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Time-division multiplexing of Mbit/s data-packets within Gbit/s data sequences through nonlinear temporal focusing

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Abstract. In this work, we report on an all-optical, real-time, nonlinear temporal compression technique based on a counter-propagating degenerate four-wave mixing interaction in birefringent optical fibres. As a proof-of-concept, we demonstrate the extreme temporal focusing and interleaving of a 10-Mbit/s data packet into a 10-Gbit/s data sequence, with record temporal compression factors ranging from 3 to 4 orders of magnitude and including non-trivial on-demand time-reversal capabilities. Our approach is scalable to different photonic platforms and offers great promise for ultrafast arbitrary optical waveform generation and related applications, while enabling the compression of THz-bandwidth optical signals from low-cost, low-bandwidth optical waveform generators.

The capability of compressing the timescale of optical waveforms beyond the bandwidth limitations of conventional optoelectronic technologies is an important functionality targeted in numerous applications for which cost-effective generation of ultrafast optical waveforms is required. To this aim, several approaches have been reported for the temporal compression of optical data packets and mostly rely on optical buffering combined to optical delay lines [1-2]. Basically, these previous demonstrations are mainly based on a time-interleaving process requiring ultra-short pulses and do not affect the signal or pattern duration. Consequently, the initial pulse width must be selected carefully to match with the output compressed repetition-rate. Furthermore, these techniques are not compatible with the temporal compression of arbitrary optical waveforms. To overcome this difficulty, one peculiar approach consists in turning the time-lens technique backwards into a temporal focusing telescope. Using this phenomenon, Foster and co-workers have demonstrated a 27-compression factor for ns-waveforms and 10-Gbit/s data packets [3]. However, the focusing capabilities of time-lens apparatus are fundamentally restricted by practical limitations of the focal length and lens aberrations due to high-order dispersion effects [3]. In this contribution, inspired by the original idea of A. Starodumov described in ref. [4], we report on a temporal compression technique exploiting a four-wave-mixing (FWM) interaction occurring between counter-propagating signals within a polarization maintaining optical fibre (PMF) [5-6]. We achieve ultra-high temporal compression factors ranging from 3 to 4 orders of magnitude and provide a proof-of-principle demonstration by compressing and multiplexing a 10-Mbit/s data packet within a 10-Gbit/s data sequence by means of a ×4350-temporal reduction.

The basic principle is illustrated in Fig. 1a. From one side of a PMF, the signal to be compressed (red) is injected with a polarization state aligned at 45° with respect to the slow and fast birefringent axes. From the opposite end, a short readout pulse (black), propagates along the slow polarization axis. When the readout pulse collides with the incoming signal, a FWM interaction leads to the emergence of a new signal (blue), co-propagating and orthogonally polarized with respect to the readout pulse. Due to birefringence, this new signal propagates at a different speed and progressively walks away from the readout pulse. The overall process repeats as the readout pulse sweeps along subsequent parts of the incident signal, thus generating an ultrafast replica of the slow input waveform. Injecting the readout pulse along the fast birefringent axis instead of the slow one will result in a time-reversal operation on top of the compression process. The compression factor M is mostly defined by the rate at which the generated signal walks away from the readout pulse, such that $M = 2n/|\Delta n|$, where n and Δn are respectively the group index and index difference between both axes of the PMF. Hence, standard PMFs lead to compression factors ranging from 10^3 to 10^4.

Figure 1b displays the experimental setup, which mainly consists in a 103-m-long PMF ($\Delta n=6.67\times10^{-4}$), surrounded by 2 optical circulators. The 10-Mbit/s data packet to be compressed is first generated from a continuous-wave (CW) laser centred at 1551-nm and carved by an intensity modulator (IM). An Erbium-doped fibre amplifier (EDFA) as well as a polarization controller (PC) are then used to amplify the 10-Mbit/s signal to 12 W peak power, whilst aligning its polarization state at 45° with respect to the PMF axes. At the opposite side of the PMF, the readout pulse consists of 6-ps pulses generated from a mode-locked laser, whose repetition rate is

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adjusted to 2 MHz so that a single pulse can propagate in the PMF at any given time. A second EDFA boosts the peak power to 3 W and a polarizing beam splitter (PBS) is used to select the axis of the PMF (fast or slow) along which the readout pulses are injected. In addition to the readout pulse, a 10-Gbit/s data sequence is combined along the orthogonal birefringent axis and is specifically designed with a 200-ps vacant time-slot to hold the temporally compressed replica of the 10-Mbit/s data packet. Finally, at the output of the system, the readout pulse and the resulting 10-Gbit/s data sequence are separated by a second PBS before detection using a 63-GHz real-time oscilloscope.

