First Real-Time Demonstration of 128 Gb/s PAM-4 Transmission over 1 km SMF using a Si Photonics Transmitter

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Abstract *Using two 120 µm long, binary driven GeSi electro-absorption modulators in parallel and an in-house developed electrical transceiver chipset, we demonstrate the first real-time transmission of 128 Gb/s PAM-4 over 1 km fiber without requiring any DSP or DAC/ADC.*

Introduction

The adoption of the 400 Gigabit Ethernet (GbE) standards has made PAM-4 the modulation format of choice for the single-mode intra-data center links. The 400GBASE standards specify 53.125 Gb/s PAM-4 per lane for 1 and 2 km and 106.25Gb/s PAM-4 for over 500m. However, also for longer fiber spans the 4x100G PAM-4 scheme is a likely candidate, as it offers the lowest practical lane count and thus the most compact transceiver. Likewise, due to the increasing data rates optical interconnects are expected to penetrate the intra-rack and intra-board interconnects[1]. Also for these applications, minimizing the power and area (both electrically and optically) is of the utmost importance.

Previously several 100G-per-λ PAM-4 transmitters have been demonstrated. However, most of them use power hungry digital-to-analog converters (DACs) and/or linear drivers to apply the electrical PAM-4 signal to a single modulator. Even then, many experiments need to rely on digital signal processing (DSP) at the transmitter and/or receiver side to compensate as much as possible the remaining distortion and channel impairments, which is often still done offline[2]. Nevertheless, a few examples of real-time experiments exist[3,4]. In ref[3], real-time 56 Gbaud PAM-4 transmission on a discrete $LiNbO_3$ travelling wave Mach Zehnder (TW-MZM) was reported. The first real-time demonstration with a silicon-based modulator was shown in ref[4], using a polymer on silicon TW-MZM modulator with online DSP at 53.125 GBaud PAM-4. Both experiments use large TW-MZMs which need to be electrically terminated (typically with a 50 Ω resistor), consuming a significant amount of power and transceiver real estate.

In this paper, we present an optical DAC solution consisting of two parallel and binary driven GeSi electro-absorption modulators fabricated on a 200 mm Silicon Photonics platform. Because the EAMs are only 120 µm long, they can be driven lumped without any transmission line electrodes and accompanying termination, saving power. This topology allows to completely remove the linearity requirement at the transmit side, both in the optics and the electronics. Combining this compact modulator with an in-house developed electrical transceiver chipset, we are able to show the first real-time single-wavelength PAM-4 link above 100 Gb/s without any electrical ADC, DAC or DSP. Bit error rates well below the KP4 forward error coding (FEC) limit are achieved over more than 1 km of standard single-mode fiber (SSMF).

PAM-4 Generation

A prototype of the transmitter[5] was fabricated on

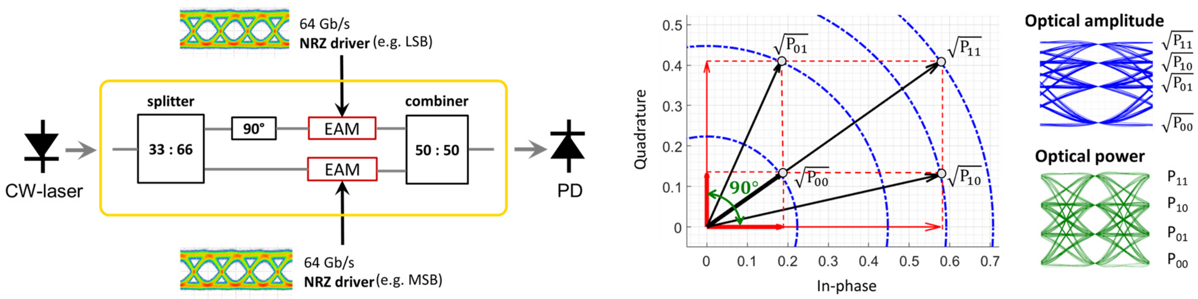
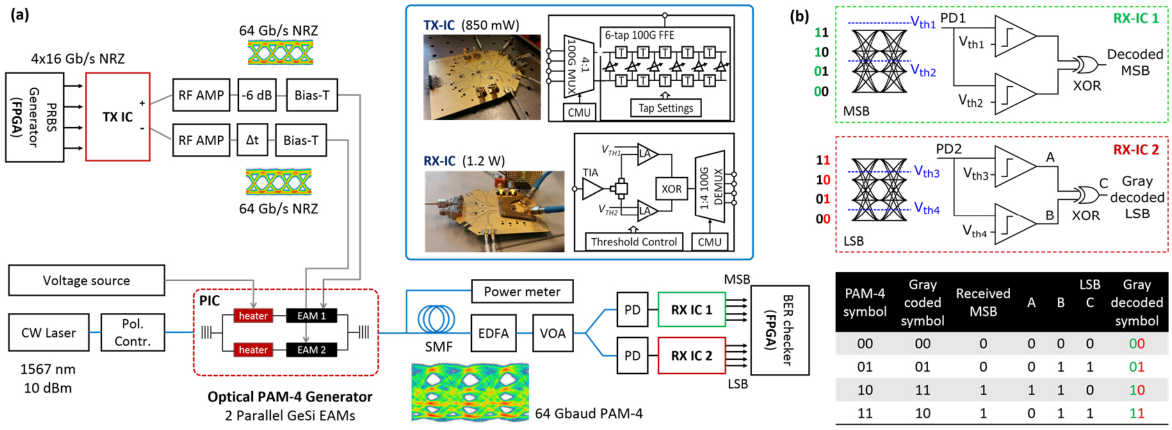


