# Joint nonlinearity and chromatic dispersion pre-compensation for coherent optical orthogonal frequency-division multiplexing systems*

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(Received 17 February 2011; revised manuscript received 16 June 2011)

This paper introduces a joint nonlinearity and chromatic dispersion pre-compensation method for coherent optical orthogonal frequency-division multiplexing systems. The research results show that this method can reduce the walk-off effect and can therefore equalize the nonlinear impairments effectively. Compared with the only other existing nonlinearity pre-compensation method, the joint nonlinearity and chromatic dispersion pre-compensation method is not only suitable for low-dispersion optical orthogonal frequency-division multiplexing system, but also effective for high-dispersion optical orthogonal frequency-division multiplexing transmission system with higher input power but without optical dispersion compensation. The suggested solution does not increase computation complexity compared with only nonlinearity pre-compensation method. For 40 Gbit/s coherent optical orthogonal frequency-division multiplexing 20×80 km standard single-mode fibre system, the suggested method can improve the nonlinear threshold (for $Q > 10$ dB) about 2.7, 1.2 and 1.0 dB, and the maximum $Q$ factor about 1.2, 0.4 and 0.3 dB, for 2, 8 and 16 ps/(nm·km) dispersion coefficients.

**Keywords:** fibre optics, nonlinearity, chromatic dispersion, coherent optical orthogonal frequency-division multiplexing

**PACS:** 42.65.Hw, 42.79.Sz **DOI:** 10.1088/1674-1056/20/11/114212

## 1. Introduction

Coherent optical orthogonal frequency-division multiplexing (CO-OFDM) has attracted interest for long-haul and high-speed transmission, due to its ability to overcome transmission impairments such as chromatic dispersion (CD) and polarization mode dispersion (PMD).[1,2] fibre nonlinear effect is a serious problem necessary to consider for the modern optical communication systems,[3−5] and it is more serious for CO-OFDM because orthogonal frequency-division multiplexing (OFDM) exhibits a higher peak to average power ratio (PAPR) at the transmitter than single-carrier formats like quadrature phase shift keying (QPSK).[6−8] Recently, electrical nonlinearity compensation for optical OFDM systems has been proposed, but the method is more suitable for optical OFDM systems with optical dispersion compensation or systems using low-dispersion fibre (6 ps/(nm·km) or 2 ps/(nm·km)) without optical dispersion compensation.[2,9−12] That is, this nonlinearity compensation method decreases the advantages that optical OFDM system can use electrical channel estimation to substitute for optical dispersion compensation, or only limited to a low-dispersion fibre system.

In this paper, we show a joint nonlinearity and chromatic dispersion pre-compensation (JNLCDC) method for CO-OFDM systems. Compared with the existing nonlinearity pre-compensation solution in Ref. [9] with the same simulation parameters, the JNLCDC method can reduce walk-off effect, hence can equalize the nonlinear impairments effectively. The simulation in this paper is carried out by means of the commercial software VPItranmissionMaker 7.6, and 40 Gbit/s CO-OFDM 20×80 km standard single-mode fibre (SSMF) simulation system is constructed. The simulation results show that the JNLCDC method can avoid using optical dispersion compensation in CO-OFDM systems even for high-dispersion fibre systems with higher input power and the 2-step JNLCDC solution does not increase more computation

*Project supported by the National High Technology Research and Development Program of China (Grant No. 2009AA01A345), the National Basic Research Program of China (Grant No. 2011CB302702), and the National Natural Science Foundation of China (Grant No. 60932004).

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complexity compared with the existing nonlinearity pre-compensation method.

