Demonstration of a 16×10-Gb/s OTDM system

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Received December 21, 2006

A 16 × 10-Gb/s optical time-division-multiplexing (OTDM) system was demonstrated experimentally with a well-designed ultrashort pulse source based on an electro-absorption modulator (EAM) and nonlinear fiber compressor. The obtained 10-GHz stable and pedestal-free pulse train has 2-ps width, high extinction ratio, and low timing jitter. An ultrafast demultiplexer based on a nonlinear optical loop mirror (NOLM) including a commercially available highly nonlinear fiber (HNLF) is employed to demultiplex data signal from 160 to 10 Gb/s. A back-to-back error-free demultiplexing experiment is 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 significantly; optical time-division-multiplexing (OTDM) is an important method of overcoming the electronic bottleneck and investigating the ultimate transmission of a single channel. The OTDM system generally consists of the following key sub-systems: ultrashort pulse source, tributary clock extraction, and ultra-high-speed optical demultiplexer. Up to now, ultra-high-speed OTDM systems have been demonstrated and investigated by several groups[1−3] with a record high speed of 1.28 Tb/s[1]. In Ref. [4], dynamic polarization-mode-dispersion at bit rate of 160 Gb/s is investigated experimentally.

We have previously reported a 4 × 10-Gb/s OTDM system[5] in which an actively mode-locked fiber ring laser (AMLFL) is used to generate short pulse train with high-quality, and an 8 × 10-Gb/s OTDM system[6] in which an stable short pulse generator consisting of an electroabsorption modulator (EAM) and two-stage compressor is employed. However, in a 16 × 10-Gb/s OTDM system, the time slot is only 6.25 ps, which sets a new challenge to the sub-systems, especially ultrashort pulse source, in which excellent features such as smaller pulse width, larger pulse peak-pedestal-ratio (PPR), and lower timing jitter are needed. In this letter, a 16 × 10-Gb/s OTDM system was demonstrated with an EAM and improved pulse compressor as the pulse generator which delivered a 1.9-ps, 10-GHz pedestal-free pulse train, and an ultrafast demultiplexer based on a nonlinear optical loop mirror (NOLM) including a commercially available highly nonlinear fiber (HNLF) which is employed to demultiplex data singal from 160 to 10 Gb/s. The system performance was verified in a back-to-back error-free demultiplexing bit error ratio (BER) test with a power penalty of around 8.0 dB. To our knowledge, this is the first 160-Gb/s OTDM system demonstration reported in China.

Figure 1 shows the experimental setup of our 160-Gb/s OTDM system. It mainly consists of two sections: the pulse generator and the NOLM-based demultiplexer. In the pulse generator after seeding pulse generation with an EAM, soliton-effect compression and SPM-based reshaping are employed, as presented in two dashed boxes of Fig. 1. In the demultiplexing section shown in dotted box of Fig. 1, all-optical demultiplexing scheme of HNLF based NOLM is utilized.

A 1544.57-nm continuous-wave light emitted from a distributed-feedback laser is carved by a bulk material InGaAsP EAM, which is biased at −2.96 V and driven by 10-GHz radio-frequency (RF) signal. The following dispersion compensating fiber (DCF) with −14 ps/nm is used for compensating linear chirp of the original pulse after EAM. Under the assumption of Gaussian pulse, the width of the compensated pulse is measured with a second harmonic generation (SHG) autocorrelator to be around 18.0 ps. In the following the pulse train passes through the soliton compression stage. Firstly the seed pulse is boosted with an erbium-doped fiber amplifier (EDFA) and injected into a 5-km dispersion shifted fiber (DSF) with a dispersion of 1.89 ps/(nm·km) and the zero dispersion wavelength (ZDW) at 1517 nm. The DSF acts as a soliton converter that reshapes the input pulse to a sech-like pulse. After the converter the pulse is slightly compressed to 16.3 ps and the optical spectrum is fitted very well by sech function. Secondly the pulse train is amplified and launched on a comb-like dispersion profile fiber (CDPF) chain, which acts as an adiabatic soliton compressor[7]. The pulse width after the CDPF is estimated to around 2.3 ps.

