the proposed OPC module

The AO-OFDM transmission system is simulated before and after employing the proposed OPC. The simulation results are obtained for both conditions and compared to each other to investigate the effectiveness of the proposed technique in mitigating the fiber non-linear impairments. During the simulation, the input optical power and pump power are set to 1 dBm and 10 dBm, respectively. The simulation parameters of the proposed OPC are listed in Table I.

TABLE I
THE PROPOSED OPC PARAMETERS

Parameters	Value	Unit
EDFA Noise figure	6	dB
Length of HNLF, L	100	m
HNLF Loss coefficient	0.97	dB/km
Non-linear Coefficient	11.5	W^{-1} km^{-1}
Dispersion of HNLF	0.0	Ps/nm/km

A. Non-linear Phase Noise

NLPN is the main impairment due to XPM, SPM, and FWM on the proposed AO-OFDM system's performance. The optical transmission system can be modelled by

$$u(z,t) = [u(0,t) + n(t)].\exp(j\emptyset) \qquad (1)$$

where u $(0,t)$ and $u(z,t)$ are transmitted and received optical OFDM signals. Moreover, $n(t)$ and z are the ASE noise and transmission distance, respectively. During the transmission, the non-linear phase shift is generated due to the non-linear impairments.

1) Self-Phase Modulation (SPM): The SPM takes place while an ultra-short pulse travels through the fiber, such as Single Mode optical Fiber (SMF). The SPM broadens the spectrum of the optical pulses but cannot change the pulse shape. The spectral broadening in the optical fiber generates frequency chirp, which adds new frequency components to the optical pulse. This new frequency produces a phase shift in the pulse and changes in the pulse's frequency spectrum.

2) Cross-Phase Modulation (XPM): When two or more optical pulses with different directions or various wavelengths propagating through one fiber, the XPM takes place by generating the non-linear phase shift due to the effects of pulses on the intensity phase of each other.

3) Four-Wave Mixing (FWM): The FWM occurs when three wavelengths interfere and produce the refractive index gratings. The gratings will interact with the signals and produce the fourth wavelength with the new frequency.

B. System Setup

This section describes the proposed system setup containing the schematics of the transmitter, multi-span fiber link, and receiver. Furthermore, the system setup is successfully demonstrated by simulating the schematics by using the Virtual Photonics Integrated (VPI) Transmission Maker 9.0. During the simulation, 29 subcarriers are generated by an optical comb generator and modulated by 4-QAM. The modulated subcarriers are transmitted over 580 km by a symbol rate of 25 Gsymbol/s.

C. Flow Chart of the Proposed System

This section contains the initial stage, implementation stage, and final stage of the proposed system setup. It explains all the needed materials and components to set up and run the proposed system. The obtained results are analyzed and evaluated by various efficiencies estimation techniques such as BER and EVM. The results showed that by using the proposed technique in the AO-OFDM systems can improve the transmission system's performance.

Fig. 4 demonstrates the flow chart of the proposed phase noise mitigation technique. In the first step, the number of subcarriers, fiber spans, transmission length, and other transmission parameters must be inserted. Then, the subcarriers are generated by OFCG. The generated subcarriers are modulated by 4-QAM modulator. Afterwards, the AO-OFDM signal is produced and transmitted over the SSMF and DCF fibers.

At the middle point of the transmission link, the amount of the phase noise can be estimated. If the amount of phase noise would be more than the predefined value, then the signal is entered to the OPC module. Inside the OPC module, the AO-OFDM signal and pump signal are given as the inputs of the OPC module. These signals are combined by a 3 dB coupler and fed into a non-linear element such as HNLF. The output of the HNLF is passed through a BPF to remove both the input and pump signals but leave the OPC signal. Afterward, the obtained OPC signal is amplified before passing to the second half of the transmission system.

By transmitting the signal from the proposed OPC, the signal is conjugated and then enters to the second half of the transmission link. The phase noise can be mitigated by adding the conjugated signal with the transmitted signal at the receiver side.

