Optical Phase Conjugation Using Nonlinear SOA for Nonlinearity and Dispersion Compensation of Coherent Multi-Carrier Lightwave Systems

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ABSTRACT We study the use of nonlinear semiconductor optical amplifier (SOA) for generating optical phase conjugate towards compensation of distortions in short distance optical fiber transmission due to Kerr nonlinearity and chromatic dispersion in coherent multi-carrier lightwave signals. We experimentally demonstrate the effectiveness of the SOA-based phase conjugator to improve the link budget with a 100 km standard single mode fiber link for 20 GHz coherent OFDM signals, with QPSK and 16QAM modulations and a corresponding net bit-rate of 40 Gbps and 80 Gbps respectively. Mid-span spectral inversion scheme is employed where the optical phase conjugate is generated through a partially degenerate four-wave mixing process in a nonlinear SOA. We demonstrate a bit error rate performance within 2×10^{-2} for an average launched power of up to 12 dBm (9 dBm) for QPSK (16QAM) coherent OFDM signals, in a 100 km fiber link. We also investigate the possible improvement in link budget using numerical simulation for 16QAM and 64QAM CO-OFDM signals with the proposed scheme.

INDEX TERMS Orthogonal frequency division multiplexing, semiconductor optical amplifier, optical phase conjugation.
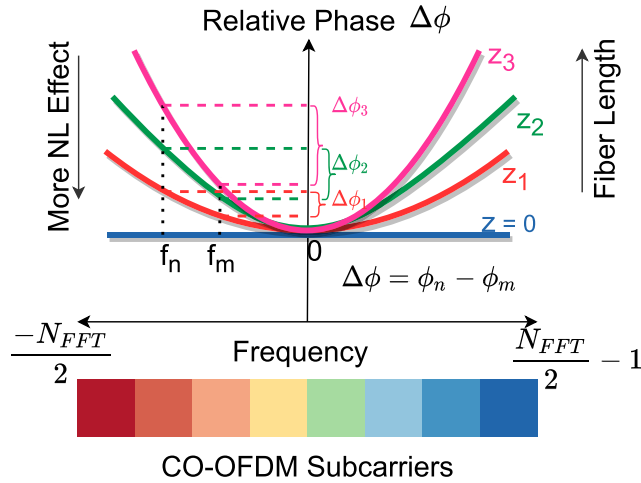
I. INTRODUCTION

Coherent optical orthogonal frequency division multiplexing (CO-OFDM) systems have been well-studied for both long-haul and short-reach optical interconnects to achieve improved spectral efficiency (SE) and bandwidth reconfigurability [1]–[3]. The use of simpler equalization algorithms and its resilience to chromatic dispersion (CD) makes CO-OFDM a strong alternate to Nyquist shaped single carrier systems.

Larger launched power levels are desirable to extend the reach of transmission in long-haul links and to increase the optical signal to noise ratio (OSNR) for supporting higher-order modulation in short-distance links. However, larger input power levels result in performance degradation due to the onset of Kerr nonlinearities in the optical fiber [4]. Compensation of distortion due to fiber nonlinearities in the

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digital domain using digital back propagation and the use of advanced machine learning techniques have been proposed in the past [5]–[8]. A survey on the various techniques to compensate Kerr nonlinearity is detailed in [9]. However, the computational complexity, limitations due to polarization mode dispersion, and fluctuating frequency offsets between the transmitter and local oscillator laser have always been a challenge to the digital compensation techniques [10]. Polarization coding scheme and its equivalent phase conjugated twin wave based fiber nonlinearity compensation are alternate methods to digital domain-only nonlinearity compensation, but requires additional processing at the transmitter and halves the spectral efficiency [11], [12]. A promising method to augment digital equalization is the use of optical phase conjugation (OPC) to optically compensate for the accumulated CD and distortion due to fiber Kerr nonlinearities in both single carrier and multi-carrier systems [13]–[18]. Long haul and ultra long haul links with OPC have been demonstrated in [15], [19], thus proving its practical viability. In most of
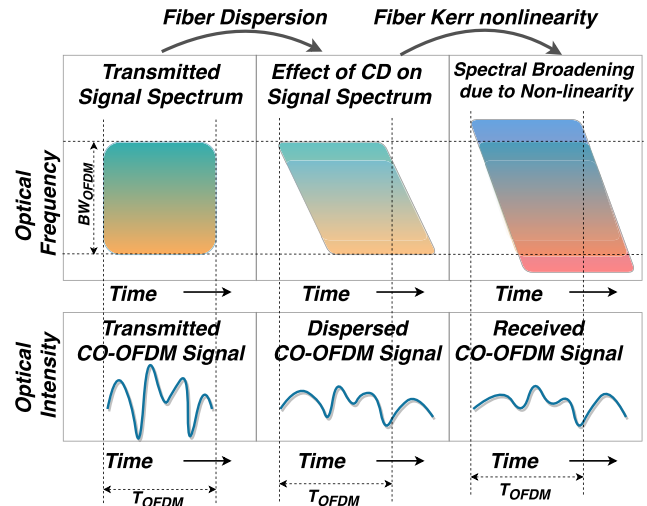
FIGURE 1. Conceptual illustration of the effect of fiber length and the nonlinear distortions between the CO-OFDM subcarriers. As the fiber length increases ($z_3 > z_3 > z1$), the relative phase between the subcarriers increases ($\Delta\phi_3 > \Delta\phi_3 > \Delta\phi1$) and there by reducing the distortions due to FWM nonlinearity.

FIGURE 2. Conceptual illustration of the effect of distortions due to chromatic dispersion and fiber Kerr-nonlinearity on a CO-OFDM signal in both time domain and in the frequency domain.

these demonstrations, highly nonlinear fiber or periodically poled Lithium Niobate was used as the nonlinear media to perform the optical conjugation. Both these nonlinear media require high optical power levels- typically greater than 100 mW- to initiate the nonlinear processes [19], [20].

