Mth-power-law method to compensate laser linewidth of 100 Gb/s PDM-CO-OFDM systems

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Laser linewidth is the important determinant of applying coherent optical orthogonal frequency division multiplexing (CO-OFDM) in optical transmission systems. The laser linewidth impairments in 100-Gb/s polarization division multiplexing CO-OFDM (PDM-CO-OFDM) system without optical dispersion compensation are compensated by the phase drift compensator (PDC) based on Mth-power-law method located at the receiver. PDC is more effective to compensate the phase drift due to laser linewidth. Simulating results show that the maximum Q factor can be increased by almost >10.0 dB for back-to-back (BtoB). For the 100-kHz linewidth system of 800-km system, a benefit of about 4.9 dB is possible for the maximum Q factor.

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Orthogonal frequency division multiplexing (OFDM) is a multicarrier transmission technique where a data stream is carried with many lower-rate subcarrier tones. Coherent optical OFDM (CO-OFDM) brings to optical communication, which is the combination of two powerful techniques, coherent optical detection and OFDM technique[1]. Together with digital coherent detection, CO-OFDM brings similar benefits such as high spectral efficiency and high receiver sensitivity as coherent transmission[2]. Polarization division multiplexing (PDM) is a very effective method for doubling spectrum efficiency of a transmission system. However, it has been shown that direct-detected PDM has a reduced tolerance to polarization mode dispersion (PMD), because the polarization demultiplexing introduces cross talk between the polarization tributaries[3]. An elegant way to overcome this PMD sensitivity is by using polarization diverse coherent detection with digital equalization instead of direct detection[3]. PDM-CO-OFDM has enabled the demonstration of various single-carrier multiple input multiple output (MIMO) experiments with bit rates up to 111 Gb/s and a superior tolerance toward chromatic dispersion and PMD[4]. In contrast to the conventional design, the CO-OFDM systems do not use any dispersion compensation fiber[5], therefore 100-Gb/s PDM-CO-OFDM without optical dispersion compensation is simulated on a long-haul transmission link in this letter.

Because coherent detection is employed in PDM-CO-OFDM, it is important to investigate the optical phase noise impact due to laser linewidth on system performance and explore the optimal approach to estimate phase evolution of OFDM signals[6]. In contrast to conventional single carrier optical transmission systems, OFDM systems transmit a data stream over a number of lower rate subcarriers simultaneously. This opens an opportunity to employ advanced phase estimation techniques. Recently some studies, such as Mth-power-law method, have been done on laser linewidth phase estimation and compensation at the receiver of 8 [6] and 10-Gb/s CO-OFDM[7].

In this letter, we conduct simulation analysis on the phase drift compensator (PDC) based on Mth-power-law method at the receiver to compensate for phase impairments originated from laser linewidth on 100-Gb/s PMD-CO-OFDM systems. We systematically study PDC against laser linewidth and the simulation results how that the PDC is very effective to compensate those phase drift in 100-Gb/s systems.

Phase noise upon optical OFDM signal reception after fast Fourier transform (FFT) consists of two components: a random noise term that can be modeled as additive Gaussian noise with zero-mean, and a common deterministic term originated from laser phase drift that affects all the subcarriers uniformly[6]. The thrust of phase compensator for laser linewidth is to extract laser phase drift from noisy received signals. Since the OFDM symbol used has tens of nano second and the laser sources both have generally about 100-kHz linewidth, which is close to the value achieved with commercially available external-cavity semiconductor lasers[5], the phase drift due to linewidth within one OFDM symbol can be considered as constant and common to all the subcarriers[6].

The channel model for the kth subcarrier in the ith symbol in PDM-CO-OFDM systems is given by[8]

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

where $\vec{\mathbf{t}}_{ik} = (t^x_{ik} t^y_{ik})^t$ and $\vec{\mathbf{t}}'_{ik} = (r'^x_{ik}\ r'^{\,y}_{ik})^t$ are the transmitted and received information symbol in the form of the Jones vector for the kth subcarrier in the ith OFDM symbol, $\vec{\mathbf{n}}_k(n^x_{ik} n^y_{ik})^t$ is the noise including two polarization components. H_k is the 2×2Jones matrix for the fiber link representing linear channel effects, $\phi_D(f_k)$ is the phase dispersion owing to the fiber CD. ϕ_k is the OFDM symbol phase noise expressed as

$$\phi_\mathrm{k} = \phi_\mathrm{G} + \phi_\mathrm{D}, \tag{2}$$

where ϕ_G is the additive Gaussian noise with zero-mean, different for each subcarrier, ϕ_D a common deterministic phase drift originated from laser linewidth, same for each subcarrier in one symbol.

