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. 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 these 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 [1].

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 blocks for the transceivers 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 200mm 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-

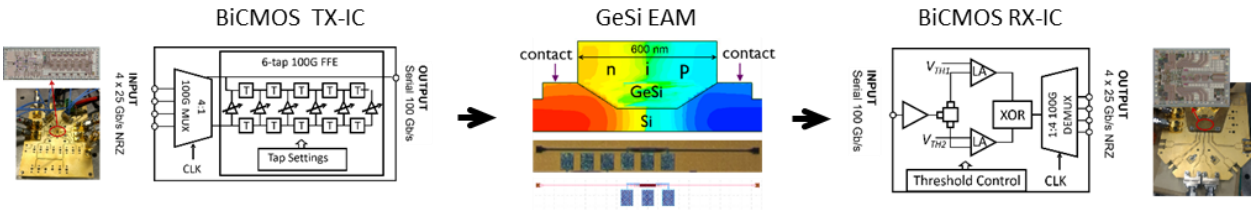

Fig. 1: (left) micrograph and architecture of the TX-IC consisting of a 4:1 MUX and a 6-tap FFE; (center) cross-section and layout of the waveguide-integrated GeSi EAM; (right) block diagram and micrograph of the RX-IC consisting of 2 comparators (for EDB decoding) and a 1:4 DEMUX.

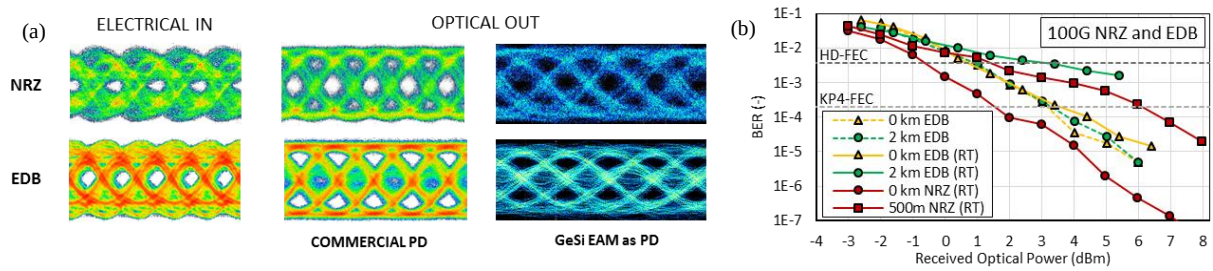

Fig. 2: (a) electrical pre-distorted inputs from the TX-IC and resulting optical eyes either captured by a commercial 50 GHz PD or by an additional GeSi EAM acting as a PD; (b) BER curves for 100 Gb/s NRZ and EDB transmissions (real-time = RT).

band (minimal TP around 1560-1565nm). More information on the design, characterization and basic performance of this modulator can be found in [2]. To operate these EAMs at 100Gb/s NRZ, in-house developed transmitter and receiver ICs (TX- and RX-IC) were used. Both chips were originally developed in a 0.13µm SiGe BiCMOS technology. The TX-IC consists of a 4:1 multiplexer (MUX) which can combine 4 quarter rate NRZ streams up to 28 Gb/s into a serial 112 Gb/s stream. This MUX is followed by a 6-tap (~9ps spaced) feed-forward equalizer to compensate any non-idealities in the following optical or electronic components in the link. As these chips were originally designed for duobinary signaling over electrical backplanes, they provide an output of a couple of hundred millivolts and require an external RF amplifier to provide a $2V_{pp}$ voltage swing to the EAM. However, these voltages are still well within the reach of the used BiCMOS technology and, as such, the chip could be extended with an additional output stage to achieve a $2V_{pp}$ swing. The RX-IC has two comparators, an XOR gate and a 1:4 demultiplexer (DEMUX). Setting one of the comparators thresholds permanently HIGH, makes the XOR port transparent and reduces the EDB-decoder to a conventional NRZ receiver. At 100 Gb/s NRZ, the transceiver chipset is able to serialize, equalize, decode and deserialize for a combined power budget of 2.2W (TX: 1W, RX: 1.2W).