## 2. Principle of JNLCDC method

Optical OFDM systems are sensitive to nonlinearity because they use very closely-packed channel (tens of MHz).[10] The nonlinear effect can be per-compensated in time-domain by adding a compensation phase $\varphi_{\rm comp}(t)$[9] that is proportional to the signal optical power $P(t)$ according to $\varphi_{\rm comp}(t) = -\gamma P(t) N L_{\rm eff}$,[11] where $\gamma$ is the fibre nonlinear coefficient, $N$ is the number of fibre spans, $L_{\rm eff}$ is an effective length of each fibre span for nonlinearity compensation. However, the compensation is derived assuming that there is small walk-off in the transmission system (low dispersion or dispersion is compensated), because the walk-off does reduce the effectiveness of this scheme where optical waveform evolves along the fibre.[10] This means nonlinearity of pre-compensation is only effective at the initial stages of the fibre link as it uses the transmitted power in its calculation. In the middle of the link, the phase shifts may not improve performance for the walk-off caused by CD of the fibre. Therefore, the method is only effective for low-dispersion fibre systems (6 ps/(nm·km) or 2 ps/(nm·km)) or high-dispersion fibre systems (16 ps/(nm·km)) with optical dispersion compensation in each span.

In this paper, by using the suggested JNLCDC method, the performance of optical OFDM systems can be improved evidently. In this method, the nonlinear phase compensation is divided into several parts while intermittently inserting electrical dispersion compensation at transmitter, hence the impact of the walk-off induced by dispersion is suppressed and the compensation effect of nonlinearity is enhanced. The setup of JNLCDC method is shown in Fig. 1. The location of JNLCDC is at the transmitter, as shown in Fig. 2.




**Fig. 1.** Setup of 2-step JNLCDC.

The following example explains the method of 2-step JNLCDC. The nonlinear compensation phase is separated into two parts: $\varphi_1(t)$ and $\varphi_2(t)$, and we have

$$\varphi_1(t) = -\gamma P(t) L_{\rm eff} N/2,$$
$$\varphi_2(t) = -\gamma P(t) L_{\rm eff} N/2. \quad (1)$$

In this case, the nonlinear phase and CD values of the optical OFDM system are divided into two parts, named 2-step JNLCDC scheme. Firstly, half of the nonlinear phase $\varphi_1(t)$ is compensated for the 1st half part of the optical fibre system, followed by the half value of total CD value of the system to mitigate the walk-off in this part. The 2nd part of the nonlinear phase $\varphi_2(t)$ is used to compensate for the nonlinear effect remained. The residual dispersion in the 2nd half of the optical fibre system is compensated at receiver by channel estimation.

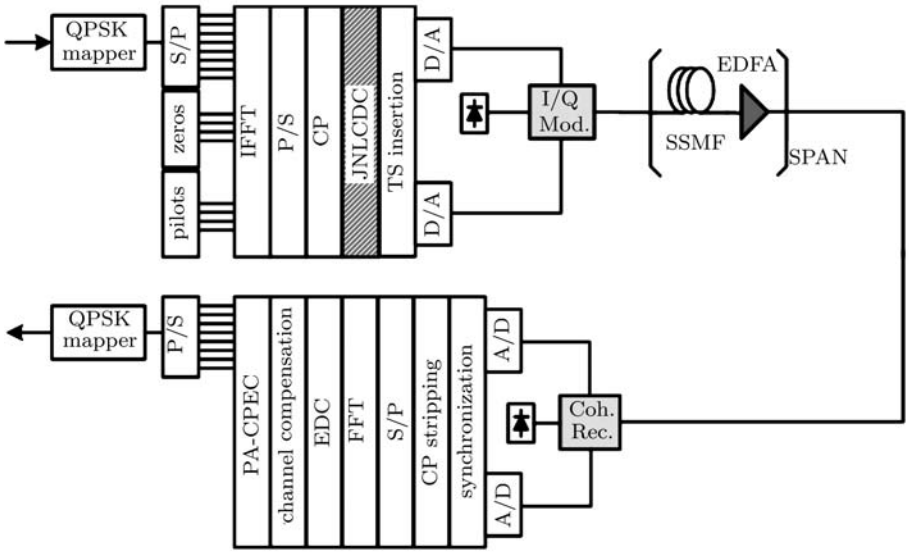



**Fig. 2.** Setup of 40 Gb/s CO-OFDM system with JNLCDC.

## 3. CO-OFDM system setup

For evaluating the performance of the suggested JNLCDC method, a 40 Gb/s CO-OFDM transmission system is constructed by commercial VPItransmissionMaker7.6 software. The setup of the system is shown in Fig. 2.

