Experimental studies on the impact of ASE noise of single-channel optical amplifiers in central office applications

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We identified the amplified spontaneous emission-amplified spontaneous emission (ASE-ASE) beat noise from the semiconductor optical amplifier, which has been overlooked in previous studies, as a cause of severe system penalties when it was used to provide single-channel amplification in a dynamic central office environment through experimental studies. Our results pointed out that the ASE-ASE beat noise of the optical amplifier, other than its gain and noise figure, has to be considered to correctly predict its performance in these new applications.

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The development of novel technologies, such as optical cross connects (OXCs), fosters the evolution of optical networks into dynamically switched systems, as optical signals can be directly processed or switched in the optical domain[1−4]. However, due to the lack of feasible all-optical solutions to some key networking functionalities, such as performance monitoring and wavelength conversion, the optical networks will consist of isolated, optically transparent domains in the foreseeable future. Central office (CO) nodes are at the intersection points of these transparent domains, and they can be built with an optical processing/switching core surrounded by optical-electrical-optical (OEO) modules at the ingress and egress ports, as shown in Fig. 1(a). The all-optical core has significant optical insertion loss[4], and one important function of the OEO modules is to boost the optical power and to overcome such loss. It is advantageous to replace these expensive OEO modules with optical devices that are able to handle optical inputs of different digital formats carried on different wavelengths.

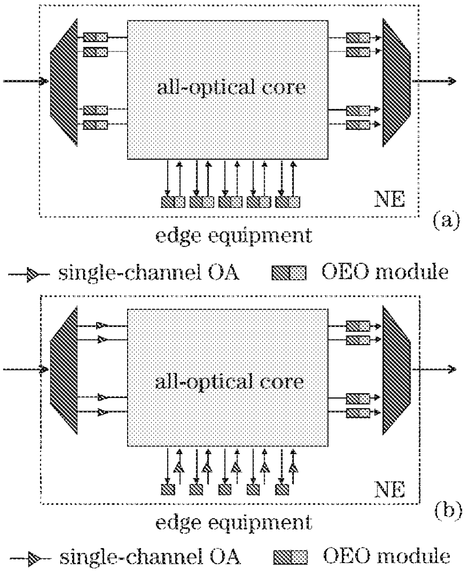

Fig. 1. CO node designs without (a) and with (b) SCOAs. OA: optical amplifier; NE: network element.

Several single-channel optical amplifier (SCOA) technologies have been developed in the past few years, including the semiconductor optical amplifier (SOA), the micro erbium-doped fiber amplifier (μ-EDFA) and the erbium-doped waveguide amplifier (EDWA), and they can provide sufficient gain over a wide spectral range around 1550 μm. They are becoming attractive low-cost alternatives to the OEO modules for the purpose of optical re-amplification in CO, as shown in Fig. 1(b). Among them, the smallest, most mature and widely available choice is the SOA[5−7]. Compared with the multiple-channel optical amplifiers, such as the EDFA, the SCOA can provide gain equalization across the various input ports, a serious challenge for the CO system designs, besides signal amplification. It also has other advantages in eliminating channel crosstalk and gain transient during switching.

Previous studies on the performance of SCOAs to determine the key parameters and the appropriate operating ranges of these devices have been exclusively carried out by using optical receivers along with a narrow band optical filter to suppress the amplified spontaneous emission (ASE) noise[5−8]. However, in the above application, since the optical wavelength involved can vary from time to time, it is infeasible to put any optical filter between the SCOA and the optical receiver. Unlike in the relatively static transmission systems, the SCOA in the dynamically switched environment of CO is also expected to cope with inputs from different routes with a large power divergence. Therefore, it is of great importance to study the performance of the SCOA in the unfiltered systems so that CO can be optimally designed and controlled with SCOAs under different input and output conditions.

Through experimental studies on the potential system penalty of using SOAs without optical filtering, we demonstrated that the performance of the SCOA can be vastly different under the unfiltered configuration, and identified the potential limitations of this scheme and their cause, which have been ignored before. Our results can, thus, provide help to the future system design of network element (NE) architectures with SCOAs.

