Real-Time 100 Gb/s NRZ and EDB Transmission with a GeSi Electro-Absorption Modulator for Short-Reach Optical Interconnects

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***Abstract*—Transceivers based on electro-absorption modulators 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 up to 500 m of standard single mode fiber and 2 km of non-zero dispersion shifted fiber is demonstrated, assuming a forward-error coding scheme with a bit-error rate limit of 3.8$\times 10^{-3}$ is used. 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-FEC 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*—Optical Interconnects, Silicon Photonics, Duobinary Modulation**

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 high spatial efficiency through lower lane counts, while maintaining the low complexity of on-off-keying-based electronics. Silicon photonics is 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. 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. However, some examples of true real-time 100 Gb/s serial rates without DSP have been demonstrated recently. 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 were reported in [9], where a InP-based traveling-wave EAM with integrated distributed feedback laser was used to transmit below the hard-decision forward error coding limit (HD-FEC) of 3.8$\times 10^{-3}$. The tranmission 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 50Ω termination. The same transmitter as in [9] was used to for a real-time 100 Gb/s NRZ link in [11]. Unfortunately, the transceiver modules were developed for metro networks, leading to unrealistic formfactors 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 silicon-organic Mach-Zehnder modulator was presented in [12], again with traveling wave electrodes and 50Ω termination. However, the proposed transceiver does pose several drawback 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. Even though organic modulators show great promise for future modulators, they still require additional post-processing steps to deposit

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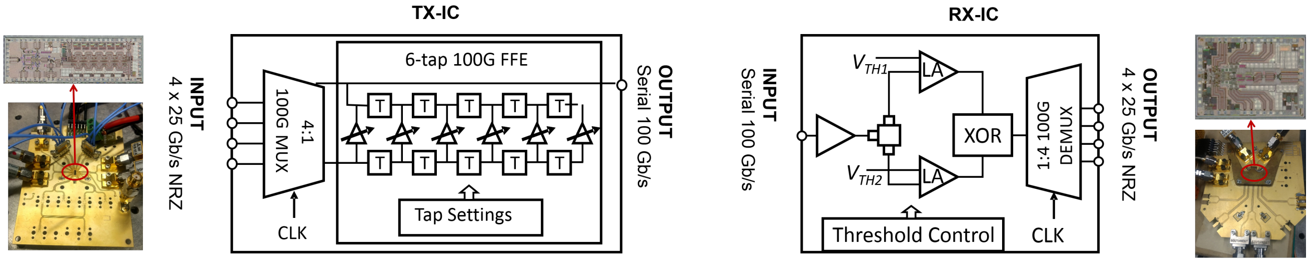


Fig. 1. Schematic representation of the used EDB architecture with TX and RX ICs photographs.

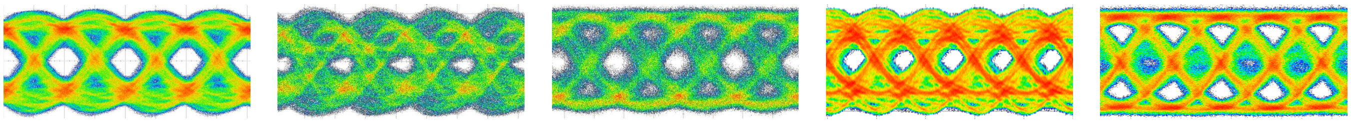

(a) (b) (c) (d) (e)

Fig. 2. Example of measured 100 Gb/s eye-diagrams (a) at output of transmitter IC and optimized for electrical NRZ transmission, (b) predistored 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

the organic material.

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 in-house developed transmitter (TX-IC) and receiver (RX-IC) chipset in a SiGe BiCMOS technology. The extremely compact GeSi EAM was fabricated on a 200 mm silicon-on-insulator platform and was driven lumped with 2 Vpp 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 demonstration 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 a invited extension of our work presented in post deadline paper during OFC 2017 [13].