The original 40 Gb/s data is first mapped onto 1024 frequency subcarriers with QPSK modulation format, which, together with 16 pilot subcarriers, are transformed to the time domain by an inverse fast Fourier transforms (IFFT) of size 2048 with a zero padding ratio of 50%. A cyclic prefix (CP) of length 256 is used, resulting in an OFDM symbol size of 2304. By parallel to series (P/S) converting, the JNLCDC module is subsequently inserted after CP. For channel estimation, training symbols (TS) are inserted into OFDM symbol sequences. The time domain samples are serialized and converted by two digital-to-analog (D/A) converters before driving in-phase/quadrature modulator (I/Q Mod.), where two Mach–Zehnder optical modulators are biased at null point, the optimal bias for optical field modulation.[6]

The optical link comprises $20 \times 80$ km SSMF, without optical dispersion compensation and the signal is singly polarized and does not consider the PMD effect. The optical amplifiers compensate for the 16-dB fibre loss in each span and have a noise figure (NF) of 6 dB. The detail parameters of transmission link are shown in Table 1.

A coherent receiver (Coh. Rec.) is used at the receiver, composed of a local oscillator laser, an optical hybrid and two pairs of balanced photodetectors. The electrical signal is first sampled by two analog-to-digital (A/D) converters. Symbol synchronization is then performed.[13] After CP stripping and series to parallel (S/P) converting, electrical dispersion compensation (EDC),[7] channel least squares estimation (LSE)[14] and pilot-assisted common phase error compensation (PA-CPEC)[15] after fast Fourier transforms (FFT) are used.

The performance of the simulation system is indicated by bit-error ratio (BER). The BER is derived from the symbol variance since the optical OFDM nonlinear distortion is approximately Gaussian distributed.[8] Therefore, the electrical signal quality is measured from the constellation $q$ and can be defined as $q = \mu_y/\sigma_y$ and $Q = 10\lg(q^2)$, averaged over all subcarriers.[10] The BER can be estimated by using $\mathrm{BER} = (1/2)\mathrm{erfc}(q/\sqrt{2})$. In order to ensure the correctness of $Q$ factor, 64 OFDM symbols are simulated, which are equivalent to 131072 ($64 \times 2 \times 1024$) bits.

**Table 1.** Transmission link parameters.

| Attenuation $\alpha$ | Dispersion $\beta_2$ | Nonlinear index $n_2$ | Effective core area $A_{\mathrm{eff}}$ |
|---|---|---|---|
| 0.2 dB/km | 16 ps/(nm·km) | $2.6 \times 10^{-20}$ m$^2$/W | 80 μm$^2$ |
| dispersion slope $\beta_3$ | gain of EDFA | NF of EDFA | laser linewidth |
| 0.08 ps/(nm$^2$·km) | 16 dB | 6 dB | 100 kHz |

## 4. Results and discussion

Figure 3 plots the $Q$ factor versus the effective length $L_{\mathrm{eff}}$ with 2-step JNLCDC scheme for a set of the input powers in each span for $20 \times 80$ km SSMF, the link parameters is listed in Table 1. The effective length is used to tune the nonlinear compensation. It is clear that for each input power the $Q$ factor improves significantly as compared with nonzero effective lengths. In the linear regime (low fibre launch powers $< -2$ dBm), where the amplifier noise becomes the limiting factor in transmission link, the system performance is similar for every effective lengths. However, in the high input power, the system is limited by fibre nonlinear impairments, so the JNLCDC method is more effective to compensate the nonlinearity and a steep increase in $Q$ factor is observed. The increase in $Q$ factor is $> 3$ dB with the input power of 5 dBm.

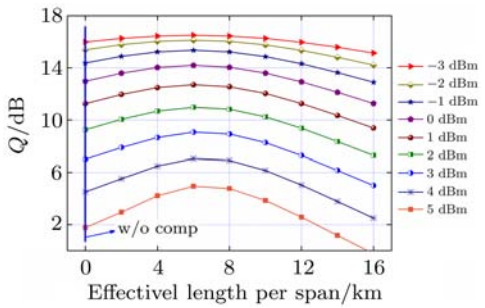



**Fig. 3.** (colour online) $Q$ factor versus effective length per span for a range of powers for $20 \times 80$ km 16 ps/(nm·km) SSMF.

