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Compact 160-Gb/s Add-Drop Multiplexing with a 40-Gb/s Base-Rate

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Abstract: We report on the first 40 Gb/s-based OTDM add-drop multiplexing at 160 Gb/s using electrically driven electroabsorption modulators. Error-free operation for all channels is obtained with an average power penalty of 1 dB.

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1. Introduction

Time-domain add-drop multiplexing (ADM) is an essential function in an optical time-division multiplexed (OTDM) network. Two operations are performed: (1) a base-rate channel is extracted from the high-speed line signal (drop function); (2) the time-slot of the dropped channel is cleared and a new channel is inserted while the through channels remain undisturbed (add function). These operations require two complementary switching windows with well-defined shapes, which is challenging at high bit-rates. ADMs with a 160-Gb/s line-rate were not reported until recently [1,2]. These demonstrations utilized gain-transparent operation of a semiconductor optical amplifier (SOA) to reduce pattern effects and noise in conventional SOA-based interferometric switches. Another choice for high-speed switching is an electroabsorption modulator (EAM). The advantages of EAM over SOA-based approaches include: (1) the switching window is generated without an interferometer; (2) only electrical control signal is required. Therefore, EAMs are promising for more compact and efficient ADM. Nevertheless, only 40-Gb/s ADM was demonstrated so far with a 10-Gb/s base-rate [3], mainly due to the limitation of switching window width.

In this work, we demonstrate the first 160-Gb/s ADM using EAMs and with the highest ever 40-Gb/s base-rate. The switching window of the EAM is shortened by the increased base-rate and also by using a standing-wave enhanced design [4]. Mixing microwave harmonics can also shorten the switching window of the EAM for a 10-Gb/s base-rate [5] but upgrading the base-rate to 40 Gb/s can reduce the number of optical channels and lead to a more efficient OTDM system. It is worth nothing that while a 40-Gb/s base-rate favors the EAM for 160-Gb/s operation, it is more challenging for SOA-based switches due the limitation of carrier life-time. This work not only represents a great advance in base-rate but also a significant reduction in complexity and cost for the next generation 160-Gb/s OTDM system.

2. Experiment and Results

The configuration of the 40Gb/s-based ADM is shown schematically in Fig. 1. Two EAMs are used to implement

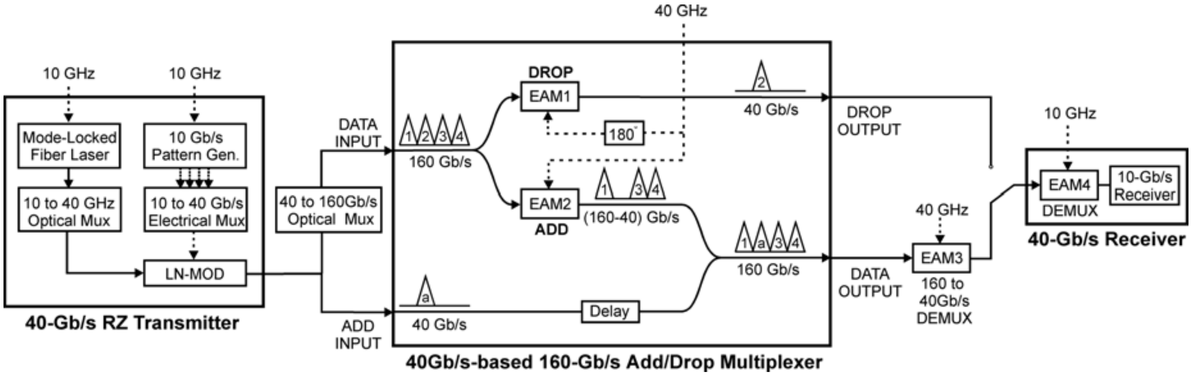
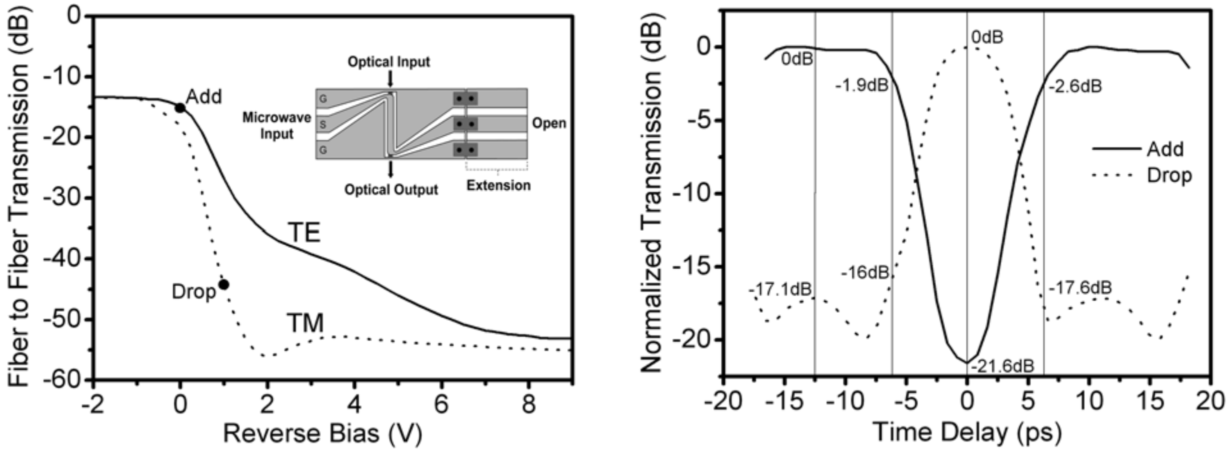


