Time domain add–drop multiplexing scheme enhanced using a saw-tooth pulse shaper

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Abstract: We experimentally demonstrate the use of saw-tooth optical pulses, which are shaped using a fiber Bragg grating, to achieve robust and high performance time-domain add–drop multiplexing in a scheme based on cross-phase (XPM) modulation in an optical fiber, with subsequent offset filtering. As compared to the use of more conventional pulse shapes, such as Gaussian pulses of a similar pulse width, the purpose-shaped saw-tooth pulses allow higher extinction ratios for the add and drop windows and significant improvements in the receiver sensitivity for the dropped and added channels.

OCIS codes: (060.4370) Nonlinear optics, fibers; (070.4340) Nonlinear optical signal processing; (050.2770) Gratings; (060.7140) Ultrafast processes in fibers..

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1. Introduction

Time-domain add–drop multiplexing (ADM) is a key functionality in all-optical networks. Having the capability to perform this function in an all-optical manner allows scaling to ultrahigh line rates, without being bound to the capabilities of electronic components. While maintaining the quality of the dropped tributary, ADM systems are also required to adequately

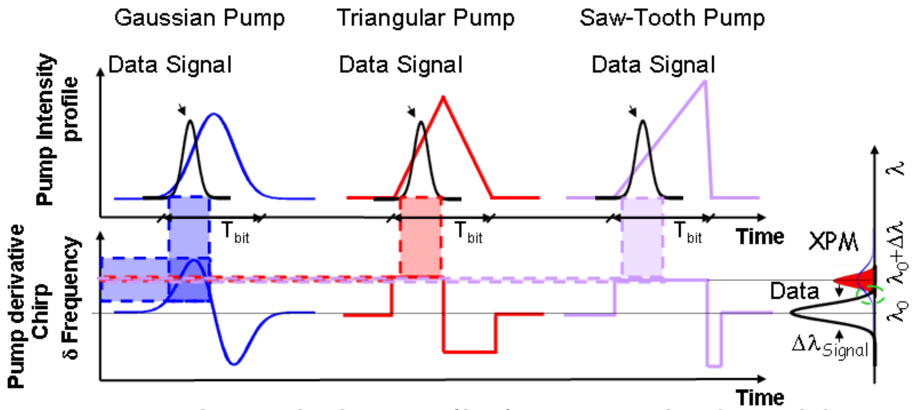

Fig. 1. Intensity and corresponding derivative profiles of Gaussian, Triangular and saw-tooth shapes.

clear the dropped bit-slot, so that new data at the tributary rate can be inserted without affecting the remaining tributaries. Several all-optical ADM techniques have been reported over the years (see e.g. [1-5]), among which the approach based on cross-phase modulation induced wavelength shifting in a highly nonlinear fibre (HNLF) is particularly attractive, mainly due to the relative simplicity of implementation [3]. According to this scheme intense control pulses (at the tributary rate) are used to impart a frequency shift through XPM onto the desired tributary channel of a co-propagating optical time division multiplexed (OTDM) data signal so that it is pushed out of its initial spectral band. This is achieved by overlapping the leading (trailing) edge of the control pulse with the (much shorter) OTDM data pulse, imposing a red (blue) shift upon its spectrum. The extent of the frequency-shift is proportional to the intensity gradient experienced by each data bit due to its interaction with the control pulse [6]. The drop function of the OTDM tributary is achieved by spectrally filtering the wavelength-shifted component. At the same time, the corresponding bit slot is cleared from the in-band signal, allowing the 'add' function to be implemented.

