All-optical signal regeneration by temporal slicing of nonlinearly flattened optical waveform

Sonia Boscolo and Sergei K. Turitsyn

Photonics Research Group, School of Engineering and Applied Science,
Aston University, Birmingham B4 7ET, United Kingdom

ABSTRACT

A novel all-optical time domain regeneration technique using nonlinear pulse broadening and flattening in normal dispersion fiber and subsequent temporal slicing by an amplitude modulator (or a device performing a similar function) is proposed. Substantial suppression of the timing jitter of jitter-degraded optical signals is demonstrated using the proposed approach.

Keywords: All-optical regeneration, nonlinear pulse broadening and flattening, temporal gating/slicing

1. INTRODUCTION

All-optical signal regeneration utilizing fibre Kerr nonlinearity has a potential of ultrahigh-speed operation and might become an important technology in future high-speed long-distance signal transmission and terrestrial photonic networks. A number of different all-optical regeneration techniques based on the fundamental nonlinear physical phenomena in optical fibers have been recently proposed. A regeneration scheme based on the utilization of signal spectral broadening due to nonlinear self-phase modulation effect has been suggested in Ref. 1. In this approach, the regeneration function is realized through a combination of spectrum broadening (e.g., near the fiber zero dispersion point or in a normal dispersion fiber (NDF)) and subsequent off-set optical filtering.[1,2] Another method to exploit fiber nonlinearity in regeneration is to use return-to-zero (RZ) signal conversion to soliton pulses in an anomalous dispersion fiber, again in a combination with optical filtering.[3,4] Also recently, the use of Kerr nonlinearity in an NDF has been addressed as a technique to reduce the effect of timing jitter at an RZ optical receiver.[5] A nonlinear pulse processor combining the intensity filtering action of a nonlinear optical loop mirror (NOLM) for signal reamplification and cleaning up with the Kerr effect in an NDF for phase margin improvement has been studied in Ref. 6.

In this paper, we propose a novel all-optical regeneration technique to suppress the timing jitter of the optical pulses. In our approach, the nonlinear mechanism that leads to the formation of parabolic pulses and resulting flattening of the signal waveform is used in all-optical 3R (reamplification, reshaping, retiming) regeneration. The method is based on nonlinear temporal pulse broadening and flattening in an NDF and subsequent slicing of the pulse temporal waveform by a modified synchronous AM (or any other device that can perform this function). The efficiency of the proposed regenerator is numerically demonstrated by application to 40 Gbit/s RZ data signals.

2. IDEA FOR THE METHOD

The proposed regenerator consists of an optical amplifier, a section of NDF, and an AM, as illustrated in Fig. 1. Qualitatively, the idea for the method is as follows. An optical pulse incoming to the regenerator is first amplified by the optical amplifier in order to enhance the effect of nonlinearity in the NDF. During transmission along the NDF, the temporal waveform of the pulse is changed to a rectangular-like profile by the combined action of group-velocity dispersion and Kerr nonlinearity.[7] As a result, the pulsewidth is broadened and the center portion of the pulse changes to be flat. By utilizing this property, the phase margin of an RZ pulse train is improved,[5] and consequently, the influence of the displacement of pulse position in time caused by timing jitter

S. Boscolo: E-mail: boscolsa@aston.ac.uk
S. K. Turitsyn: E-mail: s.k.turitsyn@aston.ac.uk

ICONO 2005: Nonlinear Optical Phenomena, edited by Konstantin Drabovich, Vladimir Makarov,
Yuen-Ron Shen, Proc. of SPIE Vol. 6259, 62590J, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.677881