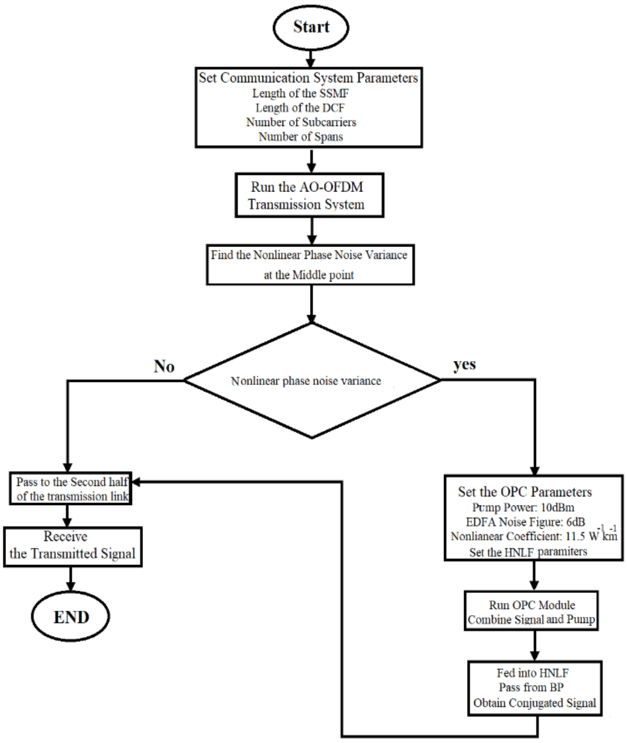

Fig. 4 Flowchart of the proposed transmission system

1) All-Optical OFDM Transmitter: The proposed transmitter includes the WSS, optical beam combiner, 4-QAM modulators, and OFCG. The proposed OFCG utilizes two Phase Modulators (PMs). Also, an Intensity Modulator (IM) is used to generate the optical subcarriers as shown in Fig. 5.

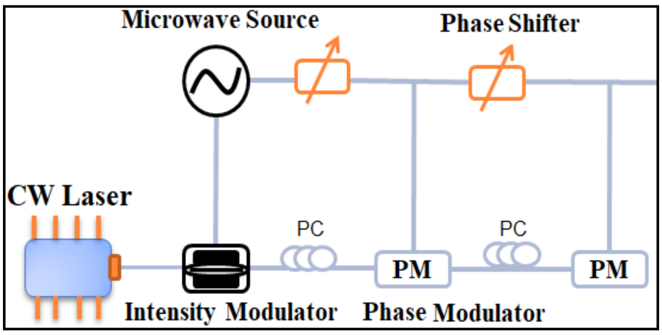

Fig. 5 The Proposed OFCG

The generated subcarriers are divided into even and odd subsets by WSS. After that, all subcarriers are modulated individually using the 4-QAM modulators, as shown in Fig. 6. Then, the modulated subcarriers are combined by the beam combiner in order to generate the AO-OFDM signal. Finally, the generated AO-OFDM signals are transmitted through a multi-span's optical fiber link. The QAM signal is produced by an IQ modulator which is supplied by two Mach-Zehnder modulators (MZMs). The linewidth of the laser and the carrier wave frequency is adjusted to 1 MHz and 193.1 THz, respectively.

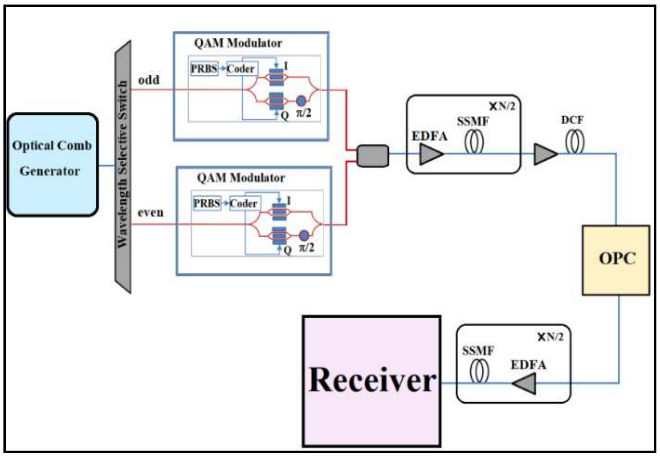

Fig. 6 Configuration of the Proposed Transmitter

2) Transmission Link: The generated signal is transmitted over multi-span optical fiber in the proposed transmission system, and phase noise is accumulated span-by-span. The transmission link contains 4 spans before and 4 spans after OPC module. Each span comprises the Standard Single-Mode Fiber (SSMF) and an EDFA (noise figure = 6 dB) to compensate for the span loss. The length of each span is fixed at 70 km in the system simulation. In addition, a 20 km Dispersion Compensation Fiber (DCF) has been used just before the OPC module to compensate for accumulated fiber dispersion. Table II illustrates the characteristics of the employed optical fibers and simulation parameters.