Most work to date in this area has used either Gaussian or $sech^2$ control pulses, which are readily generated through conventional pulse generation techniques. However, nowadays using pulse shaping technology, it is possible to reshape a very precisely specified input signal pulse into almost any other complex pulse form desired. For example, in this case, triangular or saw-tooth control pulses would be the ideal waveforms, since the uniform intensity gradient associated with their profile gives rise to a constant frequency shift across their edges [3, 6-8]. This ensures minimal distortion of the switched signal since the entire switched data pulse experiences the same frequency shift. Symmetric triangular pulses can be generated in a normally dispersive HNLF by accurately pre-chirping the incoming pulse [9], while we have recently generated saw-tooth pulses using a specially designed superstructured fibre Bragg grating (SSFBG) filter [6]. The operation of the time domain ADM scheme is schematically depicted in Fig. 1, where the intensity and time derivative profiles of conventional unshaped (Gaussian in this instance), symmetric triangular and asymmetric triangular (saw-tooth) shapes are compared. According to the intensity gradient of the control pulse shape considered, the switched data signal (black traces in the figure) experiences a different amount of XPM-induced frequency chirp, and subsequently the shifted portion of the spectrum will exhibit a correspondingly different bandwidth. This is illustrated in the spectral representation of the signals at the right-hand side of Fig. 1: for the same data signal pulse width (vertical dashed region in the figure) a much wider frequency distribution region (horizontal dashed region in the figure) is associated with the Gaussian shape. In contrast, in the case of triangular pulse shapes, no additional frequency chirp is induced by the XPM process (as illustrated by the very narrow frequency distribution region in the figure), and the bandwidth of the XPM component depends largely on the spectral width of the data pulses. If the newly generated shifted spectrum is so broad as to expand into the spectrum of the original signal

before the switch, it will cause a lower drop window extinction ratio, compromising at the same time the switching efficiency of the dropped channel [7].
However, if the control pulse profile is symmetric, see Gaussian and triangular profiles in Fig. 1, its width needs to be less than half of the OTDM bit slot to avoid overlap with adjacent pulses and at least twice the signal pulse width to ensure that the OTDM signal is switched properly. This implies that the duty cycle of the OTDM signal should be no more than 25%. Instead, if the pulse profile is asymmetric (saw-tooth profile in Fig. 1), then the system can be operated on its longer edge, so that far broader switching windows can be defined, relaxing the control pulse width requirements and allowing the ADM system to operate with much higher duty cycle OTDM signals.
In [7], we have studied the performance of saw-tooth pulses, when dropping an OTDM signal, demonstrating the far greater resilience of this scheme to timing jitter of the OTDM data pulses and in general to temporal bit misalignment between the control and data signals, as compared to more conventional Gaussian pulses. However, it is equally important to ensure that the tributary is sufficiently cleared from the OTDM data stream, and also that the adjacent tributaries are not disturbed. In this paper we show that ADM with saw-tooth pulses satisfies both of these requirements, and experimentally demonstrate that drop windows with higher extinction ratios can be achieved with respect to conventional control pulses, thus improving the overall performance and relaxing the spectral separation requirements between the dropped and remaining channels, when the new tributary is added. Preliminary results of this work were reported in [10].

2. Numerical Analysis

A clearer picture of the advantage of saw-tooth pulses over a more conventional shape is given in Fig. 2, where the simulated spectrograms of the OTDM signal are shown at various points within the system for the cases when a Gaussian (left-hand side) and a saw-tooth (right-hand side) pulse is used as a control signal for the implementation of an ADM system operating from 40 to 10 Gb/s. In our analysis, the propagation through the HNLF was calculated using the nonlinear Schrödinger equation, where we have ignored the effects of stimulated Raman scattering and self-steepening. The pulse characteristics of the various signals used in these simulations correspond to those used in the experiments presented in the following sections (data pulses with a Full Width at Half Maximum (FWHM) of 7 ps, and Gaussian and saw-tooth pulses with a FWHM of 10 ps). The FWHM of the gate function for the calculation of the various spectrograms was chosen to be 10ps. The controls were chosen to overlap with the second of the four OTDM tributary channels shown in the simulated spectrograms, referred to in the following as Channel 2. Figs. 2(a) and 2(b) show the spectrograms of the OTDM signal for both cases immediately after the HNLF. While the XPM-induced spectral broadening induced by the Gaussian pulses severely modifies the spectrum of Channel 2 by inducing a considerable amount of chirp to the tributary (Fig. 2(a)), the XPM induced by the saw-tooth pulse shifts its central frequency with minimal distortion/additional broadening (Fig. 2(b)). Furthermore, because of the comparable widths of the control and the tributary pulses, the spectrum of Channel 2 broadens almost symmetrically around its central frequency for the Gaussian shape, while it is simply shifted to longer wavelengths for the saw-tooth control shape. (Note that the circled areas in Fig. 2(b) are the spectral contents of the Channel 2 pulse which overlap with the sharper trailing edge of the saw-tooth control pulse.) Thus, the time-slot of the tributary to be dropped is not cleared optimally when a band-pass filter is placed after the HNLF at the central frequency of the original OTDM signal in the case of the Gaussian control (see circled area in Fig. 2(c)) and this ultimately results in interference when new data at the tributary rate is added in its place. The residual power levels within the slot can be substantially improved using saw-tooth control, see the corresponding circled area in Fig. 2(d). Fig. 2(e) and 2(f) show the spectrograms of Channel 2 when it is passes through a filter centred at the shifted wavelength for Gaussian and saw-tooth control pulses respectively. Satisfactory performance is achieved