In the following a self-phase modulation (SPM) based

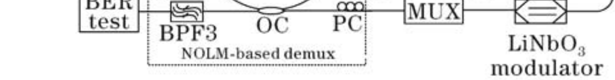

Fig. 1. Experimental setup of 16 × 10-Gb/s OTDM system.

reshaping stage is utilized, shown in the right dashed box of Fig. 1. The pulse reshaper is based on SPM induced spectral broadening in HNLF and subsequent offset filtering[8]. It has powerful functions of improving pulse quality, such as increasing pulse extinction ratio and removing pulse pedestal. At the same time, it has definite pulse compression capability, which results from temporal carving one of the pulse edges through spectral filtering the SPM-induced frequency chirp components on the edge[9]. Here the HNLF has a length of 1 km, the dispersion of −0.18 ps/(nm·km), the ZDW of 1562 nm and the nonlinear coefficient of 8.4 $W^{-1}\cdot km^{-1}$. The optical band-pass filter (BPF1) has 3-dB bandwidth of 2.0 nm. After amplified by an EDFA the pulse train is launched into the HNLF for spectral broadening, as presented in Fig. 2(b). The center wavelength of the BPF1 has around 7 nm offset from the carrier at the long wavelength direction for slicing the SPM-broadened spectrum. The autocorrelation traces of the pulse train after the BPF1 is presented in Fig. 2(a). And the optical spectra after the HNLF, after the BPF1, and after the BPF2 are measured with the optical spectrum analyzer (ANDO: AQ6315B), shown in Fig. 2(b). As presented in Fig. 2(b), after the HNLF the optical spectrum is broadened significantly. The spikes around the carrier in broadened spectrum are attributed to the pump pulse with pedestal, which is generated after adiabatic soliton compression in the CDPF. It can be found from Fig. 2(a) that the pulse after the BPF is slightly reduced to 1.9 ps and the pulse pedestal is removed completely. The obtained pulse has 3-dB spectral width of 2.2 nm and the resultant time-bandwidth product is around 0.5. This means that the compressed pulse is nearly transform-limited Gaussian pulse. At the same time, the timing jitter of the compressed pulse is calculated to be 280 fs with the von der Linde method. Such high-quality 10-GHz pulse train is data-coded by $LiNbO_3$ modulator with $2^{31}-1$ pseudo random binary sequence (PRBS) and is then time-division multiplexed by a conventional fiber-based multiplexer.

At the same time another part of broadened spectrum tapped from optical coupler (OC1) is filtered by the BPF2. It has around 8 nm offset from the carrier in the short wavelength direction. The filtered optical spectra are also shown in Fig. 2(b). In the same manner as BPF1's, the obtained pulse after the BPF2 has still no pedestal, high extinction ratio, the width of around 2.0 ps, 3-dB spectral width of 1.9 nm. For simplicity, the obtained pulse train after the BPF2 will be taken as clock pump pulse in the following 160×10-Gb/s

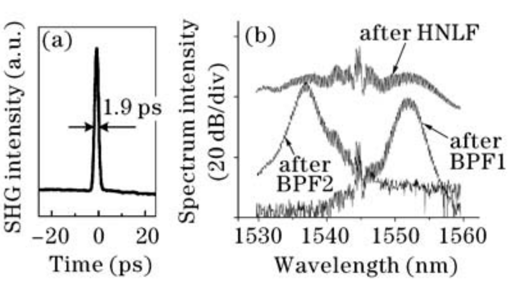

Fig. 2. (a) SHG trace of the pulse after BPF1, and (b) optical spectra after the HNLF in the reshaping stage, after the BPF1, and after the BPF2.

demultiplexing operation.

Here we adopt the slightly modified NOLM scheme for achieving 160×10-Gb/s all-optical demultiplexing. In the loop another HNLF is used as nonlinear medium, which has the same length of 1 km, the dispersion of −0.18 ps/(nm·km), the ZDW of 1555 nm, and the nonlinear coefficient of 8.4 $W^{-1}\cdot km^{-1}$. The specific modification is as following: besides 3-dB optical coupler (OC2) used to introduce clock pump pulse, another optical coupler (OC3) is also employed for constructing nearly symmetric loss map for clockwise and counterclockwise components of data signal. This design can avoid the self-switching of data signal efficiently even when its power is large enough to induce obvious nonlinear phase shift over the HNLF. As a result the NOLM intrinsic extinction ratio (IEX, defined as the ratio between the maximum and minimum NOLM output power when traversing all PC states in the loop while there is only the data signal input for NOLM) is still above 28 dB even with the large data signal. However, if the OC3 is removed the NOLM IEX would decrease greatly. Therefore the introduction of the OC3 allows larger data signal power injected into NOLM while maintaining enough IEX at the same time. Consequently the demultiplexed signal power would be larger compared with no OC3 case; the sensitivity requirement for preamplifier in the receiver is weakened and the spectral overlap of clock pulse to data signal is reduced relatively. In our experiment by adjusting the PCs (in loop and out loop), the delay between the data signal and the clock pulse, and the pump power of the clock pulse properly, the optimal demultiplexing state can be obtained. In Fig. 4 the spectra of clock and data signals measured at the NOLM output port are shown,

