Optoelectronic method for distributed compensation of XPM in long haul WDM systems

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Abstract: We propose an optoelectronic method for distributed compensation of XPM based on power-dependent phase rotation. Simulations show 2.7-dB improvement in peak *Q* for a 28-Gbaud QPSK channel with 14-Gbit/s NRZ-OOK neighbors after 3200-km transmission.
OCIS codes: (060.5410) Optical Communications; (060.2360) Fiber optics links and subsystems

1. Introduction

In long-haul optical communication systems, fiber nonlinearities such as cross-phase modulation (XPM) ultimately limit the information capacity of the link [1]. These nonlinearities are the result of the Kerr effect, which converts intensity fluctuations into nonlinear phase noise (NLPN), and may be mitigated by applying a phase shift that is proportional to the instantaneous power. Such an approach has been demonstrated as a simple means to suppress both intra-channel [2], and inter-channel [3,4], nonlinearities at the start or end of the link. However, these phase rotation based pre- or post-compensators require knowledge of the evolution of the optical waveform as it propagates through the link, which can ultimately limit their effectiveness.

Recently, distributed nonlinear compensation (NLC) has been demonstrated with optical phase conjugation (OPC) [5], and in-line phase sensitive amplifiers (PSA) [6]. These techniques periodically suppress NLPN as the signal propagates through the link, and are potentially interesting for applications in optically routed networks, where end-span techniques cannot accurately compensate for inter-channel nonlinearity. Additionally, NLC along the link using the local waveform, may be the only way to overcome the non-deterministic nonlinear interactions, which limit current state-of-the-art end-span techniques [7]. However, while OPC and PSA have shown promising results, the complexity of these techniques may be a limiting factor for their deployment.

In this work, we propose using in-line phase modulators as a simple way to achieve distributed NLC of XPM. Numerical simulations show that this effectively suppresses phase modulation from XPM on a continuous wave (CW) probe. As a test case for transmission performance, we simulate a hybrid WDM system [8], demonstrating 2.4-dB and 2.7-dB improvements in peak *Q* for a 28-Gbaud quadrature phase shift keyed (QPSK) channel with 14-Gbit/s on-off keyed (OOK) neighbors over 1600-km and 3200-km links respectively.

2. In-line compensation of XPM

Using a phase modulator to apply a phase shift proportional to the instantaneous optical power of a single wavelength is a well-known method for suppressing self-phase modulation (SPM) [2]. Similarly, compensating XPM at the receiver in both single-carrier [3], and orthogonal frequency division multiplexed (OFDM) [4], systems has been demonstrated, using a single photodetector to measure the total optical power of a band of WDM channels. The measured power is then used to drive the phase modulator, which compensates XPM over the entire band of channels simultaneously. We refer to this device as a total-intensity directed phase modulator (TID-PM).

At first glance, a TID-PM would seem to need an extremely large bandwidth, to account for the many wavelength channels. However, walk-off due to chromatic dispersion (CD) means that the high frequencies of intensity fluctuations have a minimal contribution to the overall XPM penalty in an optically amplified link [9]. This XPM efficiency characteristic is approximated with a low-pass filter. As a result, compensation of the XPM developed in a band of WDM channels simultaneously is possible by using low-bandwidth (~1 GHz) components; a photodiode, an amplifier, a filter and a phase modulator, as shown in Fig. 1.

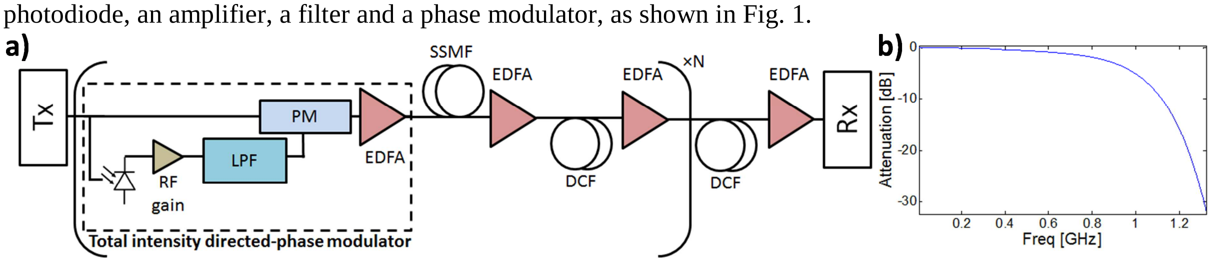

Fig. 1. a) System block diagram. LPF – low-pass filter; PM – phase modulator; b) Response of LPF used to emulate walk-off.