In comparison of the advantages of the JNLCDC method, the systems to be compared include 1) the system without any nonlinearity and dispersion pre-compensation (labeled: w/o any pre-comp); 2) the system only with nonlinearity pre-compensation like that in Ref. [9] (labeled: w/NL pre-comp); 3) the sys-

tem with 2-step JNLCDC (labeled: w/2-step JNLCDC). Simulation parameters are the same in all simulation cases. Figure 4 shows the $Q$ factor as a function of the input power in a $20\times80$ km 16 ps/(nm·km) SSMF system, where JNLCDC and NL pre-comp methods are conducted in the same simulation conditions and the link parameters are shown in Table 1. The compensation effect of NL pre-comp like that in Ref. [9] is not obvious as compared with that without any Pre-comp systems and the 2-step JNCDC method can improve the system performance evidently, especially in the high input power case.

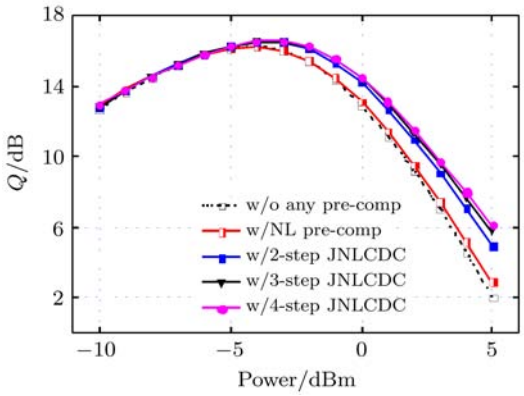



**Fig. 4.** (colour online) $Q$ factor versus input power into the first span for $20\times80$ km 16 ps/(nm·km) SSMF.

In studying the feasibility of JNLCDC method, we have compared the 2-step JNLCDC with the 3-step and 4-step JNLCDC. The idea of $n$-step JNLCDC can be deduced from 2-step JNLCDC, that is, the total nonlinear compensation phase and CD value is divided into $n$ shares equally, each part of the nonlinear phase and dispersion is pre-compensated in turn in JNLCDC module. The compensation effects are also shown in Fig. 4. With increasing step number of JNLCDC, $Q$ factor is increased, but this increase is not outstanding. Considering the complexity of hardware realization, the 2-step JNLCDC is the most cost-effect solution. The CD is a linear effect, it can be equalized easily in optical CO-OFDM systems in the electrical domain at the receiver. The JNLCDC method compensates for a part of CD at the transmitter and does not introduce much complexity compared with the NL pre-comp method.

For applying the 2-step JNLCDC method to a low dispersion fibre system, Fig. 5 shows the results for the $20\times80$ km SSMF with dispersion coefficients 2 and 8 ps/(nm·km). Without any pre-compensation, there is about 4.0 dB drop in $Q$ factor of the 2 ps/(nm·km) system compared with the 8 ps/(nm·km) fibre system at 0 dBm input power; this suggests that low dispersion fibres suffer the greatest penalty due to nonlinearity and thus allow the lowest input power. With NL pre-comp, the $Q$ factor is improved as compared with w/o any pre-compensation, but there is still 2 dB difference in $Q$ factor between the 2 ps/(nm·km) system and the 8 ps/(nm·km) fibre system at 0 dBm input power. Conversely, with 2-step JNLCDC compensation, low-dispersion fibres offer the highest improvement of $Q$ factor, while there is no obvious difference in $Q$ factor between 2 ps/(nm·km) system and 8 ps/(nm·km) fibre system for the input power less than 5 dBm. This is because the pre-compensation is more effective when the walk-off along the fibre is low.[9] The reason is that the JNLCDC method compensates part of CD at transmitter, hence the walk-off is reduced compared with the NL pre-comp scheme. The JNLCDC method also allows systems to be operated at higher powers. The nonlinear threshold (NLT), defined as the maximum power limit for the $Q$ to be $>$ 10 dB, can be increased almost 2.7 dB and 1.2 dB by 2-step JNLCDC method for the 2 and 8 ps/(nm·km) fibre systems, respectively. Correspondingly those benefits are 0.8 and 0.3 by NL pre-comp scheme.

