Simultaneous Clock Enhancing and Demultiplexing for 160-Gb/s OTDM Signal Using Two Bidirectionally Operated Electroabsorption Modulators

Nan Jia, TangJun Li, KangPing Zhong, Jian Sun, MuGuang Wang, and Jing Li

***Abstract*—We demonstrate a technique for performing optical time-division simultaneous clock enhancing and demultiplexing using two bidirectionally operated electroabsorption modulators (EAMs). The performance of the proposed setup is verified experimentally in a 160-Gb/s 100-km transmission system. The 10-GHz clock component is enhanced before launching into the clock recovery module. The recovered 10-GHz clock signal is featured with low timing jitter (<300 fs) and error-free transmission is achieved with the power penalty of ∼0.9 dB. The proposed setup has merits of simultaneously enhancing base clock component and demultiplexing.**

***Index Terms*—Clocks, demultiplexing, electroabsorption modulator (EAM), optical time-division multiplexing (OTDM).**

I. Introduction

OPTICAL time division multiplexing (OTDM) has been an attractive method for achieving high transmission rates on a single wavelength [1], [2]. In OTDM systems, optical clock recovery and demultiplexing are two essential functions. To realize the two functions, electroabsorption modulator (EAM) was gained much interest for its nonlinear transfer function which permits narrow optical switching windows with large extinction ratios [3], [4]. Several configurations of bidirectionally operated EAM have been reported to for clock recovery [5] and demultiplexing [6], [7]. However, the two functions are realized independently. To reduce the complexity and cost, simultaneous operation of both functions using a small number of devices is of particular interest. Other configurations have been reported in the literature to enable simultaneous recovery and demultiplexing [8]–[10]. However, the setups of clock recovery and demultiplexer are still complex and costly. In this letter, we propose and demonstrate an improved setup for simultaneous clock enhancing and demultiplexing in a 160 Gb/s 100 km system. In the proposed configurations, simultaneous clock enhancing and demultiplexing is realized by utilizing two bidirectionally operated EAM. The experiments results exhibit that two bidirectionally operated EAMs could enhance the proportion of 10 GHz clock component which make it easier to recover 10 GHz clock. The extracted clock is featured with low timing jitter and excellent stability.

Manuscript received May 30, 2011; revised August 05, 2011; accepted August 07, 2011. Date of publication August 18, 2011; date of current version October 12, 2011. This work was supported by the Fundamental Research Funds for the Central Universities (Beijing Jiaotong University 2009YJS005), by the National 863 High Technology Projects of China (2007AA01Z258, 2008AA01Z15), by the National Natural Science Foundation of China (60807003), by the Beijing Nova Program (2008A026), by the National Science Foundation of Beijing (4062027), and by the National Natural Science Foundation of China (60877042, 60837003).

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Digital Object Identifier 10.1109/LPT.2011.2165208

II. Principle and Discussion

In OTDM systems different data signals are combined with a delay to provide a multiplexed data signal. The optical pulses are assumed to be Gaussian function. The mathematical expression of the amplitude of kth harmonic of clock-frequency component is given by [11]:

$$m_k = \frac{\sqrt{\pi}}{T_0} e^{-\left(\frac{k\tau}{T_0}\right)^2} \sum_{n=0}^{P-1} A_n e^{\left(-\frac{ik2\pi\tau n}{T_0 P}\right)} \tag{1}$$

T_0 is the period of multiplexed signal. When $P = 16$, namely there are 16 Pulses multiplexed in a period of 100 ps. An $(n = 0, 1, 2 \ldots)$ and τ are amplitude of pulses and pulse width respectively. The amplitude of base clock frequency component $(k = 1)$ is expressed by:

$$\begin{aligned} |m_1| = {} & \frac{\sqrt{\pi}}{T_0} e^{-\left(\frac{\tau}{T_0}\right)^2} \\ & \times \Bigg\{ \Bigg[(A_0 - A_8) + \cos\left[\frac{\pi}{8}\right](A_1 - A_7 - A_9 + A_{15}) \\ & + \cos\left[\frac{\pi}{4}\right](A_2 - A_6 - A_{10} + A_{14}) \\ & + \cos\left[\frac{3\pi}{8}\right](A_3 - A_5 - A_{11} + A_{13}) \Bigg]^2 \\ & + \Bigg[-(A_4 - A_{12}) \\ & - \sin\left[\frac{\pi}{8}\right](A_1 + A_7 - A_9 - A_{15}) \\ & - \cos\left[\frac{\pi}{4}\right](A_2 + A_6 - A_{10} - A_{14}) \\ & - \cos\left[\frac{3\pi}{8}\right](A_3 + A_5 - A_{11} - A_{13}) \Bigg]^2 \Bigg\}^{-1/2} \end{aligned} \tag{2}$$

