All-Optical 10-GHz Clock Recovery from 160 Gbit/s OTDM Signals using a Mode-Locked Fibre Ring Laser

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We report on all-optical clock extraction from 160-Gbit/s OTDM signals on the basis of a passively mode-locked fibre ring laser. Results concerning optical amplitude and timing-jitter performance of 10-GHz clock signals are presented in this paper.

Introduction

To satisfy the bandwidth demand for transmission, the single-fibre capacity is expanded by increasing both the channel counts (WDM) and the channel capacity (TDM) [1-2]. Presently, optical transmission systems are typically running at data rates of 2.5 Gbit/s or 10 Gbit/s per channel. Systems employing a single-channel bit rate of 40 Gbit/s have already been advertised as a commercial product. The next generation TDM bit rate of 160 Gbit/s or higher is under active investigation in research laboratories worldwide. Electrical signal processing for date rates of 160 Gbit/s and beyond is not available at this moment. One of the most promising ways of realizing such ultra-high speed transmission systems that overcomes the electrical bottleneck is to time-division multiplex and demultiplex short-pulse data streams in the optical domain (OTDM) [2]. It is widely recognized that for the realization of ultra-high speed OTDM systems, optical clock recovery (OCR) is an essential issue. Recovered clock frequencies should be identical to that of the transmitted optical data for 3R processings, while they should be sub-harmonic frequencies for OTDM demultiplexing and add/drop multiplexing. Among the many methods proposed and demonstrated so far, optical mode-locking in a fibre ring is a promising method because of its capability to generate high-intensity ultrashort optical pulses using widely available standard pigtailed optical devices.

In this paper we demonstrate sub-harmonic frequency all-optical clock recovery, which is based on optical data pulse injection into a mode-locked fibre ring laser (MLFRL) utilizing the non-linear operation in a single semiconductor optical amplifier (SOA). We used electrical processing in the proposed OCR to satisfy the strict requirements for error-free OTDM reception [3]. The input signal to the proposed OCR scheme is 16 OTDM channels of 10 Gbit/s each. Results of experiments are presented and discussed in this paper. Of crucial importance for recovered clock signals are pulse width, jitter performance, and locking range.

OTDM Transmitter

In OTDM transmission systems, periodic pulse train of a laser source is divided in several branches by an optical coupler to form OTDM channels. Each channel has an optical gate by which electrical data is put onto an optical carrier. When a binary signal is ‘0’, the optical gate is closed and the pulse will be absorbed. In case of a binary signal ‘1’, the gate is open and the pulse will travel through an optical delay before being interleaved in time with other pulses to produce a single data stream. Proper time-delays in each branch prevent optical crosstalk between OTDM channels. For our lab-scale

experiments, we used a combination of a single optical gate and optical multipliers to emulate high-capacity OTDM data stream. Fig. 1 shows a schematic of the OTDM transmitter used for our clock recovery experiments.
A 1.6 ps, 10 GHz fibre laser operating at 1550 nm was used as the original pulse source.

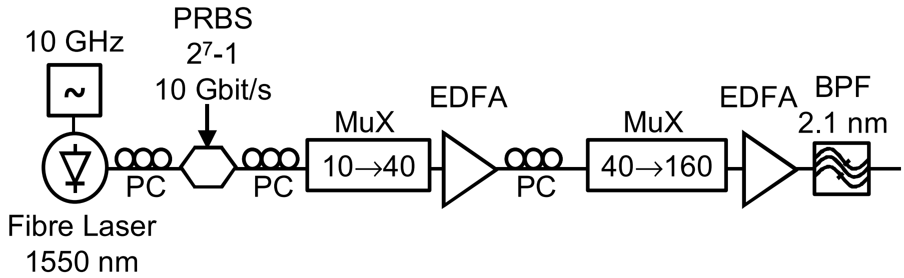
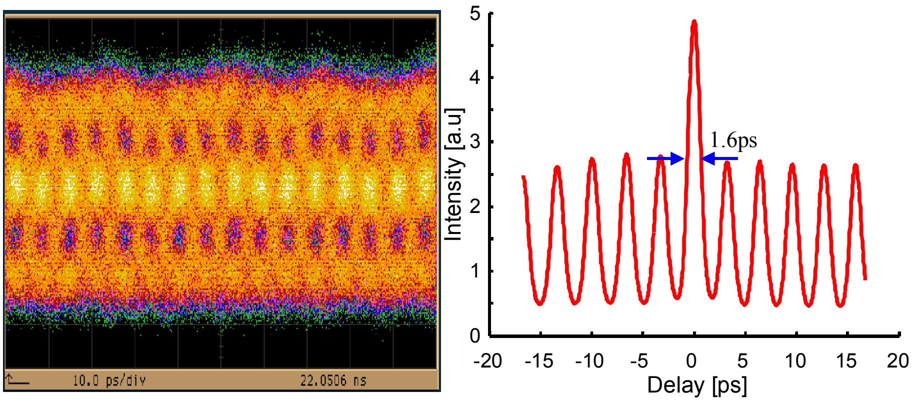