Fig. 1. Schematic setup of the 40Gb/s-based add-drop multiplexing using electroabsorption modulators. Solid line: optical link. Dotted line: electrical link.



(a) (b)

Fig. 2. (a) Static fiber to fiber transmission of the EAM for TE and TM polarizations at 1557.5nm. The solid circles are the bias points for respective operations. Insert: Layout of the standing-wave enhanced EAM. (b) Dynamic transmission at 40GHz measured by scanning a 1.5 ps pulse train. The vertical lines are spaced by 6.25 ps.

the drop function (EAM1) and the add function (EAM2) individually. A new channel can be added with the through channels passively with a coupler and a delay line. The only differences between the two EAMs are the bias voltage and the phase of the driving signal, which implies that single-chip integration is possible. The EAM used in this work has traveling-wave electrodes (CPW line) designed to overcome the RC-time limitation [6]. The device is 1000 μm long and 330 μm wide. With a 35-Ω termination, the bandwidth is > 20 GHz. The static fiber to fiber transmissions for the TE and TM polarizations at 1557.5 nm are shown in Fig. 2(a), together with the layout of the standing-wave enhanced mode. To enhance the E-O response at 40 GHz, a microwave standing-wave pattern is formed along the CPW line by adopting an open termination [4]. The spatial phase is adjusted with a 500-μm extension CPW line. TE polarization is chosen to optimize the add function and TM for the drop function. The polarization dependence can be reduced by properly compensating the strain in the quantum wells [7]. The bias voltage is 0 V for the add function and -1 V for the drop function. The EAM is driven by a 6 V_{p-p}, 40-GHz sinusoidal microwave.

By scanning a 1.5 ps, 10-GHz optical pulse train through the EAM, the gating windows are obtained as shown in Fig. 2(b), which represents the closest estimation of actual performance since the pulse source is the same as that used in the transmitter. Due to the high modulation efficiency of the EAM, the switching window can be changed for the opposite operation by adjusting only 1 V in bias voltage. The suppression of adjacent channels is over 16 dB in the drop function and the clearing of the targeted time-slot is over 21 dB in the add function. However, there can be a variation of 1.9 ~ 2.6 dB in power among the through channels in the add function. This can be reduced by moving the bias point upwards along the transmission curve in Fig. 2(a) but the extinction ratio may be reduced. In that case, the effective driving voltage must be increased by either a higher driving power or an impedance matching network to obtain the required extinction ratio.

As shown in Fig. 1, a 40-Gb/s NRZ electrical signal is generated from four 10-Gb/s 2^7-1 PRBS tributaries using an electrical multiplexer. The PRBS word length is limited by the electrical multiplexer. This 40-Gb/s signal drives a $LiNbO_3$ modulator to encode a 40-GHz optical pulse train, which is passively multiplexed from a 10-GHz, 1.5 ps pulse train generated by a mode-locked fiber laser centered at 1557.5 nm. The output 40-Gb/s RZ signal is split into two parts. One is further multiplexed to 160-Gb/s with single-polarization and the other is used as the added channel. On the receiver side, EAM3 is used to demultiplex 160-Gb/s signals back to 40-Gb/s. The switching window requirements for EAM3 in the receiver (demultiplexing) and EAM1 in the ADM (drop) are exactly the same. The 40-Gb/s receiver is composed of an optical 40- to 10-Gb/s demultiplexer (EAM4) and a 10-Gb/s electrical receiver. Even though the ADM is working with a 40-Gb/s base-rate, bit-error-rate (BER) is measured at 10-Gb/s for all 16 channels. BER measurement can be implemented at 40-Gb/s when a 40-Gb/s BER tester is available. The input power level to EAM1, EAM2, and EAM3 in the experiment is approximately -1 dBm per 40-Gb/s channel.

