



All Optical Regeneration Techniques

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ALL OPTICAL REGENERATION TECHNIQUES

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Abstract. Basic principles of all-optical signal regeneration are presented, and main state-of-art techniques are reviewed. Optical fiber and semiconductor based devices are addressed, and some recently reported 2R and 3R signal regeneration experiments are discussed.

Résumé Les principes de base de la régénération tout optique de signaux de télécommunication sont présentés, ainsi qu'une revue des principales techniques actuellement étudiées, concernant principalement les dispositifs à fibre et à semi-conducteurs. Quelques récentes expériences de régénération 2R et 3R sont également considérées.

1. INTRODUCTION

Record terabit/s point-to-point transmission systems over more than 2000 km have been reported [1], based on dispersion managed non-linear transmission techniques, without need for any regeneration device, except for simple linear optical amplifiers. However, if terrestrial photonic networks featuring dynamic routing capability are considered, more sophisticated regeneration schemes could be necessary in order to compensate for signal quality discrepancies between high data rate WDM channels which could be routed at different times over variable distances. Although classical optoelectronic regenerators constitute an attractive solution for single channel, single data rate transmission, it is not clear whether they could be a cost effective solution in a tremendously growing data bandwidth scenario. All optical regenerators, based on components which can process low as well as high bit rates signals could be an interesting alternative. In this summary, we briefly review 2R (reshaping repeater) and 3R (retiming, reshaping repeater) optical regeneration schemes for high speed optical signal processing, based on different technologies such as fibers or semiconductors.

2. MAIN SIGNAL DEGRADATIONS:

Main signal degradations in fiber systems arise from amplified spontaneous emission (ASE) due to optical amplifiers, pulse spreading due to group velocity dispersion (GVD), which can be corrected through passive dispersion compensation schemes, polarisation mode dispersion (PMD). Non-linear distortions due to Kerr non-linearity, such as cross-phase modulation which can be responsible for time jitter in WDM systems, or Raman amplification which can induce channel average power discrepancies, could impact system performance in 40 Gb/s (and of course above) WDM long haul systems.

3. PRINCIPLE OF 2R AND 3R OPTICAL REGENERATION:

3.1 2R regeneration:

If time jitter is negligible, simple amplification and reshaping processes are usually sufficient to maintain signal quality over long distances by preventing from noise and distortion accumulation. A 2R regenerator mainly consists of a linear optical amplifier followed by a data-driven non-linear optical gate (NLOG). If the characteristics of gate transmission versus signal intensity yields a thresholding and limiting behaviour, then signal extinction ratio can be improved and ASE amplitude noise partly reduced. There are two different schemes for 2R regeneration (see fig. 1):

- i) "2R self-regeneration" scheme (fig. 1-a) in which the incident signal propagates on the same optical carrier throughout the reshaping gate. In this case, incident signal is usually transferred with an improved extinction ratio but with only partial noise reduction, depending on the shape of the light transmission versus power slope. For example, if the gate is a saturable absorber, noise on symbol "0" is reduced while noise on symbol "1" is increased or at best not changed. In the case of a saturable amplifier, the opposite situation occurs. This regeneration scheme is the simplest one. The contrast ratio of the gate (ratio of transmission factor of "1" and "0") generally need not be very high in most of applications, typically 5 dB.
- ii) "2R cross-regeneration" scheme (fig. 1-b): in this case, the data are fed to the gate together with a "clean" (low noise) CW laser light source, which intensity is non-linearly modulated by the data. If the transmission versus power curve yields a steplike shape, output signal extinction ratio (ratio of symbol "1" power to symbol "0" power) can be improved wrt input, and normalized noise variance can be reduced on both "1" and "0" symbols. In addition, the accumulated chirp can be suppressed. However this scheme usually requires an optical filter to reject the incident wave, and also a good contrast ratio of typically 10 dB. Note that regeneration can be obtained even if the gate is inverting, e.g. with a saturable amplifier.

A common requirement for 2R regeneration schemes is the response speed of the gate : the gate transmission has to « adiabatically » follow the instantaneous signal power, which requires a gate recovery time usually much shorter than the bit time duration.

