Digital Compensation of SSBI in Direct Detection Multicarrier System With SOA Nonlinearities

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***Abstract*— We demonstrate an efficient signal–signal beat interference (SSBI) compensation technique for a direct-detection multicarrier optical system for the first time in the presence of nonlinear transfer function introduced by a semiconductor optical amplifier (SOA). While conventional digital SSBI compensation takes into account the nonlinear effect of photo-detection due to the square-law characteristic, nonlinear wave mixing among subcarriers can also be introduced by gain saturation if the system transfer function is nonlinear, which reduces the effectiveness of digital SSBI compensation. Using the nonlinear transfer function of SOA as an example, we show that the effectiveness of SSBI compensation can be largely restored when the nonlinearity is properly modeled through digital backpropagation.**

***Index Terms*— SSBI, OFDM, SOA, optical fiber communications, nonlinear compensation.**

I. Introduction

SEMICONDUCTOR optical amplifiers (SOA) possess unique attributes that make them stand out as an interesting area of research till date. Sharing the same fundamental device characteristics as that of a semiconductor laser with the exception of an anti-reflection coating on the facets, SOAs can be manufactured for all possible wavelengths supported by a semiconductor laser along with a wide gain bandwidth. This is one of those areas where SOAs are a step ahead of Erbium Doped Fiber Amplifiers (EDFA) and Raman Amplifiers in delivering flexibility and performance. Other signature characteristics of SOA such as small form factor, low cost, electrical pumping of charge carriers, wide spectral range, ultra-fast gain dynamics have been utilized to their fullest potential for "all optical signal processing" [1]. SOA, as a small-size, integrable device, may also offer a cost-effective solution in optical transmitters for applications in metro optical networks [2], [3]. However, some undesirable artifacts show up when high input powers drive the SOA into saturation. Unlike EDFAs that are generally operated in saturation with milliseconds carrier lifetime, SOAs when operated in saturation produce undesirable nonlinear effects as their carrier lifetime is in the order of picoseconds which is comparable to the bit time of the transmitted waveform. Gain saturation induced nonlinearities lead to pulse distortion in a single carrier modulation because the leading edge of the pulse saturates the amplifier and the available gain for the trailing edge is reduced which ultimately leads to the undesirable "Pattern Effect" [4]. Successful compensation of SOA gain saturation induced nonlinearities in a single carrier transmission system has been reported in [5], where the distorted complex optical field is coherently detected in the receiver, and correction is applied to digitally reverse the distortion based on the nonlinear model of the SOA gain dynamics.

On the other hand, for a multicarrier modulation scheme such as Orthogonal Frequency Division Multiplexing (OFDM) which is the object of this investigation, crosstalk generated by Four Wave Mixing (FWM) is the manifestation of the SOA gain dynamics that ultimately corrupts the data as reported in [3]. OFDM is a multicarrier signaling format that can provide high degree of flexibility and spectral efficiency [6], [7]. In OFDM, high speed data is partitioned into multiple orthogonal subcarriers, and the overall spectrum is tightly confined within a sharp boundary [6]. Direct-detection optical OFDM (DD-OOFDM) provides a low-cost alternative to coherent-detection as it does not require the optical local oscillator and 90° hybrid in the receiver. DD-OOFDM usually suffers from signal-signal beat interference (SSBI) originated from nonlinear mixing among signal subcarriers in the photodiode which performs square-law detection. SSBI significantly degrades the performance of DD-OOFDM, especially of the low frequency subcarrier channels. Band-offset modulation [7] has been proposed to eliminate the impact of SSBI in DD-OOFDM, by trading 50% of available bandwidth. The impact of SSBI can also be reduced by increasing the carrier-to-signal power ratio (CSPR) [8] at the cost of receiver sensitivity degradation. Iterative SSBI compensation in the digital domain has been demonstrated [9], which preserves both bandwidth efficiency and receiver sensitivity. While this technique has been shown to be effective in an optical system operating in the linear regime, its effectiveness in the nonlinear regime has not been investigated. Considering this as a prime motivational factor, in this letter, we used the SOA as a controlled nonlinear medium to investigate the impact of nonlinear transfer function in SSBI compensation. Our experimental results show that nonlinear transfer function due to SOA in the optical system makes the digital SSBI compensation less effective. The nonlinear transfer function of SOA is modeled using the technique described in [5], except only signal optical