Fig. 1. Schematic of 160-Gbit/s OTDM transmitter

The signal pulse was generated by a phase locked loop (PLL), regeneratively mode-locked fibre laser, which can emit a transform-limited sech pulse with a clean symmetric spectral profile and very low jitter. After intensity modulation at a baserate of 10 Gbit/s with a pseudo-random binary sequence (PRBS) of 2^7-1, the signal was optically multiplexed to 160 Gbit/s using four optical multipliers. In each optical multiplier, the signal was split in two branches with one arm longer than the other. The length difference is chosen as such that the bit-interleaving occurs at a double bitrate of the input. Four multipliers cause a total optical loss of about 20 dB. Therefore, we used an optical amplifier (EDFA) after two multipliers. An additional EDFA was used to amplify the 160 Gbit/s signals. This was followed by a bandpass filter (BPF) of 2.1 nm that suppresses the outband amplified spontaneous emission (ASE) noise before a transmission fibre. The eye pattern and the auto-correlator (AC) trace of 160 Gbit/s OTDM signal are presented in Fig. 2. The small amplitude variation in the eye pattern



(a) (b)

Fig. 2. 160 Gbit/s OTDM signals: (a) eye pattern generated with 40-GHz receiver and (b) auto-correlator trace

indicates that the alignment of all sixteen OTDM channels is not far from an ideal alignment. The AC side lobes are a result of the cross-correlation of the different OTDM channels. The measured FWHM of a single optical pulse is approximately 1.6 ps.

Clock Recovery

The proposed OCR scheme is schematically depicted in Fig. 3. The operation of the sub-harmonic OCR relies on the fast gain compression of the SOA by the incoming data stream. The SOA gain compression results in optical phase modulation in the cavity and mode-locks the fibre laser. The 16-channel OTDM signal was coupled into a ring laser

