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Real-Time 100 Gb/s NRZ and EDB Transmission With a GeSi Electroabsorption Modulator for Short-Reach Optical Interconnects

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***Abstract*—Transceivers based on electroabsorption modulators (EAM) are considered as a promising candidate for the next generation 400 GbE short-reach optical networks. They are capable of combining high bandwidth and low-power operation with a very compact layout, removing the need for traveling wave electrodes and dedicated 50 Ω termination. In this paper, we demonstrate the first silicon-based EAM, in combination with an in-house developed SiGe BiCMOS transceiver chipset, capable of transmitting single-lane 100 Gb/s non-return-to-zero in real-time. Transmission over 500 m of standard single mode fiber and 2 km of nonzero dispersion shifted fiber is demonstrated, assuming a forward-error coding scheme is used with a bit-error ratio limit of 3.8 × 10^{-3}. Due to the high line rate, transmission over longer fiber spans was limited by the chromatic distortion in the fiber. As a possible solution, electrical duobinary modulation is proposed as it is more resilient to this type of fiber distortion by reducing the required optical bandwidth. We show improved performance for longer fiber spans with a 100 Gb/s electrical duobinary link, resulting in real-time sub-forward error coding operation over more than 2 km of standard single-mode fiber without any digital signal processing. Finally, the possibility of a 100 Gb/s EAM-to-EAM link is investigated.**

***Index Terms*—Duobinary modulation, optical interconnects, silicon photonics.**

I. INTRODUCTION

IN ORDER to meet the growing bandwidth requirements, data centers will soon require short-reach optical interconnects to operate at 100 Gb/s and beyond. Recently, this has led to an evolution from 100 Gb/s Ethernet to 400 Gb/s Ethernet (400 GbE), for which the possible implementations are currently under discussion in the standardization committees [1]. Among the different approaches, the 4×100 Gb/s configuration -either through coarse wavelength division multiplexing or multiple fibers- seems to surface as one of the most likely candidates. A four lane 100 Gb/s non-return-to-zero (NRZ) scheme could provide an elegant solution towards a compact 400 GbE transceiver, allowing a more compact and low-cost transceiver through lower lane counts, while maintaining the low complexity of on-off-keying-based electronics.

Previously, several 100 Gb/s single-lane transmissions have been realized using four level pulse amplitude modulation (PAM-4) [2]–[5], discrete multitone (DMT) [6], [7] and electrical 3-level duobinary (EDB) [8]–[10]. However, many of these experiments, especially for PAM-4 and DMT, still rely on complex digital signal processing (DSP) at the RX and/or TX-side, typically done offline. Silicon photonics would be ideally suited to implement such a scheme as it can provide compact and low-cost transceivers. Although scaling to 100 Gb/s lane rates has proven to be difficult for silicon based-transceivers, with currently only non-real-time demonstrations which still have to rely on large traveling wave structures and/or extensive DSP [11], [12].

Nevertheless, some examples of true real-time 100 Gb/s serial rates without DSP have been demonstrated recently on other platforms. In [5], a discrete Mach-Zehnder modulator was operated at 100 Gb/s with custom designed TX and RX consuming 8.6 W. Recently, a real-time 100 Gb/s EDB modulation was reported in [9], where an InP-based traveling-wave

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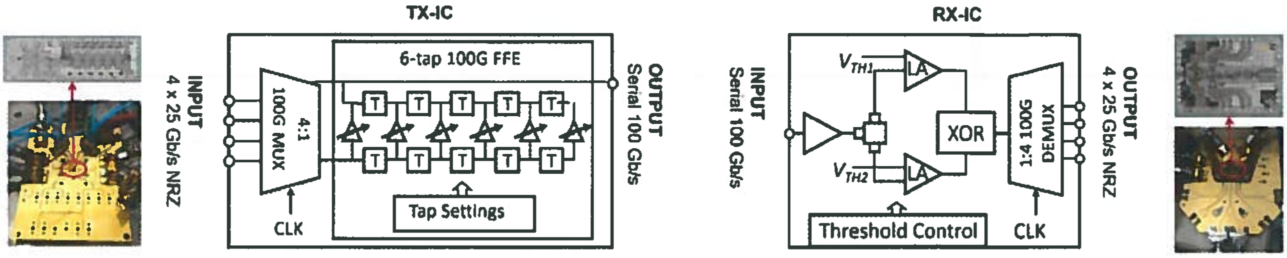
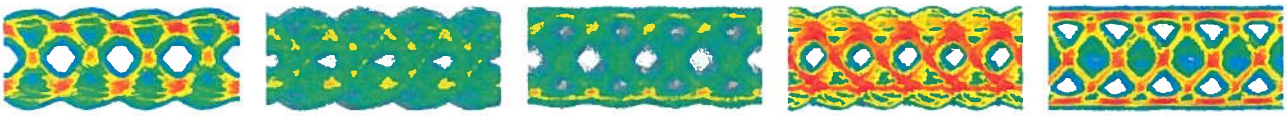


Fig. 1. Schematic representation of the used EDB architecture with TX and RX ICs photographs.



