Symmetry Enhancement Through Advanced Dispersion Mapping in OPC-Aided Transmission

Kaminski, Pawel Marcin; Ros, Francesco Da; Yankov, Metodi Plamenov; Clausen, Anders Thomas; Forchhammer, Søren; Oxenløwe, Leif Katsuo; Galili, Michael

Published in:
Journal of Lightwave Technology

Link to article, DOI:
10.1109/JLT.2021.3060548

Publication date:
2021

Document Version
Peer reviewed version

Link back to DTU Orbit

Citation (APA):
Symmetry Enhancement Through Advanced Dispersion Mapping in OPC-Aided Transmission

P.M. Kaminski, F. Da Ros, M.P. Yankov, A.T. Clausen, S. Forchhammer, L.K. Oxenløwe, and M. Galili

Abstract—In this work, we present a novel strategy to satisfy the nonlinearity compensation criteria by optical-phase-conjugation (OPC). Contrary to the most common approach, which relies on tailoring power profiles using distributed Raman-amplification, we achieve the required OPC propagation symmetry through optimized dispersion management across the link. The method is applied to transmission systems with periodic lumped amplification, and the symmetry enhancement is directly translated into a substantial increase in the OPC compensation gains. This study is based on a numerical analysis combined with experimental validation of the findings. The numerical part provides a comprehensive overview of different dispersion management techniques, and compares them against the symmetric schemes we propose. It is consistently shown that the symmetry-optimized systems provide the best performance when OPC is included, with the signal-to-noise ratio (SNR) gains reaching up to 6.6 dB and 5.2 dB for transmission of a single and seven wavelength channels, respectively. These results are verified in an experimental investigation, where we implemented and compared a standard dispersion mapping scheme to the optimized design. For all distances considered, the optimized link is demonstrated superior once OPC is included, leading up to 1.9 dB improvement in SNR for seven-channel transmission.

Index Terms—four-wave mixing, optical-phase-conjugation, quadrature-amplitude-modulation, coherent communications.

I. Introduction

As the traffic demand for telecommunication services is steadily increasing, the present day communication networks are struggling to keep up. In particular, modern fiber-optic systems are facing performance limitations due to the inherent Kerr nonlinearity of silica glass [1]–[3], which is causing signal impairments that are difficult to compensate. Suppression of the fiber nonlinearity or compensating the nonlinear distortions have therefore been attracting a lot of attention, and the problem can generally be addressed using either digital or optical techniques. Digital methods tend to introduce significant latency due to numerical complexity, and are restricted to processing a single frequency channel due to limited electrical bandwidth of the receiver [4]. [5]. On the contrary, optical approaches are close to instantaneous and suitable for multi-channel applications in wavelength-division multiplexed (WDM) systems, as the optical field is processed prior to being received. Among the optical schemes, optical phase conjugation (OPC) has been demonstrated to be a viable option to address the impairments [6]–[20], but it has remained difficult to implement efficiently in practice. The method is based on reversing and reapplying the impairments on both sides of the OPC, such that they cancel out in the end. Consequently, for achieving relevant performance gains, the OPC technique relies on a specific link design that ensures identical impairments are induced on each side. This requirement directly translates into propagation symmetry with respect to the OPC position [21], [22], which has been historically challenging to achieve and impractical to deploy. Nonetheless, OPC has been widely studied for standard links based on erbium-doped fiber amplifiers (EDFA), though they generally fail to satisfy the strict compensation criteria and only offer moderate improvement [6]–[13]. Better results can be achieved by enhancing the symmetry through manipulation of the power profiles, and indeed Raman-amplified systems with OPC have shown superior performance [14]–[20]. This approach is particularly efficient for short amplifier spacing [18]–[20], yet, it substantially increases the system’s cost and complexity.

