All-Optical Function Based on Self-Similar Spectral Broadening for 2R Regeneration in High-Bit-Rate Optical Transmission Systems

Leila Graini

Abstract—In this paper, we demonstrate basic all-optical functions for 2R regeneration (Re-amplification and Re-shaping) based on self-similar spectral broadening in low normal dispersion and highly nonlinear fiber (ND-HNLF) to regenerate the signal through optical filtering including the transfer function characteristics, and output extinction ratio. Our approach of all-optical 2R regeneration is based on those of Mamyshev. The numerical study reveals the self-similar spectral broadening very effective for 2R all-optical regeneration; the proposed design presents high stability compared to a conventional regenerator using SPM broadening with reduction of the intensity fluctuations and improvement of the extinction ratio.

Keywords—All-optical function, 2R optical regeneration, self-similar broadening, Mamyshev regenerator.

I. INTRODUCTION

THE "all-optical" functions for 2R regeneration allow to avoid the bandwidth bottleneck of optical-electrical-optical conversions. All-optical 2R regenerators are generally formed of an optical amplifier followed by a nonlinear optical gate [1]. Optical nonlinearities play an important role in the appearance of these "all-optical" functions. The key advantage lies in the instantaneous (femtoseconds) response of the Kerr nonlinearity, making them very attractive for ultra-high bit rate operation (beyond 160 Gb/s) [2]. All-optical 2R regeneration technique based on self-phase modulation (SPM) and band-pass filtering was proposed by Mamyshev [3] and, is currently considered one of the most promising technique in the optical signals regeneration due to its relative simplicity and potential low-cost implementation; this led to a large number of works shown the feasibility of this technique [4]-[6]. These have concentrated on optimizing the parameters of Mamyshev regenerators, trying to use highly nonlinear fibers as well as combining with other techniques to improve the regenerator's performance. A significant evolution of this concept consists of combining the contribution of similariton pulses with this technique [7]. A similariton (also called self-similar pulse) is an ultra-short pulse that has a parabolic intensity shape and propagated in a self-similar manner which makes it resistant to wave breaking inside the fiber optics, as well chirp linearity, and a flat and broad spectrum [8]. This device is called active Mamyshev regenerator [9], in which the

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potential efficiency and advantages of this regenerator were evaluated by combining Raman amplification to generate similariton pulses; the input power of the regenerator was strongly reduced with a large improvement of the output power. It should be noted that amplification is useful for increasing the energy efficiency of the regenerator which is considered a highly dissipative device. It is in this context that we propose to evaluate the potentialities of similaritons generating in a photonic crystal fiber (PCF) due to its high nonlinearity and low normal dispersion to improve the design of all-optical function for 2R regeneration in high bit rate transmission systems without electrical conversion. We present the improvements that can be expected on the transfer function of the nonlinear optical gate.

II. DESIGN RULES OF ALL-OPTICAL FUNCTION FOR 2R REGENERATION

The quality of the regeneration will depend strongly on the basic principle used and the architecture of the regenerator. The non-linearity of its transfer function (TF) allows to evaluate its regenerative potential. So, the determination of the regenerator TF in which describes the evolution of the output power according to the input power and the impact of the different elements on this one are the starting points to ensure the adaptation to the regeneration. A TF in the form of a step (ideal TF) is often the goal; such a function is determined by a system of two equations:

$$S = \begin{cases} P_{out} = 0 & \text{if } P_{in} < P_{CR} \\ P_{out} = 1 & \text{if } P_{in} > P_{CR} \end{cases} \quad (1)$$

where P_{CR} represent the critical power of the signal determined from the following condition:

$$\frac{\Delta f \left(P_{CR} \right)}{2} = \Delta F \quad (2)$$

with, Δf is the spectral width of the broadened spectrum, and ΔF is the spectral shift of the filter in the case of Mamyshev regenerator.

