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Measurements and Simulations of Nonlinear Noise Redistribution in an SOA

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***Abstract*—Measurements and numerical simulations of the noise statistics after a semiconductor optical amplifier (SOA) demonstrate nonlinear noise redistribution. The redistribution, which relies on self-modulation due to gain saturation and carrier dynamics, shows a strong power and bandwidth dependence and can be important for SOA-based regenerators.**

***Index Terms*—Noise, optical communications, semiconductor optical amplifiers (SOAs).**

I. Introduction

MANY DEVICES for all-optical signal processing, such as regenerators and wavelength converters, are based on the nonlinear saturation characteristics of semiconductor optical amplifiers (SOAs) [1]–[3]. The noise reduction in a saturated SOA is also used in, for example, spectrum sliced wavelength-division-multiplexing systems [4]. However, there are only few investigations on the influence of the dynamics of the SOA on the noise properties of a signal transmitted through an SOA in the saturated regime [4]–[8], although this fundamentally affects the device properties. This letter presents experimental characterization and numerical simulations showing reduction in width and, to our knowledge, for the first time a change in shape of the pdf of the signal after an SOA. The results are particularly important for all-optical regenerators employing SOAs, where the change in the tails of the noise distribution can lead to substantial bit-error-rate (BER) penalties [3], [8], [9].

II. Experimental Setup and Theoretical Model

The setup, shown in Fig. 1, consists of a continuous-wave (CW) laser (LD), a noise source in the form of a fiber amplifier (EDFA1), optical bandpass filters, the examined amplifier (SOA/EDFA2), a detector, and a BER test set. The noise on the input signal to the SOA can be varied through the combination of an attenuator (Att.) and EDFA1. The probability density functions (pdfs) are derived from measuring the BER as function of decision threshold voltage [7], [10]. We have investigated a commercial bulk InP–InGaAsP SOA and compared it to a fiber-based preamplifier.

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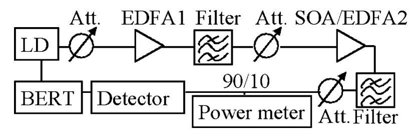

Fig. 1. Schematic of measurement setup.

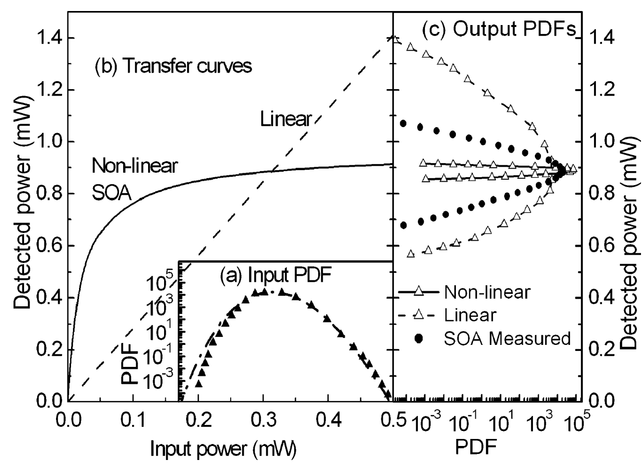

Fig. 2. (a) PDF measured after the noise source (solid triangles) compared to a noncentral χ^2-distribution (dashed–dotted line). (b) Measured static transfer function for the SOA (solid line) and a linear transfer function with the same gain as the SOA at $P_{\rm in} = -5$ dBm (dashed line). (c) Measured pdf for the SOA (solid circles) compared to the input pdf transformed with the static transfer function (open triangles and solid line) and linear transfer function (open triangles and dashed line).

In order to theoretically examine the statistical properties of the noise after the SOA we use a rate equation model including copropagating amplified spontaneous emission (ASE) noise through Langevin noise terms to perform time-domain simulations using a method similar to [11]. The noise model neglects carrier noise and saturation due to ASE. The output signal is characterized using statistical methods including histograms and central moments in order to quantify the degree of noise redistribution. The simulation parameters are chosen to give a reasonable fit to the experimental data. More details on similar simulations can be found in [8]. The use of a CW light source allows us to measure the redistribution of the input noise and the ASE noise from the SOA, while eliminating any distortions due to patterning effects.

