Title
Compact 160-Gb/s demultiplexer using a single-stage electrically gated electroabsorption modulator

Journal
IEEE Photonics Technology Letters, 15(10)

ISSN
1041-1135

Authors
Chou, H F
Chiu, Y J
Wang, W
et al.

Publication Date
2003-10-01

Peer reviewed

Compact 160-Gb/s Demultiplexer Using a Single-Stage Electrically Gated Electroabsorption Modulator

Hsu-Feng Chou, Yi-Jen Chiu, Wei Wang, John E. Bowers, *Fellow, IEEE*, and Daniel J. Blumenthal, *Fellow, IEEE*

***Abstract*—Direct 160–10-Gb/s demultiplexing using a single-stage electrically gated electroabsorption modulator is reported for the first time. The drive signal consists of two mixed microwave tones used to reduce the gating window width to under 5.7 ps for both TE and TM modes. Error-free operation is obtained without an observed error floor. This single-stage design is compared to a dual-stage demultiplexer (160–40 and 40–10 Gb/s) and experimental results show that the power penalty is lower for the single-stage demultiplexer, illustrating both the performance and complexity advantages of the new design.**

***Index Terms*—Demultiplexing, electroabsorption, optical time-division multiplexing, standing-wave device, traveling-wave device.**

I. Introduction

A CRITICAL issue in optical time-division multiplexing (OTDM) is the ability to demultiplex the high-speed line signal down to lower speed tributaries where electrical processing is feasible. While fiber-based technology has been demonstrated up to 640 Gb/s [1], semiconductor-based technology has the advantages of compactness and a higher level integration potential. Several semiconductor-based optically gated approaches have been reported including the GT-UNI [2], SOA-MZI [3], [4], and PD-EAM [5]. Two issues with these previous approaches are the presence of bit-error rate floors and the requirement for high-quality optical pulses for the gating signal. An alternative approach is to use electrically gated electroabsorption modulators (EAMs). To demutiplex 160 Gb/s down to 10 Gb/s, the gating window should be less than 6 ps at a 10-GHz repetition rate. The reported demonstrations [6], [7] utilized a 40-GHz driving signal to generate a gating window short enough for demultiplexing the signal to 40 Gb/s in the first stage. A second optical [6] or electrical [7] demultiplexing stage was then required to bring the signal down to 10 Gb/s.

We have recently demonstrated 80–10-Gb/s demultiplexing using a standing-wave enhanced EAM (SW-EAM) [8]. With our current device design, the shortest possible gating window of the EAM can be as short as 6 ps when driven by only a 10-GHz sinusoidal microwave. However, the total optical loss is too high for error-free demultiplexing. In this work, we mix both 10 and 20 GHz driving signals to effectively shorten the gating window of a single EAM for 160-Gb/s operation. We also setup a dual-stage DEMUX similar to [6] for performance comparison.

Manuscript received January 28, 2003; revised June 12, 2003. This work was supported in part by the National Science Foundation Ultra-Capacity Optical Networks Award ECS0123864.

H.-F. Chou, W. Wang, J. E. Bowers, and D. J. Blumenthal are with the Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106-9560 USA (e-mail: hubert@ece.ucsb.edu).

Y.-J. Chiu was with the Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106-9560 USA. He is now with the Institute of Electro-Optical Engineering, National Sun Yat-sen University, Kaohsiung 80441, Taiwan, R.O.C.