Fig. 1: (left) 2-bit optical DAC consisting of 2 GeSi EAMs; (right) vector diagram and eye diagrams. The red arrows represent the on- and off-state of the 2 EAMs, when driven separately. They form the basis vectors for the PAM-4 generation. The limited extinction ratio (10 dB in this example) and the resulting non-perfect zero level, are represented by the bold vectors.



PAM-4 symbol	Gray coded symbol	Received MSB	A	B	LSB C	Gray decoded symbol
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. 2: (a) Experiment setup (inset: block diagram of the BiCMOS transmitter IC and the receiver IC); (b) Implementation of the real-time PAM-4 receiver with automatic Gray code demapper.

imec's Silicon Photonics platform with two 1x2 multi-mode interferometers (MMIs), a DC phase shifter (heater) in each arm and two identical 120 µm long GeSi EAMs. The heater is set to introduce a 90° phase shift between both EAMs arm. Since the interferometers on this prototype chip are not tunable, the uneven power split of the least- and most significant bit (LSB and MSB) is emulated by biasing the LSB-EAM at higher reverse bias (introducing more insertion loss) and driving it with approximately half the swing of the MSB-EAM (6 dB attenuator in Fig. 2). However, this emulation is only an approximation of the proposed topology of Fig. 1, causing slightly unequal PAM-4 levels. With a 33:66 power split the transmitter eye levels would be perfectly equidistant when driven with the same voltage swing[5], improving the performance even further.

An in-house developed 4:1-multiplexer (TX-IC) is used to generate a 64 Gb/s 2^9-1 pseudo-random bit stream (PRBS) from 4 x 16 Gb/s PRBS signals generated by an FPGA, as is shown in Fig. 2. An analog 6-tap feed-forward equalizer to optimize the signal quality (mainly by compensating the frequency roll-off of the electrical receiver), follows the MUX. To generate two independent 64 Gb/s NRZ streams, the differential outputs of the transmitter are decorrelated with a tunable time delay and amplified to 1.1 Vpp and 2.2 Vpp to drive the LSB and the MSB EAMs, respectively. Light from a 1567 nm laser at 10 dBm is coupled in and out the optical modulator through fiber-to-chip grating couplers (insertion loss of ~6 dB/coupler). The EAMs have an estimated extinction ratio of 10 dB and insertion loss of 8 dB. The average in-fiber power after the device during operation was -10 dBm.

Real-time PAM-4 BERT

At the receiver side, the light is split 50:50 and fed to two commercial photodetectors (40 and 50 GHz bandwidth, ~0.6A/W responsivity), one for each electrical receiver (RX-IC). As no high-speed transimpedance amplifier (TIA) was available, an erbium-doped fiber amplifier (EDFA) is used to generate a sufficiently large signal at the output of the PDs. However, the EDFA can be omitted with the addition of a TIA and by replacing the grating couplers with low-loss edge couplers (<2 dB/coupler). As true real-time PAM-4 bit-error rate testers (BERT) are not yet commonly available at these rates, we implemented the receiver using two chips that were originally developed to decode 3-level duobinary[6]. Fig. 2 describes how both receiver chips (RX-ICs) are operated to measure the real-time BER of the MSB and the LSB simultaneously. This is in contrast to the few commercially available solutions at >50 Gbaud, where each of the three eyes are measured sequentially and the three BERs are averaged. For the MSB one RX-IC is set as a NRZ receiver by placing V_{th2} fixed high and centring V_{th1} around the DC-level, i.e. looking in the middle eye. This way the XOR-gate (originally needed for duobinary reception) becomes transparent[6]. To decode the LSB the comparators of the second RX-IC are set to the outer eyes of the PAM-4 signal.