III. Results

The concept of nonlinear noise redistribution is illustrated in Fig. 2. The measured input pdf is shown in Fig. 2(a). The signal-to-noise ratio of the input signal, as deduced from the pdf, is 22 dB for all cases presented in this letter. Fig. 2(b) shows the

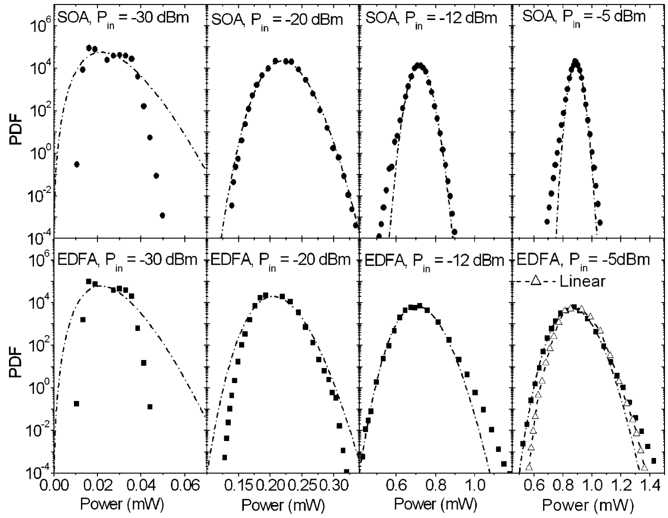

Fig. 3. Measured pdf for the SOA (top) and the EDFA (bottom) compared to a noncentral χ^2-distribution with the same mean and standard deviation. The last EDFA ($P_{\rm in} = -5$ dBm) is also compared to the linearly transferred input pdf from Fig. 2 (open triangles).

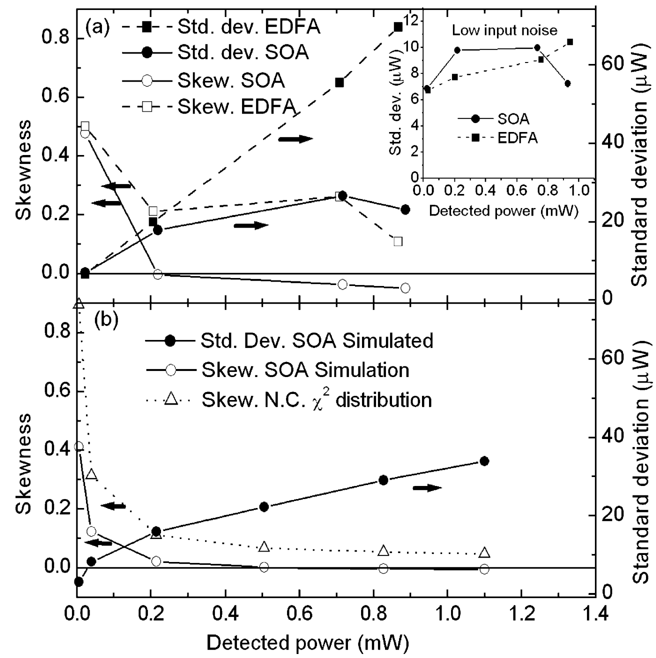

Fig. 4. (a) Measured standard deviation and skewness of the pdfs after the second amplifier (SOA or EDFA) as a function of mean output power. Standard deviation of the noise after the amplifiers with low noise input is shown in the inset. (b) The simulated standard deviation and skewness for the SOA.

measured static nonlinear transfer function, i.e., the time-averaged output power versus input power, as well as a linear transfer function, corresponding to the gain at the chosen input power. In Fig. 2(c), we compare the measured output pdf (solid circles) with the input pdf transformed using the linear and nonlinear memory-less systems represented by the curves in Fig. 2(b). The linear case corresponds to a slow device where the gain cannot follow the high bandwidth noise, which then only experiences the mean gain. The nonlinear transfer function corresponds to a high-speed device (short recovery time), so that the gain modulation follows the intensity variations of the noise instantaneously. It is clearly seen that the pdf measured after an SOA falls in between these two limiting cases.

Fig. 3 compares pdfs measured for an SOA and an EDFA (EDFA2) for different input powers. It is clearly seen how the noise distribution after the SOA narrows, compared to the EDFA, as the mean power increases. This is expected from the change of the slope of the SOA power transfer function [Fig. 2(b)] going from low to high powers. The slow dynamics of the EDFA compared to the measurement bandwidth renders the EDFA a linear device, in terms of noise transformation, despite operation beyond the dc saturation power, and no narrowing is seen.