Digital Object Identifier 10.1109/LPT.2003.818243

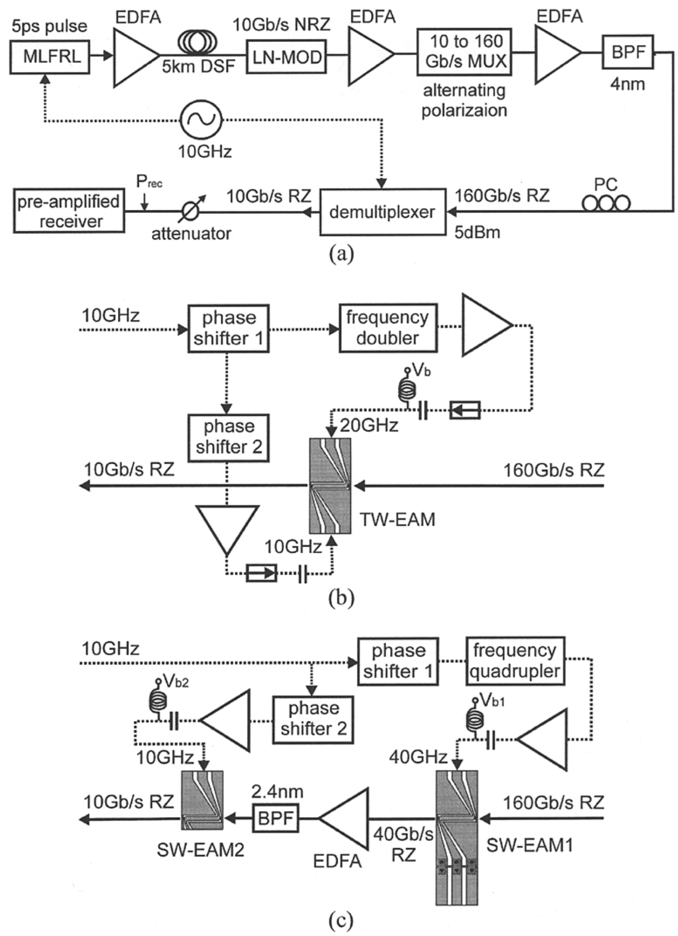


Fig. 1. (a) System configuration. (b) Single-stage demultiplexer. (c) Dual-stage demultiplexer (solid line: optical link; dotted line: electrical link).

II. Experimental Setup

The system configuration is shown schematically in Fig. 1(a). The 10-GHz 5-ps optical pulses are generated at 1555 nm using a mode-locked fiber ring laser (MLFRL). These pulses are nonlinearly compressed using 5 km of dispersion-shifted fiber (DSF). The pulsewidth after compression is around 2 ps.

The 10-GHz pulse train is encoded with $2^{31}-1$ pseudo-random binary sequence (PRBS) by an $LiNbO_3$ modulator (LN-MOD) and then optically multiplexed to 160-Gb/s return-to-zero (RZ) data format with passive delay lines and couplers. In this experiment, the 160-Gb/s signal is multiplexed with alternating polarization because the compressed pulse has relatively long tails. Single polarization multiplexing led to intersymbol interference (ISI) and error-free operation was not obtained with either DEMUX approach.

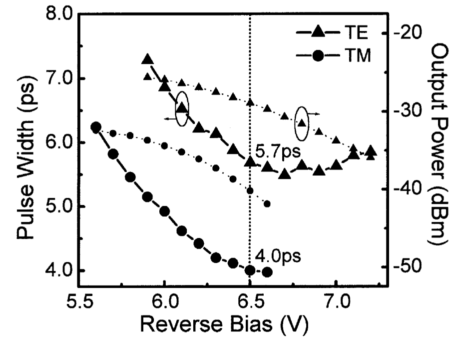
The EAMs used in this work are of the traveling-wave electrode design that can extend the active device length while still maintaining a broad band-width. A longer active length leads to higher extinction ratio (50 dB), higher modulation efficiency (30 dB/V), and lower driving voltage (1 V_{p-p} for error-free 10-Gb/s modulation) [9]. By properly adjusting the termination of the traveling-wave electrodes, the EAM can be operated in either the traveling-wave mode or the standing-wave enhanced mode to optimize the performance for a particular application [8], [10].

