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Simulation on semiconductor optical amplifier intensity noise reduction for future spectrum-sliced optical networks

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ABSTRACT

Spectrum-slicing techniques employing incoherent light are an economic, practical and therefore attractive solution for future all-optical networks, especially for wavelength-division multiplexing (WDM) transmission systems in local area networks (LAN). However, spectrum-sliced methods exhibit a large excess intensity noise factor that limits the performance of the system. In this paper, we investigate noise suppression of spectrum-sliced incoherent light using a saturated semiconductor optical amplifier (SOA). The system incorporating the noise reducing SOA is modeled and simulated using OptSim software, and the results are compared to practical schemes from the literature. Performance comparisons are made with two different broadband sources test-beds. The characteristics of the SOA gain saturation are also presented. In both cases, it is found that a high degree of intensity noise is suppressed by the use of the non-linear gain saturation characteristics of the SOA so as to achieve better system performance. The position of a modulator in the system is also investigated in order to greatly reduce the excess intensity noise.

1. Introduction

Spectrum-slicing is a relatively cheap and practical method of sharing a single broadband optical source among many user channels simply by allocating a unique "spectral slice" to each channel [1]. Spectrum-slicing is effectively achieved by "slicing" incoherent light from a broadband (ASE) source using optical filters which enable the generation of large-scale multi-wavelength light in bundles. Spectrum slicing therefore provides an attractive, high bandwidth and low-cost alternative for network applications, such as passive optical networks (PONs) and WDM, as it does not require expensive and sophisticated multiple semiconductor lasers operated at specific wavelengths.

Coherent broadband sources, such as femtosecond mode-locked lasers [2] and supercontinuum generators [3], have been previously employed in spectrum-sliced systems. However, these are complex and costly compared to incoherent broadband sources, such as erbium-doped fiber amplifiers (EDFAs), SOA amplified spontaneous emission (ASE), light-emitting diodes (LEDs) or super luminescent diodes (SLCs). These sources are usually all much cheaper and are more widely available in the market.

Although spectrum-slicing is an economical alternative to individual lasers, system performance employing incoherent light is limited due to the present of high levels of excess intensity noise in the thermal-like sources. A number of intensity noise suppression techniques have been proposed to overcome the limitation of incoherent light. For example, an optoelectronic feed-forward modulation scheme has been reported and experimentally demonstrated [4,5]. In this work by Keating et al., the noise was subtracted from the spectral slice by detecting the intensity noise in a small amount of light in order to reduce the excess intensity noise. The remaining fraction of the light was transmitted with the aid of a correction signal. However, the drawback of this method is the increase in system complexity therefore increasing the cost.

Besides optoelectronic compensation scheme, an intra-channel four-wave mixing (IC-FWM) technique has been demonstrated to reduce intensity noise [6]. This method was realized by increasing the received channel bandwidth and then subsequently increasing the signal-to-noise ratio (SNR). Another promising approach in reducing excess intensity noise is by utilising the optical nonlinearity properties of a saturated SOA. This technique has been proposed [7–12] in much previous work and is a favorable choice due to advantages such as simplicity, high efficiency and potentially low cost. In addition, a SOA can also be used simultaneously for both amplification and signal modulation [13]. For that reason, this approach is very practical and useful for applications in cost-sensitive networks.

In this paper, we model and simulate a saturated SOA-based noise reduction scheme. We present a comparison between incoherent light which comes from two ASE sources; EDFA and SOA. Simulation is performed at 2.5 GB/s and the SOA parameters are selected from previous work [14]. We then study the gain charac-

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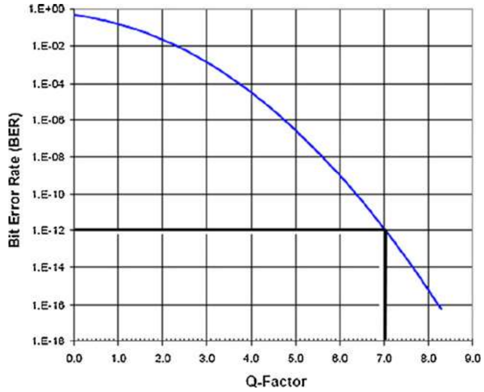

Fig. 1. BER-Q factor relationship (California Scientific, Inc.) [17].

