On the Phase Noise Enhancement of a Continuous Wave in Saturated SOA Used for RIN Reduction

Mustafa Al-Qadi, Maurice O'Sullivan, Chongjin Xie, and Rongqing Hui

***Abstract*— We report on the spectral characteristics of the phase noise enhancement of continuous-wave (CW) optical signals passing through a semiconductor optical amplifier (SOA) operating in the saturation regime and used for relative intensity noise (RIN) reduction. We show that the known effect of phase noise enhancement, attributed to the linewidth enhancement factor of the device, happens only at a limited band of the phase noise spectrum, and the actual measurable linewidth of the output CW signal may not be affected. While this phase noise enhancement is not shown as an increase of spectral linewidth, it can still affect system performance when coherent detection is used, especially in applications with relatively low symbol rates. Numerical simulations and experimental results are used to support the observation. A single spectral line from a quantum-dot mode-locked laser is used as the light source, which is known to have relatively high RIN (> −120 dB/Hz in the low frequency region). Experimental transmission of 16-QAM modulation with coherent detection has been performed at 5 GBd to assess the implication on system performance.**

***Index Terms*— Semiconductor optical amplifier (SOA), coherent communications, relative intensity noise (RIN), semiconductor lasers.**

I. Introduction

SEMICONDUCTOR optical amplifiers (SOAs) have small size, low power consumption, wide gain bandwidth, and can be integrated in photonic integrated circuits (PIC) [1]. SOAs can provide a low-cost alternative to erbium-doped fiber amplifiers (EDFAs) in fiber-optic communication systems [2], [3], notably in short reach interconnect applications based on PIC [4]. SOAs also find use in all-optical signal processing through nonlinear saturation and nonlinear wave mixing [1]. Furthermore, the reduction of relative intensity noise (RIN) of unmodulated continuous wave (CW) optical signals has been demonstrated when the signal passes through a saturated SOA [5]–[7]. Recently, multi-wavelength optical sources such as quantum-dot(dash) mode-locked lasers (QD-MLLs) have been studied in WDM and multi-lane interconnect applications [6]–[9]. Each spectral line of a QD-MLL usually has relatively low power and high RIN on the order of −120 dB/Hz in the low frequency region of up to 100MHz. An SOA can provide power amplification and RIN reduction. SOA-based RIN reduction also has lower complexity compared to other techniques based on, e.g., injection locking [9].

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RIN affects the performance of intensity modulation and direct detection systems, often used in short-reach and optical interconnection applications [1], [5]. RIN may also have strong impact in coherent systems. For coherent systems, although the effect of RIN from the local oscillator (LO) can be greatly reduced using balanced photodiode (PD) detection given high enough common-mode rejection ratio [10], the transmitter side laser RIN can limit the transmission performance, especially when high modulation orders of quadrature amplitude modulation (QAM) are employed. RIN also has a direct impact in self-coherent systems with single PD detection [8].

SOA-based RIN reduction is well known to enhance (increase) the phase noise (PN) of a CW due to the SOA's linewidth enhancement factor. *Statistical* quantification of the variance of enhanced PN has been well studied in the literature, e.g., in [11], [12]. In this letter, we study the *spectral* characteristics of the PN enhancement in this application and show that, interestingly, this PN enhancement has no or minimal effect on the measured linewidth of the CW signal. High frequency PN measurement must be used to assess the amount of the PN enhancement. To the authors' best knowledge, this observation has not been reported elsewhere in the literature. We first demonstrate the effect by numerical simulations; and then we report the measured PN and intensity noise properties of a CW signal from a QD-MLL before and after passing through a saturated SOA. Then we report results of back-to-back transmission experiments using intradyne coherent detection, with and without an SOA, to assess its impact in the transmission performance at intentionally low, yet practical, symbol rate.