Fig. 1(b) shows the configuration of the single-stage DEMUX. A traveling-wave EAM (TW-EAM) is driven by two microwave tones, 10 (24.6 dBm) and 20 GHz (23.4 dBm), respectively, from the two ends of the traveling-wave electrodes. This is a unique configuration for the TW-EAM where the microwave loss that might occur if the two tones were combined with a coupler can be eliminated. When the relative phase between the two tones is adjusted properly, the TW-EAM will see a pulse-like driving signal with a repetition rate of 10 GHz. The microwave voltage around the pulse peak can swing faster than that of the 10-GHz sinusoidal wave and, hence, shortens the gating window. The gating window of the EAM can be accessed through a pulse-generation experiment. Fig. 2(a) shows both the pulsewidth and the output power of the generated pulses using the single-stage DEMUX. The input power is 2 dBm at 1555 nm. From this figure, the bias voltage is chosen to be 6.5 V at which the pulsewidth of the transverse electric (TE) polarization is 5.7 and 4.0 ps for the transeverse magnetic (TM) polarization. Although the TM polarization has a shorter pulsewidth, its output power is more than 10 dB lower then the TE polarization. Therefore, TE polarization is adopted to ensure an adequate signal-to-noise ratio (SNR).

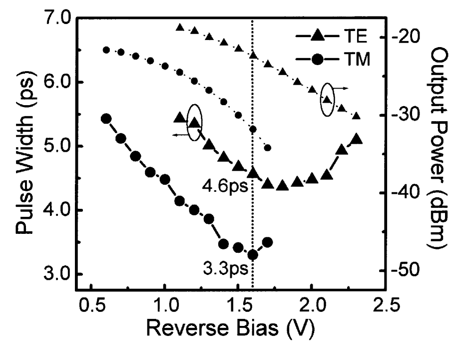
As shown in Fig. 1(c), the dual-stage DEMUX is composed of two standing-wave enhanced EAMs [10], SW-EAM1 and SW-EAM2, respectively, optimized for 40 and 10 GHz gating operations with termination line lengths of 840 and 150 μm. The microwave driving powers are 19 dBm for 40 GHz and 20 dBm for 10 GHz. Fig. 2(b) shows the 40-GHz pulse generation results of SW-EAM1. The gating window is 4.6 ps (TE) at 1.6-V reverse bias. For SW-EAM2, the bias voltage is set at 4.1 V and the gating window is 11 ps (TE). In the experiment, the output power of SW-EAM1 is no more than -20 dBm so an EDFA is inserted between the two SW-EAMs to compensate for the loss.

III. Results and Discussion

Eye histograms at different bit rates are shown in Fig. 3. They are taken with a 50-GHz digital sampling scope and a 40-GHz photodetector. The 160-Gb/s eye can hardly be seen without using a histogram. The directly demultiplexed 10-Gb/s eye (10:160 Gb/s eye) using the single-stage DEMUX is pretty clear and open. The bumps on the ground level are mainly cause by the electrical reflections in the photodetector which is evident from its impulse response. In the dual-stage DEMUX, the 160-Gb/s signal is first demultplexed to 40 Gb/s by SW-EAM1 and then to 10 Gb/s by SW-EAM2. The response of the photodetector leads to a partial closure of the 40-Gb/s eye (40:160 Gb/s eye) but when the signal is further demultiplexed by SW-EAM2, the 10-Gb/s eye (10:40:160 Gb/s eye) opens up. However, the 10:40:160 Gb/s eye is more noisy than the 10:160 Gb/s eye. Fig. 4 shows the bit-error rate (BER) curves of the two DEMUX.



(a)



(b)

Fig. 2. Pulsewidth and output power of pulses (a) generated by TW-EAM at 10 GHz and (b) generated by SW-EAM1 at 40 GHz. Input optical power is 2 dBm at 1555 nm (solid line: pulsewidth; dotted line: output power; vertical short dotted line: bias condition for the demultiplexer).

