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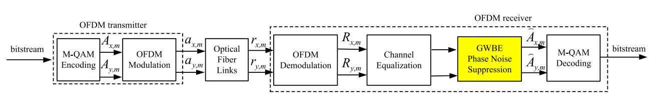

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A Novel Phase Noise Suppression Scheme Utilizing Gaussian Wavelet Basis Expansion for PDM CO-OFDM Superchannel

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Abstract: In this paper, we propose a novel Gaussian wavelet basis expansion-based phase noise suppression scheme for polarization-division-multiplexing (PDM) coherent optical orthogonal frequency division multiplexing (CO-OFDM) superchannel. We analyze the phase noise suppression principle of Gaussian wavelet basis expansion (GWBE) and experimentally demonstrated it in 400-Gb/s optical PDM-QPSK-OFDM superchannel. Compared with the traditional common phase error (CPE) suppression scheme, a Q-factor improvement of about 1.5∼3.2 dB is achieved when the number of the pilots ranges from 16 to 80. Meanwhile, we evaluate the nonlinear phase noise suppression ability by adjusting the launched power into 160 km standard single mode fiber (SSMF). The results show that the proposed GWBE scheme is obviously superior to CPE and orthogonal basis expansion (OBE) in different nonlinear phase noise scenarios. Furtherly, we extend the GWBE scheme to 800 Gb/s PDM-16QAM-OFDM superchannel. The GWBE scheme can enhance the BER performance from 1.92 E-03 to 5.87 E-04 when the number of pilots is 48.

Index Terms: PDM-CO-OFDM, Gaussian wavelet, phase noise.

1. Introduction

Due to its high flexibility, high spectrum efficiency and robustness against chromatic dispersion (CD) and polarization mode dispersion (PMD), coherent optical orthogonal frequency division multiplexing (CO-OFDM) has attracted great interest in the field of optical communication [1]–[4]. However, the sensitivity to phase noise has always been considered as a major drawback of CO-OFDM [5]–[7]. To address this problem, narrow linewidth lasers with linewidth of hundreds of kHz or less are always required at the CO-OFDM transmitter and receiver, which will increase the system cost. Apart from adopting narrow linewidth lasers, phase noise suppression method by digital signal processing (DSP) provides a cost-effective solution and it plays a more and more

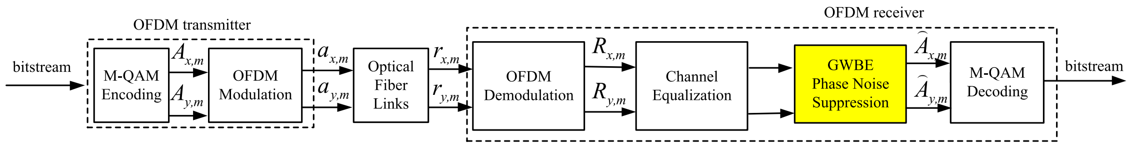


Fig. 1. Diagram of PDM CO-OFDM system utilizing GWBE method.

important role. Efficient phase noise suppression method can greatly reduce the requirement for laser.

The phase noise added to the received signal can be divided into two parts, the common phase error (CPE) and the inter carrier interference (ICI). By periodically inserting pilot subcarriers to OFDM symbols, pilot aided (PA) phase noise estimation method can effectively compensate the CPE [8], [9]. So the main challenge is in the ICI compensation. Previously, many techniques have been designed for ICI compensation. In [10]–[12], piecewise linear fit the phase noise variation is proposed and it can realize partial ICI suppression. Blind phase noise estimation by utilizing a set of test phases can effectively suppress ICI [13]. However, the suppression performance relies on a large number of test phases and the method is relatively complicated for practical implementation. Phase noise suppression methods based on orthogonal basis expansion (OBE) and eigenvector basis expansion (EBE) were proposed by Dr. Yang in [14]–[17]. By discrete Fourier transform (DFT) operation to approximate the phase noise, the OBE scheme can mitigate CPE as well as ICI. Compared with the OBE scheme, the EBE scheme uses more exact basis and has better performance. However, to get the eigenvector, back to back (BTB) pre-training is needed in the EBE scheme and it is inconvenient for practical application.