In order to get as close as possible to (1), several simple rules have been proposed to design Mamyshev regenerators [10]. The purpose of the rules is to obtain the TF with S-shape as shown in Fig. 1.
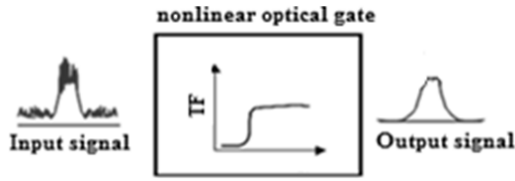
Fig. 1 Nonlinear optical gate for 2R regeneration

The all-optical 2R regeneration of Mamyshev technique based on SPM consists of broadening the optical signal by the non-linearity effect (SPM) occurring in highly nonlinear and normal dispersion fibers and then spectrally filtering by a bandpass filter optical whose center frequency is shifted with respect to the input signal frequency. So, when high power pulse (''1''bits) passes through the optical fiber, the SPM widens the spectrum of the optical signal, they are therefore transmitted by the filter producing regeneration of ''1'' bits. At the same time, noise in ''0'' bits, due to its small power, undergoes linear propagation without spectral broadening and is, therefore, rejected by the off-centered filter, producing regeneration of ''0'' bits. The regenerator configuration consists of an initially amplifier (EDFA) in order to reach the adequate peak power required for spectral broadening within the optical fiber (Fig. 2).

In the Mamyshev regenerator, all the parameters of the regenerator such as the signal (waveform, pulses duration, and the initial energy), fiber (dispersion, length, non-linear coefficient γ, losses), and the filter (frequency offset ± ΔF/± Δλ, and bandwidth δf/δλ) could modify the TF shape of the nonlinear optical gate of the regenerator and therefore affect the efficiency of it and decreases the device stability [3]. A precise knowledge of the parameters of the regenerator is therefore required to allow a signal improvement.

Our approach consists of spectrally broadening the initial optical signal in a highly nonlinear and low normal dispersion PCF under the effect of self-similar amplification. This method allowed the generation of a power, flat and broad similariton spectrums reducing then the input power and the fiber length that are required as well as improved the output power [11], [12] whereas a broadening spectrum by the SPM effects is usually accompanied by oscillatory structures [13] and requires very high input optical powers and several hundred meters of fiber.
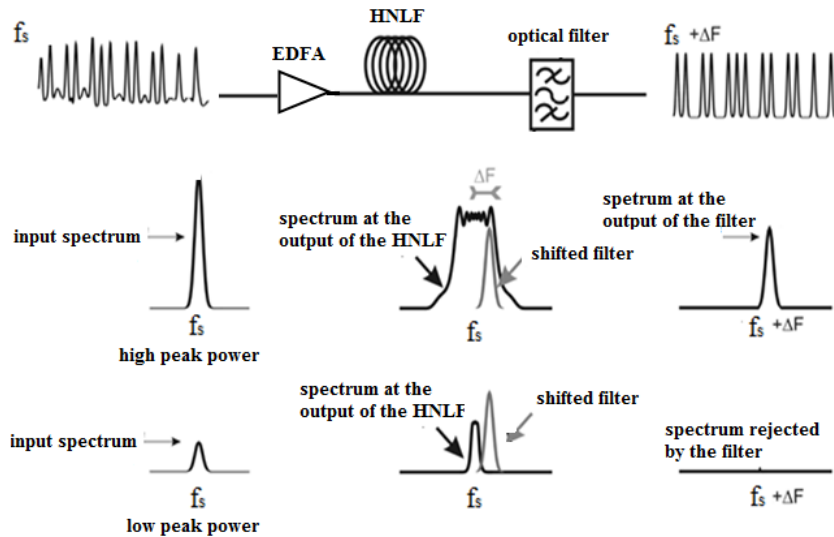

Fig. 2 The Mamyshev regenerator

Similariton pulse is result of interaction between normal dispersion, SPM and gain. Similariton is asymptotic solutions of the nonlinear wave equation with gain expressed in the following form [8]:

$$i \frac{\partial A}{\partial z} = \frac{\beta_2}{2} \frac{\partial^2 A}{\partial t^2} - i\gamma |A|^2 A + \frac{g}{2} A \qquad (3)$$

where A is the slowly varying amplitude of the pulse, α is the attenuation, β_2 is the second order dispersion and γ is the nonlinear coefficient of the fiber, and g is the distributed gain coefficient.