In this paper, we extend our previous work [23], [24] to present a comprehensive overview of enhanced dispersion design for OPC-aided transmission. Instead of controlling the power profiles by means of Raman-amplifiers, we accept the exponential power decay of standard systems, and we rely on advanced dispersion mapping to satisfy the OPC compensation criteria. The core analysis is performed for three distinct link configurations: (1) dispersion uncompensated, (2) dispersion managed, and (3) dispersion optimized. The uncompensated [6]–[8] and managed [9]–[11] scenarios are standard and well-known strategies, which provide limited propagation symmetry for systems including OPC. The dispersion optimized link is the scheme we propose to improve the symmetry, and boost the compensation gains.

The work is based on both a numerical and experimental investigation, and it is organized as follows. In Section II, we review the theoretical background for OPC-based nonlinearity compensation and discuss the typical approach of achieving the symmetry. Then in Section III, we introduce the standard and optimized systems, and analyze them numerically using the split-step Fourier method (SSFM) [25], [26]. The links are compared with respect to the impact of the transmission bandwidth, the OPC compensation gains, and the overall system performance. Finally, they are implemented experimentally in Section IV to validate
the findings, and the paper is concluded in Section V.

II. OPC Symmetry Requirements

We start by reviewing the requirements for efficient nonlinearity compensation by means of OPC. As mentioned in Section I, the technique is based on accumulating initial nonlinearity in the first part of the link, then reversing its sign by phase-conjugation of the optical field, and reapplying the same nonlinear impairments in the second part. Consequently, complete nonlinearity suppression requires identical nonlinear phase-shifts on both sides of the OPC, as in:

$$\int_0^{L_1} \gamma_1 |A(z, t)|^2 dz = \int_{L_1}^{L_1+L_2} \gamma_2 |A(z, t)|^2 dz,$$

where $L_1$ and $L_2$ are lengths of the fiber segments before and after the OPC, $\gamma_1$ and $\gamma_2$ are the respective nonlinear coefficients, and $A(z, t)$ is the complex amplitude of the optical field traversing the fiber. Note that $|A(z, t)|$ is both power and pulse shape dependent. Matching the integrals therefore requires the same powers to be induced at identical pulse shapes on both sides of the OPC, given that $\gamma_1 = \gamma_2$. Because pulse shapes are predominantly determined by the accumulated dispersion, this requirement ultimately reduces to a well-known metric of OPC effectiveness called power versus accumulated dispersion diagrams (PADD) [21], [22].

The typical approach to achieving the symmetry is depicted in Fig. 1 where the field conjugation is performed in the middle of the system, with identical fiber spans on each side. In this scheme, we require an exponential power decay on one side of the OPC, and an exponential power increase on the other side. The accumulated dispersion simply increases linearly throughout the propagation distance in both spans (Fig. 1b). In this simplest case, the OPC device is included in the middle of the link [6], and it changes the sign of the phase of $A(z, t)$, negating phase-distortions like the accumulated dispersion of even order and the nonlinear phase-shift (Fig. 1c). Note, however, that phase-conjugation does not affect $|A(z, t)|$, thus the sign of the phase impairments is irrelevant to the pulse shape. Consequently, as long as the same power is continuously achieved at opposite values of the accumulated dispersion for the signal in the first half, and its conjugate copy in the second, dispersion and nonlinearity compensation can be successfully achieved [21], [22]. This relation is captured by PADD, as outlined in Fig. 1d, and it is referred to as propagation symmetry thereafter. Aside from the symmetric PADD, the nonlinearity in this example is compensated in the reverse order of how it was accumulated, i.e. the distortions from the beginning of the first span are compensated at the end of the second span, which can lead to complete nonlinearity cancellation. However, it is noted that PADD does not account for amplifier noise [27], higher order chromatic dispersion [28] or polarization-mode dispersion (PMD) [29], all of which could limit the symmetry and reduce the compensation effectiveness. As a result, perfectly symmetric PADD does not guarantee complete nonlinearity suppression, but it still drastically improves the gains.