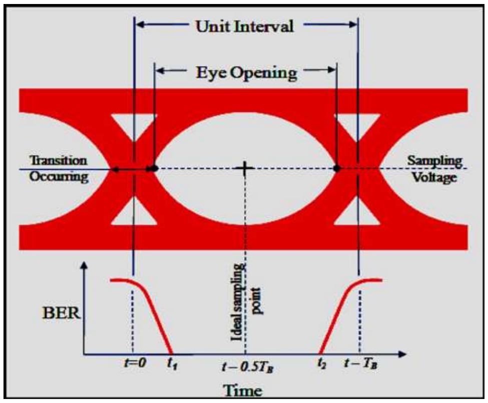

Fig. 2. Eye diagram [18].

teristics of the SOA as well as the overall performance of the system in terms of the Q-factor, bit-error-rate (BER), eye opening and eye closure. The position of a modulator in the system is also investigated as this has previously shown to influence the performance of the system [7,8,11].

2. Theory of noise suppression based on saturated soa

Previous work [5,8,15] has shown the theory of intensity noise suppression has been well documented. Zhao and Morthier [8] showed that the relative intensity noise (RIN) suppression ratio equation explained that the output optical power, mode confinement, gain coefficient as well as differential gain coefficient have to be as large as possible so as to achieve high noise reduction. On the other hand, the active region area of the SOA has to be as small as possible. In this work, it was shown that the input power and injected current of the SOA affect the parameters which are stated above and therefore affect the noise suppression.

The increment of injected current can cause SOA parameters to increase rapidly and hence increases the amount of intensity noise reduction. Also, noise reduction bandwidth increases since the bandwidth increases along with the output power. Therefore, increasing the bias current of the saturated SOA is the most effective way to achieve a large reduction of the intensity noise and thus obtain a large increase of the signal-to-noise ratio (SNR).

In this paper, the performances of the system are analyzed in terms of the Q-factor, bit-error-rate (BER), eye opening and eye closure. The Q-factor is the primary parameter which is used to predict the probability of bit errors by measuring optical signal to noise levels for a binary signal. Q-factor can be described with the following equation [16]:

$$Q = \frac{\sqrt{S(1)} - \sqrt{S(0)}}{\sqrt{N_{tot}(1)} + \sqrt{N_{tot}(0)}} \tag{1}$$

where $S(1)$, $S(0)$, and $N_{tot}(1)$, $N_{tot}(0)$ are the optical signal and total noise for a mean signal level at '1′ and '0′, respectively. Besides Q-factor, BER is a key parameter to assess the overall performance of the system. The BER can be obtained from the Q-factor (see Fig. 1).

BER is the number of received bits of a data stream over a communication channel that has been altered due to noise, interference, distortion or bit synchronization errors. It is usually expressed as ten to a negative power. An acceptable BER is 10^{-9} normally for communications. BER assesses the full end-to-end performance of a system which includes the transmitter and receiver along with the link. If the link between the transmitter and receiver is good and the signal-to-noise ratio (SNR) is therefore high, the BER will be very small. In other words, there will be less noise with high SNR. The definition of BER can be translated into a simple formula:

$$\mathrm{BER} = \left(\frac{1}{\sqrt{2\pi}}\right)\left(\frac{\exp(-Q^2/2)}{Q}\right) \tag{2}$$

Fig. 1 shows the relationship between BER and Q-factor. From the graph, we can see that the higher the value of Q-factor, the better the BER of the system. It can be seen that BER has an inverse relationship with Q-factor.

Eye diagram are an oscilloscope display which contain much useful information on the performance of the system such as eye opening and eye closure as shown in Fig. 2. The inner part of the eye diagram is called the eye opening which defines the time interval over which the received wave can be sampled without error from inter-symbol interference (ISI). The wider the opening of the eye diagram, the better it is. Eye closure refers to the distortion of the signal waveform due to ISI in the system. Eye closure is measured in units of dB. Higher eye closure indicates that the data is very noisy.