Using these components, we were able to transmit 100 Gb/s NRZ with a bit-error ratio (BER) down to 6E-9 in back-to-back link and 2E-5 over 500m of standard single mode fiber (SSMF), both well below the KP4 forward error coding limit (FEC) of 2E-4 (typically used in data center interconnects). Due to the high line rate, transmission over longer fiber spans was limited by the chromatic distortion in the fiber. In a second experiment, electrical duobinary modulation is investigated as it is more resilient to this type of fiber distortion. Here, a new version of the TX-IC was used, which was fabricated in a 55nm SiGe BiCMOS process and consumed only 0.75W. As anticipated, EDB shows improved performance for longer distances, resulting in BERs down to 1E-5 without the RX-IC (using offline error detection) and a BER of 1.4E-3 in a real-time experiment with the RX-IC after 2 km of SSMF. As there was no high-speed (>40GHz) transimpedance amplifier (TIA), in both experiments an EDFA was used to boost the signal power. An additional advantage of these GeSi devices is that they can also be used as photodetectors with a responsivity close to 1 A/W, as is demonstrated by the full-rate eye diagrams in Fig 2.a. This way a complete silicon-based optical transceiver based on a single active device type could be envisioned.

With the longest typical fiber distances in hyperscale datacenters limited to 2km, an EDB modulation based transceiver would be ideally suited for this type of interconnect, where the increased complexity of transitioning from a pure NRZ-based transceiver to an EDB-based transceiver is warranted to cover longer 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 are 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

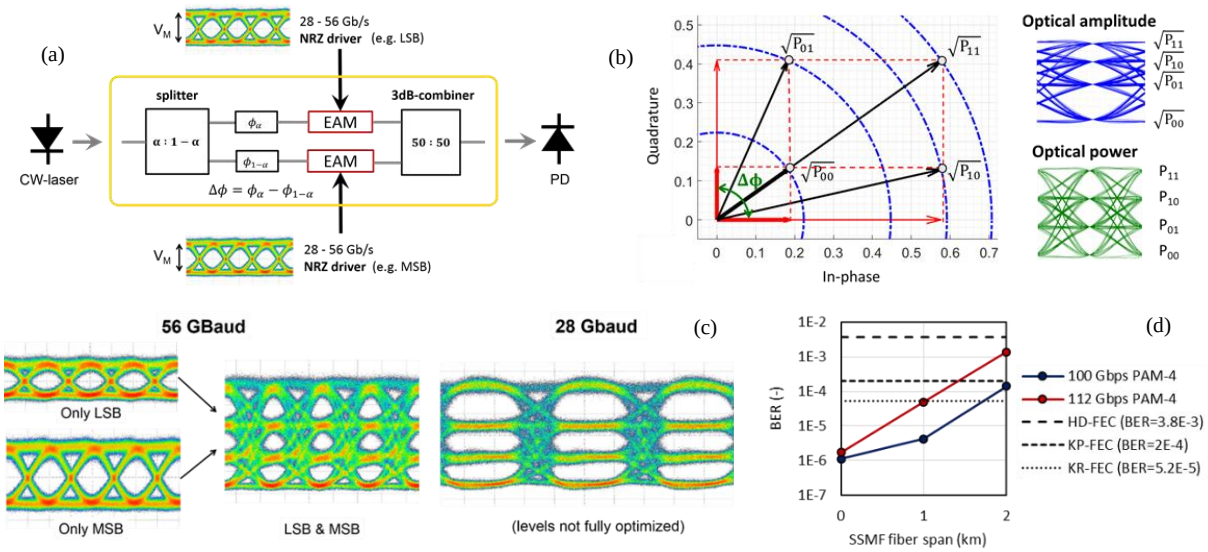

Fig. 3: (a) Proposed PAM-4 transmitter topology using 2 parallel EAMs with $\alpha = 1/3$ and $\Delta\phi = 90°$; (b) Vector diagram where the red arrows represent the on- and off-state of the 2 EAMs, when driven separately. The limited extinction ratio (10 dB in this example) and the resulting non-perfect 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 km of SSMF at ~8 dBm of received average power.

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 limit 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.

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