100 Gb/s DAC-less and DSP-free Transmitters using GeSi EAMs for Short-Reach Optical Interconnects

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Abstract: We present single-lane 100-Gb/s NRZ, electrical duobinary and PAM-4 transmitters using silicon photonics GeSi electro-absorption modulators. No DSP, DAC or traveling-wave structures are required, enabling compact and low-power transceivers for data center interconnects.

OCIS codes: (250.5300) Photonic Integrated Circuits, (200.4650) Optical Interconnects; (060.4080) Modulation

1. Introduction

As the internet keeps growing, so does the need for higher data rates on optical interconnects in and between data centers. To transition from currently deployed 100 Gigabit Ethernet (GbE) links to 400 GbE, several implementations are under investigation [IEEE 802.3bs]. A four lane 100 Gb/s scheme –either through coarse wavelength multiplexing or four parallel fibers- would be particularly interesting as it keeps the lane and laser count low, saving area, packaging cost and power. Silicon photonics would be ideally suited to implement this compact and low-power transceivers at low cost and high volume by leveraging the existing CMOS fabrication infrastructure. However, this requires the optical building blocks to operate at 100 Gb/s serial rates. In order to relax the bandwidth requirements on the electrical frontend and the optical components, PAM-4 has emerged as the most likely modulation format of choice for these next-generation 400 GbE transceivers as it requires only half the bandwidth of a conventional NRZ-based link. Nonetheless, we will show that 100 Gb/s NRZ could provide an elegant and realistic alternative towards a compact transceiver, maintaining the low complexity of on-off keying-based electronics.

Previously, Several examples of 100 Gb/s single-lane transmission been demonstrated using NRZ, electrical or 3-level duobinary (EDB), PAM-4 or discrete multi-tone (DMT). However, most of these experiments still rely on (offline) complex digital signal processing on the receiver and/or the transmitter. Furthermore, all of the limited real-time examples resort to travelling wave structures, typically a Mach-Zehnder (MZM) configuration of several millimeters long, as these can offer high bandwidth together with high extinction ratios (ER). Unfortunately, these structures are large by design and necessitate the placement of one or more power-consuming resistive terminations, making them less suitable for low-power and compact data center interconnects.

2. 100 Gb/s real-time NRZ/EDB transmission

In our research, we have focused on short germanium-silicon-based electro-absorption modulators (GeSi EAMs), as they can provide very high bandwidths, even when driven lumped (i.e. without transmission lines) at moderate voltage swings, with sufficiently high ER for short-reach interconnects. The basic building block for transmitters discussed in this paper are shown in Fig.1. The optical modulator is an 80µm long waveguide-integrated GeSi EAM and is fabricated by imec’s 200nm Silicon Photonics platform. The device has a dynamic ER and insertion loss of ~7dB when driven with 2Vpp, and modulates with a 1dB transmitter penalty (TP) from the upper C-band to low L-band.

Fig. 1: (left) micrograph and architecture of the TX-IC consisting of a 4:1 MUX and a 6-tap FFE; (center) cross-section and layout of the waveguide-integrated GeSi EAM; (right) block diagram and micrograph of the RX-IC consisting of 2 comparators (for EDB decoding) and a 1:4 DEMUX.
More power efficient as they can be non-linear, making a pure NRZ transceiver is warranted to cover these distances without having to resort to more complex schemes (e.g. PAM-4) or DSP. However, in most data centers a large majority of the interconnects are covered by 500m long fibers, making pure NRZ-based transceiver a more attractive solution in the search for the implementation with the lowest possible power consumption and form factor.

4. 112 Gb/s PAM-4 generation using 2 parallel EAMs

Nevertheless, PAM-4 still remains the main contender for 400 GbE optical interconnects. However, generating and receiving PAM-4 at line rates of 112 Gb/s has proven to be challenging. However, generating and receiving PAM-4 at line rates of 112 Gb/s has proven challenging, without relying on power-hungry tools such as digital signal processing and digital-to-analog converters. One of the main drawbacks of PAM-4, apart from the reduced eye openings due to the multi-level format, is that it introduces new requirements for the E/O-components in terms of linearity and/or requires pre-distortion techniques. Most of the PAM-4 transmitters demonstrated so far use fast electrical digital-to-analog converters (DACs) which can either generate large voltage swings (i.e. power DACs) or be followed by linear output drivers to provide sufficient voltage swing to the modulator. Both options consume significantly more than there NRZ counterparts at the same data rate. Furthermore, two NRZ drivers are likely to be more power efficient as they can be non-linear, allowing other driver topologies to be considered (e.g. a CMOS inverter). Postponing the DAC operation to the optical domain, would reduce the complexity in and the power
Fig. 3: (a) Proposed PAM-4 transmitter topology using 2 parallel EAMs with $\alpha = 1/3$ and $\Delta \phi = 90^\circ$; (b) Vector diagram where the red arrows represent the on- and off-state of the 2 EAMs, when driven separately. The limited extinction ratio (10 dB in this example) and the resulting non-perfect zero level, is represented by bold vectors. The PAM-4 constellation points (black vectors) are formed by the vector addition of the red basis vectors. (c) Optical eye diagrams at 56 GBaud and 28 GBaud; (d) BER curves for 100Gb/s and 112 Gb/s for 0,1 and 2 k of SSMF.

consumption at the transmitter significantly. Recently, several examples of DAC-less PAM-4 generators have been demonstrated, but most of them rely on large travelling wave Mach-Zehnder modulators (MZMs) and power-consuming 50Ω terminations [3]. Other modulators such as microring resonators have been used, but current demonstrations have been limited to 80 Gb/s even with extensive transmit and receiver-side digital signal processing [4]. In [5], we proposed a novel transmitter topology (depicted in Fig 3.a) based on the vector addition of 2 parallel EAMs. By introducing a 90° phase shift and 33%-66% power ratio between both EAMs, an equidistant PAM-4 eye is obtained as described in Fig 3.b. A prototype transmitter based on this topology was fabricated using the same GeSi EAMs, driven with 2 half-rate NRZ streams at 1.1Vpp and 2.2Vpp for the least and most significant bit (LSB and MSB), respectively. The maximum voltage swing could be slightly higher than in the previous experiments as the linearity requirement is completely removed from the transmit side, allowing the EAMs to be operated as switches for maximal ER. Clear open eyes were obtained at 56 GBaud as can be seen in Fig 4.c. Using this transmitter, we were able to demonstrate PAM-4 transmissions below the KP4-FEC over 2 km of SSMF at 100 Gb/s and over 1 km of SSMF at 112 Gb/s.

5. Conclusion
We have presented our ongoing work on compact and low-power GeSi EA modulators for 100G serial optical interconnects. We were able to demonstrate the first silicon-based modulators capable of transmitting 100 Gb/s NRZ over 500 m and EDB over 2 km of SSMF in real-time, as well as the first 112 Gb/s PAM-4 over 2 km of SSMF, without having to rely on power-hungry DACs, DSP and/or long travelling wave structures. These examples showcase the bright future for silicon photonics towards realizing compact, low-cost and low-power transceivers for short-reach optical interconnects at 400G and beyond.

6. Acknowledgement
This work was partially supported by imec’s industry-affiliation R&D program on Optical I/O. The authors thank the UGent BOF GOA Research Fund, the Research Foundation – Flanders (FWO), FWO-SBO and the H2020 project TERABOARD for their support.

7. References