104 Gbaud OOK and PAM-4 Transmission over 1km of SMF using a Silicon Photonics Transmitter with Quarter-Rate Electronics

Jochem Verbist[1,2], Mads Lillieholm[3], Joris Van Kerrebrouck[1], Srinivasan Ashwyn Srinivasan[4], Peter De Heyn[4], Joris Van Campenhout[4], Michael Galili[3], Leif K. Oxenløwe[3], Xin Yin[1], Johan Bauwelinck[1], Gunther Roelkens[2]

(1) IDLab, INTEC, Ghent University – imec, 9052 Ghent, Belgium (Jochem.Verbist@ugent.be)
(2) Photonics Research Group, INTEC, Ghent University – imec, 9052 Ghent, Belgium
(3) DTU Fotonik, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark
(4) imec, 3001 Leuven, Belgium

Abstract: We present a silicon photonics transmitter using four GeSi EAMs driven at 26 Gbaud with 1.2Vpp to realize the fastest reported single-wavelength PAM-4 transmission on silicon at 208 Gb/s over 1km of SMF.

OCIS codes: (250.7360) Waveguide modulators, (250.5300) Photonic Integrated Circuits, (200.4650) Optical Interconnects

1. Introduction

With the increasing bandwidth requirements for data center interconnects (DCI) the new generation DCIs will upgrade the existing 100 Gb/s links to 400 Gb/s, using either 8×26 Gbaud or 4×53 Gbaud PAM-4 depending on the fiber span as described by the IEEE 400GBASE standards. However, with these transceivers finding their way to the data center market in the coming years, research and discussion have started to shift towards the implementation of the next-generation transceivers at 800 Gb/s or even 1.6 Tb/s [1]. A 200 Gb/s/λ per lane scheme would provide an elegant upgrade towards these 0.8 TbE and 1.6 TbE interconnects, maintaining a low channel count.

However, doubling the baudrate to 100 Gbaud would require a significant increase in the performance of the optical and electrical components, requiring bandwidths of 70 GHz or more. One possibility therefore is to abandon the intensity-modulated direct-detection (IMDD) links in favor of spectrally efficient coherent links. But data centers have been hesitant to make this shift, as these metro and long-haul devices still consume significantly more power than their comparable IMDD counterparts. Hence, it will be challenging to meet the extremely compact form factor requirements. Best in class coherent modules currently require ~20W for a 200 Gb/s PM-16-QAM link using a 4x10.7 cm CFP2-DCO transceiver module. The additional power consumption of the coherent DSP and the large form factor make IMDD links still the preferred solution for these next-generation intra-data center links.

Recently, a transmitter capable of 204 Gb/s on-off keying (OOK) has been achieved using InP platforms for both the optics and electronics using offline DSP [2]. On silicon, the highest reported intensity modulated transmission with a single PD has been limited to 168 Gb/s PAM-4 using a large multi-electrode (>5 mm) traveling-wave Mach-Zehnder modulator (MZM) driven with 3.8 and 5 Vpp in combination with extensive TX-side DSP [3], making it less suited for DCI applications.

Over the last two decades, optical serializers (used in optical time division multiplexing or OTDM schemes) have attracted much research as they can generate very high data rate optical transmissions with limited bandwidth (BW) electronics. However, the need for long integrated optical delays as well as the absence of a practical and low-cost

