Abstract:

We present simple scaling rules to optimize the design of 2R optical regenerators relying on Self-Phase Modulation in the normal dispersion regime and associated offset spectral filtering. A global design map is derived which relates both the physical parameters of the regenerator and the properties of the incoming signal to the regeneration performance. The operational conditions for optimum noise rejection are identified using this map and a detailed analysis of the system behavior under these conditions presented. Finally, we demonstrate application of the general design map to the design of a regenerator for a specific 160 Gb/s system.
1. Introduction

All-optical regeneration is likely to be an important function within future optical communication systems providing a route to optical networks of increased scalability, capacity and flexibility, as well as reduced network management complexity and costs. Optical regeneration is progressively more attractive as transmission speeds increase since this places ever more stringent demands on existing impairment mitigation techniques such as dispersion and PMD compensation.

In this paper, our interest is on 2R regeneration i.e Reamplification and Reshaping of optical data pulses. An optical data stream can be corrupted by a variety of physical effects including: uncompensated dispersion, inter- and intra-channel nonlinear effects, the accumulation of Amplified Spontaneous Emission (ASE) noise, and Polarization Mode Dispersion-induced temporal pulse broadening. Intra-channel nonlinear effects, such as intra-channel Four-Wave Mixing (i-FWM) and intra-channel Cross phase modulation (iXPM) for example are responsible for the generation of ghost pulses inside zero-bit slots, amplitude fluctuation in the one-bit pulses and the introduction of timing jitter [1]. These effects are particularly severe and limit the maximum usable span length.

Over the past decade, there have been numerous experimental demonstrations of optical 2R regeneration schemes, designed to work with either On-Off keying amplitude modulated (OOK) and/or phase-shift keyed (PSK) signals. A particularly interesting fiber based regeneration technique for Return-to-Zero (RZ) OOK signals based on Self-Phase Modulation (SPM) followed by offset filtering has been proposed and experimentally demonstrated by Mamyshev [2]. This method has drawn much attention due mainly to its ease of implementation and robustness. Its main advantages include a reduced sensitivity both to environmental instabilities, as compared to systems relying on interferometric effects (e.g. nonlinear optical loop mirrors), and its low polarization sensitivity relative to other regenerating schemes based on effects such as Four-Wave Mixing. Finally, unlike other technologies that exhibit a longer response time (such as semiconductor optical amplifiers), the quasi-instantaneous response time of Kerr nonlinearities in optical fibers makes the scheme directly applicable to high bit-rate operation. Using the Mamyshev approach a number of 2R and more recently 3R optical regenerators (i.e. 2R regenerators with an additional retiming operation) have been experimentally reported at 10 Gb/s and 40 Gb/s with either OOK-RZ [2, 3] or Carrier-Suppressed RZ (CS-RZ) formats [4, 5]. The ability to handle data impaired either by iFWM [6] or ASE [7, 8] has also been confirmed. Significant advances in fiber technology, such as the emergence of holey fibres [9], fibers made of compound materials (for instance chalcogenide [8]) or bismuth oxide [10, 11], have further enhanced interest in this technique. Due to their high nonlinearity coefficient, these latter waveguides are proposed as attractive media for reducing the power budget and/or increasing the compactness of the devices.

Despite the numerous experimental demonstrations, the design optimization of such regenerators is not straightforward, because of both the wide variety of input signal parameters (pulse width, duty cycle, input power), and the numerous physical properties of the fibers (chromatic dispersion D, nonlinearity coefficient γ, and length L). To date, only a few works have introduced any form of design guideline [2, 7, 12-14] and even these have addressed the problem either within the context of a pure nonlinear regime [13, 15], or have considered only a fixed fiber length [3]. However, neither of these approaches facilitates cross-comparison between different fiber systems. In this work, we report the development of global scaling rules for the 2R regenerator based on Mamyshev’s technique. We first introduce the physical parameters of the regenerator and define associated parameters that can be used to assess the regeneration performance. From this process, we identify an optimum operation regime in terms of rejection of amplitude noise [16]. We study the quality of the regenerated pulses at the output of the regenerator for operation under these optimal conditions, and extend our conclusions with a simulation example showing the applicability of the design rules for a regenerator operating at 160 Gb/s.