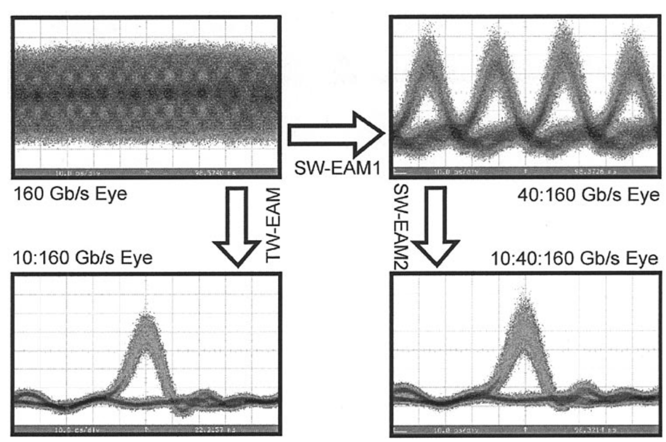


Fig. 3. Eye histograms at different bit-rates. "10:160 Gb/s eye" means the eye histogram of the 10-Gb/s signal demultiplexed from 160 Gb/s, and similarly for the others.

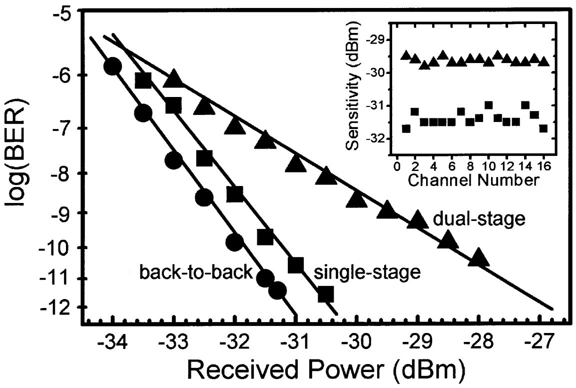


Fig. 4. BER curves of back-to-back and demultiplexed 10-Gb/s signals. Insert: Receiver sensitivity of individual channels.

Error-free operations are achieved and no error-floor was observed. The receiver sensitivities of all 16 channels were measured individually and the variation among them is primarily caused by the imperfection of the multiplexer (MUX). The averaged power penalty for the single-stage DEMUX is 1 dB and 2.8 dB for the dual-stage DEMUX. It is evident from Fig. 4 that the slope of the BER curve of the single-stage DEMUX is almost the same as that of the 10 Gb/s back-to-back (without MUX, DEMUX, and two EDFAs). On the other hand, the slope decreases for the dual-stage DEMUX, indicating a degradation in sensitivity.

The 1-dB power penalty of the single-stage DEMUX mainly comes from the ISI caused by the tails of the compressed pulse. The polarization dependence of the EAM actually helped to minimize the effect of ISI because the adjacent channels are TM polarized, which experiences higher loss. However, in the experiment, the polarizations in the MUX are not perfectly aligned, so some ISI may still occur. For the dual-stage DEMUX, the EDFA for loss compensation can degrade the SNR because the output power from SW-EAM1 is no more than -20 dBm. Therefore, the power penalty is higher and the demultiplexed eye has more noise. Increasing the optical input power beyond 5 dBm to SW-EAM1 might improve the SNR but the EAM will suffer from pattern dependence caused by the stronger photocurrent bouncing back and forth along the traveling-wave electrodes.

The operating wavelength range of the single-stage DEMUX can be measured by systematic pulse-generation experiments at different wavelengths. By setting the gating window to be less than 5.7 ps and the output power higher than the receiver sensitivity, the single-stage DEMUX is able to operate from 1545 to 1565 nm. The current polarization dependence of the EAM can be reduced by properly compensating the strain in the quantum wells [11].