The gain characteristics of the same SOA used to suppress the noise have been studied in our previous work [19] and are shown in Fig. 3. A bias current of 250 mA is injected into the SOA using the same parameters as those in our previous work. As the input power increases, the carriers in the active region become depleted leading to a decreased in the amplifier gain. From Fig. 3, the unsaturated gain is found to be around 35.5 dB. The device begins to saturate at an input power of around −7 dBm while the output saturation power of the SOA is measured to be around 7 dBm. The SOA can operate as an amplifier when the gain is in the unsaturated region and then the signal will not be affected by the SOA nonlinear response. However, operating an SOA at a higher input power in the saturated region can cause signal distortion. Though this is a drawback of an SOA, operating the SOA in saturated region can be very useful in suppressing excess intensity noise as shown in Fig. 4. As can be seen, the excess intensity noise is reduced when the SOA operates in its saturated region at higher input power signal.

Noise suppression employing a saturated SOA is very practical and economical for the spectrum slicing technique. Fig. 5 shows a schematic diagram of a typical spectrum slicing method. The source consists of filtered broadband source to generate the spectral slice.

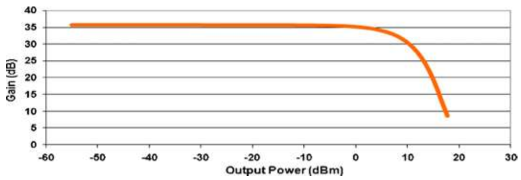

Fig. 3. Gain characteristic of SOA.

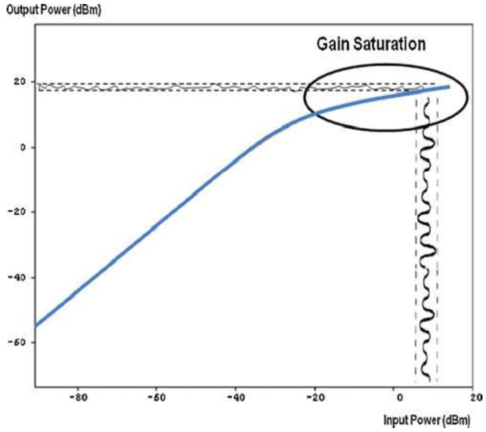

Fig. 4. Conceptual noise suppression diagram.

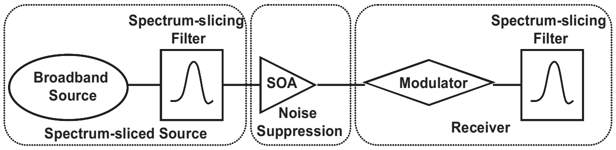

Fig. 5. Schematic diagram of spectrum slicing set-up.

The excess intensity noise in the light can be suppressed by a saturated SOA followed by a modulator at the receiver to encode data onto the slice.

3. Modeling and simulation

This spectrum slicing technique is modeled and simulated using OptSim software as shown in Fig. 6. The SOA is biased at an optimal 250 mA so as to achieve quite high noise reduction. Two types of ASE source which are an EDFA and an SOA, are studied in this simulation. The ASE from either an EDFA or SOA is sliced by a 0.6-nm bandwidth optical Bessel filter and generates the spectrum-sliced light as the input light. The sliced incoherent light is polarized before injecting it into the gain-saturated SOA.

A 0.8-nm bandwidth optical Bessel filter is also used to remove any additional ASE outside the signal bandwidth of the SOA. The spectral slice is modulated by a Non-Return-to-Zero (NRZ) with a $2^7 - 1$ pseudo-random-bit-sequence (PRBS) signal at the data rate of 2.5 GB/s and a central frequency of 1550 nm. Studies have proven that the intensity noise can be reduced greatly by modulating the input signal after the saturated SOA [7,8]. The optical signal is then converted into an electrical signal by a 5 GHz PIN photodetector and the noise reduction is observed using an electrical scope. The SOA parameters used in the simulation are selected from a previous work [14] as in Table 1.