Semiconductor optical amplifiers (SOAs) are excellent alternatives, where nonlinearities are initiated with pump power levels as low as 0 dBm [21]–[23]. The SOAs are proven to have better energy efficiency, have a smaller footprint, and supports on-chip-integration, thus making it a propitious candidate for all-optical signal processing operations. However, the nonlinear chirp introduced by the SOA due to gain fluctuations, and its noise figure due to the amplified spontaneous emission are the primary deterrents towards its use as a nonlinear medium. We had presented an experimental demonstration of OSNR retention of conjugate and signal along with chirp-free amplification of the signal with QPSK modulation in the presence of a saturating pump [24]. We recently, for the first time, experimentally demonstrated the use of SOAs as a nonlinear medium for the OPC generation for the simultaneous dispersion and nonlinearity distortion compensation of coherent QPSK and 16QAM single-carrier signals [25].

In a dispersion compensated link, the penalty due to Kerr nonlinearities is accentuated in OFDM systems due to its large peak-to-average-power ratio (PAPR) as compared to the single carrier system [26]. Figure 1 shows the relative phase ($\Delta\phi$) accumulated in the subcarriers for different fiber transmission lengths ($z_3 > z_3 > z1$) and its corresponding effect on Kerr nonlinearity. In case of a short-reach link, the dispersion induced walk-off between the subcarriers ($\Delta\phi$) is relatively smaller and thereby enhancing the fiber Kerr nonlinearity. Coherent OFDM signals also pose a much bigger challenge to the nonlinear chirp introduced by the SOA since its relatively larger PAPR is expected to induce larger gain fluctuations and hence a corresponding larger nonlinear phase noise [27]. Thus, distortions due to both fiber Kerr

nonlinearity and the SOA nonlinearity pose a bigger challenge in CO-OFDM systems where the mid-span spectral inversion based compensation is carried out with SOAs, especially in few-hop links.

In this work we demonstrate a multi-carrier modulation which has a different requirement compared to single carrier systems in terms of PAPR, phase noise and digital signal processing. We experimentally demonstrate the mid-span spectral inversion (MSSI)-aided simultaneous fiber Kerr nonlinear distortion and CD compensation of a 40 Gbps QPSK CO-OFDM and 80 Gbps 16QAM CO-OFDM signals, using phase conjugation in a nonlinear SOA in a two-span link, with each span of length 50 km. The BER performance for different noise levels of an optically compensated transmission over 100 km fiber is compared to that with back to back (B2B) signal, B2B conjugate, and 100 km fiber propagation with digital compensation. Fiber nonlinear distortion compensation is demonstrated by evaluating the performance of the link for different power levels launched into the fiber. The experimental results presented here are the first demonstration, to the best of our knowledge, of simultaneous dispersion and nonlinearity distortion compensation for coherent OFDM signals using SOA based optical phase conjugator.

The paper is organized as follows: Section 2 presents the background of mid span spectral inversion scheme with 16QAM and 64QAM CO-OFDM simulation results, Section 3 & 4 describes the details of the experimental setup and the results of the transmission of single polarization QPSK/16QAM CO-OFDM signal over 2 spans of 50 km standard single mode fiber (SSMF) and Section V concludes our findings.

II. CONCEPT AND SIMULATION RESULTS

Mid span spectral inversion where an optical phase conjugate generated typically at the middle of the span and propagated through the rest of the span is a proven method to
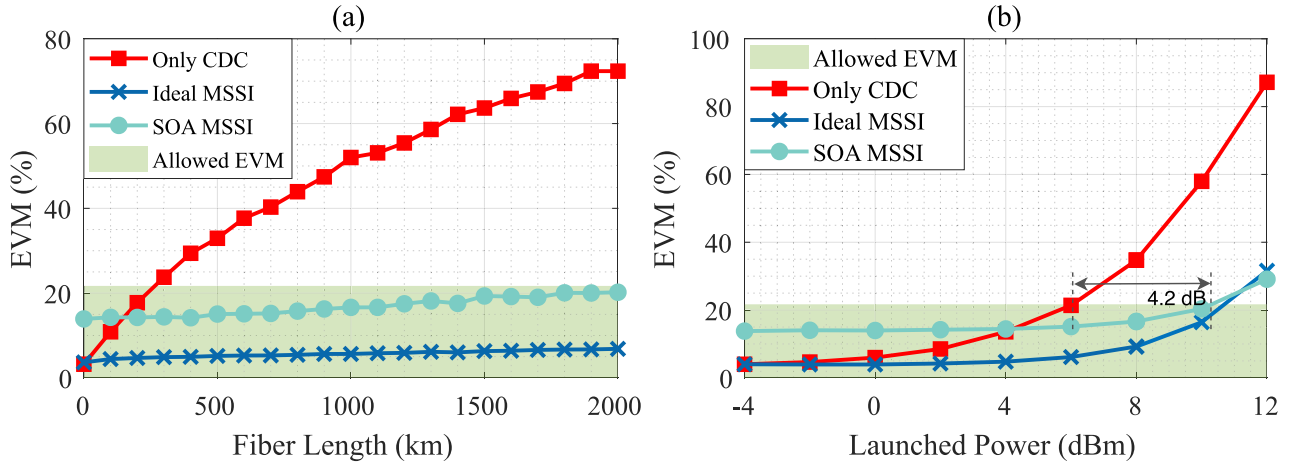
FIGURE 3. (a) Effect of transmission distance on the EVM performance of 16QAM CO-OFDM in MSSI scheme using SOA; Launched signal power into each span is 3 dBm (b) Effect of 16QAM CO-OFDM signal launch power on the EVM performance of MSSI using SOA; The transmission length is 100 km.

compensate for the dispersive and nonlinear chirp introduced in the fiber [13].