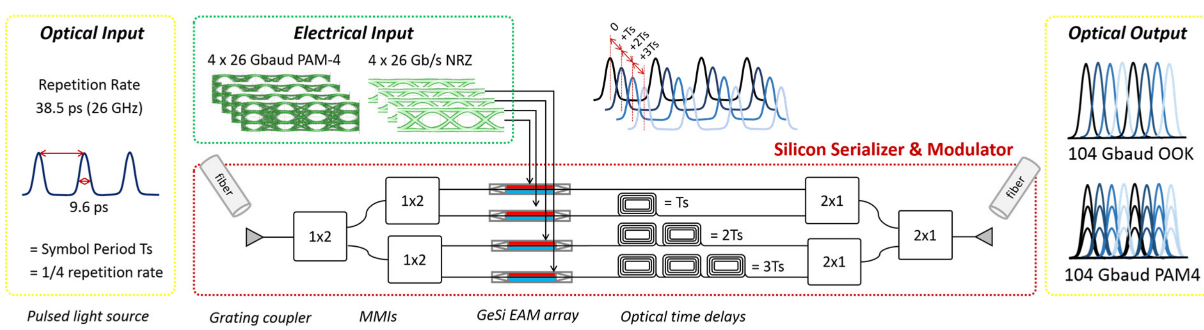

Fig. 1: Operation principle of the optical serializer and modulator: a pulsed light source at 26 GHz with a 25% duty cycle (~9.6 ps pulse width) is split into four streams using three 1×2 MMIs. Each stream is modulated by a GeSi EAM driven with 26 Gbaud NRZ (or PAM4), delayed with 0,1,2 or 3 symbols periods using spiral waveguides and combined again using three 2x1 MMIs, producing 104 Gbaud OOK (or PAM-4).

integrated pulsed light source has prevented the adoption of optical serializers in datacom applications. Nevertheless, remarkable progress has been made in recent years on integrated semiconductor mode-locked lasers (MLLs) [4-5]. In particular, the arrival of efficient and low-cost III-V-on-Si MLLs [4] could be an important turning point towards fully integrated Si-based optically multiplexed transceivers. Silicon Photonics (SiP) would be an ideal platform to integrate MLLs and optical serializers as both devices require long optical time delays, which can be made very compact and with low losses. Combining a III-V-on-Si laser with the Si multiplexer and modulator would be a promising and cost-effective candidate towards realizing 0.8 and 1.6 TbE links, maintaining the low complexity and minimal DSP associated with IMDD links without having to resort to very high bandwidth (>70 GHz) drivers and DACs at the transmitter.

In this paper, we demonstrate the first silicon modulator capable of generating 104 Gbaud OOK and PAM-4, using four GeSi electro-absorption modulators (EAMs) as an optical serializer (Fig. 1). Driving the EAMs with PAM-4, we achieve the highest reported single-wavelength bitrate for a silicon modulator (208 Gb/s) in an IMDD link. The compact EAMs (80 µm) can be operated without any long traveling-wave electrodes and power-consuming terminations (saving transceiver real estate and power) and require only 1.2 Vpp at quarter-rate speeds (26 Gbaud) thanks to the 4:1 optical multiplexing.

2. 4:1 Silicon Optical Serializer with GeSi EAMs

The silicon modulator was fabricated on imec's 200mm SiP platform. The incoming light is divided equally over four parallel branches using three 1x2 multimode interferometers (MMIs) in a binary tree (Fig.2). Per branch, an 80 µm long GeSi EAM modulates the quarter-rate electrical data. The EAM operation is based on the Franz-Keldysh effect, where the bandgap of the device shifts when an electrical field is present. These are the same type of EAMs as used in our previous work [6,7] where we measured an insertion loss of ~7 dB and extinction ratio of ~8 dB for a 2 Vpp swing. As these GeSi devices are extremely compact, they can be driven as very small capacitors without power-hungry resistive terminations. Consequently, dedicated drivers can be made extremely low-power as we recently demonstrated in [8] with a 70 Gb/s EAM driver consuming only 61 mW. Moreover, at 26 Gbaud the driver design could be optimized to consume even less. Optical delays are implemented as waveguide spirals of N×750 µm length (N=0,1,2,3). Thanks to the high index contrast of the SOI-waveguides, the spirals were realized with a bend radius of 10µm, resulting in very compact time delays with very low losses (< 0.2 dB). At 1563 nm, the measured delay difference between each arm is approximately 9.6ps. Finally, the light from each branch is combined with three 2×1 MMIs, and coupled in and out of the PIC through fiber-to-chip grating couplers (GC) with an efficiency of approximately 6 dB/coupler.

