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10 GHz Pulse Source for 640 Gbit/s OTDM based on $LiNbO_3$ Modulators and Self-Phase Modulation

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Abstract: We demonstrate a 10 GHz 680 fs pulse source tunable over the C-band, based on a CW laser, 10-GHz $LiNbO_3$-modulators and fibre-based SPM compressors. The pulses are used to generate error-free 640 Gbit/s OTDM data.
OCIS codes: (060.4510) Optical communications; (060.4370) Nonlinear optics, fibers.

1. Introduction

Pulse sources emitting short picosecond pulses at 10 to 40 GHz repetition rates have a range of important applications within the field of optical communications. High-quality pulses are required to generate ultra-high bit rate serial data signals by the optical time division multiplexing technique (OTDM) [1]. Another application is wide-band frequency comb-generation, allowing to obtain many wavelength division multiplexed (WDM) channels from a single pulse source [2]. Furthermore, the homogeneous line-spacing in the comb, determined by the pulse repetition rate, can be exploited for orthogonal frequency division multiplexing (OFDM) [3]. Pulse sources for such applications need to fulfill a number of requirements including tunability both in wavelength and repetition rate, as well as a stable operation. For high-speed OTDM in particular, there are stringent requirements of low timing-jitter and high-quality pulse shape with high extinction ratio. Mode-locked lasers can deliver the necessary high-quality pulses, but such pulse sources often have drawbacks such as unstable operation and/or limited or no tunability. Consequently, there have been many efforts on developing pulse sources based on a continuous wave (CW) laser source followed by an external electro-optic (EO) modulation scheme to generate a pulse train. Indeed, such pulse sources can potentially offer both wide tunability, stable operation, and high pulse quality. So far, the shortest pulse width obtained by EO modulation schemes is around ~2 ps at 10-40 GHz repetition rates [4-7]. A subpicosecond pulse width, as required for 640 Gbit/s OTDM, has necessitated an additional non-linear pulse compression stage [7,8]. However, in most of these demonstrations, the generated pulse is often associated with a pedestal which prevents its use for high-speed OTDM data. To date, only a 40 GHz pulse source including a four-wave mixing stage for pedestal suppression has been employed for error-free 640 Gbit/s OTDM data generation [7].

In this paper, we demonstrate a 10 GHz pulse source for 640 Gbit/s OTDM based on $LiNbO_3$ modulation followed by a polarization-independent 2-stage non-linear pulse compressor. Both stages are based on self-phase modulation (SPM) in dispersion-flattened highly non-linear fibres (DF-HNLF). The pulse source is tunable from 1535 nm to 1560 nm, emitting a 680 fs Gaussian pulse with negligible pedestal at all wavelengths. The pulse source is employed in a 640 Gbit/s on-off keying (OOK) OTDM data generation and demultiplexing experiment, where the error-free bit error rate (BER) performance confirms the high pulse quality.

2. Experimental set-up

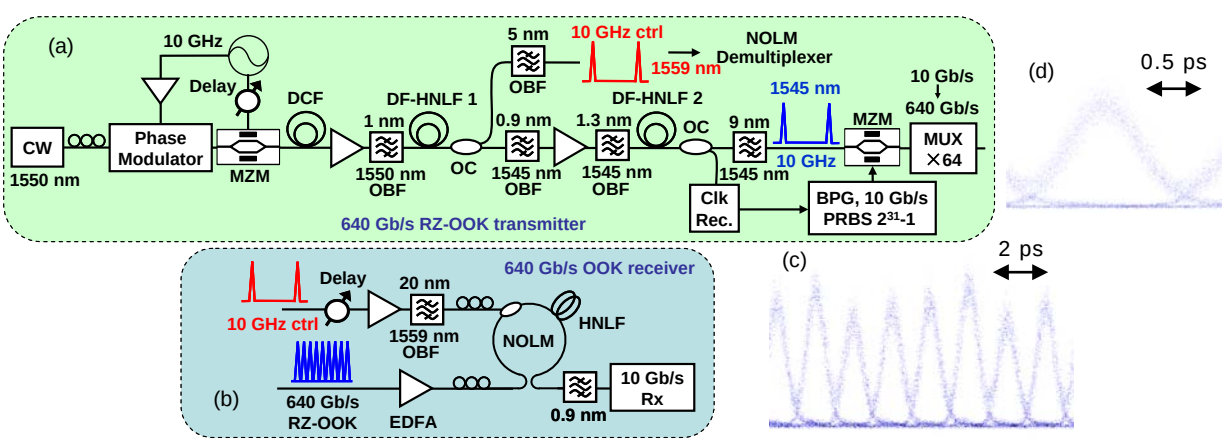

Fig. 1. Experimental setup. (a) Pulse source in a 640 Gbit/s RZ-OOK OTDM transmitter, (b) 640 Gbit/s OOK receiver ; (c) and (d) optical sampling oscilloscope eye-diagrams of the generated 640 Gbit/s RZ-OOK OTDM signal.

