Distributed Nonlinearity Compensation of Dual-Polarization Signals using Optoelectronics

Benjamin Foo, *Student Member, IEEE*, Bill Corcoran, *Member IEEE*, Chen Zhu, and Arthur Lowery, *Fellow, IEEE*

***Abstract*—We propose an optoelectronic method for the distributed compensation of nonlinear fiber distortions affecting polarization multiplexed signals. This method involves placing devices we call *total-intensity-directed phase modulators* (TID-PMs) at the start of each amplified fiber span, in order to compensate the effect of fiber nonlinearity on a span-by-span basis. Numerical simulations are used to compare our proposed method to the well-known digital back propagation (DBP) algorithm for a wavelength division multiplexed (WDM) system consisting of eight dual-polarization 16QAM (DP-16QAM) channels operating at 28 Gbaud transmitted through a 15×100km dispersion unmanaged link. These simulations show that the proposed distributed nonlinearity compensation technique increases the peak signal quality, *Q*, by 1 dB while DBP only increases peak *Q* by 0.5 dB.**

***Index Terms*—fiber nonlinearity compensation, optical Kerr effect, polarization-division multiplexing (PDM), wavelength-division multiplexing (WDM)**

I. Introduction

IMPAIRMENTS due to fiber nonlinearity limit the information capacity of modern long-haul coherent optical communication systems [1-3]. To overcome this so-called 'Nonlinear Shannon Limit', researchers have explored digital [4, 5] and optical [6, 7] approaches for lumped nonlinearity compensation (NLC). Previously, we proposed a method for distributed NLC where optoelectronic compensators, called *total-intensity-directed phase modulators* (TID-PMs), were placed along the link [8]. Our simulations showed that this method could effectively mitigate the cross-phase modulation (XPM) from on-off keyed channels in a single polarization link, both with and without dispersion management.

In this paper, we extend the TID-PM concept proposed previously so that it operates on dual-polarization signals, and evaluate the performance of a distributed NLC scheme employing the polarization diverse TID-PMs in a dispersion unmanaged (DU), wavelength division multiplexed (WDM) link. We then compare the performance of our proposed distributed NLC scheme to a single-channel implementation of the well-known digital back propagation (DBP) algorithm [4]. Numerical simulations show that placing one TID-PM at the start of each span can suppress the nonlinear impairments in multiple WDM channels simultaneously. In the simulated 15×100 km DU link carrying eight 28-Gbaud, dual-polarization 16-QAM (DP-16QAM) channels on a 50-GHz grid, TID-PMs improve the peak signal quality, *Q*, by about 1 dB for all eight channels while DBP increases peak *Q* by only 0.5 dB.

II. Distributed Nonlinearity Compensation

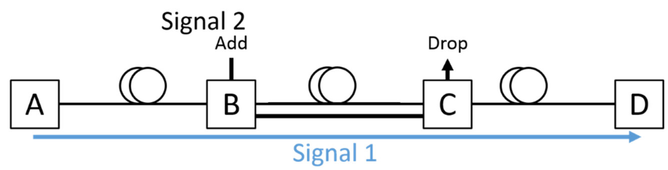

Fig. 1. Simplified block diagram of a four-node optically routed network. Signal 1 is transmitted between nodes A and D, while Signal 2 is transmitted between nodes B and C. DBP for Signal 1 is performed at either node A or D with no knowledge of the information carried by Signal 2.

Distributed NLC is being explored in response to the development of reconfigurable optically routed networks and the problems these networks present to established NLC techniques. Currently, the most studied nonlinearity mitigation schemes – DBP [4] and perturbation-theory based algorithms [5] – rely on powerful digital signal processing (DSP) applied at the end-points of the link to undo the Kerr effect. This is effective for point-to-point links, but problems can arise when the algorithm cannot accurately predict the electric field at some intermediate point [9]; such a situation may arise in an optically routed network. Take, for example, the simple optical network shown in Fig. 1, consisting of four nodes: A, B, C, and D, and carrying two independent data streams: Signal 1, and Signal 2. Signal 1 transmits data from node A to D, passing through nodes B and C, while Signal 2 carries data between the intermediate nodes, B and C. Using DBP for NLC of Signal 1 would require placing the DSP at either node A or D – the end-points of the link. Because Signal 2 cannot be measured at either of these nodes, its XPM contribution remains uncompensated as it is unknown to the algorithm. One way to overcome this is to use multiple NLC stages placed along the transmission link that each compensate a fraction of the overall distortion.

