Electronic compensator for 100-Gb/s PDM-CO-OFDM long-haul transmission systems

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We study an electronic compensator (EC) as a receiver for a 100-Gb/s polarization division multiplexing coherent optical orthogonal frequency division multiplexing (PDM-CO-OFDM) system without optical dispersion compensation. EC, including electrical dispersion compensation (EDC), least squares channel estimation and compensation (LSCEC), and phase compensation (PC), is used to compensate for chromatic dispersion (CD), phase noise, polarization mode dispersion (PMD), and channel impairments, respectively. Simulations show that EC is highly effective in compensating for those impairments and that the performance is close to the theoretical limitation of optical signal-to-noise rate (OSNR), CD, and PMD. Its robustness against those transmission impairments and fiber nonlinearity are also systematically studied.

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Optical orthogonal frequency division multiplexing (OFDM) has been a main research interest in recent years[1]. Coherent optical OFDM (CO-OFDM) combined with polarization division multiplexing (PDM) is regarded as a promising technology for high-speed optical transmission as it can provide powerful channel estimation and compensation capabilities and can also double the spectral efficiency of a transmission system[2]. In contrast with the conventional design, the CO-OFDM systems do not use any dispersion compensation fiber[3]; thus, it is important to conduct research on the performance of the PDM-CO-OFDM systems without optical dispersion compensation (ODC).

Recently, many studies have focused on using electronic compensators (ECs) at the receiver of CO-OFDM[4−8]. The use of electronic signal processing to compensate for chromatic dispersion (CD), phase noise, and polarization mode dispersion (PMD) in optical transmission offers the advantages of low cost, small size, reduced optical losses, and adaptive operation. However, these studies did not systematically conduct research on combining each compensation algorithm.

In this letter, we conduct simulation analysis on using an EC at the receiver to compensate for CD, phase noise, PMD, and channel impairments on a 100-Gb/s PMD-CO-OFDM system; here, EC includes electrical dispersion compensation (EDC), least squares channel estimation and compensation (LSCEC), and phase compensation (PC). We systematically study EC against transmission impairments, and the numerical simulations show that the EC is very effective in compensating for impairments in systems.

Assuming a long-enough symbol period, the channel model for the kth subcarrier in the ith symbol in PDM-CO-OFDM systems is given by[9]

$$\mathbf{r}'_{ik} = \mathrm{e}^{\mathrm{j}\phi_D(k)} \cdot \mathrm{e}^{\mathrm{j}\phi_k} \cdot H_k \cdot \mathbf{t}_{ik} + \mathbf{n}_{ik}, \quad (1)$$

or

$$\begin{bmatrix} r'^{x}_{ik} \\ r'^{y}_{ik} \end{bmatrix} = \mathrm{e}^{\mathrm{j}\phi_\mathrm{D} k} \cdot \mathrm{e}^{\mathrm{j}\phi k} \cdot \begin{bmatrix} h_{xx}(k) & h_{xy}(k) \\ h_{yx}(k) & h_{yy}(k) \end{bmatrix} \cdot \begin{bmatrix} t^{x}_{ik} \\ t^{y}_{ik} \end{bmatrix} + \begin{bmatrix} n^{x}_{ik} \\ n^{y}_{ik} \end{bmatrix}, \quad (2)$$

where $\mathbf{t}_{ik} = (t^x_{ik}\ t^y_{ik})^t$ and $\mathbf{r}_{ik} = (r'^x_{ik}\ r'^y_{ik})^t$ are the transmitted and received information symbols, respectively, in the form of the Jones vector for the kth subcarrier in the ith OFDM symbol; $\mathbf{n}_{ik} = (n^x_{ik}\ n^y_{ik})^t$ is the noise including two polarization components. A multiple-input Multiple-output (MIMO) model essentially relates the two outputs, r'^x_{ik} and r'^y_{ik}, to the two inputs, t^x_{ik} and t^y_{ik}[9]. H_k is the 2×2 Jones matrix for the fiber link representing the linear channel effects, and ϕ_k is the OFDM symbol phase noise owing to the phase noises from the lasers and radio frequency (RF) local oscillators (LOs) at both the transmitter and receiver[10], which is usually dominated by the laser linewidth. $\phi_\mathrm{D}(f_k)$ is the phase dispersion owing to the fiber CD[10] given by

