194 GBaud Integrated SiGe BiCMOS Multiplexer and Thin-Film $LiNbO_3$ Modulator Module

G. Raybon(1), H. G. Batshon(1), X. Chen(1), Q. Hu(1), P. Kharel(2), L. He(2), M. Zhang(2), M. Möller(3)

(1) Nokia Bell Labs, New Providence, NJ 07974, United States, gregory.raybon@nokia-bell-labs.com
(2) Hyperlight, Cambridge, MA,
(3) Saarland University, Saarbrücken, Germany

Abstract *We demonstrate 100 to 194 GBaud (GBd) on-off keyed (OOK) signal generation and short reach transmission from a hybrid integrated SiGe BiCMOS 4:1 electrical multiplexer and thin-film $LiNBO_3$ modulator.*

Introduction

Tremendous progress has been achieved in the development of high-speed small form factor optical transmitters and receivers. Today, high performance, optical transceiver modules operating at 800 Gb/s and higher using coherent optical technology are ubiquitous and commercially available [1]. The demand for bandwidth continues to drive these technologies to higher capacity, higher performance and smaller form factors. Complexity, performance flexibility and cost scale accordingly and there is always a need to drive costs down through simpler designs. Increasing the speed of the electronics to provide higher symbol rates and higher capacity can help simplify the design. In addition, one can expect to reduce the complexity of the digital signal processing (DSP) designed to compensate for hardware induced impairments if higher performing components are available. Progress in high-speed all-electronic transmitters based on electronic multiplexers and optical modulators for binary OOK signaling has lagged. The first 100 GBd OOK transmitter was demonstrated in 2005 using all electronic multiplexing with SiGe multiplexers and conventional $LiNbO_3$ modulators [2]. Higher speeds have been reported using multiplexers fabricated using Indium Phosphide (InP) Double Heterojunction Bipolar Transistor (DHBT) technology. As an example, in 2019, a 222 GBd system was reported using an InP DHBT multiplexer and a polymer modulator [3]. In addition, digital bandwidth interleaving (DBI) is another technique used to achieve high bandwidth and a 190 GBd OOK was demonstrated in 2016 [4]. . As symbol rates continue to increase, the DACs, multiplexers, amplifiers and modulators will need to be integrated or co=packaged to reduce parasitic impairments that accompany any RF signaling. Several successful experiments have been reported pairing high-speed electronics and optical modulators in a hybrid fashion [5,6,7]. In ref [7], a hybrid integrated module was constructed using a polymer modulator operating at 180 Gb/s.

Here, we report a hybrid integrated module that consists of a 4:1 electronic multiplexer complete with clock multipliers and phase control, wire bonded to a thin-film optical $LiNbO_3$ Mach Zehnder modulator (MZM). The system can be flexibly operated from 100 GBd to 194 GBd with binary OOK optical output. In contrast to the recent report in [7], we examine the performance comparison with optical equalization and digital signal processing with feed forward equalization (FFE) and Maximum a posteriori (MAP) symbol detection using look up tables (LUT). We also demonstrate short reach transmission over 450 m of SSMF at 1553 nm (7.5 ps/nm dispersion) up to 180 GBd and compare the performance using optical, electrical equalization and (MAP) symbol detection. We believe such an integrated module can be a good candidate for future high-symbol rate IM-DD systems.

