Demonstration of DP-16QAM WDM Link with In-line Nonlinearity Compensation

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***Abstract*—We demonstrate in-line nonlinearity compensation (NLC) of a 5-channel dual-polarization 16-QAM signal using opto-electronic sub-systems called total intensity-directed phase modulators (TID-PMs). NLC using a TID-PM placed before each span in an 800 km link improves the signal quality, *Q*, of the center channel by 0.4 dB at the optimum launch power.**

I. Introduction

The capacity of optical communication systems are limited by fiber nonlinearity caused by the Kerr effect [1]. As the Kerr effect is deterministic, nonlinearity compensation (NLC) can be used to undo the nonlinear distortions, thus enabling transmission beyond the nonlinear Shannon Limit. NLC research has primarily focused on 'lumped' techniques, such as digital back propagation (DBP) [2], [3], that attempt to mitigate the entire nonlinear distortion using a single compensator. Recently, there has been some interest in performing NLC at multiple points, e.g. using several optical phase conjugation (OPC) stages [4], [5]. Experimental demonstrations have shown that cascaded OPC is a slightly more effective NLC technique than single-stage OPC [4], and simulations indicate that larger performance improvements are possible [5]. Further, cascaded OPC has applications in optically routed networks, where multi-channel DBP is unable to fully mitigate inter-channel nonlinearity [3], and may even be able to overcome some of the fundamental limitations of DBP [5]. However, OPC requires high pump powers for nonlinear mixing, as well as links with carefully managed power and dispersion maps [6].

A potentially simpler implementation of distributed NLC is to use intensity-dependent phase modulators placed along the link [7], [8]. The distortion caused by fiber nonlinearity can be modeled as a phase rotation of $\phi_{NL} = \gamma L_{eff} P(t)$, where γ is the nonlinearity coefficient of the fiber, L_{eff} is the effective nonlinear length, and $P(t)$ is the power waveform of the optical signal. Therefore, applying a phase rotation of the same magnitude, but opposite direction, can undo the nonlinear distortion [9]. Our previous simulations have shown that placing a sub-system called a total intensity-directed phase modulator (TID-PM) before each fiber span can suppress the nonlinear distortion on several wavelength division multiplexed (WDM) channels [8]. The block diagram of a TID-PM is shown in Fig. 1. The incoming band of WDM channels passes through a channel-wise delay, $\Delta\tau_{in}$, to obtain the waveform at the mid-point of the nonlinear length of the span before a portion of the signal is tapped-off using an optical coupler. A photodiode is used to measure the intensity waveform, which is then electrically amplified. Because nonlinear walk-off attenuates the high-frequency components of inter-channel nonlinear distortions [10], beating products greater than a few GHz are generally negligible long-haul links. This frequency dependence of the nonlinear distortion can be emulated with a low-pass filter (LPF) [11]. Additionally, using a LPF reduces the bandwidth requirement of the other components in a TID-PM. The filtered electrical signal drives a polarization-insensitive phase modulator to undo the nonlinear distortion. Another channel-wise delay at the output undoes the effect of $\Delta\tau_{in}$, and the signal is optically amplified to recover the loss caused by the TID-PM. Similar sub-systems have been investigated for end-point compensation of both intra- and inter-channel nonlinearity [9], [11], [12].

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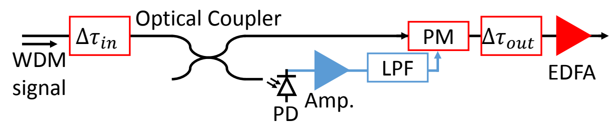

Fig. 1. Block diagram of TID-PM. $\Delta\tau_{in/out}$: Channel-wise delay; PD: Photodiode; Amp.: Electrical amplifier; LPF: Low-pass filter; PM: Polarization-insensitive phase modulator; EDFA: Erbium-doped fiber amplifier.