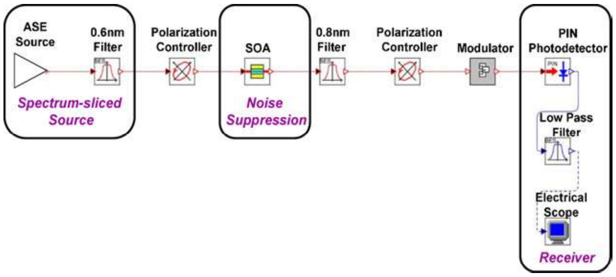

Fig. 6. Simulation schematic of spectrum slicing technique employing SOA.

Table 1
Physical SOA parameters [14].

Parameter	Symbol	Value/unit
Carrier density at transparency	N_0	$1.4 \times 10^{24}/\text{m}^3$
Internal waveguide scattering loss	α_s	$40 \times 10^2/\text{m}$
Material gain	a	$2.78 \times 10^{-20}\ \text{m}^2$
Length	L	$500 \times 10^{-6}\ \text{m}$
Width	W	$3 \times 10^{-6}\ \text{m}$
Thickness	D	$0.08 \times 10^{-6}\ \text{m}$
Confinement factor	Γ	0.3
Light frequency	w_0	193.5 THz
Bias current	I	250 mA

4. Results and discussions

Results are divided into three sub-sections – EDFA ASE source, SOA ASE source and modulation. Differences between the two types of ASE source are analyzed and compared. The third sub-section analyzes the performance of the system based on the position of the modulator within the scheme.

4.1. EDFA ASE source

Fig. 7 shows measured *Q*-factor values of the system when the EDFA is used as the ASE source. When the SOA noise reduction is not used in the system, it gives out an almost low flat rate of approximately 11 dB throughout the input ranging from −20 dBm to 25 dBm. However, by employing SOA noise reduction into the system, the excess intensity noise reduces as much as 2 dB (minimum) and 6.5 dB (maximum). The *Q*-factor improves steadily until a point at 9 dBm where it fluctuated wildly. This shows that at higher input power, more noise is suppressed.

The BER performance of the system can be viewed in Fig. 8. Before the noise is suppressed, the BER remains constant at 10^{-04} along the input power. Nevertheless, the saturated SOA gradually reduces the BER to 10^{-08} before its starts to fluctuate to 10^{-13} after at an input power of 9 dBm. This proves that the saturated SOA works as a noise reducer in the system. Also, higher input power reduces more noise at an error floor level below 10^{-10}.

Fig. 9 plots the eye opening parameter of an eye diagram in the system. The graph illustrates that the addition of an SOA has suppressed the noise progressively. At higher input powers, the eye opening becomes wider and therefore the signal is sampled without much error. Besides eye opening, eye closure readings can also be obtained from an eye diagram as shown in Fig. 10. The eye closure decreases from a constant of 4.7 dB to below than 1.5 dB at higher input power of more than 0 dBm. Lower eye closure indicates that the system is less noisy.

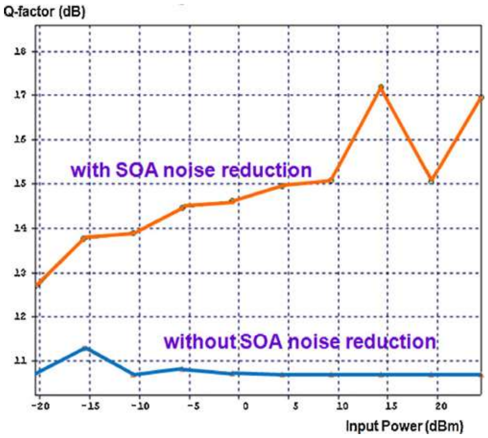

Fig. 7. *Q*-factor versus input power for EDFA source.

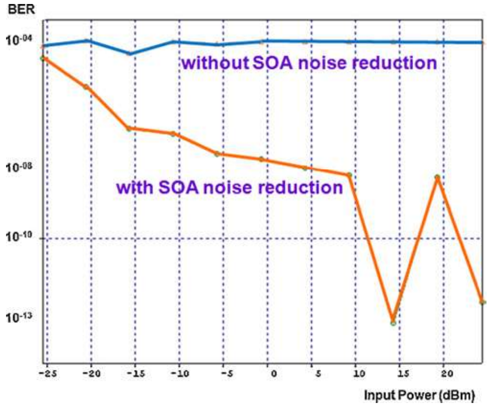

Fig. 8. BER versus input power for EDFA source.

