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Wavelength Conversion and 2R-Regeneration in Simple Schemes with Semiconductor Optical Amplifiers

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1. Introduction

Future optical networks may require both wavelength conversion and bit shape regeneration in an all-optical domain. The possibility of pulse reshaping while providing wavelength conversion may support new demands over medium and large distances links (Kelly, 2001). Indeed, during propagation the optical data signal suffers deterioration due to the amplified spontaneous emission (ASE) from optical amplifiers, pulse distortion from intrinsic dispersion, crosstalk, and attenuation. All-optical regenerators may be important components for the restoration of these signals, providing complexity and cost reductions with the avoidance of optoelectronic conversions. The regeneration could be 2R (*re-amplification* and *reshaping*) or 3R, which also provide *retiming* to solve jitter (Simon et al., 2008). Several 3R regenerators using the ***semiconductor optical amplifier*** (SOA) have been proposed, such as cascaded SOAs setups (Funabashi et al., 2006) or SOA based Mach-Zehnder interferometers (MZI) (Fischer et al., 1999).
However for small and medium distances systems, where the signal amplitude noise and distortions form the main problem and where jitter has fewer magnitudes, the simpler 2R processes can be adequate to keep signal quality (Simon et al., 1998). In addition, the SOA is a helpful device for both 2R-regeneration (Ohman et al., 2003) and wavelength conversion (Durhuus et al., 1996). Several techniques for 2R-regeneration based on SOAs have been proposed and tested, for example by using *four-wave mixing* (FWM) (Simos et al., 2004), *cross-gain modulation* (XGM) (Contestabile et al., 2005), integration within MZI (Wang et al., 2007), multimode interferometric SOA (Merlier et al., 2001), *cross-phase modulation* (XPM) with filtering (Chayet et al., 2004), and *feed forward technique* (Conforti et al., 1999). However, these techniques require complex designs and involve critical operation points, even the simplest ones based on XGM features. In addition, most of these techniques are not capable of wavelength conversion and regeneration simultaneously.
Recently a regenerator based on cross-gain modulation was proposed using one SOA for wavelength conversion (in a counter-propagating mode) and another deeply saturated SOA (synchronized by an optical delay line) to achieve cross-gain compression (Contestabile 2005). This efficient approach has similarities with the all-optical feed-forward techniques. In addition, this regenerator could not done wavelength conversion if the wavelength of the

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input signal is chosen in the output. Although good results can be obtained, this technique demonstrates to be complex since it used optical delay line and two SOAs. In this chapter, we introduce a more simple technique based on XGM (using just one SOA, an optical isolator, an optical circulator, and a CW laser) with easy robust operation at high speed reconfiguration (Ribeiro et al., 2008; Ribeiro et al., 2009a). The regeneration is based on the abrupt profile of the SOA cross-gain modulation efficiency, which is compressed at high input optical powers. The two optical carriers are amplified in the counter-propagating mode allowing conversion to another or to the same wavelength.

In addition, we present 2R-regeneration and conversion results for different kinds of deteriorated input signals. Experimental results such as eye diagrams and measured Q-factors are also shown, for various optical input powers, carriers detuning, bit rates and optical polarizations. Moreover, the estimative of the bit error rates (BER) are presented. Finally, the regenerator extinction ratio (ER) deterioration and its relation with the Q-factor improvements are discussed.

2. Experimental setup

The single-SOA all-optical 2R-regenerator setup is presented in Figure 1. This regenerator will be called 2R-converter. The experimental scheme is divided in blocks. In the first block, the optical carrier at λ_1 is modulated by pseudo random bit sequence (PRBS) data. In most cases a non–return to zero (NRZ) modulation was used, and the polarization of the input signal was controlled to maximize de modulator response.

In the *Deterioration Block,* the signal was degenerated by different types of deterioration processes to analyze the regenerative effects of this device. In Figure 1, between point 1 and 2, the three elements used to deteriorate the input signal are presented: another SOA as a booster, a buried fiber link (*KyaTera-Fapesp* Project) and an erbium doped fiber amplifier (EDFA). Different *deterioration cases* were obtained by combining these elements.

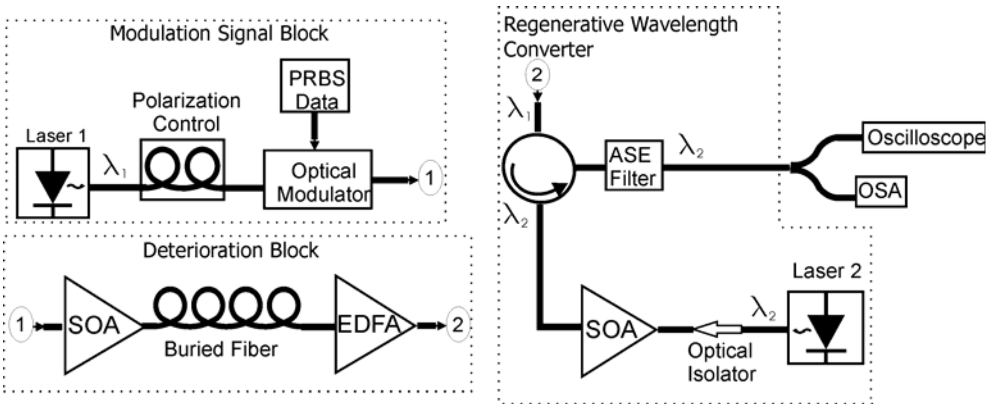


Fig. 1. All-optical 2R-regenerator and wavelength converter experimental setup.

The block for regeneration and wavelength conversion is the last one (Ribeiro et al., 2009a). In this block the modulated signal at λ_1 was converted to the wavelength of the laser 2 (λ_2), occurring regeneration and wavelength conversion simultaneously. This 2R-converter is a very simple device with just a laser CW (Continuous Wave), a non-linear SOA, an optical

circulator and an optical isolator. These last two components are needed for operation in a counter-propagating mode of the wavelength converter based on XGM. The optical filter presented in this block was used to reduce the ASE noise added by the non-linear SOA, and to allow better eye diagrams visualization at the oscilloscope. If an oscilloscope with higher sensitivity was used, this optical filter might not be needed. In this way, this optical filter after the regenerator is not considered here as a regenerator component.
The SOA features are presented in Table 1. The non-linear commercial SOA was biased at 300 mA (near the maximum supported current of 400 mA) to obtain the regenerative effects.