We propose that these TID-PMs are well suited for in-line NLC, due to the low complexity of individual modules. As each compensator is only required to remove the XPM in one span, accuracy is improved as the waveform is not greatly affected by CD for this distance. Additionally, in-line TID-PMs may be robust to optical link design; when performing NLC span-by-span, factors like link length and dispersion map may be unimportant.

To investigate the ability of in-line TID-PMs to suppress XPM, we used VPItransmissionMaker v9.1 to simulate the system shown in Fig. 1a) for distances of 1600 km (N = 20) and 3200 km (N = 40). The link comprised 80-km spans of standard single mode fiber (SSMF) with attenuation of 0.2 dB/km, 16 ps/(nm.km) CD and nonlinear coefficient (γ) 1.3 $W^{-1}km^{-1}$. The link is dispersion managed, as is common in the test case legacy system we investigate here. CD was removed using dispersion compensating fiber (DCF) with attenuation of 0.6 dB/km, -100 ps/(nm.km) CD and γ of 5.68 $W^{-1}km^{-1}$, leaving 100 ps/nm residual dispersion per span. Additional DCF was placed just before the receiver to post-compensate the residual CD. Erbium doped fiber amplifiers (EDFAs) with a 6 dB noise figure were used to compensate all losses, with gains set so that the launch power into the DCF was 7 dB lower than the launch power into the SSMF. XPM is compensated on a span-by-span basis using TID-PMs. Each TID-PM uses a 90/10 optical coupler to tap off a portion of the signal, which is received by a photodiode. The walk-off characteristic of each span is approximated by the filter response in Fig. 1b), which was obtained by truncating the analytic walk-off in [9], to 1 GHz. NLC is achieved by driving a loss-less phase modulator to oppose the phase shift caused by XPM. At the receiver, a 30-GHz optical bandpass filter was used to de-multiplex the QPSK channel before coherent reception, where it was 2× oversampled before digital signal processing. Equalization of the signal was achieved using a fractionally-spaced $T/2$ constant modulus algorithm before bit error counting. Simulations were constrained to a single polarization and laser linewidth set to zero.

3. Simulation results

We began by evaluating the received phase of a -10-dBm CW probe laser placed 50 GHz away from a 0-dBm 14-Gbit/s OOK signal after 1600-km transmission. With zero linewidth, the phase of the probe should be constant, but fluctuates due to both in-band ASE and XPM from the OOK channel. SPM is negligible on the low-power probe. Fig. 2 plots the magnitude of the Fourier transform for the root mean squared phase noise with and without in-line XPM compensation to show the spectral components of the XPM distortion, at 1 GHz measurement bandwidth. Fig. 2 also plots the phase noise spectrum with low power (-10 dBm) in the OOK channel, to determine the residual components resulting from ASE. We observe that XPM causes significant low-frequency spectral components, which can be reduced by using in-line TID-PMs. We then replaced the CW laser with a 28-Gbaud QPSK signal at -10 dBm, and observe the received constellations with (Fig. 2c) and without (Fig. 2b) the use of in-line TID-PMs. The large reduction in phase noise with the use of in-line TID-PMs confirms that XPM is suppressed.

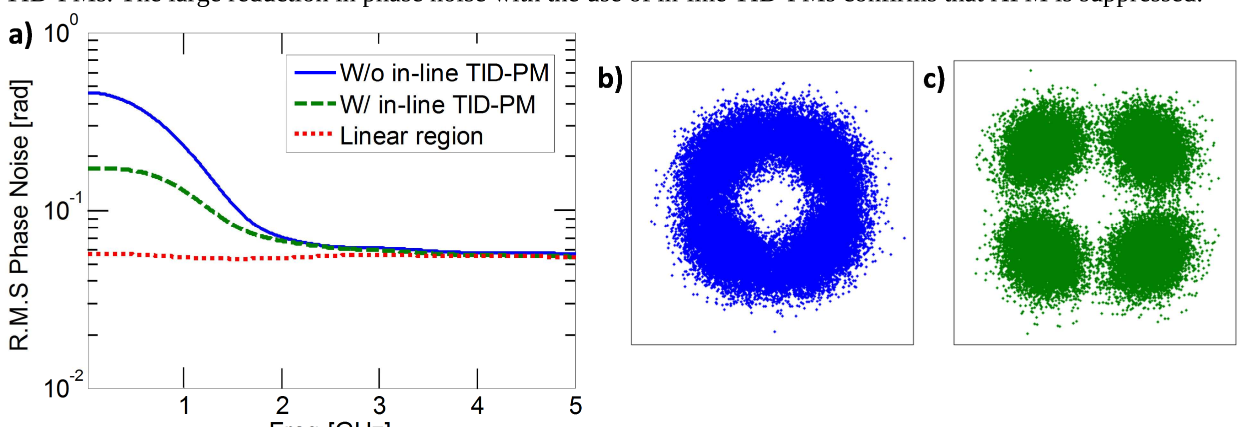

Fig. 2. a) Phase noise spectra of CW laser after 1600 km; Constellation of QPSK channel b) w/o in-line TID-PMs and c) w/ in-line TID-PMs for XPM compensation