II. Device Modeling and Simulations

We modeled RIN reduction and the associated PN enhancement caused by a saturated SOA. We carried out simulations using numerically-generated CW optical signal with RIN and PN, and passed this signal through an SOA model. The nonlinear characteristics and the gain dynamics of the SOA were modeled by the differential equation [13]:

$$\left(1+\tau_c\frac{d}{dt}\right)h\left(t\right)=h_0-\frac{\left|E_{in}\left(t\right)\right|^2}{P_{sat}}\left\{\exp\left[h(t)\right]-1\right\} \quad (1)$$

where $h\left(t\right)=\int_0^L g(z,t)dz$ is the power gain integrated along the active length of the device L. $h_0=lnG_0$ with G_0 being the small signal gain. τ_c is the carrier lifetime, $E_{in}(t)$ is the input signal complex optical field, and P_{sat} is the saturation output power of the SOA. The complex optical field at the SOA

TABLE I
MEASURED PARAMETERS OF THE SOA

Parameter	Quantity	Measured Value
G_0	Small signal gain	16 dB
τ_c	Carrier lifetime	300 ps
P_{sat}	Saturation power	5 dBm
α	Chirp parameter	5

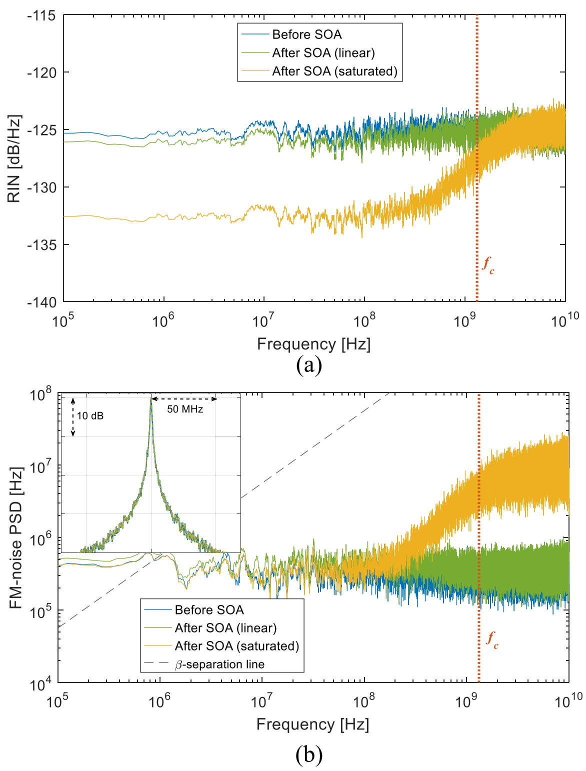

Fig. 1. Simulation results for (a) RIN and (b) FM-noise PSD before and after passing through SOA with linear ($P_{in} = -20$ dBm) and saturated ($P_{in} = 0$ dBm) operation regimes. The inset in displays the corresponding field spectra, showing no any enhancement to the linewidth.

output is given by $E_{out}(t) = E_{in}(t)\exp[(1 - j\alpha)\, h\,(t)\,/2]$, where α is the linewidth enhancement factor (chirp parameter). P_{sat} and G_0 can be determined in a steady-state measurement by varying the average input power to the SOA and measuring the average output power. τ_c and α can be determined dynamically by measuring and comparing signal waveforms at the input and output of the SOA. A standard 4$^{\text{th}}$-order Runge-Kutta method was used to numerically solve Eq. (1) [14]. In our simulations, we used the measured parameter values of the SOA, that is used in our experimental work presented in the next section, as listed in Table I.

The optical signal input to the SOA was created at 50 GS/s (sample interval $\tau = 20$ ps) with 5 million points and a RIN of -125 dB/Hz. The PN was modeled as a Weiner process with a 3-dB full-width at half-maximum (FWHM) Lorentzian linewidth of 1 MHz, and the intensity noise was also assumed to be white-Gaussian. It should be noted that these assumptions for the optical signal are for the purpose of clearly showing the impact of the saturated SOA on the spectral profiles of these noises. The actual phase and intensity noises of a practical laser signal may have non-white spectra, as will be shown in the experimental investigation of the next section. The input power to the SOA was set to -20 dBm and 0 dBm, for the linear and saturated regimes, respectively. Figure 1(a) shows the RIN of the signal before and after passing through the SOA. As expected, the RIN does not experience a significant change when the SOA operates in the linear regime. Whereas in the saturated regime the RIN is clearly reduced by approximately 7 dB for frequencies lower than the cutoff frequency determined by [5]

$$f_c = \frac{1}{2\pi\,\tau_c}\sqrt{G_{cw}^2 b^2 + 2G_{cw}b - 2b^2 - 4b - 1},$$
$$b = \frac{\ln(G_0/G_{cw})}{G_{cw} - 1} \tag{2}$$

where G_{cw} is the saturated power gain. RIN levels at frequencies higher than f_c remain unaffected. This stems from the high-pass intensity characteristic of the saturated SOA [5], [7] and it shows the importance of the carrier lifetime and the saturation depth in determining the RIN reduction efficiency. G_{cw} was found to be equal to 8.2 dB in our simulation at the input power of 0 dBm, resulting in $f_c = 1.32$ GHz.