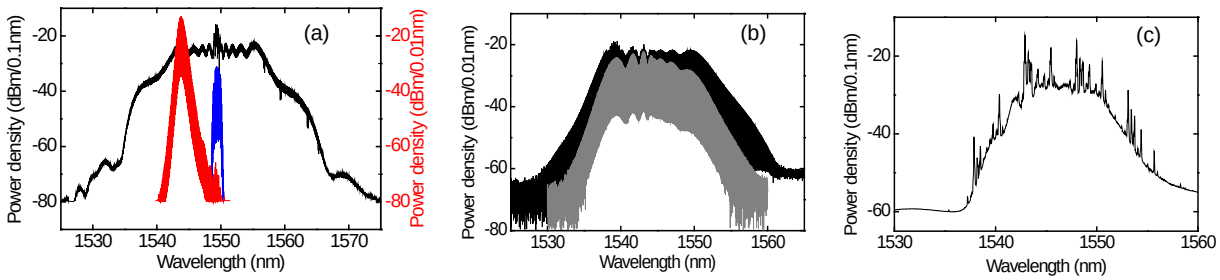

Fig. 2. (a) Optical spectra at the output of the DCF, at the output of the DF-HNLF 1 and at the input of the DF-HNLF 2; (b) 10 GHz data pulse at 1545 nm; (c) 640 Gb/s RZ-OOK data signal.

The experimental setup for the 10 GHz cavity-free pulse source based 640 Gb/s RZ-OOK transmitter and receiver is shown in Fig. 1. In the 640 Gb/s RZ-OOK transmitter, a continuous wave (CW) light at 1550 nm is launched into a cascaded phase modulator (modulation depth of 4π) and Mach-Zehnder modulator (MZM), both driven by a 10 GHz sinusoidal signal. The sinusoidal phase modulation approximates the quadratic phase modulation within a small range (about 1/6 of the period) where linear chirp can be generated and used for subsequent linear pulse compression. The MZM is used to remove the part of the CW light subjected to the lower part of the sinusoidal phase modulation (corresponding to positive chirp) and to only keep CW light overlapped with the upper part of the sinusoidal phase modulation (corresponding to negative chirp). The CW light with negative chirp is compressed into short pulses in a 400 m dispersion compensating fibre (DCF). At the output of the DCF, the generated pulse has a full width at half maximum (FWHM) of 6 ps, but with a pedestal originating from the non-linear chirp generated at the edge of the sinusoidal phase modulation, which cannot be compensated by a DCF.

After the linear pulse compression, the generated pulse is amplified to 26.7 dBm, filtered by a 1 nm filter and then launched into a 1.4 km dispersion-flattened highly nonlinear fiber (DF-HNLF 1) with dispersion D=-0.56 ps/(nm·km) and dispersion slope S=0.0052 ps/(nm^2·km) at 1550 nm, and non-linear coefficient γ~10 W^{-1}km^{-1}. A broadened spectrum is generated in DF-HNLF 1 due to self-phase modulation (SPM). Regenerated pulses with improved extinction ratio and OSNR as well as strongly suppressed pedestal can be obtained when the spectrum is filtered off-center in order to strongly suppress the original spectrum. The broadened spectrum is off-carrier filtered at 1545 nm with a 0.9 nm optical bandpass filter (OBF) to obtain the regenerated 10 GHz pulses for the data signal. The same spectrum is also filtered at 1559 nm using a 5-nm OBF to obtain the 10 GHz control pulses for the NOLM demultiplexer. The regenerated 10 GHz pulses at 1545 nm with a FWHM of 4 ps are spectrally broadened by SPM in the 800-m DF-HNLF 2 (D=-0.45 ps/(nm·km), S=0.0056 ps/(nm^2·km) at 1550 nm, γ~10 W^{-1}km^{-1}), and subsequently filtered with a 9 nm BPF at 1545 nm. The clock is recovered to trigger a 10 Gbit/s bit pattern generator (BPG). The compressed pulses are then encoded by on-off keying (OOK) with a 10 Gbit/s PRBS (2^{31}-1) signal in a MZM. The modulated 10 Gbit/s RZ-OOK signal is multiplexed in time using a passive fibre-delay multiplexer (MUX ×64) to generate the 640 Gbit/s RZ-OOK signal. The FWHM of the data and control pulses are 640 fs and 900 fs, respectively. The optical sampling oscilloscope (OSO) eye-diagram of the 640 Gbit/s OTDM RZ-OOK signal is shown in Fig. 1 (c) and a zoom-in on the eye-diagram is shown in Fig. 1 (d). A high quality 640 Gbit/s data stream with wide eye opening is achieved.