(a) (b) (c) (d) (e)

Fig. 2. Example of measured 100 Gb/s eye-diagrams (a) at output of transmitter IC and optimized for electrical NRZ transmission, (b) predistorted for optical NRZ transmission, (c) the resulting optical NRZ eye-diagram after PIN-PD, (d) predistorted for EDB transmission and (e) resulting optical EDB eye-diagram after PIN-PD.

EAM with integrated distributed feedback laser was used to transmit below the hard-decision forward error coding limit (HD-FEC) of 3.8×10^{-3}. The transmission line design of the electrode does not only increase the overall device size when compared to a lumped driven modulator, but also necessitates a power consuming 50 Ω termination. The same transmitter as in [9] was used for a real-time 100 Gb/s NRZ link in [10]. Unfortunately, the transceiver modules were developed for metro networks, leading to unrealistic form factors and power consumptions for use in short-reach optical interconnects. Finally, an impressive BER down to 10^{-10} with 100 Gb/s NRZ on a polymer Mach-Zehnder modulator was presented in [13], again with traveling wave electrodes and 50 Ω termination. However, the proposed transceiver does pose several drawbacks in terms of cost, power and footprint, when envisioned as a device for short-reach optical interconnects. Two co-packaged InP-based electrical multiplexers are required, offering a 6 Vpp differential voltage swing to drive the 1.1 cm long modulator. This results in a total power consumption -excluding the laser- of 6.85 W for the 6.5 × 2 cm transmitter module. The proposed 4 × 100 PIN-DEMUX receiver adds another 5.5 W and measures 4 × 6.9 cm. Even with the addition of transimpedance amplifier (TIA), removal of the erbium-doped optical amplifier (EDFA) in the RX from the link might be difficult as the the maximal transmitted output power is limited to −9.5 dBm.

In this paper, we present a real-time, single-lane and serial 100 Gb/s NRZ-OOK link with a silicon-based electro-absorption modulator (EAM) in combination with an in-house developed transmitter (TX-IC) and receiver (RX-IC) chipset in a SiGe BiCMOS technology. The very compact GeSi EAM was fabricated on a 200 mm silicon-on-insulator platform without any traveling-wave electrodes and/or power-dissipating terminations. Transmission of 100 Gb/s NRZ over 500 m of standard single-mode fiber (SSMF) and 2 km of non-zero dispersion shifted fiber (NZ-DSF) is reported. We also investigate the performance of EDB modulation in the same link. Successful real-time transmission at 100 Gb/s EDB, assuming a HD-FEC, is demonstrated over more than 2 km of SSMF. These are the first real-time chip-to-chip demonstrations of a 100 Gb/s NRZ or EDB link with a silicon-based waveguide modulator without the need for temperature control, material post-processing or complex DSP. This paper is an invited extension of our work presented as post deadline paper during OFC 2017 [14].

II. COMPONENTS FOR 100 GB/S SHORT-REACH OPTICAL INTERCONNECTS

At bitrates of 100 Gb/s and higher, careful design of the both electrical and optical components is needed, especially when envisioning a limited power-budget and form factor. In Section II-A, the electrical transmitter and receiver which provide the capability of equalizing and decoding 100 Gb/s NRZ or EBD in real-time are discussed. Next, the design, characterization and operation of the silicon-based EAM is presented in Section II-B.