To compensate phase drift due to laser linewidth in the PDM-CO-OFDM systems without optical dispersion compensation, PDC based on the Mth-power-law method is located after electrical dispersion compensation (EDC) and least squares channel estimation and compensation (LSCEC) in receiver, which are used to estimate $\phi_D(f_k)$, H_k, respectively. The location of compensator is shown in Fig. 1. PDC is shown as[7]

$$\phi'_D = \frac{1}{N_S}\sum_{k=1}^{N_S}\{0.25 \cdot \bmod\ (4 \cdot \arg(r'^{x}_{mk}), 2\pi)\}, \quad (3)$$

where $\arg(\cdot)$ is the phase angle of the information symbol, $\bmod(\cdot)$ is remainder after division, r'^{x}_{mk} is the received data, N_S is the number of subcarriers in one OFDM symbol.

The Mth-power-law method is firstly used to remove the data modulation and the residual phase angle consists of phase drift and Gaussian phase noise. After averaging across all the subcarriers in one OFDM symbol to remove the additive Gaussian noise with zero-mean, the phase drift due to laser linewidth is estimated. The advantage of PDC is apparent in Eq. (3), namely, it does not need the pilot subcarriers.

The performance of 100-Gb/s PDM-CO-OFDM is simulated on a long-haul transmission link, and the basic schematic of systems setup is shown in Fig. 1. A generic PDM-CO-OFDM system consists of an OFDM polarization-diversity transmitter, an optical link, and an OFDM polarization-diversity receiver, in which the capacity is double compared with non-PDM systems and polarization tracking does not need at the receiver. In the transmitter, the OFDM signal bandwidth is 50 GHz, which is split up into 2 048 subchannels, of which center 1 024 carry data together with 16 pilot subcarriers. Quadrature phase shift keying (QPSK) modulation is used for symbol mapping. The digital time domain signal is obtained by using inverse (IFFT), which is subsequently inserted with the cycle prefix (CP) length of 256 per OFDM symbol. As a result, the OFDM symbol length is 2 304. Then, training symbols (TS's) are inserted into OFDM symbol sequences for channel estimation. Having been converted into real time waveform through digital-to-analog converter (DAC), the two OFDM baseband signal parts are upconverted to single-polarization optical frequency separately by applying the real and imaginary parts of OFDM signal to an optical I/Q modulation, where two Mach–Zehnder optical modulators are biased at null point, the optimal bias for optical field modulation[9]. Then, the two polarization branches are subsequently combined by polarization beam combiner (PBC), one on each polarization. Table 1 depicts the basic parameters of the 100-Gb/s PDM-CO-OFDM system.

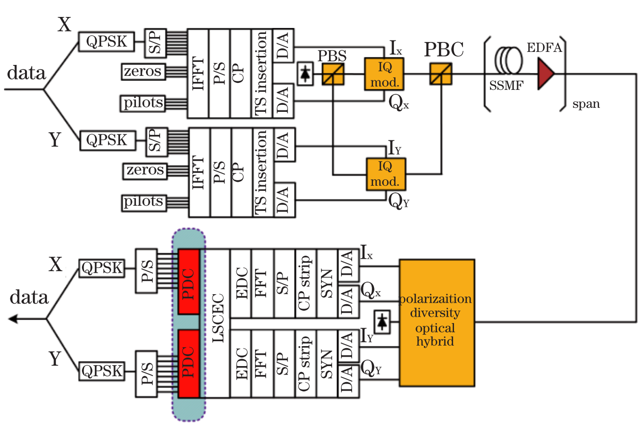

Fig. 1. Simulated setup of 100-Gb/s PDM-CO-OFDM system with PDC.

