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Fiber Nonlinearity Post-Compensation by Optical Phase Conjugation for 40 Gb/s CO-OFDM Systems *

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Fiber nonlinearity impairments in a 40-Gb/s coherent optical orthogonal frequency division multiplexing (CO-OFDM) system are post-compensated for by a new method of fiber nonlinearity post-compensation (FNPC). The FNPC located before the CO-OFDM receiver includes an optical phase conjugation (OPC) unit and a subsequent 80-km-high nonlinear fiber (HNLF) as a fiber nonlinearity compensator. The OPC unit is based on a four wave mixing effect in a semiconductor optical amplifier. The fiber nonlinearity impairments in the transmission link are post-compensated for after OPC by transmission through the HNLF with a large nonlinearity coefficient. Simulation results show that the nonlinear threshold (NLT) (for $Q > 10$ dB) can be increased by about 2.5 dB and the maximum Q factor is increased by about 1.2 dB for the single-channel 40-Gb/s CO-OFDM system with periodic dispersion maps. In the 50-GHz channel spacing wavelength-division-multiplexing system, the NLT increases by 1.1 dB, equating to a 0.7 dB improvement for the maximum Q factor.

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It is known from early studies that optical orthogonal frequency division multiplexing (OFDM) is highly susceptible to fiber nonlinearity and the optical OFDM operates optimally at channel powers less than −5 dBm at 10 Gb/s.[1] It is tempting to consider coherent optical orthogonal frequency division multiplexing (CO-OFDM) as an upgrade solution from today's 10 Gb/s to the forthcoming 100 Gb/s. Currently most installed long-haul 10 Gb/s optical fiber systems use a periodic inline dispersion map to compensate for chromatic dispersion. The nonlinear performance is poor in such installed long-haul optical systems due to the self-phase modulation (SPM) adding coherently span-on-span. Optical phase conjugation (OPC), also known as spectrum inversion (SI), was proposed by Yariv *et al.* in 1979.[2] It has been experimentally shown that OPC can compensate for chromatic dispersion, SPM, intrachannel nonlinear impairments as well as nonlinear phase noise.[3,12] However, normally OPC must be inserted into the middle position of the link and the transmission link has to be separated equally into two parts.

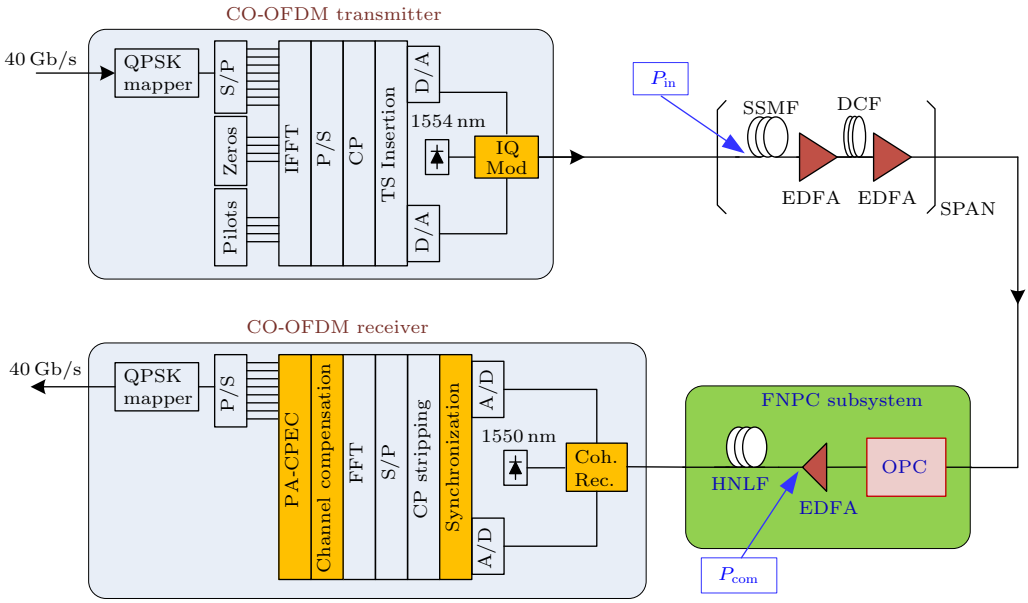


Fig. 1. Setup of the CO-OFDM with FNPC.