TABLE II
OPTICAL FIBERS CHARACTERISTICS

Fiber	Fiber Length	Nonlinearity Coefficient	Dispersion
SSMF	70 km	2.09 w/km	16 ps/nm/km
DCF	20 km	6.4 w/km	-80 ps/nm/km

3) All-Optical OFDM Receiver: The implemented receiver employs the coherent 4-QAM to demodulate the transferred signals and the OFFT is employed in order to convert the serial data to the parallel data. Fig. 7 shows the schematic diagram of the proposed receiver. It can be seen that several optical components such as cascaded Mach–Zehnder Interferometer (MZI), Electro-Absorption Modulator (EAM), and optical filters are employed in the proposed 4-order OFFT circuit. The OFFT is implemented by using three cascaded MZIs. Each MZI is composed of one optical phase shifter and one time delayer. The time delay of the first MZI is adjusted to $T_s/2$, while the time delay of the second and third MZIs are set to $T_s/4$. The phase shift of the first MZI is regulated to 0, while the phase shifts of the other MZIs are regulated to $\pi/2$ rad and 0 rad. Each transmitted signal is sampled by EAM sampling gate. Subsequently, the EAM output is filtered by an optical BPF, and the signals are detected using the coherent 4-QAM optical demodulator.

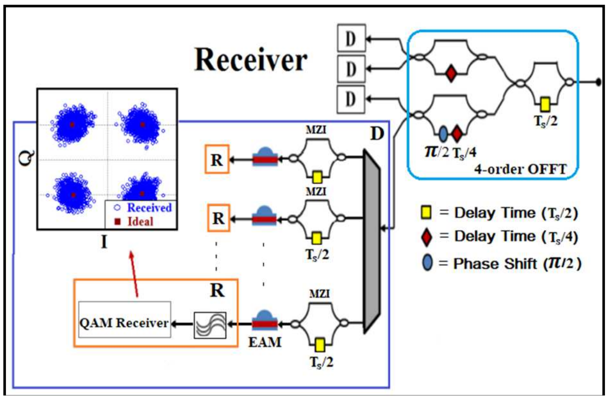

Fig. 7 Schematic of the Proposed Receiver

III. Results and Discussion

This section investigates the proposed system's tolerance against the non-linear impairments due to SPM, XPM, and FWM. In order to achieve this goal, the Error Vector Magnitude (EVM) is used to measure the effects of the fiber non-linear impairments on the performance of the proposed AO-OFDM system. In addition, to quantify the effectiveness of the proposed technique, the SNR is plotted versus the power of the subcarrier before and after employing the OPC module. Also, the impact of the NLPN on the system performance was estimated, and the results were compared with the original system.

Fig. 8 illustrates the total phase noise variances of the proposed system versus the power of subcarriers before and after employing the proposed OPC module. It can be seen that the optimum power level of the 4-QAM AO-OFDM system before employing the OPC is -3 dBm, while the optimum power level of the system after employing the OPC module is increased to 3 dBm. The results indicate that the phase noise variances of the original 4-QAM AO-OFDM system are reduced after employing the proposed OPC module. It means, after employing the proposed OPC module the system is less sensitive against the non-linear impairments.