Transmitter Module

The transmitter module is shown in Fig 1b. It

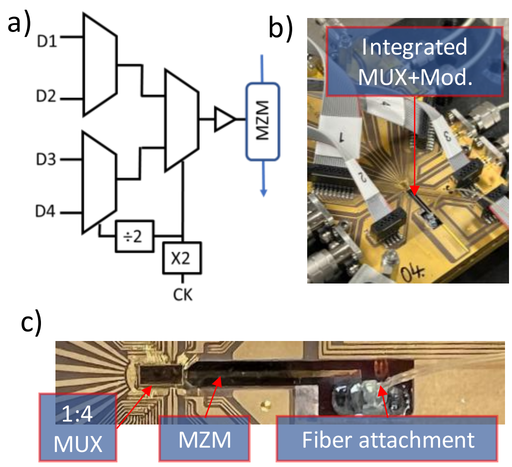

Fig. 1: a) 4:1 Multiplexer architecture b) SiGe BiCMOS multiplexer and thin-film $LiNbO_3$ modulator module. c) photo of 15mm thin-film modulator mounted on PCB.

consists of a high-speed, SiGe BiCMOS, 4:1 electronic multiplexer wire bonded with a thin-film $LiNbO_3$ modulator on a 5×7 cm PCB board that provides electrical connections for the RF input data and clock signals and DC bias points for the multiplexer. Figure 1a shows the electrical schematic for the multiplexer that includes clock circuitry containing clock multipliers and dividers as part of the module. The architecture relaxes the requirements of the input data and clock rates to ¼ the output bit rate, thus enabling readily available data sources to be connected. For example, to achieve a line rate of 180 Gb/s, 45 Gb/s data signals and 45 GHz clock signals are fed into the multiplexer. We have observed the highest possible line rate of 194 Gb/s can be obtained and is limited by the clock multiplier circuit. The will be lower depending on the FEC overhead as detailed in the results section. In addition, all of the DC bias connections are wire-bonded to the chip and controlled via the ribbon cables as shown and a separate bias control box requiring only a 5V DC supply. The output of the multiplexer is wire-bonded to the thin-film $LiNbO_3$ modulator as shown in Fig 1c and optical fibers are attached with a polarization maintaining fiber on the input. The modulator is fabricated from a commercial LN-on-insulator substrate with a 600-nm thick x-cut LN device layer, using a low optical loss etching and metallization process. The waveguide is ~ 15 mm in length and has very low waveguide loss (< 0.1 dB/cm). Wavelength dependent grating couplers are used to couple input and output optical fibers to the waveguides. Typical fiber to fiber insertion loss is ~ 10 dB which is dominated by the grating couplers. These modulators provide lower Vpi and higher bandwidth than typical $LiNbO_3$ modulators. Previous reports have shown measured bandwidth near 100 GHz [8,9].

Experimental Setup

The experimental setup of system is shown in Fig. 2(a). The four differential input OOK data signals are generated using a 4 channel digital to analog converter (DACs) which can generate independent PRBS data sequences. For the experiments 2^{15}-1 PRBS sequences with large data delays between inputs are used. The input data rates are varied from 25 Gb/s to 48.5 Gb/s to achieve output symbol rates from 100 to 194 GBd. The input voltage swing of ~400 mV (800mV differential) is applied and the sinusoidal clock signals are varied accordingly with a single-ended amplitude of ~ 1V peak-to-peak (Vpp). Light from a tunable laser is set at 1553.3 nm (193.0 THz) and amplified before input to the modulator. The fiber-to-fiber insertion loss is 19 dB which is high for this particular package but is not a limitation of the modulator design. To maintain reasonable optical signal to noise ratio (OSNR) at the output, an EDFA is used. The signal is amplified again at the output and then sent either to the receiver for back-to-back measurements or through optical fiber for short reach transmission measurements. At the receiver, an optical equalizer (OEQ) [10] is implemented with a waveshaper to compensate for device bandwidth limitations before being detected with a 100 GHz bandwidth photodiode. An example of the OEQ filter shape is shown in the figure. Once converted to an electrical signal, the data is captured with a real-time 110 GHz/256 Gs/s oscilloscope and the data is then processed with off-line DSP. We also measure the optical eye diagram on a 100 GHz sampling oscilloscope and the 194 GBd eye is shown in Fig 2b and the corresponding optical spectrum is shown in Fig 2c.