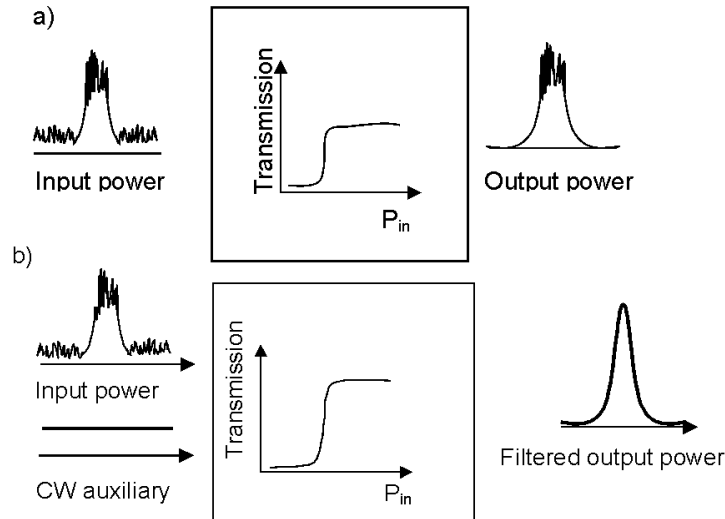


Figure 1 : sketch of 2R regeneration schemes with non-inverting gates: a) self-regeneration ; b) cross-regeneration
schémas de principe de régénération 2R à base de portes non-inverseuses: a) auto-régénération; b) régénération croisée

3.2 3R Regeneration

When jitter accumulation is also a problem, e.g. owing to cross-phase modulation (XPM) in WDM systems, or pulse edge distortions due to finite response time of non-linear signal processing devices (e.g. wavelength converters), or uncompensated polarization mode dispersion, then 3R regeneration might be necessary. Here again, we can consider two different types of resynchronising regenerators.

- i) "Data driven" 3R regenerator (3R): fig. 2 shows the basic structure of a conventional optical 3R regenerator [2], in which the non-linear optical gate is "data driven". This scheme mainly consists of an optical amplifier, a clock recovery block providing an unjittered short pulse clock stream, which is then modulated by a data driven non-linear optical gate block.

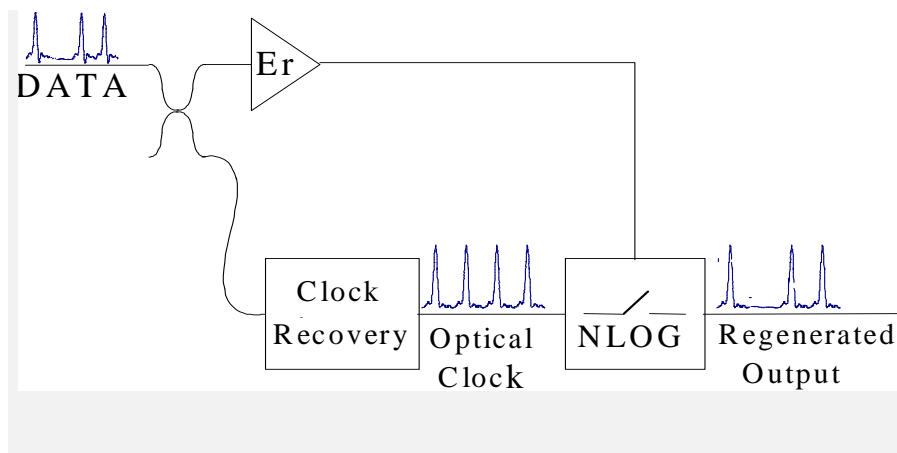


Figure 2: Principle of optical data driven 3R regeneration
Principe de régénération 3R à commande par le signal d'information

In this case the contrast ratio needs to be high (> 10 dB) but the gate recovery time can be of the same order of magnitude than the bit time slot, at least when clock pulses are short enough. Notice that this scheme is simple with an RZ format, but could also be implemented for an NRZ format, with some additional complexity.

- ii) "Synchronous Modulation" 3R regenerator (SM3R): this technique is particularly efficient with "pure" soliton pulses [3, 4]. It has recently been adapted for dispersion managed (DM) soliton transmission systems [Leclerc et al.]. It consists of combining the effects of a localized "clock driven" synchronous modulation of data, filtering, and line fiber non-linearity, which results in both timing jitter reduction and amplitude stabilization. Fig. 3 shows the principle of one of the possible SM3R schemes for DM soliton. The high dispersion fiber first converts the amplified pulse into a "pure" soliton. The filter blocks the unwanted ASE, but has also an important role in stabilizing the amplitude in the regeneration span. The data are then synchronously sinusoidally modulated through an intensity or phase modulator, driven by the recovered clock (here an electrically recovered clock).

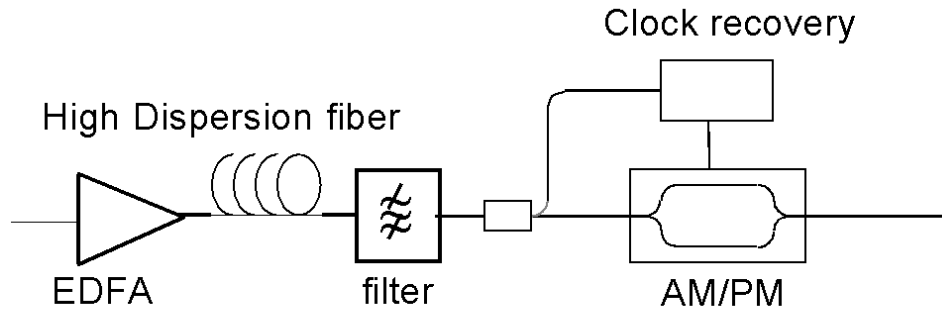


Figure 3: Principle of synchronous modulation (SM3R) optical regeneration
Principe de la régénération 3R par modulation synchrone