2. Regenerator and regeneration parameters

2.1 Regenerator principles and associated parameters

In this first section, we recall the principle of the SPM-based Mamyshev regenerator as shown schematically in Fig.1. The degraded optical pulse streams are first fed into an optical amplifier which is used to boost the power to a suitably high level at the input to the highly nonlinear fiber (HNLF). (Note that an additional filter is often inserted after the amplifier to
reject the out-of-band ASE noise). The amplified pulses are then propagated in the HNLF during which they experience spectral broadening due to Kerr-induced SPM. A narrow-band filter is used to carve into the broadened spectrum at the output of the HNLF acting both to provide intensity discrimination as discussed below, and as a pulse shaping element.

![Schematic of a typical optical regenerator based on Self-Phase Modulation.](image)

The amount of spectral broadening experienced by the signal in the HNLF is to first order proportional to the time-derivative of the pulse intensity profile. This allows one to discriminate between high and low peak power pulses simply by detuning the narrow-band filter away from the input signal carrier frequency. A detuned optical filter will collect only a small fraction of the energy of low-peak-power pulses (nominal ‘zeros’), which experience less spectral broadening than high-peak-power pulses (nominal ‘ones’). Thus, undesired ghost pulses can be suppressed at the output of the regenerator and the overall mark-to-space extinction ratio can consequently be improved.

In addition, the regenerator should perform amplitude equalization on the ‘ones’, and also the nominal shape and width of the transmitted pulses should be retained. In general this requires a condition under which the spectrum broadens in proportion to an increase in the signal power. Although this condition can be satisfied both in the normal and the anomalous dispersion regimes, nonlinear propagation within the normal dispersion regime is preferable in that it does not allow the development of modulational instability, or the nonlinear interaction of the signal with ASE, both of which can introduce additional noise [17]. Furthermore, the SPM spectra generated under conditions of normal dispersion are generally flatter, thus leading to smoother pulse shapes at the output of the regenerator.

In the work presented here, we have assumed transform-limited Gaussian pulses at the input, with a variable peak power \(P_{\text{in}}\) and a half-width at the 1/e-intensity point \(T_0\). Figure 1 lists the remaining parameters of the regenerator. The customizable parameters of the HNLF are the chromatic dispersion (\(\beta_2\)) and a half-width at the 1/e-intensity point \(T_0\). The output optical band-pass filter (OBPF) is detuned from the carrier frequency by an offset value \(\Delta F\). To adhere with our previous statements, the filter is Gaussian with a 1/e half-bandwidth of \(F_{\text{OBPF}}\), which matches the corresponding input pulse 1/e half-bandwidth \(F_0\) (i.e. \(F_{\text{OBPF}} = F_0 / (2\pi T_0)\)), and has a flat phase response. In order to distinguish the impact of the ASE noise from the intrinsic ability of the regenerator to eliminate ghost pulses, we have not considered any ASE noise in our simulations. (Nevertheless, the effects of ASE are qualitatively discussed in a separate section in the paper).

It should also be noted here that in order to be able to devise some general scaling rules, we have chosen not to consider the impact of fiber loss in this study. Although the effects of attenuation can be quite significant, the general trends described in the following sections are still valid when this is considered. Quantification of the precise effects of fiber losses will be the subject of a separate study.

2.2 Assessment of the regeneration function

The ability of the regenerator to offer both extinction ratio improvement and amplitude equalization is defined by the transfer function (TF). The TF simply describes the variation of the output pulse energy as a function of the input pulse energy. In the particular type of regenerator considered here, input pulses of the same peak power and shape but with different duration, (and hence energy), do not exhibit the same output response. As detailed in [8], the principle of the regeneration is based on the temporal derivative of the intensity profile of the pulse and not on an instantaneous power response as in an interferometric switch. As a result, the regenerator can ultimately exhibit as many TFs as there are input pulse shapes. In this
work, we overcome this limitation by considering only the case of Gaussian pulses at the input. The same remarks apply also to the output pulses. We have therefore considered that the pulse width $T_0$ and pulse shape remain largely unchanged at the regenerator output, so that we can define the TF as a function of the output pulse peak power $P_{\text{out}}$ versus the input peak power $P_{\text{in}}$ (the validity of this statement will be shown in Section 4 below).

