

First Real-Time 100-Gb/s NRZ-OOK Transmission over 2 km with a Silicon Photonic Electro-Absorption Modulator

J. Verbist^{1,2,*}, M. Verplaetse¹, S.A. Srivinasan^{2,4}, P. De Heyn⁴, T. De Keulenaer^{1,3}, R. Pierco^{1,3}, R. Vaernewyck^{1,3}, A. Vyncke^{1,3}, P. Absil⁴, G. Torfs¹, X. Yin¹, G. Roelkens², J. Van Campenhout⁴, J. Bauwelinck¹

¹IDLab, INTEC, Ghent University - imec, 9052 Ghent, Belgium

²Photonics Research Group, INTEC, Ghent University—imec, 9052 Ghent, Belgium

³BiFast, Spin-off incubation project of Ghent University-imec, IDLab, 9052 Ghent, Belgium

⁴imec, Kapeldreef 75, 3001 Leuven, Belgium

*E-mail: jochem.verbist@ugent.be

Abstract: We demonstrate the first real-time, serial 100 Gb/s NRZ-OOK transmission with an integrated GeSi EAM implemented on a silicon photonics platform. Transmission over 500m of SSMF and 2 km of dispersion shifted fiber is presented.

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

1. Introduction

In order to meet the growing bandwidth requirements, data centers push the research towards short-reach optical interconnects operating at 100 Gb/s and beyond. Currently the evolution from 100 Gb/s Ethernet to 400 Gb/s transceivers is under discussion within the IEEE P802.3bs 400 Gigabit Ethernet Task Force[1]. Several implementation options including multi-lane, multiple polarizations and/or multi-level transmissions are under investigation. A four lane 100 Gb/s NRZ scheme could provide an elegant solution to achieve 400 GbE transceivers allowing higher spatial efficiency through lower lane counts, while maintaining the low complexity of OOK-based, low-power electronics. Silicon photonics is ideally suited to provide compact and low-cost transceivers for optical interconnects, although scaling to 100 Gb/s lane rates has proven to be difficult for silicon-based transceivers. Recently, 100 Gb/s single-lane links have been realized using four level pulse amplitude modulation (PAM-4), discrete multi-tone (DMT) and electrical duobinary (EDB) [2-5]. However, these experiments rely on heavy and power-consuming digital signal processing (DSP), typically done off-line. Examples of true real-time 100 Gb/s transmissions without DSP are limited. In [6], 112 Gb/s PAM-4 modulation on a discrete Mach-Zehnder Modulator was demonstrated at 8.6W of power consumption. EDB was used to achieve real-time 100 Gb/s on a InP-based travelling-wave electro-absorption with integrated DFB-laser [7]. The transmission line structure of the modulator electrodes necessitates a power consuming 50 Ω termination. In [8], an impressive real-time BER lower than 10^{-10} was achieved with silicon-organic Mach-Zehnder modulator, again with travelling wave electrodes and 50 Ω termination. However, this device does have some drawbacks in terms of cost, power and footprint, when envisioned as a short-reach optical interconnect transceiver. The 1.1 cm long modulator was packaged with two InP-based electrical multiplexers offering a differential voltage swing of 6 Vp, resulting in a power consumption –excluding the laser– of almost 6.85 W. The transmitter module measures 6.5 x 2 cm. The proposed 4x100 PIN-DEMUX receiver adds another 5.5W of power consumption and measures 4 x 6.9 cm.

In this paper we present a real-time, serial and single-wavelength 100 Gb/s NRZ-OOK link based on an extremely compact Germanium-silicon electro-absorption modulator integrated on a 200mm silicon platform in combination with in-house designed transmitter (TX IC) and receiver (RX IC) chipsets in a SiGe BiCMOS technology. The modulator was driven lumped with 2 Vpp without any termination. This is the first real-time, single channel 100 Gb/s NRZ transmission on a silicon-based integrated modulator without any complex DSP. Transmission over 500m of standard single mode fiber (SSMF) and 2km of dispersion shifted fiber (DSF) is reported.