Item	Test condition	Values
Small signal gain	I = 200 mA	25 - 30 dB
Polarization dependent saturated gain (PDG)	I = 300 mA, P_{in}> 0 dBm	0.5 – 1 dB
Saturated output power	I = 200 mA	6 – 8 dBm
Gain peak	I = 200 mA	1550 – 1570 nm
Saturated gain recovery time	I = 300 mA, P_{in} > 0 dBm, 1555 nm	16 - 25 ps
3 dB optical bandwidth	I = 200 mA	45 nm
Active cavity length		2 mm
Bias current		up to 400 mA

Table 1. Parameters of the non-linear type encapsulated SOA.

In some *deterioration cases*, an optical attenuator was used before the oscilloscope to maintain the output signal power at the same level of the input signal, in order to carry out a bit reshaping comparison, excluding the regenerator gain.
Regenerator characterization was made for different parameter variations as for example: the optical power of lasers 1 and 2; bit rates; detuning; polarization angle of the input signal; and the extinction ratio (ER).
The different modulated input signal *deteriorations cases* are presented in the following subsections. Theses deteriorations were quantified by the signal Q-factor. This parameter is calculated by (Agrawal, 2002):

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \quad (1)$$

In (1), I_1 and I_0 are the current level of the bits levels "1" and "0", respectively; σ_1 and σ_0 are standard deviation of the level '1'and '0', respectively.

2.1 Case "SOA"

In this first *deterioration case*, another SOA was used to deteriorate the modulated input signal at λ_1. This SOA acted as a booster, amplifying and adding ASE noise. Depending on the power level of the input signal of this SOA, an overshoot related to the saturation of this device could happen. The 2R-converter performance is better for higher overshoot levels since this device totally removes the overshoot.
An optical band-pass filter was needed due to the higher level of ASE noise added to the signal. The modulated input signal Q-factor could be changed by varying the laser 1 power level and/or the bias current of the SOA used as a booster.

2.2 Case "LINK+SOA"

In this *deterioration case* the modulated signal is degenerated by dispersion and attenuation of an 18-km standard buried fiber link of the *KyaTera-Fapesp* project (www.kyatera.fapesp.br). The fiber Corning SMF-28 Standard was used. The Table 2 shows some features of this fiber. Due to the attenuation, another SOA was used to amplify the signal in order to achieve the power level (at the entrance of the 2R-converter) enough to reach regenerative effects, besides better visualization on the oscilloscope. The modulated input signal Q-factor could be changed in a similar way of the previous case.

Item	Values
Attenuation	≤ 0.22 dB/km
Dispersion	16 to 19 ps/km-nm
Effective Area	80 μm^2
Numerical aperture	0.14
Zero-dispersion wavelength	1313 nm
Polarization mode dispersion	≤ 0.2 $ps/km^{1/2}$

Table 1. Fiber Corning SMF-28 features.

2.3 Case "EDFA"

In this *deterioration case* an EDFA was used to amplify the modulated input signal adding ASE noise. The higher ASE noise addition cause higher bit level (at both "1" and "0") variance. The modulated input signal Q–factor could be modified by varying the laser 1 power and/or EDFA pump laser power.

2.4 Case "LINK+EDFA"

This *deterioration case* is similar to the *case* "LINK+SOA". The 18-km standard buried fiber link of the KyaTera-Fapesp project was used again. The dispersion effects, attenuation, and ASE noise are the deterioration effects added to the modulated input signal.

2.5 Case "SOA+LINK+EDFA"

This *deterioration case* is the more complex case. It involves the three elements used to degenerate the modulated input signal. The overshoot appearance, the noise adding to bit levels "1" and "0" and high variance in those levels turn the modulated input signal presented in this case as the most deteriorated case. Optical filters were needed to reduce the ASE noise.

3. 2R-regenerator and wavelength converter working principle

The quality of a 2R regenerator depends on its ability to suppress optical noise and to improve the extinction ratio. The ideal regenerative properties are provided by a system with a transfer function as close as possible to an ideal "S" like behavior. This refers to a characteristic function with the following properties: wide and flat dynamic range gain for bit levels "1" and "0" in order to suppress the noise, and a linear increasing curve which determines the discrimination between bit levels "0" and "1" (Simos et al., 2004).

The 2R-regenerator presented in this chapter has a characteristic function similar to the "S" like behavior. The response of the device here is similar, not equal to the "S", since it presents gain compression only for the bit level “1”. This is due to the fact that just the power level of this bit (at the high level “1”) can saturate the SOA gain. The compression of the level “1” is noticed in cases where an overshoot is presented. After the regenerator, the overshoot is removed because SOA gain is deeply saturated. In this way, the 2R-converter works as a "low-pass filter", removing "higher frequencies" present in the overshoot. Therefore, saturated gain acts as a power equalizer for the fluctuation in the bit level “1” reducing the noise. On the other way, the bit level “0” has much less improvement than bit level “1”, since its low signal power level cannot saturate the SOA.

The 2R-converter of this chapter is based on XGM effect in SOAs, and this non-linear effect always degrades the extinction ratio due to the ASE noise added by the SOA. Consequently, there is no extinction ratio improvement. However, it will be showed in this chapter that the improvements caused by the 2R-converter and quantified by Q-factor improvement can be higher than the ER degradation, at least for some cases.

The pattern dependence reduction caused by operating the 2R-converter in its optimum optical input powers could improve both the format of the bit levels “1” and “0”. As it will be shown, there is an optimum relationship between the modulated input signal power (at λ_1) and the CW signal power (at λ_2), which should be maintained for different cases in order to kept the pattern dependence effects at the same level.

As mentioned before, the regeneration in the 2R-converter occurs simultaneously with the wavelength conversion via XGM. The regenerative effects are associated with the wavelength conversion efficiency, and XGM is the simplest technique using SOA to implement wavelength conversion. In this process, a strong modulated input signal at λ_1 saturates the amplifier. A continuous wave pump signal at λ_2, injected simultaneously with the modulated signal, is modulated by the gain saturation while being concurrently amplified. The output signal, properly filtered, is a replica of the modulated input signal at a different wavelength with a phase inversion of 180^0. In this way, methods to obtain the data without phase inversion are needed. One way is to use a proper software control. Commands given to the receiver force it to associate a bit “1” (in its input) to a bit “0” (in the original data). Another way is to use others devices like an additional SOA, but it will be enlarge the ER degradation. The exploiting of the phase changes provoked by the XGM effect using an optical filter could invert the output signal without ER degradation (Leuthold et al., 2003). Others forms are for example, the use of: delay interferometer (Liu et al., 2007) and quantum dots SOAs with narrow optical filters (Raz et al., 2008).

The eye diagrams obtained after the 2R-converter presented in this chapter are inverted in phase. In this manner, the commentaries made before about the deterioration of the bit levels “1” and “0” refer to bit levels of modulated input signal. Otherwise, the improvement observed in the output signal is commented about the inverted bit levels, that is: for deterioration in the bit level “1” of the modulated input signal, the improvement is noted in the level “0” after the 2R-converter; and in a similar way for the deterioration in the level “0” of the modulated input signal.