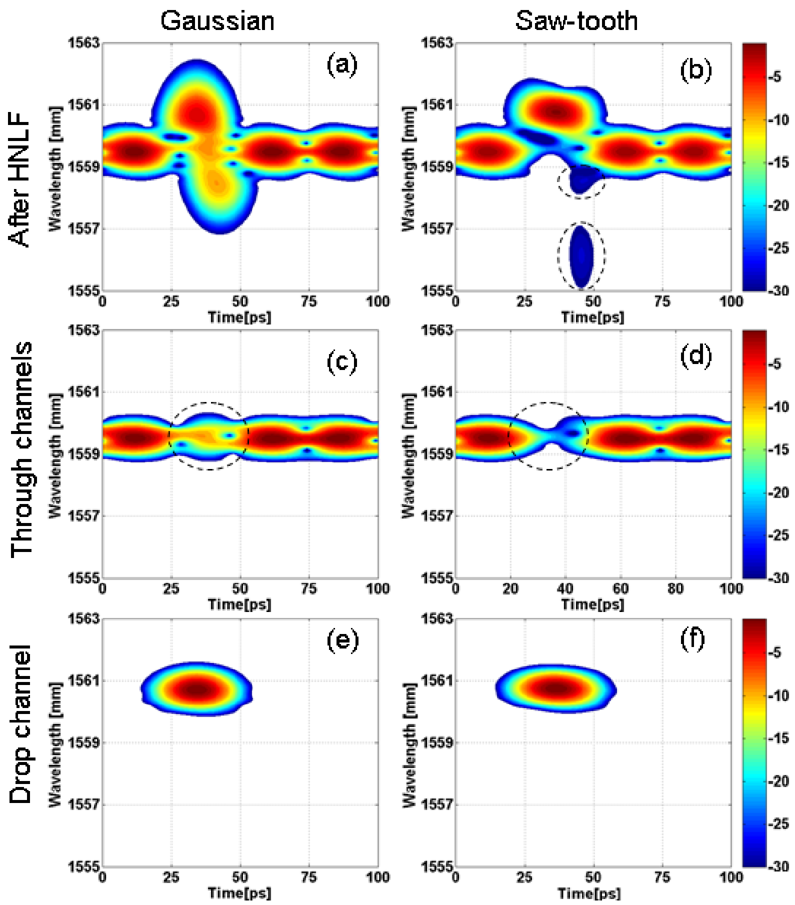

Fig. 2. Simulated spectrograms of the OTDM signal at various points of the system, when Gaussian or saw-tooth pulses are considered as the control signal (relative contour levels expressed in dB).

in both cases in this instance, although the signal obtained with the Gaussian pulses is much weaker than for saw-tooth control pulses. The strength of the filtered signal has obviously significant implications for the optical signal-to-noise ratio of the filtered tributary. Note that the benefits of using saw-tooth control pulse as opposed to Gaussian pulses in terms of resilience to timing jitter is demonstrated in [7]. Detailed experiments that verify the findings of our numerical studies are presented in the following Section.