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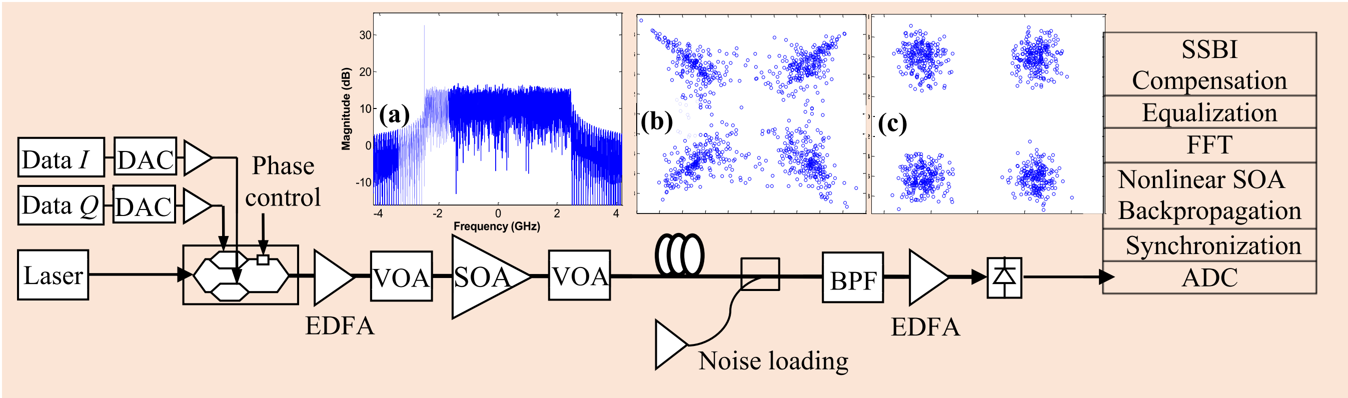

Fig. 1. Experimental setup. SOA: semiconductor optical amplifier, VOA: variable optical attenuator, BPF: band-pass filter. Insets show (a) transmitted spectrum, (b) constellation diagrams without SOA backpropagation and (c) with SOA backpropagation.

power is considered in our system based on direct detection. It is the combination of SOA nonlinearity and the square-law detection of the photodiode that complicates the digital compensation of multicarrier modulated direct detection optical systems.

We propose and validate a novel signal processing technique that efficiently accommodates the compensation of both SOA and photodetector nonlinearities.

II. Experimental Setup

The experimental setup is schematically shown in Fig. 1. A tunable laser with 100 kHz spectral linewidth is used as the optical source. The optical carrier is suppressed by setting the bias of the I/Qmodulator at the transmission null, and an RF tone is inserted at the edge of the negative sideband so that direct detection can be used in the receiver as illustrated in the inset (a) of Fig. 1. A 10.22 Gbps QPSK modulated serial data is loaded onto 63 subcarriers through serial parallel conversion and IFFT with a block size of 256. The QPSK symbols are mapped onto subcarriers 1 through 32 and 226 through 256, and the remaining subcarriers are forced to zero. A cyclic prefix of 0.37 ns duration is used to combat fiber dispersion resulting in a total OFDM symbol time of 12.326 ns. This results in an optical bandwidth of 5.11 GHz. The RF tone is inserted onto the 225$^{\text{th}}$ subcarrier (corresponding to -2.5 GHz frequency). This "gapless" spectral mapping allows improved bandwidth utilization of digital electronics in comparison to "gapped" spectral mapping [9]. The I and Q components represent the real and imaginary parts of digitally generated OFDM signal, and they are fed into a commercial CIENA optical transceiver card which was originally designed for 10 Gb/s SONET systems with electrical domain precompensation (eDCO) [10]. This card is equipped with two DACs with 21.417 GSa/s sampling rate at 6-bit resolution. An EDFA post amplifier is used after the modulator to provide adequate optical power which allows us to explore linear and nonlinear operation regions of an SOA after a variable optical attenuator (VOA). The SOA used in the experiment has a small signal gain of 15 dB at 170 mA bias current. The amplified optical signal at the output of the SOA is attenuated to -12 dBm and is transmitted through a fiber link with accumulated chromatic dispersion of 1320 ps/nm equivalent to approximately 80 km standard single mode fiber. ASE noise generated from an EDFA is used as an adjustable noise source which is combined with the optical signal through a fiber coupler to adjust the OSNR (0.1 nm resolution) at the receiver. An optical band-pass filter (BPF) with 1 nm bandwidth filters out the wide-band ASE noise. The signal optical power at the photodetector is maintained at 0 dBm throughout the experiment for consistency. The photocurrent is recorded using a 50 GSa/s digital phosphor oscilloscope with post processing implemented offline.

