100 Gbit/s Serial Transmission Using a Silicon-Organic Hybrid (SOH) Modulator and a Duobinary Driver IC

H. Zwickel,[(1)†]* T. De Keulenaer,[(2,3)†] S. Wolf,[(1)] C. Kieninger,[(1,4)] Y. Kutuvantavida,[(1,4)] M. Lauermann,[(5)] M. Verplaetse,[(2)] R. Pierco,[(2,3)] R. Vaernewyck,[(2,3)] A. Vyncke,[(2,3)] X. Yin,[(2)] G. Torfs,[(2)] W. Freude,[(1)] E. Mentovich,[(6)] J. Bauwelinck,[(2)] and C. Koos[(1,4)]**

(1) Karlsruhe Institute of Technology, Institute of Photonics and Quantum Electronics (IPQ), Karlsruhe, Germany
(2) Ghent University imec, IDLab, Department of Information Technology, Ghent, Belgium; (3) BiFAST, Ghent, Belgium
(4) Karlsruhe Institute of Technology, Institute of Microstructure Technology (IMT), Karlsruhe, Germany
(5) Now with: Infinera Corporation, Sunnyvale, CA 94089, USA
(6) Mellanox Technologies Ltd., Yokneam, Israel
*[†]These authors contributed equally to this work; Author e-mail address: *heiner.zwickel@kit.edu, **christian.koos@kit.edu*

Abstract: *100 Gbit/s three-level (50 Gbit/s OOK) signals are generated using a silicon-organic hybrid modulator and a BiCMOS duobinary driver IC at a BER of 8.5×10^{-5} ($<10^{-12}$). We demonstrate dispersion-compensated transmission over 5 km.*

OCIS codes: (250.4110) Modulators; (060.2360) Fiber optics links and subsystems

1. Introduction

Recently, the Ethernet Alliance created 100 GbE challenges [1], one of them being "The Holy Grail of 100GbE SFP+", requiring the winner to demonstrate a single-wavelength 100 Gbit/s transceiver in a 1.5 W SFP+ form factor. This competition was driven by the expectation that grouping of 100 Gbit/s lanes will enable interface rates of 400 Gbit/s, 0.8 Tbit/s or 1.6 Tbit/s. To meet the associated scalability challenges, system complexity must be kept low by using simple transmission schemes based on intensity modulation and direct detection (IM/DD) as opposed to more demanding coherent transmission. This results in high symbol rates and hence stringent requirements regarding bandwidth and power consumption of the electro-optic modulator and of the associated drive circuitry. It has been demonstrated that particularly efficient and broadband Mach-Zehnder modulators (MZM) can be obtained by using organic electro-optic (EO) claddings on top of silicon photonic slot waveguides [2], thereby combining the advantages of large-scale CMOS fabrication with the wealth of optical properties obtained by molecular engineering of organic materials. These silicon-organic hybrid (SOH) modulators feature voltage-length products down to 0.5 Vmm, more than an order of magnitude below those of conventional depletion-type silicon photonic modulators [3]. At the same time, SOH MZM do not suffer from a tradeoff between extinction ratio and chirp, which is a known problem in electro-absorption modulators (EAM) both on InP and SiGe. The viability of SOH MZM for high-speed IM/DD transmission has previously been demonstrated in a 100 Gbit/s on-off-keying (OOK) transmission experiment [4], where the devices were shown to outperform Si MZM, InP MZM and InP EAM both in terms of speed and power consumption. More recently, IM/DD transmission at 120 Gbit/s was demonstrated using four-level pulse amplitude modulation (PAM-4)[5]. However, all these experiments relied on electrical drive signals generated by dedicated laboratory test equipment such as arbitrary waveform generators or pulse pattern generators that are far too complex for scalable integration into advanced transceiver packages.

In this paper we demonstrate 100 Gbit/s IM/DD transmission by operating an SOH MZM with a BiCMOS driver chipset. We use duobinary (DB) modulation to relax the bandwidth requirements for driver electronics, modulator and receiver. In contrast to PAM-4, DB modulation is particularly simple, leveraging the low-pass behaviour of the transmitter for pulse shaping, while demodulation can be implemented by two slicers and an XOR circuit [6]. The driver chip contains a 6-tap feed-forward equalizer (FFE) and was previously used for the world's first serial transmission of a 100 Gbit/s data stream over 1.5 m of twinaxial copper cable [7], and more recently optical 3-level duo-binary transmission over 2 km in conjunction with an InP based externally modulated laser [8]. In our present experiment, we exploit this chip design to demonstrate transmission at a line rate of 100 Gbit/s over a dispersion-compensated link of 5 km standard single-mode fiber. We demonstrate a bit error ratio (BER) of 1.6×10^{-3} (8.5×10^{-5}) for the dispersion compensated 5 km link (back-to-back reference), below the threshold of hard-decision forward-error correction (FEC) with 7 % overhead [9]. Using the same components, we could also transmit an OOK signal at 50 Gbit/s over the same link. Our experiments represent, to the best of our knowledge, the fastest IM/DD transmission demonstration using a silicon-based modulator operated by an integrated driver chip.