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

At bitrates of 100 Gb/s and higher, the 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*

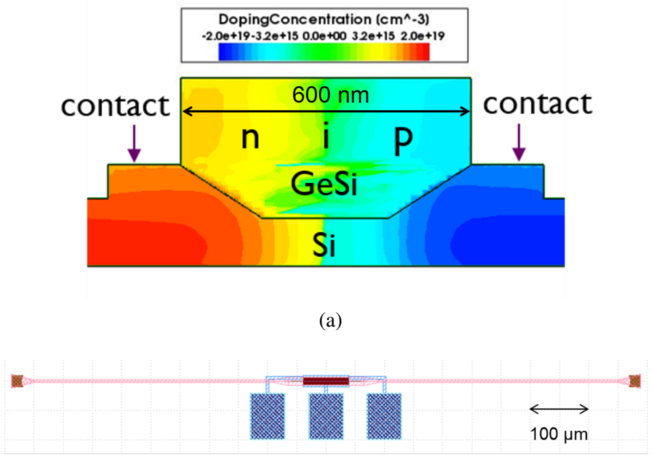
To generate and receive 100 Gb/s data in real-time an in-house developed transmitters and receiver were used. For the NRZ experiments at 1601.5 nm a first generation of the transmitter, fabricated in a 130 nm SiGe BiCMOS technology was used. For the measurements in C-band a new version of the IC implemented in a 55 nm SiGe BiCMOS process was used with improved bandwidth and power-consumption, but functionally the same. 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 choice was made to implement the equalizer on 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 [14]. Fig. 2 demonstrates the effect of the FFE when set for a 100 Gb/s NRZ transmission over a short coaxial RF-cable (Fig. 2a), predistored for 100 Gb/s optical back-to-back (B2B) NRZ transmission (Fig. 2b) and the resulting optical captured with a high-speed photodiode (Fig. 2c). 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 $1.5{\times}4.5$ mm and $1{\times}3.8$ 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 [15] was used. The chip was fabricated in a 130 nm SiGe BiCMOS process and 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 level-shifting limiting amplifiers (LA) to sample the upper and the lower eye of the typical 3-level duobinary eye. Next, an XOR-port is used to decode and convert the streams 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 an EDB to a 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 provided on the IC 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 schemes but requires quite some high-pass shaping efforts by the TX-side FFE for NRZ links. Nevertheless, error-free operation over pure electrical B2B 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.

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 wafers 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. Modulation is based on the Franz-Keldish effect, where the bandgap edge of the GeSi shifts when an electrical field is present [16]. Incorporating the Ge with ~0.8% of Si shifts the bandedge sufficiently to allow operation around 1550 nm compared to a pure Ge EAM operating around 1610 m [17]. More information regarding the design and fabrication of a 40 μm long version of this EAM can be found in [16]. 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 -2.05 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 energy/bit of less than 91 fJ/bit 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 -0.7 V, reducing the static energy per bit to 17 fJ/bit.



(a)

(b)

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 book-ended by two fiber-to-chip grating couplers.

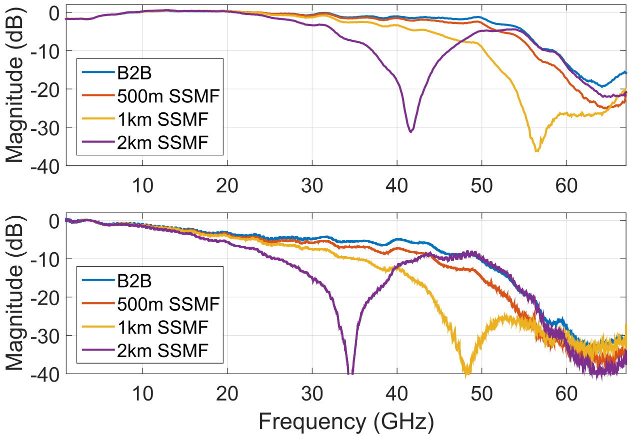


Fig. 4. Small-signal frequency response of the optical link consisting of the RF amplifier, GeSI EAM and a 50 GHz commercial PD for fiber spans up to 2 km at 1560 nm (top) and 1600 nm (bottom).

