Digital Compensation of SOA-Induced Nonlinearities in Field-Modulated Direct-Detection Systems

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***Abstract*—In this work we experimentally demonstrate the compensation of nonlinearities introduced by a semiconductor optical amplifier (SOA) operating as a power booster in a field-modulated direct detection fiber-optic system transmitter. We show that a combination of digital *pre*-compensation to deal with SOA nonlinearities, and digital *post*-compensation after Kramers-Kronig receiver for mitigating the impacts of chromatic dispersion and signal-signal beat interference (SSBI) is an effective scheme to gain ∼3dB in ROSNR in presence of SOA nonlinearity at 3dB of gain compression.**

***Index Terms*—SOA, SSBI, fiber optics communication, fiber dispersion, EDC, Kramers-Kronig, backpropagation, QAM16.**

I. Introduction

OPTICAL communication in the access layers and 5G fronthaul and backhaul require cost-effective optical systems with typically high spectral efficiency. Complex field modulation is the typical modulation scheme used to achieve this requirement. In such systems, transmitters are commonly built with photonic integrated circuits with silicon photonics for its cost effectiveness and mass manufacturability. Silicon photonics have very high insertion loss that typically exceed 10dB for complex modulation transmitters which consist of nested Mach-Zehnder modulators (MZMs). Hence optical amplification of the modulated signal is mandated in some applications that require enough transmitter power to pre-compensate for different system losses such as those from passive optical splitters or multiplexers. Semiconductor optical amplifiers (SOA) are very attractive candidates for such applications. As a miniature-size integrable device, SOA is also a good low-cost solution in optical transmitters for applications in metro-access optical networks [1], [2]. SOAs also support wavelength bands outside those of traditional EDFA operation windows. Practical SOAs struggle to boost the optical power to high levels, hence they are usually operated near their nonlinear regime. While fast and nonlinear responses of SOAs are often used for all-optical packet switching and regeneration, relatively high nonlinearity and short carrier lifetime are known disadvantages of SOAs for applications such as post- and in-line optical amplification. Fast gain saturation of an SOA at high signal power levels leads to symbol pattern-dependent signal distortion and system transmission performance impairments [3] through self-gain modulation, self-phase modulation, and inter-channel cross-talks in wavelength-division multiplexing applications.

Direct detection (DD) optical transmission systems provide low-cost solutions compared to coherent detection. In intensity modulation direct detection (IM/DD) systems, the impairments induced by SOA gain saturation can be minimized through digital post-compensation [4] at the receiver. This is achieved by using the digital backpropagation method with the known nonlinear model of SOA gain characteristics. However, in the case of field-modulated DD systems and the presence of fiber chromatic dispersion, the post-compensation method for SOA-induced impairments will be compromised. This is because self-mixing of the signal optical field due to square-law detection of the photodiode leads to signal-signal beat interference (SSBI) which prevents proper field reconstruction in the digital domain. Additionally, in the presence of fiber chromatic dispersion, the dispersion and SOA nonlinearity induced signal distortions will be inter-coupled to further complicate the field reconstruction process [4]. One way to compensate for SSBI is to provide a guard band between the carrier and the signal to isolate the effect of SSBI from the received signal. It has been shown in [5], [6], that both SSBI mitigation and receiver-side electronic dispersion compensation (EDC) [7] can be achieved by using the Kramers-Kronig (KK) receiver scheme. This is less complex, and more cost effective compared to using dispersion compensating fiber or using coherent detection. In a linear system, EDC can be performed either at the transmitter or at the receiver. But for a DD system with SSBI, EDC must be applied after SSBI suppression [5]. However, when a SOA operating at high input power is introduced into the system, the SOA-induced nonlinearity will make the overall channel no longer linear, which harms the feasibility of accurate SSBI mitigation using KK and EDC.

To solve the above-mentioned problem, in this paper we experimentally investigate using the transmitter-side nonlinear pre-compensation technique to deal with impairments introduced by the SOA gain saturation to enable successful receiver-side SSBI mitigation and EDC in the KK scheme. This compensation scheme is a solution for complex field modulated optical transmission system with KK direct detection with nonlinear components in the system such as SOA. To our best knowledge, experimental demonstration of this pre-compensation approach

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to mitigate SOA nonlinearities in a field modulated DD system with KK receivers has not been previously reported.

II. Kramers-Kronig Receiver

The KK direct detection receiver scheme [6] allows the reconstruction of the signal complex optical field from the detected intensity, given that the signal has a single sideband (SSB) and satisfies the minimum phase condition. Therefore, the optical phase information of the signal can be extracted from the directly detected photocurrent.