A. Electrical Transceiver

To generate and receive 100 Gb/s data in real-time an in-house developed transmitter and receiver were used. A first generation transmitter, fabricated in a 130 nm SiGe BiCMOS technology was used for the NRZ experiments (at 1601.5 nm). For the EDB measurements (at 1560 nm), this transmitter was replaced by a new version of the IC implemented in a 55 nm SiGe BiCMOS process with improved bandwidth and power-consumption. The transmitter IC (TX IC) consists of 2 main building blocks: a 4-to-1 multiplexer (MUX) which generates a 100 Gb/s data stream out of four 25 Gb/s streams and a six-tap analog feedforward equalizer (FFE), as can be seen in Fig. 1. The equalizer was implemented at the TX-side to reduce the dynamic range requirements on the RX-IC, at the cost of necessitating a linear output buffer after the FFE. An other possible benefit is the exclusion of noise-shaping by an FFE at the RX-side. The main drawback is the automatic optimization of the FFE in a practical system. This would require some form of back-channel (albeit at much lower speeds) to update the FFE settings, possibly from a least-mean-square engine located at the RX [15]. Fig. 2 demonstrates the effect of the FFE when set for a 100 Gb/s NRZ transmission over a short coaxial RF-cable (Fig. 2(a)), predistorted for 100 Gb/s optical back-to-back (B2B) NRZ transmission (Fig. 2(b)) and the resulting optical eye captured with a high-speed photodiode (Fig. 2(c)). The FFE taps are symbol-spaced at 9-10 ps allowing us to equalize up to 50 GHz, but only over 60 ps. At a serial rate of 100 Gb/s, the 130 nm TX-IC consumes 1 W and the 55 nm version 0.75 W. The dies measure 1.5 × 4.5 mm and 1 × 3.8 mm, respectively. In both cases the MUX and the FFE + output driver split the total power consumption in a 35%–65% way.

To decode the received signal, the receiver IC (RX-IC) presented in [16] was used. The chip was fabricated in a 130 nm SiGe BiCMOS process and performs two main tasks: it samples and decodes the incoming signal and it demultiplexes the full rate data stream into four quarter rate streams as shown in Fig. 1. Because the RX-IC was primarily designed for the reception of duobinary signals, there are two independent parallel comparators followed by two limiting amplifiers (LA) to sample the upper and the lower eye of the typical 3-level duobinary eye. Next, a XOR-port is used to decode and convert the sequences from the sampled upper and lower eye data back into the original pre-coded NRZ format. Of course, if one of the comparator thresholds is fixed HIGH the XOR-port becomes functionally transparent and the receiver reduces to a conventional NRZ decoder. This allows us to transmit and receive duobinary and NRZ signals in real-time with the same transceivers. In Section IV, we will briefly discuss why it might be interesting to switch from EDB to NRZ depending on the optical link. The chip measures 2 × 2.6 mm and consumes less than 1.2 W, of which the DEMUX contributes 0.7 W, at a serial rate of 100 Gb/s. In this version, no clock-and-data-recovery circuit is available so the alignment of the sampling clock with the optimal sample time was done manually with an external tunable time delay.

The overall bandwidth of the transceiver chipset is dominated by the bandwidth of the input amplifier of the RX-IC at 41 GHz. This suffices for duobinary modulation, but requires quite some high-pass shaping by the FFE for NRZ links. Nevertheless, error-free operation over a short electrical link was obtained for both modulation formats, when connecting the transmitter and the receiver IC with RF coax-cable. A continuous BER measurement revealed a BER of 1×10^{-12} for NRZ modulation and 1×10^{-13} for EDB modulation. At 100 Gb/s, the transceiver chipset is able to serialize, equalize, decode and deserialize for a combined electrical power consumption of 1.95 W (when using the 55 nm TX-IC). This amounts to an energy/bit of 19.5 pJ/bit, excluding the power consumption of the RF amplifier needed to drive the EAM with 2 Vpp (i.e., an additional 24 pJ/bit). Currently, an external RF-Amplifier is needed as the TX-IC was designed to transmit over electrical backplanes, requiring much less voltage swing. However, adding 1 or 2 additional amplifying stages in the TX-IC design should allow us to increase this to approximately 2 Vpp, which is quite feasible in the used BiCMOS technology with a nominal supply voltage of 2.5 V. Although this would inevitably result in a significant increase in the total power consumption of the transceiver (estimated to be +200 mW or 2 pJ/bit), it would still be much less than the 24 pJ/bit used by the external RF amplifier.

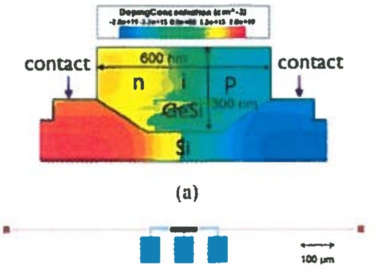


Fig. 3. (a) Cross-section of the GeSi waveguide EAM with indication of doping concentrations; (b) Layout for fabrication of the proposed 80 μm long EAM terminated by two fiber-to-chip grating couplers.