The SOA used here was a mode-adapted amplifier designed for high-gain, high output power applications[6]. It has a maximum small signal gain of ~25 dB at 1550 nm, a saturation output power of 12 dBm, a polarization dependent gain of ~1 dB, and a noise figure (NF) of ~ 7 dB. The input to the SOA was generated by a JDS Uniphase 420-B 2.5-G optical transmitter at 1557.64 nm, which was attenuated to simulate the input signal at the ingress point of the NE as in Fig. 1(b). The state of polarization of the input to the SOA was adjusted by a polarization controller to study the polarization-dependent performance. The unfiltered output from the SOA was further attenuated to simulate the potential loss within the CO by another optical attenuator, before entering an Agilent 83446A OC-48 optical receiver with a nominal sensitivity of −27 dBm. The transmitter was driven by a bit error rate (BER) tester at 2.5-Gb/s running $2^{31}-1$ pseudo random bit sequence (PRBS). To compare with previous results, in some cases we also inserted an optical bandpass filter before the optical receiver, which had a 3-dB bandwidth of 0.6 nm and an insertion loss of ~4 dB in the pass band.

In our first study, the input optical power was set to −26 dBm, which is close to the lower end of the dynamic range for error-free transmission in the system configurations using OEO regenerations as shown Fig. 1(a). The attenuation between the output of the SOA and the input of the receiver (or the filter, if used) was set to 19 dB (close to the gain of the SOA) in order to identify the SOA's maximum operating range. The bias current of the SOA was varied between 200 and 450 mA. Figure 2 shows the measured BER versus bias current under two different configurations. The error bars show the polarization dependence. The data shown in the open circles were measured with the narrow band filter placed before the receiver (the setting of the attenuator remained the same). They agree quite well with the earlier reported results[6]. The BER continuously decreases as the bias, as well as the amplifier's gain and output signal power, increases, and no error floor is shown. Therefore, the performance is the best in the high pump region under the normal filtered applications.

In contrast, the results of the unfiltered case are dramatically different. They show an optimum BER performance, which was no better than 10^{-7}, around the bias currents of ~320 mA. If the current is further increased, BER degrades instead. Similar results were obtained at a few dB higher input power levels to the SOA, where error-free transmission can be achieved, but only within this optimum window. At the low current range, the BER results are better than the filtered ones because of the addition loss of the filter. We show here that, under the unfiltered, low input power conditions, there exists an optimal operating 'window' and the optimal operating point could be quite different from the filtered case.

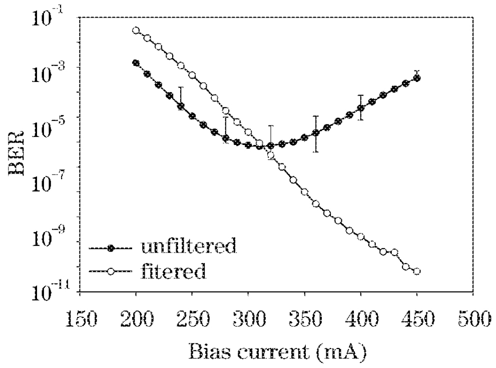

Fig. 2. BER versus bias current of the SOA under filtered and unfiltered configurations.

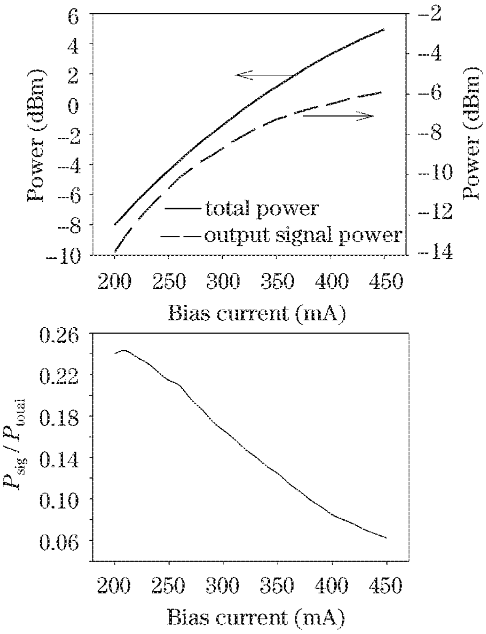

Fig. 3. Optical power at different bias conditions.

To further understand the phenomena, we made measurements on the total optical power as well as the signal power of the SOA, which are often deemed unimportant and less irrelevant in the filtered configurations. As shown in Fig. 3, we can see that the increase of the signal power becomes slow as the bias goes above 300 mA, and the percentage of signal in the total output nearly monotonically drops from ~26% to ~8% as the bias increases.