Let us consider for example the case of synchronous intensity modulation: the modulator imposes a sinusoidally shaped transmission, with a well suited extinction ratio. The maximum transmission is centered on the time slot center. If a pulse is "late", the transmission vs time slope of the modulator transmission is negative (closing), and will attenuate more the trailing edge: the pulse is thus distorted, and owing to subsequent non-linear propagation, the distorted pulse will recover progressively a soliton shape (with some energy loss to continuum), but its energy centre of gravity will move closer to the time slot centre where the modulator transmission is maximum (stable point). A symmetric reasoning holds for an "ahead" pulse, for which the leading edge is more attenuated than the trailing edge, so the pulse is pulled back to the time slot center. Note also that the "out of time slot" ASE background is attenuated. Phase modulation is also a way to correct timing jitter with the interplay between modulator induced frequency shift and chromatic dispersion effects [5]

4. BASIC FEATURES OF RESHAPING (2R) OPTICAL REGENERATION:

We would like to stress here some basic features of reshaping regenerators (we assume first no timing jitter). The main interest of 2R optical regeneration is to prevent from noise accumulation in a transmission line including a cascade of optical amplifiers. Ohlen et al. [6] have shown that the signal BER accumulation scales as:

$$BER \approx \exp\left(-k \frac{SNR}{N}\right) \text{ for linear amplifiers}$$

$$BER \approx N \exp(-kSNR) \text{ for perfect 2R reshapers}$$

The aim of a reshaping gate is to improve the *signal* noise characteristics, which can generally be represented by the optical field probability density function (pdf). If we only consider intensity dependent

nonlinear processes, and focus only on the power pdf, it can be easily shown that the output power pdf are given by the following expressions:

i) "Cross regeneration":

First, if we consider an input process X , a nonlinear transformation f and the resulting output process Y , we have:

$$\rho_Y(y) = \rho_X(f^{-1}(y)) \cdot \frac{1}{|f'(f^{-1}(y))|} \quad \text{with} \quad \begin{cases} y = f(x) \\ \rho_X : \text{pdf of } X \\ \rho_Y : \text{pdf of } Y \end{cases}$$

Équation 1

Now we consider S , D , T and R for the optical intensity of CW laser light source, D the optical intensity of Data, T the transmission of NLOG and R the optical intensity of regenerated data. We have : $R = S \times T$ and $T = f(D)$ with f the transmission function of the NLOG. We note $\rho_X(x)$ the probability density function of x variable. We can write :

$$\rho_R(r) = \int_0^{+\infty} \rho_S(s) \cdot \rho_T\left(\frac{r}{s}\right) ds$$

Équation 2

If we combine equation 1 and 2, we obtain :

$$\rho_R(r) = \int_0^{+\infty} \rho_S(s) \cdot \rho_D\left(f^{-1}\left(\frac{r}{s}\right)\right) \cdot \frac{1}{\left|f'\left(f^{-1}\left(\frac{r}{s}\right)\right)\right|} ds$$

Équation 3

The CW laser light source has a low noise, $\rho_S(s) = \delta(s - s_m)$ with s_m the mean optical power. We obtain :

$$\rho_R(r) = \rho_D\left(f^{-1}\left(\frac{r}{s_m}\right)\right) \cdot \frac{1}{\left|f'\left(f^{-1}\left(\frac{r}{s_m}\right)\right)\right|}$$

Équation 4

Let's now use these results in order to consider the signal BER evolution in different circumstances

4.2 Signal Bit Error Rate evolution through a reshaping gate:

An interesting point which has not been widely discussed is the signal BER evolution through a reshaping gate.

Let us consider a binary OOK modulated signal which has been degraded by amplified spontaneous emission (ASE) through an optical amplifier. Figure 5-a shows the pdf of "1" and "0" symbol power corresponding to an optical signal to noise ratio (OSNR) of 19 dB in a bandwidth of 0.1 nm, and with an extinction ratio (ER) of 8,1 dB.

i) Now, let us first assume we use a binary “ideal” intensity receiver, for which there is no “electronic” noise (thermal noise), so that the output voltage accurately reproduces the signal optical fluctuations (which means also that shot noise can be neglected wrt excess noise). Curve 5-b shows the BER versus decision threshold. We see that there is a minimum BER of 10^{-14} at the optimum threshold. Now, we transmit the optical signal through a perfect staircase shape transmission factor reshaping gate as shown on fig. 5-c. The output signal power pdf is strongly modified as it can be seen in fig. 5-d. The rms deviations of noise distributions are considerably narrowed, but the tails remain at a high level. This "noise redistribution" has initially been observed by 7 Now, let's use again the previously considered “ideal” receiver to detect the reshaped signal. Fig. 5-e shows the result: the minimum BER is equal to the initial signal BER, which proves that the *signal* minimum BER cannot (logically) be improved.

