Experimental Comparison of Fiber Nonlinearity Mitigation: Intra-modal FWM versus Inter-modal FWM

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Abstract: We experimentally compare fiber nonlinearity mitigation by optical phase conjugation based on either intra- or inter-modal four-wave mixing. When adjusted for same conversion efficiency, both realizations achieve similar performance in 800-km dispersion-managed single-mode fiber link.

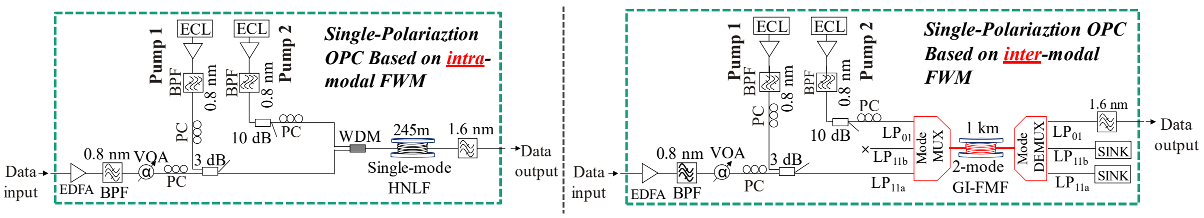
1. Introduction

The demand for high capacity leads to the transmission of higher-order modulation formats where high optical signal-to-noise ratio (OSNR) is required at the receiver. Towards this goal, higher signal launch powers are used which eventually degrade the signal quality (reach reduction) due to the transmission fiber's Kerr nonlinearity. To mitigate such nonlinear impairments, several nonlinearity mitigation schemes either in the digital domain [1−2] or optical domain [2−3] have been proposed. In contrast to the digital domain concepts, the optical domain concepts, such as optical phase conjugation (OPC) based on four-wave mixing (FWM), are not limited by receiver bandwidth, thus allowing for both intra- and inter-channel crosstalk mitigation [2]. Until recently, OPC demonstrations have been using single-mode fiber (SMF) where the spectral resources (i.e. wavelength band) are shared by all optical waves involved in the FWM process (pumps, signals, and idlers). As the wavelengths of the input signals and output idlers must not spectrally overlap, the input-wavelength acceptance range of the OPC is therefore limited. In contrast, the acceptance range can potentially be doubled by adopting inter-modal FWM in a multimode fiber, such as a few-mode fiber (FMF), because the input signals and output idlers propagate in different modes [4−7]. However, a detailed performance comparison of OPC realizations based on either SMF (intra-modal FWM) or FMF (inter-modal FWM) over the same transmission link has not been reported up to now.

In this paper, we extend our experimental investigations on fiber nonlinearity mitigation using inter-modal FWM based OPC [7] and compare the performance to an OPC that is based on intra-modal FWM. Using a 1-channel 32-GBd single-polarization 16QAM data signal in a back-to-back (b2b) scenario, the two OPC realizations are compared in terms of conversion efficiency (CE), insertion loss and implementation penalty. Later, both OPCs were placed (one OPC at a time) mid-link in an 800-km single-mode dispersion-managed fiber link for fiber nonlinearity mitigation. After adjustment of similar CEs, similar Q^2-factor improvements of 0.8 dB were obtained for each of the OPCs.

2. Experimental Setup

Fig. 1 depicts the experimental setup of the single-polarization OPCs. In order to exploit intra-modal FWM in a SMF, we employed a single-mode highly nonlinear fiber (HNLF) as a nonlinear medium in the OPC device, as shown in Fig. 1(a). In this configuration, the incoming data signal was combined with pump 1 (1541.14-nm wavelength) generated from a continuous wave (CW) external cavity laser source (ECL). The combined optical wave was coupled together with a second pump, pump 2 (1550.14-nm wavelength), via a wavelength-division multiplexed (WDM) coupler before entering the single-mode HNLF (+26-dBm 1%-SBS threshold, length 245 m, nonlinear coefficient 9.7 /W/km, attenuation 0.82 dB/km, zero-dispersion wavelength 1544 nm, dispersion slope 0.07 ps/nm^2/km). Note that an erbium-doped fiber amplifier (EDFA) in conjunction with a variable optical attenuator (VOA) was used to set the power of the incoming data to +2.6 dBm at the input of the HNLF in order to avoid saturation of the parametric process.