2. Experiment Setup

The GeSi EAM consists of a 600nm wide and 80 μ m long germanium waveguide with embedded lateral p-i-n-junction, connected via tapers to silicon waveguides, and was fabricated on imec's 200 mm silicon photonics platform. Modulation is obtained through the Franz-Keldish effect, which shifts the bandgap edge of GeSi by applying an electrical field [9]. Light is coupled in and out of the waveguide device by fiber-to-chip grating couplers which have an insertion loss of ~6 dB/coupler. An electrical RF probe (without 50 Ω termination) is used to apply the bias voltage and high speed signal.

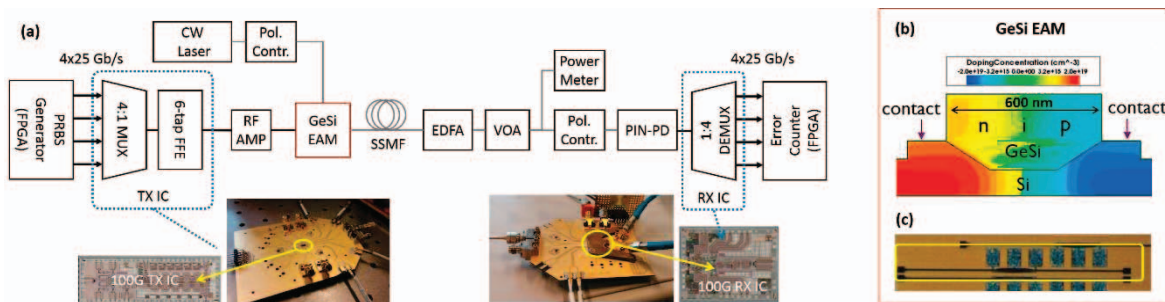


Fig. 1. (a) Experiment setup of real-time 100 Gb/s NRZ-OOK optical link, (b) cross-section of the GeSi waveguide EAM; (c) micrograph of the presented modulator.

The experiment setup is shown in Fig.1. A Xilinx Virtex FPGA generates four 2^7-1 long pseudo-random bit streams (PRBS) at 25 Gb/s, which are multiplexed with the required delays to form again a 2^7-1 long PRBS at 100 Gb/s.

A six-tap analog feedforward equalizer (FFE) on the transmitter IC (TX IC) is set to compensate the frequency roll-off and non-idealities of the following components and the link. A 50 GHz RF amplifier with internal bias-T delivers the pre-emphasized electrical signal with a 2 V_{pp} swing to the optical modulator. The in-waveguide laser power was ~ 5 dBm at a wavelength of 1601.5 nm. The EAM was biased at -1.85V for back-to-back experiments and at -2.05V for transmission experiments, resulting in a photocurrent of roughly 3.60 mA and 3.80 mA, respectively. The fiber-coupled power after the photonic IC was almost -5 dBm. With these settings we measured a dynamic extinction ratio of ~ 6 dB and an insertion loss around ~ 6 dB for the modulator. To convert the optical signal back to the electrical domain, a commercial 50 GHz PIN-photodiode with a responsivity near 0.6 A/W was used. As no high-speed (>50 GHz) transimpedance amplifier was available, an EDFA and variable optical attenuator were used to increase and control the signal power before coupling the light into the PIN-PD. The EDFA can be removed from the setup by addition of a transimpedance amplifier, which as an added benefit would also improve the transceiver performance by reducing the amount of noise in the O/E/O-link.

Finally, the 100 Gb/s data is deserialized by the electrical receiver (RX IC) into 4 x 25 Gb/s streams and fed back to the same FPGA for real-time error detection without any complex DSP or offline processing. The RX IC consists of 2 parallel level-shifting limiting amplifiers (LA), an XOR-gate and a 1-to-4 DEMUX, allowing operation as an EDB decoder (using both LAs) or as a NRZ decoder (keeping the output of one LA fixed). Both transmitter and the receiver IC were designed in-house in a $0.13\mu\text{m}$ BiCMOS technology [10]. The RX-IC occupies $\sim 1950 \times 2600 \mu\text{m}$ and consumes less than 1.2W, the TX IC occupies $\sim 1500 \times 4500 \mu\text{m}$ and consumes 1W.