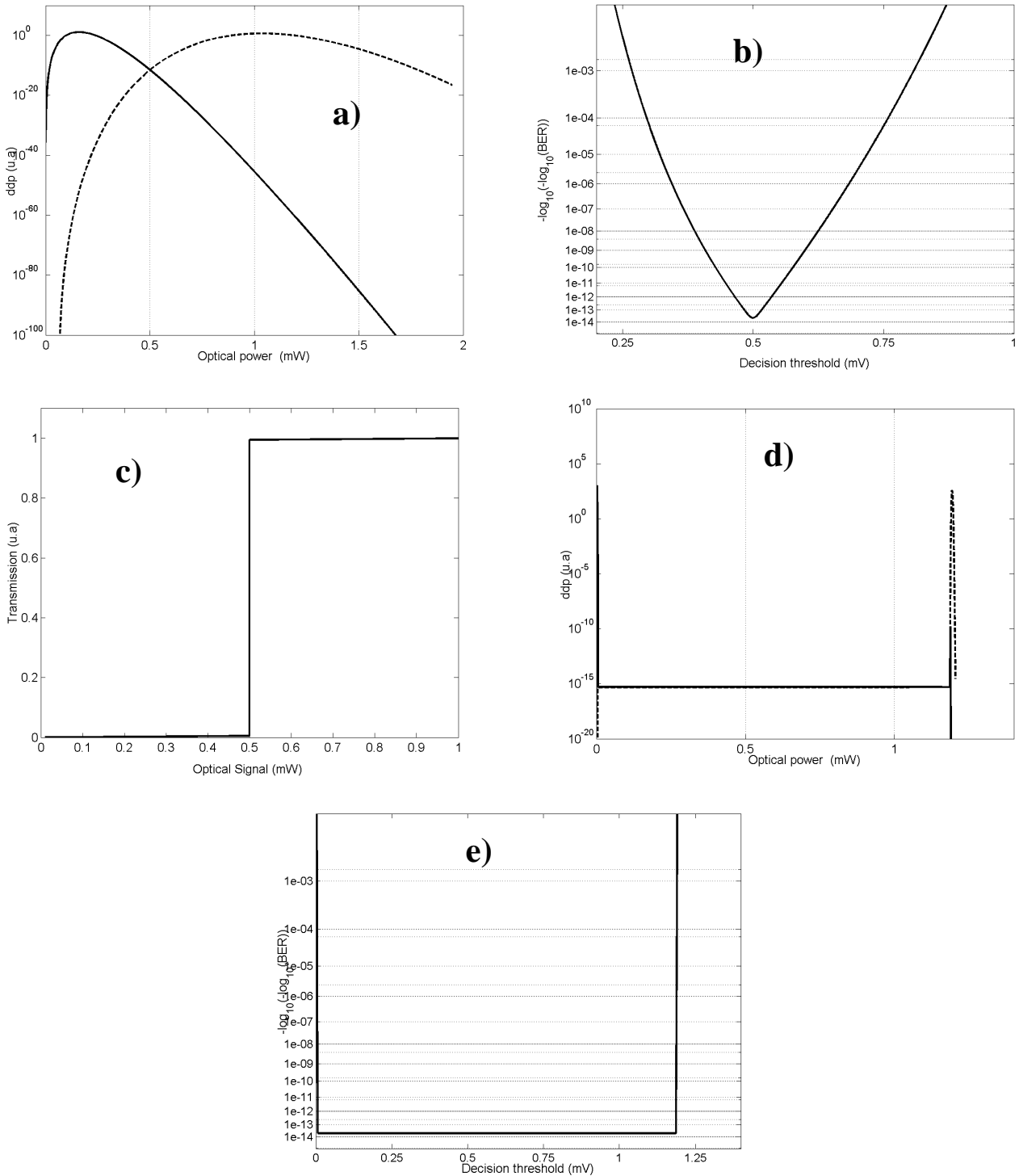


Figure 5 : pdf and BER evolution through a non-linear optical gate for 2R cross-regeneration :

- a) input mark and space power pdf for OSNR= 19 dB and Extinction ratio= 8.1 dB
- b) BER vs decision threshold for an "ideal" detector
- c) NLOG transmission vs input power

- d) NLOG output mark and space power pdf
- e) NLOG output BER vs decision threshold for an "ideal" detector

Évolution des ddp et du BER à travers une porte optique non-linéaire pour une régénération croisée