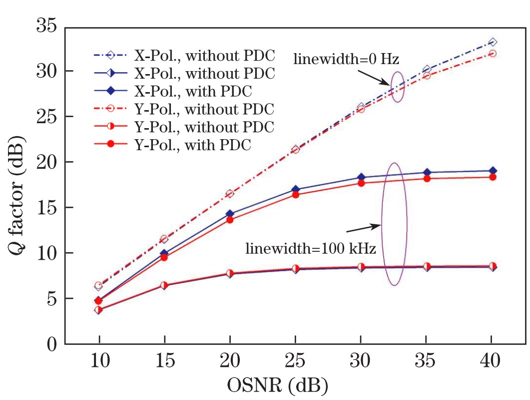

Fig. 2. Q factor versus OSNR for X-Pol. and Y-Pol. in BtoB.

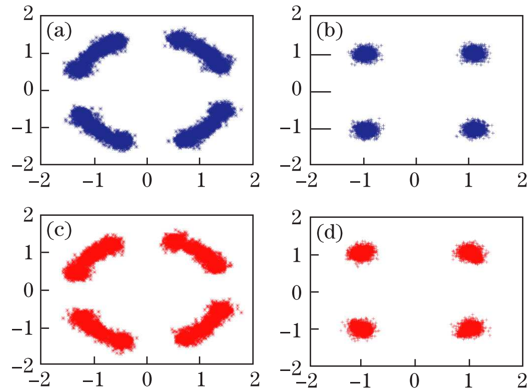

Fig. 3. BtoB Constellations in receiver with OSNR equal 40 dB and linewidth is 100 KHz. (a) X-Pol. before PDC; (b) X-Pol. after PDC; (c) Y-Pol. before PDC; (d) Y-Pol. after PDC.

The optical link consists of some 80-km standard single mode fiber (SSMF) spans without inline dispersion compensation are shown in Fig. 1. Erbium-doped fiber amplifier (EDFA) is used to compensate the fiber loss as well as to control the SSMF input power. Amplified spontaneous emission (ASE) noise is added at each EDFA, with a noise figure (NF) of 6 dB. The parameters of link are shown in Table 2.

At the receiver, the optical signal is firstly fed into the polarization diversity coherent receiver. Coherence direct down-detection[9] of each branch including two pairs of balanced photodetectors, an optical hybrid and a local oscillator laser is used. The electrical signal is sampled using an analog-to-digital converter (ADC). Symbol synchronization[6] is then performed, and the

Table 1. System Parameters

Date Rate (Gb/s)	Modulation Format	Number of FFT/IFFT	Number of Pilot Subecarriers
100	QPSK	2 048	16
Number of Data Subcarriers	Number of Zero Padding	CP Number	OFDM Symbol Size
1 024	1 008	256	2 304

Table 2. Transmission Link Parameters

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

EDC, LSCEC[3], and proposed PDC after FFT using training symbols and pilot subcarriers are needed to compensate the channel.

The constellation of received data shows four clusters of data points corresponding to four QPSK information symbols and the sources of the noise spreading each information symbol are mainly the phase noise of lasers, the nonlinearity of optical fibers and the amplified-spontaneous-noise (ASE) in the transmission system[5]. The bit error ratio (BER) derived from the symbol variance since the optical OFDM nonlinear distortion are approximately Gaussian distributed[10]. So, the electrical signal quality is measured from the constellation q and can be defined as $q = \mu_y/\sigma_y$[11] and $Q = 10\log_{10}(q^2)$, averaged over all subcarriers. The BER can be estimated by using $\text{BER} = 1/2\text{erfc}(q/\sqrt{2})$. In order to ensure the correctness of Q factor, 64 OFDM symbols are simulated equivalent to 262144 ($64 \times 2 \times 2 \times 1\,024$) bits[12,13].

Figure 2 depicts the back-to-back (BtoB) Q factor as a function of optical signal-to-noise ratio (OSNR) with and without PDC for 100-Gb/s PDM-CO-OFDM with different laser linewidths: 0 Hz, 100 Hz. First, the performances of x-polarization and y-polarization parts are almost same, whether or not with PDC. We can also see that 100-kHz linewidth induces greater Q penalty compared with zero-linewidth systems at higher OSNR. The greater OSNR is, the greater Q penalty due to linewidth is. As PDC is used when linewidth is 100 kHz, the impact of the error caused by the linewidth term is reduced and Q factor is increased, and the rising trend of Q is obvious for high OSNR. For OSNR $>$ 25 dB, the improvement of Q factor is $>$ 10 dB.