Considering that the pulse profile of the optical signal is of Gaussian shape, the electric field A (0, t) corresponding to such a pulse can be expressed in the following form:

$$A(0, t) = \sqrt{P_0} \exp\left(-t^2 / 2T_0^2\right) \qquad (4)$$

where P_0 is the peak power of the input pulse and T_0 is the temporal width.

The critical power of the signal P_{CR} gives for a self-similar broadening determined from the following condition:

$$P_{CR} = \left(2\pi.\Delta F\right)^{1/3} \left(\frac{2.\beta_2^2.T_0.L}{\gamma.G.\log G}\right) \qquad (5)$$

with [13]:

$$\Delta f = \frac{1}{\pi}\left(\frac{g\gamma E_{in}}{2\beta_2^2}\right)^{1/3} \exp\left(\frac{gL}{3}\right) = \frac{1}{\pi}\left(\frac{\gamma G E_{in} \log G}{2\beta_2^2 L}\right)^{1/3} \quad (6)$$

where G is the gain coefficient depend on the linear gain g by: $G = 10.\log(g)$, and E_{in} is the initial energy.

The self-similar spectral broadening and the optical similariton have the advantage of being independent of the initial shape of the signal pulses, and depend only on the initial energy (input power) [4], and the parameters of the fiber used for the regeneration. As these parameters are already known by our choice of the PCF used for the spectral broadening by the similariton amplification [12], it remains only the study of the effect of the optical filter parameters on the TF shape. This study consists of the research of the optimal position of this filter, in terms of the offset frequency with respect to the center frequency of the signal, and, of its form, that is to say for a Gaussian filter, its bandwidth. So the use of similariton depends on few parameters, which increases the stability of the regenerator.

For a Gaussian bandpass optical filter, its TF is:

$$H(\omega) = \exp\left(\omega - \omega_0\right)^2 / \delta\omega^2 \quad (7)$$

where ω_0 the central frequency ($\omega_0 = 2\pi f_0$) and $\delta\omega$ the bandwidth ($\delta\omega = 2\pi.\delta f$) are the two parameters that can be chosen to optimize the regenerator efficiency.

We then demonstrate the improved design of the TF of the nonlinear optical gate based on self-similar spectral broadening and the impact of the filter parameters on its efficiency in order to identify the parameters that optimize the regenerator performance. To do this, we use the similariton amplifier generated in a PCF with low normal dispersion coefficient of $D = -0.8$ ps/(nm·km) and non-linear parameters of $\gamma = 51$ [W·Km]$^{-1}$ as those used in [14], with the chosen values for the amplification gain of $g_0 = 0.6$ m^{-1}, and for the PCF length of L= 30 m [12].

The TF curves of the nonlinear optical gate based on self-similar broadening are shown in Fig. 3. These curves are obtained by numerical solution of the nonlinear Schrödinger equation with gain (3) for a Gaussian pulse. The evolution of the output peak power as a function of the initial peak power is calculated for three different spectral offset values of the filter. By utilizing an output filter with the same shape and the same band-pass as the input pulses $\delta f = 180$ GHz, the TF shape is an "S'' form and exhibiting two plateaus allows noise reduction on both "1''and ''0'' bits and can regenerate the incoming signal. However, the frequency of the regenerated signal is shifted to the new frequency of $\Delta F = 260$ GHz.

In the first plateau, the output power is constant over a range of initial power around of 1.5 W which results in a decrease in the intensity fluctuations in the '1' bits (amplitude jitter) and therefore, the regenerated pulses have the same amplitude. The second plateau defines the threshold power

which makes it possible to reduce the noise in the '0' bits, and consequently the energy contained in the '0' bits and the ghost pulses must be suppressed. Therefore, only pulses with power equal to or greater than a threshold power (0.15 W) pass through the shifted filter.
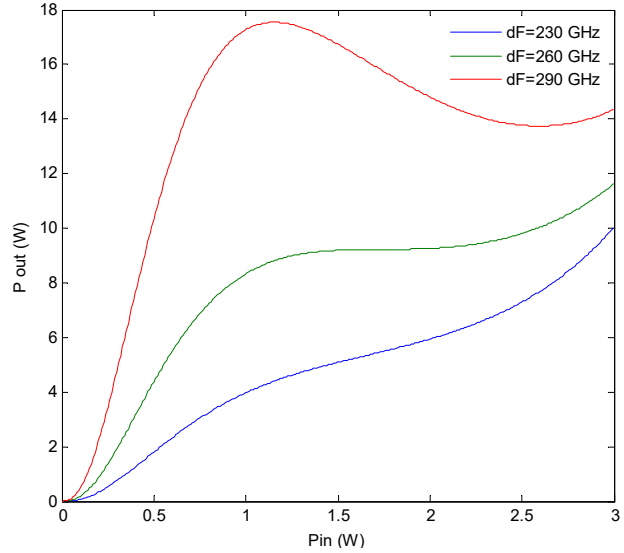