Although the links from Fig. 1 have been successfully demonstrated using distributed amplification [15], [20], matching the slopes of the power profiles is cumbersome and requires short amplifier spacing. As a result, realistic systems still suffer from the symmetry mismatch [13]–[17], which limits the compensation gains and undermines the benefits of OPC in practical applications. Aside from Raman-amplification, other ways of achieving the symmetry in PADD exist. In particular, it is not explicitly required to use the same fiber types on both sides of the OPC. In [30]–[32], the nonlinear integrals are matched by using a long transmission link on one side of the OPC, and a scaled-down compensation structure that mimics the nonlinear evolution on the other side. As a result, the propagation on each side of the OPC can still be equivalent, despite the different fiber types and transmission distances. However, because of practical equipment limitations, these demonstrations only achieved partial symmetry in PADD, which reduced the corresponding compensation gains. A similar approach was adapted in the theoretical investigation in [33], where a step-like structure was employed for the compensation, and in [34], [35], where the compensation medium was based on a dispersion-compensating or dispersion-decreasing fiber. In each system, the requirements for perfect nonlinearity cancellation were analytically derived, resulting in excellent propagation symmetry. However, such specific compensation structures are difficult to design and manufacture, which makes these methods...
extremely challenging for real-life applications. On the contrary, this work relies on readily available fiber types on either side of the OPC restricting the analysis to practical systems. Still, perfect symmetry in PADD is attained.

III. Numerical Analysis

In this section we numerically evaluate typical dispersion maps with respect to the OPC symmetry, and compare them against the optimized scenarios. The simulation setup is sketched in Fig. 2. At the transmitter side, up to seven WDM channels are generated around 1550 nm from ideal laser diodes (LDs) represented by delta functions in frequency. The LDs are modulated with independent 16-quadrature-amplitude-modulated (16-QAM) data on both polarizations, and combined altogether. The channel count, baud rate and frequency spacing are varied throughout the simulations, as indicated in the corresponding subsections. The signal is then amplified, and the out-of-band noise is filtered out, such that the starting optical signal-to-noise ratio (OSNR) is maintained at 40 dB per channel at the input to the link. Propagation is simulated using SSFM with a varying step-size [26], and PMD as well as higher order chromatic dispersion are neglected in all the simulated links to focus on the symmetry design and the respective PADDs. Noise figures of EDFA in the systems are fixed to 5 dB, and the OPC is modelled using ideal conjugation of the complex envelope of the optical field as: $A(z,t) \rightarrow A^*(z,t)$ without any penalties associated with the process. The OPC penalties are instead considered for the experimental system implementation in Section IV. After transmission, the signal is received with a standard coherent receiver followed by equalization, carrier-phase recovery and signal-to-noise ratio (SNR) estimation. The effective receiver SNR is estimated directly from the transmitted and received symbols after the entire DSP chain, according to:

$$<\text{SNR}> = E_k[|x_k|^2]/E_k[|y_k - x_k|^2],$$  \hspace{1cm} (2)

where $E[\cdot]$ is the expectation operation and $x_k$ and $y_k$ are the $k$’th transmitted and received QAM symbols, respectively [36]. The numerical analysis is performed for two-span links based on different fiber types in Section III-A and III-B. In Section III-C the simulations are extended to multi-span systems.

A. Two-span systems based on SSMF and IDF

We analyze the transmission performance and the OPC gains for three distinct transmission links: dispersion uncompensated (DU), dispersion managed (DM) and dispersion optimized (DO), as depicted in Fig. 3. Each link consists of two 80-km fiber spans with EDFA-amplification. Depending on the scenario, the spans are made of two types of fiber: standard single-mode fiber (SSMF: $\alpha = 0.2$ dB/km, $D = 17$ ps/nm/km, $\gamma = 1.3 /$W/km), and inverse-dispersion fiber (IDF: same as SSMF except for $D = -17$ ps/nm/km).

The first link under analysis is a typical dispersion uncompensated scenario (Fig. 3, DU1), which is composed of two identical SSMF spans with either a standard EDFA or OPC in the middle. Because of the exponential power decay in the spans, the resultant PADD of this system for the case with OPC is highly asymmetric, with the high power region occurring at low (positive) accumulated dispersion for the signal, and high (negative) accumulated dispersion for the conjugate (Fig. 3, DU1). As a result, the nonlinearity is mismatched between the spans, and the OPC compensation gains are known to be limited for such link design [6], [7]. The second scenario is a dispersion managed system (Fig. 3, DM1), where the accumulated dispersion of the first-span is compensated mid-way using a lumped dispersion compensating module. Its PADD is still asymmetric, as positive accumulated dispersion is maintained throughout the entire link (Fig. 3, DM1).