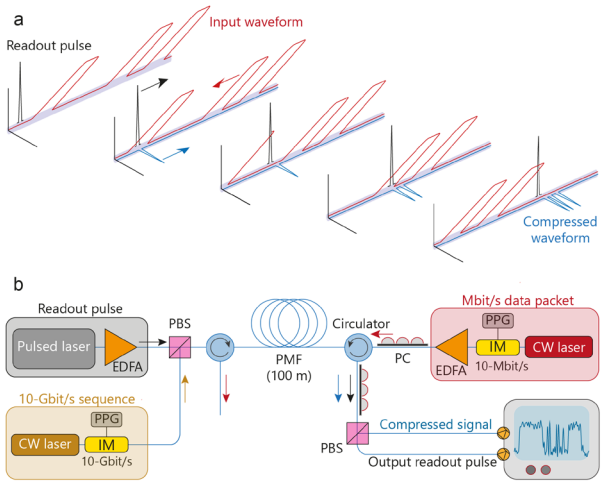

Fig. 1. (a) Principle-of-operation. (b) Experimental setup. PPG: Pulse Pattern Generator. Other Acronyms are defined in the text.

Figure 2 summarizes our experimental results. Panel (a) depicts the initial 10-Gbit/s data sequence (yellow) featuring a vacant 200-ps time-slot intended for time-interleaving of the compressed 10-Mbit/s data packet. For comparison, the autocorrelation trace of the readout pulse is also reported in black. In panel (b), we have reported the 10-Mbit/s data packet to be compressed, which extends along a sub-µs temporal window. Panel (c) first reports the output 10-Gbit/s signal when the polarization of the readout pulse is aligned along the slow birefringent axis of the PMF. This result clearly shows that the 10-Gbit/s data sequence holds a compressed replica of the counter-propagating 10-Mbit/s data packet, encapsulated inside the 200-ps time-slot. The compression factor was found to be M = 4350, in excellent agreement with the theoretical prediction of 4378. These experimental measurements have been also found in good agreement with numerical predictions (dashed lines in Fig. 2c-d) based on four coupled nonlinear Schrödinger equations. Finally, Fig. 2d illustrates the case for which the readout pulse now propagates along the fast birefringent axis of the PMF, whereas the 10-Gbit/s data sequence is swapped along the slow one. The compressed replica is now time-reversed, whereas the rest of the 10-Gbit/s data sequence remains remarkably preserved. Though expected, it is remarkable that this simple swapping of polarization axes can lead to such a non-trivial functionality.

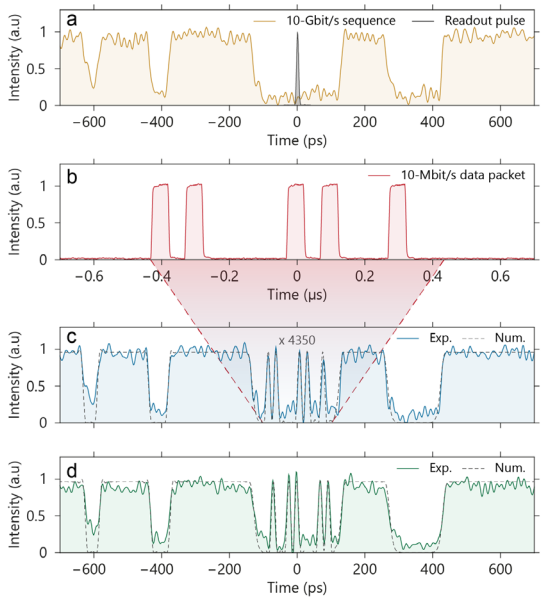

Fig. 2. (a) Initial 10-Gbit/s data sequence (yellow) and input readout pulse (black). (b) Incident counter-propagating 10-Mbit/s data packet. (c) Intensity profile (blue) of the output 10-Gbit/s data sequence when the polarization of the readout pulse is aligned on the slow axis of the PMF, demonstrating the interleaving of a ×4350 compressed replica of the 10-Mbit/s data packet. Dark dashed-lines correspond to numerical simulations. (d) Same as (c) when the polarization states of both the readout pulse and the 10-Gbit/s sequence are swapped, demonstrating time-reversal capabilities on top of temporal compression.

In conclusion, we have reported a nonlinear temporal compression technique based on a counter-propagating FWM process occurring in birefringent optical fibres. Thanks to this phenomenon, we have demonstrated the extreme time-division multiplexing of a 10-Mbit/s data packet into a 10-Gbit/s data sequence with a record compression factor of ×4350 as well as time-reversal capabilities. The present method is fully scalable to different photonic platforms, including birefringent fibers and integrated photonics, which could offer scaling factors from 10^2 to 10^5 and support the generation of THz-bandwidth optical signals from low-cost, low-bandwidth waveform sources.

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