In this work, we perform the first experimental demonstration of in-line TID-PMs in a long-haul WDM link. Using a re-circulating loop, we placed a TID-PM before each span in a 10 × 80-km dispersion unmanaged link carrying a 5-channel dual-polarization 16-QAM (DP-16QAM) signal. We found that using in-line TID-PMs improves the signal quality, Q, of the center channel by 0.4 dB at the optimum launch power, when compared to a system with equivalent loss. However, inserting a TID-PM at the start of each span results in an optical signal-to-noise ratio (OSNR) penalty of 1 dB, which is not overcome.

II. Experimental Setup

The experimental setup of the 10 × 80 km link is shown Fig. 2. Five external cavity lasers (ECLs), with <100 kHz linewidth, on a 50-GHz grid were coupled together and

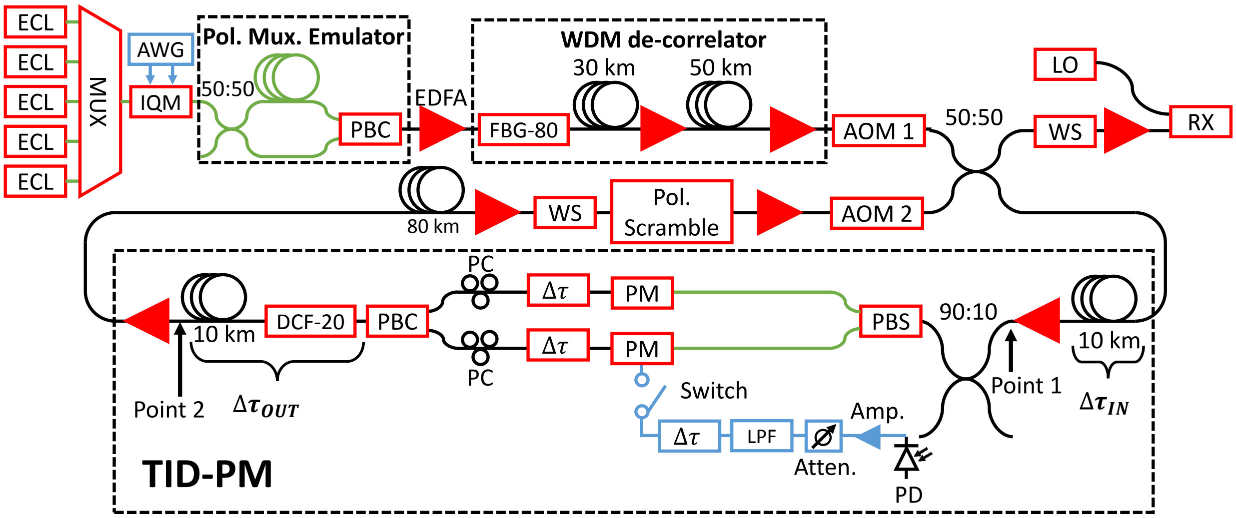

Fig. 2. Experimental Setup. Five lasers are multiplexed together and modulated with a single-polarization IQ modulator before pol. mux. emulation. The channels are de-correlated using a channelized DCM before being launched into a re-circulating loop. The loop consists of a TID-PM and one 80-km span of fiber, and the signal traverses the loop ten times before being received. Blue lines are electrical connection, green lines are polarization maintaining fiber. ECL: External cavity laser; MUX: WDM multiplexer; IQM: IQ modulator; AWG: Arbitrary waveform generator; PBC: Polarization beam combiner; FBG-80: Fiber-Bragg grating DCM for 80-km of SMF; AOM: Acusto-optic modulator; PBS: Polarization beam splitter; PM: Phase modulator; Amp.: Electrical amplifier; Atten.: Variable electrical attenuator; $\Delta\tau$: Variable delay; LPF: Low-pass filter; PC: Polarization controller; DCF-20: Dispersion compensating fiber for 20-km of SMF; WS: WaveShaper; Pol. Scramble: Loop-synchronous polarization scrambler; LO: Local Oscillator; RX: Coherent receiver.