The gain saturation of the SOA is related to the XGM wavelength conversion and to the gain compression. The last one is responsible for the noise reduction in the bit level “1” and for the overshoot elimination. The SOA gain must be deeply saturated to obtain the gain compression effects. This behavior can be noted in Figure 2. The eye diagram of the modulated input signal (λ_1) deteriorated by the *case* “SOA” is presented in Figure 2(a). This eye diagram presents overshoot caused by the gain saturation of the SOA used as a booster that deteriorated the input signal. The eye diagram of the modulated signal (λ_1) after the 2Rconverter is presented in Figure 2(b). This much clear output signal was obtained for the regeneration case where it was observed a Q-factor improvement for the converted signal at λ_2 equal to 1.5. Due to the higher level power of the modulated and CW input signals, and the high SOA bias current (300 mA), the SOA in the 2R-converter presents a saturated gain. In this manner, the eye diagram for the output signal after the regenerator presents compressed eye. The overshoots and undershoots observed in the output signal might be associated to a self-phase modulation (SPM) and/or changes in the signal phase around the narrow band optical filter. These results of compressed eye diagrams were observed for other values of the modulated input signal power. Therefore it confirms that the gain of SOA used in the 2R-converter is saturated, inducing the compression needed to the regenerative effects occurrence.

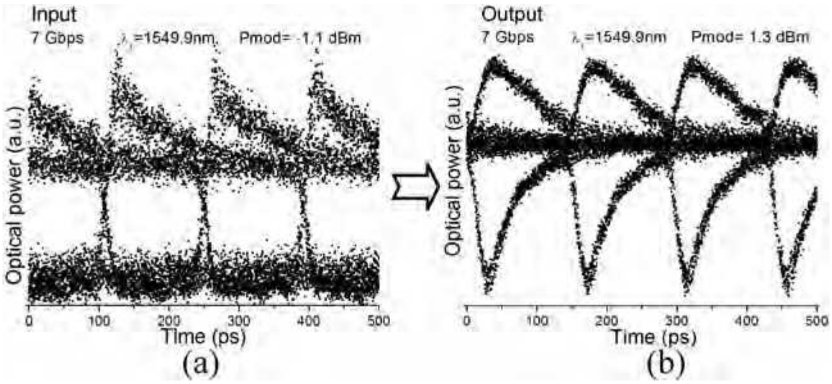


Fig. 2. Eye diagrams: (a) modulated input signal for the *deterioration case* "SOA"; (b) modulated signal after 2R-converter.

4. Optical spectrum and signal to noise ratio

The optical spectrum of the input and converted signals in those particular points of the experimental setup (Figure 1) are presented. The spectrums were obtained for the *deterioration case* "SOA" as an example, since the optical spectrum is similar to other *deterioration cases*. The *optical signal to noise ratio* (OSNR) was calculated as well as the eye diagrams were obtained corresponding to the optical spectrums illustrated in Figure 3.

The case of Figure 3 employed a wavelength conversion from 1550 to 1551 nm with a modulation rate of 7 Gbps NRZ. The Figure 3(a) shows the modulated input signal without deterioration and an eye diagram without distortions. A Q-factor of 9 and OSNR of 55.28 dB are observed in this case. Then this modulation input signal is inserted into the SOA used as a booster. The gain of this SOA is saturated due to the power level of the input signal of -2 dBm and a bias current of 130 mA (higher than current threshold). Therefore the eye diagrams presented in Figure 3(b) are obtained with much noise in the bit levels "1" and "0" as well as overshoots. After the SOA used as a booster, the Q-factor decrease to 4.3 as well as the OSNR to 37.6 dB. In this manner, this SOA presented a noise figure of 18.3 dB caused by deeply saturated gain and by extra noise added to the signal. An optical band-pass filter is needed to filter the ASE noise added. Consequently, the signal in Figure 3(c) appeared filtered with an improvement in the Q-factor to 4.8.