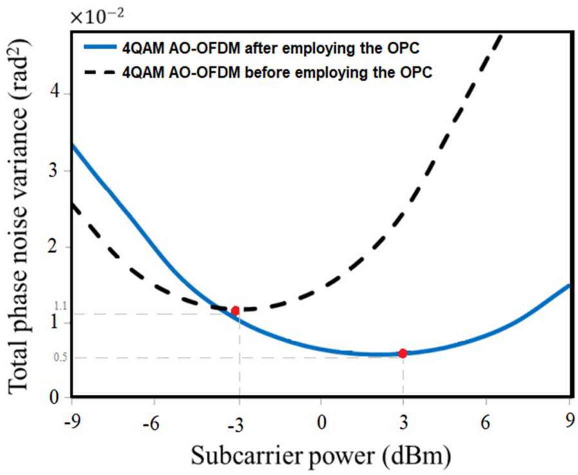

Fig. 8 Phase Noise Variance versus the Power of Subcarriers

Fig. 9 illustrates the EVMs of the 4-QAM AO-OFDM system versus the transmission distance before and after employing the proposed OPC at the middle point of the transmission link. The simulation results reveal that by increasing the fiber length, the EVMs of both systems are linearly increased. It can be seen that in all transmission distances, the EVM of the system is decreased after employing the proposed OPC module. It means the effects of the fiber non-linear impairments on the transmitted signals can be mitigated by employing the proposed OPC module at the middle point of the transmission link.

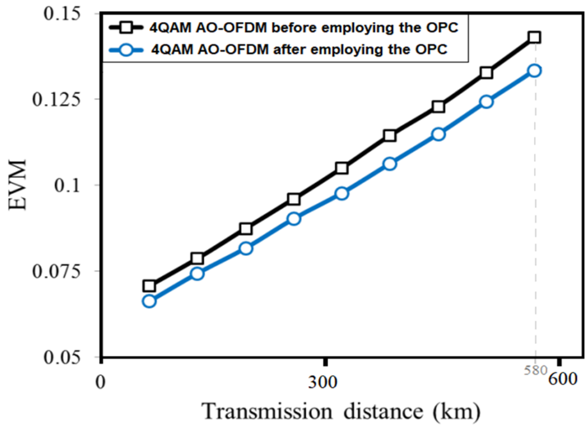

Fig. 9 EVM versus the transmission distance

Fig. 10 illustrates the EVMs of the proposed system against the power of subcarriers before and after employing the proposed OPC module. The results indicate that after using the proposed OPC module the EVM of the system for all power of subcarriers is significantly reduced. It can be seen that before and after employing the proposed OPC module, the minimum EVM of the system can be obtained when the subcarrier power is equal to -3 dBm. The results showed that the EVM is decreased by increasing the subcarrier power until -3 dBm, and when the subcarrier power increases beyond -3 dBm the EVM is dramatically increased. Before employing the OPC, the minimum EVM of the system is equal to 0.135, while after inserting the proposed OPC module at the middle point of the transmission link, the minimum EVM is reduced to 0.08.

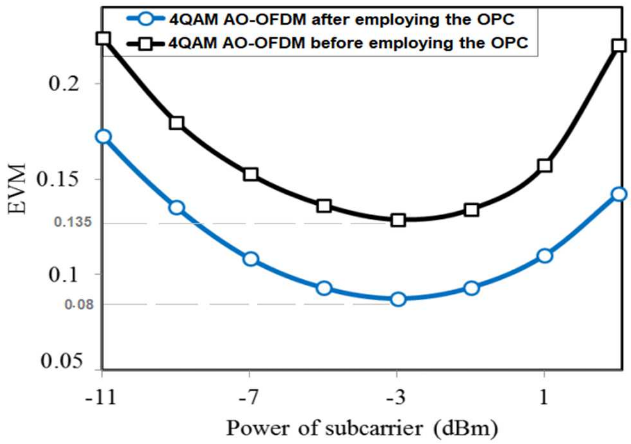

Fig. 10 EVM versus the power of subcarrier (dBm)

Fig. 11 shows the SNR of the system versus the subcarrier power before and after employing the proposed OPC module. The simulation results revealed that the SNR had been improved by ~3.4 dB by employing the proposed OPC module.