Depending on the interplay between the broadened pulse spectrum and the detuned filter position, three possible regimes for the TF can be identified, as graphically illustrated in Fig. 2. The variation of the output power relative to the input can either be non-monotonic (regime ‘A’), exhibit a locally flat region on the one-level (regime ‘B’), or be purely monotonous (regime ‘C’). It is clear that regime ‘B’ offers the largest power equalization ability, and represents the preferred operational regime.

Parameterization of the TF shape has been previously proposed in order to analytically predict the regeneration performance and concatenation effects [18, 19]. In these earlier studies, the TFs were approximated by tanh-like, sigmoid or more drastically by linear piecewise functions. Unlike these authors in our global approach we chose to define parameters directly extracted from the TFs, and to evaluate the regenerator performance on this basis. The three parameters that we use are graphically illustrated in Fig. 3, and are described below:

- The nominal input peak power for the marks $P_{\text{1 in}}$. This value is defined as the input peak power for a ‘one’ bit that locally exhibits maximum peak power compression at the output. Mathematically, this value corresponds to the input peak power at which there is a sign change in the curvature of the TF.
- Taking into consideration this $P_{\text{1 in}}$ value, an output extinction ratio $ER_{\text{out}}$ is computed for an arbitrarily fixed input extinction ratio of $ER_{\text{in}} = -10$ dB. We define the extinction ratio as the ratio between the peak powers of a ‘zero’ and a ‘one’ pulse.
- Finally, the assessment of the output power equalization on the marks is quantified by introducing the difference $\varepsilon$, which is defined as the total variation in output peak power for an input peak power ranging between -7.5 % and +7.5 % around $P_{\text{1 in}}$. The output peak power compression $\rho$ is defined as the normalized ratio $|\varepsilon|/P_{\text{1 out}}$.

It will become obvious in the following section that although the precise choice of various of these values (e.g. $ER_{\text{in}} = -10$ dB and variation in the incoming pulse peak power of ± 7.5 %) might seem somewhat arbitrary, they do not affect the generality of the developed model.
These values are only used to provide an indication of the quality of the TF for a physically reasonable choice of input signal parameters, rather than a specification of particular operating conditions.

Finally, it is also worth noting that the TF alone does not provide any information on the pulse quality at the regenerator output, or the corresponding power efficiency. These effects will be studied separately in Section 4 of this paper.

3. Modeling results

We now consider the nonlinear Schrödinger equation (NLSE) that governs the propagation of the pulse within an optical fiber. We limit the contributions of the dispersive effects to the group velocity dispersion $\beta_2$ term and the nonlinear contributions to the effects of SPM. The medium is assumed to be lossless ($\alpha=0$). We follow the well-known analysis (which can be found in [20]) which allows us to express the slowly varying pulse envelope in a standard form using the following set of normalized parameters:

\[ u(z,t) = \sqrt{N^2} U(z,t); \quad \xi = \frac{Z}{L_D}; \quad \tau = \frac{T}{T_0} = \frac{1 - \beta_1 Z}{T_0} \]

\[ L_D = \frac{T_0^2}{|\beta_2|}; \quad L_{NL} = \frac{1}{\gamma P_p}; \quad N^2 = \frac{L_D}{L_{NL}} \]

with $t$ and $z$ the time and the longitudinal position along the fiber respectively. Here, $\beta_1$ is the group velocity, $P_p$ the pulse peak power, $U(z,t)$ the normalized slowly varying field envelope of the pulses, and $L_D$ and $L_{NL}$ are defined as the dispersion and nonlinear lengths respectively. The NLSE can then be written as:

\[ i \frac{\partial u(\xi,\tau)}{\partial \xi} - \frac{\operatorname{sgn}(\beta_2) \sigma^2 u(\xi,\tau)}{2 \sigma^2} \frac{\partial^2 u(\xi,\tau)}{\partial \tau^2} + |u(\xi,\tau)|^2 u(\xi,\tau) = 0 \]

