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Phase Conjugation for Increased System Robustness

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Abstract: The transmission performance of optical phase conjugation (OPC) is assessed with a special focus on the combination with the RZ-DQPSK modulation format. We show that when OPC is employed, significant performance improvement is obtained compared to conventional DCF based transmission.

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1. Introduction

Optical phase conjugation (OPC) is an effective method to increase the signal robustness in long-haul transmission systems. OPC takes the complex conjugate from the phase response of the signal without changing the amplitude response. Several techniques have been proposed to phase conjugate an optical signal. Most of the realized OPC units are based on the following processes: four-wave mixing (FWM) in highly nonlinear fibers (HNLF), FWM in a semiconductor optical amplifier (SOA) or parametric difference frequency generation (DFG) in a periodically-poled lithium-niobate (PPLN) waveguide. Most recent OPC based transmission experiments have been conducted using a PPLN waveguide for phase conjugation. Advantages of a PPLN waveguide for OPC are that negligible noise is added to the phase conjugated signal and that it allows for high conversion efficiencies [1]. As well, since the PPLN waveguide is instantaneous and phase sensitive in its response, the OPC through a PPLN waveguide is transparent to data rate and modulation format [2] and no third order nonlinear impairments such as SPM and cross-phase modulation (XPM) occur in the phase conjugation process.

By placing a phase conjugator in the middle of a transmission link, OPC regenerates the signal indirectly: deterministic phase impairments that occurred in the first part of the transmission link (before conjugation) are cancelled by impairments that occur in the second part of the link (after conjugation). Initially, OPC was proposed to compensate for chromatic dispersion [3]. In this configuration the inline dispersion compensating fibers (DCFs) are omitted, which saves the extra loss through DCFs potentially resulting in a higher optical signal-to-noise ratio (OSNR) after transmission. As well, as can be seen in Fig. 1, a simplified design of the inline dispersion map and inline amplifiers is realized through mid-link OPC. Since the dispersion accumulates linearly along the transmission line, the phase conjugator needs to be placed in the middle of the link to obtain full dispersion compensation. Therefore OPC for chromatic dispersion compensation is typically called “mid-link OPC”. It has been shown however that when the residual dispersion is compensated for, deviations from the middle of the transmission line give negligible penalty [4].

Apart from the compensation for chromatic dispersion, OPC can be employed to compensate for deterministic nonlinear impairments resulting from the Kerr effect. The compensation of self phase modulation (SPM) induced impairments has extensively been studied [5, 6]. At high data-rates, for example 40 Gbit/s and more, transmission is mostly in the pseudo-linear regime, where intra-channel nonlinear impairments dominate the transmission penalty for state-of-the-art systems [7]. Several experiments have been reported showing that intra-channel nonlinear impairments can be compensated for by using OPC [8-10], significantly extending transmission reach. Recently, it has been shown that OPC can compensate as well for impairments resulting from nonlinear phase noise [11, 12]. Nonlinear phase noise can severely impair the performance of phase shift keyed transmission systems [13]. Hence, the application of OPC can relax link design. Simultaneous compensation of nonlinear effects and chromatic dispersion can be realized with a single OPC unit and has been shown in [8, 14].

Next generation transmission systems will likely employ advanced modulation formats. A modulation format that recently received a lot of interest is return-to-zero differential quadrature phase-shift-keying (RZ-DQPSK). RZ-DQPSK has a favorable spectral width making it robust against narrow band filtering. Furthermore it has a higher polarization mode dispersion (PMD) and chromatic dispersion tolerance at the same effective data rate as binary modulation, possibly easing deployment of 40-Gbit/s transmission over legacy fiber [15, 16]. Therefore we believe that especially for 40-Gbit/s transmission, the RZ-DQPSK modulation format offers significant advantages in providing a robust solution for high-capacity long-haul transport. A concern however with RZ-DQPSK is possible impairments by SPM induced nonlinear impairments, such as nonlinear phase noise. Since OPC can compensate for SPM induced nonlinear impairments, we investigated the combination of OPC with RZ-DQPSK. In this paper, we compare the performance of an OPC based system with the performance of a 'conventional' DCF based transmission line for 21.4-Gbit/s and 42.8-Gbit/s RZ-DQPSK.

