

Real-Time and DSP-free 128 Gb/s PAM-4 Link using a Binary Driven Silicon Photonic Transmitter

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Abstract— Optical transmitters for four-level pulse amplitude modulation (PAM-4) have attracted a significant amount of research in recent years, in large part due to the standardization of the format for the 200 and 400 Gigabit Ethernet (GbE) optical interconnects in data centers. However, combining low-power and linear operation of the electro-optical frontend with sufficiently large bandwidths has proven challenging, especially for the 100 Gb/s/λ links (i.e. employing 50 Gbaud PAM-4). The most straightforward solution has been to deal with the non-idealities of the modulator in the electrical domain: predistorting the signal levels and/or equalizing the frequency response with the help of digital signal processing (DSP). However, this typically requires fast DACs, either capable of delivering large swings (>1 Vpp) or supplemented with an additional linear amplifier to drive the optical modulator. Both options substantially increase the power consumption and the complexity of the transceiver. Rather than allocating effort to linearize the electrical to optical conversion of a single modulator, we propose a topology that performs the DAC operation in the optical domain. Two compact electro-absorption modulators (EAMs) in an interferometer layout are driven with NRZ data to generate the four-level signal in the optical domain. Using this topology, we demonstrate the first real-time 128 Gb/s PAM-4 transmission with a silicon photonic transmitter in a chip-to-chip link. In a back-to-back setup, we obtained a bit-error ratio (BER) of 4×10^{-10} without requiring any DAC, DSP, or modulators with large traveling wave structures. Over 1 km of standard single mode fiber a BER of 8×10^{-6} is recorded, still well below the KP4 forward error-coding limit. These results correspond to the lowest BERs reported for any real-time PAM-4 link at 100 Gb/s or higher, illustrating the benefit of performing the DAC operation in the optical domain.

Index Terms—PAM-4, short-reach interconnects, silicon photonics

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I. INTRODUCTION

THE recent adoption of the 400 Gigabit Ethernet (GbE) standards has made four-level pulse amplitude modulation (PAM-4) the modulation format of choice for the next-generation single-mode data center interconnects (DCI). The 400GBASE standard specifies 8 lanes of 53.125 Gb/s PAM-4 for 1 km and 2 km standard single-mode fiber (SSMF) links and 4 lanes of 106.25 Gb/s PAM-4 for 500m SSMF links, introducing the first 100 Gb/s per wavelength standard [1]. However, also for longer fiber spans a 4x100G PAM-4 scheme is a likely candidate, as it offers the lowest practical lane count and thus the most compact transceiver. Regardless of the outcome of these ongoing standardizations, the wide spread deployment of 100G-per-λ modules remains a logical step on the growth path of data centers, irrespective of the interconnect span. Possibly an even more challenging task is updating the copper interconnects to sustain these rapidly increasing data rates. Moreover, with the increasing data rates next-generation optical interconnects are expected to move to the intra-rack and intra-board interconnects [2]. Especially for these on-board optical interconnects, minimizing power and area (both electrically and optically) will be of the utmost importance.

Previously, several examples of 100G-per-λ PAM-4 links have been demonstrated [3-11]. However, many of these examples had to rely on DACs, ADCs, and/or digital signal processing (DSP) at the transmitter and/or at the receiver [5-10], leading to a significant increase in latency, power consumption, and cost. Often the required DSP at the receiver prevents online (or real-time) link experiments, even with high-end test equipment. Nevertheless, some real-time examples demonstrating 100 Gb/s single-lane PAM-4 transmission have

