Compensation of SOA Nonlinear Distortions by Mid-stage Optical Phase Conjugation

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Abstract: We investigate optical phase conjugation for compensating nonlinear distortions due to carrier dynamics in semiconductor optical amplifiers. Experiments with WDM-3×12 Gbaud 16-QAM signals show the ability to outperform a single device by 2 dB average Q^2-factor improvement.

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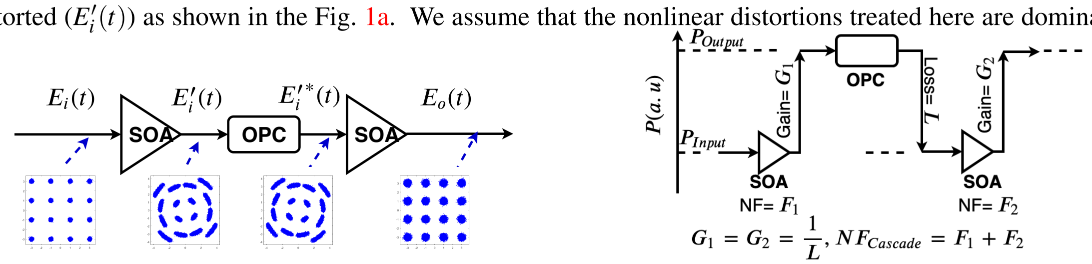
1. Introduction

Semiconductor optical amplifiers (SOAs) have attracted renewed interest in the recent times due to its integrability with photonic integrated circuits and its capability to provide ultra-wide band amplification outside the erbium bands [1]. For data center interconnections, optical amplification of signals in O-band also are of increased demand. SOAs are cost effective, compact and integrable solutions for O-band amplification over other alternatives such as Raman amplifiers or Praseodymium-doped fiber amplifiers (PDFAs). However SOAs intrinsically suffer from nonlinear phase distortions due to carrier dynamics, which can be especially adverse for pluggable transceivers operating with limited number (< 10) of WDM channels. While optimized operations of ultra-wideband SOAs for massive WDM channel counts were reported recently [1, 2], it is worthwhile to scrutinize a method for compensating nonlinear distortions suffered by fewer channel WDM signals with typical off-the-shelf SOAs. Mitigation of nonlinear effects in SOA has been demonstrated in the past using optical [3] and digital signal processing [4, 5] techniques. However, the optical technique in [3] works only for OOK modulation, while the computational complexity of the DSP techniques should be considered with higher order QAMs.

In this study, we investigate the efficacy of optical phase conjugation (OPC) to compensate the nonlinear effects of an SOA. While the mid-stage OPC method is well known for compensating nonlinear distortion in long distance optical fiber links arising from the Kerr effect [6, 7], here, we report for the first time to the best of our knowledge its capability for compensating nonlinear distortion associated with carrier dynamics in SOAs. Measurements for WDM-3×12 Gbaud-16QAM signals demonstrate an average Q^2 improvement of 2 dB for the OPC compensated system over a single SOA device. An improved performance is also demonstrated for transmission through a long fiber span which is enabled primarily because of the larger received powers at lower distortions. Our approach shows the ability to overcome the nonlinear distortion limits of SOAs for higher order QAM signals.

2. Principle of operation and implementation

The block diagram explaining the working principle of the proposed OPC-based nonlinearity compensation (NLC) scheme is shown in Fig. 1. Optical signal from the output of the transmitter ($E_i(t)$) is passed through the first SOA. In the absence of NLC, the SOA output is expected to have a gain, but the constellations are expected to be distorted ($E_i'(t)$) as shown in the Fig. 1a. We assume that the nonlinear distortions treated here are dominated by



(a) Signal evolution at different stages

(b) Signal power excursion diagram required for symmetric nonlinearity in SOAs

Fig. 1: Schematic of the OPC-based NLC to compensate SOA nonlinearity effects

self- and cross-phase modulation and that gain compression and its associated pattern effects are negligible. In order to compensate this, we use an optical phase conjugation stage, followed by a second SOA. Assuming the second SOA is identical to that of the first, the phase conjugated signal ($E_i'^*(t)$) experiences the opposite distortion in the second SOA, thus recovering the signal output distortion-free ($E_o(t)$). We use a commercial off-the shelf "nonlinear" SOAs, with reduced carrier recovery time of 25 ps (slot-interval 40 Gbaud) for our experiments. As we will see in Fig. 3a, we investigate the regime where nonlinear phase distortions are dominant. We use 12 Gbaud WDM signals for our experiments, corresponding to a symbol period (83 ps) longer than the carrier lifetime, which ensures the suppression of pattern effects. Another important issue in this study is whether or not NLC can overcome ASE noise intrinsically entailing this scheme. This scheme requires the second SOA to have the same amount of nonlinear distortions as the first SOA. This implies the OPC must necessitate a signal level reduction equivalent to the gain of the SOAs. As shown in Fig. 1b, considering OPC only as a loss element (L), SOAs with noise figures (NFs) F_1&F_2, and because the gain equals the loss ($G_1 = G_2 = 1/L$), the total NF would be approximately $F_1 + F_2$. Our approach should be able to provide the performance improvement in-terms of BER and Q^2, over the single SOA despite the additional ASE noise from the second SOA.

