Demonstration of an 8×10-Gb/s OTDM system

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Received October 18, 2004

An 8×10 Gb/s optical time-division-multiplexing (OTDM) system was demonstrated with an electroabsorption modulator (EAM) based short pulse generator followed by a two-stage nonlinear compression scheme which generated stable 10-GHz, 2-ps full-width at half-maximum (FWHM) pulse train, an opto-electronic oscillator (OEO) that extracted 10-GHz clock with a timing jitter of 300 fs from 80-Gb/s OTDM signal and a self cascaded EAM which produced a switching window of about 10 ps. A back-to-back error free demultiplexing experiment with a power penalty of 3.25 dB was carried out to verify the system performance.

OCIS codes: 060.2330, 320.7160, 250.0250.

With the maturity of wavelength-division-multiplexing (WDM) technology, the speed of a single wavelength channel also increases dramatically, optical time-division-multiplexing (OTDM) is important to overcome the electronic bottleneck and investigate the ultimate transmission speed of a single channel. The OTDM system consists of the following key sub-systems: ultra-short pulse generator, tributary clock extraction, and high-speed optical switch to perform demultiplexing. These basic optical signal-processing technologies will also find their applications in the future wavelength routing, or even packet switching all-optical networks. So far, ultra-high speed OTDM systems have been demonstrated and investigated by several groups[1−3] around the world with a record high speed of 1.28 Tb/s[1].

We have previously reported a 4×10-Gb/s OTDM system in which an actively mode-locked fiber ring laser (AMLFL), an opto-electronic oscillator (OEO) and an electroabsorption modulator (EAM) were deployed respectively to implement the above-mentioned sub-systems[4]. However, in an 8×10-Gb/s OTDM system, the time slot is only 12.5 ps, which sets a new challenge to the sub-systems. In this letter, an 8×10-Gb/s OTDM system was demonstrated with an EAM and two-stage pulse compressor as the pulse generator which delivered a 2-ps, 10-GHz pulse train, an OEO which extracted 10-GHz tributary clock from 80-Gb/s data, and a self cascaded EAM demultiplexer which produced a switching window of about 10 ps. The system performance was verified in a back-to-back error-free demultiplexing bit error rate (BER) test with a power penalty of 3.25 dB. To our knowledge, this is the first 80-Gb/s OTDM system reported in China.

The experimental setup is shown in Fig. 1. A continuous wave (CW) light with a wavelength of 1545 nm was emitted from a distributed feedback laser diode (DFB-LD) operating with an optical power of 9 dBm and launched into a commercially available bulk EAM (JAE-FOEA-310) which was biased at −3.5 V and driven by a 10-GHz sinusoidal electrical signal with a peak-to-peak voltage of 6.5 V. The CW laser was modulated by the EAM and the initial 10-GHz repetition pulses with a measured full-width at half-maximum (FWHM) pulse-width of 18.5 ps were formed. These pulses were too wide to be used in 80-Gb/s system, so pulse compression was necessary. Here we adopted a two-stage nonlinear compression scheme.

The first stage of the compressor was a 5-km dispersion shifted fiber (DSF) with a dispersion of 1.89 ps/(nm·km) at 1545 nm in which higher-order soliton compression was deployed, and the second stage was a comb-like dispersion profiled fiber (CDPF) with a total length of 4 km which was fabricated by splicing 12 sections of alternatively arranged common single mode fiber (SMF) and DSF to achieve adiabatic soliton compression[5]. The injection optical power into the first stage and the second stage was set at 15.3 and 17.2 dBm, respectively. The autocorrelation trace of the compressed pulse and the corresponding optical spectrum are given in Fig. 2, the FWHM pulse width was measured to be 2 ps and the 3-dB optical spectral width was 1 nm. The pulse width of 2 ps is only 16% of the 80-Gb/s time slot, so it was narrow enough to serve as the tributary pulse source in 80-Gb/s system. A numerical simulation based on the physical parameters of the EAM, including the chirp characteristics of the initial pulse indicated that the peak to pedestal suppression ratio of the compressed pulse was 18 dB. The timing jitter of the pulse train was also measured with a result of 650 fs; these parameters also illustrated the high quality of the pulse source. The compressed 10-GHz pulse train was modulated by a pseudo random bit sequence (PRBS) with a word length of $2^{31} - 1$ in a lithium niobate modulator, the modulated pulse train was then multiplexed to 80-Gb/s with a 1×8 passive optical fiber multiplexer. The multiplexed 80-Gb/s OTDM signal was observed by converting itself into electrical signal with a 50-GHz 3-dB bandwidth PIN photodetector connected to a 50-GHz sampling oscilloscope (Agilent 86100A). The eye-diagram of the 80-Gb/s OTDM signal