Figure 2 shows the pictorial representation of the evolution of both the frequency and intensity of the CO-OFDM signal due to dispersion and nonlinear effects. The linear chirp accumulated due to chromatic dispersion presents itself as a spread of the signal beyond its original symbol period T_{OFDM}. If the signal is launched with a sufficiently larger power, the power fluctuations in the signal result in the corresponding changes in the instantaneous phase, thus leading to a chirp due to Kerr nonlinearities in the fiber. Such fluctuations in the instantaneous phase manifest as a broadening of the signal bandwidth beyond BW_{OFDM} as shown in Fig. 2. In long-haul links, the effect of dispersion induced distortions can be advantageous for CO-OFDM as dispersion introduces walk-off between subcarriers and weakens the nonlinear interactions and hence the Kerr nonlinearity [26]. However, for short-reach, few-hop links, dispersion may not be sufficient enough to reduce the fiber Kerr nonlinearity and can severely degrade the performance.

The propagation of the conjugate generated after the first span through an equal length of the second span of fiber with identical group velocity dispersion parameter (β_2) and the nonlinear parameter (γ), results in the compensation of the dispersive and nonlinear phase accumulated in the first span, assuming identical launch powers [28]. The intensity dependent nonlinear phase accumulation depends on the effective length of the fiber- which is a function of the loss factor of the fiber. However, for short-reach links, the efficacy of the MSSI scheme is proven to be significantly large in the compensation nonlinear distortions [20]. When the optical amplifiers are employed in the link, the power fluctuations because of the ASE noise introduced by the amplifiers may cause a phase noise due to Kerr nonlinearity during the transmission. However, when the OPC is employed in MSSI configuration, the total ASE induced phase noise is suppressed by 6 dB [29].

In order to prove the utility of a SOA-based phase conjugation, we first present the results from numerical simulations for 80 Gbps 16QAM CO-OFDM signal for simultaneous dispersion and non-linearity compensation using optical phase conjugation (OPC) in mid span spectral inversion (MSSI) scheme with SOA. We consider a fiber optic link with N_{spans} spans of 50 km uncompensated SSMF. After each span, an amplifier (with noise figure 5 dB) compensates for the attenuation in the optical power. At the mid-span, we employ a spectral inversion module to generate the conjugate of the signal. We set the input OSNR to 30 dB and the optical launch power at 3 *dBm*. We numerically solve the nonlinear Schrodinger equation with the standard split-step Fourier method for the propagation of the optical signal through the fiber. We solve the coupled equations for the time-dependent gain and phase for the optical signal propagation in SOA [30]. The parameters are chosen corresponding to the experimental results shown in Section 3. The input power of the signal (having 25 kHz linewidth) and that of the pump (having 100 kHz linewidth) to SOA is −13 dBm and 0 dBm respectively. The frequency detuning between the signal and pump is set to 125 GHz. Parameters and the relevant equation used in the simulation are detailed in Appendix-1.

At the receiver, we perform digital dispersion compensation (only for the non-MSSI case), training based channel equalization, and phase noise compensation using the pilot aided technique. Figure 3(a) plots EVM as a function of the fiber length for a launched power of 3 *dBm* for the schemes involving MSSI with SOA, with ideal MSSI (An ideal MSSI is where the output complex electric field envelope is the conjugate of the input) and without MSSI (only chromatic dispersion compensation (CDC)). We see that the EVM performance of SOA-MSSI has a penalty with respect to the ideal case due to spurious FWM components generated in the SOA because of the interaction of OFDM subcarriers within the signal band [31]. However, it performs very well
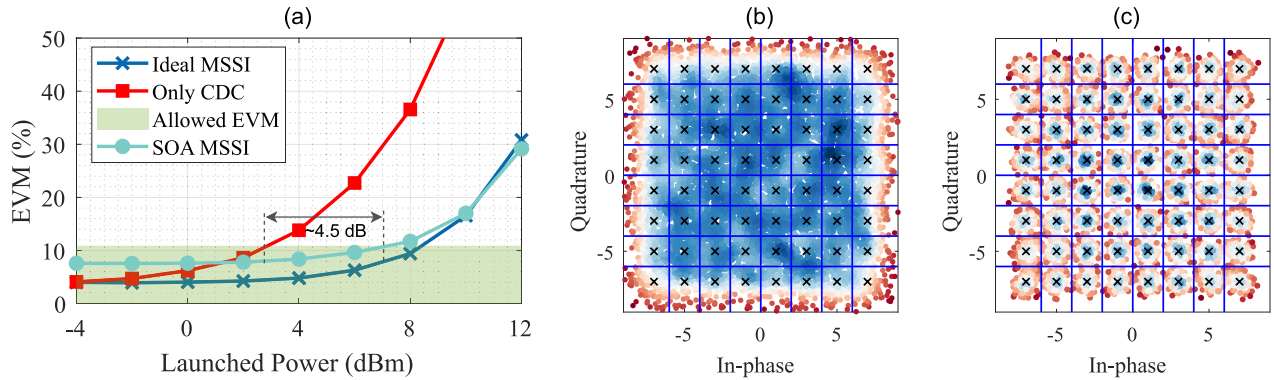
FIGURE 4. (a) Effect of signal launch power on the EVM performance of MSSI using SOA for 64QAM CO-OFDM signal transmitter over 100 km SMF (b) Constellation of 64QAM signal at 6 dBm launched power evaluated with CDC (EVM = 22.7%) (b) Constellation of 64QAM signal at 6 dBm launched power evaluated with SOA-OPC (EVM = 9.6%).

in comparison to the non-MSSI case. At a target BER of 2×10^{-2}, corresponding to the SD-FEC limit [32] and with a corresponding EVM of 21.7 %, the reach with the MSSI scheme can be extended to > 1500 km for 16QAM CO-OFDM for the given launch power level.

