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► **To cite this version:**

Julien Fatome, Christophe Finot. Scaling guidelines of a soliton-based power limiter for 2R-optical regeneration applications. 11th International Conference on Transparent Optical Network, Jun 2009, Ponta Delgada, Portugal. pp.We.P.2, 10.1109/ICTON.2009.5185274 . hal-00470026

HAL Id: hal-00470026

<https://hal.science/hal-00470026>

Submitted on 29 Jul 2010

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Scaling guidelines of a soliton-based power limiter for 2R-optical regeneration applications

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ABSTRACT

In this work, we report scaling rules for the design of all-fibered soliton-based power limiter for reamplification and reshaping (2R) regeneration process. In particular, we propose general guidelines to fix the optimum fiber length and initial power of the regenerator. We have quantitatively pointed out the optical power limiting effect of the device enabling a significant reduction of the amplitude jitter of a degraded signal. Finally, realistic numerical simulations in the context of 160 Gbit/s signals show that an efficient improvement of signal quality could be achieved by means of such a device.

Keywords: Optical regeneration, Nonlinear optics, Optical fiber, Optical Telecommunication.

1. INTRODUCTION

With the development of long haul optical telecommunication systems working at high repetition rates (40 Gbit/s and beyond), performing an all-optical regeneration of the transmission signal has become of a great interest to combat the cumulative impairments occurring during the signal propagation and overcoming the electronics bandwidth limitations of the current devices [1]. Indeed, during its propagation, the signal undergoes various degradations such as amplified spontaneous emission noise accumulation, chromatic dispersion as well as intra-channel non-linear effects. Among all the degradations, the jitter affecting the “one”-bit level of the signal appears as the most detrimental. Consequently, it is required to limit this amplitude jitter, which can be achieved by using various optical methods taking advantage of the Kerr non-linear response of optical fibers : non-linear optical loop mirrors (NOLMs) [2], four-wave mixing [3], or self-phase modulation (SPM) in normally [4] or anomalous [5] dispersive fibers (the two latest methods being known as “Mamyshev” (MR) and “spectrally filtered solitons” respectively). Whereas many works, both experimental [3, 6] and theoretical (see [7, 8] and reference therein), have recently dealt with the possibilities of MR devices, much less studies have investigated the performances of soliton-based regenerator [9, 10].

In the present contribution, we try to partially address this lack by proposing some general theoretical guidelines to optimize the choice of the device parameters. After having described our model, we will detail several significant conclusions that can be drawn and we will discuss the advantages and drawbacks of using a soliton-based configuration compared to the now wide spread MR technique. We finally illustrate the design rules by presenting numerical simulations dealing with a RZ-25 signal at a repetition rate of 160 Gbit/s.

2. TYPICAL SET-UP AND MODEL

We consider in this section the evolution of chirp-free Gaussian pulses with a full width at half maximum (FWHM) $T_{FWHM} = 2 \sqrt{\ln 2} T_0$. A typical set-up of the soliton-based regenerator is sketched in Fig. 1(a). The incoming pulsed signal is first amplified by an Erbium Doped Fiber Amplifier (EDFA) in order to reach the adequate peak power P_{ini} . During the propagation in an anomalous dispersion fiber, the degraded signal experiences self-phase modulation (SPM) providing spectral broadening. The resulting signal is then filtered by means of a centered Gaussian optical bandpass filter (OBPF) having a spectral bandwidth F_{FWHM} directly related to the input Gaussian pulses ($F_{FWHM} = 0.441 T_{FWHM}$).

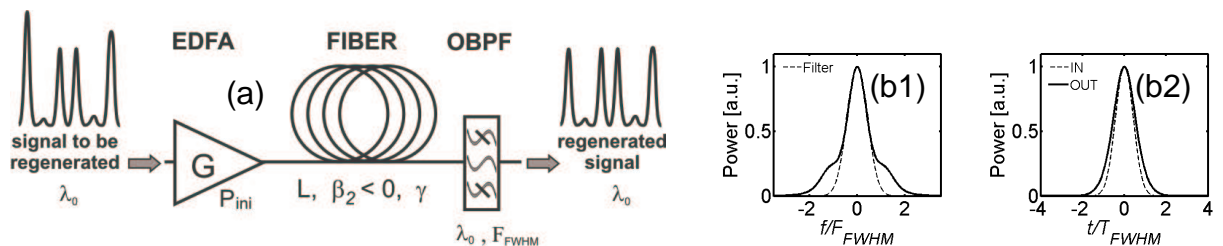


Figure 1 (a) Set-up of the soliton-based regenerator (b1) Spectrum at the output of the fiber and OBPF corresponding to the initial pulse spectrum (b2) Input and output temporal profiles.