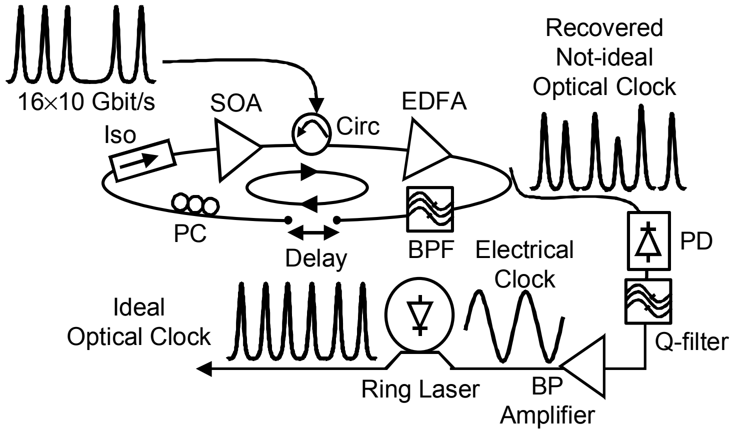


Fig. 3. A sub-harmonic 10-GHz clock recovery

by an optical circulator (Circ). The laser ring cavity was constructed entirely from fibre-pigtailed components. Optical gain was provided from a 500-µm bulk SOA. The SOA has a peak small signal gain of 22 dB at 1540 nm when driven with 300 mA and a recovery time of approximately 400 ps. An optical isolator (Iso) was put in the SOA input port to ensure unidirectional mode-locked oscillation and to minimize spurious cavity reflections. The SOA exhibited 2-dB polarization dependent gain and a polarization controller (PC) was placed at its input for performance optimization. An additional optical gain was provided by an EDFA gain block that compensates for gain fluctuations of the SOA under pulsed external signals. After the EDFA, a 50/50 fused optical fibre coupler was used to lead the mode-locked pulse train out from the ring cavity. A tunable filter (BPF) with 5-nm FWHM bandwidth selected the central wavelength of the mode-locked signal. A tunable optical delay was responsible for precise matching of the repetition frequency of the clock recovery circuit to the incoming data pattern. The cavity fundamental frequency was 8.05 MHz and the in-cavity power was 7.8 dBm. The output clock pulses were in general pattern dependent that follows roughly the modulation pattern of the incoming data stream. In order to reduce this pattern dependence, these clock pulses were converted to electrical signals by a 12-GHz photodetector, filtered by a high-Q filter (centered at 10 GHz), and amplified by a bandpass amplifier. This 10-GHz electrical clock signal was used to drive a second EDFA ring laser [4], which has an optical phase modulator in its cavity.

Results and Discussion

We adjusted the delay so that the fundamental frequency of the fibre ring is a sub-harmonic of the line frequency of data pattern. For a certain value of delay, the ring circuit generated mode-locked pulse trains with a measured FWHM of 8-10 ps. However, as expected, the pulse was not transform limited due to chirp and its temporal response had quite amount of jitter, see Fig. 4a. Jitter appears as a statistical variation in the arrival time of each bit around its predetermined arrival time. To minimize the jitter performance, we employed signal processings in the electrical domain and then converted the electrical signal back to the optical domain. Fig. 4b and Fig. 4c show the electrical clock and the regenerated optical clock at 10 GHz. We can observe that the electrical clock has a better performance with respect to the recovered optical clock. Low jitter is still visible due predominantly to the noise performance of the bandpass amplifier. Using a modulator driver of ultralow noise, we managed to generate relatively stable a short pulse train with a time jitter less than 200 fs, i.e. the minimum requirement for error-free OTDM demux, see [3].. The pulsewidth-bandwidth product of the output pulse was approximately 0.37, which is very close to that of a squared hyperbolic secant profile. We tested the locking range by slightly tuning the channel rate around 10 Gbit/s after the mode-locking was achieved. The locking range was measured to be less than 1 MHz. It is important to note here that the setup did not employ any form of stabilization mechanism by which the output can be kept stable over a relatively long period. We expect that based on its pulse quality the proposed method is a strong candidate for the clock recovery in ultrahigh capacity OTDM networking.

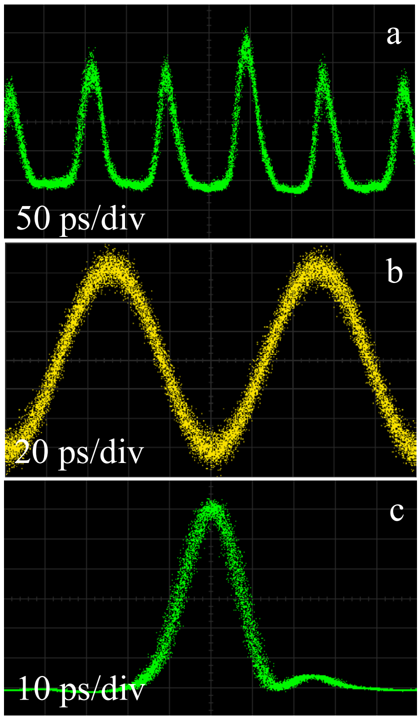


Fig. 4. Temporal response at 10 GHz: (a) Recovered optical clock, (b) Electrical clock, and (c) Regenerated optical clock.

Conclusion

We have demonstrated optical clock recovery at a sub-harmonic frequency of 10 GHz from 160 Gbit/s OTDM signals. Optical clock signals are successfully regenerated of low amplitude and time jitter performance. We believe that the recovered clock performance enables error-free ultrafast OTDM demux and add/drop mux.

Acknowledgment

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