In this paper, we firstly propose complex Gaussian wavelet basis expansion (GWBE) for phase noise suppression. Different from the OBE and EBE scheme, we utilize the Gaussian characteristics of inter carrier interference (ICI) noise. Compared with the OBE scheme, the GWBE has better phase noise fitting ability for additive white Gaussian noise while maintaining similar computation complexity. What is more, no additional BTB pre-training is needed in the GWBE scheme. We discuss the phase noise suppression principle of GWBE and experimentally demonstrate it in 400-Gb/s PDM QPSK-OFDM and 800 Gb/s PDM 16QAM-OFDM transmission system. In our experimental setup, the linewidth of the modulated laser at the transmitter and the local oscillator at the receiver is 1-MHz. In BTB transmission of QPSK-OFDM superchannel, a Q-factor improvement of about 1.5$\sim$3.2 dB and 0.7$\sim$1.7 dB are achieved compared with the traditional CPE and OBE scheme, respectively. We also compare the signal Q-factor performance after 160 km SSMF transmission with different phase noise suppression method. The results show that the GWBE scheme is obviously superior to CPE and OBE with different nonlinear phase noise. The basis number is optimized to balance computational complexity and transmission performance. Furtherly, we extend the GWBE scheme to 800-Gb/s PDM 16QAM-OFDM superchannel and analyze the transmission performance with different number of pilots. The results show that the GWBE scheme can improve the BER performance from 1.92 E-03 to 5.87 E-04 when the number of pilots is 48.

2. Technique Principle

The schematic of PDM CO-OFDM system utilizing GWBE method is shown in Fig. 1. The architecture is similar as conventional OFDM system except that GWBE phase noise suppression module is inserted between channel equalization module and M-QAM decoding module.

At the transmitter, $A_{x,m} = [A_{x,m}(0), A_{x,m}(1), \ldots, A_{x,m}(N-1)]$ and $A_{y,m} = [A_{y,m}(0), A_{y,m}(1), \ldots, A_{y,m}(N-1)]$ are the m-th encoding data block for x and y polarizations. N is the FFT size. After inverse discrete Fourier transform (IDFT) operation, the *m-th* OFDM symbol in the time domain are $a_{x,m} = [a_{x,m}(0), a_{x,m}(1), \ldots, a_{x,m}(N-1)]$ and $a_{y,m} = [a_{y,m}(0), a_{y,m}(1), \ldots, a_{y,m}(N-1)]$.

$$\begin{pmatrix} a_{x,m} \\ a_{y,m} \end{pmatrix} = \begin{pmatrix} F^H & 0 \\ 0 & F^H \end{pmatrix} \begin{pmatrix} A_{x,m} \\ A_{y,m} \end{pmatrix} \tag{1}$$

Here F^Hrepresents IDFT matrix. After optical fiber links transmission, the received signal is $r_{x,m} = [r_{x,m}(0), r_{x,m}(1), \ldots, r_{x,m}(N-1)]$ and $r_{y,m} = [r_{y,m}(0), r_{y,m}(1), \ldots, r_{y,m}(N-1)]$. Similarly, we can obtain frequency domain signal $R_{x,m} = [R_{x,m}(0), R_{x,m}(1), \ldots, R_{x,m}(N-1)]$ and $R_{y,m} = [R_{y,m}(0), R_{y,m}(1), \ldots, R_{y,m}(N-1)]$ by

$$\begin{pmatrix} R_{x,m} \\ R_{y,m} \end{pmatrix} = \begin{pmatrix} F & 0 \\ 0 & F \end{pmatrix} \begin{pmatrix} r_{x,m} \\ r_{y,m} \end{pmatrix} \tag{2}$$