In order to quantify the tolerance to nonlinear effects in the fiber, we now evaluate the EVM as a function of power launched, for the case with digital compensation of CD (without any digital compensation for nonlinear effects), ideal MSSI, and the case where MSSI is carried out with SOA for a fiber link of 100 km. For the SOA MSSI case, as the power increases, the EVM is almost constant for up to 5 dBm launch power and then increases- as the residual nonlinear distortion start to significantly affect the performance as seen in Fig. 3(b). The EVM performances are within the SD-FEC limit for launched powers even up to < 10 dBm for 16QAM CO-OFDM signal. For the non-MSSI case (only CDC), distortions due to fiber nonlinearity starts to significantly affect the performance for launched power ≈ 2 dBm and the performance degrades below the allowed FEC limit for launched powers more than 6 dBm. This illustrates the need for the mitigation of distortions due to nonlinearity, even for short-reach 100 km link, which otherwise limits the throughput of the link. These simulations show the efficacy of MSSI as a nonlinear mitigation strategy and SOA as a suitable device for realizing it. The obtained 4.2 dB power margin can be used to extend the link by about 21% in this short-reach system. In the following section, we carry out the SOA based MSSI experiment in a short-reach link with 100 km SMF.

We extend the numerical simulation for the simultaneous compensation of the distortions due to dispersion and Kerr nonlinearity for 20 GHz 64QAM CO-OFDM signal. Figure 4 (a) shows the EVM performance as a function of power launched into the spans similar to that of the 16QAM case in Fig. 3(b). For the non-MSSI case (only CDC), distortions due to fiber nonlinearity starts to significantly affect the performance for launched power ≈ − 2 dBm and the performance degrades below the allowed FEC limit for launched powers more than 2.5 dBm. Whereas, the performance of

SOA based MSSI scheme has tolerance to within the FEC limit to up to 7 dBm launch power, there by obtaining a power margin of 4.5 dB. The linewidth requirements of the pump and signal are stringent due to the higher order cardinality and hence, the pump linewidth was set to 25 kHz (it was 100 kHz for 16QAM). Also, the PAPR of the 64QAM is higher than that of 16QAM's and therefore the power input to the SOA in the OPC stage was reduced to − 18 dBm. The change of these parameters were essential for the performance metrics to be with in the standard FEC limits. Plot also shows the allowed EVM (< 10.9%) values corresponding to a SD-FEC limit of 2×10^{-2}. Figures 4 (a) and (b) shows the constellation plots of the received signal (evaluated for all the data subcarriers) for the cases with only CD compensation (CDC) and with SOA based OPC scheme at a signal launch power of 6 dBm into each span.