B. GeSi Electro-Absorption Modulator

The high-speed waveguide electro-absorption modulator was fabricated in imec's silicon photonics platform on a 200 mm silicon-on-insulator wafer with 220 nm top Si thickness and consists of a 600 nm wide and 80 μm long germanium waveguide with embedded p-i-n-junction. The cross-section of the GeSi EAM is shown in Fig. 3. Modulation is based on the Franz-Keldysh effect, where the effective bandgap of the GeSi shifts when an electrical field is present[17]. Incorporating ~0.8% of Si shifts the band edge sufficiently to allow operation around 1550 nm compared to a pure Ge EAM operating around 1610 nm [18]. More information regarding the design and fabrication of a 40 μm long version of this EAM can be found in [17]. Light is coupled in and out of the waveguide structure through fiber-to-chip grating couplers with an insertion loss of ~6 dB per coupler. The EAM was operated around 1560 nm for EDB experiments and around 1600 nm for both NRZ and EDB experiments. At a 2 Vpp swing and a bias of −2 V, the GeSi EAM has a junction capacitance of ~15 fF, leading to a dynamic average energy per bit of less than 15 fJ/bit. For a fair comparison, the static power consumption of the EAM should also be taken into consideration. For an in-waveguide power of 6 dBm at a comparable bias of −t2.05 V, the EAM produced a DC photocurrent of approximately 3.8 mA, resulting in a static average energy per bit of 76 fJ/bit. Combined, this amounts to a total average energy/bit of less than 91 fJ/bit of the EAM during all real-time NRZ experiments at 1601.5 nm. During the C-band experiments, the modulator generated a DC photocurrent of 2.39 mA at a bias of −0.85 V, reducing the static energy per bit to 20 fJ/bit. In both cases, the power consumption in the transmitter is dominated by that of the electrical front-end required to drive it.

C. Chromatic Distortion in the Fiber Channel at 100 Gb/s

Not only the electrical transceiver chipset and the optical modulator are important parts of a 100 Gb/s link, the fiber channel itself plays a significant role when operating at wavelengths

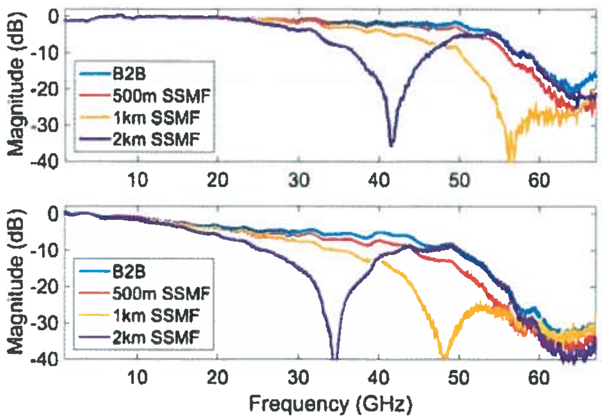


Fig. 4. Small-signal frequency response of the optical link consisting of the RF amplifier, GeSi EAM and a 50 GHz commercial PD for fiber spans up to 2 km at 1560 nm (top) and 1600 nm (bottom).

in C- and L-band. At those wavelengths the relatively large chromatic dispersion coefficient manifests itself as notches in the frequency response of the optical link, limiting the overall bandwidth. The small-signal frequency response of the modulator driven by a 50 GHz RF amplifier and received by a 50 GHz p-i-n diode is given in Fig 4 for different fiber spans (0, 500 m, 1 km and 2 km) at 1560 nm and 1600 nm . At 1560 nm, 2 km of SSMF introduces a notch around 41 GHz which degrades the frequency response in area of approximately ±14 GHz around this notch. As expected, at 1600 nm the notches are located at even lower frequencies due to the steadily increasing dispersion coefficient from C-band to L-band. This poses severe limitations on the maximal fiber span at 100 Gb/s without resorting to chromatic distortion (CD) compensation techniques such as dispersion shifted or compensated fiber links.

III. Experiment Setup

The experiment setup is illustrated in Fig. 5. A Xilinx VirteX FPGA board generates four $2^7 - 1$ long pseudo-random bit streams (PRBS) at 25 Gb/s, which are serialized to a 100 Gb/s single line rate with required delays to form a $2^7 - 1$ long stream at 100 Gb/s. In these first experiments, the possible penalty on the link performance with longer PRBS sequence was not yet investigated. Next, the six-tap analog equalizer in the TX-IC is set to compensate the frequency roll-off and other non-idealities of the following components in the link. Even though the tap settings were optimized for each experiment, a configuration with one pre-cursor, one main and 4 post-cursor taps was found to give good all-round performance and was kept for all subsequent experiments. A 50 GHz RF-amplifier with internal bias-T at the output is used to apply the pre-emphasized signal from the TX-IC with a 2 Vpp swing via an RF-probe to the bondpads of the EAM. As the EAM is a small capacitive load driven by a 50 Ω, we expect the effective voltage over the modulator to double (especially at lower frequencies) when compared to driving a 50 Ω load. However, we can use the FFE to shape the data with the inverse characteristic (i.e., a high-pass filter) to compensate the combined effect of frequency dependent losses and reflections (∼−6 dB at 50 GHz for the channel after the TX-IC output until the EAM). The measured peak-to-peak voltage in a 50 Ω load (a 70 GHz sampling oscilloscope) of the TX-IC output was approximately 200 mVpp, when set to drive the EAM (Fig 2-b). With 20 dB gain form the RF amplifier, we arrive at a swing of 2 Vpp.