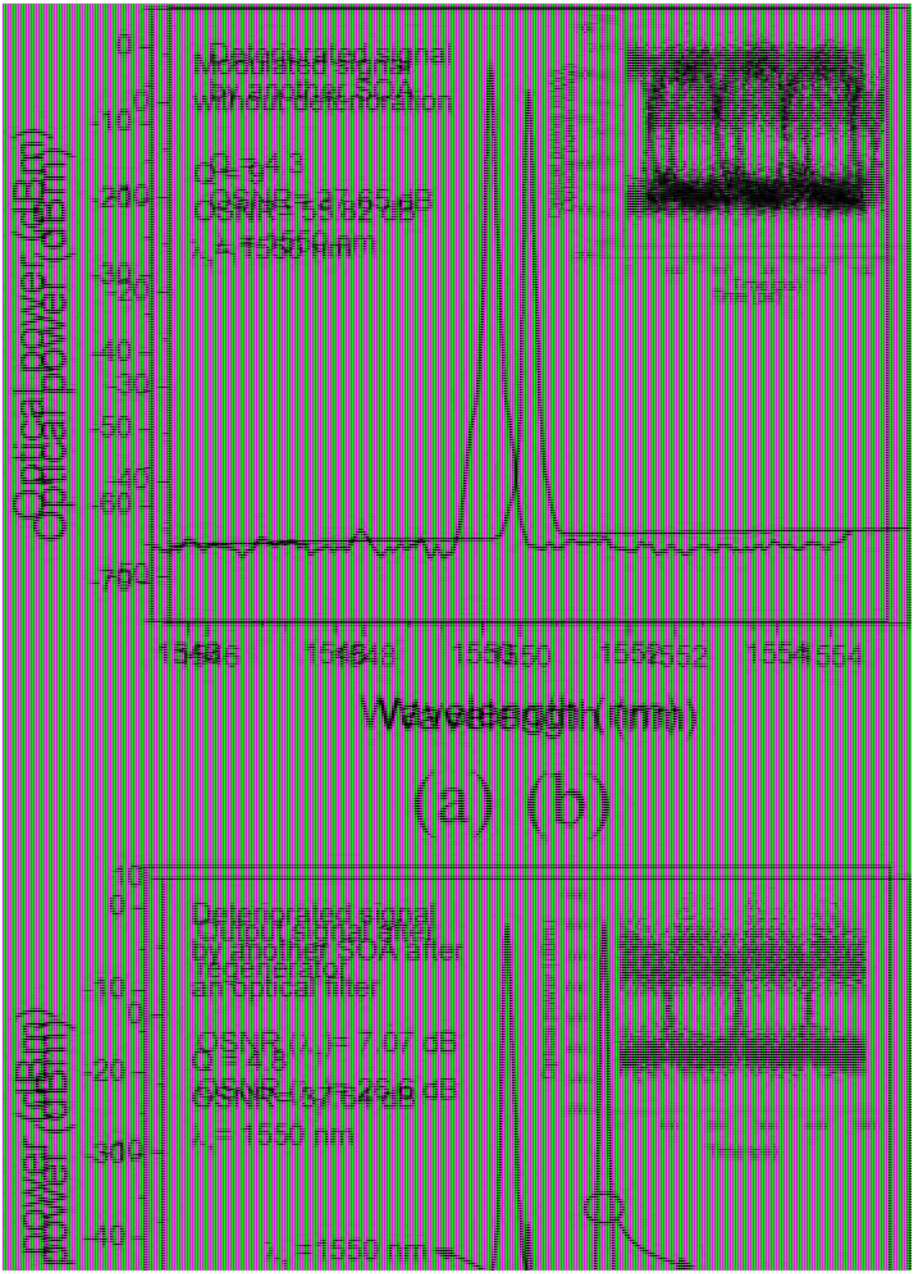


Fig. 3. Optical spectrums and eye diagrams of the *deterioration case* "SOA": (a) modulated signal without deterioration; (b) modulated signal deteriorated by another SOA; (c) modulated signal deteriorated by another SOA and filtered; (d) output signal after the 2R-converter; and (e) regenerated signal and filtered.

The optical spectrum after the 2R-converter is presented in Figure 3(d). The input signal initially at 1550 nm (λ_1) is still present but with an OSNR of 7 dB. According to the experimental setup of Figure 1, the original signal at λ_1 should not be present because the conversion scheme is a counter-propagating mode with an optical isolator that should eliminate this original signal. Nevertheless, the original signal presence after the 2R-converter could be explained by possible internal reflections in the optical isolator and in the SOA used to regenerate the signal. The regenerated and converted signal at 1551 nm (λ_2) of Figure 3(d) presents an OSNR of 26.6 dB, i. e., the SOA used in the regenerator presented a noise figure of 11 dB. As the same case mentioned before, this noise figure higher than commons values (7 a 8 dB) could be justified by the presence of both the modulated input signal power (-2 dBm) and the CW signal power (-6 dBm) as well as higher bias current (300 mA) which saturated the SOA gain, adding a lot of noise to the signal. Eye diagram is not illustrated in Figure 3(d) due to the high power level of the output signal (7 dBm). Indeed, the bit level "1" of the output signal eye diagram was in the upper part of the oscilloscope scale limit, not allowing the acquisition of points by the software Labview (using GPIB port). Despite this limitation, a reduction of the noise in bit levels "1" and "0" and an overshoot elimination were noted in the eye diagrams (quantified by Q-factor improvement from 4.8 to 7.2). These results evince that the original signal still present at λ_1 does not decrease the regenerative effects.

The regenerated and converted signal at 1551 nm (λ_2) after an optical narrow filter is illustrated in Figure 3(e). The optical filter allows an OSNR improvement to 63.2 dB. The eye diagram observed in this figure presents improvements already mentioned in the previous case. These improvements increase the Q-factor to 7.5. Through calculating the Q-factor variation from the modulated input signal, an improvement of 2.7 can be observed.

For the cases presented in this section and in Figure 3, the results after the regenerator were not attenuated to guarantee the same power level of the modulated input signal. This was made to allow the observation of the 2R-converter performance as a whole, analyzing the re-amplification and reshaping.

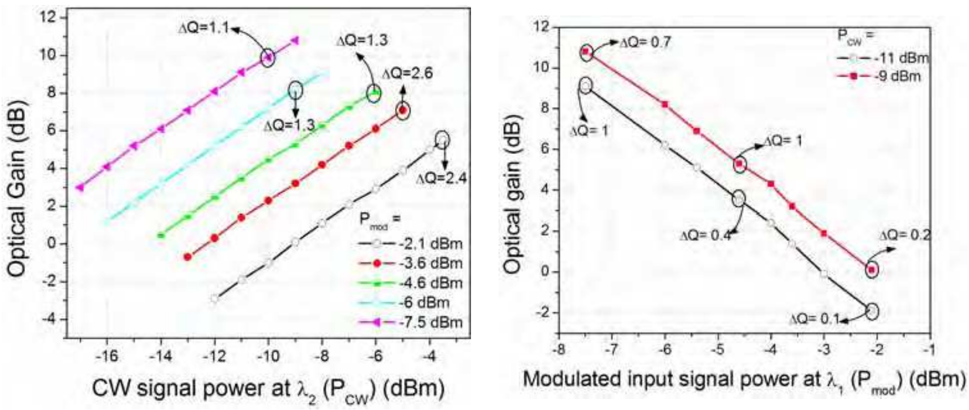
The calculation of the OSNR was made following application notes published by the manufacturer of the optical spectrum analyzer used here. Therefore the optical spectrums presented in Figure 3 are just illustrations since the accurate OSNR calculations need an operation of the optical spectrum analyzer with higher resolution and smaller span.

The optical spectrums and the OSNR were presented just for the *deterioration case* "SOA". The optical spectrums for the others *deterioration cases* are similar, presenting differences in the optical power values. In relation to the OSNR calculation, the values obtained for the other *deterioration cases* are very close, with variations due to: the optical signal power used; bias current of the SOA; and the pump laser power used in the EDFA. A study of the ER degradation will be presented in following sections in order to analyse the signal degradation after the 2R-converter that was caused by the ASE noise addition of the SOA. This study will help to understand how the noise degenerate the signal for different cases, associating these results with the OSNR deterioration. In this manner, it will be possible to estimate the OSNR behavior for the different deterioration cases not presented in this section.

5. Re-amplification

The 2R-converter presented in this chapter provides re-amplification and bit reshape. Thus, the first improvement caused by this regenerator is the signal re-amplification that will be present in this section. The *deterioration case* "SOA" is used to illustrate the optical gain originated by the 2R-converter. A wavelength conversion from 1550 nm (λ_1) to 1551 nm (λ_2) with a bit rate of 10.3 Gbps was used. The optical gain was calculated as the difference between the output signal power at λ_2 and input modulated signal power at λ_1. The results are presented in Figure 4.