IV. Conclusion

In conclusion, we have demonstrated a compact single-stage 160–10-Gb/s OTDM DEMUX using a traveling-wave electroabsorption modulator driven by dual-microwave tones. The single stage DEMUX is more compact and has a smaller power penalty than the dual-stage DEMUX. This compact DEMUX does not require high-quality gating pulses like other semiconductor-based approaches. We believe that the current limitation of alternating polarization multiplexing can be removed if the quality of the transmitter pulse is improved. This work shows that electrically driven electroabsorption modulators are capable of demultiplexing 160-Gb/s signals down to either 40 or 10 Gb/s efficiently, which is essential to next-generation OTDM systems.

References

[1] T. Yamamoto, E. Yoshida, and M. Nakazawa, "Ultrafast nonlinear optical loop mirror for demultiplexing 640 Gbit/s TDM signals," *Electron. Lett.*, vol. 34, no. 10, pp. 1013–1014, 1998.

[2] C. Schubert, S. Diez, J. Berger, R. Ludwig, U. Feiste, H. G. Weber, G. Toptchiyski, K. Petermann, and V. Krajinovic, "160-Gb/s all-optical demultiplexing using a gain-transparent ultrafast-nonlinear interferometer (GT-UNI)," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 475–477, May 2001.

[3] S. Nakamura, Y. Ueno, K. Tajima, J. Sasaki, T. Sugimoto, T. Kato, T. Shimoda, M. Itoh, H. Hatakeyama, T. Tamanuki, and T. Sasaki, "Demultiplexing of 168-Gb/s data pulses with a hybrid-integrated symmetric Mach-Zehnder all-optical switch," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 425–427, Apr. 2000.

[4] M. Heid, S. L. Jansen, S. Spalter, E. Meissner, W. Vogt, and H. Melchior, "160-Gbit/s demultiplexing to base rate of 10 and 40 Gbit/s with a monolithically integrated SOA-Mach-Zehnder interferometer," presented at the *Proc. ECOC 2002*, vol. 3, 2002. Paper 8.4.3.

[5] S. Kodama, T. Yoshimatsu, T. Ito, H. Ito, and T. Ishibashi, "160 Gb/s error-free demultiplexing by ultrafast optical gate monolithically integrating phtodiode and electroabsorption modulator," *Electron. Lett.*, vol. 38, no. 24, pp. 1575–1576, 2002.

[6] B. Mikkelsen, G. Raybon, and R.-J. Essiambre, "160 Gb/s TDM transmission systems," in *Proc. ECOC 2000*, vol. 2, 2000, pp. 125–128.

[7] E. Lach, M. Schmidt, K. Schuh, B. Junginger, G. Veith, and P. Nouchi, Advanced 160 Gbit/s OTDM system based on wavelength transparent 4×40 Gbit/s ETDM transmitters and receivers, in *Proc. OFC 2002*, 2002. Paper TuA2.

[8] H.-F. Chou, Y.-J. Chiu, L. Lau, W. Wang, S. Rangarajan, J. E. Bowers, and D. J. Blumenthal, "Low power penalty 80- to 10 Gb/s OTDM demultiplexer using a standing-wave enhanced electroabsorption modulator with reduced driving voltage," *Electron. Lett.*, vol. 39, no. 1, pp. 94–95, 2003.

[9] Y.-J. Chiu, H.-F. Chou, V. Kaman, P. Abraham, and J. E. Bowers, "High extinction ration and saturation power traveling-wave electroabsorption modulator," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 792–794, June 2002.

[10] H.-F. Chou, Y.-J. Chiu, and J. E. Bowers, "Standing-wave enhanced electroabsorption modulator for 40-GHz optical pulse generation," *IEEE Photon. Technol. Lett.*, vol. 15, pp. 215–217, Feb. 2003.

[11] S. Z. Zhang, Y.-J. Chiu, P. Abraham, and J. E. Bowers, "25-GHz polarization-insensitive electroabsorption modulators with traveling-wave electrodes," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 191–193, Feb. 1999.