During the NRZ measurements, light at 1601.5 nm is sent into the EAM with an in-waveguide power around 6 dBm, while 2 dBm power at 1560 nm was used for the EDB experiments. The EAM was biased at −1.85 V for back-to-back L-band NRZ links and slightly higher at −2.05 V during transmission experiments, resulting in a photocurrent of roughly 3.6 mA and 3.8 mA, respectively. For EDB modulation in C-band the bias was set to −0.65 V for B2B links and again increased slightly for optimal performance to −0.85 V during transmission experiments. With these settings we measured a dynamic extinction ratio of ∼6 dB at 1601.5 nm and a bit more than 7 dB at 1560 nm. The insertion loss for both modes of operation was estimated around ∼6 dB. During all experiments, the EAM was operated at room temperature without any temperature control. A commercial 50 GHz IIIV-based p-i-n photodiode (PD) converted the optical signal back into the electrical domain. As no transimpedance amplifier (TIA) with sufficient bandwidth (i.e., >50 GHz) was available, an erbium-doped-amplifier (EDFA) was used boost the maximal input power to the PD. This was needed as the sensitivity of the RX-IC is 18 mVpp for a BER of 1×10^{-12} (for EDB transmissions). The EDFA could be removed from the link with the addition of a TIA and/or by replacing the fiber-to-chip grating couplers with low-loss edge-couplers (∼1 dB/coupler), as will be discussed in Section IV-A. Finally, the received bitstream is decoded for respectively NRZ or EDB by setting the right comparator levels as discussed in Section II-A, and deserialized into four 25 Gb/s NRZ streams and fed back to the FPGA for real-time error detection.

In Section IV-C, the commercial PD was replaced by an identical copy of the GeSi on a second die, acting as a photodiode. These experiments, as well as the reference curves in Section IV-B, were done by capturing the signal from the photodetector (commercial PD or second EAM) by a real-time 160 GSa/s oscilloscope, after which the BER was calculated offline.

IV. Results and Discussion

A. *100 Gb/s NRZ Transmission*

In a first experiment, real-time NRZ transmission at 1601.5 nm was carried out using the electrical transceiver discussed in Section II-A and a commercial PD as an optical receiver as shown in Fig. 5. The real-time BER curves for transmission over several fiber spans can be seen in Fig. 6(a) and examples of received NRZ eyes captured by a 70 GHz sampling oscilloscope are shown in 2. As the RX-IC poses the main bandwidth limitation in the link and provides only deserialized quarter-rate outputs, setting the FFE is done in a two-step approach. First, the received eye is optimized through visual inspection on a sampling oscilloscope. Next, the resulting tap settings are used as a starting point for further manual optimization by minimiz-

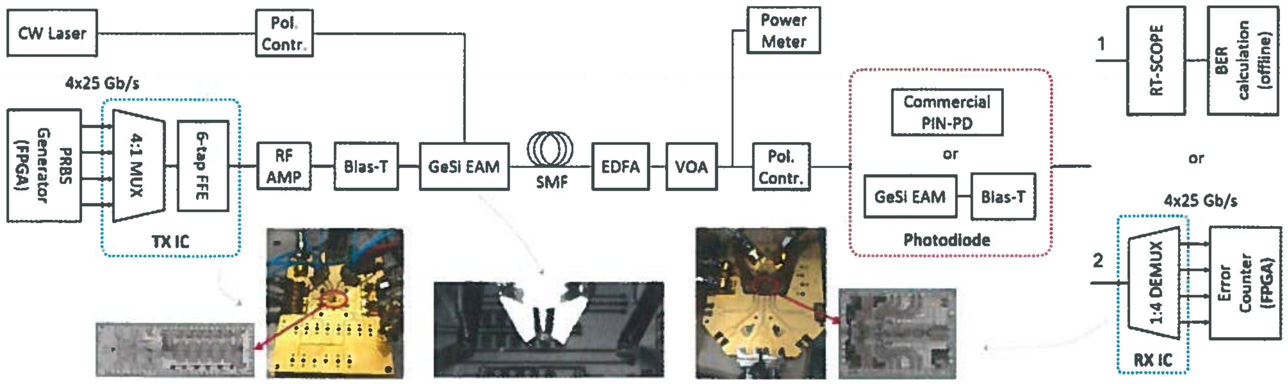
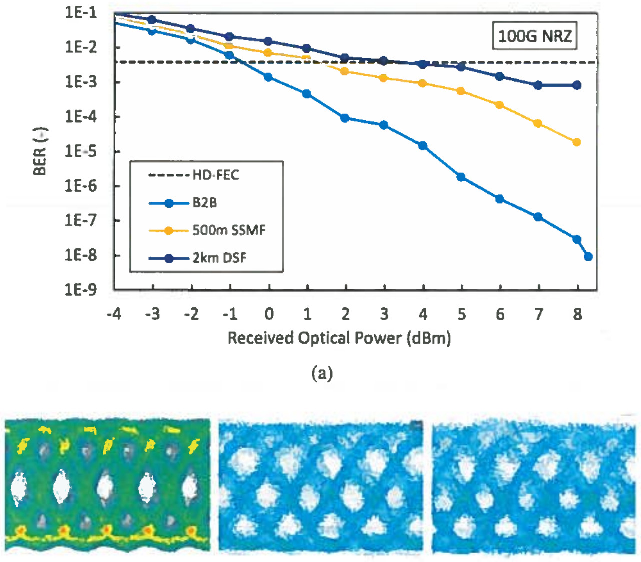