$$\phi_\mathrm{D}(f_k) = \frac{\pi \cdot c}{f^2_\mathrm{LD}} D_\mathrm{t} \cdot f^2_k, \quad (3)$$

where f_LD is the frequency of the optical carrier, c is the speed of light (m/s), D_t is the total accumulated CD in units of ps/nm, and f_k is the frequency for the kth subcarrier. To compensate for channel impairments in the PDM-CO-OFDM systems without ODC, the EC is located after fast Fourier transform (FFT) in the receiver and includes three parts, namely, EDC, LSCEC, and PC, that are used to estimate $\phi_\mathrm{D}(f_k)$, H_k, and ϕ_k, respectively. The location of EC is shown in Fig. 1, and the setup is shown in Fig. 2.

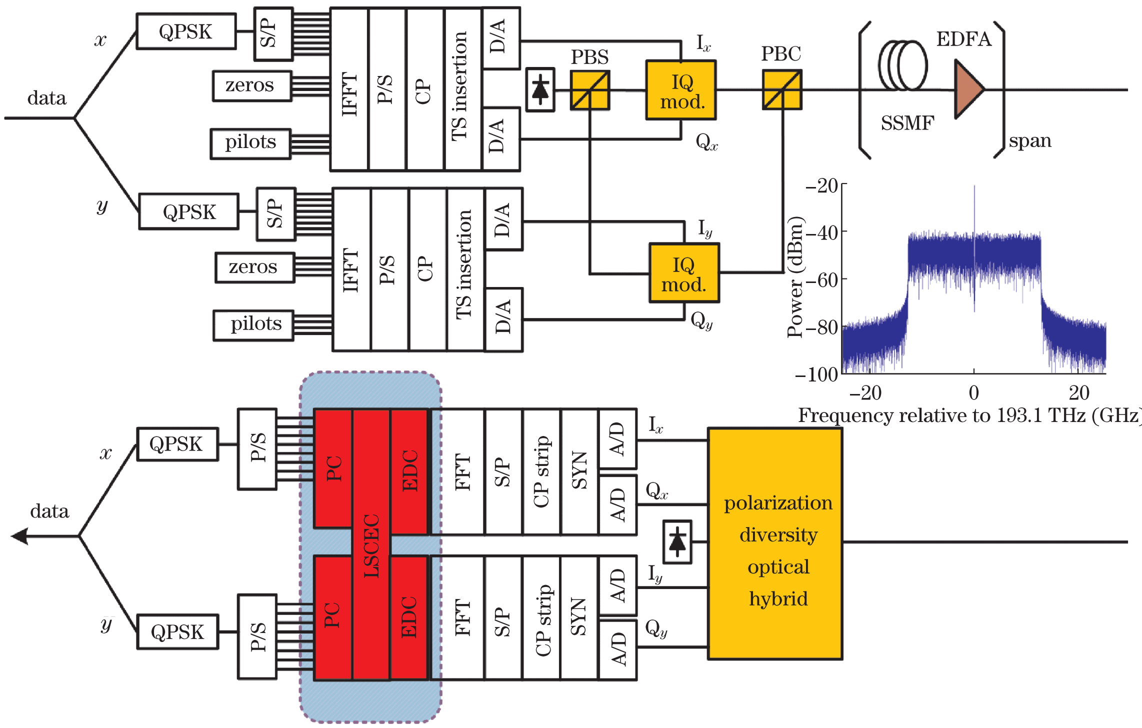

Fig. 1. Setup of 100-Gb/s PDM-CO-OFDM system. S/P: serial-to-parallel.

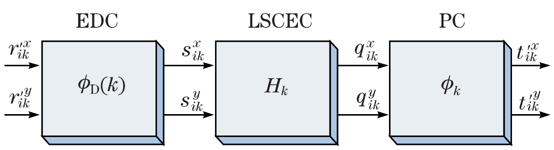

Fig. 2. Setup of EC.

