Propagation Symmetry Enhanced Distortion Compensation by Optical Phase Conjugation via Step-Profiling Fiber Links

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Abstract: Fiber spans tailored with stepwise approximate decreasing dispersion and increasing nonlinearity parameters demonstrate enhanced compensation of nonlinear signal distortion by optical phase conjugation. WDM-QAM signal simulations and experiment show gaining >1.2 dB Q^2-factor and 5~6 dB power tolerance over non-profiled links.

1. Introduction

Advances in compensation of nonlinear signal distortion due to the Kerr effect in long distance optical fiber links are of interest for increasing data transmission capacity and reach to meet growing demand. Digital signal processing (DSP) can compensate distortion by numerically solving the nonlinear Schrödinger equation (NLSE) to "backward propagate" the received signal in a virtual fiber with opposite sign parameters [1],[2]. However, computational complexity and reduced benefit for WDM signals can pose limitations. Another approach is optical phase conjugation (OPC) whereby the signal phase is reversed in sign near the mid-point of the link so that distortion from prior transmission is countered in following fiber spans. Its efficacy however relies on designing the fiber link so that the evolution of signal power with respect to fiber dispersion in pre and post OPC spans is symmetric, even with fiber loss [3]. Methods to address this include incorporating Raman gain at the output end of spans so that the power profile mirrors the decreasing power from loss from the span's input [4]. Another is by adding "dispersion loading" (D_{load}) before [3] or after [5] OPC so that the power versus accumulated dispersion in spans pre-OPC is shifted to align regions of highest power where nonlinear distortion dominates to that for post-OPC spans. It was also recently shown that using different fibers for pre- and post-OPC spans having equal magnitude but opposite sign dispersion, plus dispersion compensating every span, can achieve symmetric "re-propagation" [6]. In general, however, efficacy of these and others remains limited with commercial fibers. While numerical simulations have shown the potential of fibers with continuously decreasing dispersion parameter along its length [7], these are unavailable commercially.

In this paper, higher efficacy OPC for compensating nonlinear signal distortion in long distance fiber links is demonstrated based on tailoring combinations of different commercial fibers as a stepwise approximate decreasing dispersion and increasing nonlinearity profile to improve propagation symmetry, that is otherwise degraded by fiber loss. Numerical simulations show 3 step profiled fiber (SPF) comprising 3 fiber types enables transmission of WDM 5×32 Gbaud 64-QAM signals over 12×130 km (1560 km total) with >2 dB higher Q^2-factor and 5 dB higher launch power tolerance compared to no OPC. Experiments for WDM 5×12 Gbaud 16-QAM signals in a 2×155 km link with two step profiled spans also shows a 1.2 dB higher Q^2-factor and 6 dB higher launch power tolerance compared to no OPC, highlighting the improved performance capability over regular OPC schemes and no-OPC in general.

2. Design Concept and Simulation

Consider the NLSE in Eqn. 1 [8] describing propagation of a slowly varying pulse envelope, A, over distance, z, with moving reference time T, and fiber parameters for loss, dispersion and nonlinearity of α, β_2 and γ, respectively. Higher order dispersion and other nonlinear terms are ignored.