Submitted February 12, 1016. This work was supported by the Australian Research Council's Laureate Fellowship scheme (FL130100041) and Centre of Excellence CUDOS (CE110001018).

B. Foo and C. Zhu are with the Electro-Photonics Laboratory in the Department of Electrical and Computer Systems Engineering, Monash University, Clayton Vic. 3800, Australia (e-mails: benjamin.foo@monash.edu, chen.zhu@monash.edu).

B. Corcoran and A. Lowery are with the Electro-Photonics Laboratory in the Department of Electrical and Computer Systems Engineering, Monash University, Clayton, Vic. 3800, Australia, and also with the Centre for Ultrahigh-bandwidth Devices for Optical Systems (CUDOS), Australia (emails: bill.corcoran@monash.edu, arthur.lowery@monash.edu).

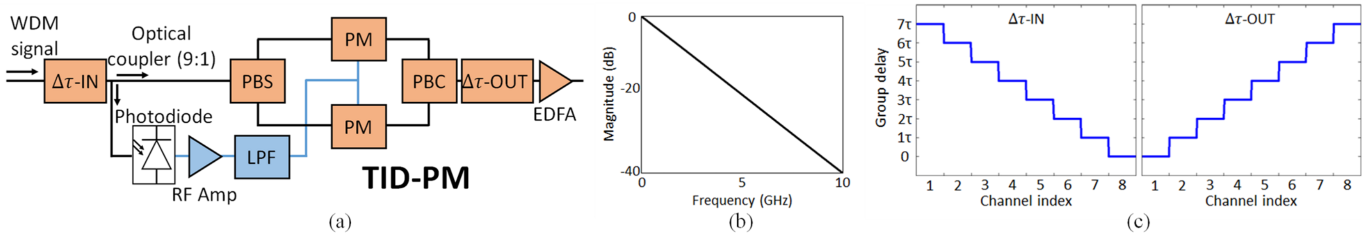

Fig. 2. a) Block diagram for polarization-diverse TID-PM nonlinear compensator. Each polarization has its own phase modulator as the modulators are polarization dependent. The black lines are optical connections and the blue lines are electrical connections. PBS – polarization beam splitter; PM – phase modulator; PBC – polarization beam combiner; LPF – low-pass filter; $\Delta\tau_{\text{-IN/OUT}}$ – channel-wise delay element; b) Response of band-limiting LPF; c) Group delay profile for input and output $\Delta\tau_N$ elements, where τ is a unit delay.

Distributed NLC has previously used: periodic optical phase conjugation [10], phase sensitive amplifiers (PSAs) [11] and inline phase rotation [8]. In the first approach, a fiber optic parametric amplifier phase conjugated the signal every six spans in a 60-span link. This system demonstrated better nonlinear performance than a single phase conjugation, and recent theoretical work [12] predicts that larger gains are possible. However, the need for precise dispersion management of the highly nonlinear fiber and the high pump power needed to achieve reasonable amplifier gain are problematic. These implementation issues are compounded by extra factors when considering the parametric amplifiers used in PSAs. In contrast, inline phase rotations can be realized using total intensity directed-phase modulators (TID-PMs), which may be simpler to implement. Phase rotations are an effective method for NLC because the nonlinear distortion can be approximated as a phase shift of [13]:

$$\varphi_{NL}\left(t\right)=\gamma L_{eff}P\left(t\right), \qquad (1)$$

where γ is the nonlinear coefficient of the fiber, $P(t)$ is the waveform of the slowly-varying intensity envelope and L_{eff} is the nonlinear effective length:

$$L_{eff}=\frac{1-e^{-\alpha L}}{\alpha}, \qquad (2)$$

for a fiber of length L and with attenuation coefficient α. The main assumption in (1) is that the shape of $P(t)$ does not change significantly during the nonlinear interaction, implying low chromatic dispersion. While this may be a good approximation for propagation over L_{eff} in a single span, it becomes inaccurate after propagation over multiple spans. This limits the efficacy of techniques that use a single phase rotation at the start or end of a link [14]. Placing TID-PMs at the start or end of every span can overcome this issue, as each TID-PM only compensates the distortions caused by low-frequency intensity fluctuations in one span. As a result, (1) provides a good approximation of the nonlinear distortions TID-PMs compensate for. Crucially for this approach, distortions due to high-frequency fluctuations do not need to be directly compensated as they become negligible after several spans due to nonlinear walk-off [15-17]. However, as this is a low-bandwidth, intensity-driven scheme, inline TID-PMs cannot deal with broadband four-wave mixing nor cross-polarization modulation (XpolM) products.