The 640 Gbit/s OOK receiver mainly consists of a non-linear optical loop mirror (NOLM) based demultiplexer followed by a 10 Gbit/s pre-amplified receiver. The NOLM is used to OTDM demultiplex the 640 Gbit/s serial data signal to a 10-Gbit/s data signal based on cross-phase modulation (XPM) in a 50 m long HNLF using 10 GHz control pulses at 1559 nm. The individual channels can be selected by tuning an optical time delay. The demultiplexed 10 Gbit/s RZ-OOK signal is extracted by a 0.9 nm OBF at 1545 nm and finally detected in a 10 Gbit/s bit error rate receiver.

3. Experimental results

Optical spectra measured at the output of the DCF, at the output of DF-HNLF 1, and at the input of DF-HNLF 2 are shown in Fig. 2 (a). The optical spectrum of the 10 GHz data pulse at 1545 nm before and after the 9 nm filter is shown in Fig. 2 (b). The 640 Gbit/s RZ-OOK signal are shown in Fig. 2 (c). From Fig. 2 (a), we can see that the spectrum at the original wavelength of 1545 nm is strongly suppressed before the pulse is launched into the DF-HNLF 2. The autocorrelation traces of the 640 Gbit/s RZ-OOK signal and 10 GHz control pulse are shown in Fig. 3 (b). As shown in Fig. 3 (a), bit error rates (BER) are measured for the 10 Gbit/s back-to-back (B2B) signal and 4 consecutive 640/10 Gbit/s demultiplexed channels. All the 4 consecutive channels show error-free performance. The best channel has a power penalty of 4.4 dB and the worst channel has a power penalty of 7.7 dB. The penalty

variation is not attributed to a lacking quality of the generated pulse (a residual pulse pedestal would result in a time-varying intersymbol interference). Instead, the RF source employed for the pulse source exhibited some instability, which also affected the BER performance after demultiplexing. A stable RF synthesizer with lower jitter is expected to give improved BER performance compared to the results presented here.

In practice, a pulse source with the feature of being wavelength tunable is desirable. Therefore, we characterize the pulse source for different wavelengths, by changing the wavelength of the tunable CW source and each time readjusting the filters. As shown in Fig. 3 (c), using a tunable Gaussian filter with a bandwidth of 750 GHz at the output of the pulse source, we obtain consistent performances of 680 fs FWHM at 1535 nm, 1540 nm, 1545 nm, 1550 nm, 1555nm and 1560 nm.

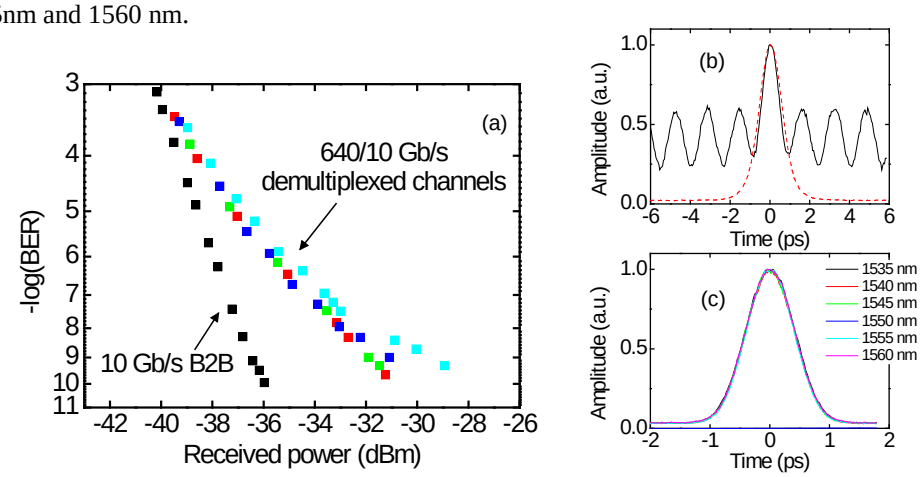

Fig. 3. (a) BER measurements of 10 Gbit/s back-to-back signal and 4 consecutive 640/10 Gbit/s demultiplexed channels; (b) Autocorrelation traces of the 640 Gbit/s data signal (black solid) and 10 GHz control pulse (red dash); (c) Autocorrelation traces of the 10 GHz data pulse at different wavelengths (1535 nm, 1540 nm, 1545 nm, 1550 nm, 1555 nm and 1560nm).

4. Conclusions

We demonstrate a 10 GHz pulse source for a 640 Gbit/s OTDM transmitter and receiver based on $LiNbO_3$ phase modulator followed by a polarization-independent 2-stage non-linear pulse compressor. Both stages are based on self-phase modulation (SPM) in dispersion-flattened highly non-linear fibres. Error-free performance for the OTDM multiplexing and demultiplexing is achieved, which confirms the high pulse quality. The pulse source can also be tuned from 1535 nm to 1560 nm, emitting a 680 fs Gaussian pulse with negligible pedestal at all wavelengths.

5. Acknowledgements

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