Fig. 3 TF for $\delta f = 180$ GHz and three different values of spectral shift of the filter
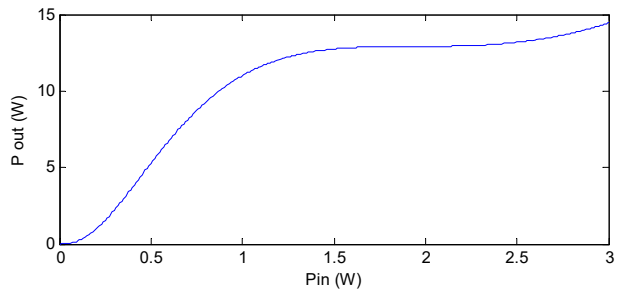

Fig. 4 TF for $\delta f = 200$ GHz and $\Delta F = 450$ GHz

Given the power dependence with the filter shift, we take note that when the filter is more shifted the noise reduction on the "0" bits are better. On the other hand, the power required is greater to have an important spectral broadening. So a compromise between the noise reduction on the "0" bits and the cost of the device must be taken into consideration. We also note that we can obtain an "S'' shape of the FT with a plateau around of a power of 2W if we adjust both parameters of the filter at once. Fig. 4 is given for $\delta f = 200$ GHz and $\Delta F = 450$ GHz, as it can be seen that when the spectral width of the filter is increased, the output power of the signal is increased too. On the other hand, the spectral width of the filter determines the pulse duration of the generated signal, the temporal width of the pulses is decreasing at the output of the filter when the bandwidth increases. So, the choice of a filter with spectral width wider than that of the initial signal can be used to realize a pulse compressor [15].

III. Concept of the Proposed 2R Regenerator

Using the improved TF listed above, we design an all optical 2R regenerator capable of regenerating an optical RZ-format signal with a repetition rate of 40 Gb/s at the wavelength of $\lambda_0 = 1550$ nm based on the similariton amplifier as shown in Fig. 5. An optical passband filter of spectral width of $\delta f = 200$ GHz ($\delta\lambda = 1.6$ nm) and whose offset is shifted by $\Delta F = 450$ GHz ($\Delta\lambda = 15553.68$ nm) with respect to the center frequency of the carrier signal f_0 ($f_0 = c / \lambda_0$) is placed after the similariton amplifier in 30 m PCF fiber and a pump laser to induce Raman amplification allowed the incoming signal pulses formation into similariton pulses [12].
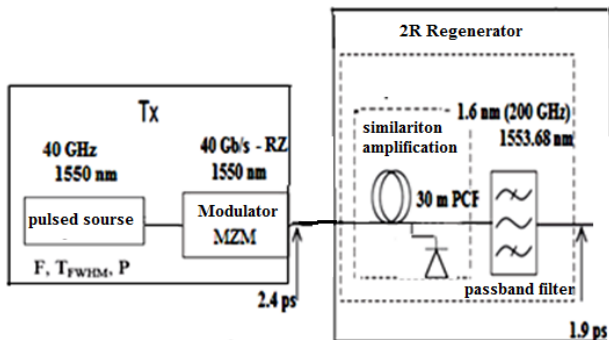

Fig. 5 2R regenerator configuration based on self-similar broadening

Considering the optical signal constitutes train of Gaussian pulses of durations $T_{FWHM} = 2.4$ ps, with two peak power values $P_{01} = 2$ W, and $P_{02} = 1$ mW, which corresponds to a '1' bit and a '0' bit respectively.