Nonetheless, the high power region of each span occurs close to zero accumulated dispersion, where some matching exists and partial nonlinearity compensation is possible [9]–[11]. Finally, we propose the dispersion optimized link (Fig. 3, DO1), which consists of SSMF in the first half and IDF in the second half. Without OPC, the link is only EDFA-amplified mid-way, such that the accumulated dispersion grows in the first span, and returns to zero in the second span (Fig. 3, DO1). For the case with OPC, an additional dispersion compensating module is added in the middle to completely compensate the dispersion from the first span. As a result, the accumulated dispersion increases from zero in the first half, and it decreases from zero in the second half (Fig. 3, DO1). The resultant PADD of this system perfectly satisfies the symmetry conditions, with identical powers induced exactly at the opposite values of the accumulated dispersion for both the signal and the conjugate (Fig. 3, DO1). Note that this map is equivalent to the ideal Raman-amplified scenario from Fig. 4, though the nonlinearity is effectively cancelled in a reversed order, i.e. the distortions from the beginning of the first span are compensated at the beginning of the second span. Nonetheless, because of the perfect symmetry in PADD, it offers major performance improvement, as we will show next.

The dispersion managed (DM1) and dispersion optimized (DO1) links require dispersion compensating modules installed mid-way. Such modules certainly exist [37], [38], and they have been previously employed for...
Our Systems: SMF/IDF

Comment: ECOC figures with adjustments.

%% SSMF & IDF Parameters / Transmission

L1 = 80; \( \text{km} \)
\( \alpha_1 = 0.2; \) \( \text{dB/km} \)
\( \gamma_1 = 1.3; \) \( \text{1/W/km} \)
\( D_1 = 17; \) \( \text{ps/nm/km} \)

EDFANF = 5;

PADDs look promising – let’s see the results!

---

Fig. 3. Analyzed transmission systems: power (solid) and accumulated dispersion (dashed) evolution in distance without (a) and with (b) OPC. (c) The resultant PADD for symmetry evaluation. Propagation of signal and conjugate marked in blue and red, respectively.

Introduce the systems:

- Dispersion Uncompensated (DU1)
- Dispersion Managed 1 (DM1)
- Dispersion Optimized 1 (DO1)

Discuss each scheme w.r.t. PADD

Fig. 4. Alternative implementation of dispersion managed (DM) and dispersion optimized (DO) links based on composite fibers: power (solid) and accumulated dispersion (dashed) evolution in distance without (a) and with (b) OPC. The resultant PADD in (c). Signal and conjugate marked in blue and red, respectively.

Fig. 5. Simulated SNR as a function of the launch power for the discussed two-span systems (DU, DM, DO) based on SSMF and IDF. Results for the links without (solid) and with (dashed) OPC for a varying baud rate and channel count, as indicated.
enhancing the symmetry of OPC-aided links with lumped amplification \(^{[39]}\), though they increase the complexity of the system. In Fig. \(4\), equivalent implementations of these links are presented (DM2 and DO2) without relying on lumped dispersion compensation. The link is now built from a composite SSMF+IDF fiber such that dispersion is completely compensated at the end of each span. Similarly to the previously discussed schemes, DM2 has positive accumulated dispersion across the entire link, resulting in poor symmetry in PADD. Whereas in DO2, the order of the fibers in the second span is reversed, such that the same powers continuously occur at the opposite values of the accumulated dispersion, leading to ideal PADD and high OPC gains. Note that DM2 and DO2 require the same amount and type of fibers, and can be interchanged by flipping the fiber ends in the second part of the system. Nonetheless, the OPC compensation effectiveness is drastically different because of the corresponding changes in PADD. Such links have been previously considered in \(^{[40]}\) in the context of the Kerr-induced perturbations, but not explicitly for OPC-based compensation.