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 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. II-B 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 degenerates 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-

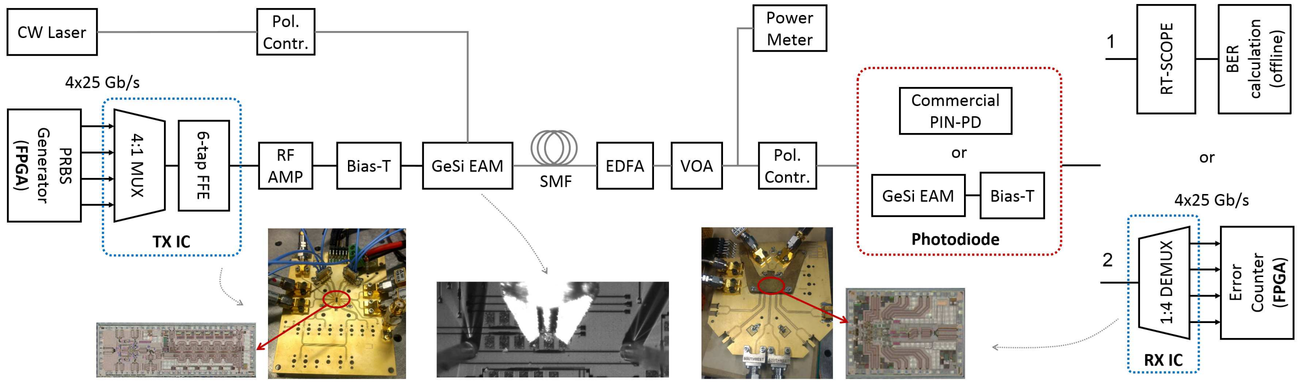


Fig. 5. Experiment setup of real-time 100 Gb/s NRZ/EDB optical link.

band. This poses severe limitations on the maximal fiber span at 100 Gb/s without resulting to chromatic distortion (CD) compensation techniques such dispersion shifted or compensated fiber.

III. Experiment Setup

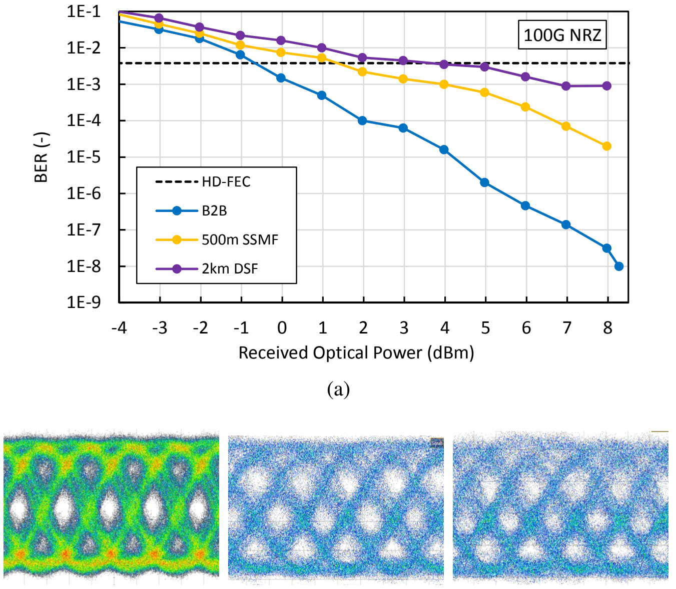
The experiment setup is illustrated in Fig. 5. A Xilinx VirteX FPGA board generates four 2^7-1 long pseudo-random bit streams (PRBS) at 25 Gb/s, which are serialized to a 100 Gb/s single line rate with required delays to form a 2^7-1 long stream at 100 Gb/s. Next, a six-tap analog equalizer in the TX-IC 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 RF-probe to the bondpads of the EAM. 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 (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}. The EDFA could be removed from the link with the addition of a TIA. 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 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. 6a and an example of a received NRZ eyes captured by a 70 GHz sampling oscilloscope are shown in Fig. 6. 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 by optimizing the received eye through visual inspection on a 70 GHz sampling oscilloscope and the resulting tap settings are then used as a start point for further manual optimization by minimizing 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. As shown in Fig. II-B 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. The maximum in-fiber power after the modulator due to the insertion loss of the EAM and two grating couplers was around -5 dBm, meaning that 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



