10 GBd SOH Modulator Directly Driven by an FPGA without Electrical Amplification

S. Wolf[1], P.C. Schindler[1], G. Ronniger[1], M. Lauermann[1], R. Palmer[1], S. Koeber[1,2], D. Korn[1] W. Bogaerts[3,4], J. Leuthold [1,5], W. Freude[1], and C. Koos[1,2]

[1] Karlsruhe Institute of Technology, Institute of Photonics and Quantum Electronics (IPQ), Karlsruhe, Germany

[2] Karlsruhe Institute of Technology, Institute of Microstructure Technology (IMT), Eggenstein-Leopoldshafen, Germany

[3] Photonics Research Group, Ghent University – imec, Department of Information Technology, Gent, Belgium

[4] *Now also with:* Luceda Photonics, Dendermonde, Belgium

[5] *Now with:* Institute of Electromagnetic Fields (IEF), ETH Zurich, Switzerland

s.wolf@kit.edu, christian.koos@kit.edu

Abstract: Using standard single-ended FPGA outputs with 270 mV_{pp} we demonstrate 10GBd OOK and BPSK transmission by directly driving a low-voltage silicon-organic hybrid (SOH) modulator. The scheme does not require electronic driver amplifiers, which paves the way to energy-efficient photonic-electronic integration.

Introduction

Short-reach optical interconnects are key to overcome communication bottlenecks in a wide range of information processing systems. In this context, increasing integration density and decreasing power consumption are of utmost importance. This requires intimate co-integration of digital electronic information processing subsystems and photonic communication modules on board- or even chip-level. For the photonic transceivers, silicon lends itself as an integration platform, leveraging mature CMOS processing and enabling large-scale integration of photonic devices along with electronic circuitry[1]. However, in many cases the rather high voltage requirements of optical transmitters in the order of several volts prohibit energy-efficient photonic-electronic interfaces, since the core voltages of state-of-the-art CMOS circuits are much smaller and amount to, e.g., 1 V or less for the 28 nm technology node. For conventional silicon photonic modulators with voltage-length products in the order of $V_\pi L$ = 10 Vmm or more[2], voltage requirements can only be reduced at the expense of footprint.

As a consequence, electrical driver amplifiers must be used to connect the modulators to the output ports of digital integrated circuits (IC). Alternatively, resonant modulators can be directly driven from a field programmable gate array (FPGA)[3]. Line rates of 2.5 Gbit/s have been demonstrated with peak-to-peak drive voltages of 1.2 V_{pp}. These devices, however, suffer from limited optical bandwidth and are often subject to strong temperature-induced drifts of the resonance wavelength.

In this paper, we demonstrate for the first time that a non-resonant silicon-based Mach-Zehnder modulator (MZM) can be driven directly with the digital outputs of an FPGA. We use the standard GTX transmitter port of a Xilinx Virtex-7 FPGA to operate a low-voltage silicon organic hybrid (SOH) modulator at a data rate of 10 Gbit/s without electrical amplification. The device exhibits a voltage-length product of 0.74 Vmm measured at DC, and is driven with voltage swing of 270 mV_{pp} at symbol rates of 10 GBd. Error-free back-to-back transmission is shown for both on-off-keying (OOK) and binary phase shift keying (BPSK). The optical OOK signal is detected with a photodiode, the output of which is directed without an amplifier to a GTX-receiver port of an FPGA. Standard signal processing modules allow measuring the bit error ratio (BER). Our findings show that ultra-efficient SOH modulators can be seamlessly integrated with digital electronics and operated with millivolt drive signals without the need for power-hungry driver amplifiers.