The optical gain versus CW signal power at λ_2 is illustrated in Figure 4(a). A gain increase with the CW signal power can be noted. This happens because the output signal was kept at λ_2. Thus, by increasing the CW signal power, the output signal power at λ_2 increases too. Since the optical gain was calculated as a function of the modulated input signal power, which is fixed for each curve in Figure 4 (a), the optical gain increases linearly with the CW signal power. In Figure 4(b), an optical gain decreasing with the modulated signal power increasing is noted, presenting higher optical gain values for the modulated signal power around -7.5 dBm. This result is associated with the SOA gain saturation. Some Q-factor improvements (figured by ΔQ) are showed in Figure 4(a) and (b) just to illustrate the dependence of this parameter with the power relation, which will be commented in other section. Here, ΔQ is defined as the difference between the Q-factor of converter signal at λ_2 and Q-factor of the modulated input signal at λ_1.



(a) (b)

Fig. 4. 2R-converter optical gain of the *deteriorated case* "SOA": (a) optical gain versus CW signal power for different input modulated signal powers; (b) optical gain versus input modulated signal power for different CW signal power.

The 2R-converter presented an optical gain varying from -3 to 12 dB. In most of the cases, the better values of Q-factor improvement occurred for higher optical gain values. In this manner, it is clear that the 2R-converter is capable to re-amplify the signal, presenting optical gain up to 12 dB, together with the bit reshape quantified by the Q-factor improvement.

These results of optical gain presented here are proper of the SOA and can be associated to the input modulated signal power and CW signal power. In this way, if the same values of the input optical powers in Figure 4(a) and (b) is used for the others *deterioration cases*, the results should be similar to the ones presented here.

6. Eye diagrams

The eye diagrams obtained from the oscilloscope clarify the improvements obtained by the 2R-converter. In this section, some eye diagrams of the different *deteriorated cases* are presented to illustrate the improvements of the bit shape. An up-conversion (1550 to 1551 nm) was employed to obtain the eye diagrams. This type of conversion causes higher ER deterioration, but in other way it also provides higher SOA gain saturation, which contributes to a better signal regeneration. Therefore, all the eye diagrams presented in this section as well as most of the results presented in this chapter were obtained from up-conversion. In addition, it is valid to comment that the output eye diagrams are inverted in relation to input signal.

Initially, input and output eye diagrams and the respective Q-factors for the bit rate of 10.3 Gbps NRZ are illustrated in Figure 5, where the output signal was not attenuated to the same level of the input modulated signal power. Therefore the illustrated eye diagrams present two regeneration effects: re-amplification and reshaping. An arbitrary unit for the optical power was considered to allow the comparison between input and output eye diagrams in same proportion.

Two *deterioration cases* are studied. The first case is "LINK+SOA", which presented a medium quality input signal (Figure 5(a)) with Q-factor of 5.7, presenting intense pulse distortion due to the intrinsic dispersion caused by the 18-km standard buried fiber link (Ribeiro et al., 2009a). The dispersion effect could be noted by the triangular form of the pulse. In Figure 5(b), the regenerated output signal presents a higher eye opening, a reduction of the overshoots, and of the bit level (at both "1" and "0") variance, facts quantified by the Q-factor increasing to Q=10.

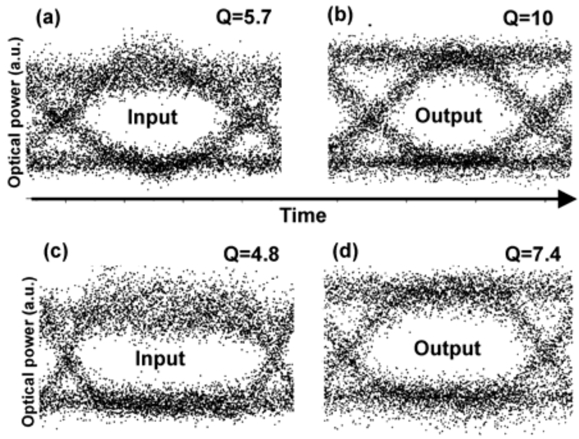


Fig. 5. Eye diagrams (NRZ, 10.3 Gbps): (a) *case* "LINK+SOA" input signal with Q=5.7; (b) output signal with Q=10; (c) *case* "SOA" input signal with Q=4.8; (d) output signal with Q=7.4 (adapted from Ribeiro et al., 2009a).

The second *deterioration case* is "SOA" (Ribeiro et al., 2009a). In Figure 5(c), the eye diagram presents low quality (Q=4.8) due to the pattern dependence effect, overshoots, and the great amount of noise added to both bit levels by the SOA used as a booster. As the case mentioned before, an improvement in the eye opening can be observed as well as an

overshoot elimination is noted by the small variance of the bit level "0" of the regenerated signal. In addition, the bit levels "1" and "0" of the regenerated signal present lower width (reduction of the bit level variance) if be compared to the inverted bit level of the input signal. These improvements are quantified by the increasing of the Q-factor to 7.4.
Eye diagrams for bit rate of 7 Gbps for the same cases mentioned before are presented in Figure 6. An important difference is that in Figure 6 the output signal is attenuated to guarantee the same level of modulated input signal power. In this manner, the unit of µW could be used. This study of output signal attenuated analyzes just the improvement provoked by the bit reshaping.

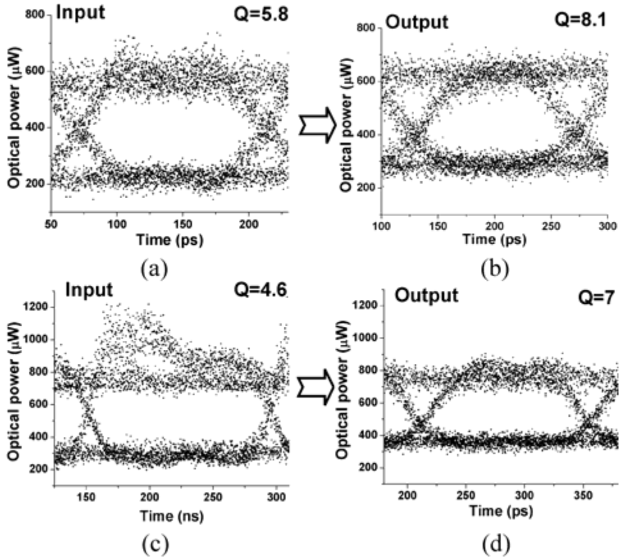


Fig. 6. Eye diagrams (NRZ, 7 Gbps): (a) *case* "LINK+SOA" input signal with Q=5.8; (b) output signal with Q=8.1; (c) *case* "SOA" input signal with Q=4.6; (d) output signal with Q=7.