Fig. 5. Experiment setup of real-time 100 Gb/s NRZ/EDB optical link.



(a)

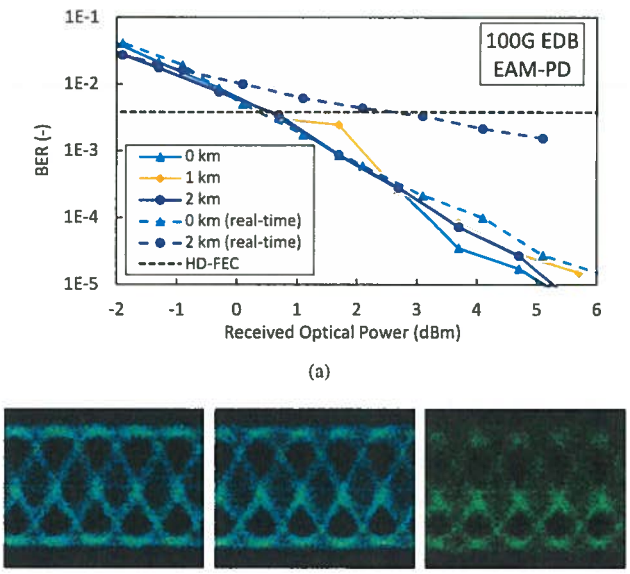
(b) (c) (d)

Fig. 6. (a) Real-time BER curves and received eye diagrams for 100 Gb/s NRZ for (b) B2B, (c) 500 m of SSMF and (d) 2 km of DSF (~8 ps/nm.km) at 1601.5 nm.

ing the BER of the quarter-rate outputs. For a B2B link, a BER of below 6×10^{-9} was obtained at an average optical power of 8.3 dBm in the PD. The hard-decision forward error coding limit (HD-FEC: 3.8×10^{-3} for 7% overhead) was reached for an average power above −0.6 dBm. Although other FEC standards exist (e.g., KR4: 5.2×10^{-5} and KP4: 2×10^{-4} for 100G PAM-4 intra-data center interconnects), this FEC limit was chosen to provide quick and easy comparisons between the different experiments in this paper, as well as in literature, as currently no standards exist for 100 Gb/s NRZ links. As shown in Fig. 4, the chromatic distortion at around 1600 nm severely degrades of the frequency response and reduces the overall bandwidth of the link. Nevertheless, we still manage to obtain a BER below 2×10^{-5} for 500 m of SSMF. Sub-FEC operation is realized for >1.5 dBm, resulting in a power penalty of 2.1 dB compared to B2B. Lastly, transmission over 2 km of non-zero dispersion-shifted fiber (NZ-DSF; dispersion coefficient of ~8 ps/(nm.km)) is investigated, requiring 3 dBm of optical power to drop below the HD-FEC limit and saturating in a BER just below 1×10^{-3} for higher powers. For B2B and 500 m SSMF, no saturation of the BER has yet occurred. Because the total dispersion of the 2 km NZ-DSF at 1601.5 nm is approximately equal to that of 1 km of standard SMF ~16 ps/nm), transmission over 1 km should result in comparable BERs, but was not measured. As the average in-fiber power after the modulator due to the insertion loss of the EAM and two grating couplers was around −5 dBm, we would only need to improve our link budget with 4.5 dB to reach the HD-FEC limit for a B2B transmission and 6.5 dB for a 500 m transmission. One possible solution would be to replace the fiber-to-chip grating couplers (~6 dB/coupler) with low-loss edge-couplers (typically 1 dB/coupler) [19]. This would boost the power budget by 10 dB, allowing us to remove the EDFA from the setup and realizing an amplifier-less link, assuming the increased input-power does not significantly change the behavior of the EAM. We would also like to indicate that current system experiments did not include a transimpedance amplifier. Adding a TIA would give a substantial improvement in sensitivity, which should be sufficient to stay under HD-FEC for an average output power of 0 dBm. This could be directly obtained by replacing the output grating coupler with a low-loss edge coupler, without changing the optical input power to the EAM.