The block diagram of a TID-PM is shown in Fig. 2a. The core idea is to use the photodiode to detect the intensity of the incoming signal, amplify it and then use it to drive phase modulators to oppose the phase perturbations caused by fiber nonlinearity [8]. As phase modulators are generally polarization sensitive, the optical signal is split into orthogonal polarizations after the TID-PM input and the same phase rotation is applied to both polarizations using separate modulators before the polarization tributaries are recombined prior to the TID-PM output. In long-haul links using dispersive fiber, nonlinear walk-off means that low-frequency components dominate both the intra-channel [16] and inter-channel [15] intensity-to-phase nonlinear interactions. In the TID-PM, we approximate this response by using an electrical filter (frequency response in Fig. 2b). As the high-frequency components are weak, the required bandwidth of the electronics used in TID-PMs can be reduced to 1-5 GHz – less than the bandwidth of a single WDM channel. Because the optimal waveform to compensate nonlinearities is actually some way into the span, a differential group delay between the channels ($\Delta\tau_{\text{-IN}}$) is used to artificially propagate the waveform to this point. A numerical sweep was used to find the optimal delay, which was near the center of the nonlinear effective length. The differential delay between channels is removed by a second delay element ($\Delta\tau_{\text{-OUT}}$) before further transmission, though there is an overall group delay experienced by the WDM signal. This delay is particularly important for compensating XPM products, and without it, inline TID-PMs only effectively mitigates self-phase modulation (SPM). In this simulation, we used optical filters, with the delay profiles in Fig. 2c, which could be achieved in practice with fiber Bragg grating structures [18]. Dispersion compensating fiber may also be effective as a non-step-wise delay element or alternatively, the TID-PM could be physically placed some distance into the span, though this would be inconvenient.

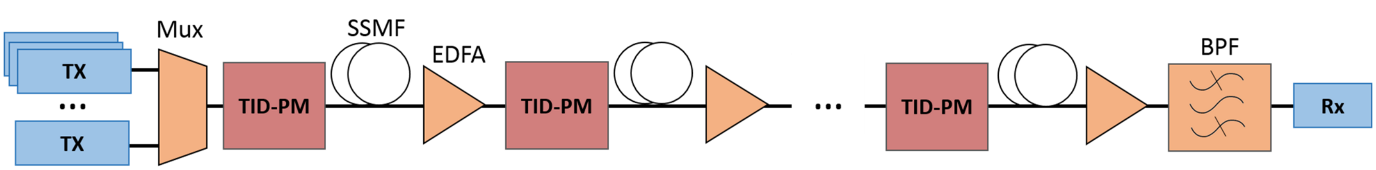

Fig. 3. System block diagram for a dispersion unmanaged system with distributed nonlinear compensation. TX – transmitter; Mux – WDM multiplexer; TID-PM – inline TID-PM nonlinearity compensator (not used in conjunction with DBP); SSMF – standard single mode fiber; EDFA – Erbium-doped fiber amplifier; BPF – band-pass filter; RX – receiver.

III. Simulation Setup

VPItransmissionMaker v9.1 was used to simulate the link in Fig. 3. The system consisted of 15×100 km spans of standard single-mode fiber (SSMF) carrying an 8-channel 28-Gbaud DP-16QAM signal on a 50-GHz grid. The SSMF had 0.2 dB/km attenuation, 16 $ps.nm^{-1}.km^{-1}$ chromatic dispersion (CD), and a nonlinear coefficient, γ, of 1.3 $W^{-1}km^{-1}$. Erbium doped fiber amplifiers (EDFAs), with 6-dB noise figures compensated all losses. All lasers had a linewidth of 100 kHz. The Manakov model [19] was used for polarization multiplexed transmission, with the polarization mode dispersion set to 0.05 $ps.km^{-0.5}$. The data on each polarization tributary was independent, and consisted of 2^{15} randomly generated bits mapped to the 16-QAM constellation. Symbols were oversampled by a factor of 2 and shaped with a digital root-raised cosine (RRC) filter with a roll-off factor of 0.01. The electrical signals were then used to drive a digital to analog converter and modulated onto the optical carriers via complex Mach-Zehnder modulators.