Despite the output signal attenuation, the behavior is similar to the cases mentioned in Figure 5. In *case* "LINK+SOA", the deterioration effects presented in the input signal of Figure 6(a) are the same presented in previous figure, as well as the improvements in the output signal (Figure 6(b)). These similarities are quantified by the Q-factors 5.8 and 8.1 for the input and output signal respectively. A decreasing of the Q-factor improvement can be noted by comparing to the previous case. This result is due to the attenuation of the output signal. Besides, this is another situation where the modulated and CW signals powers are different from the cases of Figure 5. The eye diagrams illustrations are used to observe the improvement caused by the 2R-converter, comparing the input and output signal in each case, and not to make comparisons between the different *deterioration cases* where different parameters are used.
The *deterioration case* "SOA" is presented in Figure 6(c). The input signal presented a higher overshoot as well as deterioration caused by the pattern dependence effect and ASE noise added by the SOA used as a booster. The output signal presents overshoot elimination and lower variance of both bit levels. The improvements are quantified by the Q-factor increasing from 4.6 to 7.

The others *deterioration cases* like “LINK+EDFA” and “EDFA” are illustrated in Figure 7. These eye diagrams were obtained for a bit rate of 7 Gbps NRZ. Besides, the output signal was attenuated to guarantee the same level of the modulated input signal power. In the *case* “LINK+EDFA”, the input signal illustrated in Figure 7(a) presents a high amount of ASE noise added by the EDFA, and deterioration caused by the dispersion of the buried fiber link. The bit levels of “1” and “0” present a large width, i.e., high variance. In the output signal (Figure 7(b)) the increasing of the eye opening is noticeable. It is caused by the decrease of the noise present in bit levels “1” and “0”, visualized by the variance reduction of these levels. A higher noise reduction is noted to the bit level “0” of the regenerated signal. The Q-factor was increased from 4.5 to 6.2.

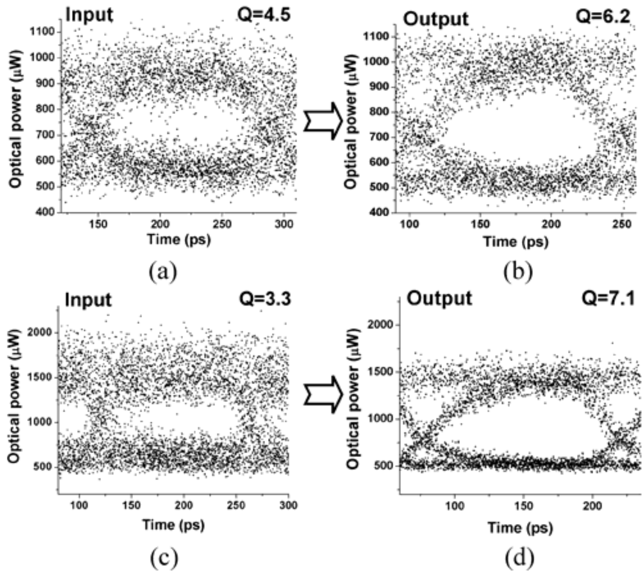


Fig. 7. Eye diagrams (NRZ, 7 Gbps): (a) *case* “LINK+EDFA” input signal with Q=4.5; (b) output signal with Q= 6.2; (c) *case* “EDFA” input signal with Q=3.3; (d) output signal with Q=7.1.

The *deterioration case* “EDFA” is illustrated in Figure 7(c). A great amount of ASE noise deteriorating the input signal with a low eye opening can be noted. This higher deterioration presented in the input signal is quantified by the low Q-factor of 3.3. In Figure 7(d), the improvement caused by the 2R-conveter can be observed. Due to the SOA gain saturation, the noise is reduced in both bit levels “1” and “0”. In the last one bit level, a lower variance can be noted. With the ASE noise reduction, the eye opening increase as well as the Q-factor to 7.1.

The last *deterioration case* illustrated involves all the degeneration effects: “SOA+LINK+EDFA”. For this last case, a bit rate of 7 Gbps NRZ as well as output signal attenuation are used (Ribeiro et al., 2009a). The Figure 8(a) illustrates the input signal which presents a higher overshoot caused by the SOA used as a booster. Besides, the input signal presents higher variance in both bit levels provoked by the ASE noise addition by the SOA and EDFA. The input signal also presents a bit enlargement caused by the intrinsic dispersion of the buried fiber link. The output signal illustrated in Figure 8(b) presents a noise reduction in both bit levels. The overshoot was reduced as well as the fluctuations presented in the bit level "1". Nevertheless, the output signal presents a lower difference between the bit levels "0" and "1", i. e., lower extinction ratio (ER). The improvement observed in Q-factor was from 5.3 to 8.6.

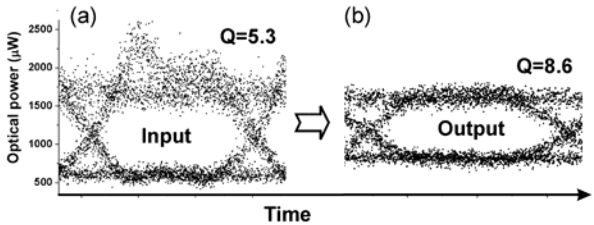


Fig. 8. Eye diagrams (NRZ, 7 Gbps): (a) *case* "SOA+LINK+EDFA" input signal with Q=5.3; (b) output signal with Q= 8.6 (adapted from Ribeiro et al., 2009a).

Due to the availability of equipments, the same bit rate could not be used for all the cases studied. In this manner, the use of modulation rate higher than 7 Gbps NRZ was used just for some measurements, but for most cases the characterization was limited to 7 Gbps.

By comparing the eye diagram of the output signal with the input, a reduction of cross point level between "0" and "1" can usually be noted. This reduction is more pronounced for cases where the output signal is attenuated. The ER degeneration is the main reason for this cross point level reduction. Another reason is the SOA gain recovery time. The rising time of the bit level "1" is slower than the falling time, decreasing the cross-point level.

The modulation RZ (Return to zero) was used in the 2R-converter characterization either. The Figure 9 presents the eye diagrams for R1 modulation that correspond to inverted RZ. A wavelength conversion from 1550 to 1551 nm was used without attenuation in the output signal. Figure 9(a) illustrates the input signal for the *deterioration case* "LINK+SOA". The pulse presents a triangular shape due to the buried fiber link. A decreasing in the variance of the bit level "1" of the input signal can be noted in Figure 9(b). An estimation of the regenerative effects was done using the variance of both bits levels. An improvement of 51% was obtained for this *deterioration case*.

The *deterioration case* "SOA" is illustrated in Figure 9(c), presenting pulse shape more rectangular and more ASE noise in the bit level "1". The output signal (Figure 9(d)) presents narrower pulses due to the gain response time of the SOA. Besides, there is a reduction in the bit level "1" variance. As the previous case, an estimate was calculated to eye opening improvement being obtained 44%.