- a) ddp de la puissance des symboles "zéro" et "un" pour un OSNR=19 dB et un taux d'extinction de 8.1 dB
- b) BER en fonction du seuil de décision pour un détecteur "idéal",
- c) Transmission de la porte optique non-linéaire en fonction de la puissance en entrée,
- d) ddp de la puissance des symboles "zéro" et "un" en sortie de la porte optique non-linéaire,
- e) BER en sortie de la porte optique non-linéaire en fonction du seuil de décision pour un détecteur "idéal".

ii) Let us now consider a theoretical experiment involving the perfect 2R nonlinear gate considered above, and a typical 10 Gbit/s commercial receiver which is degraded by thermal noise, so that the minimum required power @ BER = 10^{-9} is about -17 dB (well above the shot noise limit). Fig. 6 shows standard receiver sensitivity curves (BER vs received power on receiver) corresponding to three situations:

- Curve 6-a shows the back-to-back (BB) sensitivity curve of this receiver for an (almost) perfect 10 Gb/s optical signal (OSNR=40 dB in 0,1 nm) which would be equivalent to a pure laser source.
- Curve 6-b corresponds to the ASE degraded signal which was just considered in fig. 5 : we see that an error rate floor appears owing to the 19 dB OSNR in 0,1 nm.
- Curve 6-c corresponds to the received regenerated signal. We see somewhere (region A) a reduced penalty wrt the unregenerated case, which is not due to a reduced BER in the signal, but is rather due to the fact that the extinction ratio has been improved by the regenerator. When the incident regenerated signal power is high enough on the receiver (region B) we see that the optimum BER is exactly the same as in the unregenerated case.

From these observations, we deduce the following points regarding 2R regeneration:

- first, the regenerated signal does not have a better optimum BER (i.e. with an optimum threshold) than the original signal. "Negative" penalties which are sometimes reported arise from the improvement of the *receiver* operating conditions by the regenerator, but this does not mean there are less errors in the signal.
- second, the regenerators should always be located "early" enough in the line, at a point where the signal BER is weak enough, as it can only increase, with a linear scaling vs. the number of repeaters at best.
- third, the only way to characterize the quality impact of *signal* regeneration is by cascading many regenerators in a link, for example through a recirculation loop [8], and to operate the receiver in conditions where its own noise is not the limiting factor (i.e. at high signal power levels). However, characterizing a regenerator just in front of a receiver can give informations on the regenerator own noise only if the receiver is less "noisy" than the 2R regenerator.

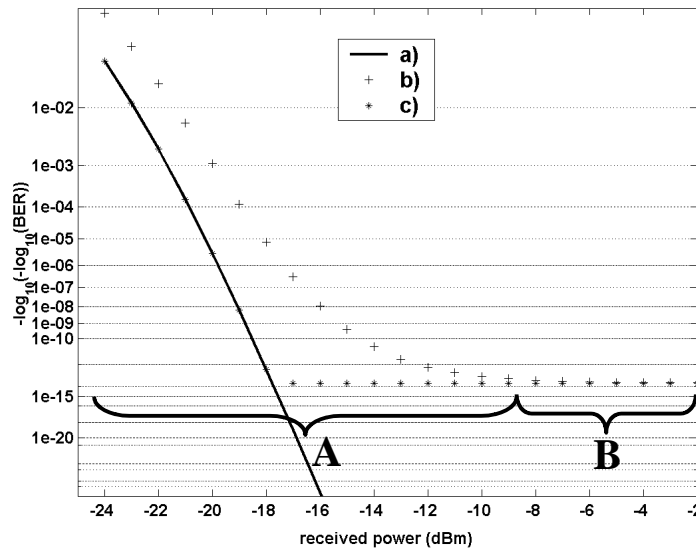


Figure 6: calculated BER vs received power with a typical commercial 10Gb/s optical receiver:

- a) with a perfect optical signal
- b) with an ASE degraded optical signal (OSNR= 19 dB ; ER=8.1 dB)
- c) with regenerated optical signal

Simulation du BER en fonction de la puissance reçue par un récepteur optique commerciale classique à 10 Gb/s:

- a) avec un signal parfait
- b) avec un signal optique dégradé par l'ESA (OSNR= 19 dB ; ER=8.1 dB),
- c) avec le signal optique régénéré.

5 REGENERATOR BUILDING BLOCKS

Let's now review some recent approaches for these different building blocks.

The core of an optical regenerator is a non-linear gate featuring signal extinction ratio enhancement and noise reduction. An optical clock recovery stage is required for 3R regenerators.

