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10 GHz pulse source for 640 Gbit/s OTDM based on phase modulator and self-phase modulation

Hao Hu, Hans Christian Hansen Mulvad, Christophe Peucheret, Michael Galili, Anders Clausen, Palle Jeppesen, and Leif Katsuo Oxenløwe

DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, Ørsteds Plads, Building 343, DK-2800 Kgs. Lyngby, Denmark
huhao@fotonik.dtu.dk

Abstract: We demonstrate a high-quality cavity-free 10 GHz 680 fs pulse source starting from a continuous wave (CW) laser. 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. The pulse source is based on a linear pulse compression stage followed by two polarization-independent non-linear pulse compression stages. The linear pulse compression stage relies on a phase modulator, which is used to generate linear chirp and followed by a dispersive element to compensate the chirp. The non-linear pulse compression stages are based on self-phase modulation (SPM) in dispersion-flattened highly non-linear fibers (DF-HNLF). The pulse source is tunable over the C-band with negligible pedestal.

OCIS codes: (060.2330) Fiber optics communications; (060.4510) Optical communications; (060.4370) Nonlinear optics, fibers.

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1. Introduction

Pulse sources emitting short picosecond pulses at 10 to 40 GHz repetition rates have a wide 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 optical time division multiplexing technique (OTDM) [1–3]. Another application is broad band supercontinuum generation, allowing to obtain many wavelength division multiplexed (WDM) channels from a single pulse source [4]. It is interesting to note that the repetition of short pulses at a fixed frequency results in the generation of phase coherent frequency combs, which means that the wavelengths of adjacent channels are phase locked to each other. Such phase coherent frequency combs could be used for spectrally efficient coherent WDM (Co-WDM) [5], optical arbitrary waveform generation (OAWG) [6] and frequency-domain based coding techniques (such as optical code division multiple access (OCDMA) [7]). Furthermore, the constant line-spacing in the comb, determined by the pulse repetition rate, can also be exploited for orthogonal frequency division multiplexing (OFDM) signal generation [8].

Pulse sources (or phase coherent frequency combs) for the above-mentioned applications need to fulfill a number of requirements including tunability both in wavelength and repetition rate, as well as 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 aiming at 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 [9,10]. Indeed, such pulse sources can potentially offer 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 [11,12]. A subpicosecond pulse width, as required for 640 Gbit/s OTDM, has necessitated an additional non-linear pulse compression stage [13–15]. 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 [13].

In this paper, we demonstrate a high-quality cavity-free 10 GHz pulse source for 640 Gbit/s OTDM based on a linear pulse compression stage followed by two polarization-independent non-linear pulse compression stages. The linear pulse compression stage relies on a phase modulator, which is used to generate linear chirp, followed by a dispersive element to compensate the chirp. The polarization independent non-linear pulse compression stages are based on self-phase modulation (SPM) in dispersion-flattened highly non-linear fibers (DF-HNLFs). 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. Phase modulator based linear pulse compression

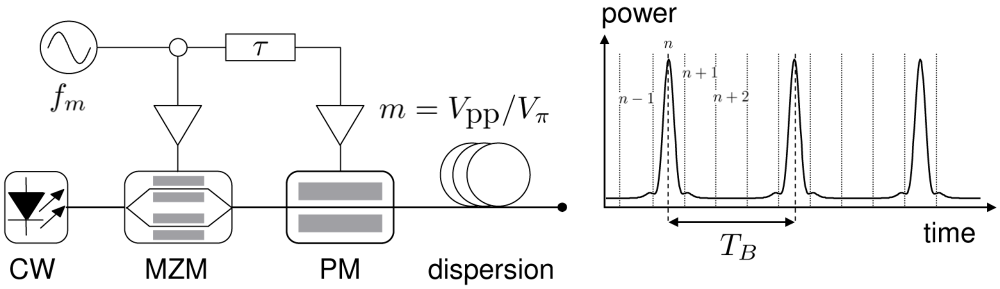

Fig. 1. Implementation of a pulse source based on electro-optic phase chirping and linear pulse compression. Division of the time interval between consecutive pulses into 4 bit slots for ×4 OTDM multiplexing.