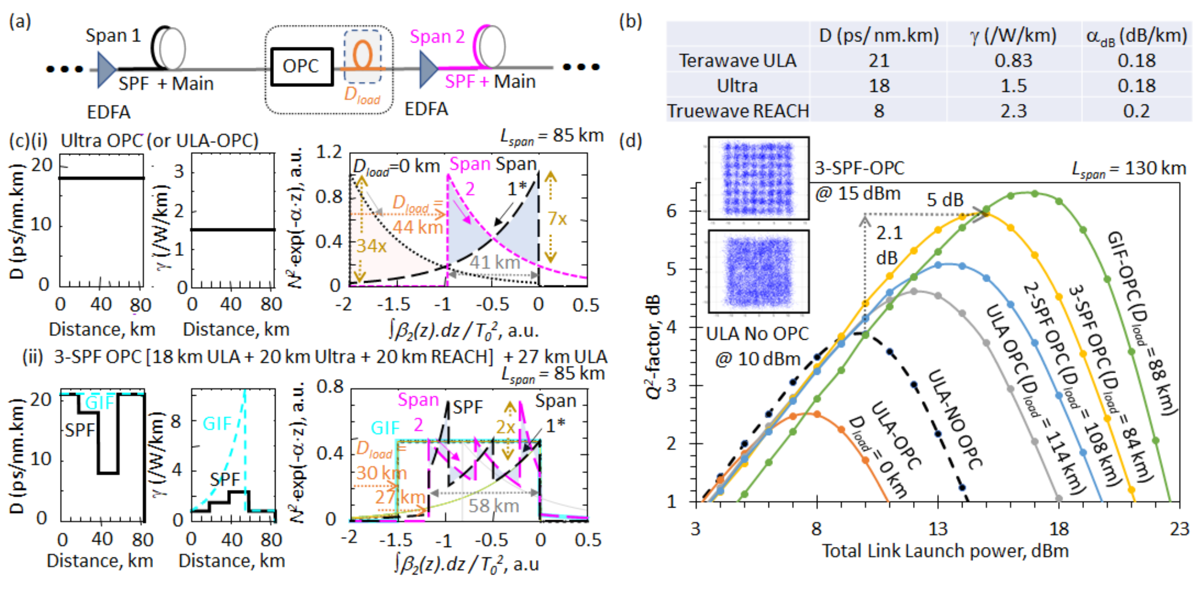
$$i\frac{\partial A}{\partial z} = -\frac{i\alpha}{2}A + \beta_2\frac{1}{2}\frac{\partial^2 A}{\partial T^2} - \gamma|A|^2 A \tag{1}$$

Applying the normalizations of time relative to input pulse width T_0 as $\tau = T/T_0$, amplitude, U as $A(z,\tau) = \sqrt{P_0}\cdot\exp(-\alpha\cdot z)\cdot U(z,\tau)$ where P_0 is the input peak power, and distance $\xi = z/L_D(0)$ in terms of the pulse dispersion length at the fiber input given by $L_D = T_0^2/|\beta_2(0)|$ gives the equivalent Eqn. 2 [8], including the parameter, $N^2 = P_0\cdot\gamma\cdot T_0^2/|\beta_2|$.

$$i\frac{\partial U}{\partial \xi} = sgn(\beta_2)\frac{1}{2}\frac{\partial^2 U}{\partial \tau^2} - N^2 e^{-\alpha z}|U|^2 U \tag{2}$$

Evidently if tailoring fiber links with appropriately increasing γ and/or decreasing β_2 with distance to counter loss so that $N^2\cdot\exp(-\alpha\cdot z)$ remains constant, then Eqn. 2 takes the form of Eqn. 1 without the loss term as originally proposed for solitons [9], to allow symmetric propagation in lossy fibers as desired for OPC. While such fibers are challenging to fabricate, this work explores the effectiveness of a stepwise approximation with commercially available fibers. A design example is presented for a 2×85 km link (L_{span} = 85 km) shown schematically in Fig. 1(a). Calculated $N^2 \cdot \exp(-\alpha \cdot z)$ versus $\int \beta_2(z) \cdot dz/T_0^2$ (i.e. normalized accumulated dispersion for integral from z = 0 up to $z = L_{span}$) were compared considering fiber parameters in Fig. 1(b) for Corning Ultra, OFS Furukawa Terawave ULA and Truewave REACH. Relevant assumed signal parameters were T_0 = 31.25 ps for a 32 Gbaud symbol period, and P_0 = 16 mW for the peak power of a NRZ PRBS signal with total average power = 16 dBm for 5 WDM channels. The OPC operation was represented by reversing in sign accumulated dispersion for the first span. For an Ultra fiber link only (Ultra-OPC), propagation is highly asymmetric, with large mismatch as shown in Fig. 1(c) (shaded area), and a peak mismatch factor as large as 34 with respect to the corresponding span input where nonlinear distortion is strongest. Introducing the D_{load} method significantly improved it as shown in Fig. 1(c), reducing the peak mismatch factor to 7. The contrasting benefit of a 3 step profiled fiber (3-SPF) is shown in Fig. 1(c). This comprised of 18 km Terawave ULA fiber followed by 20 km Ultra and 20 km REACH, giving stepwise increasing γ and decreasing β_2 over 58 km. An appended 27 km Ultra fiber gave L_{span} = 85 km. The peak mismatch factor was now reduced to just 2. Notably, the Terawave fiber is favorable for lowest N^2 translating to higher transmission performance, with or without OPC. Also shown in Fig. 1(c) is the perfect symmetry achievable in principle for a fictitious 55 km long "gamma" increasing fiber (GIF) with $\gamma(z) = \gamma(0) \cdot \exp(0.046 \cdot z)$ at a rate matched to its propagation loss of 0.2 dB/km, and β_2 and $\gamma(0)$ matching Terawave. However, a more general design would account for variable pulse width in N^2, rather than being constant (i.e. $L_{span} \ll L_D$), and as well as T_0 representing group delay walk-off between WDM channels.