The discussed systems are simulated for the case with and without OPC, and the performance is evaluated by means of the received SNR of the central channel as a function of the total launch power into each span. The results are illustrated in Fig. \(5\) for a varying baud rate and channel count in order to highlight the impact of the transmitted bandwidth on the OPC gains.

In Fig. \(5a\)-\(b\), the simulation results for the three systems depicted in Fig. \(3\) are presented for a single channel at 8 Gbd and 16 Gbd, respectively. The performance is close to identical for the considered links without OPC, as it is not impacted by the symmetry design. However, the difference is apparent once OPC is included, and the results improve dramatically. The OPC gains for DU1 and DM1 reach up to 4.6 dB at 8 Gbd and 2.1 dB at 16 Gbd, despite the limited symmetry in PADD. Note that the gains are similar, yet they originate from matching of different regions of the link. For DU1, the power profiles are heavily mismatched, but the accumulated dispersion takes both positive and negative values, allowing for weak compensation across the entire system. On the other hand, for DM1, there exists significant nonlinearity matching in the high power regions alone, where the accumulated dispersion is close to zero in both spans. Nonetheless, both schemes are clearly outperformed by DO1, which leads to the highest gains of 6.6 dB at 8 Gbd and 5.6 dB at 16 Gbd, with the performance approaching the back-to-back reference measured with neither the link, nor any additional noise loading. The improvement for DU1 and DM1 steadily decreases with increasing baud rate, while the gains remain high for DO1 with the symmetric PADD. Indeed, the higher baud rate increases the signal broadening, which consequently leads to greater temporal broadening due to accumulated dispersion according to: 
\[
\Delta T = D_{acc} \ast \Delta \lambda \]
As a result, for asymmetric PADD the temporal mismatch of the waveforms is larger at broad signal bandwidths, reducing the compensation gains.

In Fig. \(5c\)-\(d\), the results of all of the five discussed systems are presented for a single and seven WDM channels at 32 Gbd. Because of the broad transmission bandwidth, the scenarios with asymmetric PADD blend together with little to no nonlinearity suppression. However, the optimized links (DO1 and DO2) clearly stand out and offer significant improvement compared to non-OPC scenarios, gaining up to 4.6 dB and 5.2 dB for a single and seven channels, respectively. The compensation gains are higher for seven channels compared to one channel because of the additional inter-channel nonlinearity which is then also addressed.

Ultimately, it is clear from Fig. \(5\) that the symmetry design plays a key role in the OPC-aided transmission, and the optimized scenarios consistently outperform the counterparts, approaching near back-to-back performance by a small SNR margin down to 1.2 dB for seven WDM channels. Moreover, these results outline that strong symmetry in PADD is crucial for the performance improvement in broadband systems. Consistent with \(^{[12]}\), \(^{[13]}\), the compensation effectiveness of standard links reduces rapidly as the transmission bandwidth increases. However, the dispersion optimized schemes we propose demonstrate resiliency and maintain the gains even at large bandwidths.

B. Two-span systems based on SLA and IDFx2

The optimized scenarios (DO1 and DO2) form ideal PADDs, but they both rely on the availability of IDF, which does exist but is not mass produced. Therefore, the numerical analysis is also conducted for a more typical link configuration based on super-large-area (SLA) fiber and inverse-dispersion-fiber with twice the dispersion (IDFx2), as illustrated in Fig. \(6\) alongside the fiber parameters. Such fibers exist and are commercially available \(^{[9]}\)–\(^{[11]}\).