III. EXPERIMENTAL SETUP
The schematic of the experimental setup is shown in Fig. 5. In the off-line generation of OFDM symbols, a PRBS-15 bit sequence is first mapped to QPSK/16QAM symbols, and are modulated on 72 subcarriers (along with guard band, 8 pilot subcarriers, one zero frequency subcarrier) spanning a total frequency spread of 20 GHz. This frequency domain information is then converted to time domain samples through a 128-point IFFT operation. The generated complex OFDM symbol has a duration of 4.53 ns, including an 8 sample cyclic prefix, thus, capable of tolerating 27 ps delay spread. This is followed by an optimised clipping to reduce PAPR. The generated digital time domain samples are fed to high-speed arbitrary waveform generator (AWG, 23 GHz, 64 GS/s), which in turn drives the IQ transmitter where the generated 40 Gbps (QPSK)/ 80 Gbps (16QAM) CO-OFDM data is modulated on the optical carrier at 1551.11 nm (with 25 kHz linewidth). The AWG output voltage swing was optimised to reduce the nonlinear distortions due to the modulator. The output power of the modulated signal is −12 dBm. The modulated signal is then fed to the first span of standard single mode fiber (G.652D) of length 50 km through an Erbium
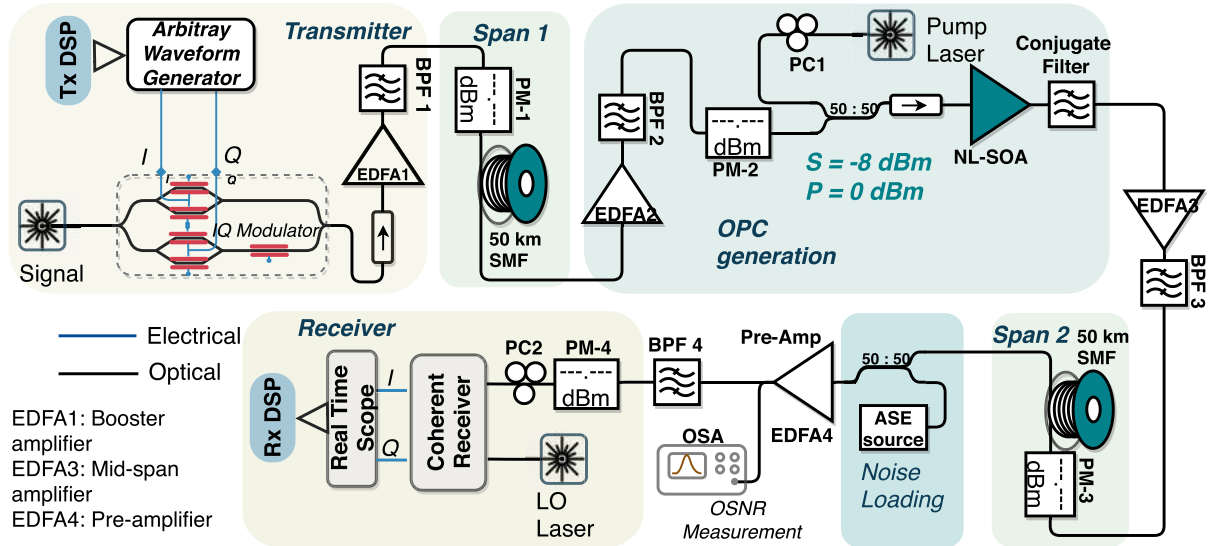
FIGURE 5. Schematic of the experimental setup to perform the simultaneous compensation of distortions due to kerr nonlinearity and dispersion of QPSK and 16QAM CO-OFDM signals using NL-SOA based OPC scheme employed in MSSI configuration.
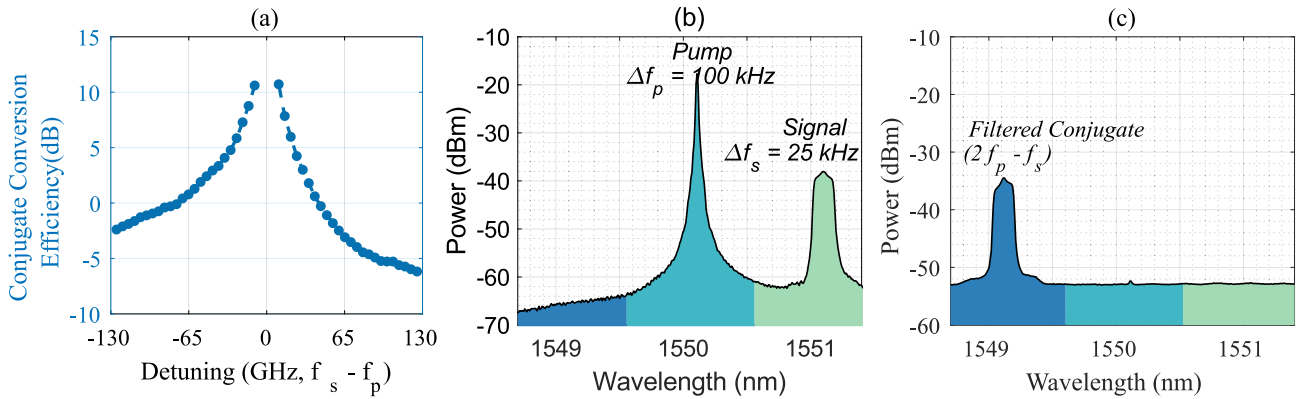
FIGURE 6. (a) Gain and conjugate conversion efficiency as a function of detuning (operated under CW condition) (b) Spectra at input (with 20 dB attenuation) of OPC stage (C) Spectra of the conjugate before coherent receiver with an OSNR of 18.5 dB.

doped fiber amplifier (EDFA1) and an in-line power monitor (PM) such that the average power at the input of the first span is maintained at 0 dBm. The expected time domain spread due to CD in the span is 136 ps (per span). We carry out the phase conjugation process of the propagated signal in a nonlinear SOA (Kamelian SOA, SOA-NL-M1-FA) through partially degenerate four-wave mixing (FWM), as shown in OPC generation block in Fig. 5. Considering signal (at frequency f_s; linewidth $\Delta f_s = 25$ kHz) and pump (at frequency f_p; $\Delta f_p = 100$ kHz), at the input to the SOA, the conjugate at frequency $2f_p - f_s$, is generated through FWM in SOA due to beat between the signal and the pump and the consequent time-dependent gain gratings generated in the SOA [23].

The strength of the generated conjugate is a function of the detuning between the pump and the signal. Figure. 6 (a) shows conversion efficiency, defined as the ratio of the output conjugate power to the input signal power, as a function

of detuning frequency ($f_s - f_p$), for an input signal power of −8 dBm and pump power of 0 dBm, for an SOA bias current of 350 mA, operated under CW conditions. The conjugate conversion efficiency is negative beyond a detuning of −65 GHz, which means the conjugate power at the output of the SOA is smaller than the input signal power. The nonlinear SOA used in our experiments has an output saturation power of 11.5 dBm and a carrier recovery time of 25 ps. The polarization dependent gain of the SOA is measured to be less than 0.55 dB and hence the polarization sensitivity of the SOA is neglected in this experiment. The results shown in Fig. 6(a) indicate a sufficiently large conversion efficiency of greater than −2 dB even at 125 GHz detuning (negative, $f_p > f_s$) and this particular detuning is selected for the experiment with data modulated signals. The conversion efficiency is decided by the average input power and hence it is maintained the same in both the cases of QPSK CO-OFDM and 16QAM CO-OFDM modulated data using EDFA2.

The spectra measured (with 4 GHz OSA resolution bandwidth) at 1% port of the tap coupler at the input of the OPC stage is shown in Fig. 6(b). The phase conjugate generated at 1549.11 nm is filtered using a programmable optical band pass filter (Finisar WS-1000S) with bandwidth 60 GHz, amplified using EDFA3 in order to maintain the signal input power of 0 dBm and fed to the second span of a similar G.652D fiber of length 50 km. The OSNR of the signal/conjugate is controlled by introducing amplified spontaneous emission (ASE) noise from an EDFA (spectrum is shown in Fig. 6 (c) for an OSNR of 18.5 dB) at the coherent receiver. The received signal, along with the output of a local oscillator (LO) laser is fed to a coherent receiver, and its output is digitized using the front-end analog to digital converters of a high-speed real-time oscilloscope (36 GHz, 80 GSa/s).