After transmission, a 2nd-order Gaussian filter with a 40-GHz bandwidth was used to de-multiplex the channel of interest, which was then coherently received and digitally processed. The signal was processed by first compensating CD, either with the overlap-add technique or by using DBP, before matched filtering with an RRC filter, equalization with a least-mean-square equalizer and carrier phase recovery using a maximum likelihood algorithm. After equalization, the errors were counted and *Q* was calculated from the bit error rate (BER) as $Q = 20\log_{10}(\sqrt{2}\times\text{erfc}^{-1}(2\times\text{BER}))$, where erfc^{-1} is the inverse complementary error function.

The simulation compared the performance of the signal with only linear equalization to its performance after NLC is applied. NLC was performed using either single-channel DBP or inline TID-PMs; the two techniques were not used simultaneously. The asymmetric split-step Fourier method with one-step-per-span was used to implement single-channel DBP [4]. Multi-channel DBP (e.g. [9]) was not considered due to the need for a large receiver bandwidth and the significant increase in computational complexity. Moreover, multi-channel DBP would be unsuitable for optically routed networks, such as the one described in Section II, where inline TID-PMs would operate. The inline TID-PMs were modeled with an overall insertion loss of 5.5 dB, including the loss from the tapped-off portion of the signal that was detected for compensation, which was recovered with a second EDFA stage. A channel-wise delay of 50 ps between adjacent channels (τ = 50 ps), corresponding to the inter-channel differential group delay after 7.8 km of SSMF, was found to be optimal.

IV. Results and Discussion

In the following results, we target a BER of 3.8×10^{-3} – the threshold for hard-decision forward error correction (FEC) codes with 7% overhead, such as Reed-Solomon codes. Fig. 4a plots *Q* vs. launch power for a central channel with no NLC (blue), DBP for NLC (green) and inline TID-PMs for NLC (red). We also plot the limit due to additive white Gaussian noise (AWGN). This graph shows that DBP improves *Q* at the optimum launch power by approximately 0.5 dB, but TID-PM achieves an increase of 1 dB. This is consistent with results previously observed in a single polarization, dispersion unmanaged link [8]. Our method slightly out-performs single-channel DBP because the TID-PM partially compensates XPM as well as SPM, while DBP only compensates SPM. In the noise-limited region (i.e. for launch powers <−2 dBm) our scheme suffers a small (0.1 dB) penalty due to the additional losses from multiple TID-PMs. For the 1500-km link shown here, some form of NLC is required to reach the FEC threshold; DBP allows the system to just meet the required BER, while the performance with inline TID-PMs slightly exceeds the error-free threshold.

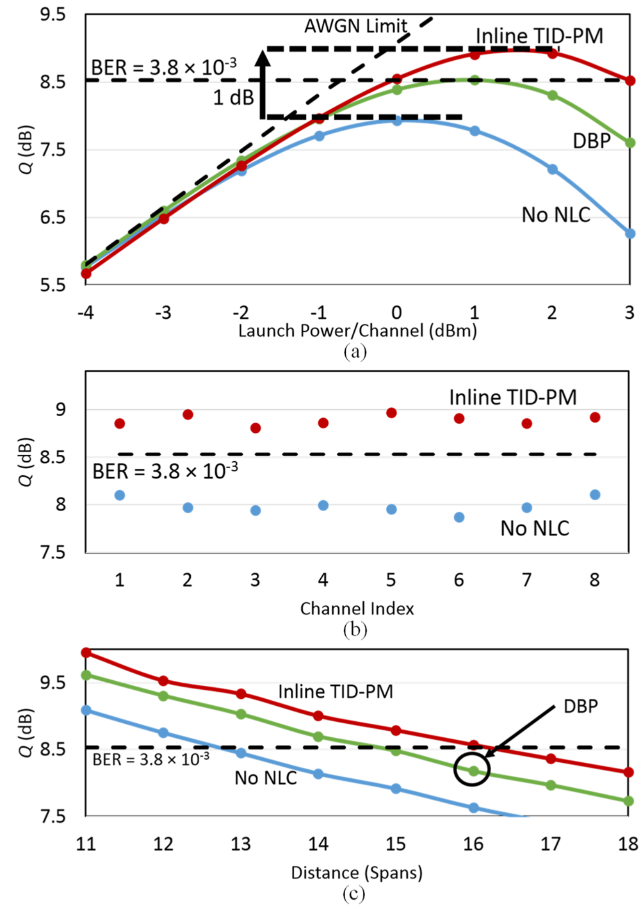

Fig. 4 a) *Q* calculated from BER vs. launch power for one of the center channels for no NLC (blue), DBP (green) and inline TID-PMs (red); b) The *Q* of each channel with no NLC at 0 dBm launch power (blue) and inline TID-PMs at 1 dBm launch power (red); c) *Q* of one of the center channels at the optimum launch for each distance.