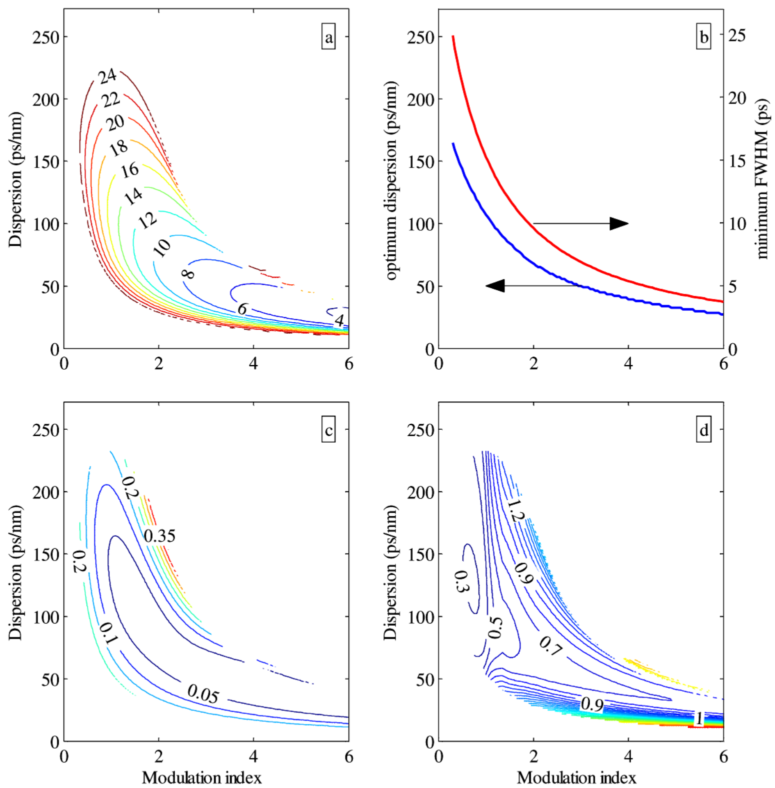

Fig. 2. a) FWHM pulsewidth (in ps) contour map as a function of dispersion and modulation index; b) minimum FWHM pulsewidth and optimum dispersion for the different modulation indices; c) ratio of the pulse energy within the immediately adjacent bit slot to the energy within the bit slot containing the generated pulse; d) contour map of the time bandwidth product.

Figure 1 shows the basic implementation of a pulse source based on frequency chirping and linear pulse compression, which consists of a continuous wave (CW) laser, a Mach-Zehnder modulator pulse carver followed by a phase modulator, both driven by a 10 GHz sinusoidal clock, and a dispersive element. The CW light is modulated and chirped by the electro-optic phase modulator and can be compressed into pulses by the dispersive element (such as a dispersion compensating fiber, DCF), which is used for chirp compensation. The sinusoidal phase modulation approximates the desired quadratic phase modulation within a small range

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(about 1/6 of the period) where linear chirp can be generated and used for subsequent linear pulse compression. Figure 2(a) shows the full width at half maximum (FWHM) of the generated pulses as a function of the phase modulation index, defined as the ratio of the peak-to-peak voltage applied to the phase modulator to its half-wave voltage V_{π}, and the amount of dispersion. Short pulsewidths can be obtained for the larger modulation indices, provided an optimum dispersion is used, as shown in Fig. 2(b). However, the pulse compression starts to saturate for large modulation indices since the generated chirp starts to deviate from the ideal linear chirp, and therefore cannot be compensated by the dispersive element. The phase modulated CW light has both positive and negative chirp, but only one of them can be compensated by a dispersive element at a time, and the other chirp will turn into detrimental pedestals. A cascaded Mach-Zehnder modulator acts as a pulse carver, which is helpful to reduce the undesired chirp and pedestals [10]. Figure 2(c) shows the ratio of the pulse energy within the immediately adjacent bit slot to the energy within the bit slot containing the generated pulse, as a function of the phase modulation index and amount of applied dispersion. A time multiplexing factor of 4 is considered in this calculation. Even in the optimum case, this ratio is still not good enough for high-speed OTDM applications [16]. Figure 2(d) shows the contour map of the time bandwidth product (TBP), which is also an estimate of the pulse quality.