3. Results and Discussion

Real-time BER tests were carried out to characterize the optical link performance with the setup shown in Fig. 1. For back-to-back (B2B) transmission a BER below 6×10^{-9} was obtained for an average optical input power to the PIN-PD of 8.3 dBm. The hard-decision forward error coding limit (BER= 3.8×10^{-3} for a 7% overhead) is reached for an average power of -0.6 dBm. Compared to the fiber-coupled power after the modulator, this requires an increase of only ~ 4.5 dB which could be realized by replacing the on-chip grating couplers ($\sim 6\text{dB}/\text{coupler}$) by low-loss edge-couplers ($< 2 \text{ dB}/\text{coupler}$) [11]. This indicates that an EDFA-less link is indeed possible.

The frequency response of the optical link for different fiber lengths is shown in Fig. 2(e). Operation in L-band (1601.5 nm) severely degrades the flatness of the frequency response for longer fiber spans due to high levels of chromatic distortion. Nevertheless, we still manage to obtain transmission over more than 500 m of SSMF with a BER down to 2×10^{-5} . Sub-FEC operation is achieved for powers >1.5 dBm, resulting in a penalty of 2 dB with respect to B2B. Finally, transmission over 2 km of DSF ($\sim 8 \text{ ps}/\text{nm}\cdot\text{km}$ dispersion) assuming FEC is also achieved for a received power of more than 4 dBm, saturating in an error-floor of 1×10^{-3} . Investigating the received eyes taken at the output of the PIN-PD in Fig. 2(a-c), we believe that the limited bandwidth of the RX IC (41 GHz) is the main contributor to the total BW, limiting the performance of the overall link. Tests with a new and faster RX IC are planned in the coming months.

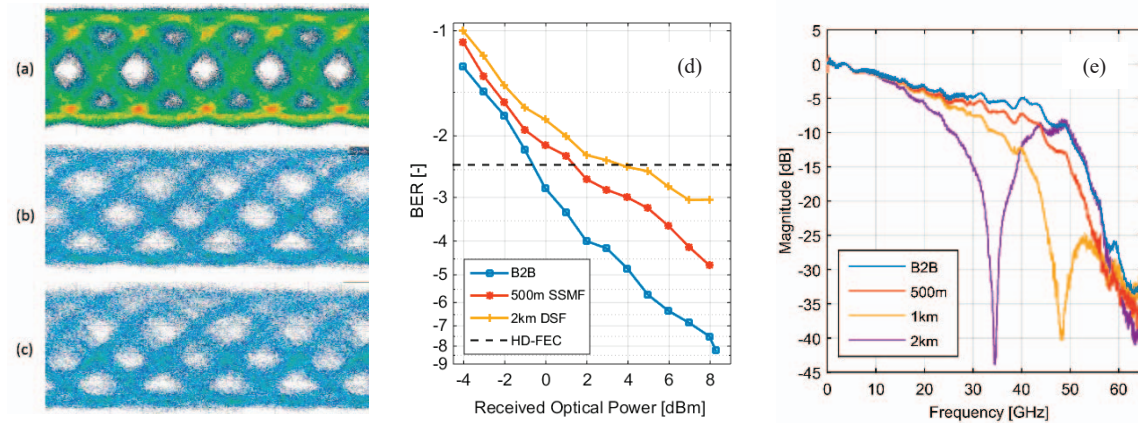


Fig. 2: Eye diagrams and for (a) 100 Gb/s B2B, (b) 500m SSMF and (c) 2km of DSF transmission captured after the PIN-PD by a 70GHz sampling scope corresponding to a received optical power of 6dBm; (d) Real-time BER curves for the same fiber lengths; (e) Frequency response of the optical link (from RF Amp to PIN-PD) for different lengths of SSMF at 1601.5nm