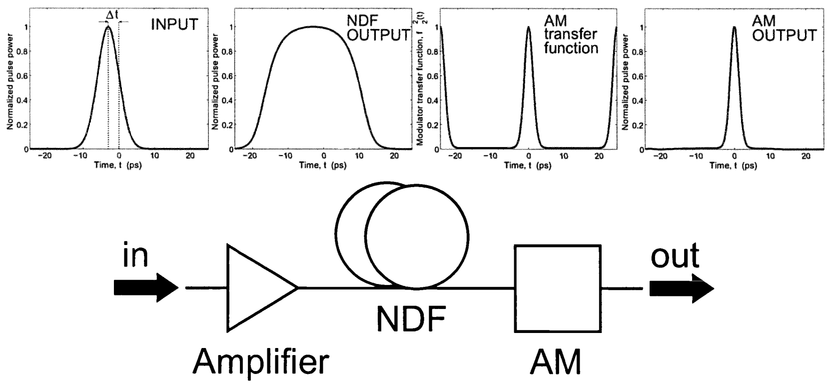

Figure 1. Schematic diagram of the proposed regenerator.

is reduced. Indeed, broadening of the pulsewidth to approximately a bit duration causes the center of mass of the pulse portion contained in the bit slot to move towards the pulse top, where timing jitter is less than in the tails as a result of flattening of the pulse envelope. Following the NDF, the pulse enters the AM. The AM retimes the pulse and acts as an optical gate in slicing the center portion of the broadened pulse temporal profile. This effective discrimination of the pulse tails against the center portion enables efficient suppression of the timing jitter of a pulse train. The pulsewidth and the shape of the output pulse from the AM are determined by the AM transfer function. The transfer function of a conventional AM may be written as[8] (see Fig. 2, dashed curve)

$$f_1(t) = \left\{ \frac{1}{2} \left[1 + x^2 + (1 - x^2) \cos\left(\frac{2\pi(t - t_0)}{T} \right) \right] \right\}^{1/2}, \tag{1}$$

where x is the extinction ratio, t_0 is the center of the modulation, and T is the bit period. In order to enhance the optical gating effect of the AM, we propose here a specially designed nonlinear transfer function given by (see Fig. 2, solid curve)

$$f_2(t) = x + (1 - x) \cos^{2m}\left(\frac{\pi(t - t_0)}{T} \right), \quad m = 1, 2, \ldots \tag{2}$$

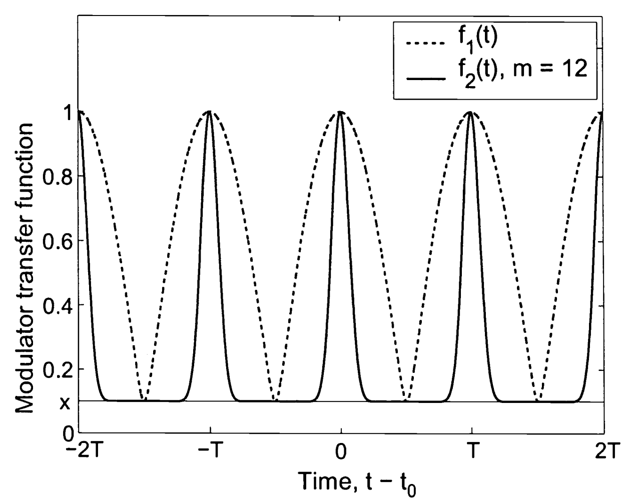

Figure 2. Standard and modified modulator transfer functions.

Here, parameter m controls the degree of narrowing and sharpening of the modulation peaks and, thus, the degree of slicing of the pulse temporal profile. Obviously, other devices with linear/nonlinear transfer functions may be used for temporal slicing. As an example, a NOLM provided with a clock could be used for this purpose. Such a gate would provide a different nonlinear transfer function from the one in Eq. (2), but would have the same essential properties of f_2 in that it would open a narrow window in time with periodicity T.