(a)

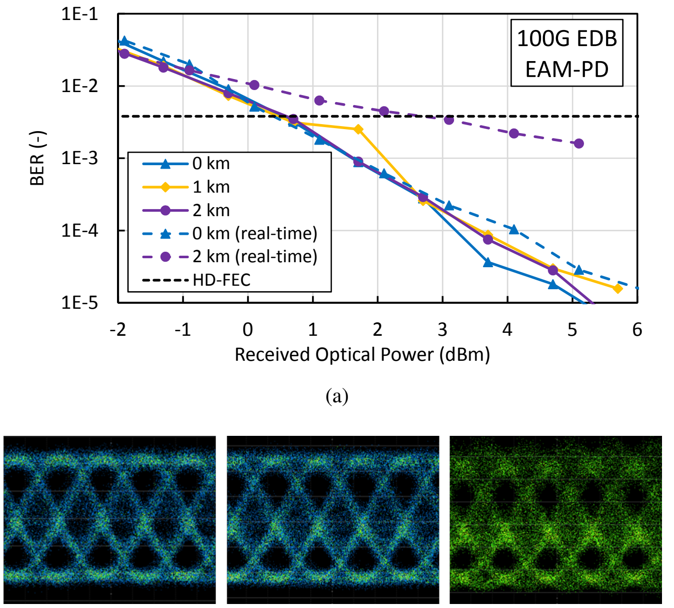
(b) (c) (d)

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 ($\sim$ 8 ps/nm.km) at 1601.5 nm.

possible solution this would be to replace the fiber-to-chip grating couplers ($\sim$6 dB/coupler) with low-loss edge-couplers (typically < 2 dB/coupler) [18]. This would boost the power budget by $>$ 8dB, allowing us to remove the EDFA from the setup and realizing an amplifier-less link. Finally, transmission over 2 km of non-zero dispersion-shifted fiber (NZ-DSF) with a dispersion coefficient of $\sim$8 ps/(nm.km), assuming FEC is also achieved, saturating in an error-floor around just below 1×10^{-3}. For B2B and 500 m SSMF no error-floor was observed. Because the total dispersion of the used 2 km DSF at 1601.5 nm is approximately equal to that of 1 km of standard SMF $\sim$16 ps/nm), transmission over 1 km should result in comparable BERs and was not measured.

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. In stead of NRZ, we now use the FFE to shape the transmitted data into an electrical duobinary format as illustrated in Fig. 2d and Fig. 2e. Next, to further minimize the effect of the CD, the operational wavelength is shifted to C-band (1560 nm). We also suspected that the capacitive loading of the EAM on the driving RF amplifier introduced noticeable reflections as the electrical amplifier should be operated with a well-matched 50Ω load at the output. Adding a 3 dB RF-attenuator at the output seemed to shield the amplifier better from reflections and resulted in cleaner eye-diagrams. The reduction in voltage swing could easily be mitigated by increasing the output swing of the TX-IC with the same amount. Lastly, as discussed in II-A a newer and faster, but functionally identical version of the TX-IC was used during these experiments. In a first experiment as a reference, BER curves for 100 Gb/s EDB (shown in Fig. 7) were measured for 0, 1 and 2 km of SSMF by capturing $>$10 million symbols with 160 GSa/s real-time sampling oscilloscope and calculating the BER offline. The optimal thresholds were determined via a histogram over a thousand symbols and was swept over the possible sampling times after interpolation the received data with a factor 10 (i.e. 16 samples/symbol at 100 Gb/s). The data is aligned and compared to transmitted signal. No other digital signal processing or filtering was used. Even though the eyes after 2 km have slightly degraded compared to 0 km and 1 km, we still have decently open eyes, as can be seen in Fig. 7 and operation down to a BER of 1×10^{-5} is possible for all fiber spans up to 2 km. Sub-FEC operation is obtained for average optical powers above 0.6 dBm for all lengths of fiber. No clear error-floor is apparent yet. In a second experiment, a real-time transmission was again investigated. For a B2B link the BER curve is fairly comparable to that of the offline measured BER curve up to 3 dBm, after which a penalty of 1 dB appears for higher powers. With 2 km of SSMF the penalty with respect to the reference curves is much larger ($\sim$2.1 dB at HD-FEC) and we can see the onset of an error-floor 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.