3. Experimental Set-up and Results

The experimental set-up is shown in Fig. 3(a). The control signal was generated by an Erbium Glass Oscillator (ERGO) pulsed laser generating ~1.5ps Gaussian pulses at the repetition rate of 10GHz and operating at 1547.5nm. The signal was then reflected off the SSFBG (the SSFBG characteristics are reported in [6]), to generate 10ps Full Width at Half Maximum (FWHM) saw-tooth pulses, and amplified up to 26dBm, before being launched through the 90% port of a coupler into a HNLF. The fibre parameters are shown in Fig. 3(a). In order to compare the saw-tooth pulse performance with that of Gaussian pulses, the SSFBG could be replaced by a conventional 0.4nm band-pass filter to generate Gaussian pulses of a similar pulse width. The two corresponding profiles, measured using linear frequency-resolved optical gating (l-FROG), are shown in Fig. 4(a).

The data signal (~7ps pulses at 1559.5nm) was generated by a gain-switched distributed feed-back (GS-DFB) laser, see Fig. 3(b). Its output was split into two paths. In the first path, the

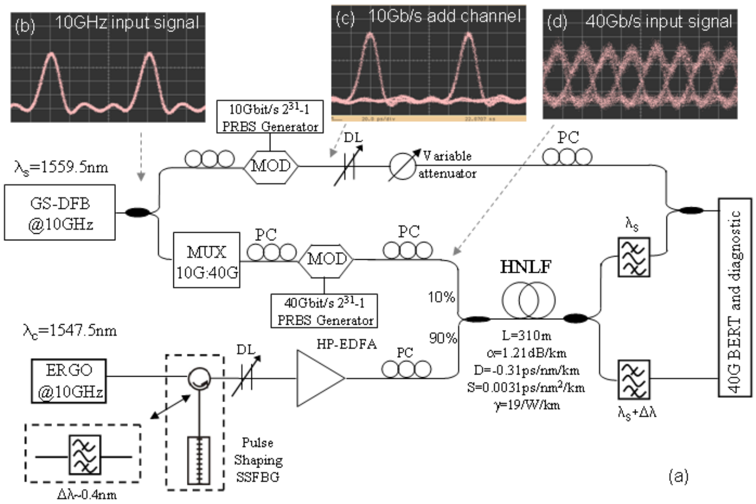

Fig. 3. (a) Experimental set-up of the Add-drop multiplexer. MOD: amplitude modulator, DL: delay line, PC: polarisation controller, MUX: multiplexer. (b) -(d) Eye diagrams at different points of the system.

signal was multiplexed up to 40GHz, amplitude modulated by a 2^{31}-1 pseudorandom bit sequence (PRBS), see Fig. 3(d), and launched into the HNLF via the 10% port of a coupler. By appropriately adjusting the optical delay line (DL) in the control arm, it was possible to shift (and subsequently drop) the wavelength of any one of the four 10Gbit/s tributaries of the multiplexed OTDM signal. In the second path, the signal, which corresponds to the new tributary for the ADM, was amplitude modulated at 10Gbit/s by a 2^{31}-1 PRBS (Fig. 3(c)) and then added to this empty time slot using a delay line and a coupler. A polarization controller and a variable attenuator were used to ensure that the added data had the same polarization and intensity respectively, as the high bit-rate OTDM signal. We thereby ensure that no performance enhancement was observed due to either polarisation multiplexing or a higher intensity "add" signal [3].

At the output of the HNLF, the data was filtered by a 0.5nm filter centred either at the shifted wavelength (offset by Δλ ~1.4nm) in order to drop out the selected tributary or at the original signal wavelength, which cleared one bit slot and facilitated the add operation.