F represents DFT matrix. When considering the transmission link impairments including CD, PMD, laser phase noise and amplified spontaneous emission (ASE) noise, the received OFDM symbol after discrete Fourier transform (DFT) for two polarizations can be rewritten as

$$\begin{pmatrix} R_{x,m} \\ R_{y,m} \end{pmatrix} = \begin{pmatrix} F & 0 \\ 0 & F \end{pmatrix} \begin{pmatrix} \phi_{x,m} & 0 \\ 0 & \phi_{y,m} \end{pmatrix} \begin{pmatrix} F^H & 0 \\ 0 & F^H \end{pmatrix} \begin{pmatrix} H_{xx} & H_{yx} \\ H_{xy} & H_{yy} \end{pmatrix} \begin{pmatrix} A_{x,m} \\ A_{y,m} \end{pmatrix} + \begin{pmatrix} w_{x,m} \\ w_{y,m} \end{pmatrix} \tag{3}$$

H_{xx}, H_{yx}, H_{xy} and H_{yy} are $N \times N$ diagonal matrix that denotes channel transmission matrix. $\varphi_{x,m} = [\varphi_{x,m}(0), \varphi_{x,m}(1), \ldots, \varphi_{x,m}(N-1)]$ and $\varphi_{y,m} = [\varphi_{y,m}(0), \varphi_{y,m}(1), \ldots, \varphi_{y,m}(N-1)]$ represent phase noise for two orthogonal polarizations. We define $\phi_{x,m} = diag(\varphi_{x,m})$,$\phi_{y,m} = diag(\varphi_{y,m})$ for convenience. $w_{x,m}$ and $w_{y,m}$ are residual error caused by additive white Gaussian noise (AWGN) for x polarization and y polarization.

Different from the OBE method, we use W to describe Gaussian wavelet orthogonal basis. Utilizing Gaussian orthogonal basis, the phase noise is expanded as

$$\begin{pmatrix} \varphi_{x,m} \\ \varphi_{y,m} \end{pmatrix} = \begin{pmatrix} W & 0 \\ 0 & W \end{pmatrix} \begin{pmatrix} \gamma_{x,m} \\ \gamma_{y,m} \end{pmatrix} \tag{4}$$

According to Eqn. (4), Eqn. (3) can be written as

$$\begin{pmatrix} A_{x,m} \\ A_{y,m} \end{pmatrix} = \begin{pmatrix} H_{xx} & H_{yx} \\ H_{xy} & H_{yy} \end{pmatrix}^{-1} \begin{pmatrix} diag(R_{x,m}) & 0 \\ 0 & diag(R_{y,m}) \end{pmatrix} \begin{pmatrix} W^* & 0 \\ 0 & W^* \end{pmatrix} \begin{pmatrix} \gamma^*_{x,m} \\ \gamma^*_{y,m} \end{pmatrix} + \begin{pmatrix} \varepsilon_{x,m} \\ \varepsilon_{y,m} \end{pmatrix} \tag{5}$$

where ε_m is residual error caused by AWGN and other additive error. Here we define

$$C_m = \begin{pmatrix} H_{xx} & H_{yx} \\ H_{xy} & H_{yy} \end{pmatrix}^{-1} \begin{pmatrix} diag(R_{x,m}) & 0 \\ 0 & diag(R_{y,m}) \end{pmatrix} \begin{pmatrix} W^* & 0 \\ 0 & W^* \end{pmatrix} \tag{6}$$

So the received symbol can be rewritten as:

$$\begin{pmatrix} A_{x,m} \\ A_{y,m} \end{pmatrix} = C_m \begin{pmatrix} \gamma_{x,m}{}^* \\ \gamma_{y,m}{}^* \end{pmatrix} + \begin{pmatrix} \varepsilon_{x,m} \\ \varepsilon_{y,m} \end{pmatrix} \tag{7}$$