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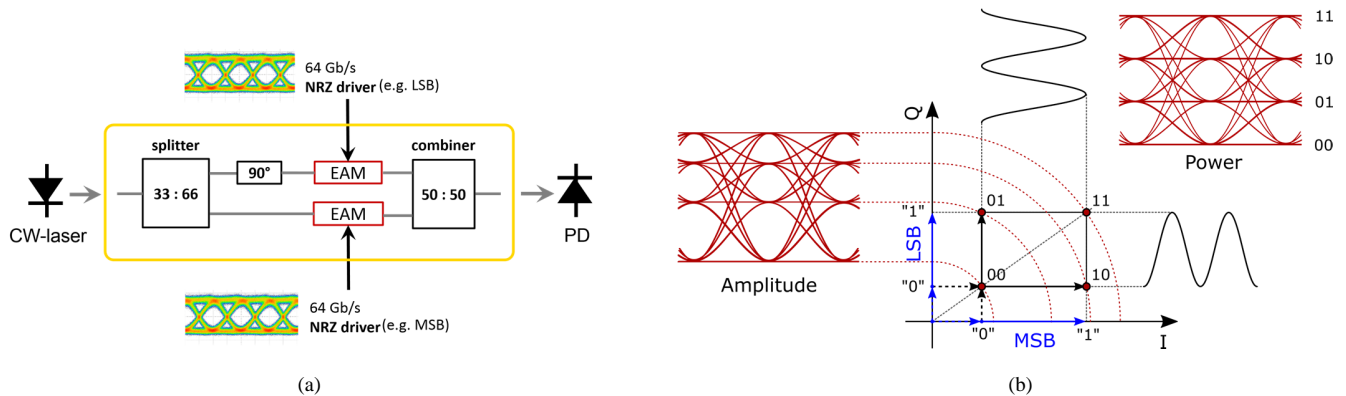


Fig. 1. (a) 2-bit optical DAC consisting of two intensity modulators (EAMs). (b) Vector and eye diagrams of the proposed topology optical PAM-4 generator. The blue vectors represent the on- and off-state of the two EAMs, when driven separately (assuming for simplicity that no phase difference is introduced between the 0 and the 1 level by the EAMs). They form the basis vectors for the PAM-4 generation and realize a rectangular constellation in the upper quadrant of the complex plane. The limited extinction ratio (ER of 10 dB in this example) and the resulting non-perfect zero level, are represented by the dotted vectors. As long as the 90° angle is preserved between both vectors, the ER does not influence the relative positioning of the power levels, only the maximal modulation depth of the PAM-4. Even if the EAMs behave as non-perfect switches (limited ER, unbalanced IL, non-zero average phase-shift), PAM-4 can still properly be generated by adjusting the phase and/or power split. Vice versa, these parameters can also be used to predistort the PAM-4 levels (e.g. to compensate for compression in the receiver). A more in-depth discussion can be found in [11].

been reported [3,4]. In [3], real-time 56 Gbaud PAM-4 transmission on a discrete LiNbO_3 Mach-Zehnder modulator

(MZM) was reported. The first real-time demonstration using a polymer on silicon MZM at 53.125 Gbaud was shown in [4], with online DSP. Both experiments employ large travelling wave modulators (at least several millimeters long) and consequently need to be electrically terminated (typically with a 50Ω resistor), consuming a significant amount of power and transceiver real-estate.

In this paper, we use a novel optical PAM-4 generator based on two binary driven GeSi electroabsorption modulators (EAMs) in an interferometer topology, as we recently demonstrated in [11]. As the EAMs are only $120\ \mu\text{m}$ long, they can be driven lumped without any travelling wave electrodes or terminations. Combining this modulator with an in-house developed transceiver chipset, we are able to demonstrate the first real-time, single-wavelength transmission of 128 Gb/s PAM-4 in a chip-to-chip link. Bit-error ratios (BERs) comfortably below the KP4 forward error coding (FEC) limit of $2.4 \cdot 10^{-4}$ are obtained for spans up to 1 km of SSMF, without requiring any power-hungry DACs, ADCs or DSP.

II. OPTICAL PAM-4 GENERATION

As all high-speed optical modulators are characterized by a non-linear transfer function, the most straightforward solution has been to compensate these non-idealities in the electrical domain by predistorting the levels of the applied PAM-4 signal and/or by equalizing the frequency response of the electro-optical channel. Although this solution can be very effective in leveraging non-ideal electrical and optical components, it comes at a substantial increase in the total power consumption, size, and complexity of the transceiver.