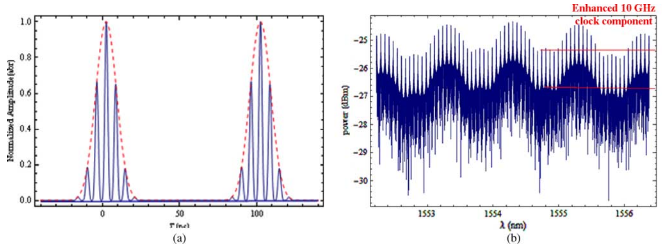

Fig. 1. Simulated waveform and spectrum of 160-Gb/s signal after EAM1. (a) Waveform; (b) spectrum.

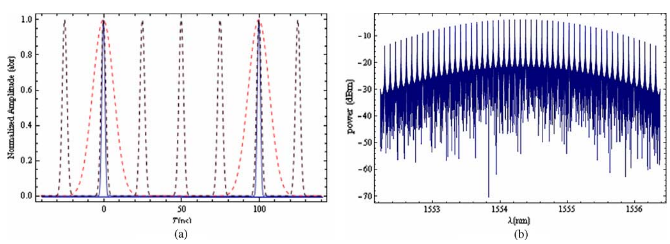

Fig. 2. Simulated waveform and spectrum of 160-Gb/s signal after two EAMs. (a) Waveform; (b) spectrum.

It can be derived that the amplitude of clock frequency component is related to duty cycle, amplitude of each tributary. The smaller is the duty cycle, the more is the harmonic components. This will affect the proportion of base clock in the harmonic components. Furthermore, according to formula 2, the difference of tributary amplitudes is helpful to obtain the 10 GHz clock component by enlarging the amplitude difference of tributary: Assumed that $A_0 = A$, $An = 0$ $(n = 1, 2, \ldots, 15)$, the amplitude of base clock component is much stronger than other harmonic components amplitude, which means the proportion of base clock component is maximum, which makes it easy to extract the 10 GHz clock components. If $An = A$ $(n = 0, 1, 2, 15)$, that is the equal-amplitude multiplexed 160 GHz signal, the proportion of 10 GHz clock component is zero, the 160 GHz clock component is the strongest. Moreover, each harmonic clock component can be obtained by multiplexing difference amplitude tributary. Simulated waveform and spectrum of 160 GHz signal after the EAM1 are shown in Fig. 1(a) and (b), respectively. In Fig. 1(a), the equal-amplitude 160 GHz signals was switched into unequal-amplitude signals by EAM1, the 10 GHz clock components is partly enhanced, as shown in Fig. 1(b). When signal passed through the cascaded EAMs, Fig. 2(a), the 10 GHz clock component is further enhanced, Fig. 2(b).

III. Results and Discussion

We tested this setup of simultaneous clock enhancing and demultiplexing using two bidirectionally operated EAM in a 160 Gb/s OTDM 100 km transmission experiment. The transmitter has a picosecond pulsed fiber laser (PSL-10-1T, CALMAR OPTCOM Model), which produces an optical pulse train at repetition rates of 10 GHz (Full width at half maximum, FWHM $= 1.5$ ps, $\lambda = 1555.83$ nm) with timing jitter less than 75 fs. The 10 GHz pulse train is then launched in an external LiNbO3 Mach–Zehnder modulator (MZM) driven by a pattern generator (Agilent N4901B, $2^7 - 1$). A homemade fiber delay line multiplexer is used to provide a multiplexed 160 Gb/s data signal at the input of the fiber link, Fig. 3(a). The 160 Gb/s