In order to analyze the impact of SOA nonlinearities on the OFDM signal and to compensate them, we need to have an adequate knowledge of SOA nonlinear transfer function and the gain dynamics, which can be modeled by a differential equation [5]

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

where $h\left(t\right)=\int_0^L g(z,t)dz$ is the instantaneous gain integrated along the SOA length L, $h_0=lnG_0$ with G_0 the SOA small signal gain, τ_c is the SOA carrier lifetime, P_{in} is the input power to the SOA and P_{sat} is the SOA saturation output power. The instantaneous signal output power from SOA is then

$$P_{out}(t)=P_{in}(t)\exp[h\left(t\right)] \qquad (2)$$

For the direct detection optical receiver described here, post compensation is based on the received optical signal $P_{out}(t)$ which is distorted by the nonlinearity of SOA. The goal of the receiver digital signal processing (DSP) is to retrieve $P_{in}(t)$ with the knowledge of $P_{out}(t)$, which is accomplished by numerically solving (1) and (2). This is equivalent to a process which models the optical signal propagated backward through the SOA, and thus commonly referred to as SOA backpropagation technique [5]. The SOA parameters such asP_{sat}, τ_c and G_0 are deterministic, which can be determined beforehand. More specifically, P_{sat} and G_0 can be determined experimentally by varying the input launch power to the SOA and observing the output power, as shown in the Fig. 2(a). With -11 dBm input optical power, the gain suppression is approximately 3 dB with respect to the small signal gain, and

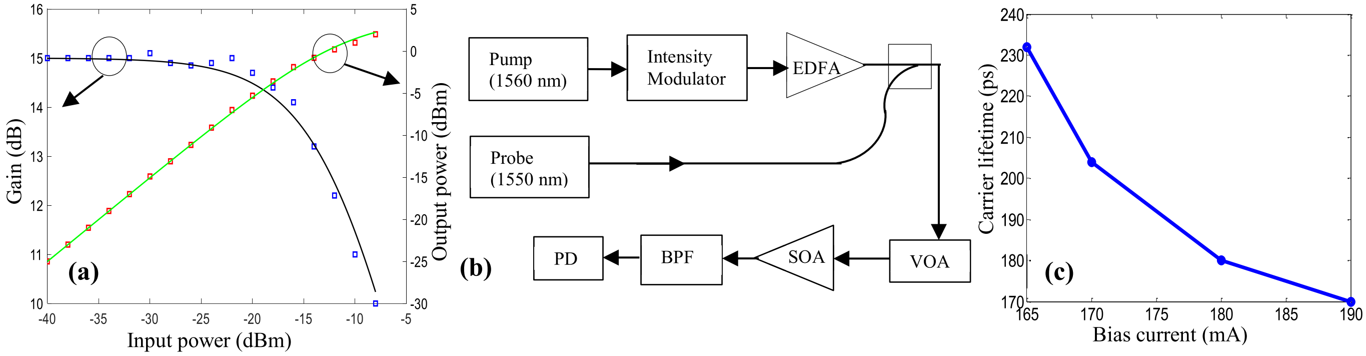

Fig. 2. (a) SOA gain characteristics: experimental (squares), theoretical (dark lines), (b) experimental setup for SOA carrier lifetime characterization, (c) SOA carrier lifetime versus bias current.