(a) (b)

Fig. 1: Experimental setup of a polarization sensitive OPC based on: (a) intra-modal FWM in a SMF, (b) inter-modal FWM in a GI-FMF.

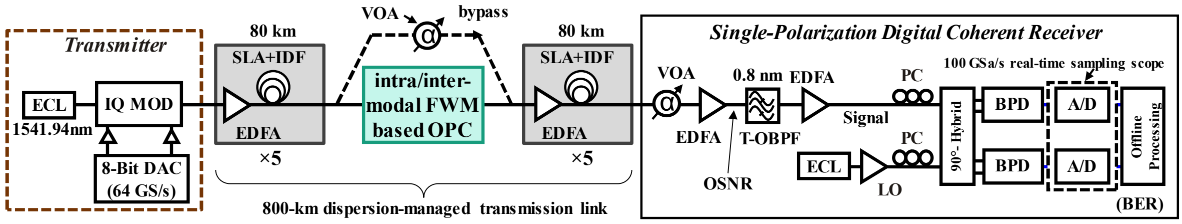


Fig. 2: Experimental setup of the OPCs used independently as a mid-link spectra-inverter in an 800km dispersion-managed link.

An optical bandpass filter (BPF) placed after the HNLF selected the desired idler as the output data signal of the OPC device. Contrary to Fig. 1(a), the OPC configuration shown in Fig. 1(b) adopts a 2-mode graded-index (GI)-FMF as the nonlinear medium. In order to exploit inter-modal FWM in the FMF, one of the pumps (Pump 2, 1550-nm wavelength) was injected into the fundamental mode (LP_{01}) via a mode multiplexer (MUX) to the GI-FMF. The second pump (Pump 1, 1541.14-nm wavelength) was combined with the incoming signal and both optical waves were coupled to the LP_{11a} mode of the FMF via the mode MUX. At the FMF output, a mode-DEMUX separated the desired idler and pump 2 (both in the LP_{01}-mode) from the input signal and pump 1 (both in the LP_{11}-modes). Finally, the generated idler was filtered out using a 1.6 nm optical bandpass filter.

The nonlinearity mitigation performance evaluations of both OPCs were conducted by placing the OPCs mid-link in an 800-km dispersion-managed link. Each span of the link (80km) is made up of a super-large area fiber (SLA), and an inverse dispersion-shifted fiber (IDF) (provided by OFS Denmark). After the first half of the link, the transmitted data signal was sent to the second half of the link either via an OPC or without an OPC (i.e., bypass). In order to investigate the impact of the insertion losses of the OPCs, a VOA was used to emulate the loss of a particular OPC in the bypass of the link. The investigations were carried out using a single-channel data-aided 32 GBd single-polarization 16QAM data signal with a root-raised cosine pulse shaping (10% roll-off). The data was generated from a transmitter that consisted of an ECL at 1541.94 nm, a single-polarization IQ modulator driven by an 8-bit 64-GS/s digital-to-analog converter (DAC) via a pair of driver amplifiers. A digital coherent receiver with a VOA (intended for noise loading) was used. The received data signal was combined with a local oscillator (LO, 100-kHz linewidth) in a 90° optical hybrid. Two balanced photodiodes (BPD) enabled the O/E conversion and the analog waves were digitized using an analog-to-digital converter (ADC, 100 GS/s, 33-GHz bandwidth). Offline receiver digital signal processing (DSP) included data-aided channel estimation, frequency domain MIMO equalization, and blind phase recovery, compensation of residual modulator I/Q imbalances and phase errors using a real-valued MIMO time-domain equalizer (101 taps) before de-mapping and bit-error ratio (BER) counting.