The digitized output is post-processed using off-line digital signal processing (DSP) algorithms, which includes (correlation-based) time and (blind) frequency synchronization, training symbols based channel estimation/ equalization and pilot subcarriers assisted phase noise correction [33]. In this demonstration, we have considered a signal bandwidth of 20 GHz and corresponding to this spectral width, the conversion efficiency variation is measured to be less than 1 dB. The employed training symbols based frequency domain equalization in the digital domain corrects for this non-flat channel and as well as for the system response. Performance is then evaluated from the processed symbols and bits by estimating the bit error rate (BER, averaged over 1 million bits) and error vector magnitude (EVM). We do not employ any dispersion or nonlinearity compensation algorithm in the DSP stage for the OPC scheme.

IV. RESULTS AND DISCUSSION

Figure 7 shows the BER performance of the 40 Gbps QPSK CO-OFDM signal as a function of measured OSNR for different transmission conditions. The back-to-back (B2B) signal (represented with blue dashed line) represents the performance of the modulated signal in the absence of fiber and OPC stage and these results are further used as a reference to estimate the OSNR penalty.

The signal is then fed to the OPC stage and the generated conjugate signal is filtered and coherently detected. The received data is first conjugated, processed using the standard CO-OFDM DSP algorithms [33] and the performance of the same is evaluated as a function of the OSNR as shown in Fig. 7 with a red dotted curve.

We observe about 2.3 dB penalty with respect to the B2B case at a BER of 1×10^{-3} because of the inter modulation products due to FWM of CO-OFDM subcarriers [13], [31]. The input power to the SOA was -8 dBm, which is sufficient to induce FWM of CO-OFDM subcarriers. Hence use of lower input power can reduce this observed OSNR penalty, but at the cost of affecting the power budget at high launched powers. The performance of the signal after transmission through 100 km SMF is ascertained by carrying out a CD
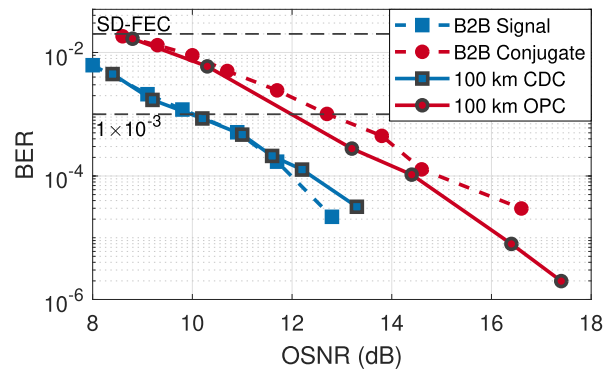

FIGURE 7. BER performance of the signal and generated conjugate for different OSNR values for 40 Gbps QPSK OFDM signal under back-to-back condition and after propagation through fiber. Results with optical phase conjugation and that with digital compensation of chromatic dispersion is shown, for a launched power of 0 dBm into each span (length 50 km each).

compensation (CDC) in the digital domain through frequency domain equalization and the corresponding results are shown in blue lines. Note that, the dispersion incurred ($17 \times 100 \times 0.16 = 272$ ps) is about ten times the tolerable limits (27 ps) allowed by the cyclic prefix. These results are similar to the B2B signal transmission cases as the DSP completely compensates for the fiber induced dispersion effects (power launched was less than the nonlinear threshold and hence there is no distortions due to fiber nonlinearity).

We now proceed to perform the mid span spectral inversion (MSSI) where the signal after the first span is fed to SOA along with a CW pump. The generated conjugate is allowed to propagate through the second span, where it is expected to compensate for the effect of the accumulated phase due to dispersion in the first span. For the OPC case, the off-line DSP does not include CDC. BER of the received signal is ascertained as a function of OSNR as shown in the red color curve (represented with ○ markers and legend "100 km OPC"). We observe that the results are similar to the B2B conjugate case. The slight improvement in performance observed is attributed to the reduction of SOA nonlinear phase distortion due to reduced PAPR of the dispersed OFDM signal. Thus, the efficacy of an SOA-based optical phase conjugation for CO-OFDM signal to compensate the linear chirp due to dispersion is established, albeit with a penalty due to the SOA. The observed penalty of 2.3 dB can be further reduced by lowering the input signal power to SOA below -8 dBm, which would be in the range of received powers in a practical link.