3. MODELLING RESULTS

In the sample system used for demonstration of the technique, the amplifier is an erbium-doped fiber amplifier with a noise figure of 4.5 dB. The NDF is 0.5 km long, and has a dispersion of $-20\,\mathrm{ps/(nm\,km)}$, a nonlinear coefficient of $4.28\,(\mathrm{W\,km})^{-1}$, and an attenuation of 0.24 dB/km. As a typical illustrative input for the proposed regenerator, without loss of generality, we use 40 Gbit/s pseudorandom RZ single-channel pulse trains of length $N = 1024$ after transmission in a system whose transmission performance is severely limited by timing jitter.[9] This presents a good model situation to demonstrate the action of the regenerator. The input full-width at half-maximum (FWHM) pulsewidth is approximately 7 ps. The timing jitter Δt of a pulse train is calculated as the average over all marks in the pattern of standard root-mean-square time position characteristics,[10] where the integration for each logical one is performed over the corresponding bit timing slot,

$$\Delta t = \left[\frac{1}{N}\sum_{i=1}^{N}(T_i - \langle t\rangle)^2\right]^{1/2}, \quad t_i = \frac{\int_{-T/2}^{T/2}\mathrm{d}t\, tP_i(t)}{\int_{-T/2}^{T/2}\mathrm{d}t\, P_i(t)}, \quad T_i = t_i\frac{\langle P_i\rangle}{\langle P_{\mathrm{tot}}\rangle}, \quad \langle t\rangle = \frac{1}{N}\sum_{i=1}^{N}T_i. \tag{3}$$

In Eq. (3), t_i is the time position of the center of mass of the i-th bit in the pattern, $P_i(t)$ is the instantaneous optical power of the i-th bit, $\langle P_i\rangle$ is the average optical power of the i-th bit, $\langle P_{\mathrm{tot}}\rangle$ is the average power of the pattern, and the weighted center of mass T_i accounts for discrimination of the zero bits against the one bits. To account for more statistical realizations, Δt is averaged over four pseudorandom pulse trains. The calculations are made for the optical field filtered by a Gaussian optical filter to limit the bandwidth of the amplified spontaneous emission noise. Transfer functions (1) and (2) are used for the AM. The modulation peak t_0 in (1), (2) is set to the average time shift $\langle t\rangle$ of the pulses incoming to the AM, which is here approximately zero.

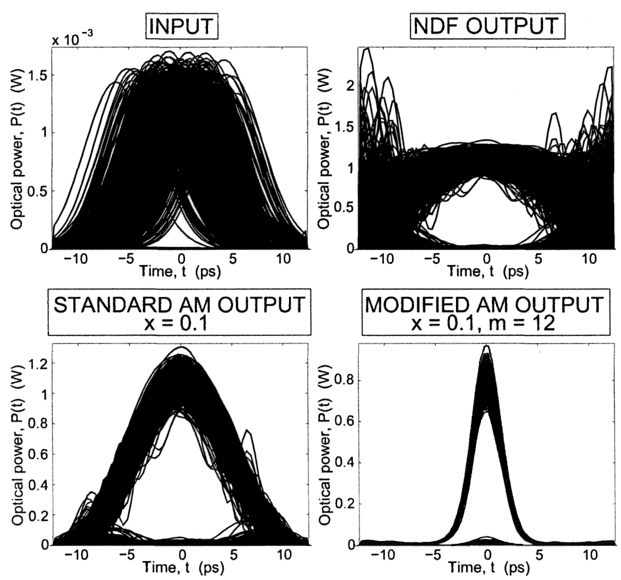

Figure 3. Optical eye-diagrams in the regenerator.