These results proved that the 2R-converter is capable to regenerate RZ signals. Nevertheless, the results present in this chapter use just NRZ modulation since this modulation type is more complex. Furthermore the Q-factor used to quantify the regenerative effects is just provided by the oscilloscope for the NRZ modulation type.

The overshoot elimination presented for the cases in which another SOA was used to amplify the modulated input signal is a good feature of the 2R-converter. In optical systems, the overshoot could be added to the signal from different forms, one of them is the use of the PISIC technique used to increase the speed of the electro-optical switching using SOAs (Gallep & Conforti, 2002) (Ribeiro et al., 2009b).

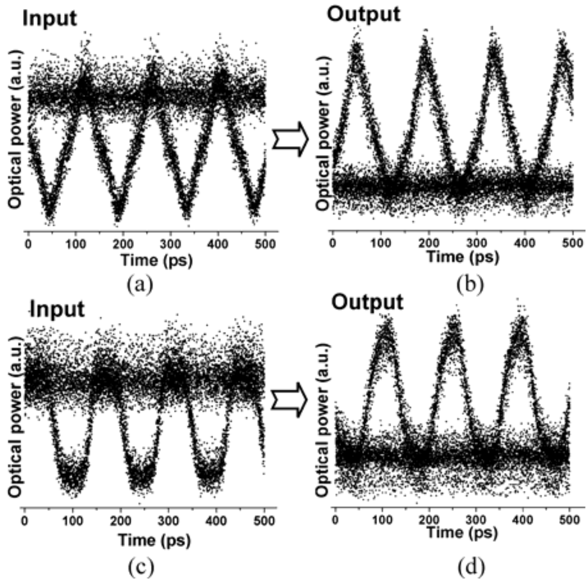


Fig. 9. Eye diagrams (R1, 7 Gbps): (a) *case* "LINK+SOA" input signal; (b) output signal; (c) *case* "SOA" input signal; (d) output signal.

The overshoots presented in the *deterioration case* "SOA", "LINK+SOA", and "SOA+LINK+EDFA"are eliminated by the 2R-converter as could be observed in Figure 5, 6, and 8. This elimination occurs due to the saturation effects of the SOA gain. The SOA does not maintain the gain level for those higher power values present in the overshoots. In this manner, the overshoot is not transferred to the CW signal by the wavelength conversion.
Therefore, the 2R-converter is a possible solution to eliminate the overshoot of an optical signal. Despite the overshoot elimination, the signal after the regenerator will present ER decreasing, as it will be shown in future sections. Thus, the analysis if the overshoot elimination can compensates for the ER degeneration is necessary.

7. Optical polarization

The input light polarization dependence of the wavelength conversion is very important since polarization is an unpredictable factor in real optical systems and an automatic polarization controller can be expensive. The SOA used in the 2R-converter presents a *polarization dependent saturated gain* (PDG) of less than 1 dB. Studies of the input polarization angle influence in the 2R-converter performance were done to confirm this value.
By adjusting de polarization controller, different polarization angles of the modulated input signal were obtained to analyse the Q-factor and gain variation. The Figure 10 presents eye diagrams of different polarization angles for the *deterioration case* "SOA". The modulated input signal changes very little for each polarization angle. In this manner, the eye diagram presented as *input* is representing all the input eye diagrams. The eye diagrams following in the time scale illustrate the variations noted in the output signal for some input polarization angles. The regenerative effects are presented in all the output signal with overshoot elimination and the reduction of the bit levels "1" and "0" variance.

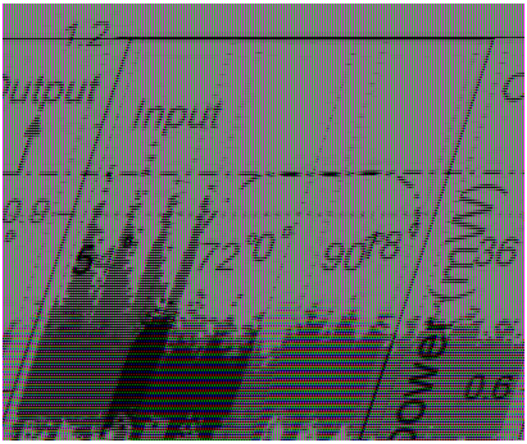
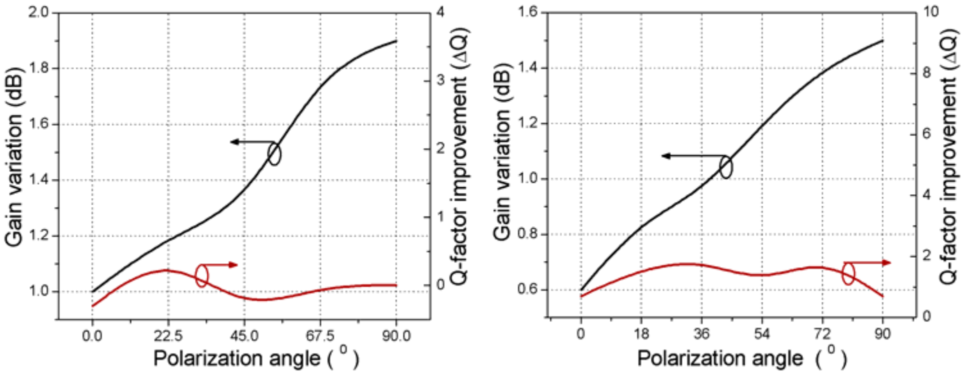


Fig. 10. Eye diagrams for different polarization angles of the input signal for the *deterioration case* "SOA".

Observing the eye diagrams for different polarization angles of the input signal, regenerative and power variations could be noted. These variations can be better observed in Figure 11 (a) where the optical gain varying from 0.6 to 1.5 dB is observed. In addition, it was observed that for this deterioration case, the Q-factor improvement (ΔQ) varied from 0.7 to 1.9.



(a) (b)

Fig. 11. Gain and Q-factor improvement variation as function of different input polarization angles for the *deterioration case*: (a) "SOA" and (b) "LINK+SOA" (adapted from Ribeiro et al., 2009a).

A study of the *case* "LINK+SOA" was done in a similar manner, obtaining the results presented in Figure 11(b). In this case, a gain variation of 0.9 dB and a Q-factor improvement variation of 0.9 were obtained.

In general, the 2R-converter presented low dependence with the input signal polarization, fact proved by the results in Figure 11, with a gain variation of less than 1 dB. This behavior is explained by the use of a SOA with low PDG. Thus, the 2R-converter has this advantage of low polarization dependence, with a practical effect in real systems where the fiber income signal polarization is not known or cannot be controlled.