The DSP chain is composed of the algorithms shown in Fig.2(b): signal normalization, up-sampling, time-recovery, equalization, demodulation and BER counting. We study three equalization modes with varying parameters. For both back-to-back and transmission, we sweep for the optimal number of taps when using T-

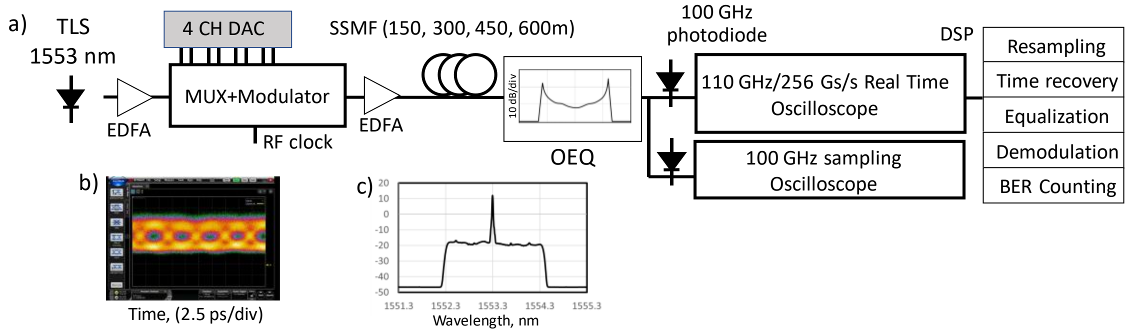

Fig. 2: a) Experimental set-up for short reach transmission measurements of MUX/Modulator module from 100 to 194 GBd. b) Measured optical eye diagram at 194 GBd and c) corresponding optical spectrum after OEQ.

spaced FFE and compare results with and without MAP symbol detector of varying LUT sizes. For smaller symbol rates we achieve best performance without using neither FFE nor MAP detection. However, as the rate increases, we increase the FFE taps from 7 to 21 and LUT size from 3 to 9 going from 100 Gb/s to 194 Gb/s. Results are shown in Fig. 3.

Short reach transmission measurements were demonstrated over varying lengths of standard single mode fiber (SSMF) with dispersion of 16.6 ps/nm/km. BER was measured after 150, 300, 450 and 600 meters. The launch power into the fiber was controlled at -1.5 dBm and no optical or digital dispersion compensation was used.

Results and Discussion

Figure 3 shows the measured BER vs received optical power at the photodiode for line rates ranging from 100 to 194 Gb/s. BER performance is compared for the system using OEQ only to that including DSP with FFE+MAP. We observe that for rates 100 and 140 Gb/s the module performs very well without DSP (at least at BER level of ~$1e^{-7}$ and higher). At bit rates above 140, we see a clear improvement adding the DSP (FFE + MAP). The improvement is most notable at 180 GBd at the 7% FEC threshold ($3.8e^{-3}$) where there is a 5 to 6 dB difference in received power to achieve a BER below the threshold. At 194 GBd the FFE+MAP enables operation below the 33% HD staircase code FEC threshold ($2.24e^{-2}$) [11] and approaching the 20% FEC threshold ($1.2e^{-2}$). Clear and open eye diagrams are shown in Fig 3(b) for line rates from 100 to 194 Gb/s measured with the OEQ except for the 100 Gb/s eye which is measured without the OEQ.

Fig. 3(c) shows the measured BER as a function of transmission distance (and dispersion on the upper axis for 1553 nm) for line rates of 160 Gb/s and 180 Gb/s. Transmission over 150m is attained for 160 and 180 GBd within the 7% FEC threshold with and without FFE+MAP added. For 300m, transmission is possible below the 20% threshold while for 450 meters, transmission is only possible using FFE at 160 GBd and FFE with MAP at 180 GBd. The net transmitted information rate is reduced by the FEC overhead. For 7% FEC, the net rates are 93.5, 130.8,149.5, 168.2 and 181.3 Gb/s while for 20% FEC, the net rates are reduced to 83.3, 116.7, 133.3, 150 and 161.7 Gb/s. In principle, the modulator module can be operated in the O-band where most short-reach IMDD systems are designed and equivalent transmission distances near 2 km could be achieved at the edges of the O-band (1260, 1360 nm). Only the fiber coupling scheme to the modulator would have to be redesigned for operation in the O-band.