Pilots is uniformly inserted in each OFDM symbol. $S_pA_{x,m}$ and $S_pA_{y,m}$ mean pilot subcarriers in m-th OFDM symbol. We define $S = \left(\begin{smallmatrix} S_p & 0 \\ 0 & S_p \end{smallmatrix}\right)$. So

$$\begin{pmatrix} S_pA_{x,m} \\ S_pA_{y,m} \end{pmatrix} = SC_m \begin{pmatrix} \gamma_{x,m}{}^* \\ \gamma_{y,m}{}^* \end{pmatrix} + \begin{pmatrix} S_p\varepsilon_{x,m} \\ S_p\varepsilon_{y,m} \end{pmatrix} \tag{8}$$

Utilizing least mean square error (LMSE) principle, the estimation value can be written as

$$\begin{pmatrix} \gamma_{x,m}{}^* \\ \gamma_{y,m}{}^* \end{pmatrix} = \left[(SC_m)^H SC_m \right]^{-1} (SC_m)^H \begin{pmatrix} S_pA_{x,m} \\ S_pA_{y,m} \end{pmatrix} \tag{9}$$

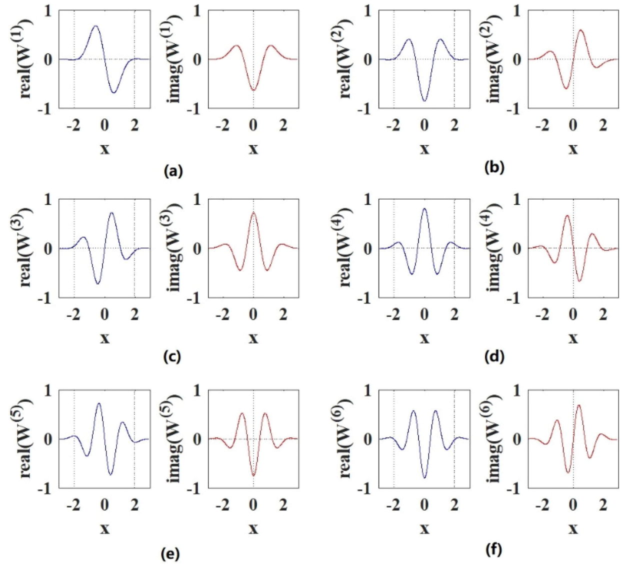


Fig. 2. Complex Gaussian wavelets with (a) 1st order (b) 2nd order (c) 3rd order (d) 4th order (e) 5th order (f) 6th order.

After channel equalization and phase noise suppression, we finally get the received symbol.

$$\begin{pmatrix} \widehat{A}_{x,m} \\ \widehat{A}_{y,m} \end{pmatrix} = C_m \begin{pmatrix} \gamma^*_{x,m} \\ \gamma^*_{y,m} \end{pmatrix} \tag{10}$$

Here we analyze the principle of complex Gaussian wavelet. In optical fiber communication system, the laser phase noise can be modeled as Wiener random process $\varphi_i = \varphi_{i-1} + \upsilon_i$ and υ_i obey the Gaussian distribution. The phase noise introduced by inter-channel interference is not considered here. ICI can be approximated as an additive Gaussian noise [18], [19]. Due to the additive Gaussian noise characteristic of ICI, the OBE and EBE scheme that utilize DFT basis or eigenvector basis cannot approximate it. While in our scheme, we utilize complex Gaussian wavelet and it has a better fitting ability for ICI noise. Complex Gaussian wavelet can be constructed by complex Gaussian equation $W = e^{-jx}e^{-x^2}$. Complex Gaussian wavelet set is n-order derivative of complex Gaussian equation, $W^{(n)} = (e^{-jx}e^{-x^2})^{(n)}$. Fig. 2 shows the *1st*, *2nd*, *3rd*, *4th*, *5th*, *6th* order complex Gaussian wavelets. In this paper, 13 complex Gaussian wavelet bases $\{conj(W^6)\cdots conj(W^1), 1, W^1 \cdots W^6\}$ (1 vector, 6 complex Gaussian wavelet basis and their conjugations) are used.