8. Input optical power: the modulated and the CW signals

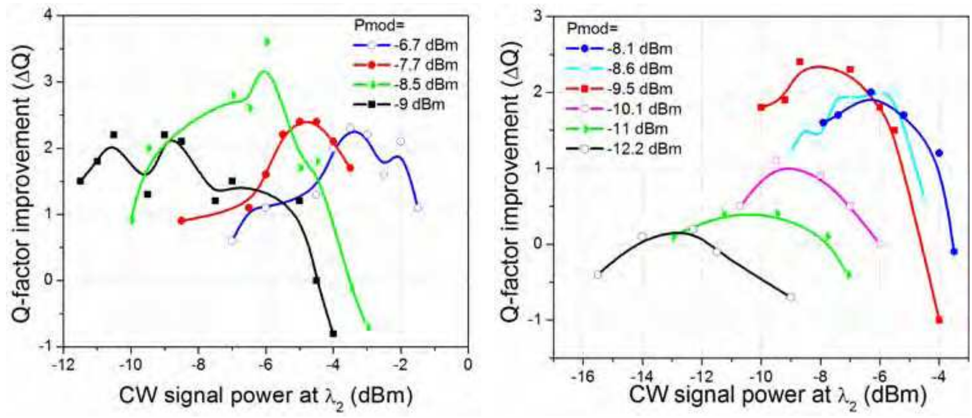
The power levels of the modulated (λ_1) and CW (λ_2) signals are important to achieve the SOA gain saturation used in the 2R-converter, necessary for regeneration and conversion by XGM effect. Moreover, the power levels of these input signals affect the power level of the output signal and the quality of the input signal. A study of the Q-factor improvement for different power level pairs of CW and modulated channels, for each different case of deterioration was done. For the cases presented in this section, up-conversions were performed from 1550 to 1551 nm at a rate of 7 Gbps, with attenuation of the output power to guarantee the same level in relation to the modulated input signal power.

In the Figure 12(a) (*case* "SOA") it is noted that there is a Q-factor improvement increasing while the CW signal power increases, with a maximum ΔQ value for a power value of the CW signal above from 2 to 3 dB, compared to the modulated signal input power. After this maximum, there is a decrease of ΔQ with the CW signal power increasing. In the case of the -9 dBm modulated signal power, there is a different behavior with two ΔQ value peaks, which occur for values of CW signal power equal to or greater than 1 dB in relation to the modulated signal power. However, the decrease after these peaks is maintained.

The relation between power and Q-factor improvement can be understood considering the cases of -6.7 dBm and -7.6 dBm of modulated signal power. In these cases, for levels of CW signal power lower than the modulated input signal, the SOA does not reach the desired saturation to attain greater conversion efficiency and regenerative effects. Therefore, higher ΔQ values do not exist. However, for CW signal power values above from 2 to 3 dB, the ideal saturation is accomplished. Moreover, the power level of the output signal at λ_2 becomes more influenced by this CW signal power. From this value of CW power, the SOA gain saturation becomes very intense due to the higher power injected in this device, without efficiency in the XGM conversion, leading to a ΔQ decreasing.

Another factor that influences the behavior of these curves is the input signal quality, which is dependent of the modulated signal power. For example, the curve of the -9 dBm modulated signal power has a different behavior and lower ΔQ values, because it has the highest Q-factor initial value, which is 6 while the other cases vary from 4.2 to 5. This curve has the highest Q-factor even with the lowest power level, because the signal has low amplification from the SOA used as a boster, adding less noise and overshoot. Thus, the ΔQ improvement is small because it has a large input Q value. A Q-factor improvement up to 3.3 for a total input power (P_{mod} + P_{CW}) of -9.3 dBm was observed. Besides that, it was obtained a Q-factor improvement for input power values from -15.8 dBm to -1.68 dBm.

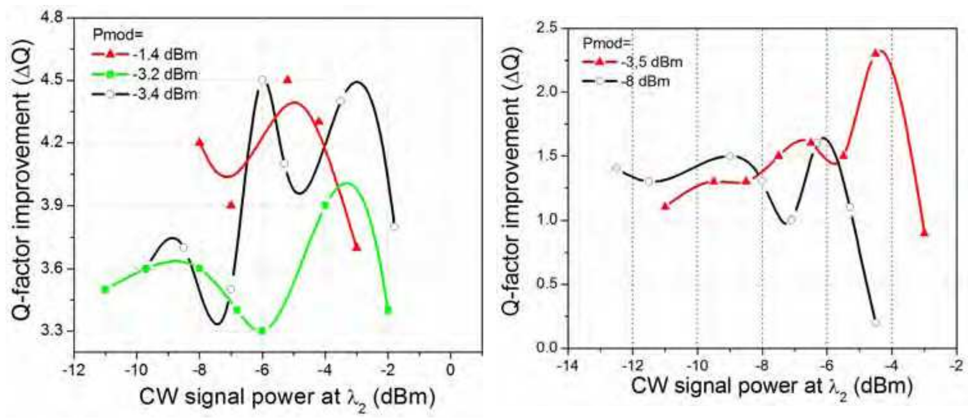
The *case* "LINK+SOA" is shown in the Figure 12(b), where is possible to observe a behavior like the *case* "SOA", with maximums of ΔQ for the CW signal power above 1 to 2.5 dB compared to the modulated signal input power. The justification for this behavior is also associated with the SOA gain saturation. For this case, lower ΔQ values were obtained. However, it was observed a Q-factor improvement for values of total input power from -19 dBm to -6 dBm. Since there is link attenuation, the power values of the modulated signal could be extended to small power values (-12.2 dBm).



(a) (b)

Fig. 12. Q-factor improvement versus input optical power (modulated and CW) for the *deterioration cases*: (a) "SOA" and (b) "LINK+SOA".

The Figure 13(a) (*case* "EDFA") shows the Q-factor improvement as a function of CW signal power for three cases of modulated signal input power. It reveals a similar behavior, but with less ΔQ variation, since the scale is represented from 3.2 to 4.8 units. Moreover, there are more oscillations between ΔQ minimums and maximums. This behavior may be partly explained by the utilized scale, since these variations between minimums and maximums are actually just from 0.2 to 0.4 units. Another reason may be inaccuracies when the Q-factor values were obtained directly from the oscilloscope.



(a) (b)

Fig. 13. Q-factor improvement versus input optical power (modulated and CW) for the *deterioration cases*: (a) "EDFA" and (b) "LINK+EDFA".

The ΔQ maximums occurred for values of the CW signal power from 0.8 to 3.6 dB below the values of the modulated signal input power. This occurs since the power levels of the modulated signal already have high values; therefore the CW signal powers cannot assume