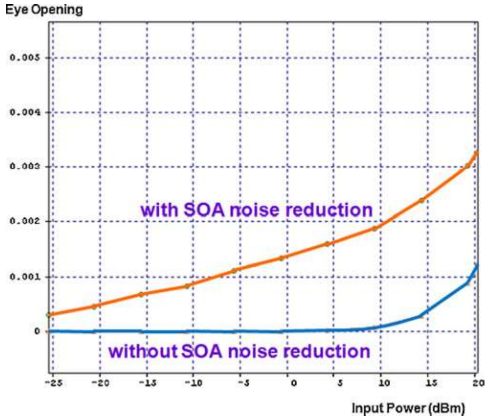

Fig. 9. Eye opening for EDFA source.

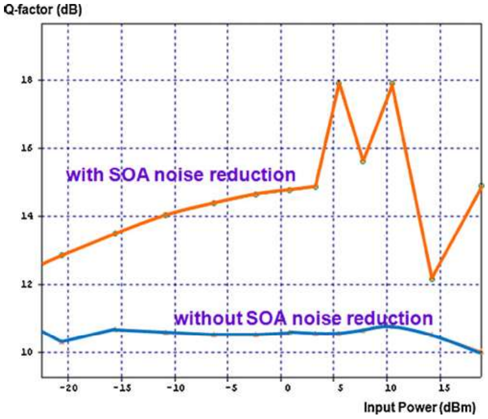

Fig. 11. *Q*-factor versus input power for SOA source.

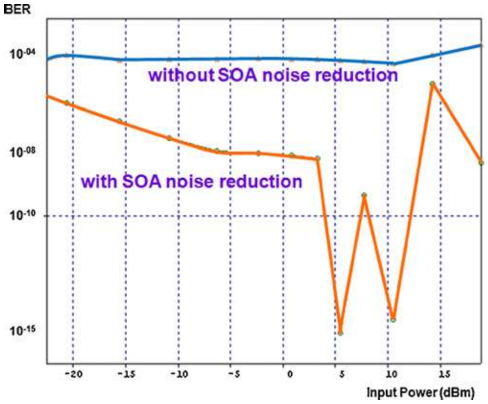

Fig. 12. BER versus input power for SOA source.

4.2. SOA ASE source

The EDFA is replaced by an SOA as the ASE source. The *Q*-factor is shown in Fig. 11. Basically, the *Q*-factor of an SOA source has the same trend as in Fig. 7. But, SOA source faced a drastic increment at a smaller input power of 3 dBm as compared to EDFA source which increase dramatically at higher input power of 9 dBm. As a result, smaller input power of only 3 dBm is required in order to reduce more noise in an SOA source. Furthermore, the maximum *Q*-factor improvement is higher than EDFA source which is 7.5 dB.

The BER performance of an SOA source also undergoes the same trend as EDFA source as shown in Fig. 12. However, less noise is achieved in using SOA as the ASE source whereby the BER improves to 10^{-15} as compared to EDFA source which experienced a maximum BER of 10^{-13}. The eye opening of this system experienced an increment along the input power until it reaches a peak at an input power of 6 dBm before it starts to fluctuate wildly as shown in Fig. 13. Overall, the noise is suppressed by the saturated SOA throughout the input power.

Fig. 14 shows the eye closure of a system using SOA source. This system achieved better eye closure as compared to EDFA source system whereby the eye closure is reduced to 1 dBm when saturated SOA is employed into the system.

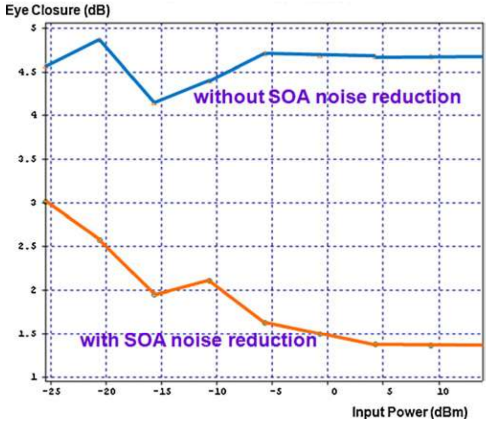

Fig. 10. Eye closure for EDFA source.

