Optical data transmission using periodic in-line all-optical format conversion

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Abstract: We introduce a novel transmission technique of periodic in-line all-optical format conversion between return-to-zero and non-return-to-zero-like aimed at delaying the accumulation of format-specific impairments. A particular realization of this approach using in-line normal dispersion fibre-enhanced nonlinear optical loop mirrors at 40 Gbit/s data rate is presented.

OCIS codes: (060.2330) Fiber optics communications; (070.4340) Nonlinear optical signal processing; (230.1150) All-optical devices

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1. Introduction

To release the full potential of optical fibre transmission systems and achieve higher transmission capacity, a lot of research on modulation formats has been done in recent years. In conventional transmission lines, return-to-zero (RZ) and non-return-to-zero (NRZ) are the two modulation formats most often used. At high bit-rates, for both modulation formats transmission is limited by the accumulation of nonlinear impairments along the line [1, 2, 3, 4]. Recent studies [5, 6] have shown that in long-haul transmission systems RZ turns out to be superior compared to NRZ [5], in virtue of a higher robustness to nonlinear signal distortion. Therefore, to reduce the impact of nonlinearity, typically NRZ is used at low powers, and consequently, systems employing such a modulation format are mainly limited by degradation of the signal-to-noise ratio due to accumulation of amplified spontaneous emission noise. In high bit-rate, strongly dispersion-managed RZ systems, the optimal transmission regimes are at higher powers (compared to NRZ) and are limited by nonlinear effects [4, 7, 8]. Such nonlinear impairments mainly manifest themselves as signal amplitude noise (amplitude fluctuations in the “ones” and/or growth of noise and radiative background in the “zeros”), and signal timing jitter. Even when the amplitude noise is reduced [9, 10, 11, 12, 13], timing jitter can be still an important limiting factor in RZ transmission systems. It is also well-known that the NRZ modulation format is resistant to timing jitter. Thus, in high bit-rate systems with strong dispersion management the key *limiting factors are different for different data formats*, or in other words, are *format dependent*.

All-optical modulation format conversion might become a necessary technology for future all-optical networks, which may employ miscellaneous formats. Although various all-optical format converters between RZ and NRZ have been demonstrated, including nonlinear optical loop mirrors (NOLMs) [14], and semiconductor optical amplifiers [15], to the authors’ best knowledge, the feasibility of optical data transmission using periodic in-line format conversion has not been reported before. In this paper, we propose a novel transmission technique based on periodic in-line all-optical conversion between RZ and NRZ-like formats. The aim of the approach is to alternate format-specific transmission impairments in order to delay their accumulation along the link. As an example of the general method, the following transmission scheme is examined at a 40 Gbit/s data rate. The RZ pulses transmitted in a first stage (400 km) are reamplified, cleaned up, and converted to NRZ-like pulses by a nonlinear signal processor based on a normal dispersion fibre (NDF)-enhanced NOLM. After the RZ-format transmission stage, the timing jitter of pulses is accumulated. In a second stage (also 400 km), the lower-power NRZ-like pulses are gradually reconverted to RZ pulses by means of optical filtering and fibre dispersion, and regenerated by a conventional NOLM. The partial propagation in the form of NRZ-like reduces the jitter accumulation, and thus, leads to overall improvement of the system performance.

2. System description

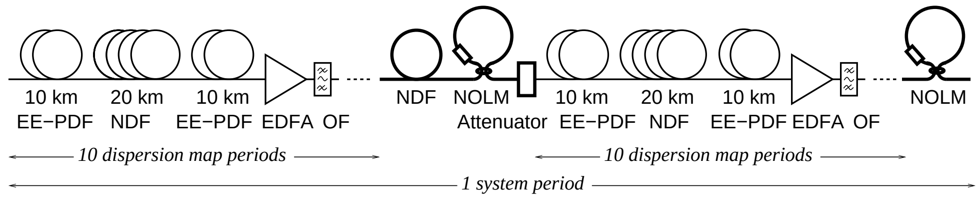

Fig. 1. Schematic diagram of one element of the periodic transmission system.