3. Experimental setup

Schematic of the experimental setup is shown in Fig. 2. The SOA is proposed to be used as pre-amplifier at the receiver, and its performance with and without OPC compensation is studied. In the transmitter, three CW lasers at frequencies (f_s) 192.65 THz $\pm$ 50 GHz are modulated with a single polarization IQ modulator at 12 Gbaud, with 16QAM symbols generated by two channel 12 GS/s AWG with a PRBS $2^{15}-1$ pattern, thus generating 144 Gbps WDM signal. This 3×12 Gbaud 16QAM WDM-signals is launched to an 80 km SMF with an input power of 2 dBm, ensuring the signal propagation linear. Transmission in a preceding 80km SMF provided WDM

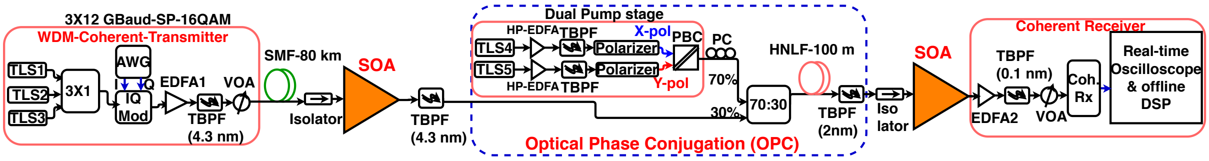


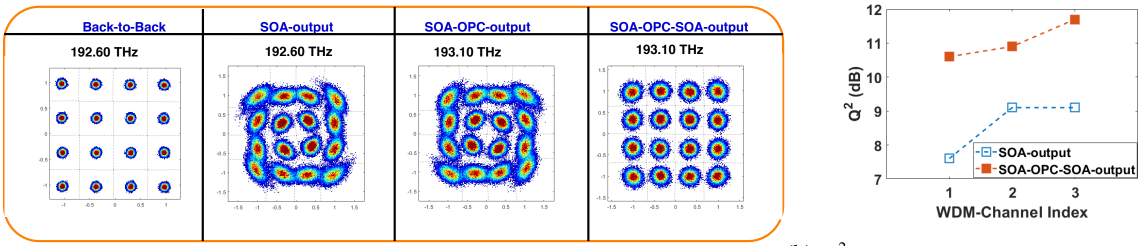
Fig. 2: Experimental setup to demonstrate the SOA-with NLC for compensating SOA nonlinear effects.

channel decorrelation (> 544 ps) before the SOA. The output of the fiber is amplified with the first SOA stage (Kamelian, SOA-NL-L1-N-C-FA, P_{sat}= 10 dBm, carrier recovery time : 25 ps). SOAs are characterized for its gain and nonlinear distortions with WDM signals at different input power and drive currents. Further they are operated such that both SOAs show symmetric nonlinear distortion, corresponding to a SOA drive current (I_{drive}) of 150 mA each. The amplified, but the phase distorted output from the first SOA is fed as the input to the conventional HNLF-based OPC stage, which uses dual pump configuration with orthogonal polarization to ensure the polarization insensitive conjugate generation as shown in Fig. 2. Pump lasers (at f_{P1} 191.7 THz, f_{P2}=194 THz) are operated below the Brillouin threshold of 100 m HNLF, at around 26 dBm each. The conjugate of the WDM signals with a conversion efficiency of -7 dB is generated at a frequency ($f_c = f_{P1} + f_{P2} - f_s$) 193.05 $\mp$ 50 GHz. The phase conjugate signal is filtered and given as the input to the second SOA. The loss at the OPC stage is adjusted such that the input power to the two SOA stages are identical. The output is fed to a polarization diverse-coherent receiver and the real time oscilloscope (33 GHz and 80 GSa/s) output is used for further offline DSP to calculate BER and Q^2 values of all the WDM channels. The OPC and the second SOA stage is bypassed for generating the results corresponding to a single SOA. The EDFA in the receiver end is used just for our convenience in the characterization stage. 1% of the power is fed to the optical spectrum analyzer through tap-couplers from all the relevant stages for real-time monitoring of OSNRs and the gain values. We also compare the performance of the SOA vs SOA with NLC when it is used as a booster amplifier. For these experiments, the 80 km fiber is removed, and a 160 km long fiber is connected *after* the SOA stage.

4. Results and Discussions

The experimental results for SOA and that with NLC when it is used at the receiver, after 80 km transmission is shown in Fig.3. An input power of -14.5 dBm is maintained at both the SOAs. The constellation plots for different stages of the experiments for the first WDM channel (192.60 THz, with phase conjugate at 193.10 THz) are shown in Fig. 3a. It is evident that the signal constellation is phase distorted after the SOA without NLC. The constellation at the output of OPC shows a conjugated effect. After the NLC element following the first SOA, the clean constellation without nonlinear distortion is obtained. The performance is quantified by evaluating the Q^2 value and BER for each WDM channel, for both single SOA and SOA with NLC stage. The corresponding results are shown in Fig. 3b, which clearly indicates an average Q^2-factor improvement of > 2 dB.