Our approach benefits from the use of scaling factors and allows us to derive a global set of solutions by only considering any one solution of the standard form. For example, if $u(z/L_D,T/T_0)$ satisfies Eq. 3, then for any real number $\delta$, the pulse envelope $\delta u(\delta^2 z/L_D,\delta T/T_0)$ is still a solution of Eq. 3 [20]. From a practical point of view, if we consider two pulses with different initial peak powers ($P_1$, $P_2$), and different initial pulse widths ($T_1$, $T_2$) but of the same initial shape, then these pulses will evolve to the same scaled profiles in both time and frequency when two conditions are fulfilled: (a) that the fiber length in the two cases is the same proportion of the dispersion length ($L_1/L_D = L_2/L_D$); and (b) that they exhibit the same $N^2$ value ($L_{NL1}/L_{NL1} = L_{NL2}/L_{NL2}$). This scaling rule drastically reduces the complexity of the problem, as global bit-rate-independent conclusions can be derived from the analysis of a single case in which the four aforementioned parameters $T_0$, $P_p$, $\beta_2$ and $\gamma$ are arbitrarily fixed.

By using these scaling factors, and by virtue of the normalized quantities $N$, $L_{NL}$ and $L/L_D$, where $L_{NL}$ is defined with respect to the nominal input peak power $P_{in}$, our calculations demonstrate that it is possible to relate the three TF parameters ($P_{in}$, ER out and $\rho$) to the physical parameters of the regenerator (fiber parameters $L$, $\gamma$, $\beta_2$ and filter detuning $\Delta F$). The interdependencies between the three parameters can be represented in the two-dimensional space formed by the normalized fiber length $L/L_D$ and the normalized output filter detuning $\Delta F/F_D$, as shown in the multi-contour plot of Fig. 4.

Figure 4 shows that the two-dimensional space is split into two distinct areas that correspond to the ‘A’ and ‘C’ TF regimes, with the ‘B’ regime lying along the common boundary. For a fixed $\Delta F/F_D$ ratio, a small $L/L_D$ ratio yields a non-monotonous TF variation (regime ‘A’), whereas a monotonic variation (regime ‘C’) is experienced at high $L/L_D$ ratios. This illustrates the spectral evolution of the pulse along the fiber length: For short fiber lengths the SPM-spectrum is characterized by ripples which lead to the features of regime ‘A’, whereas for longer lengths the SPM-broadening has saturated and the extra energy of higher power pulses only contributes to an increase in the power that passes through the offset filter (regime ‘C’). More interestingly, we identify the region of maximum power equalization (regime ‘B’) over a large range of $N$ values when operating under specific conditions for the fiber length and filter detuning.
The map directly provides simultaneous access to the parameters to be employed and to the expected performance. Additionally, some interesting observations can be made at this stage. As it might be expected, the output extinction ratio improvement is mainly determined by the position of the output filter and a minimum offset detuning value of $1.5\times F_0$ is necessary to significantly improve the input extinction ratio. The extinction ratio improvement has a remarkable dependence on the length of propagation as, the variation of the output extinction ratio for high input peak powers is progressively altered and tends to saturate when increasing $\Delta F/F_0$ for a fixed $L/L_D$ ratio. This behavior is accounted for by the development of pedestal structures in the wings of ghost pulse spectra (i.e. the onset of wave-breaking), which are more likely to be sampled by the detuned filter.

As far as the optimal regime ‘B’ is concerned, we have found a relationship between the optimal fiber length $L_{opt,B}$ and the corresponding $N_1^{in}$ value (defined as $(\gamma P_1^2 T_0^2/\beta_2)^{1/2}$):

$$L_{opt,B} = L_D \frac{K_0}{N_1^{in}}$$  \hspace{1cm} (4)

where $K_0$ is a fitting constant equal to 0.382 (with a ±4% error) over a range of $N$ values between 5.5 and 23. Although this relation has been found numerically rather than analytically, we note that it is of a similar form as the relations describing both the optical wave-breaking distance for Gaussian pulses [21] and supercontinuum design rules [22]. There is a linear relationship between the optimal normalized filter detuning $\Delta F/F_0$ and the corresponding $N_1^{in}$ value:

$$\Delta F/F_0 \approx 0.71 N_1^{in} - 2.13$$  \hspace{1cm} (5)

Equation 4 shows that a balance needs to be maintained between the dispersive and nonlinear contributions and demonstrates that a design consideration based solely on the value of the fiber nonlinearity is therefore insufficient. Again, we emphasize that the proposed rules, as well as the map of Fig. 4, are directly applicable to any bit-rate systems by an appropriate setting of the input pulse duration $T_0$ and only depend on the pulse shape characteristics.