B. 100 Gb/s Duobinary Transmission

In order to realize successful transmission up to 2 km of SSMF, a couple of changes are made to the experiment setup. First, the FFE is re-optimized to shape the transmitted data into an electrical duobinary format, as illustrated in Fig. 2(d) and Fig. 2(e). Next, to further minimize the effect of the CD, the operational wavelength is shifted to C-band (1560 nm). A 3 dB attenuator is added to the output of the RF-amplifier to shield this 50 Ω driver from the reflections due to the mainly capacitive loading by the EAM, especially at lower frequencies. As consequence, the FFE can be used more efficiently, as it has to put less effort in attenuating these frequency components when shaping the channel. Lastly, as discussed in Section II-A a newer and faster, but functionally identical version of the TX-IC was used during these experiments. In a first experiment BER curves for 100 Gb/s EDB (shown in Fig. 7) were measured for 0, 1 and 2 km



(a)

(b)

Fig. 7. (a) Measured BER curves for duobinary modulation at 1560 nm. The full lines (-) correspond to offline calculated BERs from data captured with a real-time oscilloscope and the dotted lines (–) are real-time end-to-end measurements with the electrical receiver. (b) Examples of a 100 Gb/s EDB eye diagrams at 5 dBm of average optical power in a commercial PD after 0, 1 and 2 km of SSMF.

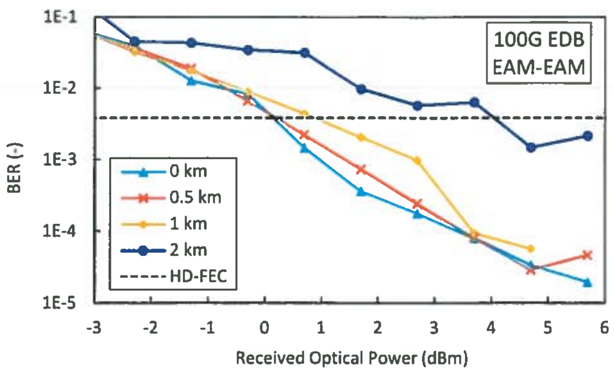


Fig. 8. Offline measured BER curves for duobinary modulation at 1560 nm for a EAM-to-EAM link.

of SSMF by capturing >10 million symbols with a 160 GSa/s real-time sampling oscilloscope and calculating the BER offline. The optimal thresholds were determined via a histogram over a thousand symbols and was swept over the possible sampling times after interpolation of the received data with a factor 10 (i.e., 16 samples/symbol at 100 Gb/s). The data is aligned and compared to the transmitted signal. No other digital signal processing or filtering was used. Even though the eyes after 2 km have slightly degraded compared to 0 km and 1 km, we still have decently open eyes, as can be seen in Fig. 7 and operation down to a BER of 1×10^{-5} is possible for all fiber spans up to 2 km. Sub-FEC operation is obtained for average optical powers above 0.6 dBm for all lengths of fiber. No clear saturation of the BER is apparent yet. In a second experiment, real-time transmission was again investigated. For a B2B link, the BER curve is fairly comparable to that of the offline measured BER curve up to 3 dBm, after which a penalty of ~ 1 dB appears for higher powers. With 2 km of SSMF the penalty with respect to the reference curves is much larger (~ 2.1 dB at HD-FEC) and we can see the onset of BER saturation emerging. Nevertheless, we still manage to obtain successful sub-FEC operation up to 2 km of SSMF, a clear improvement compared to NRZ modulation discussed in Section IV-A.