Meanwhile, we compare the computation complexity of the OBE, EBE and GWBE scheme. The computation complexity is related to the numbers of subcarriers (N), pilots (M) and basis (L). We use the number of multiplication operations to evaluate the computation complexity. According to Eqn. (6), Eqn. (8) and Eqn. (9), the number of multiplication operations in GWBE is $O(NL) + O(NL\log_2 N) + O(8ML^2 + 8L^3 + 2ML) + O(2NL)$, which is similar as the OBE scheme. While in the EBE scheme, BTB pre-training will bring about $O(2N\log(L)) + O(N_eN^2)+O(N^3)$ additional multiplication operations. So in the terms of computing complexity, no additional multiplication operations will be introduced.

3. Experimental Setup

Fig. 3 shows the experimental setup of the phase noise suppression method based on Gaussian wavelet basis expansion. 400 Gb/s PDM QPSK-OFDM and 800 Gb/s PDM 16QAM-OFDM transmission system are demonstrated. We adopt the similar scheme in our previous work [20]

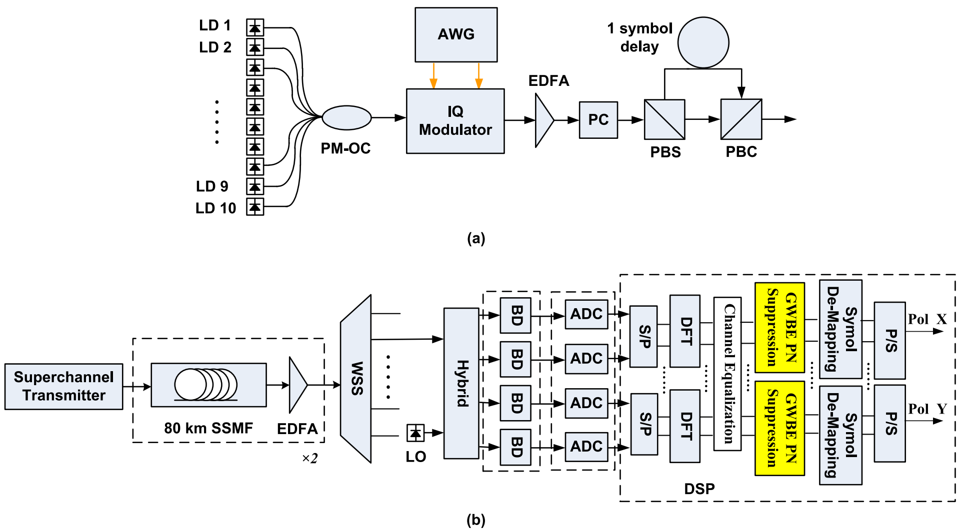


Fig. 3. Experimental setup of (a) superchannel transmitter (b) PDM CO-OFDM superchannel with Gaussian wavelet basis expansion for phase noise suppression.

to generate the optical superchannel, as shown in Fig. 3(a). At the transmitter, 10 laser diodes (LD1∼LD10) centered from 1549.072 nm to 1549.792 nm with frequency spacing of 0.08 nm (10 GHz) are combined by polarization-maintaining optical coupler (PM-OC). The line-width of the lasers are about 1 MHz. A Tektronix arbitrary waveform generator (AWG70002A) operating at 10 GS/s is used to generate the baseband OFDM frame. In each frame, 200 OFDM symbols are generated. The FFT size is 512. 40 subcarriers as guard band, 80 subcarriers are used as pilots for phase noise estimation. The cyclic prefix (CP) length is 64. Before signal transmitted, preamble is added to the data block. The preamble includes two Chu-sequences of 128-subcarrier length for synchronization and four Chu sequences of 512-subcarrier length for channel estimation. After modulated by an IQ modulator, the 10-subband superchannel is power amplificated by an EDFA. Polarization-division-multiplexing (PDM) is emulated by a polarization controller (PC), a polarization beam splitter (PBS), a tunable optical delay line and a polarization beam combiner (PBC). A superchannel consists of continuous 10 subbands with total data rate of 400 Gb/s is generated at the output of the transmitter.