5.1 Fibre based gates

Kerr-shutter [9] and non-linear optical loop mirror (NOLM) [10] are probably the first studied gates for regeneration applications. The ultra fast response of Kerr non-linearity is a major advantage of these devices for high speed signal processing. Using a Kerr-shutter, a 40 Gbit/s optical regenerator has been reported [11]. But the weak silica fiber non-linearity requires typical peak power \times length products of 0.5 W \times km. Long fibre lengths (several km) and polarisation sensitivity to incoming signal are drawbacks for WDM field deployment. Recently, a new polarisation insensitive gate based on self phase modulation spectrum filtering was reported [12], with a good thresholding-limiting characteristics. Fig. 7-a and 7-b show the principle of operation: it consists of a non-linear fiber piece followed by a slightly detuned optical filter. A "1" symbol will give rise to a high frequency deviation, reaching the filter passband, so power will pass through the filter. With a "0" symbol, the residual power (e.g. due to noise) cannot yield a sufficient frequency deviation in order to reach the filter passband, and no power leaks out of the filter. Several regeneration experiments were reported at 40 and 80 Gb/s based on this technique [13,14,15]. However, new highly nonlinear materials should replace the holey silica fiber, in order to decrease the operating power (typ. 100 mW) by one decade.

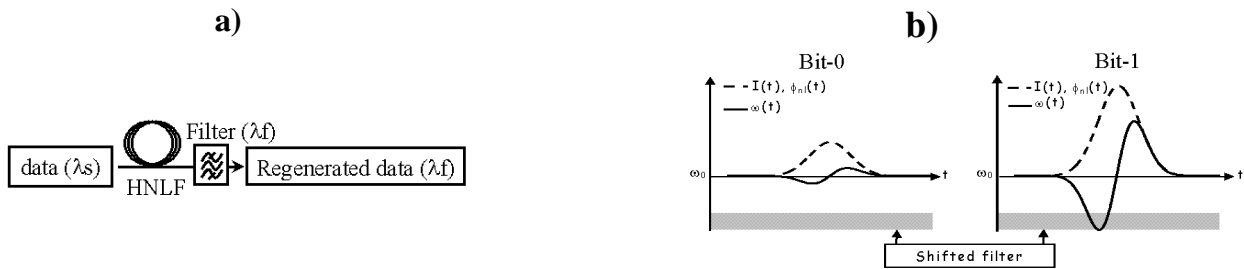


Figure 7: operation principle of the fiber-based SPM + filter optical gate

principe d'une porte optique à base d'automodulation de phase dans une fibre associée à un filtrage optique.

5.2 Semiconductor based optical gates

Although not as fast as fibre based devices, these gates are much more compact. One can consider "active devices", i.e. that require an electrical power supply like semiconductor optical amplifier (SOA) based devices, and "passive devices", like saturable absorbers [16]. Considering saturable absorbers, we refer to another paper which gives a good state-of-the-art in this special issue.

5.2.1 Active semiconductor based optical gates:

An extensive review of SOA based gates can be found in ref. 17

i) Cross gain modulation (XGM) gates.

The principle is shown in fig. 8.

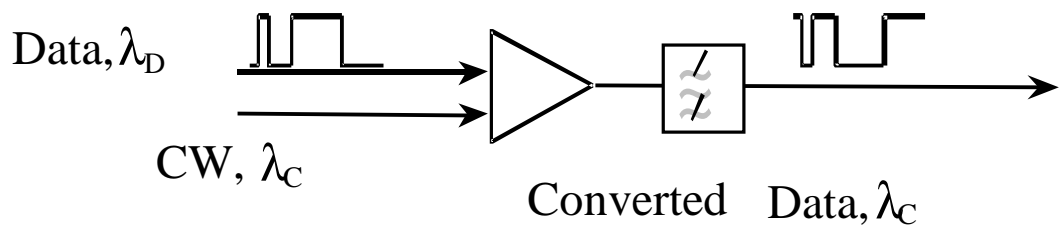


Fig. 8 : principle of operation of an XGM based gate.
principe d'une porte optique à base de XGM.

Both data signal and a local CW wave are fed to a SOA . The strong signal modulates the gain through saturation. If the medium gain linewidth is homogeneously broadened as it is the case with standard SOAs, the information is transferred to the CW "probe" wave, but with an inverted data pattern. An optical filter blocks the data wavelength. This wavelength converter generally allows a cleaning of data "0" symbol noise, but is less efficient for "1" symbols. Also, the extinction ratio is degraded to to band filling effects which translate the gain curve depending on the carrier density compression. The gain recovery time presently limits the operation speed to about 40 Gb/s, in a co-propagative configuration.

- ii) **Cross phase modulation (XPM) gates.** The principle is shown in fig. 9. We consider the general case of differential operation, which yields better results [18].