According to Fig. 4, the fiber length and filter position need to be carefully chosen to ensure operation in the optimal regime ‘B’. However, it is interesting to note that there is a quite broad region close to the boundary between regimes ‘A’ and ‘B’, where the ratio $\rho$ does not change significantly. This provides a convenient route towards relaxing the design considerations without greatly affecting the TF shape.
Finally, it follows from Eq.2 and 4 that the optimum length $L_{\text{opt,B}}$ scales inversely to the square root of the $\beta_3 \gamma$ product. This favors the use of highly nonlinear, compound glass fibers (see e.g. [8, 10, 11]), whose extremely high nonlinearities are usually accompanied by large values of chromatic dispersion. However, these fibers also exhibit significantly higher propagation losses, which are likely to compromise the validity of this observation.

4. Properties of the regenerated pulses

As mentioned earlier, for the design optimization of a 2R regenerator, an analysis of the TF characteristics should also be accompanied by in-depth assessment of the quality of the regenerated pulses. We therefore examine the characteristics of the optical pulses at the output of the regenerating system, in terms of time-bandwidth product (TBP), pulse width, chirp and induced timing jitter. We specifically focus on the preferred operation regime ‘B’. Then, according to Eq. 4, 5 and Fig. 4 each value of $N_{1}^{\text{in}}$ corresponds to a unique set of regenerator parameters.

![Graphs showing TBP, temporal FWHM, normalized output pulse chirp, and timing jitter as functions of $N_{1}^{\text{in}}$.](image)

In Fig. 5a we plot the variation observed in the TBP, as we move along the ‘B’ contour. It is to be noted that the pulses deviate only slightly from the transform-limited case (0.441), especially for larger values of $N_{1}^{\text{in}}$. We attribute the degradation of the TBP at small values of $N_{1}^{\text{in}}$ to the more pronounced peaked structure of the SPM broadened spectrum which is reflected in the filtered spectrum at the output of the regenerator. Unlike the TBP, the temporal FWHM of the pulse is decreases smoothly with increasing $N_{1}^{\text{in}}$ (see Fig. 5b). As far as the shape of the output pulse is concerned, a slight asymmetry can be observed – however this is found to be negligible and it is even less noticeable at high values of $N_{1}^{\text{in}}$ as depicted in Fig. 6.
Fig. 6. Normalized intensity profiles: (a) before linear chirp compensation, and (b) and after linear chirp compensation. As a reference, an initial Gaussian pulse is also shown (dashed lines).

A closer examination of the chirp reveals that it varies in a rather linear fashion across the largest portion of the output pulses for all values of $N_1^{\text{in}}$, and that the chirp rate is positive (Fig. 5c). This behavior is characteristic of the pulse evolution close or above the optical wave breaking condition [23]. A consequence of the chirp on the pulses is that they acquire an additional timing delay relative to linearly propagating pulses, which is a function of $N_1^{\text{in}}$. In order to quantify this power-dependent timing delay we introduce the quantity $T_{m_1,\delta}$ as follows:

$$ T_{m_1,\delta} = \left| T_{m_1} \left[ (1 + \delta)P_1^{\text{in}} \right] - T_{m_1} \left[ (1 + \delta)P_1^{\text{in}} \right] \right| $$

(6)

where

$$ T_{m_1} \left[ P_1^{\text{in}} \right] = \lim_{\tau \to \infty} \frac{\int_{-\infty}^{\tau} t I(L, t) \, dt}{\int_{-\infty}^{\tau} I(L, t) \, dt} $$

(7)

$T_{m_1,\delta}$ traces the relative variation of the temporal position (i.e. the timing jitter) of the output pulses over an input peak power variation of $\pm 7.5\%$ (i.e. $\delta = 0.075$) around $P_1^{\text{in}}$. The temporal position of the pulse is defined as the first-order moment integral (center of gravity) $T_{m_1}$ of the pulse intensity profile $I$, which depends intrinsically on the input pulse peak power $P_1^{\text{in}}$ (Eq. 7). We demonstrate in Fig. 5d that this variation is almost independent of the operating value $N_1^{\text{in}}$, so that the same amount of timing jitter is introduced whatever the operating condition along the ‘B’ contour. The amount of timing jitter is found to be around 8% of the initial pulse width $T_0$. The abrupt variation at small values of $N_1^{\text{in}}$ is explained by the presence of a small asymmetry of the output pulses which affects the computed $T_{m_1}$ value.