The initial pulses with peak power value of $P_{01} = 2$ W, which corresponds to a '1' bits are transformed into an optical similariton train with a broad and flat spectrum during propagation in the 30 m PCF (Fig. 6 (a)) subsequently spectrally filtered around the frequency F_f. The signal is seen to be spectrally shifted with respect to its initial frequency f_0 (Fig. 6 (b)). As a result, the frequency F_f is defined by: $F_f = f_0 + \Delta F$ ($\lambda_f = \lambda_0 + \Delta\lambda$), the spectral width of the regenerated pulses is then equal to the spectral width of the optical filter which is greater than the initial spectral width δf ($\delta\lambda$), and the time duration of the regenerated pulses is smaller than the time duration of the initial pulses (1.9 ps at $\lambda_f = 1553.68$ nm) with output peak power value of 13 W as shown in Fig. 6 (c). This power corresponds to the plateau of the TF shown in Fig. 4. This configuration serves to make a first stage of the regenerator as a pulse compressor whose interest is to eliminate the effect of intersymbol interference in the regenerator [3] and to reduce the Brillouin effect in the fiber [4].

Note that the pulses with input peak power value of $P_{02} = 1$ mW correspond to the noise in ''0'' bits, due to its small power, undergoes linear propagation in the PCF without spectral broadening under similariton amplification and is, therefore, rejected by the off-centered filter, In addition, these simulations also showed the possibility for large spectral widening by self-similar broadening, a spectral bandwidth of about 70 nm is produced (Fig. 6 (a)) with good flatness in the center of the spectrum reducing the power variations (amplitude jitter) between the regenerated pulses induced by Mamyshev regenerator and appears on the pulses of the output signal [3], [16]-[18]. Indeed because of the spectrum ripples due to the SPM broadening and the position of the optical filter with respect to these ripples the pulses of different peak powers are not extracted at the same time of the regenerator, leading then to a time jitter of the regenerated pulses which varied depending on the incoming pulse power. Also, these ripples could lead to the power variation of the regenerated pulses. So, the spectral filtering of the similariton spectrum can enhance the capacity of the regenerator.

Note that the proposed method implies a conversion of the wavelength of the initial signal that may be a disadvantage when it is desirable to have a regeneration function transparent to the wavelength. In order to overcome this wavelength conversion, it is possible to cascade two regenerators having an opposite frequency offset; double-stage configuration [3]. Indeed, the proposed configuration makes it possible to reduce the number of amplifiers required with respect to a conventional regenerator by using similariton amplification at the first stage; the high peak power of these pulses induces sufficient spectral broadening in the second stage.

To investigate the performance of the proposed regenerator to eliminate the ghost pulses in the ''0'' bits, and to reshape the pulses in the ''1'' bits, a simulation model is used. In this model light from pulsed source at 1550 nm is carved into 50% RZ pulses and modulated (modulator extinction ration of 8 dB) by 40 Gb/s a pseudo random bit sequence (PRBS) pattern. Amplitude jitter of the input signal is artificially degraded. Fig. 5 illustrates the schematic block diagram model for regeneration simulation.

Fig. 7 shows the regeneration of a degraded signal with strong fluctuations of the "1" bits. Ghost pulses are clearly visible in the "0" bits of the input signal which lead to reducing the extinction ratio of the signal. At the input of the regenerator, the initial extinction ratio was 8.5 dB. After passing through the regenerator, the quality of the signal is clearly improved with a suppression of the noise on the '0' bits as well as the ghost pulses. With regards to amplitude jitter, the improvement is also remarkable. We get a near perfect reshaping of the degraded signal. The square root of the initial amplitude jitter has indeed been estimated at 25% of the initial peak power at the input of the regenerator. This value is decreased by up a 3% after regeneration. The output extinction ratio of the regenerated signal is then 20.6 dB.

IV. Conclusion

Nonlinear effects in fiber are almost instantaneous which makes optical function based on the fiber devices very attractive for high bite rate optical transmission systems. However, despite the rise of special fibers called microstructured, they are still not very compact and require high powers. To overcome this inconvenience, we have developed an all-optical function for 2R regeneration device based on the Mamyshev regenerator combined with the

contributions of similaritons generated in microstructured fibers of PCF-type. The numerical study implemented in this article reveals the optical similariton very effective for all-optical 2R regeneration. The use of similariton depends on few parameters, which increase the device stability and allow to improve the output extinction ratio of the optical signal, to suppress the ghost pulses in '0' bits and to reduce intensity fluctuations in '1' bits as like as the amplitude jitter.