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In this Letter, a new method of fiber nonlinearity post-compensation (FNPC) by OPC for 40 Gb/s CO-OFDM systems with periodic dispersion maps is discussed. The FNPC including OPC and a subsequent 80-km-high nonlinear fiber (HNLF) can be located in the receiver and is shown in Fig. 1 and the transmission link does not have to be disconnected. The fiber nonlinearity impairment in transmission link is post-compensated for after OPC by transmission through the HNLF with a large nonlinearity coefficient. Semiconductor optical amplifiers (SOAs) attract more and more attention due to their nonlinear applications in recent years.[13] OPC is realized by four wave mixing (FWM) in an SOA with a locally generated laser pump and this process can operate over a greater wavelength range and achieve high conversion efficiencies and the architecture of OPC is shown in Fig. 2. The simulations show that the fiber nonlinearity impairment can be observably reduced by employing FNPC in 40-Gb/s CO-OFDM systems with periodic dispersion maps for both single-channel and 50-GHz-spacing wavelength-division-multiplexing (WDM) systems.

It can be seen from Fig. 2 that the optical data signal E_s is first combined with the amplified output of a pump laser using a coupler and fed into a 1-mm-long SOA to provide a high FWM efficiency. In order to improve the FWM efficiency, the pump power is far stronger than the signal light. Inside the SOA, the pump signal at 1552 nm and the data signal at 1554 nm generate an FWM product at 1550 nm, where the FWM product has the inverted signal spectrum from the incoming data signal. Finally, an Er-doped fiber amplifier (EDFA) and band pass filter (BPF) are used to amplify and filter the conjugate signal. The following is the OPC parameters set for the single-channel system in the simulation: the injection current of the SOA is set to 300 mA and the input optical powers into SOA are 11 and -2 dBm for the control and the data signals, respectively and the BPF is set to 1 nm.

Since the sign of the Kerr effect term is inverted after OPC, the fiber nonlinear impairment appearing in the transmission link (before OPC) can be compensated for by the impairments that occur in the HNLF (after OPC). The condition for fiber nonlinearity compensation reads[4]

$$\gamma_T \bar{P}_T L_T = \gamma_{\rm com} \bar{P}_{\rm com} L_{\rm com}, \tag{1}$$

where γ_T and $\gamma_{\rm com}$ are, respectively, the nonlinearity coefficients of the transmission link fiber and the HNLF in units of $\mathrm{W^{-1}km^{-1}}$. L_T and $L_{\rm com}$ in km are the lengths of the transmission link fiber and the HNLF, respectively and the length of the compensation HNLF, $L_{\rm com}$ is only 80 km, far shorter than L_T. $\bar{P}_T$ and $\bar{P}_{\rm com}$ in Watt are the path-averaged optical powers, where $\bar{P}_T = \frac{1}{L_T}\int_{-L_T}^{0} P_{\rm in}(z)dz$ and $\bar{P}_{\rm com} = \frac{1}{L_{\rm com}}\int_{0}^{L_{\rm com}} P_{\rm com}(z)dz$. $P_{\rm in}$ denotes the input power into the fiber span of the transmission link and $P_{\rm com}$ denotes the input power into the HNLF in Fig. 1.

To satisfy the condition (1), the Kerr effect $\gamma_T \bar{P}_T$ in the transmission link should be L_2/L_1 approximately times the HNLF length. To increase the Kerr effect in the transmission link, first an HNLF with $\gamma_1 = 7.8\,\mathrm{W^{-1}km^{-1}}$ is used,[4] which is six times larger than the transmission link fiber with $\gamma_2 = 1.3\,\mathrm{W^{-1}km^{-1}}$. Second, the input power $P_{\rm com}$ into the HNLF is increased much higher than the input power $P_{\rm in}$ into the transmission link (in Fig. 1). We can thus approximately satisfy the conditions shown in Eq. (1) with those two methods. According to the CO-OFDM systems with periodic dispersion maps in this study, FNPC is used to compensate only for the nonlinearity effect. Therefore, we have assumed that the wavelength of the zero dispersion term of the HNLF is 1554 nm, the transmitter laser wavelength. The dispersion slop of the HNLF is $0.03\,\mathrm{ps/nm^2}$ and the loss is 0.2 dB/km.

The basic schematic diagram of the 40-Gb/s CO-OFDM is shown in Fig. 1 and the parameters are the same as those in Ref. [5]. There are 2048 subcarriers (1024 for data with quadrature phase shift keying modulation) and the cycle prefix (CP) length of 256 per OFDM symbol. For channel estimation, training symbols (TSs) and 16 pilot subcarriers are inserted into OFDM symbol sequences.