We then simulated a dispersion managed hybrid WDM link, a type of configuration which may be found when upgrading legacy links, which is representative of the worst-case scenario for nonlinear performance of QPSK [8]. The WDM signal consisted of seven channels, all with the same average power, on a 50-GHz grid; the center channel carries 28-Gbaud QPSK while the other six channels carry 14-Gbit/s NRZ-OOK. 14-Gbit/s second channels were used as VPI requires a factor of 2^N for the time window. We compared the performance of in-line and post-compensation of XPM using TID-PMs for 1600-km and 3200-km transmission. The post-compensating TID-PM was modeled similarly to the in-line TID-PMs described previously. In this case, the effect of walk-off on the XPM efficiency characteristic was approximated with a trapezoidal filter, identical to the one in [3]. We optimized this filter for each link length, using a filter with a flat pass band of 500 MHz (100 MHz), rolling off to a stop band attenuation of 30 dB at 1 GHz (200 MHz) for 1600-km (3200-km) transmission.

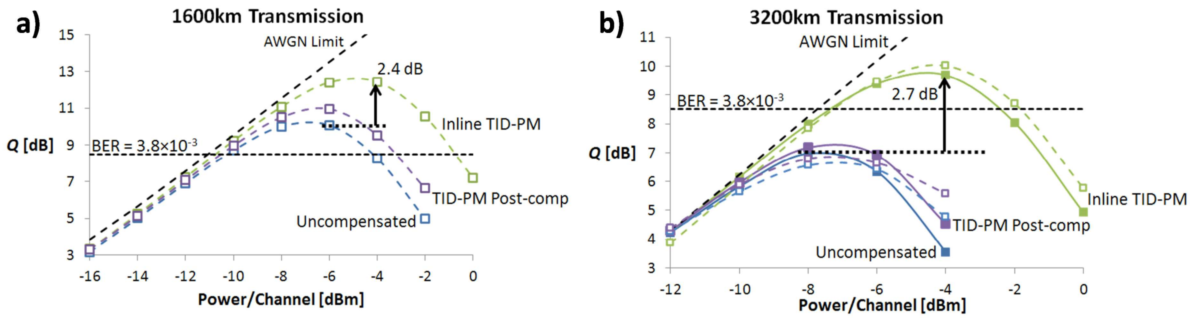

Fig. 3. System performance against launch power per channel for: a) 1600-km transmission and b) 3200-km transmission. Open markers are Q from constellation variance; Solid markers are Q from BER.

Fig. 3 plots signal quality, Q, against launch power per channel for a) 1600-km transmission and b) 3200-km transmission. We calculated Q from the constellation variance (open markers) and BER (closed markers), with Q from BER calculated as $20 \times log_{10}[\sqrt{2} \times erfc^{-1}(2 \times BER)]$. After 3200-km transmission (Fig. 3b), both derivations of Q are reasonably similar at the optimal launch power, but Q from constellation variance underestimates the impairment due to phase noise in the nonlinear region. At this distance, there is a 2.7-dB improvement from using in-line TID-PMs, but only a negligible (<0.3 dB) benefit from post-compensation. For 1600-km transmission, we only plot Q from constellation variance (BER = 0), and observe a 2.4-dB increase in peak Q for in-line NLC and a 1-dB increase for post-compensation. As the transmission distance is increased, the filter used by the post-compensator to approximate nonlinear walk-off becomes less accurate, leading to poorer compensation. In contrast, the in-line TID-PMs provide a similar performance improvement for both distances, outperforming post-compensation significantly. Although we have simulated a OOK/QPSK link here, prior art shows that TID-PM can compensate XPM in high capacity coherent WDM systems [4], and preliminary simulations show that in-line TID-PM should also provide considerable benefits in modern, dispersion unmanaged links.

4. Conclusion

Distributed methods of nonlinear compensation may be an attractive way to overcome the limitations of traditional end-point techniques. In-line TID-PMs provide a simple method of achieving in-line XPM compensation. Our simulations show that in-line TID-PMs are effective at suppressing XPM, and that they can improve the performance of a 28 Gbaud QPSK channel with 14 Gbit/s OOK neighbors by 2.7 dB after 3200-km transmission and 2.4 dB after 1600-km transmission.

Acknowledgements

We thank VPIphotonics (www.vpiphotonics.com) for support under their universities program. This work is supported under the Australian Research Council's Laureate Fellowship scheme (FL130100041) and Centre of Excellence CUDOS (CE110001018).

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