The first equalization step is EDC, which aims to remove the effect of fiber dispersion. This is achieved by training the system with a known sequence, and then comparing the phases of all received symbols with the transmitted symbols. The estimated CD phase drift can be formally written as

$$\phi_\mathrm{D}(f_k) = \frac{1}{N_\mathrm{TS}} \sum_{m=1}^{N_\mathrm{TS}} \left\{ \arg(r_{mk}^{\prime x}) - \arg(t_{mk}^x) \right\}, \quad (4)$$

where $\arg(\cdot)$ is the phase angle of the information symbol, N_TS is the number of train symbols (TSs), t_{mk}^x is the known transmitted data, and $r_{mk}^{\prime x}$ is received symbol. Averaging the phase difference over all TSs for each subcarrier is adopted in EDC.

After obtaining $\phi_\mathrm{D}(f_k)$ by EDC, the Jones matrix H_k is estimated by LSCEC. The pair of TSs are inserted before the symbol sequence in transmitter and can be written as

$$t_{1k} = \begin{bmatrix} t_{1k}^x \\ 0 \end{bmatrix}, \; t_{2k} = \begin{bmatrix} 0 \\ t_{2k}^y \end{bmatrix}. \quad (5)$$

Assuming that one TS pair experiences the same channel effect, the received TSs are then expressed by

$$\begin{bmatrix} s_{1k}^x \\ s_{1k}^y \end{bmatrix} = \begin{bmatrix} h_{xx}(k) & h_{xy}(k) \\ h_{yx}(k) & h_{yy}(k) \end{bmatrix} \begin{bmatrix} t_{1k}^x \\ 0 \end{bmatrix} = \begin{bmatrix} h_{xx}(k) \cdot t_{1k}^x \\ h_{yx}(k) \cdot t_{1k}^x \end{bmatrix}, \quad (6)$$

$$\begin{bmatrix} s_{2k}^x \\ s_{2k}^y \end{bmatrix} = \begin{bmatrix} h_{xx}(k) & h_{xy}(k) \\ h_{yx}(k) & h_{yy}(k) \end{bmatrix} \begin{bmatrix} 0 \\ t_{2k}^y \end{bmatrix} = \begin{bmatrix} h_{xy}(k) \cdot t_{2k}^y \\ h_{yy}(k) \cdot t_{2k}^y \end{bmatrix}. \quad (7)$$

Thus, the channel matrix can be expressed as[6]

$$H_k = \begin{bmatrix} h_{xx}(k) & h_{xy}(k) \\ h_{yx}(k) & h_{yy}(k) \end{bmatrix} = \begin{bmatrix} s_{1k}^x/t_{1k}^x & s_{2k}^x/t_{2k}^y \\ s_{1k}^y/t_{1k}^x & s_{2k}^y/t_{2k}^y \end{bmatrix}. \quad (8)$$

An effective method in reducing the impact of the error caused by the noise term, i.e., the last term in Eq. (1) is to apply averaging with a moving average algorithm over time and/or frequency[2]. Time averaging was thus adopted in this letter. For time averaging, typical average window lengths are between 5 and 50, depending on the system configuration. Furthermore, in order to minimize the influence of nonlinearities on channel equalization, a TS is usually constructed so that it exhibits a low peak-to-average power ratio (PAPR)[2].

Phase noise is usually dominated by the laser linewidth; thus, the phase noise originating from laser phase drift within one OFDM symbol can be considered as constant and common to all the subcarriers[11]. Here, 16 pilot subcarriers distributed in the center region of the OFDM frequency spectrum were used for PC, and the constant phase drift values of each OFDM symbol due to linewidth were obtained by averaging the phase difference across all of the pilot subcarriers in this symbol. This can be expressed as[11]

$$\phi_k = \phi_i = \frac{1}{N_\mathrm{Pilot}} \sum_{k=1}^{N_\mathrm{Pilot}} \left\{ \arg(q_{ik}^x) - \arg(t_{ik}^x) \right\}, \quad (9)$$

where N_Pilot is the number of pilot subcarriers in one OFDM symbol, and q_{ik}^x is signal behind EDC and LSCEC. After EC, the estimated $\mathbf{t}_{ik}$, denoted as $\mathbf{t}'_{ik}$, can be expressed as

$$\mathbf{t}'_{ik} = \mathrm{e}^{-\mathrm{j}\phi_\mathrm{D}(k)} \cdot \mathrm{e}^{-\mathrm{j}\phi_k} \cdot H_k^{-1} \cdot \mathbf{r}'_{ik}. \quad (10)$$