Rather than allocating transceiver resources in linearizing the electrical-to-optical conversion of a single intensity modulator, we propose to postpone the DAC operation until the optical domain by using two parallel intensity modulators [11]. This

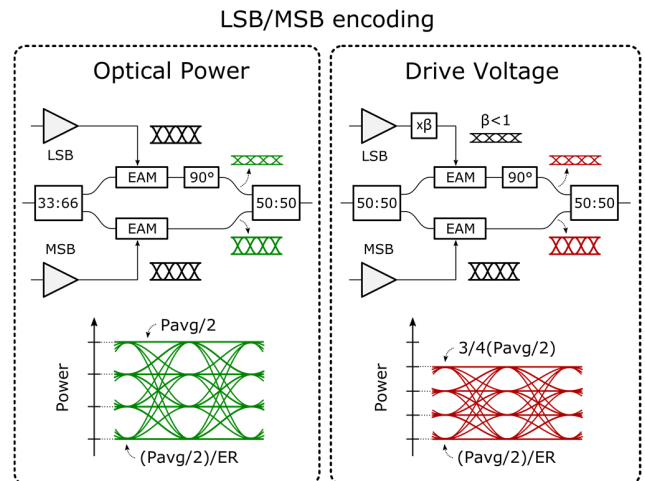


Fig. 2. Two different versions of the optical PAM-4 generator using two parallel EAMs in an interferometer with 90° phase difference: (left) using an unequal optical power split and (right) using an unequal drive voltage. To achieve equidistant PAM-4 with either of these topologies, the OMA (optical modulation amplitude) of the MSB needs to be twice the OMA of the LSB, when driven separately. This condition translates to (left) a 66:33 power ratio or (right) a $1:\beta$ voltage swing ratio ($\beta < 1$, with $\beta=0.5$ for a linear EAM) between the MSB and the LSB EAM. Although both versions generate equidistant PAM-4, they do not have the same efficiency. Comparing the eye diagrams produced by both versions, we see that the optical power split always produces a OMA that is 33% better (or 1.25 dB higher) than the OMA of the voltage weighted version, for a given modulator and average input power (P_{avg}).

removes the linearity requirements at the transmit side, both in the optics and the electronics. Adding a second modulator means we also need to provide a second modulator driver. Still, two NRZ drivers are likely to be more power efficient than one multilevel driver. Both drivers can be designed for non-linear operation, allowing other driver topologies to be considered (e.g. inverters) and maintaining compatibility with CMOS-based electronics and all the advantages that come with it.

Recently, we proposed a topology consisting of two intensity modulators in interferometer with 90° phase difference, where

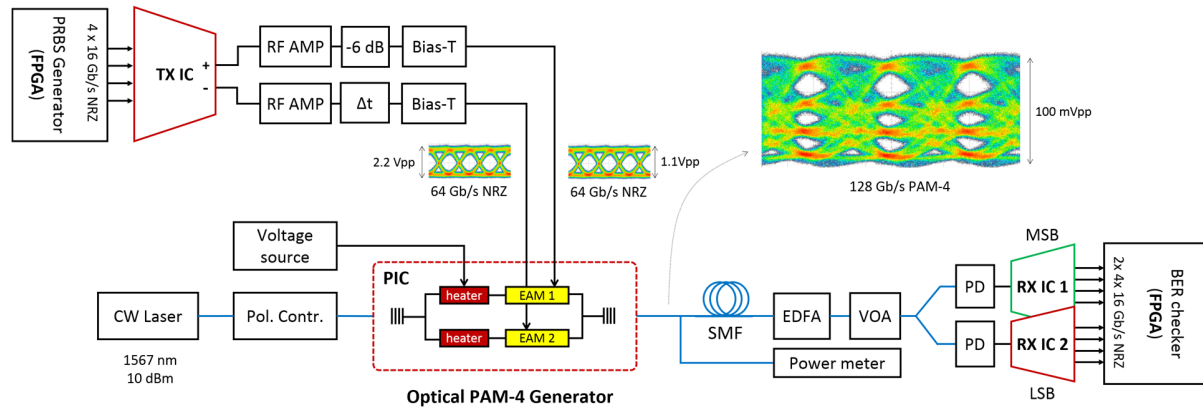


Fig. 3. Experiment setup for the 128 Gb/s PAM-4 link

the LSB/MSB coding is realized through a 33:66 power ratio between both branches (Fig.1.a) [11]. Fig.1.b provides a more detailed explanation of the optical DAC operation using a vector diagram drawn in the first quadrant of the complex plane. The EAMs are $120\mu\text{m}$ long GeSi-based devices fabricated on imec's 200mm platform. Their operation is based on the Franz-Keldysh effect. The bandgap of the material shifts when an electrical field is applied, changing its optical absorption spectrum. More information about on these GeSi devices can be found in [12,13]. EAMs have the advantage that they can be made very short (minimizing the modulator capacitance and allowing them to be driven as a small lumped capacitor), removing the need for long transmission lines and power-consuming resistive terminations. However, to be able to drive the EAMs with commercially available $50\ \Omega$ -drivers (i.e. RF amplifiers), we have placed $50\ \Omega$ resistors between the bondpads of each modulator to provide a matched interface on the PIC. These resistors are not necessary for the operation of the transmitter and can easily be omitted when integrated with a dedicated driver. Moreover, we recently demonstrated that such a dedicated driver for these type of EAMs can be made extremely power efficient, consuming only 61 mW at 70 Gb/s or less than 0.9 pJ/bit [14].

