Silicon-Organic Hybrid (SOH) IQ Modulator for 100 GBd 16QAM Operation

S. Wolf[1], H. Zwickel[1], C. Kieninger[1,2], Y. Kutuvantavida[1,2], M. Lauermann[1], J. Lutz[3], L. Altenhain[3], R. Schmid[3], W. Freude[1], C. Koos[1,2], and S. Randel[1]

(1) Karlsruhe Institute of Technology, Institute of Photonics and Quantum Electronics, Karlsruhe, Germany
(2) Karlsruhe Institute of Technology, Institute of Microstructure Technology (IMT), Karlsruhe, Germany
(3) Micram Microelectronic GmbH, Bochum, Germany
s.wolf@kit.edu, christian.koos@kit.edu, sebastian.randel@kit.edu

Abstract: We generate record-high line rates of 400 Gbit/s (100 GBd 16QAM) using a silicon-based IQ modulator. With a BER=1.9×10^{-2} we transmit a net data rate of 333 Gbit/s, the highest value for a semiconductor-based modulator.

OCIS codes: (060.1660) Coherent communications; (060.233) Fiber optics communications; (130.4110) Integrated Modulators

1. Introduction

With the per-fiber capacity being pushed to its limit, dense photonic integration together with high electro-optic bandwidths are promising approaches to further reduce the cost per bit in coherent optical communication systems.

Recently, a signal with a data rate of 1.08 Tbit/s (504 Gbit/s per polarization) has been generated with a lithium-niobate modulator using polarization-division multiplexed (PDM) 64-quadrature amplitude modulation (64QAM) at a symbol rate of 90 GBd [1]. While lithium-niobate modulators offer good performance, they are not well suited for dense integration. Semiconductor-based modulators are considered promising alternatives. Using InP modulators, a 77 GBd 32QAM PDM signal was generated corresponding to a data rate of 770 Gbit/s (385 Gbit/s per polarization) [2]. However, in contrast to InP, the silicon (Si) photonic platform allows small form factors combined with low-cost fabrication and mature CMOS processes. The generation of up to 227 Gbit/s has been demonstrated using conventional Si modulators [3], [4]. However, these devices suffer from a rather low modulation efficiency with π-voltage-length products of the order of 10 Vmm [5], which usually requires comparatively high drive voltages of several volts and increases the power dissipation in the associated drive amplifier stages. In [6]–[12], we demonstrated that silicon-organic-hybrid (SOH) modulators, combining Si slot waveguides with highly efficient electro-optic cladding materials, allow high-speed modulation up to 63 GBd 16QAM [9] (252 Gbit/s on a single polarization) at π-voltage-length products of 1 Vmm and below. Using a thin-film polymer-on-silicon modulator the authors of [13] demonstrated 90 GBd quadrature-phase-shift keying (QPSK), however the π-voltage of their device is 3.5 V [14].

In this paper, we demonstrate an SOH modulator with a π-voltage of 1.6 V which supports 100 GBd operation with higher-order modulation formats. We generate 16QAM signals at 50 GBd, 80 GBd, and 100 GBd corresponding to a line rate of up to 400 Gbit/s on a single polarization. This is, to the best of our knowledge, the highest single-polarization data rate reported for a semiconductor-based optical modulator. The electrical energy dissipation in the modulator amounts to 30 fJ/bit per bit –a record-low value for a semiconductor-based modulator at this symbol rate.

2. Silicon-Organic Hybrid (SOH) Modulator

Our SOH inphase/quadrature (IQ) modulator in a nested Mach-Zehnder modulator (MZM) configuration comprises 600 µm long phase shifter sections, the cross-section of which is depicted in Fig. 1a. The optical field is strongly confined within the 120 nm wide slot between two silicon (Si) rails, which is filled with the organic electro-optic (EO) material SEO250. This material offers good stability [15], similar to the previously used material SEO100, for which operation at 80 °C was demonstrated [12]. The silicon rails are connected to the coplanar ground-signal-ground (GSG) electrodes via thin *n*-doped silicon slabs and electrical vias [7]. In this configuration, the modulating electric field strongly overlaps with the optical field, which leads to a high modulation efficiency. The device used in this experiment was fabricated in a standard 248 nm deep-UV (DUV) process at A*Star IME, Singapore, and is co-integrated with other silicon-photonic devices such as germanium photodiodes and thermal phase shifters on the same wafer. The EO material is deposited in a post-processing step, and the chromophores in the EO material are aligned in a dedicated one-time poling process such that push-pull operation of the MZM is achieved when applying a signal to the signal electrode [6]. For DC voltages, we measured a π–voltage of 1.6 V, corresponding to a π-voltage-length product of $U_\pi L = 1$ Vmm. The bandwidth of SOH modulators is limited by an inherent *RC*-characteristic resulting from the capacitance of the slot waveguide which is charged and discharged via the Si slabs.