The basic schematic of 100-Gb/s PDM-CO-OFDM is shown in Fig. 1, which shows 2048 subcarriers, of which the center of 1024 carries quadrature phase-shift-keying (QPSK) data together with 16 pilot subcarriers. The cycle prefix (CP) length of 256(12.5%) or 512(25%) per OFDM symbol was subsequently inserted after inverse fast Fourier transform (IFFT). Then, the TSs were inserted into the OFDM symbol sequences for channel estimation. After digital-to-analog (DA) converter, the two OFDM baseband signal parts were upconverted to single-polarization optical frequency separately by optical inphase/quadrature (I/Q) modulation, in which two Mach-Zehnder modulators (MZMs) were biased at the null point[12]. The two polarization branches were subsequently combined by polarization beam combiner (PBC), one on each polarization. Table 1 depicts the basic parameters.

The optical links consisting of some 80-km standard single mode fiber (SSMF) spans without ODC are shown in Fig. 1. Amplified spontaneous emission (ASE) noise was added at each erbium-doped fiber amplifier (EDFA), with a noise figure (NF) of 6 dB. The parameters of link are shown in Table 2.

At the receiver, the optical signal was first fed into the polarization diversity coherent receiver. Coherence direct down-detection[12] of each branch, including two pairs of balanced photodetectors (an optical hybrid and a LO laser), was first used. After DA convevter, symbol synchronization (SYN)[13] was then performed, and the EC proposed in this letter after FFT was needed to compensate for the channel impairments. The linewidth was assumed to be 100 kHz for both transmitter and receiver lasers. This value is close to that achieved with commercially available external-cavity semiconductor lasers[3].

The constellation of the received data shows four clusters of data points corresponding to four QPSK information symbols; the sources of the noise spreading each information symbol are mainly the phase noise of lasers, the nonlinearity of optical fibers, and the ASE noise in the transmission system[3]. The bit error rate (BER) is derived from the symbol variance since the optical OFDM nonlinear distortion are approximately Gaussian distributed[14]. Thus, the electrical signal quality is measured from the constellation q and can be defined as $q = \mu_y/\sigma_y$[15] and $Q = 10\lg(q^2)$, averaged over all subcarriers. The BER can be estimated using BER$= 1/2\ \mathrm{erfc}(q/\sqrt{2})$. In order to ensure the correctness of the Q factor, 64 OFDM symbols were simulated equivalent to 131072 (64×2×1024) bits. VPIsystems' VPItransmissionMakerWDM V7.6 was used for the simulations.

Figure 3 depicts the back-to-back (B2B) Q factor as a function of optical signal-to-noise rate (OSNR) for 50-Gb/s single-polarization CO-OFDM and 100-Gb/s PDM-CO-OFDM, where the PDM-CO-OFDM uses a different number of TSs pairs (N_{TS}) for the EC. The theoretical Q factor versus OSNR is calculated as the value of the definition of Q in Ref. [15] through Eb/No (the energy per bit to noise power spectral density ratio) that has been initially calculated by OSNR. As the number of TSs of EC increases, the impact of the error caused by the noise term is reduced and Q is increased. However, when the number of TSs is greater than 10, the rising trend is not obvious, and the performance becomes approximately equal to the theoretical curve. Considering the efficiency and effectiveness, the number of TSs is set to 6, and the required OSNR for Q=10 (BER=10^{-3}) becomes ~13 dB in this letter. We can see that the 100-Gb/s PDM-CO-OFDM induces about 2-dB Q penalty compared with the 50-Gb/s single polarization. This is because the date rate for PDM is doubled without increasing the required electrical bandwidth[4].

In the presence of large CD in nonlink dispersion compensation systems, there is a large phase variation across the subcarriers. Figure 4 shows the phase of OFDM subcarriers estimated by EDC in EC with N_{TS}=6, OSNR=13 dB, and CP=25% for different residual CDs at 5000 and 10000 ps/nm. The phase shift caused by dispersion is significant, and the CD-induced phase variations are larger towards the edge of the OFDM spectrum. When the residual CD is increased by multiples, the phase shift also follows a corresponding increase.