The RIN of the optical signal introduces carrier density modulation of the SOA, which is known to result in a modulation of the phase of the optical signal through the chirp of the SOA [1], [13]. As the FM noise is often used to describe the spectral properties of the PN, the latter, obtained from measurement, can be converted into the FM noise power spectral density (PSD) through:

$$S_{FM}\,(f) = \frac{f^2 PSD\{\Delta\varphi\,(\tau)\}}{4sin^2\,(\pi f \tau)}, \quad \frac{1}{T_m} \le f \le \frac{1}{2\tau} \tag{3}$$

where $\Delta\varphi\,(\tau)$ is the phase difference sequence of the complex optical field sampled at a time interval τ, and T_m is the measurement interval. Figure 1(b) shows the FM noise PSDs of the same optical signals of Fig. 1(a). After passing through the SOA, the FM noise PSD of the optical signal is the superposition of the original FM noise of the laser source and the extra FM noise generated at the SOA. At low frequencies below f_c, the SOA-induced PN PSD is flat due to the low-pass characteristic of the carrier density modulation, and thus the SOA-induced (additive) FM noise increases as a function of f^2 as indicated by Eq. (3). The increment of FM noise as the function of frequency ceases for $f > f_c$, due to the roll-off of the low-pass function, hence the overall FM noise PSD reaches a plateau. The example in Figure 1(b) shows that the FM noise generated at the SOA is higher than that of the input signal for frequencies higher than ~500 MHz, after which there is an observable ~15 dB enhancement, and the overall spectral profile of the FM noise after the SOA is no longer white. Note that enhancement of FM noise PSD at high frequencies can start to decrease when the RIN has low spectral components at higher frequencies, as will be experimentally shown below.

As the FWHM linewidth of an unmodulated optical signal is determined mainly by the low frequency components of the FM noise PSD, typically below the intersection with a so-called *β-separation line* [15], the high-frequency PN enhancement does not affect the measurable linewidth of the CW signal. As a novel observation in this work, the inset in Fig. 1(b) shows the optical field spectra before and after the SOA, where the spectral shape is unaffected by the SOA even for frequencies at which the normalized spectral density is as low as -40 dB. However, a coherent system performance depends heavily on the high frequency components of the

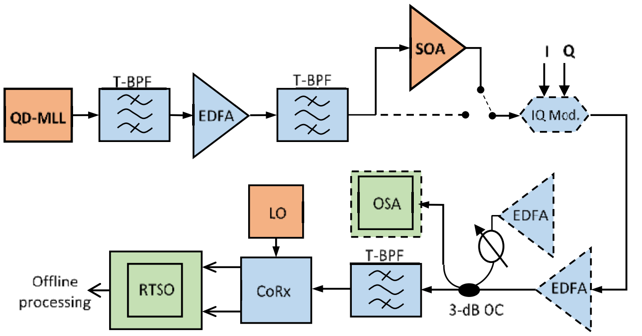

Fig. 2. Schematic of the experimental setup used for phase and intensity noise measurements and back-to-back coherent transmission. Dashed-outlined blocks are used only for the coherent transmission setup. QD-MLL: quantum-dot mode-locked laser; T-BPF: tunable bandpass filter; CoRx: coherent receiver; RTSO: real-time sampling oscilloscope.

FM-noise PSD; and the PN of a CW signal with non-white FM noise is better quantified by a *Lorentzian-equivalent linewidth* (LEL) [16], rather than the traditional −3-dB or −20-dB linewidth measures. LEL is determined by the FM noise at a specified sampling frequency. In our simulation, the LEL evaluated at a sampling frequency of 5 GHz was found to be enhanced from 1 MHz to nearly 15 MHz after the saturated SOA. This large enhancement is a result of the assumed white RIN spectrum extending beyond f_c, which may not be realistic for practical lasers. Thus, PN enhancement in the high frequency region for practical lasers with lower high-frequency RIN PSDs could be much lower.