Conclusion

We have demonstrated 100 to 194 GBd OOK operation of a SiGe-BiCMOS electrical multiplexer circuit with a thin-film $LiNBO_3$ MZ modulator hybrid packaged module. Performance is compared using different levels of equalization and DSP. Short reach transmission is also measured at 160 and 180 GBd.

Acknowledgements

We acknowledge support by H. Langenhagen and others of Micram Microelectronic in Bochum, Germany (now fully merged with Keysight Technologies) as well as C. Uhl (formerly with Saarland University) for making available the used SiGe 4:1 MUX prototype device.

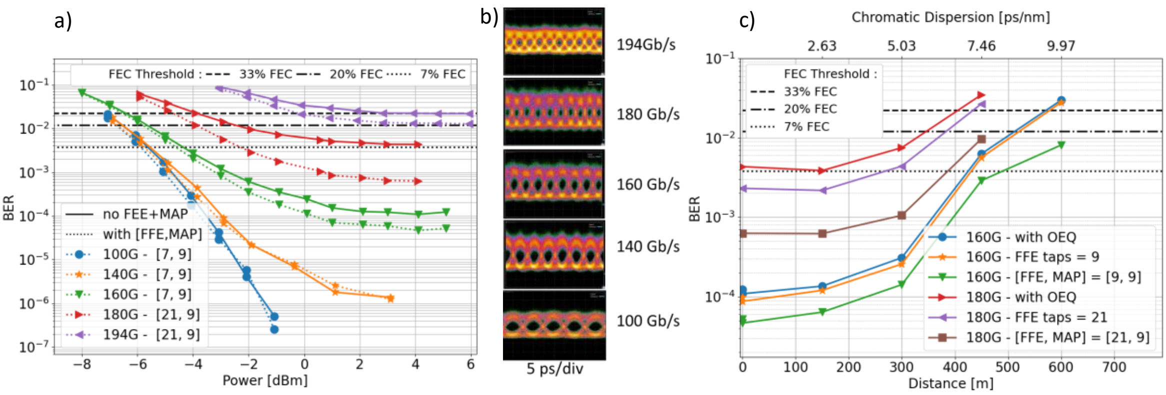

Fig. 3: a) Back-to-back BER with (solid line) and without FFE+MAP (dashed line), b) optical eye diagrams for 100 (no OEQ) and 140 to 194 GBd (OEQ only) and c) short reach transmission measurements plotted as a function of distance (m) and dispersion (ps/nm).

References

[1] effectphotonics.com/insights/the-evolution-to-800g-beyond.

[2] P. J. Winzer, G. Raybon, M. Duelk, “107 -Gb/s optical ETDM transmitter for 100G Ethernet transport,” European Conf. on Optical Communications, TH4.1.1, 2005, DOI: 10.1049/cp:20050847.

[3] H. Mardoyan, Haïk Mardoyan1, Filipe Jorge2, Benedikt Baeuerle3,4, Jose Manuel Estaran1, Wolfgang Heni 3,4, Agnieszka Konczykowska2, Muriel Riet2, Bernadette Duval2, Virginie Nodjiadjim2,Michel Goix2 Jean-Yves Dupuy2, Marcel Destraz 3,4, Claudia Hoessbacher 3,4, Yuriy Fedoryshyn4, Huajun Xu5, Delwin Elder5, Larry Dalton5, Juerg Leuthold4, Sébastien Bigo1 et. al., “222-GBaud on-off keying transmitter using ultra-high-speed 2:1-selector and plasmonic modulator on silicon photonics,” European Conf. on Optical Communications, COC, 2021, DOI: 10.1049/cp.2019.1024.