3. Experimental Results

We initially investigated the intra-modal FWM effect in the HNLF. In this scenario, pump powers of +14.1 dBm and +14.2 dBm for pump 1 and pump 2, respectively, were sent to the HNLF. The achieved CE, for a signal power of +2.6 dB, was about -20 dB. The CE is defined as the ratio of the idler power (with pumps on) to the signal power (with pumps off). Shown in Fig. 3(a) are the optical spectra (0.1-nm resolution bandwidth) for the cases "pumps on" and "pumps off" measured at the output of the single-mode HNLF. Similarly, we also exploited inter-modal FWM in a GI-FMF. Fig. 3(b) shows the optical spectra at the output of the mode DEMUX for the case with "pumps off", at the output of the LP_{11a}, while for the case "pumps on", the output of the LP_{01} mode is shown. Note that our metric for the performance comparison of the intra- and inter-modal FWM effects was based on the same CE. Thus, for the exploitation of the inter-modal FWM in the GI-FMF we used pump powers of +27.5 dBm and +21.7 dBm for pump 1 and pump 2, respectively. With a signal power of +8.3 dBm, the CE was also about -20 dB. Note that in order to achieve a good phase-matching in the GI-FMF, the pump wavelength allocation was determined based on group delay vs wavelength measurements as shown in [7]. It can be seen in Fig. 3(b) that leakages of optical waves from the higher-order modes (e.g. LP_{11a} mode) are observed in the fundamental mode (LP_{01}) and vice-versa, and this is due to the finite extinction of the used mode MUX and DEMUX which is about -16 dB.

To evaluate the linear performance of both OPCs, b2b measurements were conducted by employing noise loading. The measured BERs were converted to Q^2-factors using the relation: $Q^2_{\mathrm{dB}} = 20\log_{10}\left[\sqrt{2}\,\mathrm{erfc}^{-1}(2\cdot\mathrm{BER})\right]$. Fig. 3(c) shows the summary of measured Q^2-factors vs. OSNR for the cases; (i) without the OPCs, (ii) with the OPCs. It can be seen that the OSNR implementation penalty at Q^2-factors = 8 dB is ~ 0.6 dB (i.e. compared to the AWGN theory). The measured OSNR penalties of the OPC based on intra-modal FWM (shown by red symbols) and inter-modal FWM (shown by blue symbols), in comparison with the case without the OPCs, were 0.1 dB and 0.4 dB, respectively (at Q^2-factor = 8 dB). The slight difference in the OSNR penalty is attributed to the difference in the insertion loss of the OPCs