The longitudinal evolution of the complex electric field $\psi(z,t)$ can then be modeled using the standard non-linear Schrödinger equation (NLSE) including a second order dispersion β_2 and a non-linear coefficient γ [11] :

$$i \frac{\partial \psi}{\partial z} = \frac{\beta_2}{2} \frac{\partial^2 \psi}{\partial t^2} - \gamma |\psi|^2 \psi . \quad (1)$$

In order to make our results applicable to a wide range of experimental situations (i.e. for different input temporal widths as well as for various nonlinear and dispersive fiber parameters), it is beneficial to transform Eq. (1) into the following normalized form [11] :

$$i \frac{\partial u}{\partial \xi} = - \frac{1}{2} \frac{\partial^2 u}{\partial \tau^2} - |u|^2 u, \quad (2)$$

where u , τ and ξ are the normalized parameters defined as

$$u(\xi, \tau) = N_{in} U, \quad U(\xi, \tau) = \frac{\psi}{\sqrt{P_0}}, \quad \tau = \frac{T}{T_0}, \quad \xi = \frac{z}{L_D}. \quad (3)$$

L_D , N_{in} , N_{out} and ξ_L are the dispersion length, the ‘‘soliton’’ orders, and the normalized fiber length defined as follows :

$$L_D = \frac{T_0^2}{|\beta_2|}, \quad N_{in} = \sqrt{\gamma P_{in} L_D}, \quad N_{out} = \sqrt{\gamma P_{out} L_D}, \quad \xi_L = \frac{L}{L_D}. \quad (4)$$

3. REGENERATION PERFORMANCE AND OPTICAL LIMITING PROPERTIES

In order to assess the ability of the device to efficiently perform the expected optical limiting function, a widely used parameter is the transfer function (TF) which links the input and output peak powers (or equivalently with our normalized N_{in} and N_{out} parameters). Depending on the fiber length ξ_L , we have identified that the interplay between nonlinearity and chromatic dispersion leads to three possible regimes for the TF, as graphically illustrated in Fig. 2a. For $\xi_L < 1.55$, the TF is characterized by a Rise and Fall evolution (regime ‘A’). On the contrary for $\xi_L > 1.55$, the TF become purely monotonous (regime ‘C’), which should obviously be banned for the purpose regeneration. The most interesting behavior is observed for $\xi_L = 1.55$ where the TF exhibits a locally flat region called plateau (regime ‘B’).