When this optical signal is directly detected by a photodiode, a photocurrent $I(t)$ is produced. Let $E_s(t)$ be the complex envelope of the received band-limited signal with a bandwidth B, and E_0 be the amplitude of a CW tone which is used to beat with the modulated signal. $E_s(t)$ can be reconstructed through [6],

$$E_s\ (t) = \left\{ \sqrt{I\left(t\right)}\exp\left[i\emptyset_E\left(t\right)\right] - E_0 \right\}\ \exp\left(i\pi Bt\right), \quad (1)$$

$$\emptyset_E\ (t) =\ H\left\{\log\left[I\left(t\right)\right]\right\} \quad (2)$$

where, $H\{\cdot\}$ is the Hilbert transform function, $\emptyset_E(t)$ is phase restored using KK algorithm.

Although the photodetector performs a nonlinear square-law detection, when the minimum phase condition is satisfied, linear reconstruction of the complex optical field is possible [6]. The additive noise also remains additive after field reconstruction. This linear detection characteristic permits both SSBI mitigation and EDC in receiver signal processing. This is under the assumption that the transmission system before the receiver is also linear.

III. SOA Impairments and Compensation

When an SOA is introduced into the system as a post amplifier (or booster) at the transmitter, its nonlinear response to the optical signal is typically pattern dependent. This violates the linear system requirement for complex field reconstruction after KK detection at the receiver end, which results in reduced efficiency of SSBI mitigation and EDC. The impact of SOA nonlinearity cannot be compensated at the receiver because of the simultaneous presence of both chromatic dispersion and SSBI. Since the SOA is used as the post amplifier at the transmitter and its transfer function is deterministic, it is most convenient to pre-compensate for the SOA's nonlinear transfer function, both amplitude and phase, in the transmitter DSP. By doing this, both SSBI mitigation and dispersion compensation can still be performed digitally at the KK receiver.

To compensate for the impact of SOA nonlinearities, one first needs to model the SOA nonlinear transfer function using the differential equation [4]

$$\left(1 + \tau_c \frac{d}{dt}\right) h\ (t) = h_0\ - \frac{P_{in}\left(t\right)}{P_{sat}} \exp\left(h\left(t\right) - 1\right) \quad (3)$$

where, $h\ (t) = \int_0^L g(z,t)dz$ is the integrated instantaneous gain over the SOA length L, $h_0 =\ -lnG_0$, where G_0 is the small signal gain of the SOA. $P_{sat} =\ E_{sat}/\tau_c$ is the saturation power, where E_{sat} is the saturation energy of the SOA and τ_c is the effective carrier lifetime. P_{in}, is the input power to the SOA. The output optical field from the SOA is

$$E_{out}\ (t) =\ E_{in}\left(t\right) * \exp\left(\left(1 - \mathrm{i}\alpha_H\right) h\left(t\right)/2\right) \quad (4)$$

where, α_H is the chirp factor. Digital compensation of SOA nonlinear transfer function can be implemented by numerically solving (3) using fourth-order Runge-Kutta method [4]. The SOA parameters in (4), such as P_{sat}, τ_c and G_0, are deterministic. Their values can be determined experimentally by varying the power input to the SOA and observing the output power, as shown in Fig. 1(a). At a bias current of 140mA, the SOA carrier lifetime is approximately 350ps in our experimental setup. The measurement details can be found in [8]. At an input power around -9 dBm, we observe a gain compression of 3dB in comparison to the small signal gain.

IV. Experimental Setup

To demonstrate the digital pre-compensation technique of SOA nonlinearities in a field modulated DD system, we have conducted experiments using 14Gbaud QAM-16 modulated optical signal in the experimental setup shown in Fig. 1. A digital root raised cosine filter with a roll-off factor β of 0.1 was used for pulse shaping after the QAM-16 signal generation. This is followed by the pre-compensation procedure as described above. These offline processing stages were implemented at 5 Sa/Sym to accommodate the spectral broadening that results from the nonlinear pre-compensation process. Selecting the oversampling ratio in real-time implementation is an important parameter for the trade-off between implementation complexity, power consumption and system performance, which is out of the scope of this work. Subsequently, the pre-compensated signal is resampled to match the 60GS/s DAC rate and spectral pre-emphasis is applied to compensate for the transmitter's electro-optic frequency roll-off. Some access applications use amplified links, especially in those front-haul applications that use many passive multiplexing/demultiplexing or splitting components in modern WDM access applications; therefore, the experiment studies OSNR rather than the receiver power starvation.