For a given CP, the theoretical tolerated CD can be obtained from[16]

$$D_{\mathrm{Tolerance}} = \frac{\tau_{\mathrm{CP}}}{B_{\mathrm{Raw}}} \cdot \frac{f^2}{c}, \tag{11}$$

$$B_{\mathrm{Raw}} = \frac{R_{\mathrm{nominal}}}{2\log_2(M)}, \tag{12}$$

where $D_{\mathrm{Tolerance}}$ is the tolerance of CD (s/m), τ_{CP} is the length of CP (s), f represents the center frequency of the OFDM band (193.1 THz) R_{nominal} is the normal data rate (b/s), M is the constellation size, and the factor 2 results from the use of PDM. For this 100-Gb/s system with QPSK modulation, B_{Raw} is 25 GHz. Based on Eq. (11) for CP=12.5% and 25%, the tolerance CDs in theory are 25000 and 50000 ps/nm, respectively (Fig. 5)

Q factor as a function of CD (ps/nm) for different CP lengths is shown in Fig. 5, where N_{TS}=6 and OSNR=13 dB. EC offers significant benefits to systems, and when CD is less than the theoretical value of 25000 and 50000 ps/nm for CP=12.5% and 25%, respectively, the performance is almost free from the impact of CD and similar to that of other non-dispersion

Table 1. System Parameters

Data Rate	Modulation Format	Number of FFT/IFFT	Number of Pilot Subcarriers
100 Gb/s	QPSK	2048	16
Number of Date Subcarriers	Number of Zero Padding	CP Number	OFDM Symbol Size
1024	1008	256, 512	2304, 2560

Table 2. Transmission Link Parameters

Attenuation α of SSMF	Dispersion β_2 of SSMF	Dispersion Slope β_3 of SSMF	Nonlinear Index n_2 of SSMF
0.2 dB/km	16 ps/nm/km	0.08 ps/nm^2/km	2.6×10^{-20} m^2/W
Effective Core Area A_{eff} of SSMF	PMD of SSMF	Gain of EDFA	NF of EDFA
80 μm^2	5.0 ps/$\sqrt{\mathrm{km}}$	16 dB	6 dB

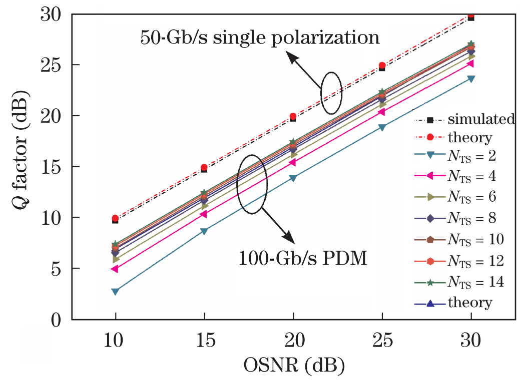

Fig. 3. Q factor versus OSNR in B2B.

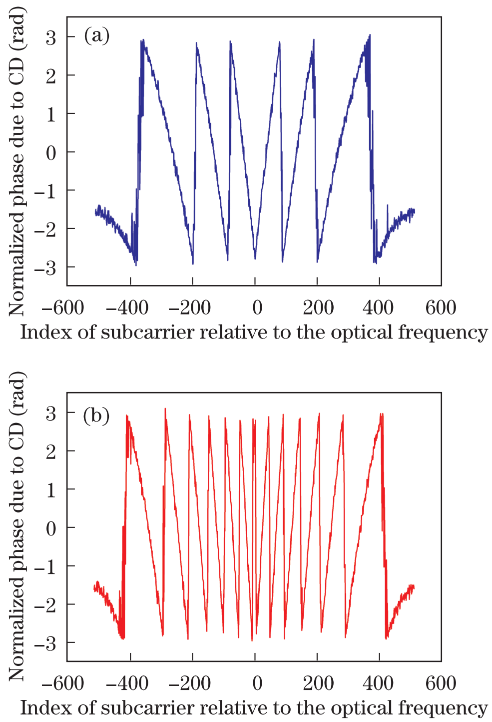

Fig. 4. Phases of the subcarriers estimated by EDC with N_{TS}=6, CP=25% and OSNR=13 dB for (a) 5000 and (b) 10000 ps/nm.