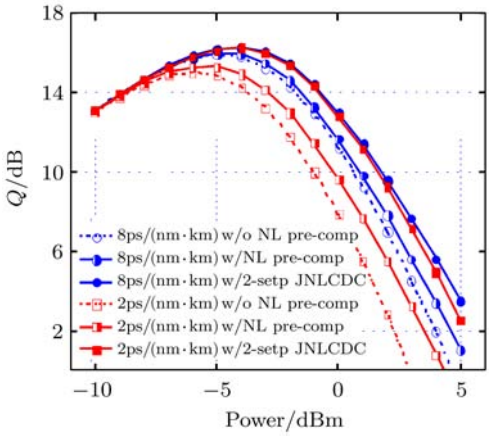



**Fig. 5.** (colour online) $Q$ factor versus input power into the first span for 8 and 2 ps/(nm·km) fibre of 1600 km link.

Figure 6 shows the constellation diagrams in receiver after $20\times80$ km 2 ps/(nm·km) SSMF transmission, the input power in each span equals 0 dBm. Figure 6(a) shows the case without any pre-compensation case, while Figs. 6(b) and 6(c) show the NL pre-comp case and the 2-step JNLCDC case respectively. We can see that the scatting range of constellation points in Fig. 6(b) is better than Fig. 6(a) and Fig. 6(c) is the best one. Figure 6 verifies that the 2-step JNL-

CDC can compensate nonlinear penalty remarkably in comparison with the other 2 approaches.

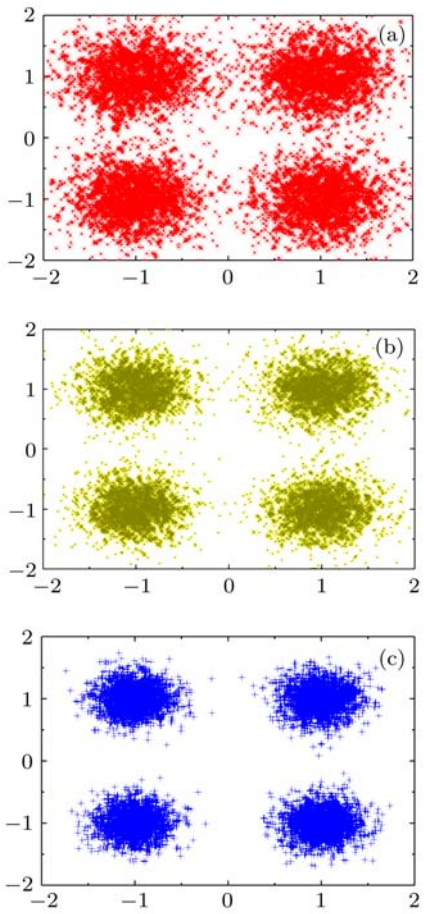



**Fig. 6.** (colour online) Constellations in receiver after 1600 km for 2 ps/(nm·km) fibre with input power in the first span equal to 0 dBm: (a) without any pre-compensation method, (b) with NL pre-comp method, (c) with 2-step JNLCDC compensation method.

## 5. Conclusions

A joint nonlinearity and chromatic dispersion pre-compensation method has been proposed for the CO-OFDM system. In this method, the nonlinear phase compensation is divided into several parts while intermittently inserting electrical dispersion compensation is given at transmitter, hence the impact of the walk-off induced by dispersion is reduced. In this way, the JNLCDC method can equalize the nonlinear impairments more effectively. Compared with the existing only nonlinearity pre-compensation method in Ref. [9], the JNLCDC method is not only suitable for low-dispersion fibre systems, but also effective for high-dispersion fibre transmission systems without optical dispersion compensation. For 40 Gbit/s 20 × 80 km SSMF systems, the JNLCDC method can improve the nonlinear threshold (for $Q > 10$ dB) about 2.7, 1.2 and 1.0 dB, and the maximum $Q$ factor about 1.2, 0.4 and 0.3 dB for 2, 8 and 16 ps/(nm·km) fibre systems, respectively. The method allows the CO-OFDM system to avoid using optical dispersion compensation even for high-dispersion fibre system with higher input power, and the 2-step JNLCDC solution does not increase more computation complexity compared with the nonlinearity pre-compensation.

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