(a)

(b)
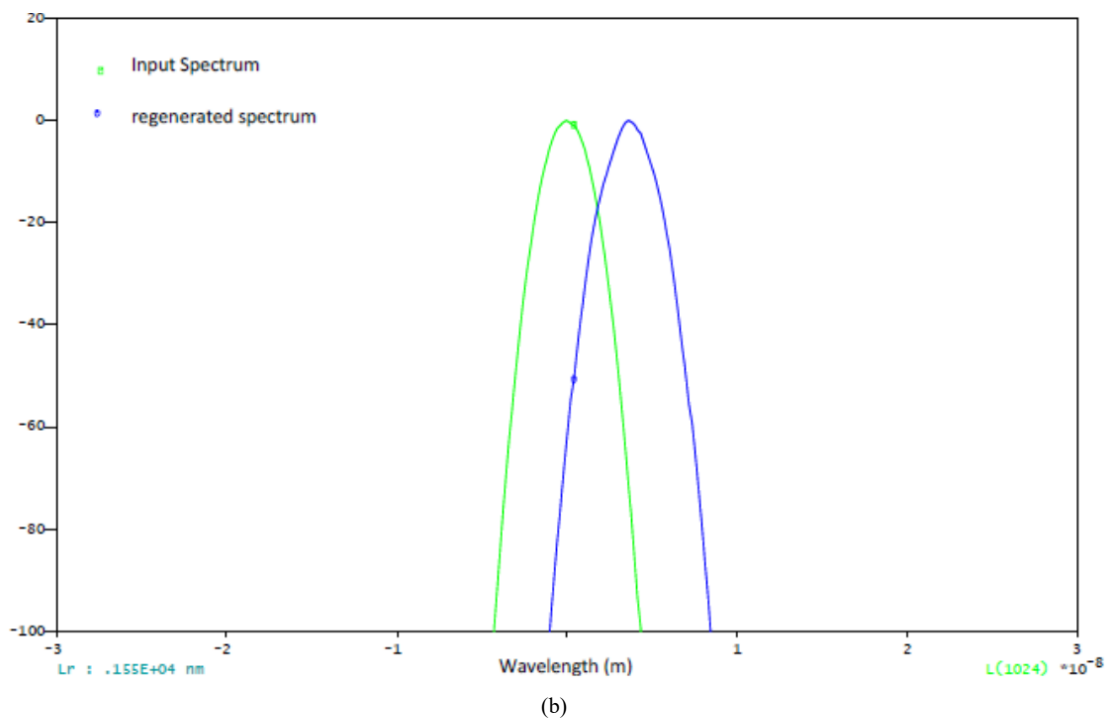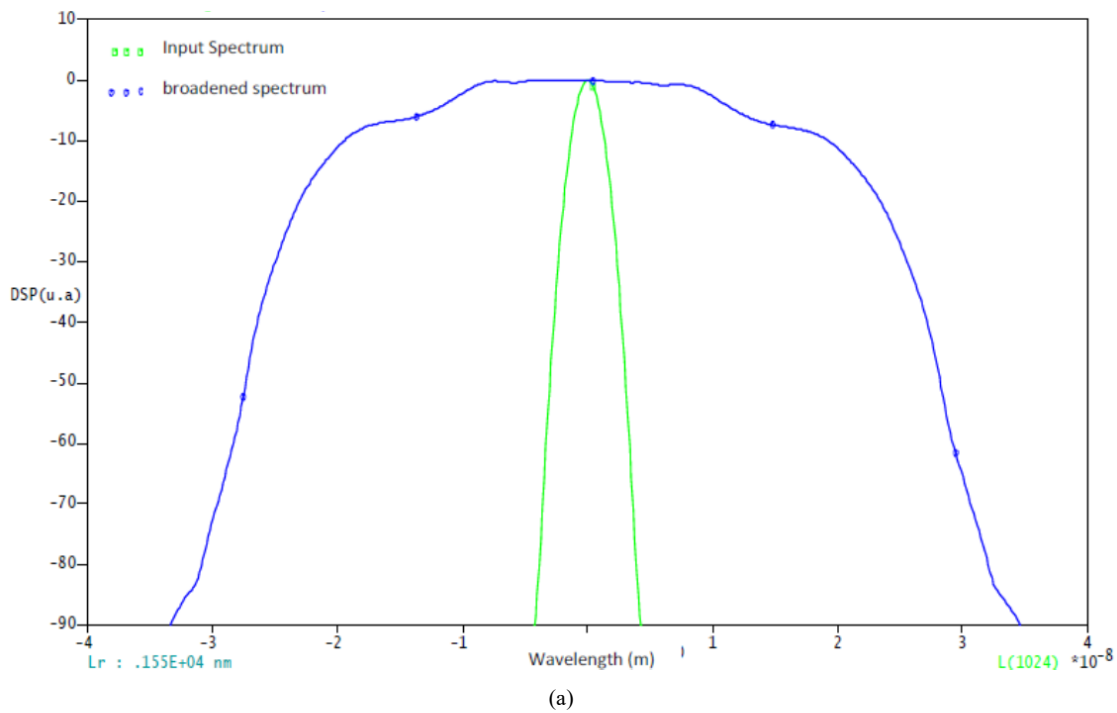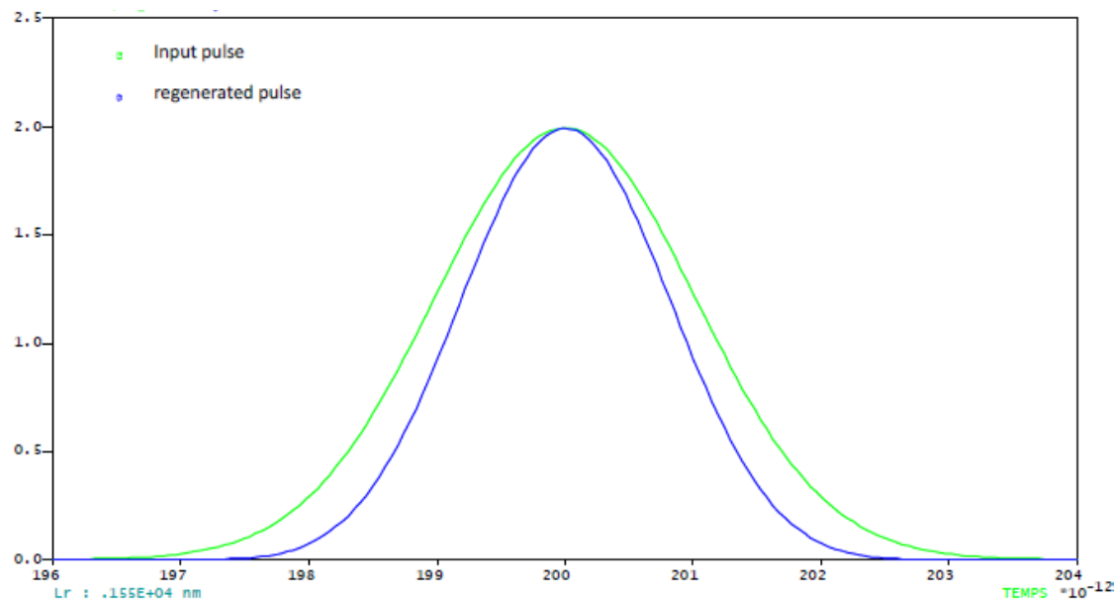
(c)