Figure 3 shows the optical eye-diagrams at the regenerator input, the NDF output, and the regenerator output when both the conventional AM (1) and the modified AM (2) are used. In this example, x is set to 0.1, $m = 12$ in (2), and the gain of the amplifier is 34.2 dB. The eyes are generated from a single pulse train. It can be seen that the input eye is closed mainly due to a significant timing jitter of the optical pulses. The evaluated timing jitter is $\Delta t_{\mathrm{in}} = 5.9\,\mathrm{ps}$. Dispersion and nonlinearity in the NDF broaden the pulse duration and simultaneously flatten the pulse shape. In Fig. 3, the FWHM pulse width is broadened to approximately 26 ps. Consequently, the eye opening at the NDF output is appreciably wider than at the regenerator input. It is also seen that the amplitude jitter of pulses at the center of the bit period is smaller, while there is a slight increase of amplitude noise on the zero level of the pulses. The evaluated timing jitter at the NDF output is $\Delta t_{\mathrm{NDF}} = 3.1\,\mathrm{ps}$. Note that this effective reduction of timing jitter is due to the displacement of the centers of mass of the portions of broadened pulses contained in the bit slots towards the pulse flat tops. The eye-diagrams at the regenerator output show that, although the time shifts of pulses are efficiently restored by both types of AM, the ability of timing restoration of the modified AM is clearly superior. Indeed, in this example, the estimated timing jitter is $\Delta t_{\mathrm{out}} = 1.3\,\mathrm{ps}$ when the standard AM is used, and $\Delta t_{\mathrm{out}} = 0.31\,\mathrm{ps}$ when the modified AM is used. The shape and width of the regenerated pulses are mainly determined by the AM transfer function. It is seen that, when the standard AM is used, the pulse shape is not substantially changed as compared with that at the regenerator input, and the FWHM pulsewidth is approximately 12 ps. On the other hand, when the modified AM is used, the regenerated pulses exhibit sharper edges and a narrower width. In the example of Fig. 3, the FWHM pulsewidth is approximately 3 ps. The slicing and reshaping of the NDF-broadened pulse waveforms by the modified AM are responsible for the excellent retiming function of this type of AM.

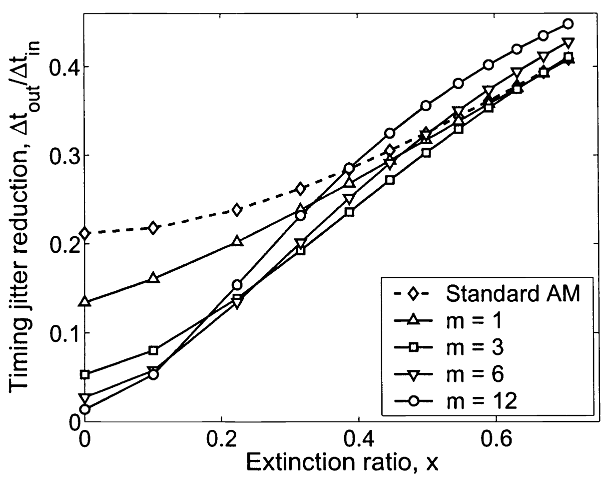

Figure 4. Timing jitter reduction factor versus extinction ratio.

Figure 4 shows the ratio of the signal timing jitter at the regenerator output to the timing jitter at the regenerator input, $\Delta t_{\mathrm{out}}/\Delta t_{\mathrm{in}}$, as a function of the extinction ratio x for some values of parameter m in (2). The timing jitter reduction factor for the conventional AM is also shown. It can be seen that for both AM types, the strength of time restoration decreases with increasing x, as it was to be expected. For small values of x, the retiming capability of the modified AM is significantly stronger than that of the conventional AM, and the strength of time restoration increases with increasing values of m. Jitter reductions down to 2% are possible with the modified AM. For high values of x, medium values of m perform better, and the retiming capabilities of the two types of AM are comparable.

For fixed fiber parameters, the nonlinearity enhancement in the NDF is determined by the input pulse power to the fiber, which can be varied by tuning the gain of the amplifier. Note that in a wavelength-division multiplexed (WDM) system one can use a single in-line amplifier for all channels before demultiplexing and per-channel regeneration. Figure 5 illustrates the results of the optimization of the amplifier gain in terms of timing jitter reduction when both the modified AM with $m = 6$ and the conventional AM are used. Here, $x = 0.1$. For gains less than the optimum one, less pulse broadening and flattening is achieved in the NDF, while for gains larger than the optimum one, the pulsewidth after propagation in the NDF is broadened appreciably beyond the timing slot. Both factors reduce the retiming capability of the AM.