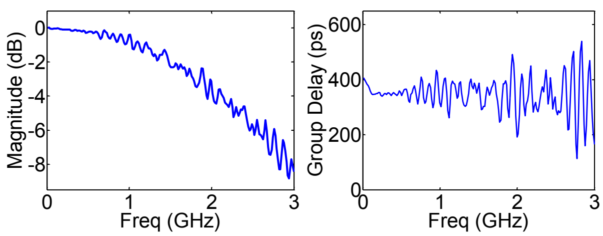

Fig. 3. Measured frequency response (left) and group delay (right) of Mini-circuits SBLP-1870+ LPF.

modulated using an IQ modulator with 35-GHz bandwidth. The transmitted data was generated in MATLAB and then stored on a 90 GSa/s arbitrary waveform generator (AWG) before driving the IQ modulator. Polarization multiplexing was emulated by using a polarization-maintaining 3-dB coupler to split the signal into two paths of equal power, and a length of polarization maintaining fiber was inserted in one arm to create a delay of 286 symbols between the two paths before they were combined with a polarization beam combiner (PBC). The five WDM channels were de-correlated by using a Teraxion channelized Fiber-Bragg grating dispersion compensating module (DCM) and 80 km of single mode fiber (SMF), a 30-km spool combined with a 50-km spool, to create a delay of 15 symbols between adjacent channels. Erbium-doped fiber amplifiers (EDFAs) were placed after each spool to minimize the OSNR penalty caused by the de-correlator.

A recirculating loop was used to emulate span-by-span NLC using in-line TID-PMs, with each loop consisting of the TID-PM and one 80-km span of fiber. The TID-PM was placed before the SMF span because the nonlinear distortion is more closely correlated to the waveform at the beginning of the span, where the signal power is high. A 10-km spool of SMF was used to implement the input channel-wise delay, $\Delta\tau_{in}$, and then an EDFA set the power into the TID-PM, which was the same as the launch power into the span. This EDFA was placed after the 10-km span to avoid nonlinear distortions in the $\Delta\tau_{in}$ element. A 90:10 coupler then tapped off a portion of the signal to be detected on a 10-GHz photodiode. A fixed-gain electrical amplifier and a variable attenuator boosted the signal to the required level before low-pass filtering. The LPF was a Mini-Circuits SBLP-1870+, whose frequency response and group delay are given in Fig. 3. This filter was chosen because its frequency response below 2 GHz is similar to the analytic XPM response for channels with 50-GHz frequency separation, using the analysis in [10]. After filtering, an RF delay line ensured that the electrical and optical paths were matched, and then the signal was used to drive two phase modulators. A switch is used to enable or disable NLC. The two phase modulators emulate a single polarization-insensitive phase modulator by splitting the signal into its orthogonal components and modulating each polarization tributary with the same signal before re-combining them. As the phase modulators used in this experiment did not have polarization-maintaining outputs, polarization controllers were required to manually align the states of polarization into the PBC. Optical delay lines were used to ensure path matching between the two optical paths. After the PBC, another 10-km spool of SMF and a spool of dispersion compensating fiber (DCF) that compensates 20 km of SMF were used to implement $\Delta\tau_{out}$. The total loss of the components in the TID-PM, between Points 1 and 2, was 10.5 dB: 0.5 dB each for the 90:10 coupler, polarization beam splitter, and PBC; 3.5 dB across the phase modulators; 1 dB for the optical delay lines; 2 dB for the second span of SMF; and 2.5 dB for the DCF. An