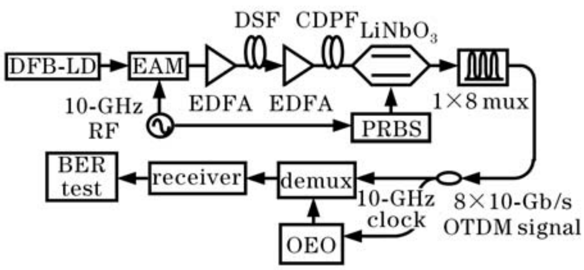

Fig. 1. The experimental setup of 8×10-Gb/s OTDM system.

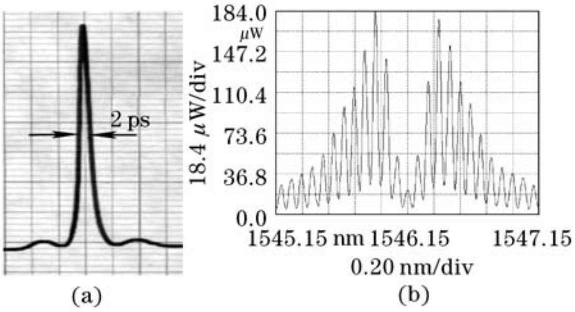

Fig. 2. The autocorrelation trace (a) and the optical spectrum (b) of the compressed 10-GHz pulse.

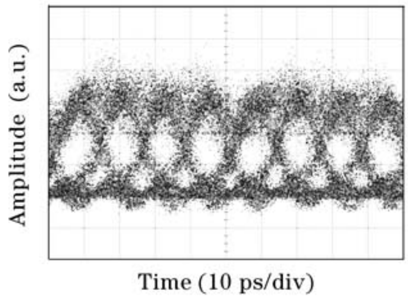

Fig. 3. The eye-diagram of 80-Gb/s OTDM signal.

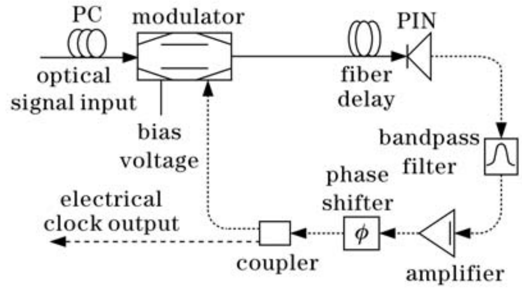

Fig. 4. The configuration of OEO.

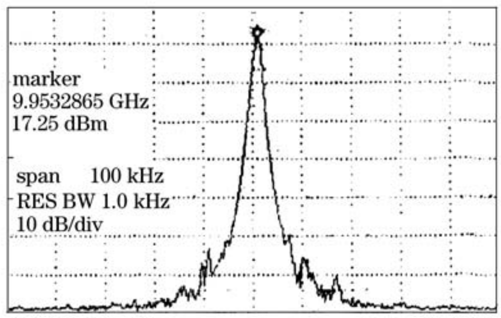

Fig. 5. The electrical spectrum of the extracted 10-GHz tributary clock.

is shown in Fig. 3, a clear eye opening indicated good multiplexing; the smear of the eye was attributed to the limited bandwidth of the photodetector.

Eye-diagram is not sufficient to verify the performance of the 80-Gb/s system, because error floor after demultiplexing cannot be observed on the oscilloscope. In order to do that, a back-to-back demultiplexing BER test experiment has to be carried out.

Before demultiplexing, local 10-GHz tributary clock controlling the demultiplexer should be extracted from 80-Gb/s OTDM signal. In this experiment, the tributary clock extraction was carried out using an OEO. Figure 4 shows the configuration of OEO, it consists of a $LiNbO_3$ modulator, a section of fiber delay, a photodetector (PIN) with a 3-dB bandwidth of 12 GHz, a 10-GHz electrical amplifier, an electrical narrow band pass filter with a center frequency of 10 GHz and a Q factor of 1000 and a phase shifter. The OEO has its own free running frequency, but this frequency can be injection locked to an external optical signal and even be injection locked to the sub-harmonics of the signal[6]. The sub-harmonic injection locking is the basis on which tributary clock extraction is performed. Before this experiment, the best result of clock extraction using this configuration was from 40-Gb/s OTDM signal to 10 GHz[6,7], in this experiment, we for the first time experimentally proved that the OEO was also applicable to extract 10-GHz clock from 80-Gb/s signal. The extracted clock was a sinusoidal wave in electrical domain; the electrical spectrum of which is shown in Fig. 5, with a spectral integration method[8], the timing-jitter of the extracted 10-GHz clock was calculated to be only 300 fs.