(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 after 0, 1 and 2 km of SSMF.

With the longest typical fiber distances in hyperscale data-center 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 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

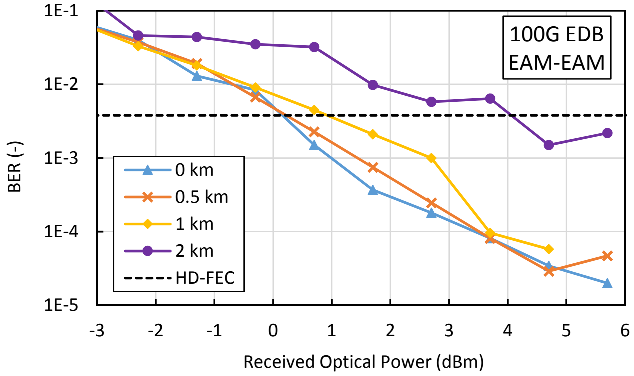


Fig. 8. Offline measured BER curves for duobinary modulation at 1560 nm for a EAM-to-EAM link.

section IV-A a more attractive solution in the search for the implementation with the lowest possible power consumption and form factor.

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

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 point as 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 a the EAM-to-PD link. For a fiber spans of 1 km a reduction in eye height is noticeable Fig. 9c, leading to slightly higher average optical power of 0.9 dBm to reach the to reach the FEC-limit (a penalty of 0.7 dB). At 2 km the eye degradation is even more pronounced (Fig. 9c), 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 for the EAM-based PD) might rapidly degraded the link performance. Nevertheless, the possibility of fully 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 on a germanium-silicon EAM in combination with 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 NRZ we achieved successful transmission, assuming FEC, for 500 m of SSMF and 2 km of DSF, which was comparable to 1 km of SSMF. In a B2B link the minimal BER was less than 6×10^{-9}. 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 silicon-based transceiver working at line rates of 100 Gb/s using the GeSi EAM as a modulator and 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.

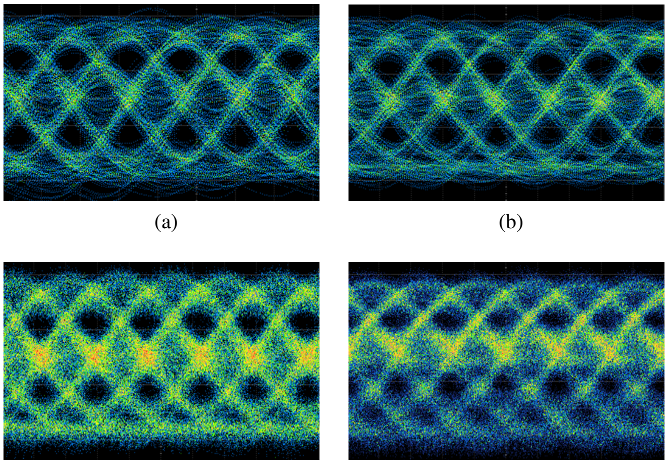


Fig. 9. Measured eye-diagrams of 100 Gb/s EDB transmission at 1560 nm for (a) B2B, (b) 500 m, (c) 1 km, (d) 2 km of SSMF.

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