3. Transmission Experiments and Discussion

Fig. 2 shows the experimental setup that was used to characterize the Si serializer and modulator, together with a die photo of the PIC. CW light at 1563 nm is launched into a cascaded MZM (biased at minimal transmission and acting as a pulse carver) and phase modulator (PS) modulated by a 26 GHz sine wave generator. 230m of DCF is added to provide additional compression to the pulses, ensuring a FWHM of less than 9.6 ps when measured with a 70 GHz PIN-PD. Inspection of the optical spectrum reveals eleven 26 GHz spaced lines within 3 dB (Fig 3.b). However, with the addition of an optical waveshaper acting as bandpass filter the spectrum of the frequency comb could be limited down to less than 2.5 nm without any observable penalty. This opens up the possibility to use a single MLL with a sufficiently broad comb to feed multiple channels in a WDM scheme (e.g. 4 OTDM-based channels out of a 12 nm comb). Next, an EDFA amplifies the pulses to provide a 13 dBm average input power to the PIC. A four channel 65 GSa/s arbitrary waveform generator (AWG) creates four uncorrelated 2^9-1 long pseudo-random symbol streams of NRZ or PAM-4. These are amplified to 1.2 Vpp and applied to the EAMs through two GSGSG RF-probes. All four

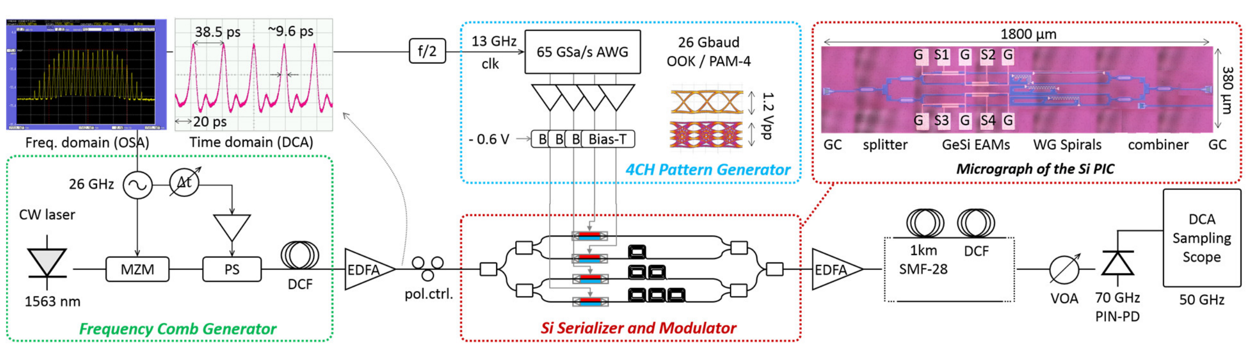

Fig. 2. Experimental setup for transmission of 104 Gbaud OOK and PAM-4 over a single λ using a Si modulator

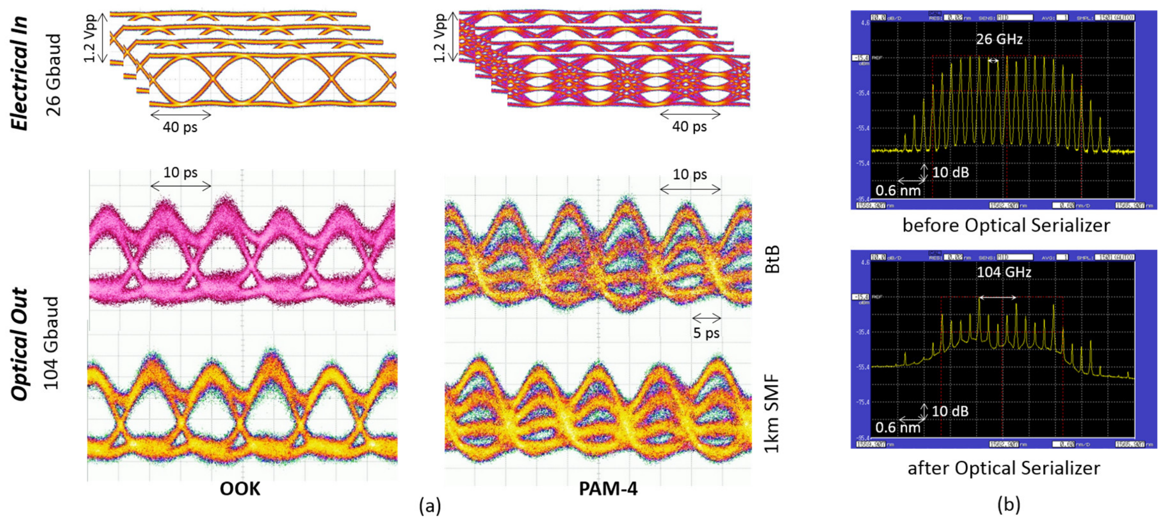

Fig. 3: (a) Eye diagrams captured by a 50 GHz sampling oscilloscope: 26 Gbaud electrical inputs (OOK/PAM-4) and received optical eyes in BtB and after 1km of SMF at 104 Gbaud OOK and PAM-4 (b) optical spectra before and after the optical serializer