Since the output pulses have a smooth and linear chirp, it is possible to consider offset filter with a phase response designed to compensate this chirp (alternatively a suitable length of anomalously dispersive fiber can be used for the same purpose). In Fig. 5a, b and 6 we have included the corresponding plots that represent the TBP, the normalized pulse width and the pulse shapes respectively after optimum linear chirp compensation is applied, demonstrating that it is possible to achieve almost identical characteristics to the input pulses.

5. Discussion

In the following subsections we examine the impact of various system parameters on the regenerator performance. In particular, we consider: how some variation in the input pulse parameters (i.e. the pulse width and temporal chirp) can affect the regenerator TF; how the power efficiency and extinction ratio of the regenerating system are affected by the operating conditions; and how coherent interference between adjacent pulses nonlinearly propagating in the HNLF can degrade the regeneration. In addition, we provide qualitative comments on the contribution of ASE noise, and discuss the consequences of using an output filter with a bandwidth other than the nominal $F_0$ value considered above on the TF parameters. Finally, we summarize our observations and draw some conclusions on how to go about choosing the best operating conditions for a given system.

5.1 Pulse width variation and residual dispersion
In order to ensure robust operation, a regenerator should be able to demonstrate tolerance to input pulse width variations and residual chirp, since these are both likely to be affected during transmission by environmentally-driven chromatic dispersion variations, ASE-signal interaction and polarization-mode dispersion. Since the TF is dependent on the intensity derivative of the input pulse [8], a variation in the input pulse width would be translated into a variation in the output pulse energy. For the case of unchirped pulses, the consequence of this variation can be appreciated from a study of Fig. 4, where an increase (decrease) in the pulse width may shift the operating condition e.g. from regime ‘B’ to regime ‘A’ (‘C’), due to the dependence of $L_D$ on $T_0$. In Fig. 7a, we show TFs obtained when the pulse width is varied from -20% to 20% of its nominal value $T_0$, when the system is operating in regime ‘B’ with a fixed value $N_{1}^{in}=10$ (defined for the nominal value $T_0$).

The appreciation of the effects of residual chirp is less straightforward to establish. Following [24, 25], we have adopted a simple approach that consists of positively (negatively) prechirping the input pulse by linear propagation in a segment of anomalous (normal) dispersion fiber. This has allowed us to vary the pulse width at the input of the regenerator by either +10% or +20% of the nominal $T_0$ value. The corresponding TFs are plotted in Fig. 7b, again for nominal operation in regime ‘B’ with a value $N_{1}^{in}=10$. All modified TFs are of type ‘A’ and exhibit a higher output pulse energy than the unchirped case. This behavior originates from the fact that the SPM spectra are not as flat when the input pulses are chirped [21].

From these results, we can conclude that the regeneration is not significantly compromised by the presence of large variations in both the input pulse width and the residual chirp. It could be argued that cascading a second regeneration stage, as is frequently done with Mamyshev regenerators to eliminate any overall-frequency shift, might be beneficial in terms of offering an additional power equalization step. In this way all power fluctuations at the end of the first stage could be fully compensated.

5.2 Output Extinction ratio, energy yield

![Fig. 7. (a): TFs for an input pulse width variation between -20% and +20% relative to $T_0$. (b): TFs for linearly chirped input pulses with either positive (C>0) or negative (C<0) linear chirp. The axes correspond to normalized pulse energies with respect to energies $E_{1,opt}^{in}$ and $E_{1,opt}^{out}$ of the unchirped nominal case for $N_{1}^{in}=10$.](image)

![Fig. 8. Output extinction ratio $ER_{ext}$ improvement (a) and energy yield (b) as a function of $N_{1}^{in}$ when operating along the optimal regime ‘B’.