III. Experimental Setup and Results

The experimental setup used for RIN and PN characterization and transmission experiments is shown in Fig. 2, where the dashed-outlined blocks are used only for the coherent transmission. We use a single-section InAs/InP QD-MLL [7] operating in the 1550 nm wavelength window as the light source, which has a relatively high RIN (>-120 dB/Hz at the low frequency, and an average RIN [7] of −28.4 dB in the 25kHz-5GHz frequency window). This laser simultaneously emits approximately 50 spectral lines with 25 GHz line spacing, and we selected a single spectral line with two narrowband (∼0.3 nm and ∼0.9 nm bandwidth) optical filters at 1537.33nm. The measured FWHM linewidth of the selected line was 4 MHz. The signal is optically amplified to 0 dBm by an EDFA inserted between the two optical filters. Then the optical signal is coupled into an SOA. The SOA is biased at 240 mA injection current, resulting in $G_0 = 16$ dB small signal gain. With the 0 dBm input power, the SOA operates in the saturation regime. The optical signal before and after the SOA is down-shifted to the RF domain through a phase diversity coherent receiver employing an external-cavity laser (ECL) as the LO with <50 kHz spectral linewidth and <-140 dB/Hz RIN. Thus, the impacts of both PN and RIN of the LO on the measurement are negligible compared to those of QD-MLL. The I and Q components of the complex RF signal are captured and stored by a real-time sampling oscilloscope (RTSO) at 50 GS/s with 2×10^6 sample points (duration of 40 μs) and processed offline by MATLAB. 10 different waveforms were captured for each case to confirm the consistency of the results. The optical power input to the coherent receiver was

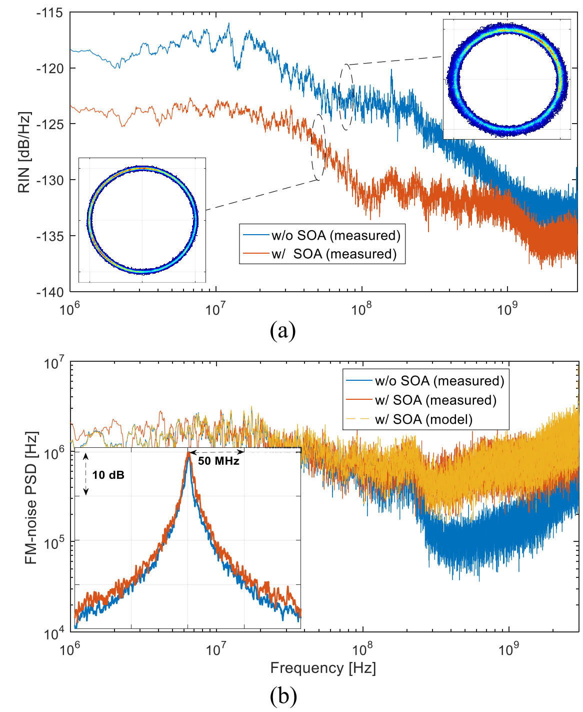

Fig. 3. Measured (a) RIN and (b) FM-noise PSDs before and after passing through the SOA with saturated ($P_{in} = 0$ dBm) gain. The insets in the upper plot display the complex-plane scatter plots of the normalized complex envelopes without and with passing through the SOA, within 5 GHz bandwidth. The inset in the lower plot shows the corresponding measured field spectra.

kept constant for all measurements so that the instrumentation noise contribution is constant for all cases.

The RIN is obtained by extracting the magnitude perturbations of the complex envelope (after frequency down-shifting to the origin) and calculating the spectrum. Figure 3(a) shows the RIN with and without passing through the saturated SOA, with a clear reduction of 6 ∼ 7 dB at low frequencies, with measured average RIN reduction from −28.4 dB to −35 dB over the frequency range from 25 kHz to 5 GHz. The measured FM-noise PSDs are shown in Fig. 3(b). Note that the QD-MLL inherently has non-white FM noise spectral profile before the SOA (blue), and the high-frequency spectral region near 1 GHz has about a decade lower FM noise PSD compared to that at lower frequencies [16], [17]. FM-noise PSD is enhanced after passing through the SOA (orange) with similar high-pass characteristic explained above in the previous section. The FM-noise PSD enhancement starts to reduce for frequencies higher than 1 GHz due to the low levels of RIN PSD shown in Fig. 3(a). The field spectra, displayed in the inset, show only a negligible 8% linewidth enhancement (36 MHz to 39 MHz at −20 dB). On the other hand, the LEL measured at 5 GHz sampling frequency was found to be enhanced by 155% (from 0.95 MHz to 2.43 MHz). As will be shown next, this enhancement will have noticeable performance impact in coherent transmission for systems with relatively low symbol rates, e.g., in access or mobile network back/front-haul applications.