To ensure that one TID-PM per span can undo the nonlinear distortions present on multiple WDM channels, Fig. 4b plots the *Q* of all eight channels with no NLC (blue) and inline TID-PMs for NLC (red) at the optimum launch power per channel for each system: 0 dBm and 1 dBm respectively. While none of the channels achieve the target BER with only linear equalization, all channels satisfy this requirement when inline TID-PMs are used. Additionally, the *Q* of all channels is increased by 0.8 – 1 dB, showing that inline TID-PMs are not sensitive to what fraction of the overall impairment is caused by SPM compared to XPM.

Fig. 4c plots the peak value of *Q* versus link length. The maximum reach without the use of NLC is about 1300 km, increasing to 1500 km with DBP, and further to 1600 km with inline TID-PMs, increases of 15% and 23% respectively. This is in good agreement with the reach improvement estimated by the increase in peak Q.

One concern regarding inline TID-PMs is practical implementation, as they need to be deployed at each amplifier location. While more difficult than implementing DBP, which operates at a single point, deploying inline TID-PMs may be less work than other distributed NLC schemes, which require careful management of dispersion and power maps [11]. Further work is needed to ascertain whether TID-PMs can compensate for multiple spans in one unit. Additionally, while one TID-PM per span is performs well with 8 WDM channels, this approach will not work for WDM systems with a large number of channels. As XPM between widely-spaced WDM channels is negligible [20], a single TID-PM cannot accurately compensate the nonlinear distortions over large bandwidths. To overcome this, a bank of TID-PMs should be used at each NLC node, with each TID-PM compensating a band consisting of only a few WDM channels, as shown in Fig. 5. Banding can be accomplished with an optical de-multiplexer, and adjacent bands would be used to help estimate the nonlinear distortion on the target band. After compensation, the bands would be recombined with a multiplexer. This functionality may be added as a sub-system to reconfigurable optical add/drop multiplexers (ROADMs), if a ROADM was placed at the start of each fiber span.

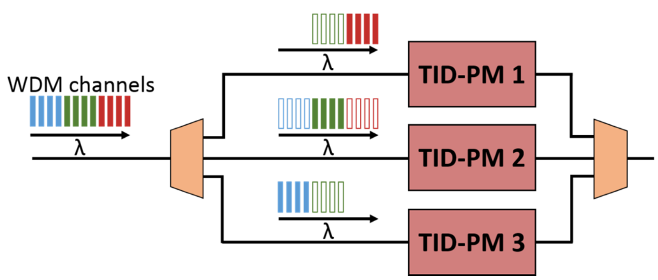

Fig. 5. Block diagram of the proposed bank of TID-PMs for wideband NLC. The incoming WDM signal is 'banded' using a de-multiplexer and a TID-PM is used to undo the distortions in each band before the corrected signals are re-combined before further transmission with a multiplexer. Solid-color channels are the band to be compensated in that arm, while open channels are used to estimate the nonlinear distortion, but are not compensated.

V. Conclusion

We have used numerical simulations to show that distributed NLC using TID-PMs could suppress nonlinear distortions in next-generation long-haul coherent optical communication systems. Our method has superior performance to single-channel DBP, and can also compensate for nonlinear distortions on multiple wavelength channels simultaneously. For an 8-channel, 28-Gbaud DP-16QAM signal transmitted over a 15×100km DU link, our simulations show that inline TID-PMs improves the Q of all channels by about 1 dB compared to when NLC is not used, while single-channel DBP using 1-step-per-span only increases peak Q by 0.5 dB.

Acknowledgments

The authors thank VPIphotonics (www.vpiphotonics.com) for the use of their simulation software.

References

[1] P. P. Mitra and J. B. Stark, "Nonlinear limits to the information capacity of optical fibre communications," *Nature*, vol. 411, pp. 1027-1030, 2001.

[2] A. D. Ellis, J. Zhao, and D. Cotter, "Approaching the non-linear Shannon limit," *J. Lightwave Technol.*, vol. 28, pp. 423-433, Feb. 15 2010.