2. Driver chipset and SOH modulator

The schematic of the driver chipset is depicted in Fig. 1a. The 100 Gbit/s signal is generated by an integrated driver circuit which comprises a 4:1 serializer, a 6-tap feed-forward equalizer (FFE), and an output stage delivering up to 1 V_{pp}. Figure 1b shows a cross section through the two arms of the SOH MZM. The device was fabricated in silicon-

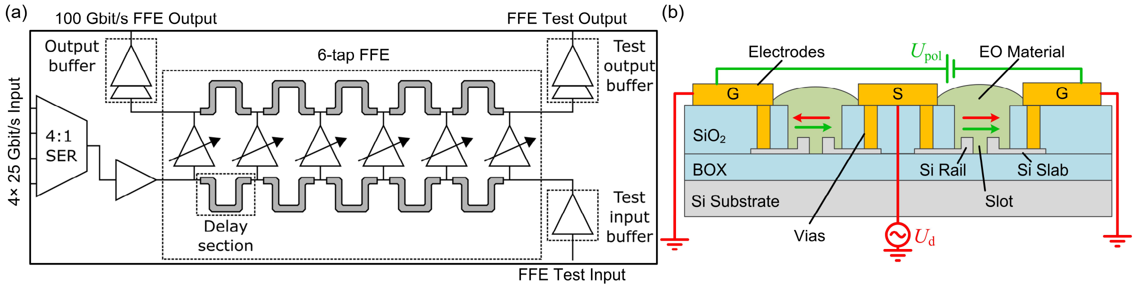

Fig. 1: (a) Schematic of the driver circuit, comprising a 4:1 serializer, a 6-tap feed-forward equalizer (FFE) and an output buffer. **(b)** Cross section of a silicon-organic hybrid (SOH) Mach-Zehnder modulator (MZM). Each arm comprises an optical slot waveguide, filled with an electro-optic (EO) organic cladding material. Aluminum (Al) vias and thin conductive *n*-doped silicon slabs connect the ground-signal-ground (GSG) transmission line to the rails of the slotwaveguide. During a one-time poling process, a DC voltage U_{pol} (green circuit) is applied across the floating ground electrodes at an elevated device temperature to align the molecules in the EO material along the poling field lines. After cooling, the alignment is frozen (green arrow), and the poling voltage can be removed. For push-pull operation of the MZM, the modulating voltage U_d as applied to the signal electrode induces an electric field in the slot (red arrow) that is anti-parallel (parallel) to the molecule orientation in the left (right) arm of the MZM.

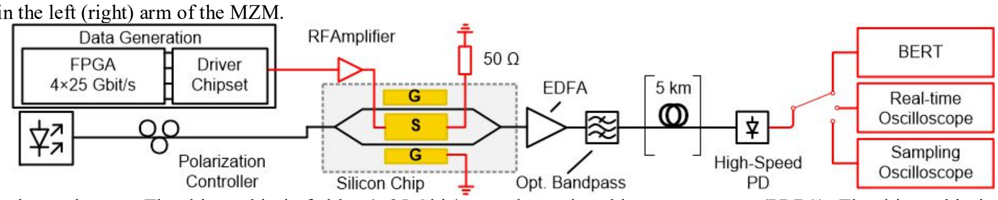

Fig. 2: Experimental setup: The driver chip is fed by 4×25 Gbit/s pseudo-random binary sequences (PRBS). The driver chip is used here to generate a 50 Gbit/s on-off keying (OOK) signal or a 100 Gbit/s duobinary (DB) signal. The driver chip output connects via a coaxial cable to a radio-frequency (RF) amplifier and a microwave probe to the SOH Mach-Zehnder modulator. The modulator is terminated by a 50 Ω impedance. Light from a laser source is coupled to the silicon chip via grating couplers. After modulation, the optical signal is amplified, optionally transmitted over a fiber and detected on a photodiode (PD). The PD can be connected to a bit error ratio tester (BERT), a sampling oscilloscope and a real-time oscilloscope.