The configuration of the self cascaded EAM demultiplexer is shown in Fig. 6[9]. The input 80-Gb/s OTDM signal passed via a circulator through the EAM where it was switched for the first time, the passed signal was then conducted into the feedback loop where it was amplified to compensate the relatively larger insertion loss of the EAM, and subsequently filtered by an optical band-pass filter before it passed the EAM from the opposite direction for the second time. The optical delay-line was adjusted to synchronize the two passes. The average optical power injected into the demultiplexer was 4.6 dBm; the erbium-doped fiber amplifier (EDFA) in the feedback loop had a saturation power of 6 dBm. The EAM was biased at -3.2 V, the 10-GHz electrical signal was from OEO and amplified to a peak-to-peak voltage of 6 V to drive to EAM. With the conventional single pass configuration as in Ref. [4], a wide switching window of about 20 ps can be obtained, such wide window could not well suppress the adjacent tributary channel cross-talk in 80 Gb/s, in our experiment, the single pass configuration was also tried with a best BER of only 2×10^{-3}. The self cascaded configuration shortened the switching window to about 10 ps if the electrical phase shifter and the optical delay-line were carefully adjusted, Fig. 7 shows the eye-diagram of the demultiplexed 10-Gb/s tributary signal. The clear and open eye is a sign of high quality of the demultiplexed signal. The BER performance of the demulitplexed tributary signal was given in Fig. 8. An error free demultiplexing was successfully obtained. The power penalty at the BER of 10^{-9} was 3.25 dB. The power penalty maybe introduced by the following reasons: insufficient peak-to-pedestal suppression of the compressed 10-GHz pulse, imperfect multiplexing, not narrow enough demultiplexing window and rather large insertion loss of the EAM demultiplexer which may degrade tributary optical signal-to-noise ratio (OSNR).

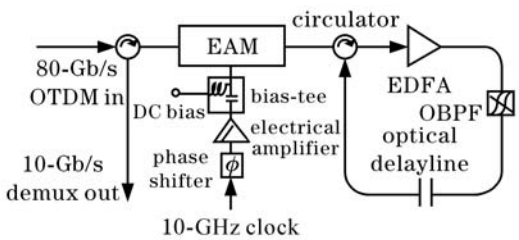

Fig. 6. The configuration of self cascaded EAM demultiplexer.

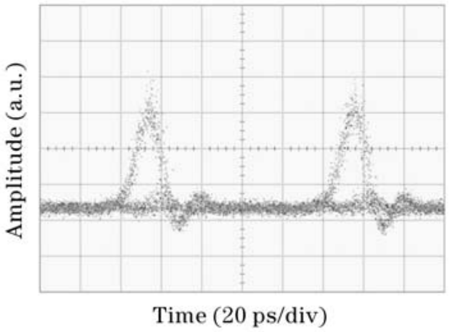

Fig. 7. The eye-diagram of the 10-Gb/s demultiplexed signal (20 ps/div).

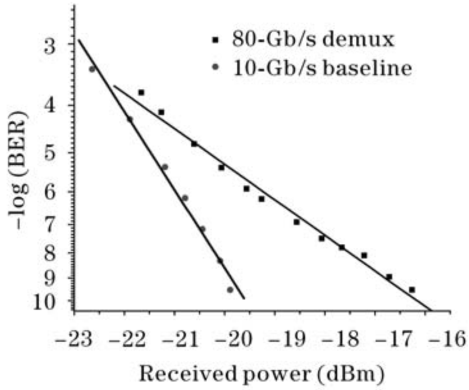

Fig. 8. The BER performance of the 8 × 10-Gb/s OTDM system.

In this letter, enabling technologies of 8 × 10-Gb/s OTDM system were discussed. An EAM based short pulse generator followed by a two-stage nonlinear compressor was used to generate 2-ps FWHM, 10-GHz tributary pulse train with a peak-to-pedestal suppression ratio of 18 dB, and a timing jitter of 650 fs; 10-GHz clock extraction from 80-Gb/s OTDM signal was demonstrated for the first time with a timing jitter of 300 fs; self cascaded EAM demultiplexer was also presented to shorten the demultiplexing window down to about 10 ps. The system performance was validated in a back-to-back demultiplexing experiment; error free demultiplexing was successfully achieved with a power penalty of 3.25 dB.

This work was supported by the National Natural Science Foundation of China under Grant No. 60444008904010247 and 60177019. L. Huo's e-mail address is huoli00@mails.tsinghua.edu.cn.

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