Fig. 3 also includes noncentral χ^2 distributions plotted using the first- and second-order moments calculated from the measured pdfs. The poor agreement at -30 dBm is explained by the low optical power at the detector, which leads to a dominance of electrical noise from the receiver. At higher powers, the agreement in the SOA case is fairly good with some deviations in the tails, which are attributed to noise redistribution and will be investigated later in this section.

Fig. 4(a) shows the standard deviation and skewness of the measured pdfs, plotted against the mean power. The skewness is the normalized third-order central moment and describes the asymmetry of the pdf [12], with a positive–negative number indicating a long high–low power tail. The nonlinear transfer function of the SOA reduces the width of the pdf compared to the linear EDFA. This noise compression is seen both for the case with high input noise but also when the noise at the input is low (inset). For low input noise, the higher ASE noise of the SOA is seen at low powers, while at high power, the noise suppression due to gain saturation and self-modulation reduces the noise for the SOA.

The noise level of the detector can also be deduced from Fig. 4(a) by noting that in all cases the standard deviation approaches the same finite value for low powers. This indicates a noise level of about 6 μW, which fits fairly well with the noise equivalent power of the detector, specified to be 3 μW at 10 GHz. For the cases with high input noise, the optical noise clearly dominates at higher input powers, while for the low input noise cases, the optical noise is comparable to the detector noise.

Furthermore, it is seen in Fig. 4(a) that the noise redistribution in the SOA gives a shift from positive to negative skewness when the power is increased. This shift toward negative skewness for higher powers indicates that the usual approximation of a noncentral χ^2-distribution no longer holds, since this distribution always has positive skewness. A narrowing of the pdf was also observed in the experiments in [7] for a similar amount of gain compression. The functional form was said to be well approximated by a noncentral χ^2-distribution, but the approximation was not quantified. A negative skewness means a higher probability of errors for a mark symbol, which to some degree counteracts the reduction of the standard deviation, compared to the linear case, and should be considered when for example all-optical regeneration in SOA-based devices is considered. Simulated results are also included in Fig. 4(b) and show a similar behavior. The skewness of the simulation is compared to that of a noncentral χ^2-distribution calculated from the simulations. The simulations show a shift toward negative skewness.

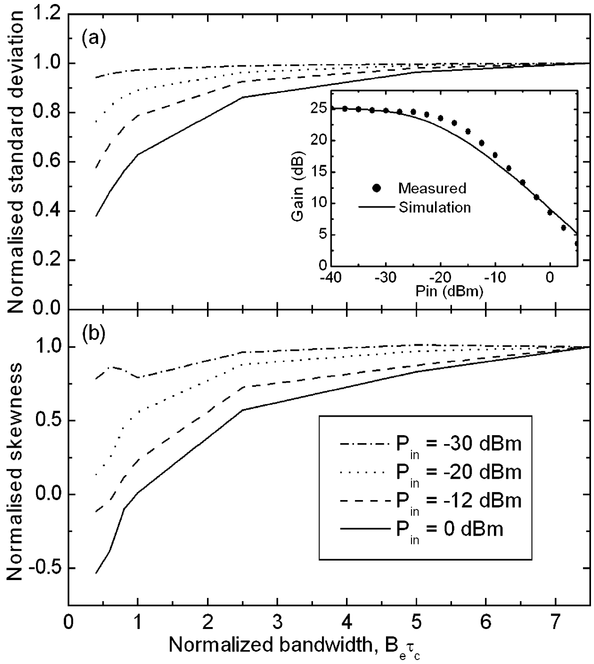

Fig. 5. (a) Simulated standard deviation and (b) skewness, normalized with respect to the linear case and the value of each curve at $B_e\tau_c = 7.5$. In both cases, the results are plotted as function of detection bandwidth normalized with respect to the inverse of the carrier lifetime of the SOA and are shown for different input powers.