As shown in Fig. 4(b), and when using saw-tooth control pulses (as compared to a Gaussian signal), higher and more confined spectral density of the wavelength-shifted components (minimum chirped switched output), due to the constant time-derivative of the pulse shape, can be achieved. The benefit of using saw-tooth pulses in terms of extinction between the dropped and through tributaries is evident in the inset to Fig.4 (b), where the two XPM

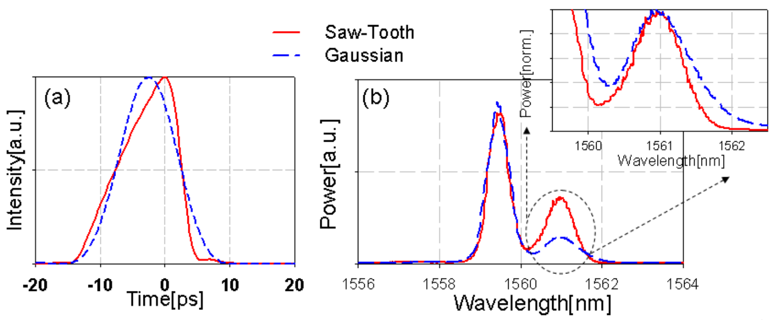

Fig. 4. (a) 10ps saw-tooth (red solid trace) and Gaussian (dashed blue trace) intensity profiles. (b) Corresponding spectra of the data signal only at the output of the HNLF, when saw-tooth (red solid trace) and Gaussian (dashed blue trace) are used as the control signals. The inset shows a zoomed-in detail of the XPM components, normalized in power.

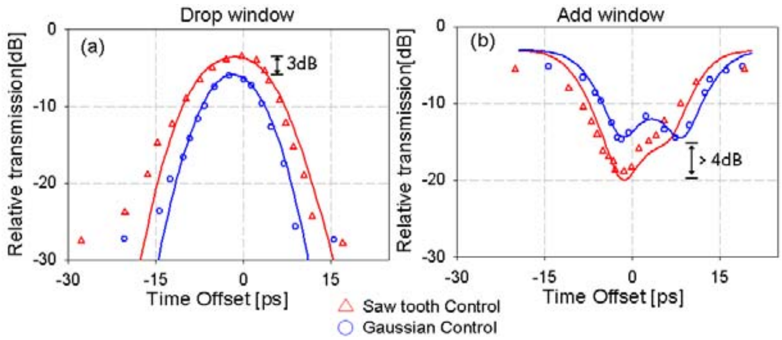

Fig. 5. Measured (symbols) and simulated (solid lines) add (a) and drop (b) windows for saw-tooth (red triangles) and Gaussian (Blue circles) shapes.

components are shown in a power-normalized plot for easier comparison. Note that these spectral traces are plotted on a linear scale, so any spectral components at shorter wavelengths than the original spectral peak, which are ~10dB lower than the wavelength shifted spectral peak (as predicted by the simulation results in Fig. 2) will not be visible here.

Figure 5 compares the measured (and corresponding simulated) add and drop windows for the two cases. These measurements, carried out using the data signal at the repetition rate of 10Gbit/s, were obtained by varying the time delay between the control and data signals, and evaluating the corresponding output optical powers after the filter was either offset at the shifted wavelength (drop) or centred at the original signal wavelength (add), respectively. The use of the saw-tooth pulse provides >4dB improvement in bit-slot clear-out efficiency, ~3dB improvement in drop channel efficiency and improved resilience to timing jitter due to the broader drop switching window. The smooth edges of the windows are caused by the comparable widths of the data and control signals used in our measurements. The double peak feature of the add window for the Gaussian control reflects the symmetry of its shape: the XPM induced wavelength shift of the data signal (clearing of the data signal original wavelength) can be achieved when the data signal overlaps with either side of the control edges. This is not the case for asymmetric shapes, which are characterized by one peak only. It should be noted, however, that for the same wavelength-shift, the Gaussian pulses require ~2dB less average power compared to the saw-tooth pulses due to the fact that Gaussian pulses have a larger gradient (albeit more localised) at their optimal operating point [6].

Eye diagrams at the output ports of the ADM for the dropped, through and added channels, when the two pulse shapes are used, are shown in Fig. 6. As can be appreciated, the higher extinction ratio of the drop window when using saw-tooth pulses allows better bit-slot clearance so that the new tributary can be added with enhanced performance, as compared to the case of Gaussian pulses. To confirm the benefit of using saw-tooth control pulses in this scheme, we performed bit-error rate (BER) measurements on all data signals. Since the data and control signals were optimally synchronized, the dropped channel after the ADM exhibited similar BER performance for the two cases, as shown in Fig. 7(a). Note that this would not be the case if the data signal was characterized by some phase noise. As was demonstrated in [7], in case of incoming data signal characterized by timing jitter, the saw-tooth control pulses would provide much better drop channel performance.