Similarly to Fig. \(3\), the systems based on SLA+IDFx2 form 80-km fiber spans, and are categorized as dispersion managed (DM) and dispersion optimized (DO), with the corresponding PADDs sketched in Fig. \(6\). DM link is made of SLA followed by IDFx2 on both sides of the OPC, whereas the fiber order is reversed on one of the sides for DO. For completeness, we analyze the link with the right side of the OPC reversed (referred to as DO1 thereafter - illustrated in Fig. \(6\), and the left side of the OPC reversed (DO2). Ultimately, the simulated configurations include:

- DM: SLA+IDFx2 → OPC → SLA+IDFx2;
- DO1: SLA+IDFx2 → OPC → IDFx2+SLA;
- DO2: IDFx2+SLA → OPC → SLA+IDFx2.

Note that the PADD symmetry for the optimized schemes is not ideal anymore because of the mismatch in the group velocity dispersion between the two fiber types (Fig. \(3\), DO), which directly impacts the OPC gains. Moreover, the compensation requires that the exact nonlinearity generated in SLA is reapplied in IDFx2, yet the fibers have different nonlinear coefficients \(\gamma\)’s, leading to unequal phase-shifts as in Equation \(^{[1]}\). Consequently, we have to
launch different powers into the span before and after the OPC to equalize the nonlinearity. Although it could seem sufficient to maintain the ratio of launch powers inversely proportional to the ratio of γ’s, it might not lead to the best result as the optimum power levels for symmetric propagation are also impacted by variations in other propagation parameters, e.g. the second-order dispersion, which determines pulse shape evolution, and the fiber loss, which defines change of power across ranges of pulse shapes. As the fiber parameters are fixed, it might not be possible to consistently restore the correct nonlinearity across the entire range of pulse shapes regardless of the ratio of powers, and some mismatch will inevitably occur. To minimize this mismatch, we rely on numerical optimization of the relative launch powers with respect to the receiver SNR, and we refer the readers to [41] for a more in-depth discussion on the OPC symmetry scaling principles. For convenience, we define the relative input power difference as ΔP [dB] = P1 [dBm] − P2 [dBm], where P1 is the power into the first span, and P2 is the power into the second span. Both powers are jointly optimized to maximize the performance, resulting in an optimum ΔP of the system. The results for seven WDM channels at 32 Gbd are presented in Fig. 7 for DM and in Fig. 7-d for DO1 and DO2.

In Fig. 7a, the maximum SNR of DM system is given as a function of ΔP. As the order of the fibers is the same on both sides of the OPC, the maximum SNR is attained at P1 = P2 = 9 dBm for the case without OPC and P1 = P2 = 10 dBm for the case with OPC, respectively. In Fig. 7b, the input power sweep is shown at the optimum power difference, ΔP = 0 in this case, to visualize how the result was obtained. Because of the weak symmetry in PADD for DM link, the OPC gains are significantly limited, resulting in a modest 0.6 dB improvement in SNR. This result is compared against the previously analyzed
C. Multi-span analysis

Because the SLA+IDFx2 links are commercially available and thus more accessible, the analysis of these systems is extended to multi-span simulations. To maintain the characteristics of the analyzed links (DM, DO1, DO2), the corresponding N-span systems are formed by repeating the patterns on each side of the OPC N/2 times, as illustrated in Fig. 9. For the case with OPC, the conjugation is only performed once, and always in the middle.

Similarly to Fig. 7 the relative launch power optimization is performed for a varying number of spans, and the results of seven-channel transmission at 32 Gb/s are presented in Fig. 9 for DM and in Fig. 9a for DO1 and DO2. As expected, it is confirmed that the optimum relative power difference is independent of the number of spans, with a fixed $\Delta P = 0$ dB for DM, and $\Delta P = \pm 3$ dB for DO1 and DO2. The optimum $\Delta P$ values are used to compare the maximum performance of each of the systems with and without OPC as a function of the transmitted distance, with the results presented in Fig. 9b. Alongside the discussed configurations, we provide linear transmission results of DM system to serve as a reference, and they are obtained by maintaining the optimum launch powers from DM without OPC, but completely neglecting the fiber nonlinearity across the link ($\gamma = 0$). For clarity, the corresponding linear results for DO1 and DO2 are omitted, as they approach the same SNR as DM linear due to similar total transmission loss.