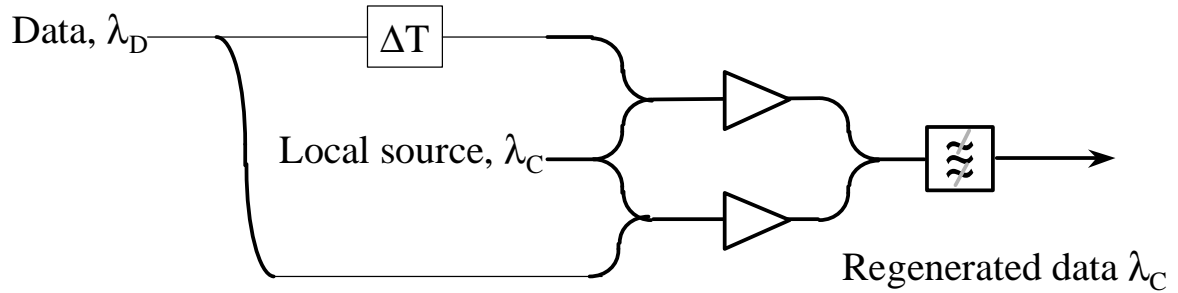


Fig. 9-a: Principle of differential operation of an XPM SOA based Mach-Zehnder Interferometer
Principe de fonctionnement en mode XPM différentiel dans un interféromètre de Mach-Zehnder à base de SOA.

In order to obtain a better extinction ratio improvement, it has been proposed [Durhuus] to use the phase-amplitude coupling effect of the SOA medium. The basic principle thus consists of incorporating an SOA in the arms of an interferometer. Here we consider for simplicity a Mach-Zehnder Interferometer. Two additional arms are added for allowing driving pulses to reach independently the SOAs. Let's now explain how this gate works: the wave to be switched on (probe) is fed to the interferometric path input, and if the interferometer arms phase difference is π , no power leaks out from the output side ("dark fringe"). Now, if a "control" pulse (here a data pulse) is fed to one SOA, the gain saturation effect modifies the carrier density, which gives rise to a phase shift. This phase shift opens the interferometer ("bright fringe") and the probe wave passes through the interferometer. Now, if the interferometer needs to be switched off before the gain recovery time, a second pulse (here a ΔT delayed copy of the opening data pulse) is fed to the second SOA, with the right power amount in order to obtain the same phase shift as above: in this case, the interferometer is returned to the initial π -phase shift difference, with a blocking state. This scheme allows rectangular switching windows with a time duration much shorter than the carrier recovery time (~ 100 times shorter). However, the switching power levels should be more accurately controlled than in the previous case. Other interferometer types have been addressed: Sagnac, also called NOLM , Michelson [19], DISC (delayed interferometric semiconductor gate [20]).

- iii) **Ultrafast Nonlinear Interferometer gate:**

Another very interesting gate is the UNI [21]. The principle is shown in fig. 9-b.

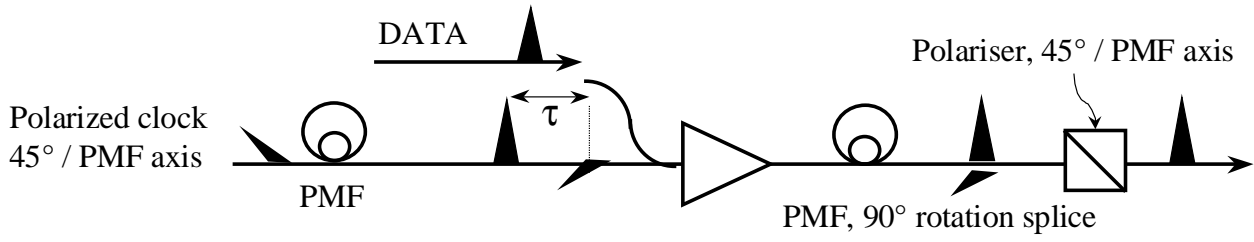


Fig. 9-b: Sketch of the Ultrafast Nonlinear Interferometer
Principe d'un interféromètre non-linéaire ultra rapide

This gate is based on a polarisation interferometer including a single SOA. It consists of two equal length polarisation maintaining fiber (PMF) pieces coupled on each side of an SOA chip, but with their neutral axes crossed by 90°. The probe pulse is polarized, with its axis oriented at 45° wrt the input fiber fast axis. In this way, the pulse is splitted in equal amplitude “fast” and “slow” pulses, due to polarisation group delay differences, and cross the SOA with a respective time delay τ . At the SOA output, because the output PMF has its axes crossed wrt the input PMF, the “fast” pulse propagates now on the slow axis, and reciprocally, so that at the PMF output, the two pulses overlap. Finally, a polarizer with its axis at 45° of the pulses polarization axes forces the remaining transmitted pulses to interfere. If the pulses phase difference is π , no light is transmitted (dark fringe) resulting in a “lo” gate state. Now, if a saturating control pulse (here a strong data pulse) is fed to the amplifier during the time slot τ , then the “late” probe pulse will experience a lower gain and also an increased phase shift wrt the “fast” probe pulse: then both pulse will interfere constructively (bright fringe), and the gate state is “hi”. This UNI has first demonstrated a capability of 100 Gb/s signal processing. Its only drawback is some bulkiness.