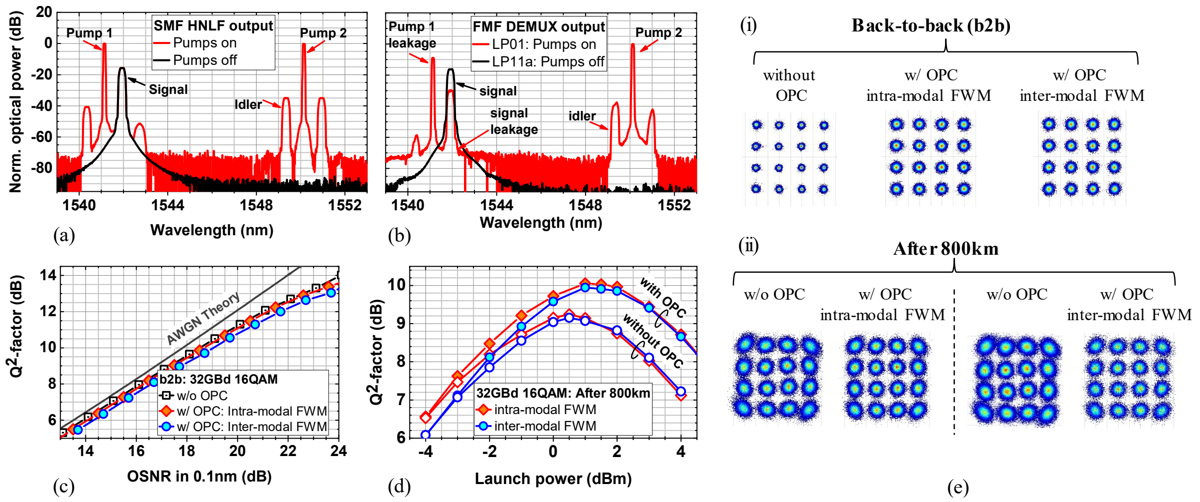


Fig. 3: Optical spectra (at a resolution bandwidth = 0.1 nm): (a) at the output of the single-mode HNLF (intra-modal FWM), (b) at the output of the FMF mode demultiplexer (inter-modal FWM). (c) Measured b2b Q^2-factor vs. OSNR. (d) Measured Q^2-factor vs. launch power after 800-km transmission using OPCs based on either intra- or inter-modal FWM. (e) Received 32 GBd single-polarization 16QAM constellation diagrams with and without the intra- and inter-modal FWM based OPCs: (i) back-to-back (max. OSNR), (ii) after 800 km transmission at +1-dBm launch power.

(~3 dB) due to the additional loss by the mode MUX and DEMUX in the inter-modal FWM based OPC. The nonlinearity mitigation performance of the OPCs were evaluated. First, the intra-modal FWM based OPC was placed in the transmission link. The maximum measured Q^2-factor was 10.05 dB at optimum launch power of +1 dBm as shown in Fig. 3(d). Next, a VOA was placed in the bypass which emulated the OPC insertion loss. The measured maximum Q^2-factor for the case without the OPC was found to be 9.24 dB, resulting in Q^2-factor improvement of 0.8 dB offered by the intra-modal FWM based OPC. Secondly, the inter-modal FWM based OPC was placed in the transmission link. In this scenario, the measured maximum Q^2-factor was 9.95 dB at an optimum launch power of +1 dBm. In the case without OPC, the achieved maximum Q^2-factor was 9.15 dB at a launch power of +0.5 dBm. Consequently, 0.8-dB Q^2-factor improvement was achieved by the OPC. Therefore in our experiments, both the intra- and inter-modal FWM based OPCs provided the same nonlinearity mitigation performance. The constellation diagrams at maximum OSNR in the b2b cases with and without OPCs based on either intra- or inter-modal FWM are shown at the top of Fig. 3(e). After transmission over the 800-km link, the constellation diagrams at a launch power of +1 dBm for the cases with and without OPCs are also shown at the bottom of Fig. 3(e).

4. Conclusions

We experimentally compared the nonlinearity mitigation capabilities of two different types of mid-link optical phase conjugators (OPC) for a 32-GBd single-polarization 16QAM data signal. One OPC was based on (conventional) intra-modal FWM in a highly nonlinear single-mode fiber (HNLF) while the other OPC was based on inter-modal FWM in a 2-mode graded-index few-mode fiber (FMF). In our realization, the FMF-OPC exhibited ~3 dB higher insertion loss due to the mode-MUX/DEMUX required, which caused ~0.3 dB higher implementation penalty in the b2b scenario. However, after adjusting both OPCs for the same idler conversion efficiency of about -20 dB (by deliberately reducing the HNLF-OPC pump powers), both OPCs yielded similar nonlinearity mitigation improvements of ~0.8 dB at similar optimum launch powers of +1 dBm in transmission over a dispersion-managed 800-km fiber link. The results indicate that the quality of the inter-modal FWM process is comparable to that of the conventional intra-modal FWM.

5. Acknowledgement

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6. References

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