As a sample system for demonstration of the technique, we consider a periodic transmission line where each amplifier span consists of effective core area enlarged positive dispersion fibre (EE-PDF) and NDF [13] (see Fig. 1). The dispersion is 20 ps/(nm km) for the EE-PDF and -20 ps/(nm km) for the NDF. The effective area is 110 μm^2 for the EE-PDF and 30 μm^2 for the NDF. The attenuation is 0.2 dB/km in the EE-PDF and 0.24 dB/km in the NDF. Each span also includes an erbium-doped fibre amplifier (EDFA) that compensates for the energy losses, and an optical Gaussian filter that limits the bandwidth of the noise. The EDFA has a noise figure of 4.5 dB. Note that the transmission performance of the considered system is severely degraded by both nonlinear interactions-induced amplitude noise and timing jitter when regenerators are not used [13]. One element of the periodic transmission system is composed of two cells, and each cell amounts to ten amplifier spans. The length of NDF within an amplifier span is 20 km for both cells, while the length of EE-PDF within an amplifier span is 20.027 km for the first cell and is varied about 20 km in the second cell. A nonlinear optical pulse processor consisting of a section of NDF and a NOLM follows the first cell. The NDF is 0.5 km long and has the same fibre parameters as those of the NDF used in transmission. The NOLM incorporates a 50:50 coupler, and a 1.5 km loop of dispersion-shifted fibre with zero dispersion, an effective area of 25 μm^2, and an attenuation of 0.3 dB/km. Unbalancing of the NOLM is achieved with an optical attenuator asymmetrically placed in the loop, and the loss of the loop attenuator is -27.1 dB. The NOLM is operated in the stable region just after the peak of its switching curve. An extra gain is added to the EDFA prior to the pulse processor so as to provide both adequate enhancement of the nonlinearity in the NDF and adequate power level at the NOLM input. During propagation in the NDF, the temporal waveform of a RZ pulse is changed to a rectangular-like profile by the combined action of group-velocity dispersion and Kerr nonlinearity [16]. As a result, the pulse width is broadened and the centre portion of the pulse is changed to be flat. By utilising this property, the phase margin of a pulse train is improved [17]. The phase margin improvement enables reduction of the influence of the displacement of pulse position in time caused by timing jitter. The unbalanced NOLM acts as a saturable absorber and, hence, filters out low-intensity noise and dispersive waves from the higher-power pulse [18]. This allows for restoration of the pulse amplitude and cleaning up of the distorted pulse. In the case of a pulse train, the noise and radiative background in the zero timing slots is suppressed by the saturable absorption action of the NOLM, and the amplitude jitter of ones is also reduced [12]. An optical attenuator lowers the pulse power at the pulse processor output. During porpagation in the second cell, the NRZ-like pulse emerging from the pulse processor is gradually reconverted to a RZ pulse by the combined action of filtering and fibre dispersion. An identical NOLM to the one used in the pulse processor is placed at the end of the second cell. It provides 2R (reamplification, reshaping) regeneration function [12].

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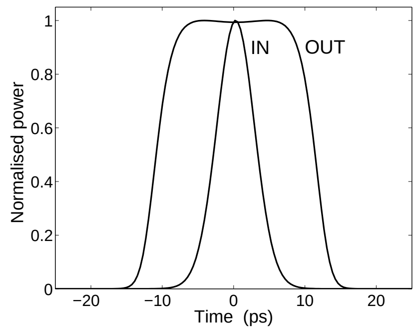

Fig. 2. Pulse shapes at the input and ouptut of the NDF-NOLM pulse processor.

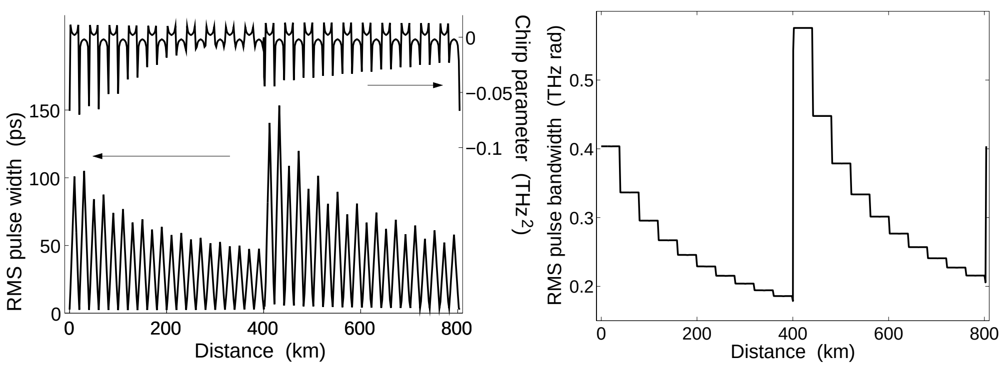

Fig. 3. Evolution of the stationary pulse width (left, upper curve), chirp (left, lower curve), and bandwidth (right) over one period of the system.

3. Transmission simulations and results

First, to illustrate the technique, single chirp-free Gaussian-shaped pulses are launched into the system, with a peak power and a full-width at half-maximum (FWHM) pulse width of approximately 1.5 mW and 6 ps, respectively. The pulses settle to a steady state after a short initial transition distance because of the stabilising effect of the regenerating elements in the system. Figure 2 shows an example of the stable pulse shapes for the system at the input and output of the NDF-NOLM based pulse processor. The evolution of the stationary root-mean-square (RMS) pulse width, chirp parameter, and RMS bandwidth over one period of the system is plotted in Fig. 3. The starting and ending point is the output of the conventional NOLM. One may see that the pulse dynamics along the transmission line is quasi-linear. Indeed, the pulse bandwidth keeps a constant value within each amplifier span, while undergoing a jump at the filter locations. On the other hand, the bandwidth exhibits a large change at the locations of the nonlinear regenerative elements placed into the system. This indicates that the periodical deployment of such elements into the system changes the quasi-linear propagation regime into a stable autosoliton propagation regime which is strictly nonlinear. Here, the term “autosoliton” means a stable pulse whose characteristics are fixed by the system [19].