Fig. 3(b) shows the signal transmission and detection of PDM CO-OFDM superchannel with Gaussian wavelet basis expansion for phase noise suppression. After 2 spans of 80-km standard single mode fiber (SSMF) transmission, a Finisar Waveshaper 4000S based on liquid crystals on silicon (LCoS) is served as a wavelength select switch (WSS) to select each subband for detection. The WSS has a minimum filtering bandwidth of 10 GHz and wavelength resolution of 1 GHz. The subband is sent into a 90° hybrid and then interferes with a local oscillator (LO). The linewidth of the local oscillator laser is 1-MHz. After balanced detectors (BD), the polarization diverse signals are sampled by a real-time digital storage oscilloscope (Tektronix DPO72004B) operating at 50 GSa/s. Then the sampled data are processed offline. After removing CP, the signals are transformed to frequency domain by DFT and perform channel equalization. GWBE as discussed above is performed for phase noise suppression.

4. Experimental Results

The optical spectra of 10 carriers generated by 10 LDs is shown in Fig. 4(a). After OFDM modulation and polarization-division-multiplexing, the optical spectra at the output of the superchannel transmitter is shown in Fig. 4(b).

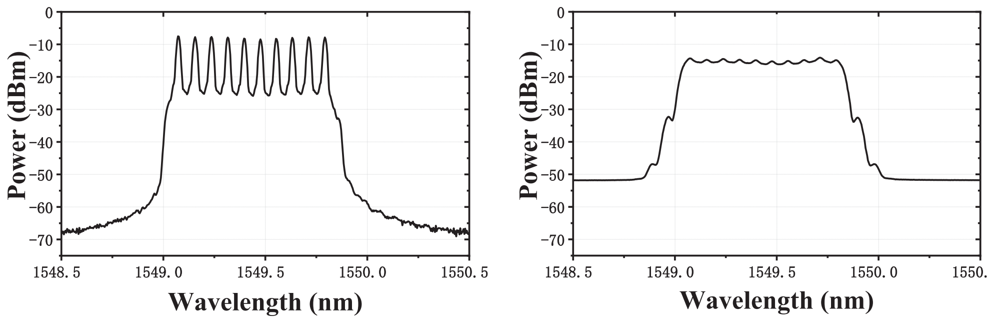


Fig. 4. Optical spectra of (a) 10 optical carriers (b) output of the superchannel transmitter.

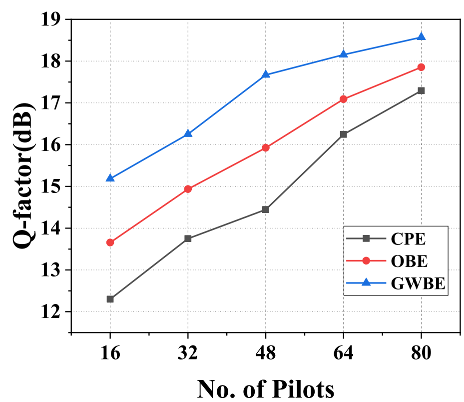


Fig. 5. Q-factor performance versus the number of the pilots.