These first generation devices are implemented with standard 1×2 multimode interferometers with equal power split, both at the input and at the output of the interferometer. Therefore, the LSB/MSB weighing between both branches can be achieved by reducing the voltage swing to the LSB-EAM, as illustrated in Fig. 2. In the experiment setup, shown in Fig. 3, a 6 dB attenuator was placed after one of the RF amplifiers. Due to the non-linear characteristics of the EAMs this does not perfectly correspond to a 3 dB lower optical modulation amplitude in the LSB arm. Additional corrections are applied by slightly adjusting the bias voltage of the LSB-EAM. However, this emulation only approximates the intended PAM-4 generation, resulting in slightly unequal PAM-4 levels and reducing the overall performance. With a 33:66 power split the transmitter eye levels would be perfectly equidistant if both modulators were driven with the same voltage swing, no matter their specific transfer function (assuming no parasitic phase shift is introduced between the 0 and the 1 by the EAM) [11]. This

33:66 power split can easily be accomplished by replacing one of the MMIs with a tunable Mach-Zehnder interferometer (e.g. consisting of two MMIs and a thermal phase shifter). Moreover, Fig. 2 also shows that the version with unequal power split will always be more efficient than version with unequal drive voltage version. For a given modulator, maximum drive voltage and optical input power, the power split version produces a PAM-4 with a 1.25 dB higher OMA. A micrograph of the used photonic IC (PIC) with equal power split can be seen in Fig.4.

An in-house developed transmitter (TX-IC in Fig.4) is used to multiplex four 16 Gb/s pseudo-random bit streams (PRBS), originating from the FPGA, into one serial 64 Gb/s 29-1 long PRBS signal. After the MUX, an analog 6-tap feed-forward equalizer can be set to improve the frequency response of the following components in the channel. In our experiments, it was mainly used to compensate the strong frequency roll-off of the electrical receiver and the RF amplifier. The differential outputs of the TX-IC are decorrelated with a mechanically tunable time delay to provide independent 64 Gb/s NRZs streams to each modulator. Finally, the signals are externally amplified to 1.1Vpp and 2.2Vpp for the LSB and the MSB EAM, respectively. The voltage swing could be slightly higher than in the previous experiments on similar devices [11] as the device is permitted to operate non-linearly, allowing the EAMs to be operated as switches for maximal ER. Light from a 10 dBm laser at 1567nm is coupled in and out of the PIC through fiber-to-chip grating couplers with an insertion loss of approximately 5.5 dB/coupler. The EAMs have an estimated insertion loss of 8 dB and a dynamic extinction ratio of approximately 10 dB, resulting in an average in-fiber power around -10 dBm during operation.

III. REAL-TIME PAM-4 BER TESTER

Using a transmitter as discussed in the previous section allows us to generate open PAM-4 eyes up to 64 Gbaud without any DSP, thanks to the optical DAC topology. However, receiving these signals in real-time is particularly challenging as a commercial 64 Gbaud PAM-4 bit-error rate tester (BERT) did not yet exist at the time of the experiments. Real-time oscilloscopes are not an option as the captured data has to be saved and processed offline. Still, even with a fast enough