Fig. 6 Regeneration of pulses based on self-similar broadening: (a) Spectrum of the incoming pulses for P = 2 W (green line), and the broadening spectrum by similariton amplification (blue line), (b) Spectrum of the incoming pulses (green line) and of regenerated pulses (blue line), and (c) Waveform of the incoming pulse (green line) and of regenerated pulse (blue line)
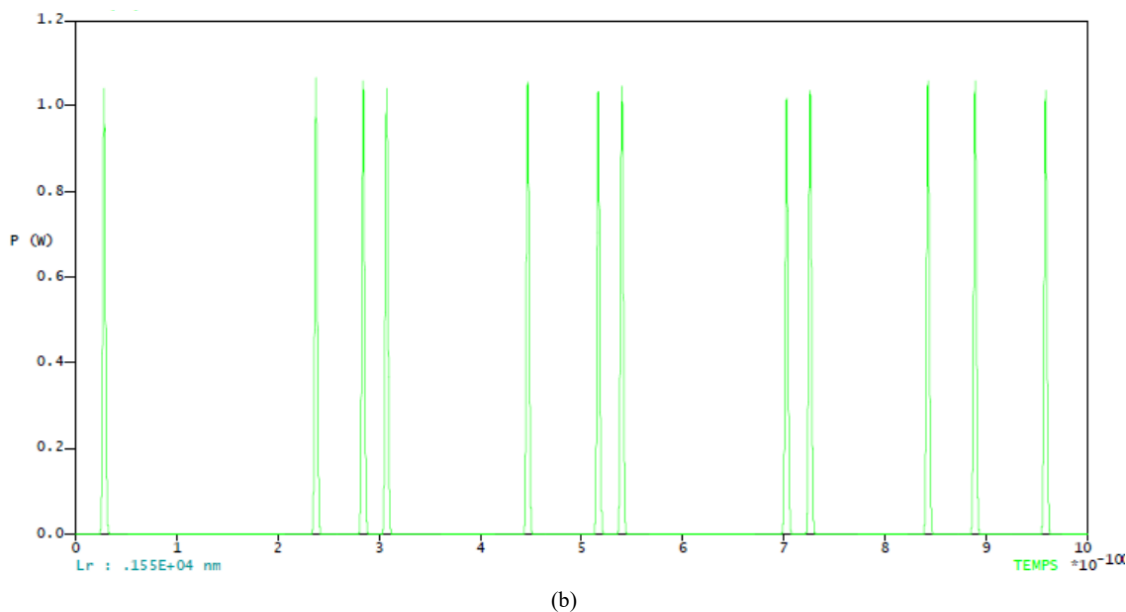