To better evaluate the performance of GWBE scheme, we use 10 different random number of seeds to generate different transmitted bit sequences and calculate the averaged performance. The CPE and OBE scheme are also executed for comparison. Fig. 5 shows the Q-factor performances versus the number of the pilots in back to back (BTB) case. The Q-factor is calculated by the estimation method in [21]. Each subband in the superchannel have similar performances and as reference we only depict the subband 4. We adjust the number of pilots from 16 to 80 and test the correspondingly Q-factor of CPE, OBE and the proposed GWBE scheme. From the results, we can see increasing the number of the pilots can effectively improve system performance. However, it will also occupy more valid data subcarriers. Compared with traditional CPE scheme, a Q-factor improvement of about 1.5∼3.2 dB is achieved for GWBE scheme. Compared with OBE scheme, a Q-factor improvement of about 0.7∼1.7 dB is achieved. Reducing the number of the pilots can increase the margin and correspondingly improve spectral efficiency. Fig. 6 shows the QPSK constellation with different phase noise suppression method. It is obvious that the constellation by GWBE scheme is more convergent. The proposed GWBE scheme can effectively suppress laser phase noise caused by large laser linewidth.

Fig. 7 shows the Q-factor performance versus the number of the basis in BTB transmission case. When the basis number is less than 7, increasing the basis number can improve the phase noise fitting ability, therefore improve the Q-factor performance. When the basis number is greater than 9, the Q-factor tends to be stable. Large basis number will increase computational complexity. In our experiment setup, the basis number is set to 6 to simultaneously balance computational complexity and transmission performance.

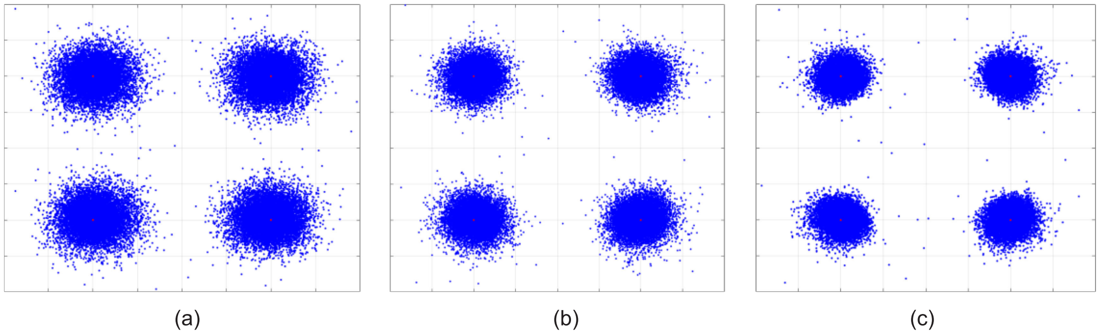


Fig. 6. Signal constellation by (a) CPE, (b) OBE, and (c) GWBE.

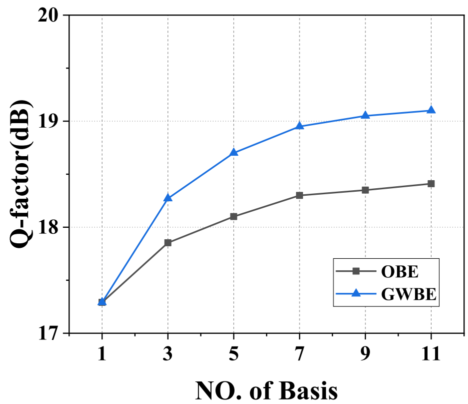


Fig. 7. Q-factor performance versus the number of the basis.