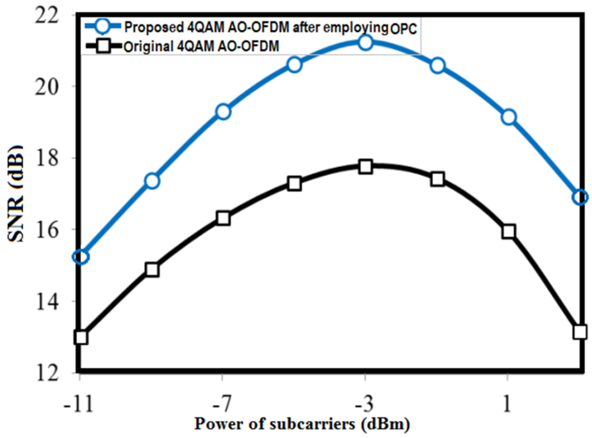

Fig. 11 SNR versus the power of subcarrier

Fig. 12 illustrates the constellation diagrams of the received signals before and after using the proposed OPC module. The simulation results show that after employing the proposed OPC module, the constellation diagram of the 4-QAM AO-OFDM system becomes more squeezed around the ideal constellation and the received signals are closer to the ideal point. It means after employing the proposed OPC module in the 4-QAM AO-OFDM system. The received signals have higher tolerance towards the fiber non-linear impairments as compared to the received signal before employing the OPC module.

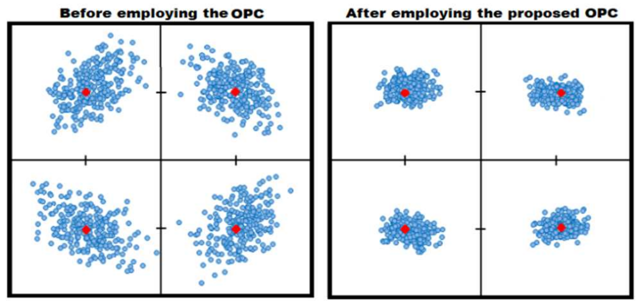

Fig. 12 Constellation diagrams of the 4-QAM AO-OFDM system before and after employing the proposed OPC module

In order to improve the performance of the system, the OPC module can be repeated during the transmission link. Fig. 13 illustrates the configuration of the transmission link with two OPC modules.

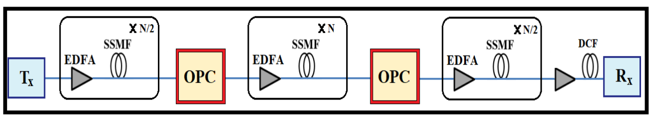

Fig.13 Configuration of the transmission link with two OPC modules

Fig. 14 shows the EVM versus the transmission distance in the proposed AO-OFDM system with various numbers of employed OPC modules. As expected, by increasing the transmission distance, the EVM is increased, while in all the transmission distances, the EVM of the proposed system with two employed OPC is lower than the EVM of the proposed system with one employed OPC. The results revealed that when the subcarriers are transmitted over 580 km, by increasing the number of the employed OPC, the EVM decreased from 0.135 to 0.125. The obtained results indicated that by increasing the number of the employed OPC modules, the EVM is decreased by 7%. It means, increasing the number of the employed OPC modules can improve the performance of the transmission system.

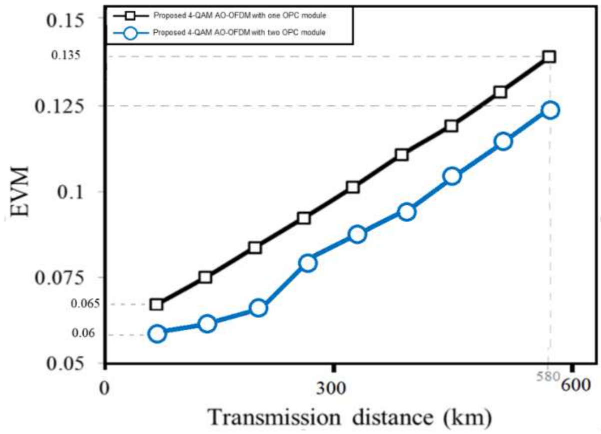

Fig. 14 EVM versus transmission distance in the system with various number of OPC modules

Fig. 15 depicts the SNR of the 4-QAM AO-OFDM system versus the subcarrier power by employing one and two OPC modules. The simulation results reveal that by increasing number of the employed OPC from one to two modules, the SNR has been improved by ~0.8 dB.