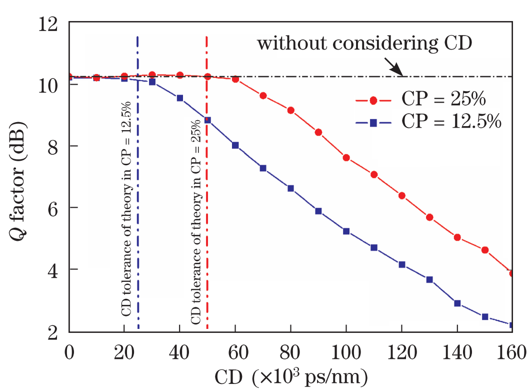

Fig. 5. Q factor versus CD with N_{TS}=6 and OSNR=13 dB.

systems; note that the 25000- and 50000-ps/nm dispersion values correspond to about 1560 and 3125 km in SSMF, respectively. However, once these are beyond the theoretical value, the time shift of subcarriers due to CD transcends the scope of CP and can destroy the orthogonality between subcarriers, making it difficult to maintain electricity domain compensation. In this case, CP length matching with EDC is also very important and must be first designed for the systems. PMD is one of the major sources of impairment for high speed optical fiber transmission and causes frequency-dependent phase changes and polarization rotations[6]. For a given CP, the theoretical tolerated differential group delay (DGD) is represented by[9]

$$\mathrm{DGD_{MAX}} \leq \tau_{\mathrm{CP}}, \tag{13}$$

where $\mathrm{DGD_{MAX}}$ is the maximum DGD (s), and τ_{CP} is the length of CP (s). Based on Eq. (13) for CP=12.5% and 25%, the tolerated DGD values in theory, are 5000 and 10000 ps, respectively (see Fig. 6).

To ensure the accuracy of the EC-based channel compensation, the amount of DGD needs to be limited. Figure 6 compares Q as a function of DGD (ps) for different CP lengths with N_{TS}=6 and OSNR=13 dB. When DGD<5000 and 10000 ps, in theory for CP=12.5% and 25%, respectively, the PMD-induced penalty can be ignored and EC is considered highly robust against fiber PMD. Otherwise, the PMD-induced penalty quickly takes off as DGD increases, exceeding those theoretical thresholds of CP. Thus, the compensation for DGD of EC is limited by the time length of CP. This indicates that the EC capacity of compensating DGD is also based on the appropriate length of the CP.

OFDM symbol phase noise from the lasers is another source of impairment for PDM-CO-OFDM systems that are usually dominated by the laser linewidth. To assess the performance in the presence of laser linewidth, Q as a function of linewidth (kHz) is shown in Fig. 7, where N_{TS}=6, and OSNR=13 dB. Linewidth induces greater Q penalty compared with zero-linewidth systems without PC. When PC is used, the impact of the error caused by the linewidth term is reduced, and Q factor is significantly increased; thus, the rising trend of Q is obvious for higher linewidth. When linewidth is smaller than 160 kHz with PC, the linewidth-induced penalty is < 1 dB.

CO-OFDM is highly susceptible to fiber nonlinearity[6]. We investigate the nonlinear tolerance (NLT) of the 100-Gb/s EC-based PDM-CO-OFDM signal compared with single polarization. To assess the NLT, a transmission link consisting of 10 optical amplified 80-km spans without ODC was used. The parameters of the link are

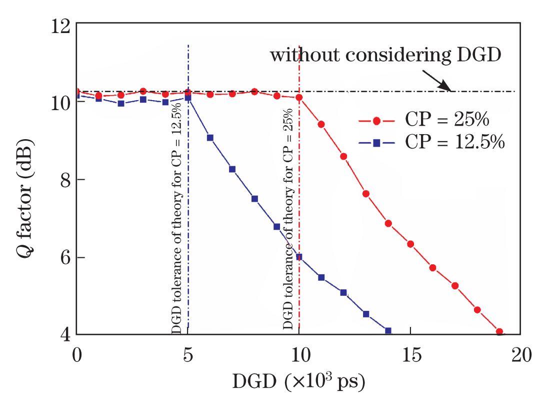

Fig. 6. Q factor versus DGD with N_{TS}=6 and OSNR=13 dB.