3. 10 GHz pulse source for 640 Gbit/s OTDM

The experimental setup for the 10 GHz cavity-free pulse source-based 640 Gb/s RZ-OOK transmitter and receiver is shown in Fig. 3. In the 640 Gb/s RZ-OOK transmitter, CW light at 1550 nm is launched into a cascaded phase modulator (modulation depth of 4 π) and Mach-Zehnder modulator (MZM), both driven by a 10 GHz sinusoidal signal. 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), in order to reduce the pulse pedestal. The CW light with negative chirp is compressed into short pulses in a 400 m DCF At the output of the DCF, the generated pulses have a FWHM of 6 ps, but with a pedestal originating from the non-linear chirp generated at the edge of the sinusoidal phase modulation, which is not sufficiently suppressed by the MZM and cannot be compensated by a DCF, as shown in Fig. 4(a).

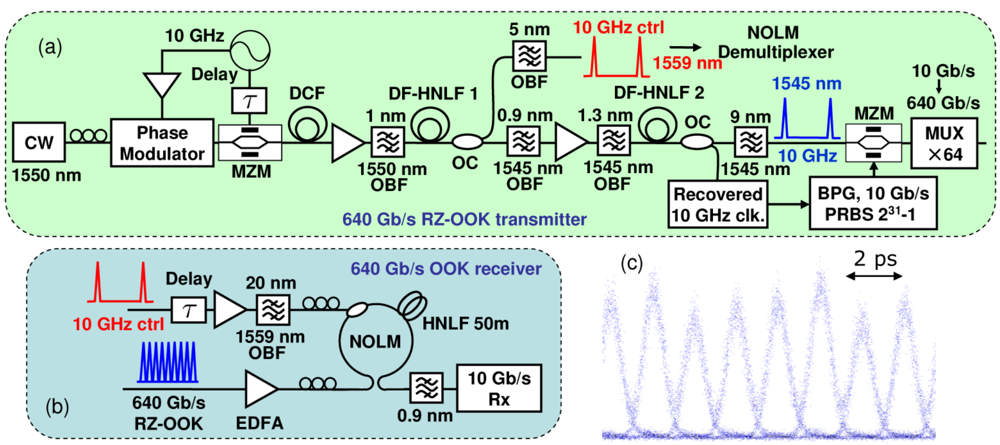

Fig. 3. Experimental setup. (a) Pulse source in 640 Gbit/s RZ-OOK OTDM transmitter; (b) 640 Gbit/s OOK receiver; (c) optical sampling oscilloscope eye-diagram of the generated 640 Gbit/s RZ-OOK OTDM signal.

In order to suppress the residual pedestal, the pulses are launched into a Mamyshev regeneration stage to completely remove the pedestal [17]. 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

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1.4 km dispersion-flattened highly nonlinear fiber (DF-HNLF 1, dispersion D=−0.56 ps/(nm·km) and dispersion slope S=0.0052 ps/(nm^2·km) at 1550 nm, non-linear coefficient γ~10 W^{-1}km^{-1}). A broadened spectrum is generated in DF-HNLF 1 due to self-phase modulation (SPM), as shown in Fig. 4(b). 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 (Fig. 4(b)). The same spectrum is also filtered at 1559 nm using a 5-nm OBF to obtain the 10 GHz control pulses for the non-linear optical loop mirror (NOLM) demultiplexer (Fig. 5(c)). In order to compress the pulses to a width shorter than 1 ps, as required for 640 Gb/s OTDM applications, 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 centered at 1545 nm (Fig. 4(c)). Since the SPM is not dependent on polarization, the nonlinear pulse compression is polarization independent, which makes the pulse source quite stable even over a long term.