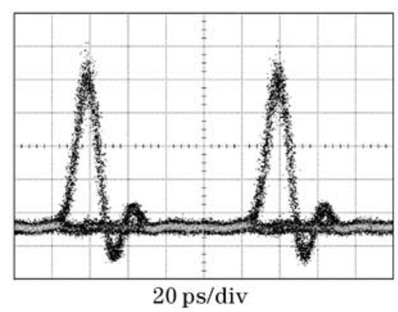

Fig. 3. Eye diagrams of 10-Gb/s demultiplexed from 160-Gb/s signal.

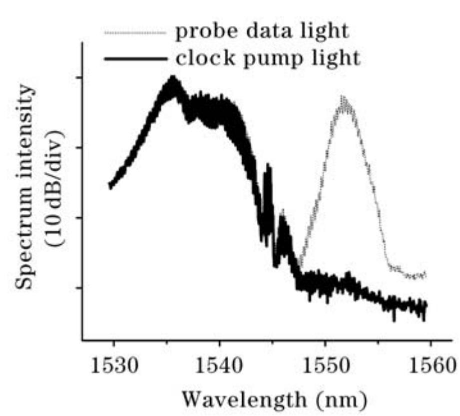

Fig. 4. Spectra of clock (around 1537 nm) and data (around 1552 nm) signals measured at the NOLM output port.

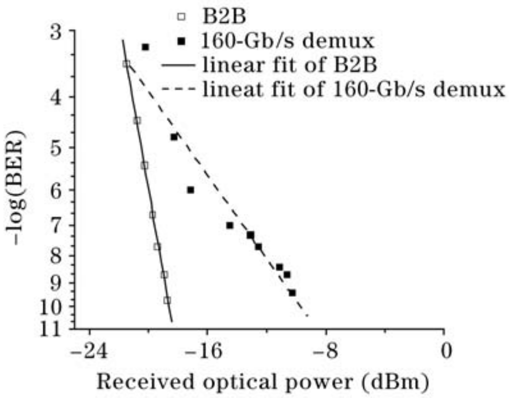

Fig. 5. BER measurement for demultiplexing to 10 Gb/s from 160-Gb/s signal in back-to-back configuration.

illustrating there is around −27-dB spectra overlap from pump clock to probe data. At the NOLM output port the BPF3 with 1.4-nm 3-dB bandwidth is utilized to extract the demultiplexed signal. The eyediagrams of the demultiplexed 10-Gb/s signal are shown in Fig. 3. The demultiplexed eyediagrams are very open and the non-target time-division channel is suppressed sufficiently. Figure 5 shows the BER curves for 10-Gb/s back-to-back case and the 10-Gb/s channel demultiplexed from 160-Gb/s signal. With respect to the B2B case, the demultiplexed signal has around 8-dB power penalty for receiver sensitivity at the BER of 10^{-9}. We think the penalty is attributed to demultiplexing procedures as well as pulse broadening through the BPF3. The penalty induced by pulse broadening is estimated to around 2.0 dB. To reduce spectral overlap between clock pulse and data signal greatly it is necessary to insert a BPF with large bandwidth at the point 'a' (see Fig. 1). However, limited to our laboratory condition, the important filter has not been employed, which is thought to be the main reason for the relatively large power penalty. Additionally, the walk-off between the data signal and the clock pulse is estimated to around 3.16 ps. If the wavelengths of data and clock are set at two sides of the ZDW of the HNLF in NOLM or the length of the HNLF is reduced simply, the walk-off can be reduced greatly and the power penalty attributed to the walk-off induced channel crosstalk can be removed.

In this letter, an experiment demonstration of 16×10-Gb/s OTDM system was carried out successfully. An EAM-based short pulse generator followed by a well-designed nonlinear fiber compressor was used to generate ultrashort pulse source with high quality, small width, high PPR, and low timing jitter. A NOLM-based demultiplexer including a commercially available HNLF is employed to demultiplex from 160 to 10 Gb/s successfully with error-free to validate the system performance.

This work was supported by the National Natural Science Foundation of China (No. 60577033), and the Basic Research Foundation of Tsinghua National Laboratory for Information Science and Technology (TNList). Y. Yang's e-mail address is yyf02@mails.thu.edu.cn.

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