With the longest typical fiber distances in hyperscale datacenter limited to 2 km, 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 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 500 m long fibers, making pure NRZ-based transceiver as demonstrated in Section IV-A a more attractive solution in the search for the implementation with the lowest possible power consumption and form factor. In both scenarios, combining 4 of these transceivers in a 4-channel Coarse Wavelength Division Multiplexing (CWDM) scheme, could be used to realize a compact and low-complexity 400 GbE transceiver. Eventhough the EAM does not operate over the whole C-band, a 1-dB link power penalty bandwidth of more than 30 nm was reported for a similar, but shorter GeSi EAM in [17]. This bandwidth should be more than enough to support a 4λ-CWDM configuration (i.e., for 400 GbE links), albeit located partly in (the upper) C-band and partly in (the lower) L-band. This reasoning is further validated by the successful 100 Gb/s transmissions in this work at 1560 nm and 1601 nm, with limited penalty.

C. 100 Gb/s Duobinary Transmission: EAM-to-EAM

The proposed EAM is not only ideally suited as modulator, but can also function as a high-speed photodiode by increasing the reverse bias beyond the ideal modulation bias point to absorb as much light as possible. Fig. 9 shows the eye-diagrams for different lengths of fiber in such an EAM-to-EAM link. A 40 GHz RF-probe, a 65 GHz bias-T and a 50 cm long coax-cable were used to deliver a reverse bias of 3 V to an identical copy of the EAM located on a different die. As this setup posed an additional BW-limitation, only offline BER measurements using EDB at 1560 nm were performed for which the results are depicted in Fig. 8.

For fiber lengths up to 0.5 km the measured BERs correspond well to the BER-curves of the EAM-to-PD link. For fiber spans of 1 km, a reduction in eye height is noticeable (Fig. 9(c)), leading to slightly higher average optical power of 0.9 dBm to reach the FEC-limit (a penalty of 0.7 dB). After 2 km, the eye degradation is even more pronounced (Fig. 9(d)), but even now, sub-FEC operation is obtained above 4.1 dBm of optical input power. A similar, but smaller increase in power penalty was also observed for the real-time 2 km PD-based link. This indicates that, in the presence of severe CD, additional bandwidth reductions in the E/O/E (e.g., by the bandwidth-limited input buffer of the RX-IC or by the additional 40 GHz RF-probe and 50 GHz coax-cable

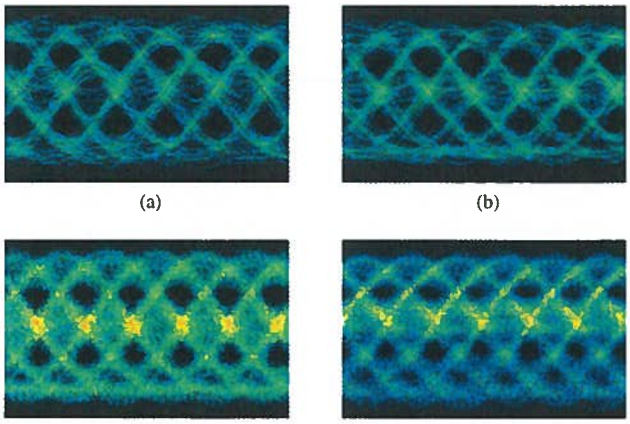

(a) (b) (c) (d)

Fig. 9. Measured eye-diagrams of 100 Gb/s EDB transmission at 1560 nm for (a) B2B, (b) 500 m, (c) 1 km, (d) 2 km of SSMF, captured by a 2nd GeSi EAM acting as a PD.

for the EAM-based PD) might rapidly degraded the link performance. Nevertheless, the possibility of a silicon photonics transceiver operating at line rates of 100 Gb/s based on the GeSi EAM acting as modulator and as photodetector is validated.

V. CONCLUSION

In this paper, we have presented real-time, single-lane and serial 100 Gb/s transmission with NRZ-OOK as well as electrical duobinary using a germanium-silicon EAM in combination with an in-house developed BiCMOS-based transmitter and receiver chipset, without any need for DSP. The EAM was driven lumped without any termination with 2 Vpp. For 100 Gb/s NRZ, we recorded BERs down to 6×10^{-9} in a back-to-back link, as well as successful transmissions, assuming FEC, over 500 m of SSMF and 2 km of NZ-DSF, which was comparable to 1 km of SSMF. We identified the chromatic distortion of the fiber channel as the main limitation in the link, degrading the frequency response even for relatively short fiber spans of 0.5 km to 2 km due to the high line rate. As a possible solution, a 3-level duobinary modulation scheme was investigated and verified to be much more resilient towards this effect, allowing real-time sub-FEC operation up to 2 km of SSMF. Finally, the possibility of a silicon-based transceiver working at line rates of 100 Gb/s using the GeSi EAM both as modulator and as photodiode, was demonstrated for EDB modulation up to 2 km of SSMF. 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.

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Authors' biographies not available at the time of publication.