An additional advantage of this topology is that it inherently implements a Gray code demapping of the received PAM-4 symbol (which is typically required after the receiver), as explained in Fig. 3.b. This demapping amounts to an additional XOR operation on the received "LSB" with the MSB. However, in a test setup one can chose to Gray code the transmit data or not. When transmitting PRBS coded data, the XOR operation of two PRBS encoded streams results in a time-shifted PRBS stream on which the BERT (implemented in the FPGA) can lock.

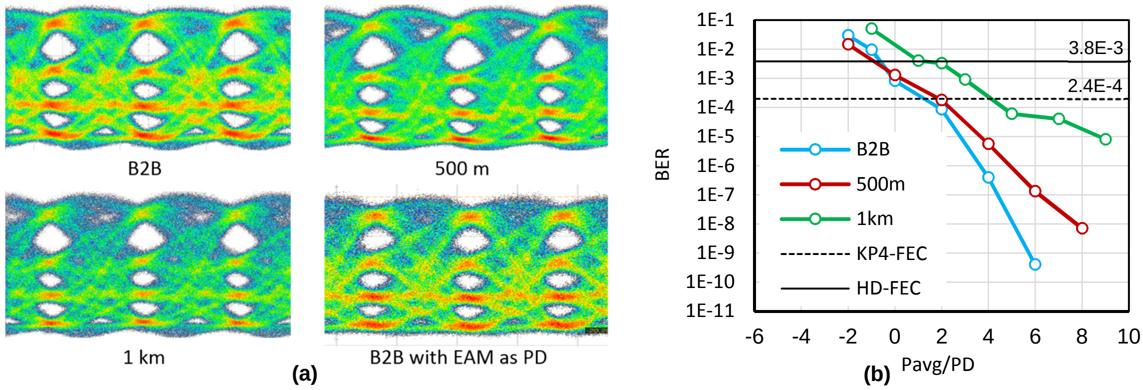


Fig. 3: (a) Eye diagrams for 64 Gbaud PAM4 captured by a 50GHz sampling scope and a commercial 50 GHz PD; (b) B2B, 500 m and 1 km of SSMF real-time BER curves at 64 Gbaud

Results and Discussion

To characterize the performance of the PAM-4 transmitter, the eyes are first optimized by inspection on a sampling oscilloscope (50 GHz BW). Clear open eyes are obtained up to 1 km SMF for fixed FFE settings (fig. 3.a). Then the photodiode is connected to the RX-ICs and the FFE parameters have to be re-optimized to minimize the BER, indicating that the RX-IC is indeed the limiting component of the real-time link. Nevertheless, BERs comfortably below the KP4-FEC are obtained for all transmissions (Fig. 3.b), going as low as 4E-10 for back-to-back (B2B) transmission, 7E-9 after 500m of SSMF and less than 8E-6 after 1 km of SSMF. The link is primarily limited by the high chromatic distortion in the fiber at 1567nm. These BERs correspond to the lowest values reported for a real-time >50 Gbaud PAM-4 link, confirming the superior eye quality of the optical DAC solution. An additional advantage of a transmitter based on EAMs, apart from the low power consumption and compactness, is that the same device can also serve as a photodiode by biasing the EAMs at maximal absorption. Fig. 3.a shows a 64 Gbaud PAM-4 eye received by one of the EAMs of the transmitter on a separate die. Apart from a slight increase in noise (most likely the lower output power caused to the additional grating coupler and the probed setup), switching from the commercial PD (with a flat frequency response up to 50 GHz) to the EAM as PD without changing any transmitter settings, results in little or no visible degradation. This confirms that these type of EAMs do not only have a high responsivity (>0.8A/W) as was observed in ref[5], but that they also exhibit a flat frequency response at these high frequencies. This makes them well-suited as a linear optical receiver. Using the same component for both the transmitter and the receiver greatly simplifies the yield optimization of a silicon-based optical transceiver for high-volume production.

Conclusion

We have presented a compact silicon-based transmitter capable of generating 64 Gbaud PAM-4 by using two parallel and binary driven 120 µm long GeSi EAMs. In combination with an in-house developed electrical transceiver chipset, we were able to show 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. These results not only illustrate the advantages of shifting 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 100G-per-wavelength optical interconnects.

Acknowledgements

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