(a)

(b)
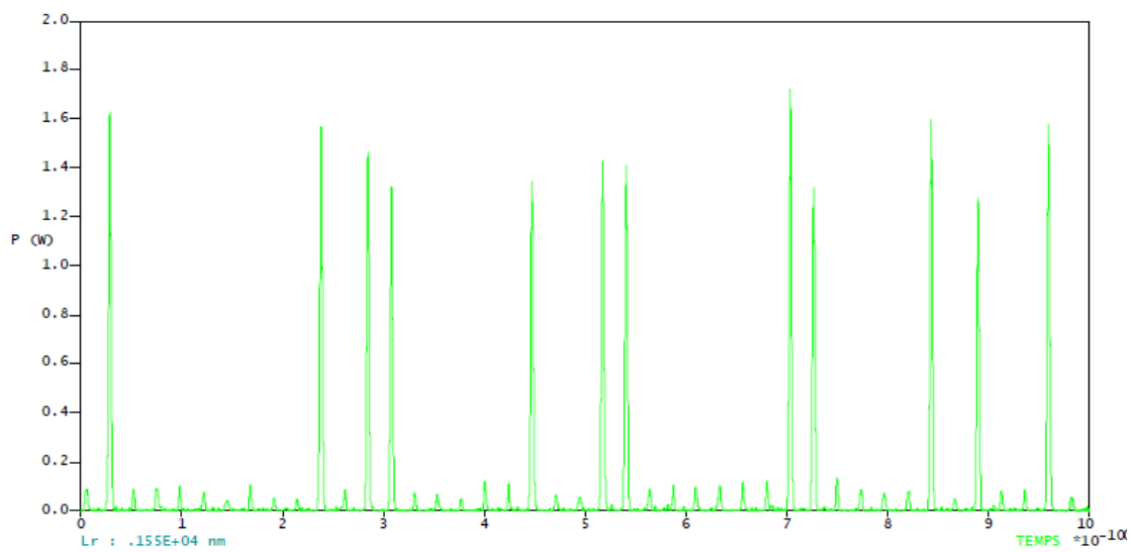
Fig. 7 Regeneration of a degraded optical signal, incoming signal (a), and regenerated signal (b)

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