SOH Electro-Optic Modulator

The SOH MZM consists of two phase shifters which are operated in push-pull mode, see Fig 1(a). The cross-section of a typical SOH phase shifter is depicted in Fig 1(b). The quasi-TE polarized light is guided by silicon slot waveguides that are covered with an organic electro-optic material. The optical field is strongly enhanced in the slot due to the discontinuity of the electric field component normal to the interface between silicon and cladding[4], see Fig. 1(b). The rails of both phase shifters in the MZM are electrically connected to a ground-signal-ground (GSG) transmission line via thin conductive silicon slabs. An applied electrical voltage thus drops mainly across the slot of each phase shifter, leading to a high overlap of the modulating field with the optical mode. During the fabrication process, the chromophores of the electro-optic material are aligned by a poling process. The field orientation of the

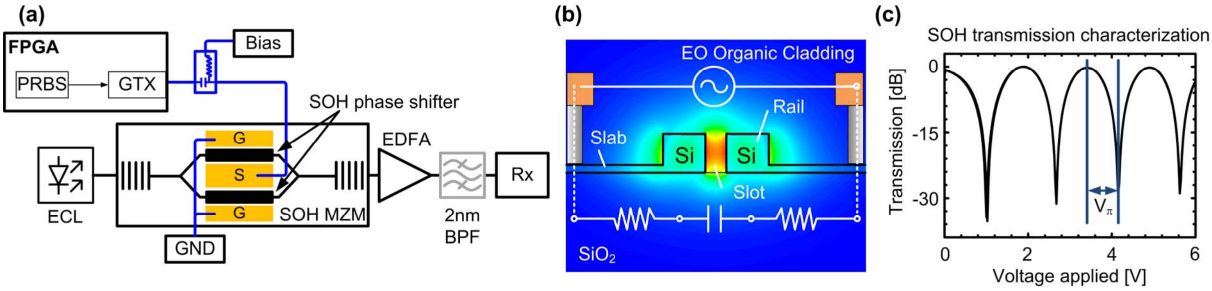

Fig. 1: (a) Experimental setup for directly driving an SOH modulator with the GTX interfaces of a Virtex-7 FPGA. A PRBS signal is mapped to the electrical GTX output that is connected to the Mach-Zehnder modulator (MZM) without further amplification. The MZM consists of two 1 mm long SOH phase shifters that are driven by a ground-signal-ground (GSG) transmission line. The optical carrier from an external cavity laser (ECL) is modulated in the SOH MZM, and an erbium-doped fiber amplifier (EDFA) compensates the insertion loss before the signal is fed to the receiver (Rx). For coherent detection, an optical modulation analyzer (OMA) is used, whereas direct detection relies on a single photodiode. In this case a 2 nm bandpass filter (BPF) suppresses ASE noise of the EDFA. (b) Cross-section of a single SOH phase-shifter. The silicon slot waveguide (w_{Slot} = 120 nm, w_{Rail} = 240 nm, h_{Rail} = 220 nm) is coated with the electro-optic material SEO100. Electrodes are connected to the silicon rails via thin conductive slabs. (c) DC-Transmission curve of MZM modulator. The voltage required for a π-phase shift of the MZM is V_π = 0.74 V measured at DC with a bias voltage of 3.7 V.

GSG transmission line and the poling direction result in push-pull operation of the MZM[5]. To increase the modulation bandwidth, a static gate field of 0.1 V/nm is applied between the bulk silicon and the SOI device layer to increase the conductivity of the thin silicon slabs by an electron accumulation layer[6]. As a cladding, the commercially available material SEO100 from Soluxra LLC is used. This material combines good temperature stability with high electro-optic performance. In our 1 mm-long SOH MZM, we measure a π-voltage of 0.74 V at DC, as depicted in Fig 1(c). This allows for efficient modulation even at low drive voltages. Note that the π-voltage is measured at a 3.7 V bias to eliminate screening effects caused by free charges in the cladding at small DC fields[5].

Data Transmission Setup

The experimental setup is depicted in Fig. 1 (a). Laser light from an external cavity laser (ECL) is coupled to the SOH MZM. The signal at the output of the modulator chip is amplified by an erbium-doped fiber amplifier (EDFA) in order to compensate for the insertion loss. After amplification, the signal is received by either a coherent receiver (Rx) using a local oscillator for coherent BPSK demodulation or by direct detection with a fast photodiode for OOK signals. For OOK, a 2 nm bandpass filter (BPF) suppresses amplified spontaneous emission (ASE).