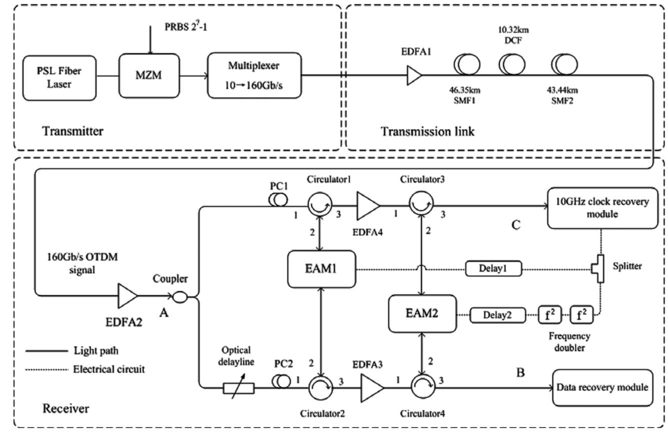

Fig. 3. Experimental setup of 160-Gb/s OTDM system. PSL: Picosecond fiber laser. MZM: Mach–Zehnder modulator. PC: Polarization controller. EDFA: Erbium-doped fiber amplifier.

data signal is then amplified by erbium-doped fiber amplifier1 (EDFA1) and fed into the 100.11 km transmission link. As shown in Fig. 3, the 100.11 km transmission link consists of three parts: two spans of single mode fiber (SMF) with lengths of 46.35 and 43.44 km, and a span of dispersion-compensation fiber (DCF) with length of 10.32 km. DCF is used to compensate the dispersion caused by the two spans of SMF.

At the receiver, the 160 Gb/s data signal is split at the 3 dB-coupler into two branches: one is used for clock recovery; the other is used for further demultiplexing. Before launching into the EAM1, the one used for clock recovery passes a polarization controller (PC) and the other one passes an optical delay line and polarization controller, where the optical delay line was used to select different OTDM channels. Then, via two circulators, the signals in the two branches pass the EAM1 in opposite directions. The two switched output signals in opposite directions are amplified by EDFA3 and EDFA4, respectively. The signals in the two branches pass the EAM2 in opposite directions via the other two circulators. The switched output signals of the EAM2 are used for two ways: one is launched into clock recovery module based on phase-locked (PLL). The other is fed into data recovery module. The recovered 10 GHz electrical clock signal is spitted into two parts: one part fed into the electrical input of the EAM1 to close the loop of PLL; the other part is multiplied to 40 GHz and fed into the electrical input of the EAM2. By adjusting the delay line, the RF power and the bias voltage, EAM1 can generate a shortened switching window of about 20 ps (FWHM) at the repetition rates of 10 GHz. And EAM2 can generate an optimized switching window of 6 ps (FWHM) approximately with a suppression ratio of better than 23 dB. The outstanding extinction ratio of EAM2 ensures sufficient rejection of all other channels to eliminate crosstalk.

By adjusting the phase shift of the extracted clock, the 10 Gb/s signal can be demultiplexed with high quality. In Fig. 4(a), the 10 GHz clock component is not prominent in the multiplexed signal. When the 160 Gb/s signal is switched into 40 Gb/s by EAM1. Eye diagram of demultiplexed 10 Gb/s signal after two EAMs are shown in Fig. 4(b). The enhanced 10 GHz clock is shown in Fig. 4(c). The bias voltage of EAM1 and EAM2 is -2.8 v and -1.4 v, respectively. Simultaneously, the 10 GHz

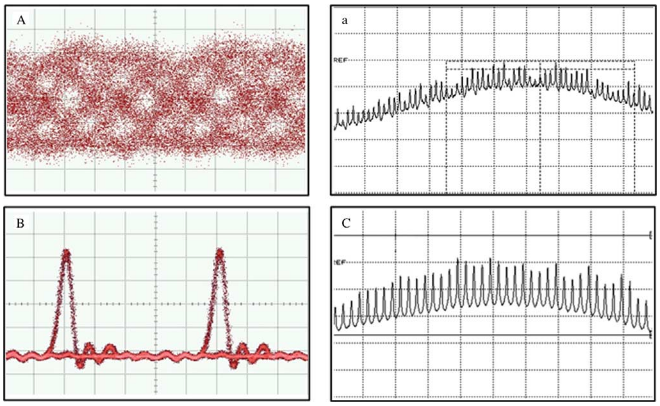

Fig. 4. Eye diagrams of the positions at A, B, C in setup. (A) Eye diagrams of 160-Gb/s signal at receiver part. (a) Spectrum of 160-Gb/s signal. (B) Eye diagrams of demultiplexed 10 Gb/s from 160 Gb/s. (C) Spectrum of enhanced 10-GHz clock after EAMs.