The SPF effectiveness was evaluated by numerical simulations. The input was a dual polarization (DP) 32 Gbaud 5 channel WDM signal on a 50 GHz grid generated at around 1550 nm and modulated with 64-QAM data (2^{13}-1 PRBS). This was amplified and launched into a transmission link of 12×130 km spans (1560 km total) based on Terawave ULA fiber. Ideal OPC was performed after the 6th span as a phase sign reversal. Transmission was compared for the above described 58 km 3-SPF, 55 km GIF, plus 38 km 2-SPF (3-SPF without REACH). Terawave ULA constituted the remainder for L_{span} = 130 km. The D_{load} stage was Ultra fiber with length optimized for best performance. At the receiver, the center channel was demodulated and its Q^2-factor evaluated from the constellations. The reference case was all Terawave fiber spans and no OPC (ULA-no OPC). As Fig. 1(d) shows, 3-SPF OPC gave >2 dB higher Q^2-factor and 5 dB higher launch power tolerance for same performance as ULA-no OPC. Its Q^2-factor was also 1.4 dB higher than for the Terawave link with OPC and D_{load} (ULA-OPC), and only 0.3 dB worse than ideal GIF-OPC. For 2-SPF, Q^2-factor was reduced by 1 dB, but still 0.4 dB better than ULA-OPC.



	D (ps/ nm.km)	γ (/W/km)	α_{dB} (dB/km)
Terawave ULA	21	0.83	0.18
Ultra	18	1.5	0.18
Truewave REACH	8	2.3	0.2

Fig. 1. (a) Link schematic for higher efficacy compensation of nonlinear distortion by OPC using SPF before main fiber, all based on commercial fiber types in (b). (c) Evolution of $N^2 \cdot \exp(-\alpha \cdot z)$ from Eqn. 2 for pre and post OPC transmission in 85 km spans using Ultra fiber (i) exclusively (Ultra-OPC), or (ii) after 58 km 3-step fiber (3-SPF OPC), or fictitious 55 km fiber with exponentially increasing γ (GIF-OPC). (d) Numerically simulated Q^2-factor and (inset) constellations for WDM 5×32 Gbaud DP-64-QAM signal after 12×130 km (1560 km) of either ULA, or 38-58 km SPF or 55 km GIF plus ULA (main), assuming ideal OPC and span amplifier noise figure = 5 dB.

3. Experiment and Results

A proof-of-concept experiment was performed using the set-up in Fig. 2. Five DP-12 Gbaud WDM channels on a 50 GHz grid were generated around 1550 nm and modulated with the same 16-QAM data (2^{15}-1 PRBS). The channels were combined, polarization multiplexed, amplified and filtered then propagated in 30 km of Ultra fiber for WDM channel decorrelation before launching into a 2×155 km link also based on Ultra fiber. The 2-SPF was comprised of 21 km Ultra and 20 km REACH, followed by 113 km Ultra (main). Performance was compared to a link comprising 155 km spans of Ultra fiber only with OPC (Ultra-OPC) and without. The OPC was implemented as shown in Fig. 2(b) with dual orthogonal CW pumps at 1543 and 1561 nm driving polarization insensitive four wave mixing in a 100 m long highly nonlinear fiber for a conjugated signal centered at 1553.5 nm. Optimized D_{load} lengths after OPC were 113 and 126 km for 2-SPC and Ultra-OPC, respectively. At the receiver, the center channel was filtered and coherently detected before offline DSP for signal demodulation. The Q^2-factor was calculated from constellations and bit error rate (BER) counted from the expected pattern. Results in Fig. 3 show similar general trends to simulations with 2-SPF-OPC outperforming both Ultra-OPC and no OPC. Compared to no OPC, Q^2-factor was enhanced by 1.2 dB and launch power tolerance for same performance extended by 6 dB. The BER showed similar features with significantly improvement below the hard decision FEC limit (4.5×10^{-3}). This is despite non ideal OPC adding significant penalty. Adding Terawave fiber for 3-SPF-OPC is expected to further enhance performance.