For the experiment, we use a Xilinx XC7VX485T FPGA on a VC707 evaluation board. A pseudo-random binary sequence (PRBS) of length 2^{31}-1 is generated on the FPGA and fed to a single GTX transmitter (Tx) for OOK and BPSK modulation. GTX transceivers are specified to operate at a maximum of 0.5 V_{pp} for single-ended operation in the low frequency limit. In our case, we measured a swing of about 310 mV_{pp} from the electric eye diagram at the transmitter output. The Xilinx GTX interfaces are neither designed to drive photonic devices nor do they provide a flat frequency response. As a consequence, the GTX interface exhibits a strong low-pass characteristic. We compensated it by an internal digital 3-tap finite-impulse response (FIR) filter. Using this filter the output port swing reduces further to 270 mV_{pp} for our experiment.

Transmission Experiment

In a first experiment, we generate OOK and BPSK signals, which are received and recorded for offline signal analysis. The experimental results are summarized in Fig. 2. OOK signals are obtained by biasing the SOH MZM at the quadrature point. A real-time oscilloscope records the output current of a fast pin photodiode delivered to a 50 Ω impedance. We use Matlab to analyze the signal. We do not employ any post-equalization. Eye diagrams for the electrical drive signal and the optical signal as received are depicted in Fig 2 (a) and (b), respectively. We do not measure any errors in approximately 390.000 recorded bits. The extracted quality-factor Q = 6.7 for the transmission indicates error-free operation (BER = 10^{-11}). Comparison of both eye diagrams in Fig. 2(a) and (b) suggests that bandwidth limitations are mainly due to the GTX modules. This is in agreement with an independent measurement of the SOH MZM, which exhibited a modulation bandwidth of approximately 15 GHz – well above the bandwidth of the GTX modules. Hence, without further bandwidth degradation, it would be possible to improve signal quality by increasing the length of the phase shifters, thereby improving modulation depth at the expense of device bandwidth. Alternatively, when keeping the device

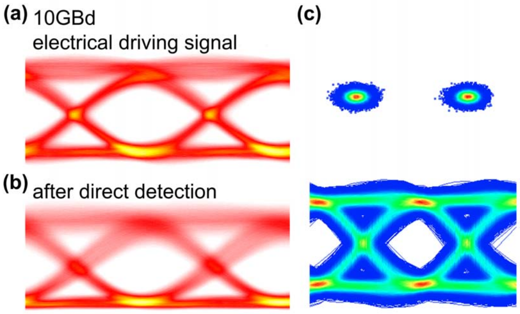

Fig. 2: Experimental results after offline processing. Eye diagrams of (a) electrical output of GTX transmitter and (b) after direct detection by a photodiode. The quality of eye diagrams indicates error-free detection. (c) Constellation diagram and eye diagram for BPSK signal with measured EVM value of 13.7 %. No errors measured during 62 µs.

geometry, this modulator could be used at higher symbol rates if supported by the proper electronic driver.

With the same driver signals, but operating the modulator in the null point, BPSK signaling is achieved. We use an optical modulation analyzer (OMA) with an external local oscillator (LO) for coherent detection. Signal analysis includes digital polarization alignment, frequency and phase adjustment, and post-equalization. Signal quality is determined by the error vector magnitude (EVM). We measure error-free transmission with an EVM of 13.7 %. This is in agreement with the bit-error analysis of the recorded data stream with approximately 620 kbit. The corresponding constellation and the eye diagram for the BPSK signal are shown in Fig. 2(c). Even without post-equalization, error-free transmission is observed. The EVM is 21.5 %, and no errors were found in the recordings. These experiments show for the first time that non-resonant silicon-based MZM can be driven directly by standard FPGA outputs without further amplification.