(a)

(b)
On the basis of the discussion presented so far, it follows that operation at high values of $N_{\text{in}}$ is favorable in terms of both extinction ratio improvement and pulse quality. However, when operating at high powers, the power spectral density of the signal reduces, since the SPM-induced spectral broadening is more pronounced. Therefore, the proportion of energy that passes through the offset filter decreases with increasing $N_{\text{in}}$. Additionally, this reduction in spectral density at high values of $N_{\text{in}}$ is accompanied by optical signal-to-noise ratio (OSNR) degradation in the presence of out-of-band ASE noise [26]. These considerations lead to a trade-off between the improvement in the regenerator performance and the energy yield of the system (i.e. the ratio of the power at the output of the filter to the power at the input of the fiber), as shown in Fig. 8. Inter-pulse interactions during their propagation in the HNLF are also likely to further restrict the maximum value of $N_{\text{in}}$ that can be used in the systems as discussed below.

5.3 Interaction between adjacent pulses

Up to this point, we have concerned ourselves with the study of the propagation of single Gaussian pulses in the regenerator. It is important however, to study the limits at which the consideration of a stream of pulses will affect the system operation. Under the combined effects of normal dispersion and nonlinearity, Gaussian pulses typically broaden and evolve into trapezoidal-shaped pulses, as illustrated in Fig. 9a. The extent of the pulse broadening has therefore to be investigated to address the possibility for adjacent pulses to spread and as a result partially collide within the HNLF. In that case, both coherent interference and nonlinear interactions would result in strong oscillations in the temporal profile of overlapping pulses [27]. The possibility of a collision is determined by the pulse duration with respect to its time slot, that is to say the pulse duty cycle.

Fig. 9a shows that the pulse width within the HNLF increases with the value of $N_{\text{in}}$. Interactions between adjacent pulses are therefore likely to be more severe when operating at high peak powers. We have simulated the propagation of three adjacent pulses of the same nominal peak power $P_{\text{in}}$, when operating under regime ‘B’. We have observed the fluctuations in peak power between adjacent filtered output pulses, caused by pulse-to-pulse interactions, and compared them to the pulse peak power obtained for the single pulse case. Fig. 9b summarizes the results we obtained for three different duty cycles, namely 33%, 25% and 20%. It is clear that there is a maximum $N_{\text{in}}$ value below which adjacent pulse interaction does not compromise the regeneration. These $N_{\text{in}}$ values were quantified as 10, 20 and more than 25 respectively for the three values of duty cycles that we considered. One can therefore operate at high peak powers when the pulse duty cycle is sufficiently low. However, the possibility that the incoming pulses suffer from timing jitter should also be considered, since this will further restrict the maximum $N_{\text{in}}$ value.

![Fig. 9. (a) Temporal evolution of the input pulse for various $N_{\text{in}}$ values; the bit slot occupation for 20, 25, and 33% duty cycle is also shown. (b) Variation of the peak power of three propagating pulses relative to the single pulse case as a function of $N_{\text{in}}$, for duty-cycle values of 20%, 25% and 33%.

5.4 ASE noise contribution

Having explored the design of the 2R regenerator in the absence of any incoherent noise, we take the opportunity to present some qualitative statements on the main consequences of the contribution of ASE. Firstly, the presence of in-band ASE noise will critically affect the ‘one’ pulses by introducing some distortions in the pulse shape, thereby affecting both the pulse width $T_0$ and the peak power [8]. Within reasonable limits of OSNR degradation, any
variations in the pulse width will affect the operation of the regenerator in the same fashion as was described in Subsection 5.1 above. Additionally, it is obvious that the filtering action of the regeneration system favors the elimination of ASE noise. Any in-band ASE can be rejected by operating with a large filter offset value, whereas out-of-band ASE can be rejected by placing an ASE rejection filter at the input of the HNLF [26].