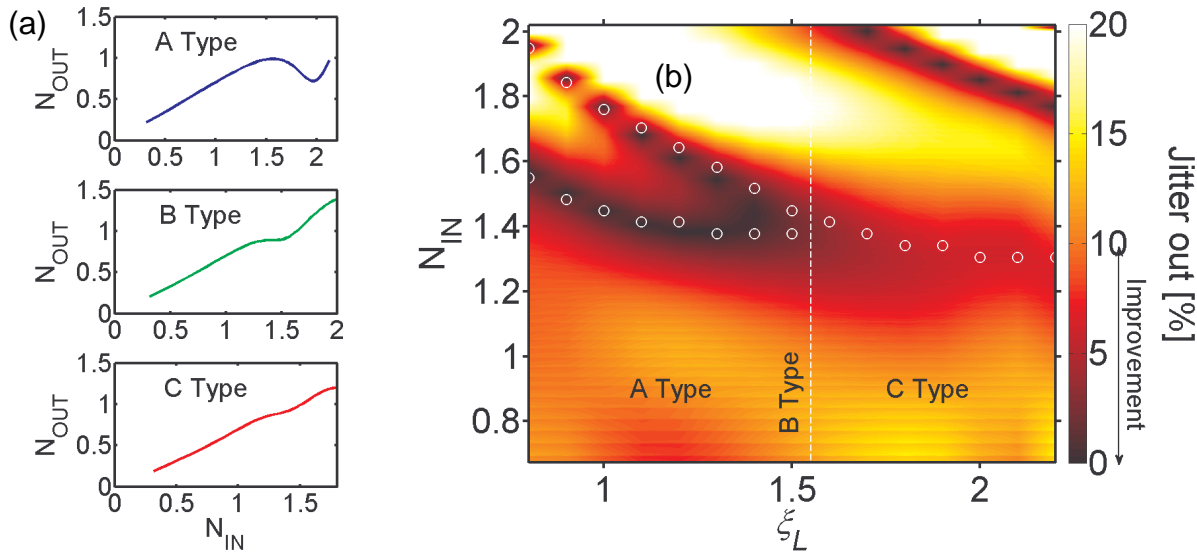


Figure 2 (a) Illustration of the three possible TF types for the soliton-based regenerator : Rise and Fall evolution (A), locally flat evolution (B) and monotonous variation (C) (b) Output signal amplitude jitter as a function of the fiber length and input peak power for an input amplitude jitter of 10%. The circles represent the inflexion points.

In order to better quantify the limiting properties of the optical device, we have computed the output amplitude jitter (defined as the amplitude of the peak power variations of the regenerated signal) for a given input fluctuation of 10% of the initial signal. Results are shown of Fig. 2b on a two-dimension map that enables us to quickly determine the optimum set of parameters. Let us note for the MR design, a more complex map was

required since an additional parameter, i.e. the spectral offset of the OBPF, had to be taken into account [8]. From map of Fig. 2b, we have found that a fiber length $\xi_L = 1.4$ combined with an initial power $N = 1.45$ gives the best amplitude jitter reduction. This also confirms that the B-shape is very well suited for regeneration. But from those measurements, we can also conclude that whereas using a C-type TF clearly provide any improvement, it can be worthy to use a A-type TF for which the non-optimum point does not translate into severe penalty. It seems on the contrary that such a kind of TF offers a range of working powers larger than B-type, which can constitute an attractive advantage in the practical design of the device.

4. IMPACT OF THE REGENERATOR ON OTHER PARAMETERS

As it has been shown in previous papers [7, 8], the impact of an optical 2R regenerator based on self-phase modulation is not restricted to amplitude jitter reduction and other pulse parameters are affected by the nonlinear propagation followed by spectral filtering. We have carried out a similar analysis as the one reported in [7, 8] where several points had been investigated in the context of MR and we compare the two configurations.

We have first investigated how the soliton-like regenerator affects the extinction ratio of the signal. For an input extinction ratio of -10 dB, the resulting extinction ratio after regeneration is -9.5 dB. In other words, our device does not provide any enhancement or degradation of this point and the transmission through the regenerator for low powers is close to linear.

We have also evaluated the temporal impact of our device. From Fig. 3, we can make out that the temporal width after the regenerator for the optimum working point is close to the initial temporal width. However, there is a slight power-dependence of this data, which may lead to some temporal width fluctuations of the regenerator. An additional potential drawback that has been highlighted in MR configurations is that the offset spectral filtering induces a delay which can potentially translate into detrimental temporal jitter [7]. As our configuration is based on central filtering, we are not affected by such a negative point.

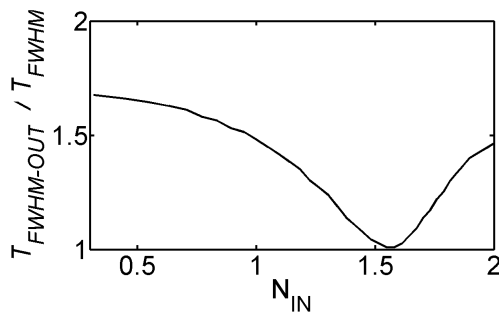


Figure 3 FWHM at the output of the regenerator as a function of N .