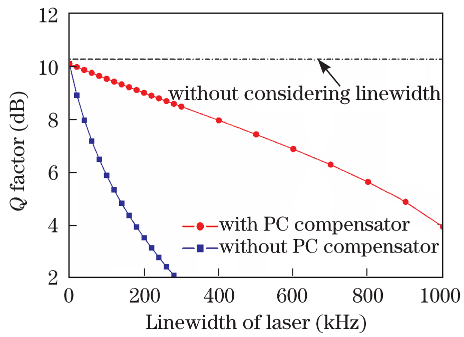

Fig. 7. Q factor versus linewidth with N_{TS}=6 and OSNR= 13 dB.

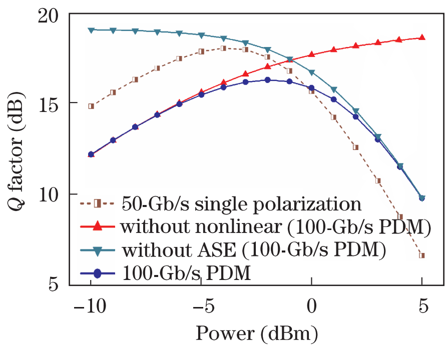

Fig. 8. Q factor versus input power into the first fiber span for different circumstances after 800 km.

shown in Table 2. The fiber nonlinear coefficient was 1.3 $\mathrm{W^{-1} \cdot km^{-1}}$, ASE noise was added at each optical amplifier with NF=6 dB, and the laser linewidth was set at 100 kHz.

Figure 8 shows the Q factor as a function of the input power into the first fiber span after 800 km with N_{TS}=6 and CP=25% for 50-Gb/s single polarization CO-OFDM and 100-Gb/s PDM-CO-OFDM in different circumstances: non considering ASE, non considering fiber nonlinearity, and both included. The 2-dB drop in Q of the 100-Gb/s PDM-CO-OFDM systems compared with the 50-Gb/s single polarization system at lower powers (about < -2 dBm) suggests that the ASE becomes the limiting factor in transmission link. When a high input power is used (about >0 dBm), fiber nonlinearity plays a decisive role. On the contrary, PDM systems performance is better than single polarization, and the improvement of Q is more than 1 dB. This is reasonable since PDM leads to low power per polarization part that helps to suppress the nonlinear impairment.

Figure 9 shows the constellations before and after EC in the receiver after 800 km with the input power into the first fiber span equal to -2 dBm. After EDC in Fig. 9(b), the rotation due to CD is compensated by EDC. Once the PMD and channel impairments are compensated by LSCEC in Fig. 9(c), the constellations then form four scattered points. Finally, the phase noise due to the laser linewidth of 100 kHz is compensated by PC.

In conclusion, we present a study on the effect of EC in the receiver for 100-Gb/s PDM-CO-OFDM transmission systems, in which EC is used to compensate for CD, PMD, and phase noise. EC can well compensate for

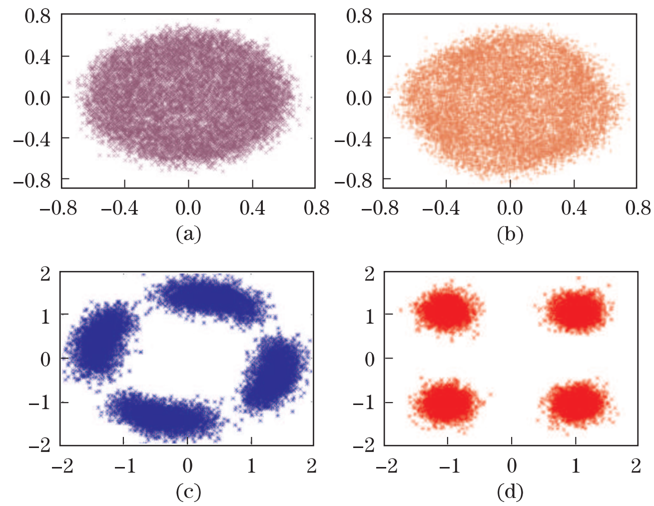

Fig. 9. Constellations for the compensator in receiver after 800 km with input power in the first span equal to -2 dBm (a) before EC; (b) after EDC in EC; (c) after LSCEC in EC; (d) after PC in EC.

these impairments and is highly robust against transmission impairments.

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