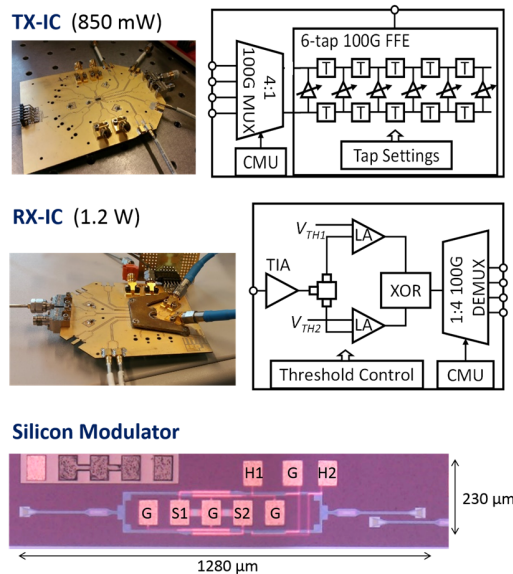
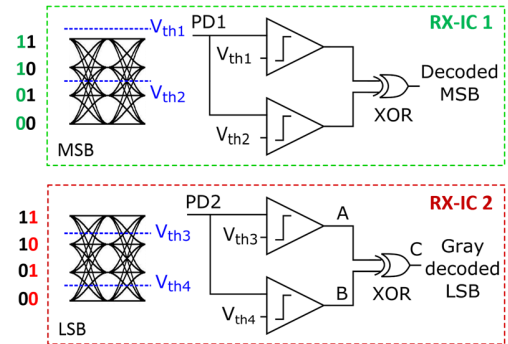


Fig. 4. Photograph and block diagram of the BiCMOS transmitter IC (TX-IC), the BiCMOS receiver IC (RX-IC), and an annotated die micrograph of the silicon photonic modulator. More details about the TX-IC and RX-IC can be found in [15].

BERT it is often difficult to estimate what the performance of the link would be without any high-end test equipment.

Therefore, we implemented a custom electrical receiver using an in-house developed chip (RX-IC) that was originally designed to decode a 3-level duobinary signal [15]. Fig. 4 shows the block diagram of the RX-IC as well as a photograph of the die mounted on a high-speed printed circuit board. The receiver consists of two comparators to monitor the upper and lower triangular duobinary eyes. Their outputs are XOR-ed to reproduce the original binary data and finally deserialized to a quarter-rate NRZ signal. Fig. 5 explains how two of these receivers can be used to obtain both the most and least significant bit (MSB and LSB) of the PAM-4 signal simultaneously. This is in contrast to the few currently available solutions, where each of the three eyes is evaluated sequentially and the three BERs are averaged.

The received PAM-4 signal is split 50:50 and fed to two photodetectors, one for each RX-IC. Both photodetectors have a similar responsivity (~ 0.6 A/W) and a flat frequency response (important to prevent any signal distortion when converting to the electrical domain) up to 40 and 50 GHz. Alternatively, we could have opted to split the signal after the conversion in the electrical domain, saving one photodiode. However, as the RX-IC only provides a demultiplexed and retimed output, the second photodiode could be used to monitor the eye diagram during the optimization of the equalizer settings for optimal BER (i.e. the BER of the MSB or the LSB depending on which photodiode is being monitored). As no linear high-speed transimpedance amplifier (TIA) was available, an erbium-doped fiber amplifier (EDFA) was used to provide a sufficiently large signal at the inputs of the RX-ICs. The EDFA can be omitted by replacing the relatively inefficient grating couplers with low-loss edge couplers (< 2 dB/coupler) and adding a TIA.



PAM-4 symbol	Gray coded inputs	Received MSB	A	B	C	Gray decoded outputs
00	00	0	0	0	0	00
01	01	0	0	1	1	01
10	11	1	1	1	0	10
11	10	1	0	1	1	11

Fig. 5. Implementation of the real-time PAM-4 receiver with automatic Gray code demapper and bit-error rate tester (BERT).

Decoding the MSB is relatively straightforward, as the duobinary receiver can be easily reduced to a conventional binary receiver by setting the threshold V_{TH1} to its highest possible level, making the XOR operation transparent for the second comparator. The MSB is then received by centering V_{TH2} around the DC-level, looking into the middle eye.

To decode the LSB, each comparator of RX-IC 2 is set to the middle of one of the outer eyes. However, the outer eyes by themselves do not provide sufficient information to decide the received LSB. It is instructive to think of a duobinary receiver as a device determining if a symbol transition happened inside (delivering a 1) or outside (delivering a 0) both comparator thresholds. Combining this information with that of the MSB (i.e. has a symbol transition happened in the upper or lower half of the eye), resolves exactly which eye of the three has seen a symbol transition and therefore the LSB. Lastly, to obtain the LSB we need to XOR it once more with the MSB. However, we purposefully omit this operation as the receiver now also performs an automatic demapping of a Gray encoded PAM-4 symbol, making this an additional advantage of this receiver topology, as Gray mapping and demapping is a required action set by most data center transceiver standards. Furthermore, in a test setup one can choose to Gray code the transmitted data or not, as this does not affect the BER performance when transmitting PRBS data. As both the MSB and the LSB are essentially two equal length PRBS streams, XOR-ing both will produce again an equivalent PRBS stream on which the BER counter (implemented on the FPGA) can lock.