Extension of the optical reach is achieved with an increase in signal power launched into the fiber. However, it is to be ensured that the corresponding Kerr nonlinearity introduced by the fiber does not limit the system performance. We now proceed to evaluate the nonlinearity resilience of the proposed SOA-based OPC scheme. Power launched into the fiber span is increased in steps of 2 dB and the system performance is compared for the cases with and without the OPC scheme. It is ensured that the launched power in each span is identical, while the signal and CW pump powers at the input of the
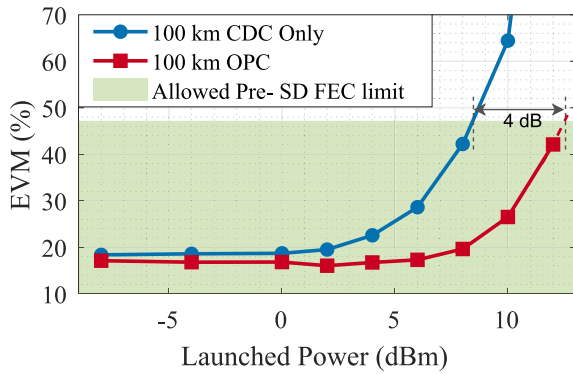
FIGURE 8. Comparison of CDC and OPC EVM performance of 40 Gbps QPSK CO-OFDM as a function of input launched power.
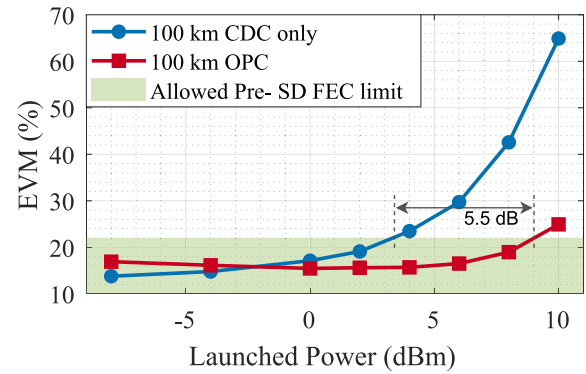
FIGURE 10. Comparison of CDC and OPC EVM performance of 80 Gbps 16QAM CO-OFDM as a function of input launched power.
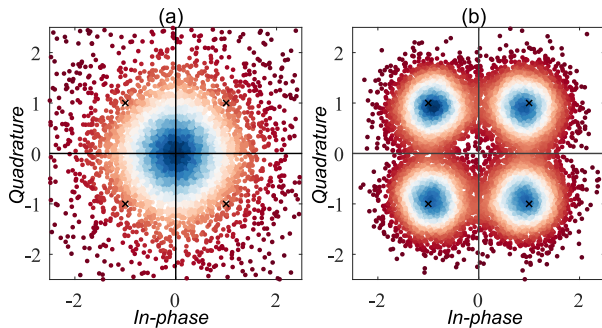
FIGURE 9. (a) Constellation of QPSK signal at 12 dBm launched power evaluated with CDC (BER = 0.5) (b) Constellation of QPSK signal at 12 dBm launched power evaluated with OPC (BER = 1.6×10^{-2}).

OPC stage are maintained at −8 dBm and 0 dBm respectively. Figure 8 shows the EVM performance of 40 Gbps QPSK CO-OFDM signal as a function of launched power for both the cases. In both cases, the EVM performance degrades with the increase in the launched power to the fiber as a result of Kerr nonlinear distortions.

No DSP algorithm is applied to compensate for the accumulated nonlinear effects, and hence the EVM performance of the CDC scheme (without MSSI) is within the allowed SD-FEC limit for launched powers of only up to about 8 dBm. In the case that employs the OPC scheme, the power at which the EVM starts to degrade beyond the SD-FEC limit is found to be > 12 dBm (4 dB more than the CDC case). This indicates that the system employing OPC has better nonlinear tolerance to Kerr nonlinearity induced distortions. Constellation plots of the CO-OFDM signal (from all the data subcarriers) evaluated using only CDC and with OPC corresponding to a launched power of 12 dBm is shown in Fig. 9 (a) and Fig. 9 (b) respectively. This additional 4 dB power budget can be used to increase the link length or improve the split ratio. In order to demonstrate the transparency of the scheme to modulation formats and bit rates in CO-OFDM, we now proceed to evaluate the nonlinearity resilience of the OPC scheme for 16QAM CO-OFDM signal, with all other experimental parameters maintained identical to the QPSK case. Figure 10 shows the EVM performance of 80 Gbps 16QAM

CO-OFDM signal as a function of launched power, with and without OPC.

The relatively poorer performance of the conjugate for smaller launched powers ($< −3$ dBm) is attributed to the lower OSNR of the input signal and hence that of the conjugate. In the case that employs MSSI scheme, the power at which the EVM starts to degrade beyond the SD-FEC limit is about 9 dBm, which is larger by 5.5 dB as compared to the case without the MSSI scheme, thereby indicating the improved nonlinear tolerance of the OPC system. We obtain the nonlinear tolerance of about 4.2 dB improvement in launched power in simulations as shown in Fig. 3 (mismatch in value compared to the experiment could be due to difference in SOA parameters used in simulations, where the SOA nonlinearities are overestimated). Since 16QAM modulation has a stringent phase noise margin (16.9°) compared to QPSK (45°) [34], the benefit of OPC in correcting the nonlinear phase noise is more pronounced with a corresponding increased power budget. Constellation plots of the 16QAM CO-OFDM signal (from all the data subcarriers) evaluated using only CDC and with OPC corresponding to a launched power of 8 dBm are shown in Fig. 11 (a) and Fig. 11 (b) respectively. A clear constellation diagram of the signal in the OPC scheme indicates the improved quality (about two orders of magnitude improvement in BER compared with only CDC scheme) of the received signal after optically corrected for dispersion and nonlinearity.

It should be noted that the dispersion introduced by the fiber may not be large relative to the symbol duration of the OFDM frame and it may be possible to compensate for the linear CD through cyclic prefix, thus completely avoiding the need for OPC. However, all-optical compensation with OPC would enable the use of CO-OFDM even without the cyclic prefix, thus improving the spectral efficiency. OFDM inherently involves frequency domain processing and hence, it may be argued that the benefits of avoiding equalization of CD with OPC are not valuable in terms of minimizing DSP complexity. However, OPC plays a critical role in compensating nonlinear impairments. Coherent OFDM is expected to pose a larger challenge towards nonlinear tolerances due
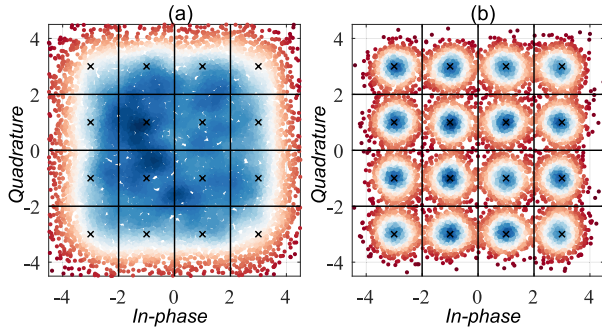
FIGURE 11. (a) Constellation of 16QAM signal at 8 dBm launched power evaluated with CDC (b) Constellation of 16QAM signal at 8 dBm launched power evaluated with OPC (BER = 7.5×10^{-3}).

to the increased PAPR as indicated in Fig. 2(a) and hence, improving the power budget in the access network scenario is more challenging in this case. Through the detailed experimental results, we have proved that the power budget can be improved with the use of SOA-based OPC for both QPSK and 16QAM modulations in CO-OFDM.