Carrier suppressed optical single sideband (OSSB) signal generated by an I/Q modulator is fed to the SOA after a variable optical attenuator (VOA) which adjusts the signal power. The SOA device used (from INPHENIX) has a maximum noise figure of 9dB. The output of the SOA is combined with an optical carrier from a second external cavity laser (ECL) at 1550 nm to generate the SSB signal that satisfies the minimum phase condition for KK detection [6]. The target frequency separation between the two ECLs was set to (Symbol Rate/2 + 1 GHz); but the actual exact frequency separation may vary by 200~400 MHz due to the accuracy tolerance of the ECLs. The power of the inserted optical carrier is also controlled by a VOA to adjust the carrier to signal power ratio (CSPR). CSPR is defined as the ratio of the CW carrier power to the modulated signal power. Each power component was measured separately before the combination in the experiment. A polarization controller is used to align the state of polarization of the carrier component with that of the

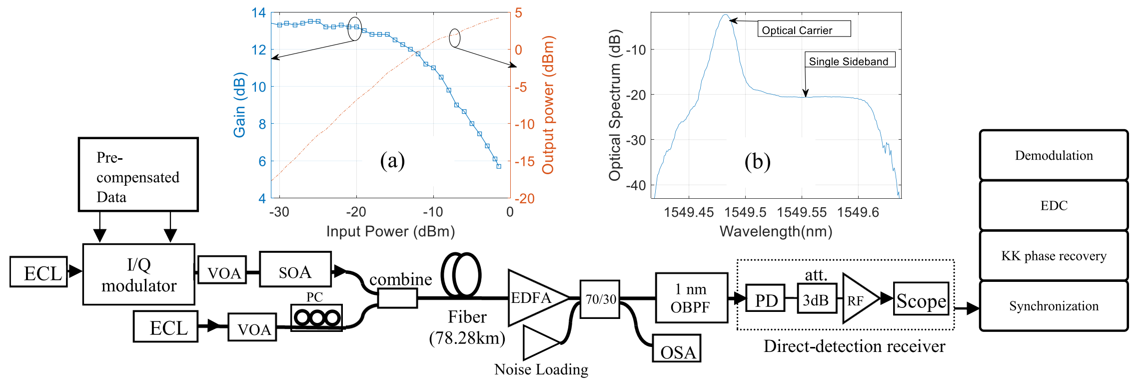

Fig. 1. Experimental Setup. ECL: external cavity laser, VOA: variable optical attenuator, SOA: semiconductor optical amplifier, OBPF: optical band pass filter, PC: polarization controller, OSA: optical spectrum analyzer. Inset (a) shows experimental SOA gain characteristics plot, (b) Single sideband optical spectrum measured by OSA with 0.01 nm resolution bandwidth.

modulated signal sideband from the SOA before they combine. The inset (b) in Fig. 1 shows the OSSB spectrum measured by an optical spectrum analyzer with 0.01 nm resolution bandwidth.

The combined OSSB optical signal is sent into $78.28\,\mathrm{km}$ optical fiber with an effective core area of $145\mu\mathrm{m}^2$ and $1683.02\ ps/\mathrm{nm}$ accumulated chromatic dispersion. Another EDFA is used as an adjustable amplified spontaneous emission (ASE) noise source which is combined with the amplified optical signal through an optical fiber coupler. This is in order to enable system performance assessment under different values of optical signal to noise ratio (OSNR). A 1-nm bandwidth optical band-pass filter (OBPF) is used to block the wide band ASE noise before the photodiode. The total signal optical power that reaches at the photodiode is maintained at 4.5 dBm throughout the experiment for consistency.

The electrical signal at the photodiode output is amplified and sampled by a real-time oscilloscope for analog-to-digital conversion (ADC) at 100GS/s sampling speed. The sampled signal waveform is processed offline in Matlab to recover the original 14Gbaud QAM-16 signal with the data rate of 56Gb/s. 107428 symbols (429712 total bits) were used for BER counting.

In the receiver DSP, the frequency response of receiver frontend was compensated, and the captured signal was re-sampled to 5 Sa/Sym. A DC component was then re-inserted to replace the DC component that was blocked by the AC-coupled RF amplifier. After KK field reconstruction and down-sampling to 2 Sa/Sym, frequency-domain dispersion compensation is applied to remove the impact of the fiber CD. This is followed by the down-conversion of the complex QAM signal center frequency to zero, matched filtering, clock recovery, T-spaced adaptive equalization to remove residual ISI, and carrier phase recovery based on the blind phase search before symbol-to-bit hard decision de-mapping.