IV. RESULTS AND DISCUSSION

The stand-alone performance of the transmitter is first assessed by connecting one of the photodiodes directly to a 50 GHz sampling oscilloscope and tuning the equalizers settings towards best eye quality. The heater was detuned slightly to

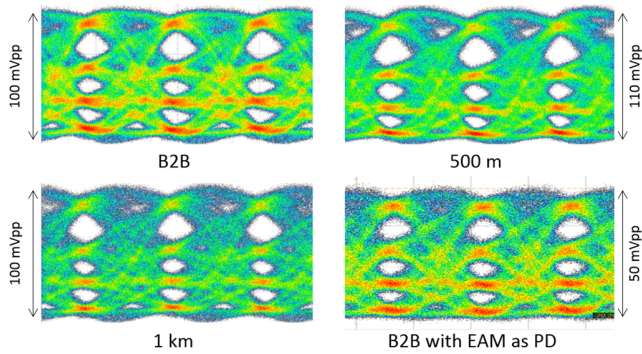


Fig. 6. Eye diagrams at 64 GBaud in the back-to-back case and after transmission over 500 m and 1 km of standard single mode fiber. An eye diagram with a GeSi EAM used as photodetector (back-to-back) is also shown.

produce a smaller phase difference, increasing the OMA of the upper eye without reducing that of other eyes as described in [11]. As long as the receiver is not limited in dynamic range, this effect can be used to improve the BER. Fig. 6 shows the eye diagrams in the back-to-back (B2B) case and after transmission over 500 m and 1 km of standard single mode fiber. Clear open eyes are obtained for all links. Next, the photodiode is connected again to the RX-IC to evaluate the real-time BER performance. The FFE parameters have to be re-optimized to minimize the BER, indicating that frequency response of the RX-ICs indeed limits the link performance. Furthermore, as the receiver was designed for 3-level duobinary reception, it did not need to be extremely linear. For example a symmetrical, gradually saturating transfer function would suffice to decode duobinary without experiencing large sensitivity penalties. Nevertheless, for PAM-4 almost error-free operation was obtained in a back-to-back link with BERs down to 4×10^{-10} . For transmission over 500m and 1 km of SSMF we measured BERs of 7×10^{-9} and 8×10^{-6} , respectively, which is well below the KP4-FEC limit of 2.4×10^{-4} commonly used in data center interconnects, as shown in Fig. 7. These BERs are to the lowest reported values for a real-time PAM-4 link above 50 Gbaud [9,10]. This affirms once more the performance benefit of the DAC-less solution over a single multilevel driven modulator as was previously observed for the modulator used in this experiment [11], as well as for other optical DACs such as segmented MZMs [7] and polarization multiplexed EAMs [17].

Apart from their compact form factor and high bandwidth, the EAMs can also be used as photodetectors by setting them to maximal absorption. In [15,16], we already observed that the EAMs can be used as optical receivers for 100 Gb/s NRZ and 3-level duobinary with a high responsivity (~ 0.8 A/W for 80 μ m devices). However, to receive PAM-4, the frequency response should ideally be as flat as possible. We can compare the performance by switching the transmitted eye between the photodiode with a known flat response beyond 50 GHz (upper left eye diagram in Fig.6) and one of the transmitter EAMs biased at -3V on a separate die (lower right eye diagram in Fig. 6). Apart from some additional noise, likely due the added insertion loss of the extra grating coupler and 3dB-splitter, little

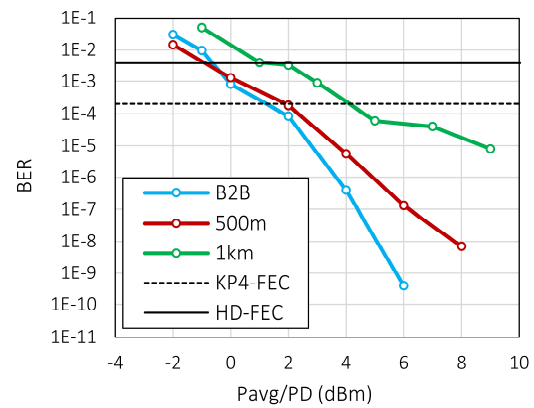


Fig. 7. Real-time BER curves at 64 Gbaud for back-to-back, 500m and 1km of SSMF.