The optical link consists of some 80-km standard single mode fiber (SSMF) spans, with optical dispersion compensation and the signal is singly polarized (no polarization-mode dispersion). The fiber has a loss of 0.2 dB/km, dispersion coefficient $16\,\mathrm{ps\cdot nm^{-1}\cdot km^{-1}}$, nonlinearity coefficient $1.3\,\mathrm{W^{-1}km^{-1}}$. The loss of the SSMF and the dispersion-compensated fiber (DCF) in each transmission fiber span are compensated for by Er-doped fiber amplifiers (EDFAs), where the input power of the DCF is 6 dB less than that of the SSMF. Amplified spontaneous emission noise (ASE) is added at each EDFA, with a noise figure (NF) of 6 dB.

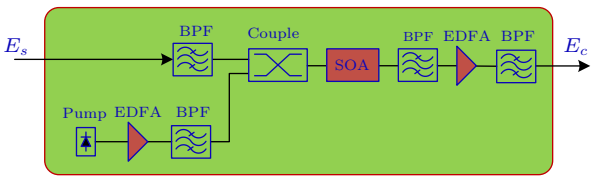


Fig. 2. Setup of the OPC in FNPC.

At the receiver, coherence direct down-detection[6] including two pairs of balanced photodetectors, an optical hybrid and a local oscillator laser are used first. After the ADC, symbol synchronization[7] is performed. The channel least-square estimation (LSE) proposed in Ref. [8] after fast Fourier transform (FFT) based on the training symbols and pilot subcarriers are used to estimate the channel transfer function. The average phase of the pilots of each OFDM symbol is finally used for pilot-assisted common phase error compensation (PA-CPEC).[9]

The linewidth is 100 kHz for both transmitter and receiver lasers. The bit error rate (BER) derived from the symbol variance since the optical OFDM nonlinear distortion are approximately Gaussian distributed.[10] Thus, 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 the subcarriers. The BER can be estimated by using BER $= \frac{1}{2}\mathrm{erfc}(q/\sqrt{2})$. In order to ensure the correctness of Q factor, 64 OFDM symbols are simulated equivalently to 131072 ($64\times2\times1024$) bits. VPIsystems' VPItransmissionMakerWDM V7.6 is used for simulations.

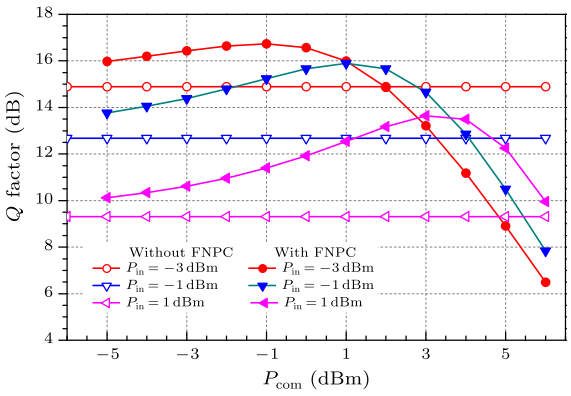


Fig. 3. Q factor vs P_{com} with FNPC for a set of P_{in} after 800 km for the single-channel system.

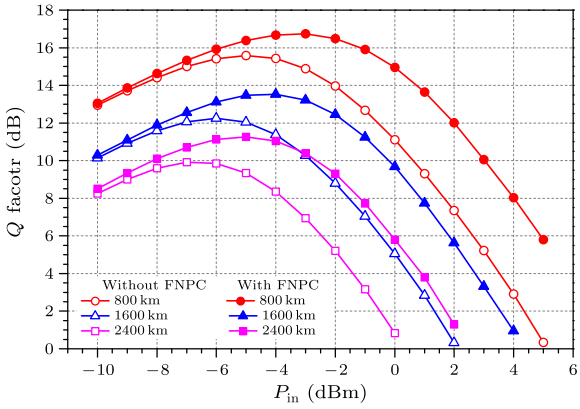


Fig. 4. Q factor vs P_{in} with and without FNPC for the single-channel system.

Figure 3 shows the Q factor as a function of the input power P_{com} into the HNLF with FNPC and without FNPC for a set of input power P_{in} into the fiber span of the 800-km transmission link for the single-channel CO-OFDM system. When P_{in} is higher, the required compensation power P_{com} is larger, then Q is greatly improved. The system is limited by fiber nonlinear impairments in the high input power, so FNPC is more effective to compensate for the nonlinearity.

For a set of transmission length in the single-channel CO-OFDM system, the Q factor as a function of transmission input power P_{in} with and without FNPC using the optimum compensated power P_{com} is shown in Fig. 4. In the linear regime (low fiber launch powers < -7 dBm), where the amplifier noise becomes the limiting factor in the transmission link, the system performance is similar whether or not with FNPC. However, for high input powers, a steep increase in the Q factor is observed with FNPC for every link length.