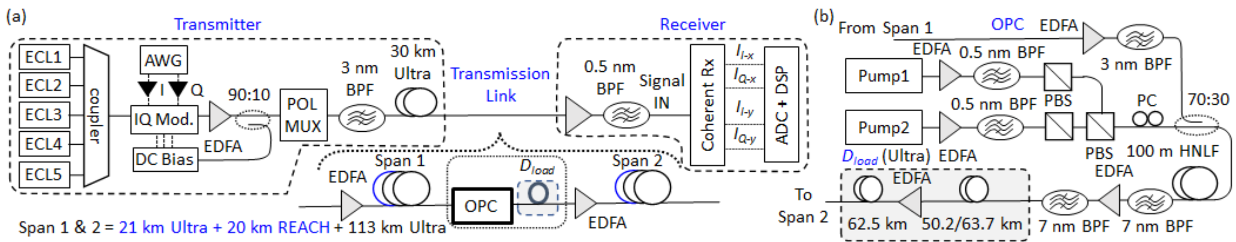


Fig. 2. Experimental set-ups of WDM 5×12 Gbaud DP-16 QAM signal transmitter and receiver for 2-SPF OPC link with 21 km Ultra + 20 km REACH fiber before 113 km Ultra and mid-link (b) OPC and D_{load} stage of Ultra fiber with length optimized for minimum BER.

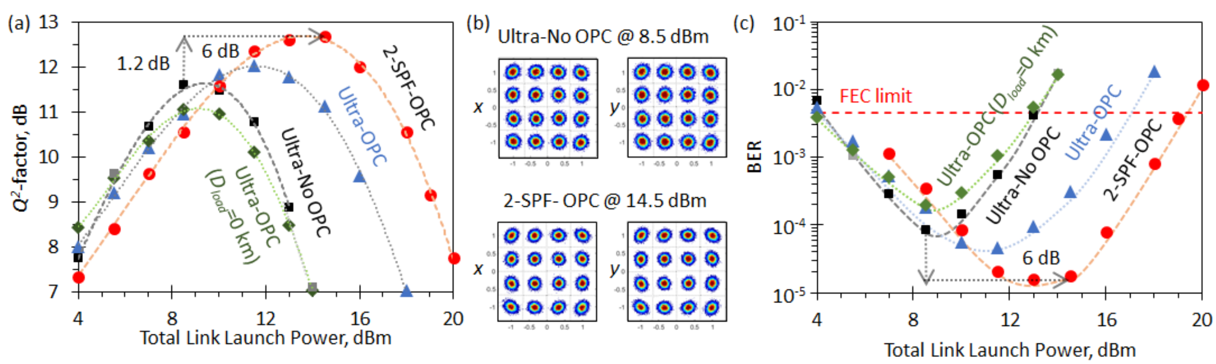


Fig. 3. Experimental (a) Q^2-factor, (b) *x-y* pol. constellations and (c) BER of WDM 5×12 Gbaud DP-16-QAM signal in 2 span fiber link comprising 41 km 2-SPF before 113 km Ultra or 155 km Ultra only, and OPC + optimized D_{load}=113 and 126 km, respectively or no OPC.

4. Conclusions

Stepwise approximate profiling of both dispersion and nonlinearity in optical fiber links demonstrated significant enhancement of OPC efficacy for compensating nonlinear distortion compensation via improved propagation symmetry. Simulations and experiments for commercially available fiber parameters showed significantly higher performance and nonlinear distortion tolerance of QAM signals over regular OPC schemes and no OPC in general.

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5. References

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