or no additional signal degradation is observed. This validates that the EAMs not only have a high responsivity but also a flat frequency response up to at least 50 GHz, making them well-suited for receiving multilevel signals. Having a single active high-speed optical component for both the transmitter and the receiver, would greatly simplify the yield optimization of such a silicon-based transceiver, paving the way towards high-yield and high-volume production.

Silicon photonics is very promising platform for data center interconnects, due to its ability to realize compact and low-cost transceivers in high volume leveraging existing CMOS fabrication infrastructure. As demonstrated in this paper, SiP is capable of delivering very compact transceivers that can operated without the need for DSP, DACs or high-power electronics. The next step would be to combine this modulator with in-house developed dedicated drivers [14] and TIA[18], and realize a low power analog fronted of a silicon transceiver with a dynamic power consumption of less than 2.5pJ/bit (excluding the laser): 61 mW to drive the MSB EAM, 45 mW for the LSB (as it needs half the swing), 10-20 mW for the heater and 190 mW for the TIA.

The main downside of silicon-on-insulator (SOI) platform is that lacks a native means for optical amplification, and as such no light source. However, many possible solutions exist [19]: lasers can be grown epitaxially on the SOI (heterogeneous integration) or butt-coupled to the PIC during assembly without having to interfere with the SOI. Recently, transfer printing has gained quite some attention as a promising and -most importantly- cost-effective way to selectively transfer pieces of III-V material (e.g. a laser) to a SOI wafer or PIC. The same technique could be used to replace the GeSi EAMs with III-V-based EAMs to allow operation in O-band, as the GeSi Franz-Keldysh effect devices are intrinsically limited to C- and L-band. Another option would be the use of O-band waveguide-integrated EAMs on silicon based on the quantum-confined Stark effect through multiple quantum well structures, as are currently being developed [20]. However, the proposed optical DAC topology is not limited to EAMs, in fact *any* intensity modulator could be used.

V. CONCLUSION

We have presented a compact silicon-based transmitter capable of generating 64 Gbaud PAM-4 using two binary driven 120 μm long GeSi EAMs in parallel. Combined with an in-house developed electrical transceiver chipset, we were able to demonstrate the first real-time 64 Gbaud PAM-4 transmission over more than 1 km of SSMF in a chip-to-chip link, without requiring any power-hungry electrical ADCs, DACs or DSP. Integration with the custom-designed BiCMOS drivers of [14] would allow us to realize a 1 pJ/bit transmitter frontend (excluding the laser). These results not only illustrate the advantages of carrying out the DAC operation to the optical domain and thus eliminating the need for linear electronics and optics, but also the capabilities of silicon photonics towards realizing extremely compact and low-power transceivers for 100 Gb/s/ λ optical interconnects.