To assess the implication of PN enhancement on the coherent 16-QAM transmission, the I/Q modulator in the setup of Fig. 2 is driven by 5 GBd Nyquist (RRC roll-off of 0.1) signal at 21.4 GS/s. The received signal is digitally captured at

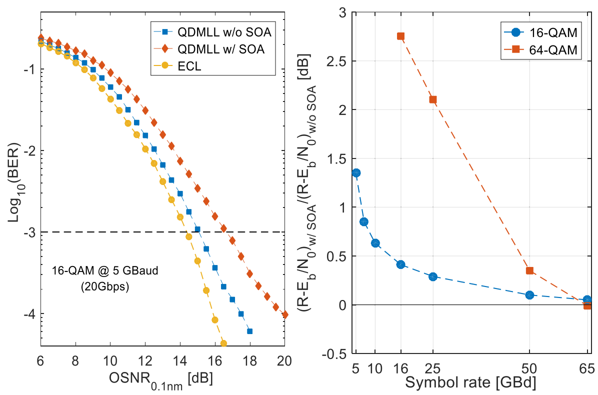

Fig. 4. (Left): Experimental BER as a function of OSNR for a 16-QAM coherent link at 5 GBd, with and without SOA-based RIN reduction. ECL with RIN < -140 dB/Hz was used as the transmitter CW source for comparison. (Right): Simulations of required E_b/N_0 difference [dB] as a function of baud.

25 GS/s and processed offline. The signal processing included normalization, resampling to 2 Sa/Sy, matched filtering, frame and symbol synchronization, adaptive equalization, carrier phase recovery with the blind phase search (BPS), and symbol-to-bit hard decision for BER calculation. The BPS window half-length was optimized for each case (8 for ECL and 6 for QD-MLL) [16]. Despite the RIN reduction, Fig. 4 shows that the OSNR performance is degraded by about 1.5 dB at BER $= 10^{-3}$ when the signal passes through the SOA. A computer simulation based on the measured CW waveforms reveals that RIN reduction alone would improve the required OSNR by about 0.2 dB, while the enhancement of high-frequency FM noise introduced a 1.7 dB OSNR degradation. This degradation can be more severe if a higher order modulation is used such as 32- or 64-QAM at the same baud. Nonetheless, the overall impact of the opposing results of RIN reduction and PN enhancement will depend on the symbol rate and the radial and angular cardinality of the QAM constellations. Figure 4(right) shows the results of simulations of 16- and 64-QAM signal transmission, based on using the measured complex waveforms of the beat tone [18] with and without the saturated SOA, at different symbol rates. The results are presented in terms of the difference of the required per-bit signal-to-noise ratio (R-E_b/N_0) to achieve a threshold BER of 10^{-3}. The BPS window size was optimized for each case. It is clear that with increasing the symbol rate the effect of the enhanced PN reduces. The faster drop of penalty as a function of symbol rate for the case of 64-QAM is attributed to the higher radial cardinality in the constellation compared to 16-QAM, which gains more improvement from the RIN reduction.

IV. Conclusion

We have investigated the spectral properties of the phase noise enhancement of a CW optical signal passing through a saturated SOA in the application of RIN reduction. The results were expressed by simulation and experiments in term of the FM noise and optical field spectra. A QD-MLL is used as the laser source which has a relatively high RIN (>-120 dB/Hz) at the low frequency region. We showed that although the CW signal experiences PN enhancement, the linewidth of its optical field spectrum does not show significant broadening. This is because the low-frequency part of the FM noise spectrum does not experience significant enhancement. The performance of the SOA has been analyzed through a rate equation model, and simulated results agree well with the measured FM noise spectra when the signal passes through the SOA. The performance impact of the high-frequency FM noise increase in a coherent system has been measured experimentally. The trade-off between RIN reduction and high-frequency FM noise enhancement should be optimized for phase-sensitive transmission applications through the joint design of the SOA and system power budget and QAM constellations.

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