Based on the above data, since the optical bandwidth is much larger than the electrical bandwidth, we use the following equation to estimate the detected SNR[9]

$$\mathrm{SNR} = (\eta P_{\mathrm{sig}})^2 / \left[(h\nu/e)^2 4kTB_{\mathrm{e}}/R + \eta h\nu 2B_{\mathrm{e}}(P_{\mathrm{sig}} + MP_{\mathrm{noise}}) + 2\eta^2 P_{\mathrm{sig}} P_{\mathrm{noise}} 2B_{\mathrm{e}}/B_{\mathrm{o}} + M\eta^2 \gamma P_{\mathrm{noise}}^2 2B_{\mathrm{e}}/B_{\mathrm{o}}\right]. \quad (1)$$

Here we assume $R = 1$ kΩ, optical bandwidth $B_{\mathrm{o}} = 40$ nm, the electrical detection bandwidth B_{e} =1.25 GHz, the detector efficiency $\eta = 1$, and the number of the ASE mode $M = 2$. γ is a parameter added here to account for the non-uniform ASE spectrum[10] and its position relative to the input wavelength, which will lead to a different correlation value for the ASE-ASE beat noise than the flat spectrum assumption taken in Ref. [9]. We used $\gamma = 1/6$. The four terms in the denominator represent the thermal noise, the shot noise, the signal-ASE beat noise, and the ASE-ASE beat noise, respectively. Conventionally, as the filtered case in

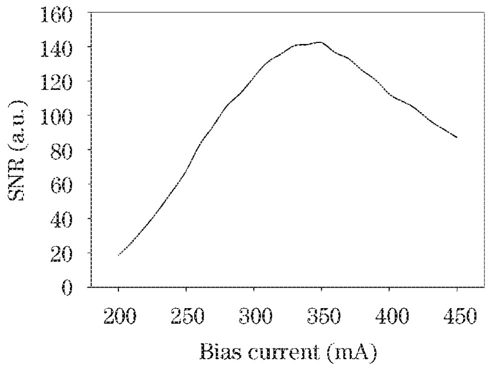

Fig. 4. Estimation of SNR versus bias current.

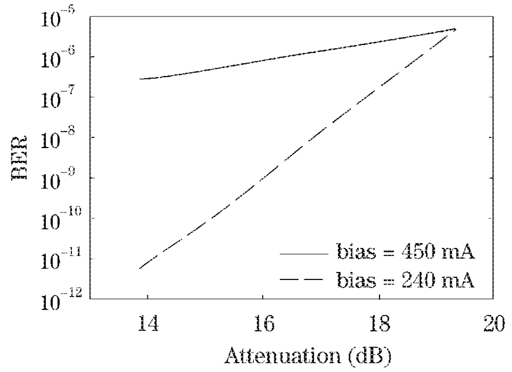

Fig. 5. BER versus attenuation under different bias conditions.

Fig. 2, the ASE-ASE beat noise is considered negligible, as P_{noise} after filter is much smaller than P_{sig}[9]. Under the unfiltered situations, this term can be rather significant as the P_{noise} is large.

Our estimation in Fig. 4 shows good agreement with our experimental results with an optimal operating point around bias current of ~330 mA, above which the ASE-ASE beat noise term grows much faster and causes the deterioration of the SNR. It illustrates that the ASE-ASE beat noise, which has negligible impact in normal applications, becomes one of the dominant noise sources when the SOA is biased above 350 mA.

Our study also reveals that, when the ASE-ASE beat noise dominates, the SNR performance dependence on the receiving power is also different. Figure 5 shows the measured BER when the power at the receiver was varied, under two different SOA biases. We can see that increasing the optical power at the receiver no longer effectively improves the BER performance when the ASE-ASE noise dominates, as the noise power increases nearly as fast as the signal. This again verifies that, under high bias conditions, it is the ASE-ASE noise that limits the system performance, in contrast to the low current cases. Note that, since the ASE-ASE beat noise has the same dependence on B_{e} as the other sources of noise, it is expected that similar phenomena as what we observed at 2.5 Gb/s will also occur at higher data rates.

In this letter, we studied the potential system application of SCOAs in CO optical nodes. In contrast to the previous studies, our results reveal that the ASE-ASE beat noise induced BER penalty can be a limiting factor of the transmission performance and may affect the use of SCOA at high bias conditions. Our studies suggest that many otherwise overlooked parameters of the SCOA, such as the total ASE noise, should be analyzed in such applications to correctly predict its performance in CO applications. Our results could help on designing optical NE with SCOAs and the optimal control algorithm for such SCOAs.

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