V. Experimental Results and Discussion

For complex field modulated optical signal with direct detection, the effect of SSBI is determined by CSPR of the optical signal. Although a high CSPR helps reducing SSBI, it would increase the required OSNR to achieve an acceptable BER.

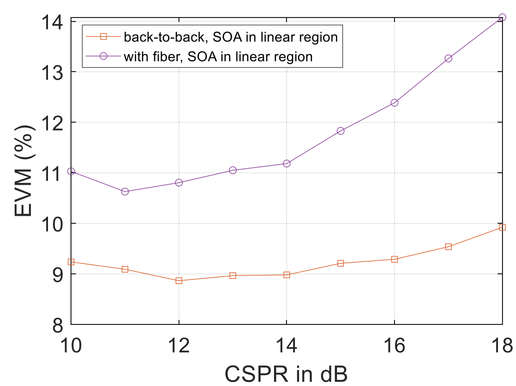

Fig. 2. Experimental EVM vs CSPR for back-to-back setup with OSNR = 44dB (square markers) and with fiber with OSNR = 40dB (circle markers) when SOA is operated in its linear region.

This is because with high CSPR, most of the signal optical power resides in the CW tone while the signal-carrying sideband is relatively weak. To find the optimum CSPR level for KK detection we used error vector magnitude (EVM) as the system performance measure, which is a measure of the average distance of the received complex symbol from its ideal position in the constellation diagram [9]. This is a reliable measure for QAM modulated optical signals. We measured EVM of the received QAM-16 signal with varying CSPR values when the SOA is operated in linear region. Fig. 2 shows the measured EVM in percentage, as a function of CSPR in dB. Noise-loading was not applied in these EVM measurements. For the back-to back setup without transmission fiber, OSNR at 0.1 nm resolution bandwidth was 44dB measured before OBPF. After $78.28\,\mathrm{km}$ fiber was inserted into the system and the gain of the EDFA pre-amplifier was increased to compensate for the fiber attenuation loss, OSNR was decreased to 40dB. The signal optical power at the photodiode was maintained at 4.5 dBm throughout the experiment. In the back-to-back setup, the EVM is relatively insensitive to CSPR between 10 to 18dB because of the relatively high OSNR. With transmission fiber, EVM deteriorated much faster when CSPR is higher than 14dB, mainly because of the smaller OSNR. Overall, the optimum CSPR is around 11dB for

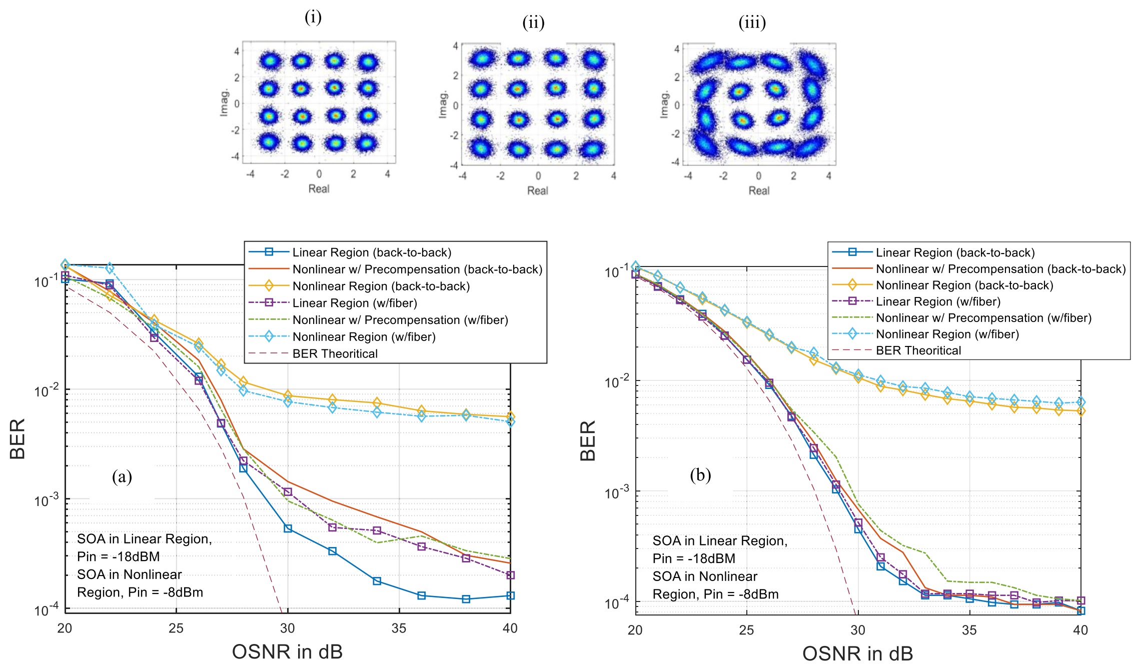

Fig. 3. Experimental measurements (a) and simulated results (b) of BER vs. OSNR for back-to-back and with fiber setups, Insets (i), (ii), (iii) show typical constellation diagrams of received QAM-16 signal when the SOA is operating in linear region, nonlinear region with and without pre-compensation for impairments, respectively.