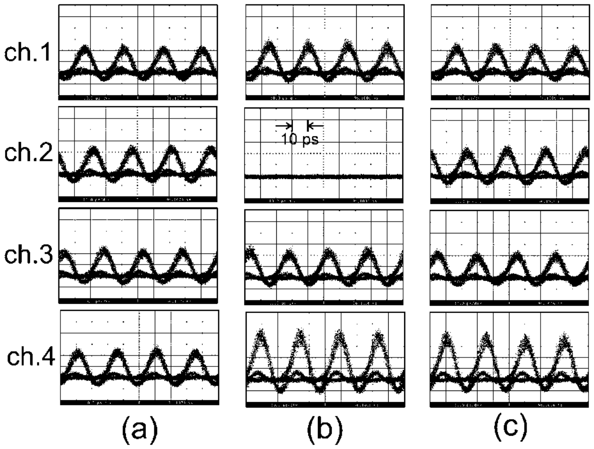


Fig. 3. 40-Gb/s eye diagrams of the four channels in the 160-Gb/s signal (a) back to back; (b) after ch.2 is dropped; (c) after a new 40-Gb/s channel is added.

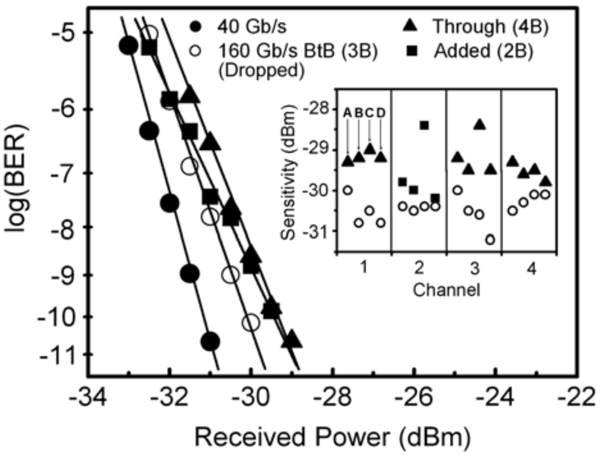


Fig. 4. BER curves measured at 10Gb/s. The insert shows the receiver sensitivities of the four 10-Gb/s tributaries in each 40-Gb/s channel

The eye diagrams of the 160-Gb/s signals cannot be fully resolved by using a 50-GHz electrical sampling scope with a 40-GHz photodetector. Instead, the 160-Gb/s signals are sampled after the 160- to 40-Gb/s demultiplexer (EAM3), which extracts the four 40-Gb/s channels individually. Fig. 3(a) shows the eye diagrams of the four channels in the back-to-back 160-Gb/s signal. The bumps on the bottom of the eyes are caused by the response of the photodetector. After EAM2, a 40-Gb/s channel (ch.2) is cleared, as shown in Fig. 3(b). The eye amplitude of ch.4 is about 2 dB higher than the other two through channels, in agreement with the pulse scanning results in Fig. 2(b). A new 40-Gb/s channel is then added to the cleared time-slot and Fig. 3(c) shows no observable sign of interference.

Fig. 4 shows the results of BER measurements. The received power is measured at the input of the 10-Gb/s receiver. The 40-Gb/s line is obtained by sending a 40-Gb/s signal to the 160-Gb/s receiver (EAM3 plus the 40-Gb/s receiver). There is a 1-dB power penalty when the input is changed to the 160-Gb/s back-to-back (BtB) signal. The penalty mainly comes from the finite suppression ratio of the 160- to 40-Gb/s demultiplexer. Note that the 160-Gb/s BtB line also represents the BER result for the dropped channel. The averaged power penalty for the four 40-Gb/s channels (ch.1 to 4) are 1.3, 0.8, 1.4 and 0.7 dB, respectively, which results in an overall power penalty of 1 dB. A low power penalty of 0.8 dB for the added channel (ch.2) indicates that the clearing of the time-slot in the add function is successful and the interference with the residue of the dropped channel is negligible. The 2-dB variation in power among the through channels (ch.1, ch.3 and ch.4) only results in a 0.6 ~ 0.7 dB difference in power penalty, which is believed to be a consequence of the varied signal-to-noise ratio due to the power variation.

3. Conclusion

By using standing-wave enhanced EAMs, 160-Gb/s ADM with a 40-Gb/s-base-rate is demonstrated for the first time. The averaged power penalty is as low as 1 dB. The operation does not require interferometers and optical control pulses as in SOA-based switches. Together with a 40-Gb/s high base-rate, this work shows that compact and efficient ADMs can be realized with EAMs.

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