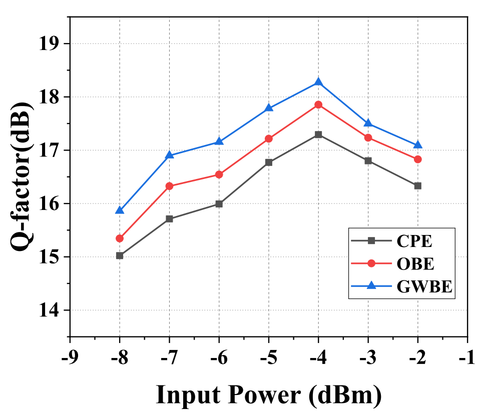
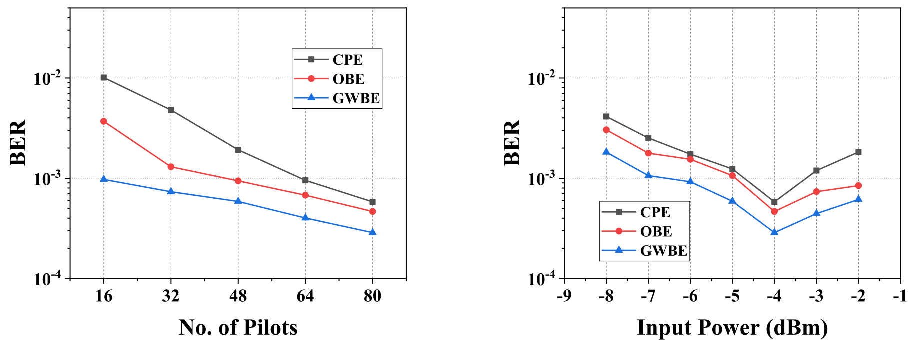


Fig. 8. Q-factor performance versus the launch power per channel.

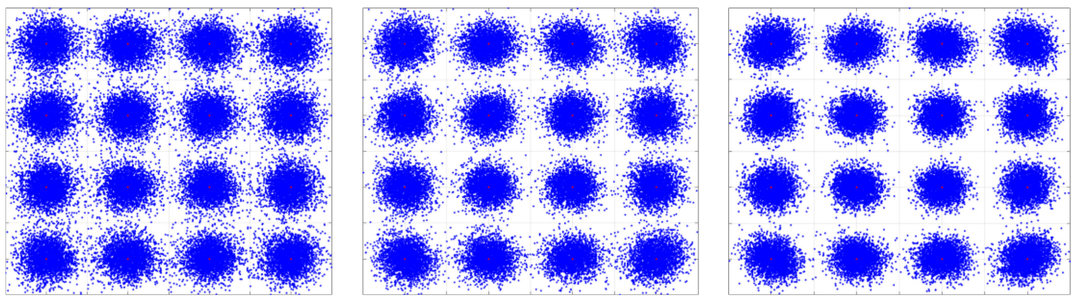
We also compare the transmission performances for CPE, OBE, and GWBE after 160 km SSMF transmission. We adjust the input power to each span. The launch power per channel is set from −8 dBm to −2 dBm, as show in Fig. 8. From the results, we can see the GWBE scheme is obviously superior to CPE and OBE with different nonlinear phase noise.

Furtherly, we extend the GWBE scheme to higher order modulation format. High order modulation format signal is more sensitive to phase noise. We verify the GWBE scheme in PDM 800 Gb/s 16QAM-OFDM superchannel. Similarly, we test subband 4 as reference. The BER performance versus the number of the pilots in BTB case is shown in Fig. 9(a). The proposed GWBE scheme



(a) (b)

Fig. 9. BER performance versus (a) the number of the pilots (b) the launch power per channel.



(a) (b) (c)

Fig. 10. Signal constellation of (a) CPE, (b) OBE, and (c) GWBE.

can enhance the BER performance from 1.92 E-03 to 5.87 E-04 when the number of pilots is 48. The BER performance versus the launch power per channel after 160km transmission is shown in Fig. 9(b). Fig. 10 shows the signal constellation of the three phase noise suppression methods. The proposed GWBE shows distinct advantage.

5. Conclusions

In this paper, Gaussian wavelet basis expansion (GWBE) is proposed and experimentally demonstrated for phase noise suppression. Compared with the traditional CPE suppression scheme, a Q-factor improvement of about 1.5∼3.2 dB is achieved in 400-Gb/s optical PDM QPSK-OFDM superchannel. Furtherly, we extend the GWBE scheme to 800 Gb/s PDM 16QAM-OFDM superchannel. The GWBE scheme can enhance the BER performance from 1.92 E-03 to 5.87 E-04. Experimental result shows that the proposed scheme is a promising phase noise suppression method for future CO-OFDM system.

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