The BER curves for the three through and added channels are shown in Fig. 7(b). As expected, similar performance was obtained for all of the through channels, since they are not interfering with the two control shapes. Considering the added channel, similar receiver sensitivity as compared to the other through-channels was achieved when saw-tooth pulses were used, while a power penalty of ~1.2dB was obtained when using Gaussian pulses. This extra penalty originates from a non ideal clearance of the dropped window, see corresponding eye diagrams in Fig. 6. We next studied the receiver sensitivity for the added channels as a function of the filter detuning (the peak powers of the control signal were adjusted correspondingly for optimum performance). As can be seen in Fig. 7(c), the saw-tooth control

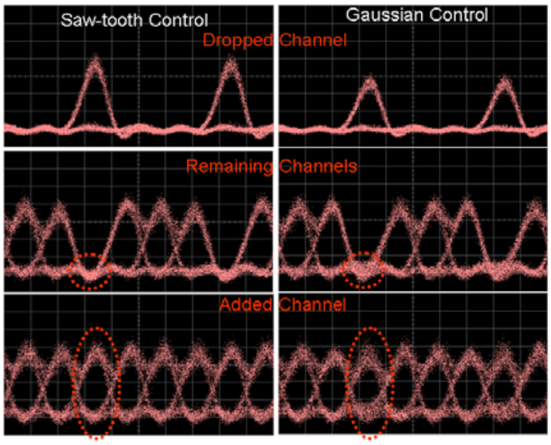

Fig. 6. Eye diagrams of the ADM for the dropped (top row), through (middle row) and added (bottom row) channels, when saw-tooth (left) or Gaussian (right) control pulses are used.

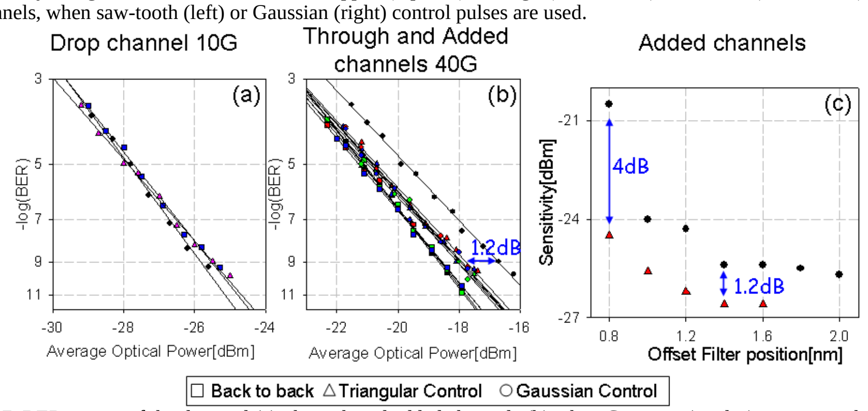

Fig. 7. BER curves of the dropped (a), through and added channels (b) when Gaussian (circles) or saw-tooth (triangles) control pulses are considered. Back- to-back curves are also reported for reference. (c) Power sensitivity of the added channel (right) as a function of the offset filter position when saw-tooth (triangles) or Gaussian (circle) control pulses are used.

pulses show better performance especially at relatively low $\Delta\lambda$, where an improvement of ~4dB was achieved for $\Delta\lambda$=0.8nm relative to the Gaussian pulse shape. This implies that a better use of the overall spectral bandwidth can be foreseen, when considering saw-tooth pulses as opposed to Gaussian pulses.

4. Conclusion

We have experimentally demonstrated the performance benefits of using saw-tooth shaped control pulses in an ADM system based on XPM in a HNLF and subsequent offset filtering. Significant improvement in the receiver sensitivity was achieved for the added channel relative to the use of Gaussian control pulses with a similar width. We believe that this approach could be applied to much higher bit rate systems by properly scaling the width of the shaped pulses and the bandwidth and offset of the filter.

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