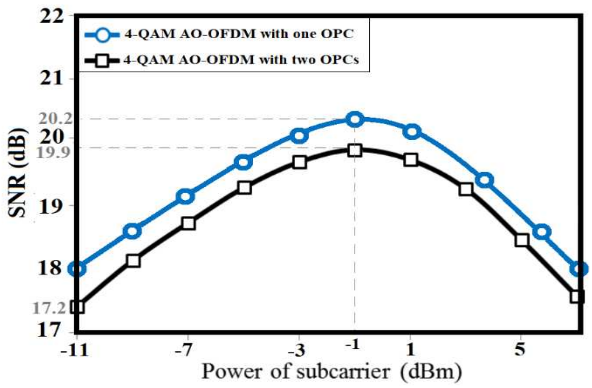

Fig. 15 SNR versus the power of subcarrier with various number of employed OPC

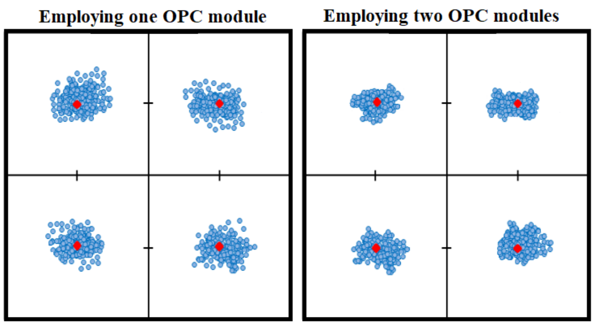

Fig. 16 Constellation diagram for the system with various number of OPC modules

Fig. 16 depicts the constellation diagrams of the received signals in the 4-QAM AO-OFDM system by employing one and two OPC modules. The simulation results show that after employing the proposed OPC module for the second times, the constellation diagram of the 4-QAM AO-OFDM system becomes more squeezed around the ideal constellation and the received signals are closer to the ideal point. It means, after employing the OPC module for the second times, the received signals have higher tolerance towards the fiber non-linear impairments than the received signals in the system, which uses only one OPC module.

IV. CONCLUSION

In order to compensate effects of the non-linear impairments in optical transmission systems, an efficient scheme has been proposed for the AO-OFDM transmission systems by inserting the OPC module at the middle point of the transmission link. The schematic diagram of the proposed 4-QAM AO-OFDM transmission system has been demonstrated successfully, and the performance of the transmission system has been examined by using VPI transmission maker 9.0 software. This study found that after employing the proposed OPC module, the minimum EVM reduced from 0.135 to 0.08, and SNR improved by ~3.4 dB. The obtained results indicate that by employing the proposed technique, the effects of the non-linear fiber impairments have been substantially mitigated, and the performance of the transmission system has been highly improved.

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REFERENCES

[1] J. Wang, C. Jiang, H. Zhang, X. Zhang, V. C. M. Leung, and L. Hanzo,“Learning aided network association for hybrid indoor LiFi-WiFi systems, ” *IEEE Transactions on Vehicular Technology.*, vol. 67, no. 4, pp. 3561–3574, Apr. 2018.

[2] A. M. Jaradat, J. M. Hamamreh, and H. Arslan, “OFDM with subcarrier number modulation,” *IEEE Wireless Commun. Lett.*, vol. 7, no. 6, pp. 914-917, Dec. 2018.

[3] M. S. Islim, S. Videv, M. Safari, E. Xie, J. J. D. McKendry, E. Gu, M. D. Dawson, and H. Haas, “The impact of solar irradiance on visible lightcommunications,” *J. Lightw. Technol*., vol. 36, no. 12, pp. 2376–2386, June. 2018.

[4] T. Q. Wang, H. Li, and X. Huang, “Analysis and mitigation of clipping noise in layered ACO-OFDM based visible light communication systems,” *IEEE Trans. Commun.*, vol. 67, no. 1, pp. 564-577, Jan. 2019.

[5] B. G. Guzmán, A. A. Dowhuszko, V. P. G. Jiménez, and A. I. Pérez-Neira, “Robust cooperative multicarrier transmission scheme for optical wireless cellular networks*,” IEEE Photonics Technol. Lett*., vol. 30, no. 2, pp. 197–200, Jan. 2018.