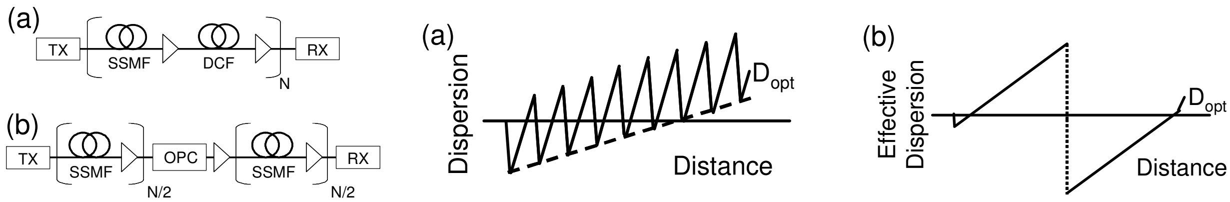

Fig. 1: Experimental setup and effective dispersion map for (a) a conventional DCF aided and (b) an OPC aided transmission system.

2. Comparison DCF and OPC for 21.4-Gbit/s RZ-DQPSK

In order to enable long-haul transmission experiments, a re-entrant re-circulating loop is employed as described in [17]. The performance of OPC is compared to the performance of DCF for chromatic dispersion compensation, transmitting 22 channels modulated with 21.4-Gbit/s RZ-DQPSK. The channel spacing in these experiments is 50 GHz and the pulse width is 50%. The re-circulating loop consists of three 94.5-km spans of standard single mode fiber (SSMF). The loss of the SSMF spans is compensated for by using a hybrid Raman/EDFA structure for signal amplification. The input powers are -2.9 dBm/channel and -4 dBm/channel for the OPC and the DCF based configuration, respectively. The optimization of the DCF based transmission system is further described in [18]. A loop-synchronous polarization scrambler (LSPS) is used to reduce the statistical correlation of loop-induced polarization effects. In the OPC based transmission system, the signals are optically phase conjugated in the middle of the transmission link by a PPLN subsystem. The realization of the PPLN subsystem is discussed in detail in [17]. After transmission, the post compensation is optimized on a per channel basis. In these DQPSK based transmission experiments no pre-coding is used, hence the bit error rate (BER) test set is programmed for the expected output sequence.

The maximum feasible transmission distance for the DCF based configuration is restricted to 7,200 km. For the OPC based configuration, a record transmission of 10,200 km is obtained with an average Q for all 22 WDM channels higher than the forward error correction (FEC) threshold, assuming a 7% redundancy code for which a Q of 9dB correspond to error-free transmission after FEC (BER after FEC<10^{-12}) [19]. The Q-factor of a typical channel as a function of the transmission distance is plotted for the OPC and the DCF based configuration in Fig. 2f. At shorter distances, the Q-factor of the OPC based configuration is about 0.5 dB higher than that of the DCF based transmission system. After 5,000-km transmission, the Q-factor of the DCF based configuration deviates from the linear decrease whereas the OPC based performance is virtually unaffected despite the higher launch power into the SSMF. We conjecture that the performance degradation of the DCF aided transmission results from SPM induced nonlinear impairments, including nonlinear phase noise.

3. Comparison DCF and OPC for 42.8-Gbit/s RZ-DQPSK

Employing the same transmission line as described in the 21.4-Gbit/s RZ-DQPSK transmission experiment, the performance is assessed for 42.8-Gbit/s RZ-DQPSK with and without OPC [14]. The 40-Gbit/s line rate is especially interesting since it is part of the SDH/SONET hierarchy. The input powers are set to -3 dBm/channel and -3.5 dBm/channel for the OPC and the DCF based configuration, respectively. The back-to-back performance of the 21.4-Gbit/s RZ-DQPSK and the 42.8-Gbit/s RZ-DQPSK is depicted in Fig. 2e. At low Q values a 3dB difference in OSNR is present between the 21.4-Gbit/s and 42.8-Gbit RZ-DQPSK curves, which is to be expected due to the difference in data rate. For high Q values, the OSNR difference between the modulation-formats increases to 6dB. The cause of the increase in OSNR difference at high Q is a result of modulator imperfections that are more severe for 42.8-Gbit/s RZ-DQPSK and the 0.2-nm narrowband optical filter that is used before the receiver. The impact of the narrowband filter on 42.8-Gbit/s RZ-DQPSK can be seen in the back-to-back eye diagrams with (Fig. 2a) and without (Fig. 2b) narrowband filtering.