on-insulator (SOI) technology using a standard 248 nm deep-UV (DUV) process on a commercial fabrication platform [10]. The EO material was deposited in a post-processing step. Each arm of the MZM consists of a slot waveguide, comprising two 240 nm wide and 220 nm high silicon rails which are separated by a 160 nm wide slot. The modulating radio-frequency (RF) signal is guided by a coplanar ground-signal-ground (GSG) aluminum (Al) transmission line and co-propagates with the optical carrier along the 1 mm long modulator. The electrodes are connected to the silicon rails of the slot waveguide by Al vias and 70 nm thin conductive *n*-doped silicon slabs. The RF field drops mainly across the narrow slot where the light is highly confined, thus leading to a strong overlap of the optical mode and the modulating electric field. The modulator is functionalized by filling the slot waveguide with the commercially available EO organic cladding material SEO100. This material combines a large EO coefficient of $r_{33} = 110$ pm/V with good thermal stability, enabling high-speed operation of an SOH modulator at 80° C as shown in previous experiments [11]. To activate the macroscopic $\chi^{(2)}$-nonlinearity, the microscopic molecular dipoles in the organic material need to be aligned in a one-time poling process. To this end, a poling voltage U_{pol} is applied across the (floating) ground electrodes at an elevated temperature. After cooling the device, the EO-active chromophores remain aligned as indicated by green arrows in Fig. 1(a), and the poling voltage can be removed. The modulating field (red arrows) induced by the RF drive voltage U_d is oriented parallel to the chromophore alignment in one and antiparallel in the other phase modulator, which results in a push-pull operation of the MZM. The voltage-length product $U_\pi L$ of the 1 mm long MZM is measured to be 1.1 Vmm, slightly larger than previously reported values due to a different EO material.

3. Experimental Setup

The experimental setup is depicted in Fig. 2. With a pseudo-random binary sequence (PRBS, length 2^7-1), generated in a field-programmable gate array (FPGA) we test the transmitter, which comprises the driver chip embedded in a connectorized testboard, an RF amplifier with a nominal bandwidth of 70 GHz and an SOH MZM. Coaxial cables interface the testboard and the RF amplifier. A microwave probe applies the signal to the modulator, which is terminated with an external 50 Ω impedance. The modulator is biased at its quadrature point. The bandwidth-saving electrical DB driver signal provides then three optical power levels. As compared to an optical DB format, the optical three-level signal is not optimum in terms of signal-to-noise power ratio and reach, but it allows bandwidth-saving signal processing in the electrical part of the transmitter and receiver. After detection with a 70 GHz photodiode, the DC-part of the photocurrent is removed, and the resulting electrical DB signal shows much relaxed bandwidth requirements. The optical carrier at a wavelength of 1550 nm is provided by an external cavity laser

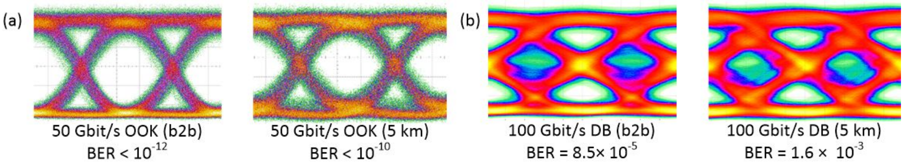

Fig. 3: Eye diagrams for (a) 50 Gbit/s OOK and (b) three-level 100 Gbit/s signaling, both for back-to-back (b2b) configuration (left) and for transmission over a 5 km dispersion compensated fiber link (right). 50 Gbit/s signals are found to be error-free; for three level 100 Gbit/s, all BER values stav below the FEC threshold for 7% overhead.

(ECL) and coupled to and from the PIC via grating couplers. An erbium-doped fiber amplifier (EDFA) compensates the fiber-to-fiber insertion loss of 18 dB, which is caused by non-optimized grating couplers, imperfect strip-to-slot waveguide transitions and by waveguide losses. The on-chip loss can be reduced below 2 dB in future designs [11]. A 1.5 nm wide band-pass filter removes the out-of-band amplified spontaneous emission (ASE) noise. The photodiode output is connected to either a bit error ratio tester (BERT), a sampling oscilloscope, or a 62 GHz real-time oscilloscope.

4. Results

OOK transission is demonstrated at a line rate of 50 Gbit/s. Figure 3a shows eye diagramms recorded with a photodiode and a sampling oscilloscope. The BER is measured with a BERT. At 50 Gbit/s, error-free transmission at BER < 10^{-10} (BER < 10^{-12}) was possible over a 5 km dispersion-compensated fiber link (for a back-to-back measurement). Using the same devices, optical three-level transmission is demonstrated at a line rate of 100 Gbit/s. After opto-electric conversion with a photodiode the received signal is recorded with a sampling rate of 160 GSa/s. Figure 3b shows the eye diagrams generated from the recordings for a back-to-back measurement and transmission over the 5 km fiber link. Offline BER measurements are performed without any equalization on the receiver side. For the back-to-back measurement the BER extracted from real-time recordings is 4.3×10^{-4}, which can be improved to 8.5×10^{-5} by using a gate field of 0.1 V/nm to increase the conductivity of the doped silicons slabs of the SOH MZM [12]. After transmission over 5 km, the BER measured from the recordings is 1.4×10^{-3}, clearly below the hard-decision FEC threshold for 7% overhead. The power consumption of the modulator is estimated to be 16 mW corresponding to 160 fJ/bit, assuming that the electrical energy is dissipated in the terminating resistor. The power consumption of the driver chip amounts to 700 mW. We have previously shown that SOH modulators can be operated with peak-to-peak voltages well below 1 V_{pp} [13]. In a fully integrated package, the drive amplifier can hence be omitted, and the total power consumption for the 100 Gbit/s transmittter will stay below 1 W. This is well compatible with the power ratings of highly compact SFP+ packages.