The two most important parameters governing the noise redistribution are the level of gain saturation and the device speed. Since the finite speed of the device results in noise redistribution only within a limited bandwidth, the dependence on carrier dynamics can be investigated by changing the detection bandwidth. In Fig. 5, simulations of the variance (a) and the skewness (b) are plotted as functions of the detection bandwidth for different input powers. Since the standard deviation and the skewness depend on the detection bandwidth even without any noise redistribution, the curves have been normalized by the values obtained in the linear case for each bandwidth in order to show only the dependence due to the gain dynamics. Furthermore, the curves are normalized with their respective values at the maximum simulated bandwidth. For low input powers, i.e., small saturation (see inset in Fig. 5), the amplifier is more or less linear, which means that the difference between the static and linear transfer functions is small, and the bandwidth dependence is not dramatic. Hence, both the variance and skewness are fairly constant in Fig. 5. However, for high input powers, i.e., in the gain saturation regime, the bandwidth is more important due to the gain–carrier dynamics. Both the variance and skewness show that there is a substantial redistribution of the noise at small bandwidths. For larger measurement bandwidths, the self-modulation due to gain dynamics is slow, relatively, and the redistribution is smaller. This shows that the noise redistribution is strongly dependent on the speed of the device as dictated by the carrier dynamics. At an intermediate input power of -20 dBm, corresponding to a small degree of gain saturation, both the variance and skewness already show some noise redistribution.

IV. Conclusion

By measuring and simulating the noise distribution after optical amplification in an SOA, we have shown that the gain dynamics imposes important changes to the noise statistics. Both noise suppression and changes in the form (e.g., skewness) of the noise distribution are observed, with important consequences for all-optical regenerators. To our knowledge, this is the first time that the change in the shape of the noise distribution expected from the curvature of the nonlinear intensity transfer function of the SOA is measured. The degree of noise redistribution was shown to depend strongly on the device speed and the level of gain saturation, with significant noise redistribution seen already at fairly modest saturation.

References

[1] B. Mikkelsen *et al.*, "All-optical noise reduction capabilities of interferometric wavelength converters," *Electron. Lett.*, vol. 32, pp. 566–567, 1996.

[2] J. Leuthold and M. Kauer, "Power equalization and signal regeneration with delay interferometer all-optical wavelength converters," *Electron. Lett.*, vol. 38, pp. 1567–1569, 2002.

[3] A. Labrousse *et al.*, "Standard mode 40 Gbit/s performance analysis of evanescent coupling 'active-passive' Mach–Zehnder interferometers for all-optical regeneration," *Electron. Lett.*, vol. 39, pp. 1201–1202, 2003.

[4] M. Zhao *et al.*, "Analysis and optimization of intensity noise reduction in spectrum-sliced WDM systems using a saturated semiconductor optical amplifier," *IEEE Photon. Technol. Lett.*, vol. 14, no. 3, pp. 390–392, Mar. 2002.

[5] K. Sato and H. Toba, "Reduction of mode partition noise by using semiconductor optical amplifiers," *IEEE J. Sel. Topics Quantum Electron.*, vol. 7, no. 2, pp. 328–333, Mar./Apr. 2001.

[6] M. Shtaif and G. Eisenstein, "Noise properties of nonlinear semiconductor optical amplifiers," *Opt. Lett.*, vol. 21, pp. 1851–1853, 1996.

[7] ——, "Experimental study of the statistical properties of nonlinearly amplified signals in semiconductor optical amplifiers," *IEEE Phton. Technol. Lett.*, vol. 9, no. 7, pp. 904–906, Jul. 1997.

[8] F. Öhman *et al.*, "Noise and regeneration in semiconductor waveguides with saturable gain and absorption," *IEEE J. Quantum Electron.*, vol. 40, no. 3, pp. 245–255, Mar. 2004.

[9] J. Mørk *et al.*, "Analytical expression for the bit error rate of cascaded all-optical regenerators," *IEEE Photon. Technol. Lett.*, vol. 15, no. 10, pp. 1479–1481, Oct. 2003.

[10] B. Chan and J. Conradi, "On the non-Gaussian noise in Erbium-doped fiber amplifiers," *J. Lightw. Technol.*, vol. 15, no. 4, pp. 680–687, Apr. 1997.

[11] D. Cassioli *et al.*, "A time-domain computer simulator of the nonlinear response of semiconductor optical amplifiers," *IEEE J. Quantum Electron.*, vol. 36, no. 9, pp. 1072–1080, Sep. 2000.

[12] B. Saleh, *Photoelectron Statistics*. New York: Springer-Verlag, 1978, ch. 2.