Without OPC, it is found that DM outperforms DO1 and DO2 by up to 0.7 dB at 1600 km, which corresponds to 20 spans. For such cases, DM is superior because the high-power regions always occur in the less nonlinear SLA fiber, whereas for DO the high-power regions on one of the sides occur in IDFx2. Because of the limited symmetry in PADD, inclusion of OPC only marginally improves DM scenario by an additional 0.7 dB, and it is still 1.1 dB down relative to the linear DM performance. On the other hand, OPC substantially enhances DO1 and DO2 schemes by up to 4.1 dB as the corresponding PADDs are much more symmetric. Ultimately, both DO1 and DO2 are superior for the case with OPC, and they offer up to 3.4 dB net gain in SNR for 1600 km transmission, when compared to DM configuration without OPC. Thanks to inclusion of OPC as well as advanced dispersion mapping, DO1 and DO2 in fact outperform linear DM scenario by up to 1.6 dB, indicating a high degree of compensation and a substantial increase in the allowed launch powers, which consequently improves the OSNR and SNR at the receiver. For the linear system, the launch power is bounded to lower values, which limits the OSNR and SNR at the receiver, despite the fact that the nonlinearity is then neglected.

IV. Experimental Analysis

In this section, we verify the efficiency of the method experimentally using the links depicted in Fig. 9. The spans are made of SLA and IDFx2 fibers spliced together, and the scenarios under test are defined as:
The experimental analysis is conducted for seven WDM channels at 32 Gb/s with 16-QAM dual-polarization modulation, which is consistent with the numerical simulations. Similarly, SNR of the central channel is again used as the performance metric. However, real-life limitations that can hinder the symmetry are now included, in particular the fibers' PMD as well as dispersion slopes (SLA: 0.06 ps/nm/km; IDFx2: -0.13 ps/nm/km).

A. Experimental Setup

The setup is sketched in Fig. 10, and it largely resembles the simulation system from Fig. 2. Seven WDM channels are generated on a 37.5 GHz grid using 10-kHz linewidth external cavity lasers (ECLs) at around 1540 nm, and they are modulated using two modulators (one for even, and one for odd channels). The channels are combined, amplified and polarization-multiplexing is emulated with additional delay lines. The transmission is based on two time-synchronized recirculating loops with an optional OPC in the middle. Each loop consists of two spans of 80-km SLA+IDFx2 fiber with EDFA-amplification. An additional EDFA follows by a gain flattening filter (GFF) to compensate the residual loop loss and equalize the gain tilt, respectively. Whereas two acousto-optic modulators (AOMs) are used for loop control. The signal enters the first loop through AOM1, and it starts circulating (AOM1 set to block, AOM2 set to pass). After a specified number of turns (each turn being 160 km), it passes to the second loop and circulates it in the same manner via AOM3 and AOM4. The first loop emulates the link before the OPC (Link1), with each span made of SLA+IDFx2 composite fiber for both DM and DO1 links. In the second loop (Link2), the fiber order of each span is maintained for DM, though it is reversed for DO1 to enhance the symmetry in PADD (see Fig. 3). After transmission, the signal is received with a coherent receiver followed by a DSP chain and SNR estimation.

The OPC implementation is sketched in Fig. 11 and it relies on degenerate four-wave-mixing (FWM) in a strained highly nonlinear fiber (HNLF) using a bidirectional loop configuration for polarization insensitive operation [12]–[14]. At the OPC input, the signal at 1540 nm is combined with a high-power pump around 1545 nm before entering the HNLF (α = 0.82 dB/km, γ = 9.7 W/km, L = 254 m, S = 0.07 ps/nm²/km, and zero-dispersion wavelength at 1544 nm), where the conjugate wave (idler) is generated around 1550 nm. The input signal power (P_s) is optimized and maintained at around 14 dBm for both polarizations to minimize the conversion penalty, whereas the pump power (P_p) operates just below the stimulated Brillouin scattering (SBS) threshold of the HNLF at 25 dBm per polarization, which results in output conversion efficiency of -6 dB, as calculated from the ratio between the idler and signal powers at the output of the HNLF. At the output of the OPC, the signal and the pump are suppressed using an optical band-pass filter (OBPF) with a bandwidth of approximately 2.5 nm to match the transmitted data spectrum. To minimize the total OPC loss, dedicated WDM couplers are used for combining the pump with the signal at the OPC input, and they also provide additional pump suppression at the OPC output. After filtering, the conjugated signal alone passes through the rest of the transmission system. This OPC implementation leads to a small back-to-back conversion penalty of 0.3 dB in SNR, which becomes completely negligible at longer transmission distances [45]–[47].