Loop-Back Experiment

In a second experiment, the FPGA board is used both as a date source and a sink. We again transmit OOK signals but now connect the photodiode output to a GTX receiver on the same board, Fig. 3. EDFA and BPF are again used for loss compensation and elimination of ASE. Signal generation and reception is performed with the Chipscope software provided by Xilinx. We measure a real-time BER of 6.6×10^{-6}. This is significantly worse than in the transmission experiments with offline data processing, but still well above typical forward-error correction (FEC) thresholds. We believe that the lower reception quality is due to the single-ended operation of the differential GTX Rx inputs, which are fed by the high-speed photodiode with the small 30 mV_{pp} output

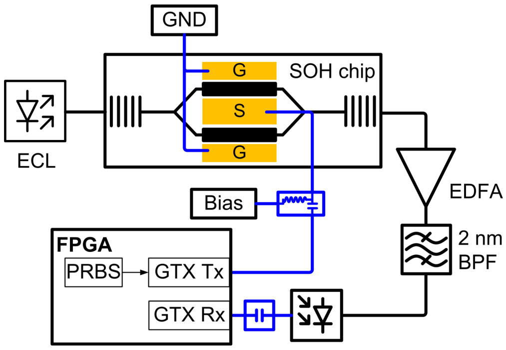

Fig. 3: Experimental setup for Loop-Back experiment: Laser light from an ECL is coupled to the SOH modulator that is directly driven from the GTX Tx output of the FPGA. After being amplified by an EDFA, the modulated signal is bandpass filtered before the photodiode using a 2 nm filter. The electrical signal extracted from the photodiode is again connected to the same FPGA without further electrical amplification. Data analysis showed BER of 6.6×10^{-6}.

voltage, which is significantly smaller than the input voltage of 150 mV that is specified for the GTX Rx.

Conclusion

We demonstrate for the first time a non-resonant silicon-based modulator that is directly driven from digital FPGA outputs to optically transmit OOK, and BPSK signals. We show error-free operation at a data rate of 10 Gbit/s. Moreover, we directly received OOK signals with a standard FPGA GTX receiver in a loop-back experiment, leading to a BER of 6.6×10^{-6}. These results show the feasibility of energy-efficient amplifier-less photonic-electronic co-integration.

Acknowledgements

We acknowledge support by the European Research Council (ERC Starting Grant 'EnTeraPIC', 280145), the EU-FP7 projects PHOXTROT and BigPipes, the PIANO+ project OTONES, the Alfried Krupp von Bohlen und Halbach Foundation, the Karlsruhe School of Optics and Photonics (KSOP), the Karlsruhe International Research School for Teratronics (HIRST), and the Karlsruhe Nano-Micro Facility (KNMF).

References

[1] J. S. Orcutt et al., "Open Foundry Platform for High-Performance Electronic-Photonic Integration," Opt. Express, Vol. **20**, no. 11, pp. 12222-12232 (2012)
[2] T. Baehr-Jones et al, "Ultralow Drive Voltage Silicon Travelling-Wave Modulator," Opt. Express, Vol. **20**, no. 11, pp. 12014-12020 (2012)
[3] D. Brunina et al, "10-Gb/s WDM Optically-Connected Memory System Using Silicon Microring Resonators," Proc. ECOC, Mo.2.A.5, Amsterdam (2012)
[4] J. Leuthold et al., "Silicon-Organic Hybrid Electro-Optical Devices," IEEE J. Sel. Topics Quantum Electron., Vol. **19**, no. 6, pp. 3401413 (2013)
[5] R. Palmer et al., "High-Speed, Low Drive-Voltage Silicon-Organic Hybrid Modulator Based on a Binary-Chromophore Electro-Optic Material," J. Lightw. Technol., in press (2014)
[6] L. Alloatti et al., "Optical Absorption In Silicon Layers in the Presence of Charge Inversion/Accumulation or Ion Implantation," Appl. Phys. Lett. Vol. **103**, no. 5, p. 051104 (2013)