Next, the stationary pulse peak power, width, and chirp reached during single pulse propagation are used as input parameters for transmission of 2^7-1 pseudorandom single-channel pulse trains at 40 Gbit/s. The signal quality is evaluated in terms of the standard (Gaussian-based) Q-factor. A fifth-order Bessel filter is used as a receiver electrical low-pass filter. Figure 4 shows

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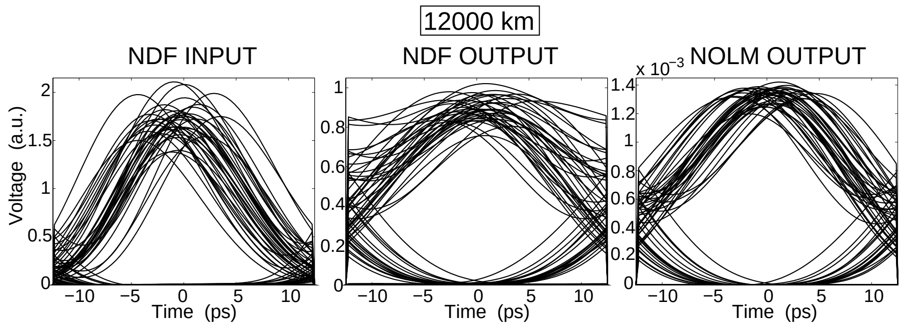

Fig. 4. Eye-diagrams in the NDF-NOLM signal processor.

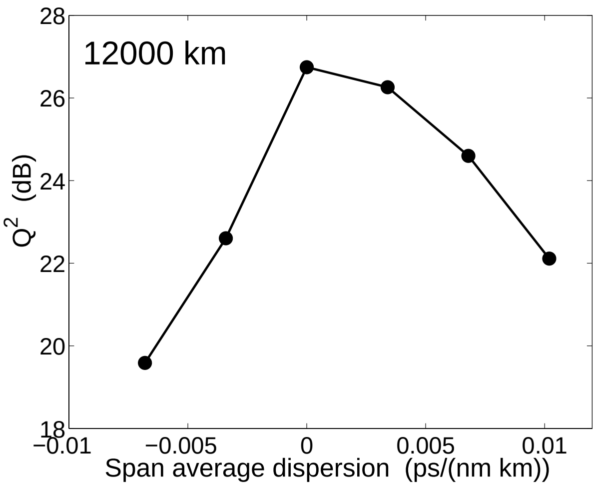

Fig. 5. *Q*-factor at the NDF-NOLM signal processor output versus the span average dispersion of the second cell of the system period.

an example of signal eye-diagrams in the NDF-NOLM based signal processor after 12000 km transmission. Here, the cut-off frequency of the receiver electrical filter is 30 GHz. The eyes are generated from a single pulse train. It can be seen that the eye at the NDF input is closed mainly due to a significant timing jitter of the optical pulses. There is no visible amplitude noise on the zero level of the pulses because the accumulation of background noise is efficiently suppressed by the in-line deployed NOLMs. Dispersion and nonlinearity in the NDF broaden the pulse duration and simultaneously flatten the pulse shape. In this example, the FWHM pulse width is broadened from 6.2 ps to 24.3 ps. Consequently, the eye opening at the NDF output is wider than at the NDF input. The broadening and flattening of the pulse temporal waveform leads to an effective reduction of the timing jitter. Indeed, broadening of the pulse width 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 pulse tails as a result of flattening of the pulse envelope. It is also seen that the amplitude jitter of pulses at the centre of the bit slot is slightly smaller. The eye opening at the NOLM output is wider still, due to a sensible reduction of the amplitude jitter given by the NOLM.

An important issue to be investigated is the tolerance of the transmission scheme to the path-averaged dispersion of the line. Here, the line path-averaged dispersion is tuned by varying the

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span average dispersion in the second cell of the periodicity element of the system. Figure 4 shows the signal Q-factor at the NDF-NOLM signal processor output after 12000 km transmission as a function of the span average dispersion of the second cell of the system period. Here, the cut-off frequency of the receiver electrical filter is optimised to 80 GHz. To account for more statistical realizations, the Q-factors are averaged over four pseudorandom pulse trains. It is seen that the optimum average dispersion is zero. This dispersion value yields unchirped pulses at the nonlinear signal processor input.

4. Conclusion

We have proposed a novel transmission technique based on periodic in-line conversion between RZ and NRZ-like formats aimed at suppressing the accumulation of format-specific impairments. As a particular realisation of the general idea, we have investigated the performance of a system with in-line NDF-enhanced NOLMs spaced by 800 km at 40 Gbit/s data rate.

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