EAMs were biased at –0.6V. After the PIC, an EDFA and variable optical attenuator set the average input power to a 70 GHz PIN-PD (0.6 A/W). Finally, the eyes are captured by a 50 GHz sampling oscilloscope. The average in-fiber power after the PIC is -14 dBm during operation, mostly dominated by the 12 dB insertion loss of the grating couplers. These can be replaced by more efficient edge-couplers (~1.5 dB/coupler), bringing the in-fiber power close to -5 dBm. Transmission is tested back-to-back (BtB) and over 1km of SMF followed by 150m DCF (15.9 ps/nm) to compensate for the accumulated chromatic dispersion at 1563 nm.

Fig.3 shows the captured eye diagrams for 104 Gbaud OOK and PAM-4. At 104 Gb/s OOK, we can see clear open eyes, both BtB and after 1km fiber. Based on the Q-factor, we estimate a BER below 7E 7 for BtB and 5E-6 after 1km of SMF, without any on or offline equalization. For PAM-4 transmission, the relative placement of the electrical PAM-4 levels is slightly adjusted to compensate for the compression caused by the non-linear E/O transfer function of the GeSi EAMs. Apart from these adjusted levels, no DSP or equalization is used to generate the 208 Gb/s PAM-4 eyes. At record speeds of 208 Gb/s, the different PAM-4 levels are still clearly distinguishable even after 1km of SMF. Here, the estimated BERs are 8.9E 3 for a BtB link and 9.9E 3 after 1 km of SMF, already below the soft decision FEC of 2E–2 as is commonly used in 200 Gb/s coherent transceivers without using any equalization. Further improvement of the BER is expected by implementing an alternative approach for PAM-4 generation using two binary-driven EAMs in parallel, as was demonstrated in our previous work [7].

4. Conclusion

We have demonstrated the fastest single-wavelength silicon modulator capable of generating 208 Gb/s PAM-4 and 104 Gb/s OOK using 4 GeSi EAMs driven at quarter-rate (26 GBaud) with only 1.2 Vpp and without any equalization. With the arrival of compact and low-power III-V-on-Si mode locked lasers [4], an optically serialized silicon transceiver with low-power, quarter-rate electrical drivers [8] could be a promising and cost-effective solution for future 800G (4×200G) and 1.6T (8×200G) short-reach optical interconnects using a single laser source.

4. Acknowledgement

The authors thank imec's optical I/O program for the fabrication of the EAMs.

5. References

[1] 2018 Ethernet Alliance Roadmap –www.ethernetalliance.com

[2] H. Mardoyan, et al., "204-GBaud On-Off Keying Transmitter for Inter-Data Center Communications," OFC, San Diego, (2018), PDP-Th4A.4.

[3] E. El-Fiky et al., "168-Gb/s Single Carrier PAM4 Transmission for Intra-Data Center Optical Interconnects," PTL, vol. 29, no. 3, (2017)

[4] Z. Wang et al., "A III-V-on-Si ultra dense comb laser", Light: Science & Applications, 6, pp. e16260 (2017).

[5] H. Hu et al. "Single-source chip-based frequency comb enabling extreme parallel data transmission", Nature Photonics,12, (2018)

[6] J. Verbist et al., "First real-time 100-Gb/s NRZ-OOK transmission over 2 km with a silicon photonic electro-absorption modulator," OFC, Los Angeles, (2017), PDP-Th5C.4

[7] J. Verbist et al., "DAC-less and DSP-free PAM-4 Transmitter at 112 Gb/s with Two Parallel GeSi Electro-Absorption Modulators," in ECOC, Gothenburg (2017), Th.PDP.C.5

[8] H. Ramon et al. "70 Gb/s 0.87 pJ/bit GeSi EAM Driver in 55nm SiGe BiCMOS", ECOC, Rome (2018), Tu3E.5