Other interesting differences with a device relying on a normally dispersive fiber is that in the context of soliton regeneration, the power involved in the process is significantly lower : whereas MR set-ups usually require $N > 8$ for convenient operation, N close to 1 has been found enough. Moreover, the central filtering combined with relatively modest spectral broadening leads to a very good energy yield with more than 40 % of the initial energy remaining in the filtered signal, which has to be compared with a typical yield of 10 % for MR configurations [8]. The soliton-based device is therefore much power efficient. Using lower power in the regenerator has also the additional beneficial consequence of limiting the temporal broadening of pulses before filtering and therefore to limit the nonlinear interaction between adjacent pulses of a sequence so that patterning effects that have been observed in Mamyshev regenerators are avoided.

5. REGENERATION OF A 160 Gbit/s SIGNAL

In order to validate our proposed design rules, we have tested the present regenerator on a 160-Gbit/s 1.5-ps pseudo-random bit sequence (PRBS) degraded after propagation into a 500-km long dispersion-managed transmission line. Figure 4a illustrates the resulting degraded signal. We can observe a large amplitude jitter calculated to be 14% (rms value) of the average peak-power. The regenerator is made of a highly nonlinear fiber (HNLF) having the following parameters, $D = 0.7$ ps/nm/km, $\gamma = 10.5$ /W/km and $L = 1$ km ($\xi_L = 1.3$).

Figure 4b represents the calculated rms amplitude jitter at the output of the regenerator as a function of the input average power. We can achieve a huge decrease of the intensity fluctuations with an optimum working power of 14.6 dBm for which the output jitter is then reduced to only 4.7%. Moreover, as shown by the statistical distribution of the amplitude peak-power, the extreme events of peak-to-peak variations are reduced from more than 40% to less than 20% of the average peak-power. The resulting regenerated eye-diagram is plotted in Fig. 4c and shows a very good improvement of the signal quality with a clear eye opening, corresponding to an increase of the usual Q-factor from $Q=8$ to $Q=27$ at the output of the regenerator.

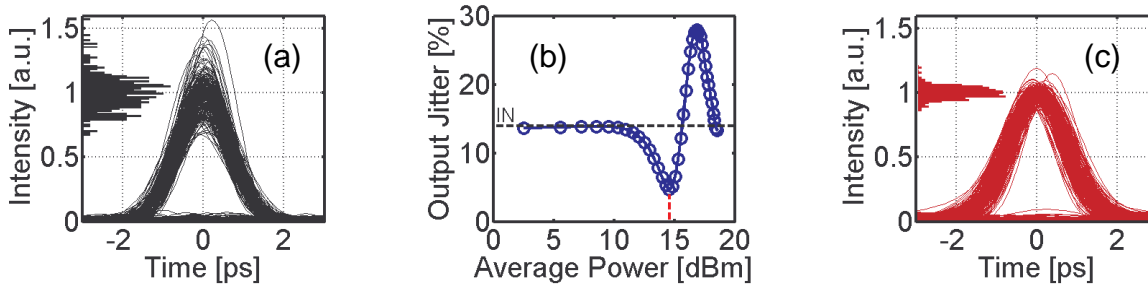


Figure 4 (a) Input degraded signal (b) Output rms amplitude jitter as a function of average power (c) Output signal for an average power of 14.6 dBm.

6. CONCLUSIONS

We have numerically studied the performance of a regenerator based on the spectral centered filtering of a signal broadened in an anomalous dispersive fiber. We have proposed general guidelines to find the optimum fiber length and initial power of the regenerator and we have quantitatively pointed out the optical limiting features of the device enabling a significant reduction of the amplitude jitter of a degraded signal. Results have been assessed by realistic numerical simulations in the context of 160 Gbit/s signals.

Compared to existing techniques such as Mamyshev techniques, the present approach does not provide any extinction ratio enhancement of the data. However, this noticeable drawback can be quite easily overcome by an additional stage based on a saturable absorber [1], which have now become suitable for high speed signals up to 160 GHz [12]. We have also shown that this approach presents several beneficial features, such as improved yield or the absence of additional timing jitter in the process. Moreover, compatibility with wavelength multiplexed signals has already been investigated [9] and can also benefit from bidirectional schemes [6].

We would like to thank T. Chartier and T. Nguyen for fruitful discussion. This work has benefited from the financial support of the Agence National de la Recherche (FUTUR and PERSYST II projects).

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