[4] X. Chen, S. Chandrasekhar, S. Randel, G. Raybon, A. Adamiecki, P. Pupalaikis, P. J. Winzer, “All-electronic 100-GHz Bandwidth DAC Generating PAM Signals up to 190-GBaud,” Journal of Lightwave Technology, vol. 35, no. 3, pp. 411-417, 2017, DOI: 10.1109/JLT.2016.2614126

[5] P. Groumas, Z. Zhang, V. Katopodis, A. Konczykowska, J. Y. Dupuy, A. Beretta, A. Dede, J. H. Choi, P. Harati, F. Jorge, V. Nodjiadjim, M. Riet, R. Dinu, G. Cangini, E. Miller, A. Vannucci, N. Keil, H. G. Bach, N. Grote, M. Spyropoulou, H. Avramopoulos, and Ch. Kouloumentas, “Tunable 100 Gbaud Transmitter Based on Hybrid Polymer-to-Polymer Integration for Flexible Optical Interconnects,” Journal of Lightwave Technology, vol. 34, no. 2, pp. 407-418, 2016, DOI: 10.1109/JLT.2015.2463730

[6] B. Bauerele, W. Heni, Y. Fedoryshyn, C. Hoessbacher, U. Koch, A. Josten, T. Watanabe, C. Uhl, H. Hettrich, D. L. Elder, L. R. Dalton, M. Möller, and J. Leuthold, “Dual-Drive Plasmonic Transmitter with Co-Designed Driver Electronics Operated at 120 GBd On-Off Keying,”, Optical Fiber Communications Conference, 2019, M2F.3, DOI: 10.1364/OFC.2019.M2F.3.

[7] D. Moor, Y. Fedoryshyn, H. Langenhagen, J. Müllrich, R. Schmid, C. Uhl, M. Möller, U. Koch, Y. Horst, B. I. Bitachon, W. Heni, B. Baeuerle, M. Destraz, H. Xu, L. E. Delwin, L. E. Johnson, P. Bakopoulos, E. Mentovich, L. Zimmermann, and J. Leuthold, “180 GBd Electronic-Plasmonic IC Transmitter,” Optical Fiber Communications Conference, M2D.3 OFC, 2022, DOI: 10.1364/OFC.2019.M2F.3.

[8] X. Chen, G. Raybon, D. Che, J. Cho, and K.W. Kim, “Transmission of 200-GBaud PDM PCS 64-QAM Signals Modulated via a 100-GHz Thin-film LiNbO3 I/Q Modulator,” Optical Fiber Communications Conference, F3C.5, 2021, DOI:10.1364/OFC.2021.F3C.5.

[9] C. Wang, M. Zhang, X. Chen, M. Bertrand, A. Shams-Ansari, S. Chandrasekhar, P. Winzer and M. Lončar, “Integrated Lithium Niobate Electro-optic Modulators Operating at CMOS-Compatible Voltages,” Nature, vol. 562, pp. 101-104, 2018, DOI: 10.1038/s41586-018-0551-y.

[10] C. R. Doerr, P. Winzer, G. Raybon, L. Buhl, M. Cappuzzo, A. Wong-Foy, E. Chen, L. Gomez, M. Duelk “A Single-Chip OEQ Enabling 107-Gb/s Optical Non-Return-to-Zero Signal Generation, European Optical Conference on Optical Communications, TH4.2.1, ECOC, 2005, DOI: 10.1049/CP:20050853.

[11] L. M. Zhang and F. R. Kschischang, "Staircase Codes With 6% to 33% Overhead," Journal of Lightwave Technology, vol. 32, no. 10, pp. 1999-2002, 2014, DOI: 10.1109/JLT.2014.2316732.