[6] B. G. Guzmán, and V. P. G. Jiménez, “DCO-OFDM signals with derated power for visible light communications using an optimized adaptive network based fuzzy inference system,” *IEEE Trans. Commun*., vol. 65, no. 10, pp. 4371–4381, Oct. 2017.

[7] S. Doğan, A. Tusha, and H. Arslan, “OFDM with index modulation for asynchronous MTC networks,” *Sensors.*, vol. 18, no. 2, pp. 1280-1288, Apr. 2018.

[8] X. Cheng, M. Zhang, M. Wen, and L. Yang, “Index modulation for 5G striving to do more with less,” *IEEE Wireless Commun.*, vol. 25, no. 2, pp. 126-132, Apr. 2018.

[9] W. Xu, M. Zhang, D. Han, Z. Ghassemlooy, P. Luo, and Y. Zhang, “Real-time 262-Mb/s visible light communication with digital predistortion waveform shaping,” *IEEE Photon. J.*, vol. 10, no. 3, pp. 1-10, Jun. 2018.

[10] T. Q. Wang, and X. Huang, “Fractional reverse polarity optical OFDM for high speed dimmable visible light communications,” *IEEE Trans. Commun.*, vol. 66, no. 4, pp. 1565-1578, Apr. 2018.

[11] X. Zhang, Z. Babar, R. Zhang, S. Chen, and L. Hanzo, “Multi-class coded layered asymmetrically clipped optical OFDM,” *IEEE Trans. Commun.*, vol. 67, no. 1, pp. 578-589, Jan. 2019.

[12] A. W. Azim, Y. L. Guennec, and G. Maury, “Spectrally augmented hartley transform pre-coded asymmetrically clipped optical OFDM for VLC,” *IEEE Photon. Technol. Lett.*, vol. 30, no. 23, pp. 2029-2032, Dec. 2018.

[13] X. Liu, J. Li, and Z. Huang, “Analysis of the single-FFT receiver for layered ACO-OFDM in visible light communications,” *Journal of Lightwave Technology*., vol. 38, no. 2, pp. 4757–4764, Sep. 2020.

[14] M. Elkarim, M. Elsherbini, H. M. Abdelkader, and M. H. Aly, “Exploring the effect of LED nonlinearity on the performance of layered ACO-OFDM,” *Appl. Opt*., vol. 59, no. 4, pp. 7343–7351, Aug. 2020.

[15] T. Zhang, Y. Zou, J. Sun, and S. Qiao, “Design of PAM-DMT-based hybrid optical OFDM for visible light communications,” *IEEE Wireless Communications Letters.*, vol. 8, no. 1, pp. 265-268, Feb. 2019.

[16] J. He, and J. Shi, “An enhanced adaptive scheme with pairwise coding for OFDM-VLC system,” *IEEE Photonics Technology Letters.*, vol. 30, no. 13, pp. 1254-1257, July. 2018.

[17] Y. Sun, F. Yang, and J. Gao, “Comparison of hybrid optical modulation schemes for visible light communication,” *IEEE Photonics Journal.*, vol. 9, no. 3, pp. 1-13, June. 2017.

[18] M. L. Tran, S. Kim, T. Ketseoglou, and E. Ayanoglu, “LED selection and MAP detection for generalized LED index modulation,” *IEEE Photon. Technol. Lett*., vol. 30, no. 19, pp. 1695–1698, Oct. 2018.

[19] B. Karanov, M. Chagnon, F. Thouin, T. A. Eriksson, H. Bulow, D. Lavery, P. Bayvel, and L. Schmalen, “End-to-end deep learning of optical fiber communications,” *IEEE/OSA J. Lightw. Technol*., vol. 36, no. 20, pp. 4843–4855, Oct. 2018.

[20] C. Chen, W. Zhong, and D. Wu, “Non-Hermitian symmetry orthogonal frequency division multiplexing for multiple-input multiple-output visible light communications,” *IEEE/OSA J. Opt. Commun. Netw*., vol. 9, no. 1, pp. 36–44, Jan. 2017

[21] A. Yesilkaya, E. Basar, F. Miramirkhani, E. Panayirci, M. Uysal, and H. Haas, “Optical MIMO-OFDM with generalized LED index modulation,” *IEEE Trans. Commun*., vol. 65, no. 8, pp. 3429–3441, Aug. 2017.