5.5 Impact of the filter bandwidth

So far, we have required that the pulse width at the output is maintained the same as that at the input. However, it is possible to consider a different filter bandwidth at the output for duty cycle conversion applications [28]. A variation in the output filter bandwidth does not affect the global trends presented in Fig. 4. For a fixed fiber length, it is possible to retrieve a ‘B’-type regime by simply adjusting the filter position. For example, use of a broader (narrower) filter requires smaller (larger) filter offset ΔF, which will affect the regenerator performance by reducing (increasing) the output extinction ratio, while at the same time, the energy efficiency of the system will also be increased (decreased). However, it also needs to be appreciated that a broader (narrower) filter bandwidth will increase (reduce) the output pulse asymmetry, since a larger (smaller) amount of rippled spectrum will be allowed to pass through the filter.

6. Applying the design rules to specific optical systems

The study presented in this paper links the system parameters, such as bit rate and pulse duty cycle, to the various parameters of the regenerating system, such as the fiber properties, the required power levels and the filter offset. Using the specifications of the map presented in Fig. 4 as a starting point, it is evident that the optimum operating conditions for such a regenerator will depend on several factors, such as the available spectral bandwidth, the power budget and even the nature of the predominant impairments targeted during the regeneration process. In the discussions above we have highlighted the various performance trade-offs that have to be taken into account when designing a regenerator for a specific system. For example, taking all of the above into account we concluded that for a 33% duty-cycle a maximum N1 in value somewhere in the range 7-10 is likely to provide the best overall compromise between the different effects (see Fig. 9).

We tested the applicability of our design rules in a simulation example that considered 33% RZ Gaussian data pulses at 160 Gb/s. Note that such pulses can be generated using a source like that reported in [29], or by using simple OTDM techniques. We transmitted a 2^23-bit-long Pseudo-Random Bit Sequence with an average power of 15.5 dBm into two segments of 80 km of standard fibre with complete dispersion compensation (second and third-order). The simulation was performed by using commercial software (VPI TransmissionMaker from VPISystems). Intrachannel cross-phase modulation and four-wave mixing introduced noise into the signal, as shown in the optical eye diagram of Fig. 10 (top). The data sequence was then fed into a 2R regenerator, which was designed according to our design rules. The HNLF included in the regenerator had a chromatic dispersion D=-0.78 ps/nm-km, a nonlinearity coefficient γ=20 W⁻¹km⁻¹ and a total length L=347 m. According to Fig. 4, this regenerator operates in regime ‘B’ when the normalized output filter offset is 3.3 and N1 in is 7.75. This value corresponds to a pulse peak power P1,peak=1.92 W, or an average power of 340 mW at the input of the regenerator. We considered ideal amplification, i.e. no ASE noise within the link. Figure 10 compares the optical eye diagrams at the input and the output of the regenerator. Corresponding intensity distributions for the one- and zero- bit pulses are also plotted (as calculated at the center of the eye corresponding to the center position of the bit slot (t=0)).
The statistical data show that both suppression of the ghost pulses and reduction in the amplitude noise distribution on the ones is achieved. According to Fig. 10, the variance of the distribution of the amplitude noise is reduced by a factor of ~2. The introduction of timing jitter manifests itself by adding some asymmetry on the output optical eye diagram.

7. Conclusion

We have presented simple and generalized scaling rules for the design of 2R optical regenerators based on SPM in normally dispersive fibers. Our present study, which was restricted to the case of Gaussian input pulses and lossless fibers, has shown that the regenerator performance can be mapped onto a parameter space defined by the fiber properties (as expressed by L/L_D), and the filter offset position. Our scaling rules show how the bit-rate (pulse width) affects the system performance, and we have identified the optimal operating conditions which ensure power equalization for a broad range of incoming powers. We have also identified the trade-off that exists between performance and energy efficiency, and have examined the characteristics of the regenerated pulses under different operating conditions. A detailed extension of the study to include the effects of fiber loss is naturally of great practical interest, as is extension of the mapping concept to other pulse forms. Our initial studies in both of these directions confirm that the trends that we have identified in the present study can be extended directly to both of these cases, albeit with quantitative changes to the design maps [30]. A study of the impact of other high-order effects (e.g. Stimulated Brillouin Scattering, Stimulated Raman Scattering or Two Photon Absorption) is also likely to be of interest depending on the precise nature of the fiber host material (e.g. silica- or non silica-based).

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References and Links