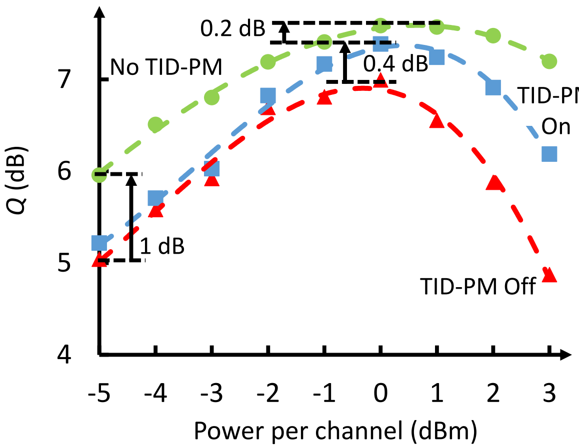

Fig. 4. Q vs launch power for the center DP-16QAM channel with fitted curves.

EDFA placed after the second 10-km spool of SMF sets the power launched into an 80-km span of transmission fiber. The loss of the span was compensated with another EDFA, and a WaveShaper (WS) with 1-THz bandwidth removed out-of-band noise. A polarization scrambler was used to change the state of polarization in the fiber every loop, and the signal traversed the loop ten times to emulate a 10×80-km link.

At the receiver, a 40-GHz bandwidth WS de-multiplexed the center channel. The optical signal was then pre-amplified to -1 dBm and coherently detected using a local oscillator (LO) with <100 kHz linewidth and a coherent receiver with 25-GHz bandwidth. The electrical signal was captured on an 80 GSa/s real-time sampling oscilloscope, and stored for offline processing. Digital signal processing involved frequency offset removal, electronic dispersion compensation using the overlap-add technique, and dynamic equalization using a 2-stage, 21-tap constant-modulus algorithm (CMA), where a single-radius CMA equalizer initialized the taps of a radial-decision-directed CMA equalizer. Phase noise was corrected using maximum likelihood sequence estimation, and the number of errors were counted directly to determine the bit error rate (BER).

III. Results and Discussion

Figure 4 plots Q against launch power for the center channel with in-line TID-PMs active (blue) and inactive (red), and when in-line TID-PMs are completely removed (green). Q is calculated from BER as $Q = 20\log_{10}(\sqrt{2}\mathrm{erfc}^{-1}(2 \times \mathrm{BER}))$, where erfc^{-1} is the inverse complementary error function. Using distributed NLC results in a 0.4-dB increase in Q at the optimum launch power. The performance improvement increases to 1.3 dB in the nonlinear transmission regime, indicating that in-line TID-PMs effectively suppress the nonlinear distortion. The performance of in-line TID-PMs could be improved by replacing the off-the-shelf LPF used here with a filter more closely resembling the response in [8].

The OSNR penalty resulting from the 10.5-dB insertion loss of the TID-PM is found be approximately 1 dB by comparing the Q with and without TID-PMs at low power. In this demonstration, the OSNR penalty is not overcome by the improved nonlinear performance, as the system with in-line TID-PMs performs 0.2-dB worse than the system without in-line TID-PMs at the optimum launch power. It should be possible to reduce the TID-PM insertion loss to around 8 dB by using ultra-low-loss phase modulators (modulators with 2-dB loss are commercially available) with polarization-maintaining output pigtails to remove the need for the optical delay lines, and implementing $\Delta\tau_{out}$ with a 10-km DCF.

IV. Conclusion

In conclusion, we have experimentally verified that phase modulators placed along a link are an effective way to mitigate the distortion caused by fiber nonlinearity. For a 5-channel, 28-Gbaud DP-16QAM signal transmitted through a 10×80 km link, in-line TID-PMs increased the peak Q of the center channel by 0.4 dB, when compared to a link with the a matched loss. However, inserting a TID-PM at the beginning of each span results in a 1-dB OSNR penalty, which is not overcome. While the nonlinear performance improvement of in-line TID-PMs currently does not overcome this OSNR penalty, this demonstration confirms that the low-bandwidth TID-PMs can suppress nonlinearity on polarization-multiplexed signals in long-haul links.

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