B. Experimental Results

The characterization results are presented in Fig. 12 in terms of the received SNR, and each link is considered with and without OPC for distances up to 2500 km. For DO1 link including OPC, the power into the spans before the OPC (Link1) is approximately 3 dB higher than the power after the OPC (Link2), such that the relative nonlinear phase-shifts are equalized. This is consistent with the optimum power difference ∆P from the numerical analysis in Section 11. Similarly, in this specific case we refer to average launch power instead. For all other system
configurations, the input power is kept the same on both sides of the OPC.

The SNR results for a single loop turn on each side of the OPC are illustrated in Fig. 12b. Without OPC, DM scenario is superior to DO1, consistent with the numerical analysis in Section V.3 because the improved symmetry in PADD does not provide gains until OPC is included. With OPC, DO1 link consistently outperforms DM for all transmission distances (Fig. 12b), achieving gains up to (1) 2.8 dB compared to DO1 without OPC, (2) 1.9 dB compared to DM without OPC, and (3) 0.4 dB compared to DM with OPC (Fig. 12c). Equivalently, inclusion of OPC in DO1 yields over 80% reach enhancement at SNR=12 dB for this scheme, and more than 40% increase when compared to the standard DM mapping without OPC. This improvement is achieved despite practical limitations, e.g. imperfect PADD and in-loop power fluctuations, amplifier and OPC noise, higher order dispersion and PMD, and the wavelength shift induced by OPC.

V. Conclusion

In this work, we presented a novel approach to designing systems with perfectly symmetric PADD, and we provided a numerical and experimental overview of dispersion mapping techniques for EDFA-amplified transmission systems including mid-link OPC. Instead of employing Raman-pumping to optimize the power along the transmission, the symmetry was achieved by designing the dispersion profiles of the link. The analyzed systems generally fall into three categories:

- dispersion uncompensated (DU);
- dispersion managed (DM);
- dispersion optimized (DO).

The links are based on SSMF and IDF fiber types, though we also presented an approximate implementation based on commercially available SLA and IDFx2 links.

In the first part, we conducted a numerical evaluation of the links for a varying baud rate and channel count. It was shown that the symmetry in PADD becomes increasingly more important for broadband systems due to more rapid changes in pulse shape evolution. Despite this challenge, the optimized scheme with symmetric PADD (DU and DM) and maintained the gains as bandwidth increased. Similar results were obtained for multi-span transmission, where DO showed the highest OPC gains and the best overall performance for all the considered transmission distances, achieving up to 3.5 dB net gain in SNR at 20 spans (3200 km), when compared to non-OPC configurations.

In the second part, the method was experimentally validated using SLA+IDFx2 composite fibers. We implemented the systems (DO and DM) using two time-synchronized recirculating loops, and measured the performance with and without mid-link OPC for distances up to 2500 km. Similarly to the numerical analysis, the dispersion optimized scheme (DO) was superior when OPC was included, with net gains in SNR up to 1.9 dB relative to non-OPC configurations.

In conclusion, we demonstrated an effective, yet simple, way of satisfying the OPC symmetry conditions without the need for complex amplification schemes, and the method as well as results could be of significant practical importance for the OPC-aided system design.

Acknowledgment

DNRF Research CoE, SPOC (ref. DNRF123), the ERC CoG FRECOM (771878), the Villum YIP OPTIC-AI (29344), OFS Denmark for HNLF, and Fraunhofer HHI for transmission link.

References

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JLT.2021.3060548, Journal of Lightwave Technology