the system with fiber. When the input optical power to SOA was set to -18 dBm, gain saturation is negligible, and in this linear regime pre-compensation was not necessary. When the input optical power to SOA was increased to -8 dBm, the SOA optical gain was reduced by approximately 3dB compared to the small-signal gain. In most practical applications, the SOA needs to operate in this nonlinear region in order to provide high enough optical power at the output. Digital pre-compensation of SOA nonlinearity was then applied in the transmitter DSP based on (3) and (4). Next, we fixed the CSPR value at 11dB and investigated the BER performance as the function of OSNR. The measured results are shown in Fig. 3(a).

Fig. 3(b) shows simulation results of the same system to verify the scheme of pre-compensating SOA induced nonlinearity. In the simulation we used signal modulation coding identical to the one we used for experiments. Transmission impairments that are taken into consideration using analytical models are SOA induced nonlinearity, fiber dispersion, fiber attenuation, and the fiber nonlinearity using split-step simulation. Transmitter impairments are accounted for by assuming a baseline of 24dB equivalent SNR. To vary the OSNR, optical noise is added to represent ASE noise generated due to optical amplification. At the receiver, the simulation included thermal noise, shot noise, RF amplifier noise, and the noise of oscilloscope. Thermal noise and shot noise were calculated using the equations $\sigma_{th}^2 = 4kT/R_L$ and $\sigma_{sh}^2 = 2q\Re P_s$, where $k = 1.28 \times 10^{-23} J/K$ is the Boltzmann's constant, $T = 300^{\circ} K$ is the absolute temperature, $R_L = 50\Omega$ is the load resistance, $q = 1.6023 \times 10^{-19} C$ is the electron charge, $\Re = 0.27\ A/W$ is the photodiode responsivity and $P_s = 4.5$ dBm is the received average signal optical power [10]. 3.5dB noise figure was assumed for the RF pre-amplifier. A 3dB RF attenuator used in the experiment between the photodiode and pre-amplifier to avoid saturation of the amplifier was also included in the simulation.

In both (a) and (b) of Fig. 3, three scenarios are presented based on the SOA operation condition and the application of pre-compensation: (a) SOA is operated in the linear region, (b) SOA is operated in the nonlinear region and without digital pre-compensation, and (c) SOA is operated in the nonlinear region but with digital pre-compensation. Insets (i), (ii), (iii) in Fig. 3 show typical constellation diagrams of the received QAM-16 signals when the system is operated under these three conditions. Consider back-to-back setup in Fig. 3(a), when SOA is operated in the linear region with a low input power of -18 dBm to the SOA, the BER can reach 10^{-4} at high OSNR values of around 40dB. When the input signal optical power to the SOA is increased to -8 dBm so that SOA operates in the nonlinear regime, the minimum BER is degraded to approximately 5×10^{-3} at the same OSNR. Then, with the application of digital pre-compensation at transmitter, the BER degradation caused by SOA nonlinearity can be significantly reduced, and the BER approaches to 3×10^{-4} which is close to the level of linear operation. Fig. 3(a) also shows similar BER performance improvement due to digital pre-compensation in the system with transmission fiber. Not only the level of BER floor at high OSNR was reduced by more than an order of magnitude, the required OSNR for BER of 10^{-2} was also increased by 3dB compared to the case without pre-compensation. These results indicate that the combination of digital pre-compensation in the transmitter for SOA nonlinearity and digital post-compensation for fiber chromatic dispersion at the receiver after KK field reconstruction can effectively improve the system performance.

VI. Conclusion

In this work we have experimentally demonstrated the mitigation of both SOA nonlinearity and fiber dispersion in field-modulated direct detection systems. The compensation of SOA nonlinearity was accomplished by pre-distorting the signal using SOA nonlinear model at transmitter side, and the impact of chromatic dispersion was compensated in the receiver through digital post-compensation. Clear system performance improvement by 3dB of OSNR at BER level of 10^{-2} was observed due to SOA *pre*-compensation when the SOA nonlinearity was at 3dB of gain compression.

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