The 10 GHz 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 RZOOK signal is multiplexed in time using a passive fiber-delay multiplexer (MUX ×64) to generate the 640 Gbit/s RZOOK signal. The FWHM of the data and control pulses are 640 fs and 900 fs, respectively (Fig. 5(a)). The optical sampling oscilloscope (OSO) eye diagram of the 640 Gbit/s OTDM RZ-OOK signal is shown in Fig. 3(c). A high quality 640 Gbit/s data stream with wide eye opening is achieved. The amplitude variation is due to the not fully optimized OTDM multiplexer.

The 640 Gbit/s OOK receiver consists of a 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 the 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, pre-amplified, photo-detected and finally sent into a 10 Gbit/s bit error rate analyzer.

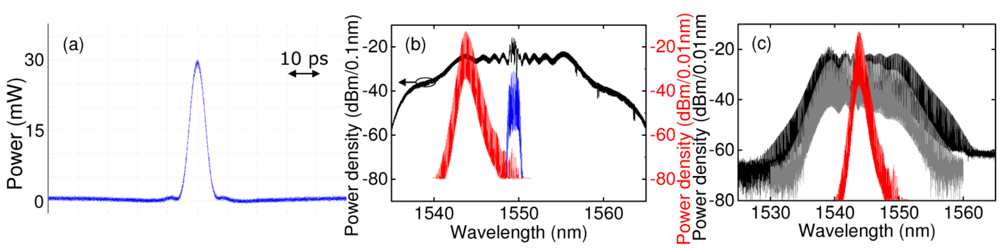

Fig. 4. (a) Waveform of the pulses after the phase modulator based linear pulse compression (at the output of the DCF) recorded using an optical sampling oscilloscope; (b) Optical spectra at the output of the DCF (blue), at the output of the DF-HNLF 1 (black, resolution of 0.1 nm and the others with the resolution of 0.01nm) and at the input of the DF-HNLF 2 (red); (c) Optical spectra of 10 GHz data pulse at 1545 nm at the input (red) and output of the DF-HNLF 2 (black) and after (grey) the subsequent 9 nm filter.

The first stage of the nonlinear pulse compression (or spectral broadening) is mainly used to reshape the pulses and remove the pedestal by the off-center filtering. As shown in Fig. 4(b), the spectrum after the linear pulse compression at the original wavelength of 1545 nm is strongly suppressed before the pulse is launched into the DF-HNLF 2. The spectrum at the input of DF-HNLF 2 is newly generated, which corresponds to clean pulses with high extinction ratio. The optical spectra of the 10 GHz data pulse at 1545 nm before and after the 9 nm filter are shown in Fig. 4(c). The autocorrelation traces of the 640 Gbit/s RZ-OOK signal and 10 GHz control pulses are shown in Fig. 5(a). The spectra of the 640 Gbit/s RZ-OOK signal and the 10 GHz control pulses are shown in Fig. 5(b).

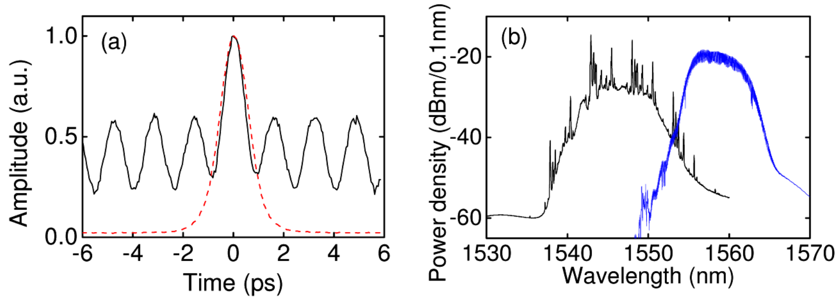

Fig. 5. (a) Autocorrelation traces of the 640 Gbit/s data signal (black solid) and 10 GHz control pulses (red dash); (b) Optical spectra of the 640 Gb/s RZ-OOK data signal and the 10 GHz control pulses.