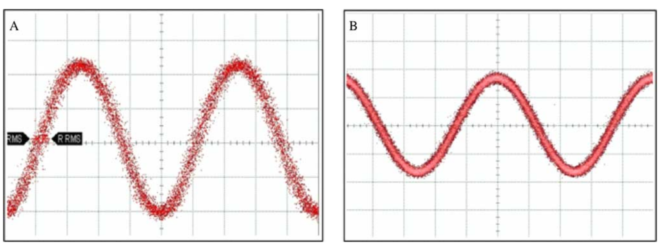

Fig. 5. Waveform of the 10-GHz extracted clock from 160-Gb/s OTDM.

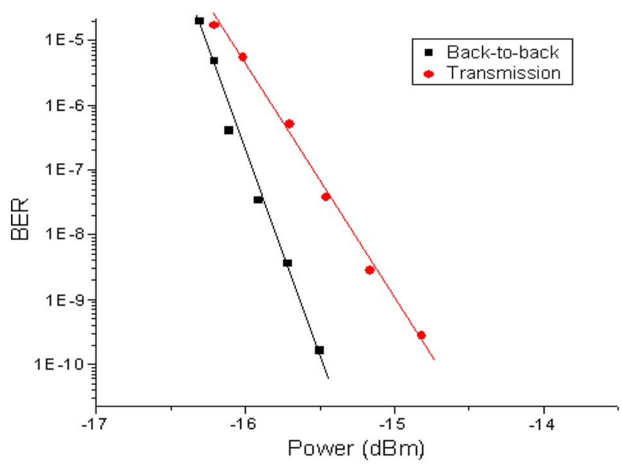

Fig. 6. BER measurements of 160 to 10 Gb/s.

clock component is enhanced after two EAMs. Therefore, it can be easily recovered by the phase-locked loop (PLL) module provide by the NEL Company. The 10 GHz clock component from 160 Gb/s OTDM signal is shown in Fig. 5(a). Integrating the noise pedestal results in the root mean square (RMS) timing jitter of about 1.15 ps. On contrary, after being enhanced by two EAMs, the recovered 10 GHz clock component is shown in Fig. 5(b). Integrating the noise pedestal results in the RMS timing jitter of about 300 fs. The extracted 10 GHz clock component exhibits excellent phase stability. By finely tuning the variable electrical delay line and the bias of the EAM1 and EAM2, error-free demultiplexing is achieved.

Fig. 6 shows bit error rate (BER) measurements of 160 Gb/s to 10 Gb/s after transmission over 100 km and back to back (B2B) against the received power, respectively. After 100 km transmission, the received sensitivity ($\mathrm{BER} = 10^{-9}$) measured at data recovery module is -14.75 dBm, corresponding sensitivity of Back-to-Back of the same BER performance measured at data recovery module is -15.65 dBm. The power penalty is $\sim$0.9 dB. This is caused by amplified stimulated emission (ASE) noise of the EDFA and demultiplexer of the two EAMs.

IV. Conclusion

In conclusion, we have demonstrated a simultaneous clock enhancing and demultiplexing by using two bidirectionally operated EAM. Excellent locking stability with no channel hopping was achieved in the 160 Gb/s OTDM 100 km transmission system allowing error-free 160 Gb/s to 10 Gb/s demultiplexing with the penalty of $\sim$0.9 dB. The experiments results exhibit that the bidirectionally operated EAM could enhance the proportion of 10 GHz clock component and make it easier to recover 10 GHz clock. The extracted clock is featured with low timing jitter (less than 300 fs) and excellent stability.

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