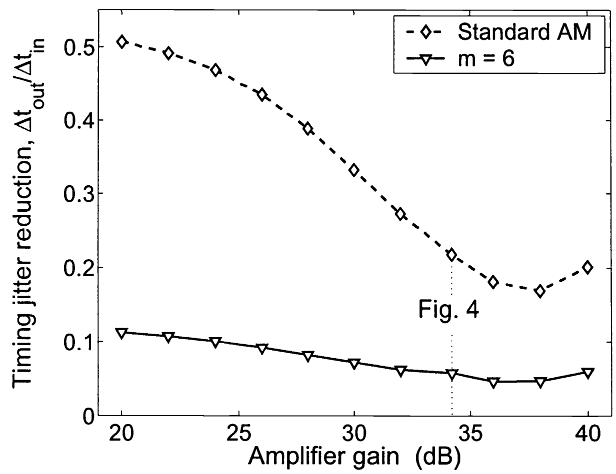

Figure 5. Timing jitter reduction factor versus amplifier gain.

4. CONCLUSION

We have proposed a novel technique in all-optical 3R regeneration based on the use of an AM (or any device with a similar function of temporal gating/slicing) enhanced by the effect of Kerr nonlinearity in an NDF. The regenerator suppresses the timing jitter of the optical signals by slicing of the nonlinearly broadened and flattened temporal waveforms of pulses. The efficiency of the technique has been demonstrated by application to timing jitter-degraded 40 Gbit/s single-channel RZ pulse trains. The proposed regenerator design does not depend essentially on the particular transmission scheme to which the regenerator is applied, and has a broad range of possible applications in timing jitter-limited optical systems. In particular, it can be used in WDM systems by applying the regenerator after signal demultiplexing. Moreover, the scheme could be combined with a saturable absorber, such as a NOLM, to achieve full 3R regeneration of the degraded optical signals.

REFERENCES

1. P. V. Mamyshev, "All-optical data regeneration based on self-phase modulation effect," in *Proc. ECOC*, pp. 475–477, 1998.
2. G. Raybon, Y. Su, J. Leuthold, R.-J. Essiambre, T. Her, C. Joergensen, P. Steinvurzed, K. Dreyer, and K. Feder,"40 Gbit/s pseudo-linear transmission over one million kilometers," in *Proc. OFC*, Paper No. FD10, 2002.
3. B. Dany, P. Brindel, O. Leclerc, and E. Desurvire, "Transoceanic 4 × 40 Gbit/s system combining dispersion-managed soliton transmission and new 'black-box' in-line optical regeneration," *Electron. Lett.* **35**, pp. 418–420, 1999.
4. A. Sahara, T. Inui, T. Komukai, H. Kubota, and M. Nakazawa, "40-Gb/s RZ transmission over transoceanic distance in a dispersion managed standard fiber using a new inline synchronous modulation method," *IEEE Photon. Technol. Lett.* **12**, pp. 720–722, 2000.
5. M. Suzuki, H. Toda, A. H. Liang, and A. Hasegawa, "Improvement of amplitude and phase margins in an RZ optical receiver using Kerr nonlinearity in normal dispersion fiber," *IEEE Photon. Technol. Lett.* **13**, pp. 1248–1250, 2001.

6. S. Boscolo and S. K. Turitsyn, "All-optical nonlinear pulse processing based on normal dispersion fiber-enhanced nonlinear optical loop mirror," *IEEE Photon. Technol. Lett.* **16**, pp. 1912–1914, 2004.
7. H. Nakatsuka, D. Grischkowsky, and A. C. Balant, "Nonlinear picosecond-pulse propagating through optical fibers with positive group velocity dispersion," *Phys. Rev. Lett.* **47**, pp. 910–913, 1981.
8. H. Kubota and M. Nakazawa, "Soliton transmission control in time and frequency domains," *IEEE J. Quantum Electron.* **29**, pp. 2189–2197, 1993.
9. S. Boscolo, S. K. Turitsyn, and K. J. Blow, "All-optical passive quasi-regeneration in transoceanic 40 Gbit/s return-to-zero transmission systems with strong dispersion management," *Opt. Commun.* **205**, pp. 277–280, 2002.
10. D. Marcuse, "RMS width of pulses in nonlinear dispersive fibers," *J. Lightwave Technol.* **10**, pp. 17–21, 1992.