[3] R.-J. Essiambre, G. Kramer, P. J. Winzer, G. J. Foschini, and B. Goebel, "Capacity limits of optical fiber networks," *J. Lightwave Technol.*, vol. 28, pp. 662-701, Feb. 4 2010.

[4] E. Ip and J. M. Khan, "Compensation of dispersion and nonlinear impairments using digital backpropagation," *J. Lightwave Technol.*, vol. 26, pp. 3416-3425, Oct. 15 2008.

[5] X. Liang and S. Kumar, "Multi-stage perturbation theory for compensating intra-channel nonlinear impairments in fiber-optic links," *Opt. Express*, vol. 22, pp. 29733 - 29745, Nov. 20 2014.

[6] A. Chowdhury, G. Raybon, R.-J. Essiambre, J. H. Sinsky, A. Adamiecki, J. Leuthold, C. R. Doerr, and S. Chandrasekhar, "Compensation of intrachannel nonlinearities in 40-Gb/s pseudolinear systems using optical-phase conjugation," *J. Lightwave Technol.*, vol. 23, pp. 172-177, Jan. 1 2005.

[7] S. Kumar and D. Yang, "Optical backpropagation for fiber-optic communications using highly nonlinear fibers," *Optics Lett.*, vol. 36, pp. 1038-1040, Apr. 1 2011.

[8] B. Foo, B. Corcoran, and A. Lowery, "Optoelectronic method for inline compensation of XPM in long-haul optical links," *Opt. Express*, vol. 23, pp. 859-872, Jan. 26 2015.

[9] E. Ip, "Nonlinear compensation using backpropagation for polarization-multiplexed transmission," *J. Lightwave Technol.*, vol. 28, pp. 939-951, 2010.

[10] H. Hu, R. M. Jopson, A. H. Gnauck, M. Dinu, S. Chandrasekhar, X. Liu, C. Xie, M. Montoliu, S. Randel, and C. J. McKinstrie, "Fiber nonlinearity compensation of an 8-channel WDM PDM-QPSK signal using multiple phase conjugations," in *Optical Fiber Communication Conference*, San Francisco, CA, 2014, p. M2C.2.

[11] S. L. I. Olsson, B. Corcoran, C. Lundström, T. A. Eriksson, M. Karlsson, and P. A. Andrekson, "Phase-Sensitive Amplified Transmission Links for Improved Sensitivity and Nonlinearity Tolerance," *J. Lightwave Technol.*, vol. 33, pp. 710-721, Feb. 1 2015.

[12] A. D. Ellis, M. E. McCarthy, M. A. Z. Al-Khateeb, and S. Sygletos, "Capacity limits of systems employing multiple optical phase conjugators," *Opt. Express*, vol. 23, pp. 20381-20393, Aug. 10 2015.

[13] G. P. Agrawal, *Nonlinear Fiber Optics*: Academic Press, 2013.

[14] A. J. Lowery, "Fiber nonlinearity pre- and post-compensation for long-haul optical links using OFDM," *Opt. Express*, vol. 15, pp. 12965-12970, Oct. 1 2007.

[15] T.-K. Chiang, N. Kagi, M. E. Marhic, and L. G. Kazovsky, "Cross-phase modulation in fiber links with multiple optical amplifiers and dispersion compensators," *J. Lightwave Technol.*, vol. 14, pp. 249-260, Mar. 1996.

[16] L. B. Du and A. J. Lowery, "Improved single channel backpropagation for intra-channel fiber nonlinearity compensation in long-haul optical communication systems," *Opt. Express*, vol. 18, pp. 17075-17088, Aug. 2 2010.

[17] L. B. Du and A. J. Lowery, "Improved nonlinearity precompensation for long-haul high-data-rate transmission using coherent optical OFDM," *Opt. Express*, vol. 16, Nov. 7 2008.

[18] G. Bellotti, S. Bigo, P.-Y. Cortès, S. Gauchard, and S. LaRochelle, "10 × 10 Gb/s cross-phase modulation suppressor for multispan transmissions using WDM narrow-band fiber Bragg grating," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 1403-1405, Oct. 2000.

[19] C. R. Menyuk and B. S. Marks, "Interaction of polarization mode dispersion and nonlinearity in optical fiber transmission systems," *J. Lightwave Technol.*, vol. 24, pp. 2806-2826, July 2006.

[20] D. Marcuse, A. R. Chraplyvy, and R. W. Tkach, "Dependence of cross-phase modulation on channel number in fiber WDM systems," *J. Lightwave Technol.*, vol. 12, pp. 885-890, May 1994.