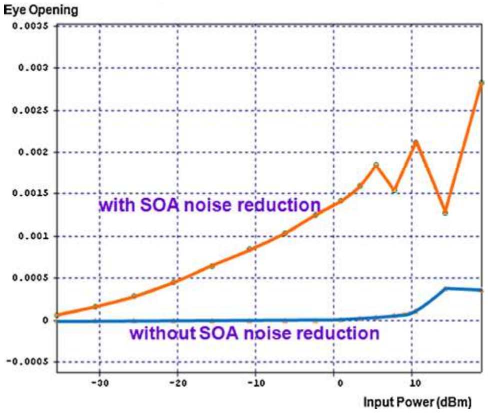

Fig. 13. Eye opening for SOA source.

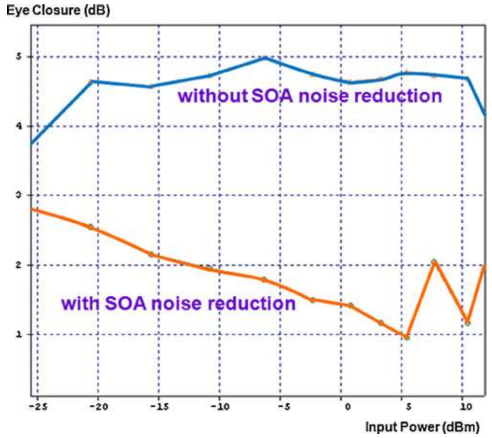

Fig. 14. Eye closure for SOA source.

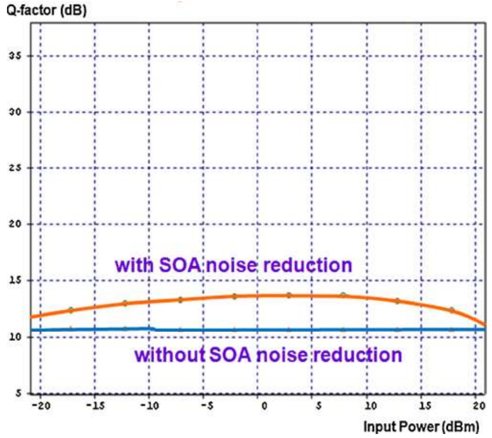

Fig. 15. *Q*-factor value for modulating signal before saturated SOA.

4.3. Modulator

The position of the modulator in the system has an effect on the performance of the system. According to McCoy [11], studies have shown that the intensity noise can be significantly reduced by modulating the signal after the saturated SOA [7,8,11]. For that reason, two positions of the modulator are investigated in this paper – modulating the signal before the saturated SOA and modulating the signal after the saturated SOA. We will look only at the EDFA as the ASE source since both ASE sources are proven to provide excess intensity noise into the system as been discussed in the previous section.

Fig. 15 shows the *Q*-factor value when the signal is modulated before the saturated SOA. The noise suppression increases at smaller input power but decreases at higher input power. On the other hand, when the modulator is placed after the saturated SOA, the *Q*-factor increases at all input powers although it fluctuated at a high input power as shown in Fig. 7. These results show that placing a modulator after the saturated SOA can greatly reduce the intensity noise in the system.

5. Conclusions

We have demonstrated an all-optical technique designed to suppress the excess intensity noise inherent in spectrum-sliced incoherent light systems by incorporating a gain-saturated SOA into the system. The gain characteristics of the saturated SOA are also presented. Systems employing two types of broadband ASE source have been compared. It was found that both the EDFA source and SOA source introduced excess intensity noise into the system so as to allow the noise suppression to take place. From the study, the SOA ASE source performs slightly better than EDFA ASE source as more noise is suppressed and therefore it gives better system performance. Finally, it has also been proved that modulating the signal after the gain-saturated SOA significantly reduces the intensity noise.

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