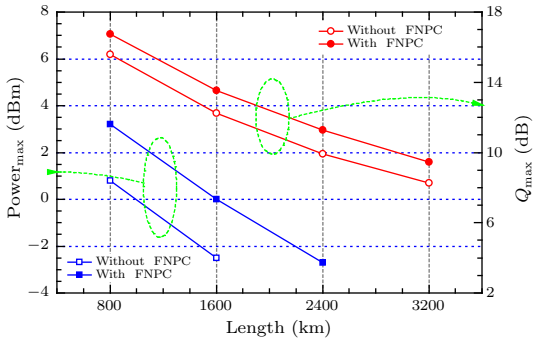


Fig. 5. Maximum Q and maximum power P_{max} for NLT vs transmission length with and without FNPC for the single-channel system.

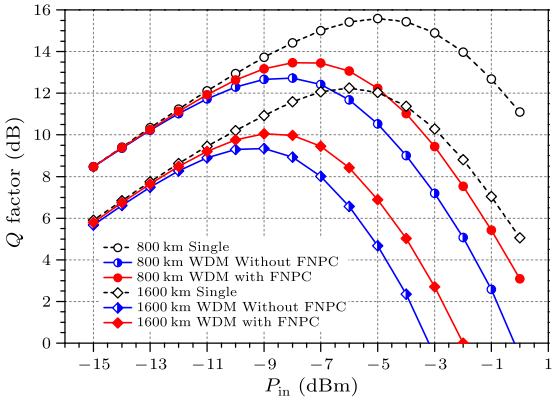


Fig. 6. Q factor vs P_{in} per channel with and without FNPC using the optimum P_{com} for WDM and single-channel systems.

The maximum Q_{max} and maximum power P_{max} versus the transmission length for the single-channel system are shown in Fig. 5. P_{max} defines the nonlinear threshold (NLT) as the maximum power limit for the Q to be larger than 10 dB. As the transmission distance increases for uncompensated systems, both Q_{max} and P_{max} decrease due to the increase of the fiber nonlinearity. Q_{max} reduces from 15.6 dB to 8.3 dB as the fiber link increases from 800 km to 3200 km and P_{max} changes from 0.8 dBm to -2.5 dBm as the length increases from 800 km to 1600 km. For each transmission length, FNPC offers significant benefits to CO-OFDM in both Q_{max} and P_{max}. An improvement of about 1.2 dB in Q_{max} is obtained for all transmission distances. FNPC also allows systems to be operated at higher powers. P_{max} of the NLT can be increased by almost 2.5 dB for those transmission lengths, since more fiber nonlinear impairments are compensated for by FNPC.

To quantify the nonlinear compensation achieved by FNPC in the WDM system, a 7-channel WDM system with 50-GHz channel spacing is simulated, each channel using 40-Gb/s CO-OFDM. The basic parameters of CO-OFDM are the same as those for single-channel. For the WDM system, the following are the parameters of OPC: the injection current of the SOA is set to 500 mA, the input optical powers into the SOA are 20 and −1 dBm for the pump and input data signals, and the BPF is set to 5 nm. For the optical spectrum, the peak at 1554 nm is the pump signal and the input signals are with the center channel at 1558 nm and the FWM product signals are with the center channel at 1550 nm.

Figure 6 shows the results for the central wavelength channel (1558 nm) of the WDM systems. It compares the Q factor as a function of the input power $P_{\rm in}$ per wavelength channel into the fiber span for WDM and single-channel systems. About 4.0 dB drop in Q of the uncompensated WDM systems compared with the uncompensated single-channel system at higher powers suggests that cross phase modulation (XPM) from neighboring channels is more significant in WDM systems. Thus XPM limits the effectiveness of FNPC. However, for WDM systems, 1.1 dB improvement of $P_{\rm max}$ is achieved, equating to a 0.7 dB improvement for $Q_{\rm max}$.

We show that FNPC can be employed to post-compensate for fiber nonlinearity impairments in CO-OFDM systems.This makes it unnecessary to disconnect the existing fiber transmission link and insert OPC into the middle. The maximum Q factor improvement of about 1.2 dB and the NLT improvement of about 2.5 dB are obtained for 40 Gb/s CO-OFDM with periodic dispersion maps when FNPC is used. In the WDM system with 50-GHz channel spacing, the performance of 40 Gb/s FNPC-aided CO-OFDM is compared with long haul transmission system without nonlinearity compensation. The results indicate that WDM fiber nonlinear impairments can also be compensated for by FNPC configuration.

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