Figure 3 shows the X-Pol. and Y-Pol. constellation before and after PDC in receiver for BtoB with linewidth of 100 kHz and OSNR equal to 40 dB. Before the compensator, each constellation point is rotated around the origin due to phase drift of laser linewidth. The phase drift is correct by PDC, giving the distinct symbols with the constellation, and the constellation reduces to four points.

To assess the performance of the PDM-CO-OFDM system in the presence of laser linewidth, the Q factor as a function of linewidth (kHz) is shown in Fig. 4, where OSNR is 20 dB. PDC offers significant benefits to systems. Compared to zero-linewidth system, the Q penalties are 2.4 dB with PDC and 8.9 dB without PDC as linewidth is 100 kHz and this improvement of Q is 6.5 dB by PDC, noting that 100 kHz of linewidth is close to the value achieved with commercially available external cavity semiconductor lasers. When linewidth is higher, the impairments are larger beyond the scope can be compensated and PDC is more ineffective to compensate the phase drift. When linewidth is greater than 250 kHz, the linewidth-induced penalty cannot be compensated with PDC.

The performance of 100-Gb/s PDM-CO-OFDM with PDC is simulated on a long-haul transmission link. To assess the nonlinear tolerance (NLT), a transmission link consisting of 10 optical amplified 80-km spans without optical dispersion compensation is used, and the parameters of link are show in Table 2. The fiber nonlinear coefficient is 1.3 W^{-1}·km^{-1}, ASE noise is added at each optical amplifier with NF=6 dB. Figure 5 show the Q factor as a function of the input power into the first fiber span in different circumstances: zero-linewidth, linewidth=100 kHz with and without PDC. For any input

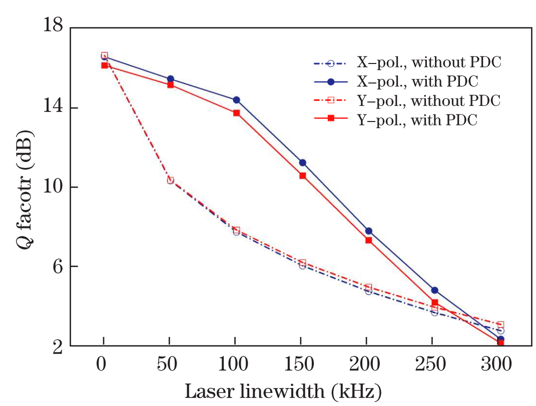

Fig. 4. BtoB Q factor versus linewidth (kHz) with and without PDC and OSNR=20 dB.

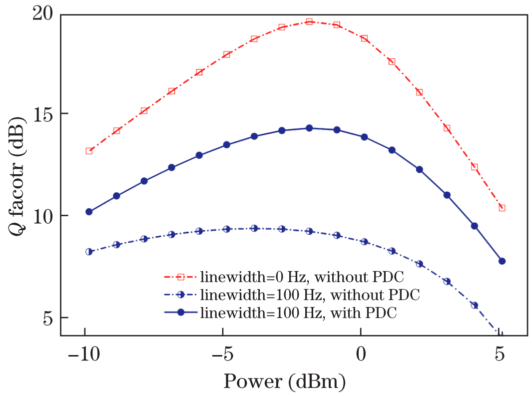

Fig. 5. Q factor versus input power into the first fiber span after 800 km.

power, the drop in Q of the 100-kHz linewidth uncompensated system is very significant compared with the zero-linewidth system suggests that the laser linewidth becomes the limiting factor in coherent transmission link. PDC offers significant benefits to long-haul 100-Gb/s PDM-CO-OFDM. When PDC is used, systems performance is greater increased, and the improvements of the maximum Q factor is about 4.9 dB from 9.4 to 14.3 dB.

In conclusion, we present the study on the effect of the PDC based on Mth-power-law method for 100-Gb/s PDM-CO-OFDM without inline dispersion compensation transmission systems, in which PDC is located in the receiver and used to compensate phase impairments due to laser linewidth. After study on the theory of PDC compensating phase drift, the simulation is implemented to study the effect of PDC. When PDC is used, system performance is improved significantly and the improvement of maximum Q factor is about 4.9 dB for 800 km system with 100-kHz linewidth.

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