An additional advantage of the proposed modulator is that the same structure could be used as a high-speed photodiode. Fig. 3 shows an example of the received eye for such an EAM-to-EAM optical link at 100 Gb/s where an identical copy of the EAM on a separate die was used as a receiver. The bias voltage for the RX EAM was applied through an electrical RF probe and set to 5V to ensure maximal light absorption. Although this was not further investigated, observing the frequency response of a EAM-to-EAM link and comparing the received eye in Fig.3(a) to that from a commercial III-V-based PIN-PD in Fig.2(a) we can see a small degradation for the EAM as PD. This is attributed to the absence of a well-matched 50Ω output of the EAM-PD, which is expected by the RX IC and is internally present on the commercial PIN-PD. Nevertheless, a complete silicon transceiver with 100 Gb/s NRZ-OOK line rates link based on a GeSi EAM as a modulator and photodetector is achievable.

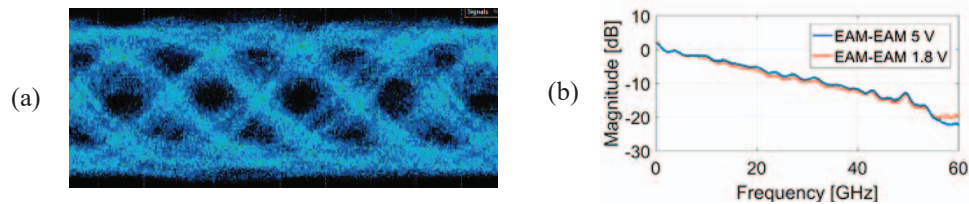


Fig. 3: (a) Eye diagram for a 100Gb/s EAM-to-EAM link (TX EAM $V_{bias}=1.8V$, RX EAM $V_{bias}=5V$); (b) Frequency response of the EAM-to-EAM link for a reverse bias of 1.8V and 5V on the RX-EAM.

4. Conclusion

We have demonstrated a serial 100 Gb/s NRZ-OOK transmission based on an integrated GeSi EAM, fabricated in a 200mm silicon photonics platform in combination with an in-house designed SiGe BiCMOS transmitter and receiver chipset. Successful transmission over 500m of SSMF and 2km of DSF was achieved and verified in real-time without the need for any DSP. These results showcase the capabilities of silicon photonics as a possibly disruptive technology for compact and low-power transceivers for 400 GbE short-reach optical interconnects.

5. Acknowledgement

This work was supported by the imec IAP on Optical I/O for the Ge EAM, the UGent IOF for the Tx/Rx ICs, the H2020 TERABOARD project, the UGent BOF and the FWO.

6. References

- [1] "IEEE P802.3bs 400 Gigabit Ethernet Task Force." [Online]. Available: <http://www.ieee802.org/3/bs/>
- [2] C. Caillaud et al., "Low cost 112 Gb/s ...," in ECOC, Valencia, 2015, PDP
- [3] P. Dong et al., "Four-channel 100-Gb/s...", in OFC, Los Angeles, CA, 2015, Th5B.4 - PDP
- [4] W. Bo et al., "Single-Lane ...," in ECOC, Dusseldorf, Germany, 2016, pp. 1148-1150
- [5] J. Lee et al., "Serial 103.125-Gb/s transmission...", in OFC, 2014, San Francisco, CA, 2014, PDP - Th2.A.4
- [6] J. Lee et al, in ECOC , ID:0604, Valencia, 2015.
- [7] X. Yin et al., "First Demonstration of ...," in ECOC, Dusseldorf, Germany, 2016, PDP
- [8] Katopodis et al. "Tunable transmitter ...", in OFC, Anaheim, CA, 2016, Tu2A3
- [9] S. A. Srinivasan et al, OFC, Anaheim, CA, 2016, pp. 1-3.
- [10] M. Verplaetse et al., "Real-Time 100 Gb/s ...," in Journ. Of Lightw. Techn., 2017, available online
- [11] A. Dewanjee et al., "A low-loss ...," 2014 IEEE Photonics Conference, San Diego, CA, 2014, pp.560-56