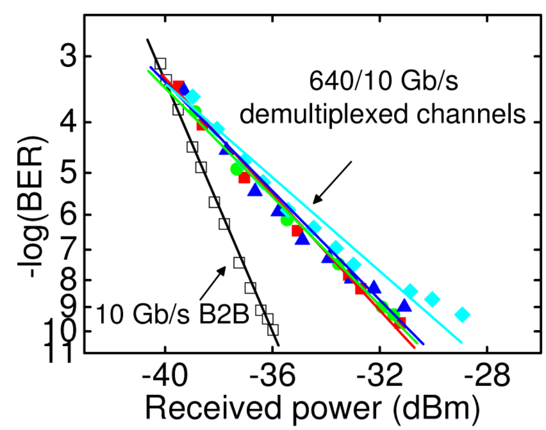

Fig. 6. BER measurements of 10 Gbit/s back-to-back signal and 4 consecutive 640/10 Gbit/s demultiplexed channels.

As shown in Fig. 6, 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 lacking quality of the generated pulses (a residual pulse pedestal would result in a time-varying intersymbol interference). Instead, the RF source employed for the pulse source exhibits some instability, which affects the BER performance after demultiplexing. A more stable RF synthesizer with lower jitter is expected to give improved BER performance.

4. Tunability of the pulse source

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. 7(a), using a tunable Gaussian filter (programmable wavelength selective switches) 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. In addition, by adjusting the bandwidth of the Gaussian filter (500 GHz, 750 GHz, 1 THz, 1.25 THz and 1.5 THz) Gaussian pulses with different FWHM (970 fs, 680 fs, 590 fs, 550 fs and 520fs) can be obtained, as shown in Fig. 7(b) and (c). The minimum time bandwidth product (TBP) of

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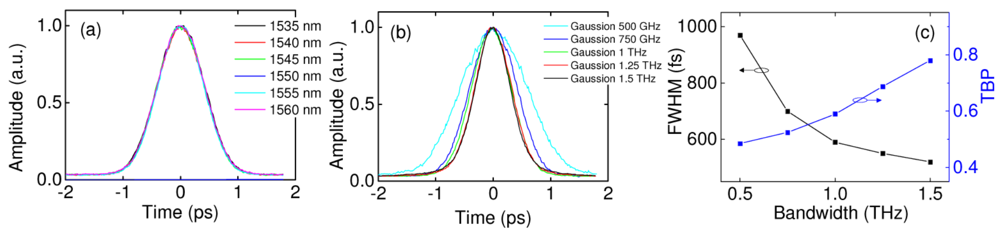

Fig. 7. (a) Autocorrelation traces of the 10 GHz data pulse at different wavelengths; (b) Autocorrelation traces of the 10 GHz data pulse with different 3-dB bandwidth (500 GHz, 750 GHz, 1 THz, 1.25 THz and 1.5 THz); (c) the FWHM and time bandwidth product (TBP) for different bandwidths.

0.485 is achieved at the minimum bandwidth of 500 GHz. The transform limited TBP (0.441 for Gaussian pulses) is not achieved because nonlinear chirp is generated at the edge of the broadened spectrum at the output of the DF-HNLF 2 and this cannot be compensated by dispersive elements. The TBP increases with the filter bandwidth since more uncompensated nonlinear chirp passes the filter when the bandwidth of the filter is larger. In principle, a transform limited TBP could be obtained if the spectrum was broadened enough and only a small portion in the center of the spectrum where only linear chirp is generated was filtered out.

5. Conclusions

We have demonstrated 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 fibers. 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. Different pulse widths can be obtained by adjusting the bandwidth of the subsequent Gaussian filter.

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