REFERENCES

- [1] "IEEE P802.3bs 400 Gigabit Ethernet Task Force." [Online]. Available: <http://www.ieee802.org/3/bs/>
- [2] Consortium for On-Board Optics (COBO), [Online] <https://onboardoptics.org>
- [3] M. Chagnon, M. Osman, M. Poulin, C. Latrasse, J. Gagné, Y. Painchaud, C. Paquet, S. Lessard, and D. Plant, "Experimental study of 112 Gb/s short reach transmission employing PAM formats and SiP intensity modulator at 1.3 μm ," *Opt. Express* 22, 21018-21036 (2014).
- [4] M. A. Mestre *et al.*, "Compact InP-Based DFB-EAM Enabling PAM-4 112 Gb/s Transmission Over 2 km," in *Journal of Lightwave Technology*, vol. 34, no. 7, pp. 1572-1578, April 1, 2016.
- [5] Justin Lavrencik, Varghese Antony Thomas, Siddharth Varughese, and Stephen E. Ralph, "DSP-Enabled 100 Gb/s PAM-4 VCSEL MMF Links," *J. Lightwave Technol.* 35, 3189-3196 (2017)
- [6] W. Wang *et al.*, "First Demonstration of 112 Gb/s PAM-4 Amplifier-free Transmission over a Record Reach of 40 km Using 1.3 μm Directly Modulated Laser," *2018 Optical Fiber Communications Conference and Exposition (OFC)*, San Diego, CA, 2018, pp. 1-3.
- [7] Alireza Samani, David Patel, Mathieu Chagnon, Eslam El-Fiky, Rui Li, Maxime Jacques, Nicolás Abadía, Venkat Veerasubramanian, and David V. Plant, "Experimental parametric study of 128 Gb/s PAM-4 transmission system using a multi-electrode silicon photonic Mach Zehnder modulator," *Opt. Express* 25, 13252-13262 (2017)
- [8] J. Sun *et al.*, "A 128 Gb/s PAM4 Silicon Microring Modulator," *2018 Optical Fiber Communications Conference and Exposition (OFC)*, San Diego, CA, 2018, pp. 1-3.
- [9] J. Lee *et al.*, "Demonstration of 112-Gbit/s optical transmission using 56GBaud PAM-4 driver and clock-and-data recovery ICs," *ECOC*, 2015, Valencia, 2015, pp. 1-3.
- [10] A. Chiuchiarelli *et al.*, "Single Wavelength 100G Real-Time Transmission for High-speed Data Center Communications," in *OFC*, 2017, Los Angeles, W4I.2.
- [11] J. Verbist *et al.*, "DAC-Less and DSP-Free 112 Gb/s PAM-4 Transmitter Using Two Parallel Electroabsorption Modulators," in *Journal of Lightwave Technology*, vol. 36, no. 5, pp. 1281-1286, March 1, 2018.
- [12] M. Pantouvaki *et al.*, "Active Components for 50 Gb/s NRZ-OOK Optical Interconnects in a Silicon Photonics Platform," in *Journal of Lightwave Technology*, vol. 35, no. 4, pp. 631-638, Feb. 15, 2017.
- [13] S. A. Srinivasan, P. Verheyen, R. Loo, I. D. Wolf, M. Pantouvaki, G. Lepage, S. Balakrishnan, W. Vanherle, P. Absil, and J. V. Campenhout, "50 Gb/s C-band GeSi Waveguide Electro-Absorption Modulator," in *2016 Optical Fiber Communications Conference and Exhibition (OFC)*, March 2016, pp. 1-3.
- [14] H. Ramon *et al.*, "70 Gb/s 0.87 pJ/bit GeSi EAM Driver in 55nm SiGe BiCMOS," *2018 European Conference on Optical Communication (ECOC)*, Rome, 2018, Tu3E.5 (to be published)
- [15] J. Verbist *et al.*, "Real-Time 100 Gb/s NRZ and EDB Transmission With a GeSi Electroabsorption Modulator for Short-Reach Optical Interconnects," in *JLT*, vol. 36, no. 1, pp. 90-96, Jan. 2018.
- [16] J. Verbist *et al.*, "100 Gb/s DAC-less and DSP-free Transmitters using GeSi EAMs for Short-Reach Optical Interconnects," *2018 Optical Fiber Communications Conference and Exposition (OFC)*, San Diego, CA, 2018, pp. 1-3.
- [17] W. Huang *et al.*, "Optical DAC for Generation of PAM4 Using Parallel Electro-Absorption Modulators," *ECOC* (2016), Dusseldorf, Germany, pp. 1-3
- [18] J. Lambrecht *et al.*, "56-Gb/s Silicon Optical Receiver using a Low-Noise Fully-Differential Transimpedance Amplifier in SiGe BiCMOS," in *ECOC* (2018), Rome, Tu3E.6 (to be published)
- [19] Z. Wang *et al.*, "Novel Light Source Integration Approaches for Silicon Photonics" in *Laser & Photonics Reviews*, 11: 1700063, 2017
- [20] A. Srinivasan, C. Porret, E. Vissers, P. Geiregat, D. Van Thourhout, R. Loo, M. Pantouvaki, J. Van Campenhout, "High-contrast quantum-confined Stark effect in Ge/SiGe quantum well stacks on Si with ultra-thin buffer layers", *Conference on Lasers and Electro-Optics Pacific Rim*, (2018).



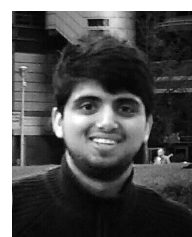
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Peter De Heyn biography not available at time of publication



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