We had already proved that the efficiency of SOA-based phase conjugation generation is uniform across the C-band [25] in the case of single carrier transmission, and as long as the pump wavelength is adjusted so that the detuning range is maintained at 125 GHz, we expect similar performance for CO-OFDM. The signal power of −8 dBm at the input port of SOA was very specific to this experiment, just to demonstrate the efficacy of SOA-based OPC for nonlinearity compensation at high launched powers to the fiber. The input signal power to the SOA can further be reduced, as we would expect in any practical link, and hence EDFA2 and BPF2 can be avoided, resulting in improvement of the overall power consumption and wall-plug efficiency. For fixed short reach transmission systems, the use of CO-OFDM could be advantageous as the use of higher cardinality of QAM does not demand any change in the receiver DSP algorithm. In such short-reach, few-hop links, launching signals at higher powers can be beneficial to have increased OSNR at the receiver, albeit at a cost of having distortions due to fiber nonlinearity. For few-hop links, the proposed SOA-based phase conjugation is an ideal solution of compact, integrable, bit-rate, and modulation format independent solution for compensating distortions due to dispersion and Kerr nonlinearities. The proposed SOA based MSSI scheme can be applied for Nyquist superchannel system for the simultaneous compensation of the nonlinear distortions and dispersion for the entire superchannel. Any residual distortions due to dispersion in the link due to small asymmetry in the fiber length can be corrected using the cyclic prefix addition to the CO-OFDM symbol and frequency domain equalization in the signal processing. Residual distortions due to Kerr nonlinearity in the link due to small asymmetry in the launched power to the spans can be corrected using pilot subcarriers based phase error estimation in the signal processing. A detailed analysis on the distortion tolerance on the length asymmetry when SOA based OPC is

employed is a future topic to study. Also, this scheme can be further extended to polarization multiplexed configuration based on the polarization-insensitive phase conjugate generation as reported in [35].

V. CONCLUSION

In this paper, we have demonstrated the use of SOA-based optical phase conjugation for the compensation of distortions due to both fiber Kerr-nonlinearity and chromatic dispersion for a signal modulated CO-OFDM in both simulations and experiments. Most of the existing digital compensation algorithms show logarithmic implementation complexity, only support per-channel basis nonlinearity compensation, and have limitations dues to polarization mode dispersion effect and uncertainty of the optical carrier frequency. In simulations, we have shown the reach extension of up to 2000 km for 20 GHz 16QAM CO-OFDM signal, launched at 3 dBm launched power per span. We have also shown through simulations that the launched power can be increased up to 10 dBm for a 100 km link and be within the SD-FEC performance limits. The simulation results with 64QAM CO-OFDM shows a 4.5 dB additional power margin when SOA-based OPC is employed in the link. We have experimentally demonstrated the BER and EVM performances are within the SD-FEC limits for > 12 dBm (9 dBm) launched power for QPSK (16QAM) CO-OFDM system. The SOA based OPC poses a 2.3 dB OSNR penalty in the back-to-back operating condition, only because of the high input power set, specific to this demonstration. CO-OFDM typically results in larger symbol duration and hence the effect of phase noise transfer in the OPC generation and the nonlinear phase distortions in SOA are the possible performance degrading factors. Nonlinear SOAs are advantageous over other optical signal processing media such as HNLF, PPLN, silicon waveguide as they require only ≈ 0 dBm pump power for good conversion efficiency. With a very compact and chip-integrable structure, SOAs are a strong alternative choice of nonlinear media for all-optical signal processing applications for coherent multi-carrier lightwave systems.

APPENDIX

Four wave mixing in SOA, which is responsible for the conjugate generation is modeled by solving the rate equation for the integrated gain [36], given as

$$\frac{dh}{dt} = \frac{g_0 L - h}{\tau_c} - \frac{P_{in}(\tau)}{E_{sat}}[exp(h) - 1], \quad (1)$$

where $h(t) = \int_0^L g(z, t)dz$ is the integrated gain of the amplifier, $g(z, t)$ is the gain experienced by the signal at a specific z along the length (L) of the SOA at a time instant t, τ_c is the spontaneous carrier lifetime and E_{sat} is the saturation energy of the amplifier.

P_{in} is the total input power as a function of time and g_o is the small signal gain, decided by the dimensions of the SOA, confinement factor and the carrier density. Equation 1

**TABLE 1.** SOA Parameters used in the simulation.

Parameter	Value
Unsaturated gain $g_0 L$	10
Internal loss $\alpha_{int} L$	4
Carrier lifetime τ_c	$25\ ps$
Saturation power $P_{sat} = E_{sat}/\tau_c$	$2\ mW$
Linewidth enhancement factor α_{LW}	4
Carrier heating nonlinear gain suppression factor ϵ_{ch}	$0.5\ W^{-1}$
Spectral hole burning nonlinear gain suppression factor ϵ_{shb}	$2\ W^{-1}$
Carrier heating gain phase coupling factor α_{ch}	2

is solved using a predictor-corrector algorithm [37], for the input power levels derived from the total input field.

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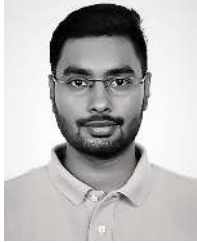
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