The gain, BER and OSNR values for a single SOA is compared with that of the SOA with NLC in Table. 1. Optimum gain are found to be ≈18 dB for single SOA and ≈19 dB for the SOA with NLC, respectively. BER is improved by two orders of magnitude for Ch1 and Ch3, while one order of magnitude for Ch2. The smaller improvement in the central channel (Ch2) can be attributed to its large distortion due to cross phase modulation compared to other two channels. Inspite of reduction in OSNR for SOA with NLC, the BER performance is better because of the nonlinearity compensation effected through the phase conjugation stage.



(a) Constellations at different stages of operation for WDM-channel 1

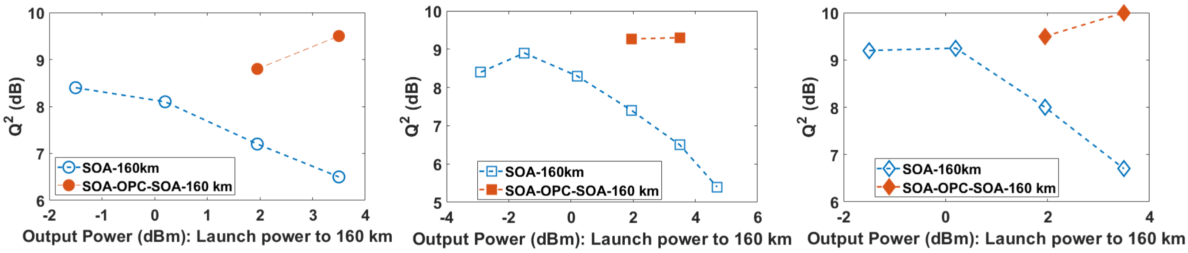
(b) Q^2 values for all three channels after SOA alone and SOA-with NLC scheme

Fig. 3: WDM-3X12Gbaud-16QAM-Results when the SOA/SOA-with NLC is used after 80 km fiber span, SOAs I_{drive}= 150 mA, P_{in}=-14.5 dBm , Ch1:192.6/193.1, Ch2:192.65/193.05, Ch3:192.7/193.0 THz

Table 1: WDM-3X12 GBaud 16QAM;P_{Sig}=-14.5 dBm to both SOAs at 150 mA-after 80 km fiber, **OSNR$_{in}$= 35.6 dB**

Scheme	SOA-Ch1	SOA-OPC-SOA-Ch1	SOA-Ch2	SOA-OPC-SOA-Ch2	SOA-Ch3	SOA-OPC-SOA-Ch3
Gain (dB)	18	19.5	18	19.5	17.4	19.2
BER	1.4×10^{-2}	3.3×10^{-4}	4.1×10^{-3}	2.2×10^{-4}	3.9×10^{-3}	7.9×10^{-5}
OSNR$_{out}$ (dB)	29.6	26.4	29.7	26.3	29.5	26.8

We now proceed to demonstrate the feasibility of the scheme as a booster amplifier with 160 km fiber transmission and the corresponding results are shown in Fig. 4. Here in all cases, the input power to the SOAs is varied keeping the same fixed I_{drive}= 150 mA. A maximum output power of 4 dBm at SOA gain of 19 dB is launched into the fiber. At 4 dBm power, nonlinearity in the fiber is still weak. The results are compared to the case where the SOA is replaced with the SOA with NLC stage, for similar power levels. SOA with NLC outperformed the single



(a) Q^2 vs Output power- Ch1 (b) Q^2 vs Output power- Ch2 (c) Q^2 vs Output power- Ch3

Fig. 4: WDM-3X12Gbaud-16QAM-Results when the SOA/SOA-with NLC is used as a booster amplifier before 160 km fiber span, I_{drive}= 150 mA, Ch1:192.6/193.1, Ch2:192.65/193.05, Ch3:192.7/193.0 THz

SOA even in its low distortion, low-power regime of operation, and for all three channels, as shown in Fig. 4. The signal performance after the compensation stage is quantified by a Q^2 factor improvement of around 3.5 dB in all the channels at a launch power of 4 dBm. This is due to the high output power capability of the SOA with NLC with minimum nonlinear distortion. That is, though the OSNR after SOA with NLC is worse, more fiber launch power improves the OSNR at the receiver, and in turn higher Q^2 value can be achieved and hence longer reach.

5. Summary

An all optical nonlinear distortion compensation based on OPC for SOAs has been demonstrated for the first time. With the implementation of SOA with NLC, an average Q^2-factor improvement of 2 dB is achieved despite the additional ASE due to the NLC. These results, along with the implementation of OPC in SOA platform [8], provides a promising solution for a practical 1.3 μm amplifier solutions for future.

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