the corresponding output power is about 0.8 dBm. The SOA gain compression is negligible when the input optical signal power is less than -20 dBm. The carrier lifetime of the SOA is determined for different bias currents using a pump-probe measurement technique as shown in Fig. 2(b) and explained as follows. We adopt two CW lasers, namely pump and probe operating at 1560 nm and 1550 nm respectively. A $2^{15} - 1$ length PRBS sequence is generated by an Arbitrary Waveform Generator (Tektronix AWG70002A), and an optical intensity modulator modulates this data on to the pump signal. The modulated pump is amplified by an EDFA and is combined with the probe signal via an optical 3 dB coupler. A variable optical attenuator is used to control the launch power to the SOA. The SOA is operated in saturation and the amplified signal is filtered using a tunable optical filter tuned to select the probe wavelength. The filtered probe signal is detected by a photodiode, sampled and analyzed offline in MATLAB. When SOA is operated in saturation, the gain of the SOA is modulated by the pump waveform, which introduces the modulation on the probe through cross-gain and cross-phase modulation. The cross-gain modulation alone allows us to accurately characterize the carrier lifetime. We simultaneously acquire the pump waveform before SOA and the probe waveform after SOA. The pump waveform is digitally filtered by a low-pass filter with the transfer function $\frac{1}{1+j2\pi t/\tau_c}$. The carrier lifetime τ_c of the SOA can be determined by best fitting the filtered pump waveform with the inverse of the probe waveform using the least-squares criterion. Fig. 2(c) shows the measured carrier lifetime as the function of the SOA bias current using the technique discussed above. As expected, with the bias current increase, the carrier lifetime is reduced to some extent due to the carrier density increase within the SOA active region and the enhanced stimulated recombination. At the bias current of 170 mA, the measured carrier lifetime of the SOA is approximately 200 ps.

III. Result Analysis and Discussion

In order to quantitatively evaluate the impact of SSBI on the system performance, we use Error Vector Magnitude (EVM) as the performance metric in our experiments, which has shown to be a reliable measure for high level modulated optical signals including linear and nonlinear impairments [11]. An important system parameter determining the effect of SSBI is CSPR, which is the ratio between the carrier power and the integrated power across all signal subcarriers. A high CSPR results in a low SSBI because the mixing between the carrier and the data subcarriers is much stronger than the mixing among data subcarriers. But an increased CSPR would result in a degradation of the required OSNR in the receiver because a significant portion of the optical power is in the optical carrier and the signal subcarriers are relatively weak. Although the optimum CSPR is around 0 dB for the gapped OFDM [12], whereas, the optimum CSPR for the gapless OFDM is approximately 4 dB [9]. In our experiments, two different values of CSPR, 2 dB and 6 dB, are used.

To study the impact of nonlinearities in the system introduced by the SOA, we consider two different optical power levels P_{in} =-20 dBm and P_{in} =-10 dBm, at the input of the SOA. Measured EVMs as the function of OSNR are reported in Fig. 3 with different SSBI compensation algorithms and in different system conditions.

At a low input power (-20 dBm), the SOA operates in a linear regime. For a relatively low CSPR of 2 dB, consider OSNR of 27 dB in Fig. 3(a). The SSBI compensation algorithm [9] improves the mean EVM of the OFDM signal from 25.8% (dashed green line) to 13.4% (dashed black line) providing a net improvement of 12.4%. EVM reported here is averaged over all subcarrier channels. As we reduce the OSNR to 18 dB, the net improvement in EVM after SSBI compensation decreases to 8.6 % suggesting the impact of high ASE noise that reduces the effectiveness of SSBI compensation. Likewise, for CSPR of 6 dB as shown in Fig. 3(b), at 27 dB OSNR, the SSBI compensation algorithm improves the mean EVM of the OFDM signal from 20.6% (dashed green line) to 12.5% (dashed black line) providing a net improvement of 8.1%. By comparing Fig. 3(a) with Fig. 3(b), it is clearly evident that a signal with lower CSPR is more susceptible to SSBI induced crosstalk, which is in agreement with [9].

At a higher input power of -10 dBm, the SOA operates in the significantly nonlinear regime, and the SSBI compensation algorithm described in [9] becomes less effective compared to the linear case. For instance, for a CSPR of 2 dB, the EVM is reduced from 28.5% to 21.6% through SSBI compensation at 27 dB OSNR as shown in Fig. 3(a), and the improvement is only 6.9%. This clearly indicates the impact of SOA nonlinearities in reducing the effectiveness of digital