Notice that a key point in achieving very high data rate operation of any opto-optic gate is the need for co-propagative configuration for data and clock. In fact, despite very short carrier recovery times, a contrapropagative configuration operation speed is limited by the chip length: this is due to the fact that a “probe” pulse has to “wait” until the previous active control pulse has gone out of the chip before a new operation can be set-up. For a 1 mm long InP based device, this time is typically 15 ps.

Let's now briefly review some works on active nonlinear optical gates.

Among active semiconductor gates, work has been focused on bistable lasers [22] and mostly on SOA based devices. First reported SOA based optical gates was a Sagnac interferometer incorporating one SOA as the non-linear element [23,24]. However these gates are much better suited for high speed OTDM demultiplexing [25]. Other high speed and well shaped optical gates are SOA-based Mach-Zehnder or Michelson interferometers [26,27], which can be data driven with polarisation independence up to 40 Gbit/s, with excellent performances [28]. Main features of interferometric non-linear gates are signal extinction ratio enhancement and noise variance reduction. 100 Gbit/s optical logic gate based on an ultrafast nonlinear interferometer (UNI) using an SOA in a birefringent interferometer was reported [29], while feasibility of data regeneration at 40 Gb/s with this gate was demonstrated [30].

5.2.2: Passive semiconductor nonlinear optical gates:

Multi-quantum well based saturable absorbers have been known for long. However, the contrast ratio of a transmitting saturable absorber is usually weak, because the thickness of the MQW stack cannot be too high. This is not a problem for Laser mode-locking applications. However, for applications under consideration here, a contrast ratio of at least 5 dB is required. This has been achieved by placing the MQW absorber inside a reflective microcavity [16]. Now, the absorption recovery lifetime is typically in the range of nanoseconds, without some special processing. In order to reduce this lifetime, different techniques are presently investigated in the InGaAsP/InP system: low temperature epitaxial growth [16], high energy ion bombardment [31], and more recently iron doping [32].

5.3 Clock Recovery

For optical 3R regeneration, a synchronous jittered short pulse stream clock has to be recovered from incident signal. Many solutions meeting these requirements have been reported, which cannot all be reviewed here. We only focus on polarisation independent and potentially ultrahigh speed schemes for RZ formats. All-optical clock recovery through optical injection of mode-locked lasers, either in semiconductor [33] or Erbium doped fibre [34] could yield low jitter, short pulse clocks. Phase locked loop techniques using a high speed non-linear optical element as phase comparator [35], could also yield good performance above 100 GHz. Recently, a self-pulsating laser clock recovery was demonstrated at 40 GHz [36, 37, 38].

6 SOME RECENT RESULTS ON OPTICAL REGENERATION

We briefly review here some recent results on polarisation independent regeneration schemes for data rates above 10 Gbit/s.

6.1 2R regeneration

Although 2R regeneration looks very attractive because of its simplicity and bit rate flexibility [39, 40], it is not clear whether it could be used above 10 Gb/s with a high degree of cascability, because it would require devices with a very short transition time response. However, self-regeneration in a microcavity saturable absorbers has recently been used in order to increase by 30 % the transmission length of a 20 Gbit/s system laboratory experiment, enabling a 7800 km transmission [41].

6.2 3R regeneration

“All-electronic” signal processing is rapidly progressing, with recent demonstration of a 40 Gbit/s optoelectronic repeater using InP-HEMT technology [42]. Several 3R optical regenerator architectures have also been demonstrated. All optical fibre devices were first reported, and have shown now 20 [43], and 40 Gbit/s [44] operation capability over 1 million km. On the semiconductor technology side, hybrid regenerator structures using optoelectronic clock recovery stage and all optical SOA based non-linear interferometric gates have been demonstrated (with BER assessment) at 10 [45], 20 [46,47] and 40 Gb/s [48]. Cascadability of up to 100 regenerators in recirculation loop at 40 Gbit/s has been reported [49] with multistage interferometric gates, as we have shown that cascaded non-linear gates significantly improve signal regeneration [50].

Finally, InP electro-optic modulators have successfully been used for polarisation insensitive in-line amplitude and phase synchronous modulation of soliton signals up to 40 Gb/s, enabling error-free transmission over more than 20 000 km [51].

7. CONCLUSION

High speed WDM photonic networks will probably require signal regenerators. Although significant progress has been achieved these last years, it is not yet clear to-day whether all building blocks of a 3R all optical regenerator will be as easily integrated as for an electronic device, with cost effective targets, particularly in a dense WDM context. This means that optical signal processing solutions should yield superior or not otherwise available functionalities, such as bit rate flexibility, or better: simultaneous regeneration of several WDM channels in a single chip. In this latter case, new materials have to be developed, such as quantum box (or at least dot) materials with controlled dot sizes.

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