5. Summary

We demonstrate a silicon-organic hybrid (SOH) modulator controlled by an integrated BiCMOS duobinary driver chip with 6-tap FFE. We show 100 Gbit/s optical three-level transmission over a 5 km dispersion-compensated single-mode fiber link with a BER below the threshold of hard-decision FEC with 7% overhead. Likewise, 50 Gbit/s on-off keying (OOK) transmission over the same link is found to be error-free. Our experiments represent, to the best of our knowledge, the fastest IM/DD transmission demonstration using a silicon-based modulator operated by an integrated driver chip.

6. References

[1] J. D. Ambrosia *et al.*, "The 2015 Ethernet Roadmap," Ethernet Alliance White Paper, (2015)
http://www.ethernetalliance.org/wp-content/uploads/2015/03/EthernetAlliance_Roadmap_whitepaper_FINAL-032015-21.pdf

[2] C. Koos *et al.*, "Silicon-Organic Hybrid (SOH) and Plasmonic-Organic Hybrid (POH) Integration," J. Lightwave Technol., Vol. **34**, no. 2, pp. 256 (2016).

[3] S. Koeber *et al.*, "Femtojoule Electro-Optic Modulation Using a Silicon-Organic Hybrid Device," Light Sci. Appl., Vol. **4**, no. 2, p. e255 (2015).

[4] W. Hartmann *et al.*, "100 Gbit / s OOK Using a Silicon-Organic Hybrid (SOH) Modulator," European Conference on Optical Communication (ECOC) 2015, *PDP 1.4, (2015)*

[5] H. Zwickel *et al.*, "120 Gbit / s PAM-4 Signaling Using a Silicon-Organic Hybrid (SOH) Mach-Zehnder Modulator," European Conference on Optical Communication (ECOC) 2016 Th.2.P2.SC2.14, (2016)

[6] J. Wei *et al.*, "400 Gigabit Ethernet Using Advanced Modulation Formats: Performance, Complexity, and Power Dissipation," IEEE Commun. Mag., Vol. **53**, no. 2, pp. 182 (2015).

[7] J. Van Kerrebrouck *et al.*, "100 Gb / s Serial Transmission over Copper using Duo-binary Signaling," *Design Con 2016 (2016)*

[8] X. Yin *et al.*, "First Demonstration of Real-Time 100 Gbit/s 3-level Duobinary Transmission for Optical Interconnects," European Conference on Optical Communication (ECOC) 2016 Th.3.B.5 (PDP), (2016)

[9] M. Scholten *et al.*, "Continuously-Interleaved BCH (CI-BCH) FEC Delivers Best in Class NECG for 40G and 100G Metro Applications," Optical Fiber Communication Conference (OFC)/NFOEC 2012, NTuB3. (2012)

[10] Institute of Microelectronics, Agency for Science, Technology and Research (A*STAR), *https://www.a-star.edu.sg*

[11] M. Lauermann *et al.*, "Generation of 64 GBd 4ASK Signals Using a Silicon-Organic Hybrid Modulator at 80°C," Opt. Express, Vol. **24**, no. 9, p. 9389 (2016)

[12] L. Alloatti *et al.*, "100 GHz Silicon–Organic Hybrid Modulator," Light Sci. Appl., Vol. **3**, no. 5, p. e173 (2014)

[13] S. Wolf *et al.*, " DAC-less Amplifier-less Generation and Transmission of QAM Signals Using Sub-Volt Silicon-organic Hybrid Modulators", J. Lightwave Technol. Vol. **33**, p. 1425 (2015)

Acknowledgements: We acknowledge support by the European Research Council (ERC Starting Grant 'EnTeraPIC', 280145), EU-FP7 projects PhoxTroT and BigPipes, Alfried Krupp von Bohlen und Halbach Foundation, Helmholtz International Research School for Teratronics (HIRST), Karlsruhe School of Optics and Photonics (KSOP), and Karlsruhe Nano-Micro Facility (KNMF). The 100Gbit/s electronics is developed by the BiFast spin-off incubation project, funded by the industrial research fund of Ghent University.