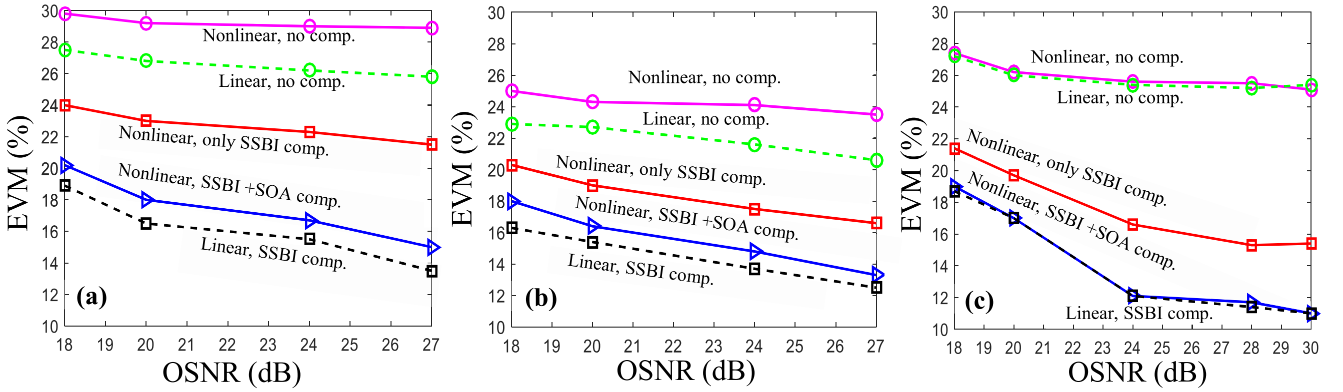

Fig. 3. EVM as a function of OSNR for SOA input powers of -20dBm (dashed lines) and -10dBm (solid lines). (a) CSPR = 2 dB with 80km standard SMF, (b) CSPR = 6 dB with 80km standard SMF, and (c) CSPR = 2 dB, back to back. Open circles: no SSBI compensation, squares: after SSBI compensation, and triangles: after SOA backpropagation and SSBI compensation.

SSBI compensation. The same observation holds also for CSPR of 6 dB as shown in Fig. 3(b). Thus, the digital SSBI compensation algorithm has to be modified by taking into account the SOA nonlinearity in the system. This can be achieved by performing digital backpropagation of SOA to compensate its gain dynamics described by (1). By taking SOA nonlinearity into consideration, the modified algorithm significantly improves the effectiveness of digital SSBI compensation. For CSPR of 2 dB as shown in Fig. 3(a), at an OSNR of 27 dB, EVM is further reduced from 21.6 % without digital SOA backpropagation to 15 % after digital SOA back propagation, providing an additional improvement of 6.6%. This only leaves a gap of approximately 1.5 % in EVM between linear (dashed line with squares) and nonlinear (solid line with triangles) regimes. The same performance improvement also holds for CSPR of 6 dB as shown in Fig. 3(b). Typical constellation diagrams at the lower frequency subcarriers (most affected by SSBI) without and with SOA backpropagation are shown in the inset (b) and (c) of Fig. 1 for SOA input power of -10 dBm with a CSPR of 2 dB.

Note that in the system with 1320 ps/nm accumulated dispersion in the transmission fiber, adding SOA backpropagation significantly improves the effectiveness of digital SSBI compensation, but it does not completely eliminate the impact of nonlinear effect introduced by the SOA. Fig. 3(c) shows the EVM versus OSNR measured under the same condition of Fig. 3(a) with CSPR of 2 dB, but without the transmission fiber. In this case SOA backpropagation improves the EVM of nonlinear system to the same level of the linear system. In fact, the chromatic dispersion in the transmission fiber has the effect of converting the nonlinear phase modulation created by the SOA into an intensity noise [13]. But this nonlinear phase modulation cannot be retrieved at the receiver after direct detection, and hence resulted in an approximately 1.5 % degradation of SSBI compensation as shown in Fig. 3(a) and 3(b).

IV. Conclusion

In conclusion, we show that nonlinear transfer function of an SOA in a DD-OOFDM system may significantly decrease the effectiveness of SSBI compensation. We have demonstrated an improved digital SSBI compensation technique in a fiber system with SOA operating in the nonlinear regime based on nonlinear backpropagation of SOA. The effectiveness of the improved SSBI compensation has been experimentally verified for DD-OOFDM systems with different parameters including CSPR and the depth of SOA saturation.

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