The feasible transmission distance for a Q-factor ~10 dB is limited to approximately 5,000 km and 3,000 km for the OPC and the DCF based configuration, respectively. Fig. 2c depicts the phase eye diagram and Fig. 2d the amplitude eye diagram, of the 42.8-Gbit/s RZ-DQPSK signal after 4,500-km transmission with OPC. The performance as a function of transmission distance for a typical channel of the OPC and the DCF based configuration is depicted in Fig. 2g. At low transmission distances, the performance difference is about 1dB in Q-factor. Similar to the experiments at 21.4 Gbit/s, after 2,500-km transmission, the Q-factor of the DCF based configuration deviates from the linear decrease whereas the OPC based performance is virtually unaffected. As can be seen in the back-to-back eye diagram (Fig. 2a), an extra penalty arises in this experiment due to imperfections of the parallel RZ-DQPSK modulator (e.g. a broad '1' rail for RZ-DQPSK signal), resulting in additional nonlinear phase noise impairments after transmission. In the OPC aided transmission experiment the SPM induced nonlinear impairments resulting from both modulator imperfections and transmission line are reduced through mid-link OPC [11], resulting in an increased transmission reach. Comparing for the OPC based transmission, the performance of the 42.8-Gbit/s RZ-DQPSK modulation format (Fig. 2g) to the performance of 21.4-Gbit/s RZ-DQPSK modulation format (Fig. 2f), it can be seen that doubling the data rate and spectral efficiency results in a decrease in feasible transmission distance by about a factor of two. For the DCF based transmission a larger performance decrease is measured.

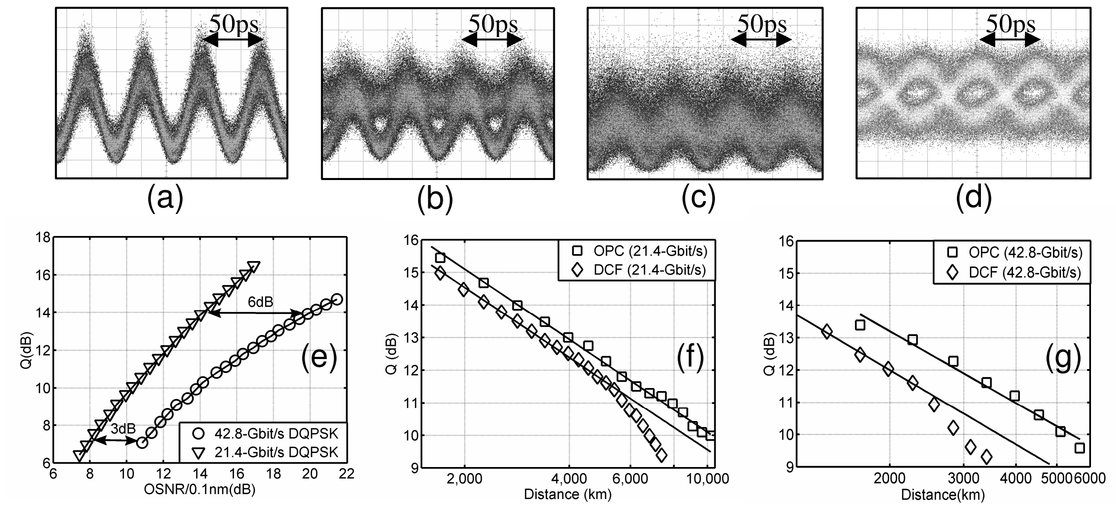

Fig. 2: 42.8-Gbit/s RZ-DQPSK phase eye diagrams (a) back-to-back single channel, (b) back-to-back /w narrowband filtering, (c) phase eye diagram after 4,500km transmission with OPC /w narrowband filtering, (d) intensity eye diagram after 4,500km transmission with OPC /w narrowband filtering, (e) Back-to-back sensitivity for 21.4-Gbit/s and 42.8-Gbit/s RZ-DQPSK, (f) Q as function of transmission distance /w and /wo OPC for 21.4-Gbit/s RZ-DQPSK, (g) Q as function of transmission distance /w and /wo OPC for 42.8-Gbit/s RZ-DQPSK.

4. Outlook

Considering the advantages of OPC for transmission applications we see significant potential when combined with high data rate transmission. Transmission systems operating at a 10-Gbit/s line rate have been greatly optimized in recent years and further development foremost focuses on providing low-cost robust solutions. From the results obtained for 40-Gbit/s RZ-DQPSK, we see that the transmission performance of 40-Gbit/s RZ-DQPSK using OPC provides an excellent robustness against SPM induced nonlinear impairments and hence could be a robust solution for future long-haul transport systems.

5. Conclusions

Optical phase conjugation can be employed to increase the signal robustness in long-haul transmission systems. For 21.4-Gbit/s and 42.8-Gbit/s RZ-DQPSK modulation we compared the performance of a DCF and OPC aided system over a long haul transmission distance and show that at both data rates a significant improvement in feasible transmission distance is obtained by using OPC.

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