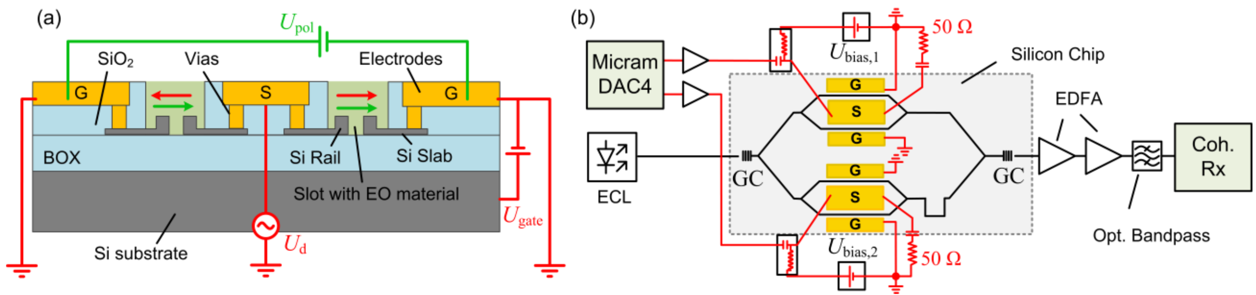

Fig. 1: Silicon-organic hybrid (SOH) IQ modulator for 100 GBd operation. **(a)** Cross-section of the SOH Mach-Zehnder modulator (MZM). Electrical vias and *n*-doped silicon slabs connect the ground-signal-ground (GSG) transmission line to the silicon rails. The 120 nm wide slot between the silicon rails is filled with the electro-optic material SEO250. In order to align the chromophores in the same direction in both arms of the MZM (green arrows), a poling voltage is applied across the floating ground electrodes in a dedicated poling procedure at elevated temperatures. Applying signals to the GSG transmission line then leads to electrical fields (red arrows) oriented in the same direction as the chromophores in one arm, and in the opposite direction in the other arm of the MZM. This results in push-pull operation. A gate voltage between ground and Si substrate induces an electron accumulation layer, leading to an increased *RC* device bandwidth. **(b)** Experimental setup for signal generation. The IQ modulator consists of two nested MZMs. The electrical drive signals from the Micram DAC4 are amplified to a peak-to-peak voltage of approximately 1.5V_{pp}, and are fed to the GSG lines of the SOH MZMs via RF probes. Bias tees are used to apply DC voltages in order to set the device's operating point. An external 50 Ω impedance terminates the transmission lines. At the receiver, we amplify the optical signal using two erbium-doped fiber amplifiers (EDFA).We remove out-of-band noise using an optical bandpass filter, and finally detect the signal using a coherent receiver (Coh. Rx)

When applying a so-called gate field, an electron accumulation layer increases the slabs' conductivity, and consequently increases the modulation bandwidth. Using a gate field, an SOH MZM with a bandwidth of 100 GHz has been demonstrated [16].

3. Experimental Setup

The experimental setup is depicted in Fig. 1b. For the signal generation we use a BiCMOS digital-to-analog converter (DAC, Micram DAC4). It features a continuously adjustable sampling rate of up to 100 GSa/s at a physical resolution of 6 bit. The effective number of bits (ENoB) remains above 4.5 bit up to the Nyquist frequency. The analog 3 dB bandwidth is as high as 40 GHz and shows a smooth roll-off to -6 dB at the Nyquist frequency. More detailed information on the DAC can be found in [17]. The quaternary I and Q drive signals are derived from a random symbol sequence with a length of 2^{15} symbols. The signals are amplified to a peak-to-peak voltage of approximately 1.5 V_{pp} using two 70 GHz radio-frequency amplifiers. The drive signals are coupled to the GSG transmission lines of the MZMs using RF microwave probes. The optical carrier is provided by an external-cavity laser (ECL), and is coupled to and from the SOH IQ modulator via grating couplers. We apply a gate field of 0.1 V/nm. At the receiver, the signal is fed to a two-stage erbium-doped fiber amplifier (EDFA) to compensate the modulator's insertion loss. The fiber-chip coupling loss amounts to 4.5 dB per interface, caused by non-optimized grating couplers. The on-chip insertion loss of the IQ modulator amounts to approximately 11 dB, which contains the intrinsic 3 dB loss of the nested MZM structure. Upon optimization of the device, we expect that the on-chip losses can be reduced to less than 5 dB [8]. An optical bandpass filter with a 1.5 nm passband removes out-of-band amplified spontaneous emission (ASE) noise. We use a coherent receiver with a bandwidth of 45 GHz (Tektronix OM4245), and record waveforms using a four-channel 70 GHz oscilloscope (Tektronix DPO77002SX). Signal analysis is performed using offline digital signal processing (DSP) in Matlab. The DSP includes a digital timing recovery, a 33-tap fractionally spaced adaptive feed-forward equalizer that is adapted using a least-mean-square stochastic gradient scheme. Finally, we count the bit errors after hard decision.

4. Experimental results

We generate 16QAM data signals at symbol rates of 50 GBd, 80 GBd and 100 GBd. The received constellation diagrams are shown in Fig. 2. For the 200 Gbit/s signal (50 GBd 16QAM), we measure a BER of 1.5×10^{-5}. At 80 GBd (320 Gbit/s), the measured BER is 4.4×10^{-3}. Both measurements yield values below the threshold of 4.5×10^{-3} for hard-decision forward error correction (FEC) with a 7% overhead [18]. Considering the FEC overhead, this leads to net data rates of 186 Gbit/s and 299 Gbit/s, respectively. At 100 GBd, 16QAM modulation results in a line rate of 400 Gbit/s, and we measure a BER of 1.88×10^{-2}. The OSNR (in a spectral width of 0.1 nm) is 27.5 dB from which we find an implementation penalty of 8.5 dB at 100 GBd. Considering a 20 % FEC overhead, this results in a net data rate of 333 Gbit/s. This experiment constitutes the fastest signal generation experiment using a

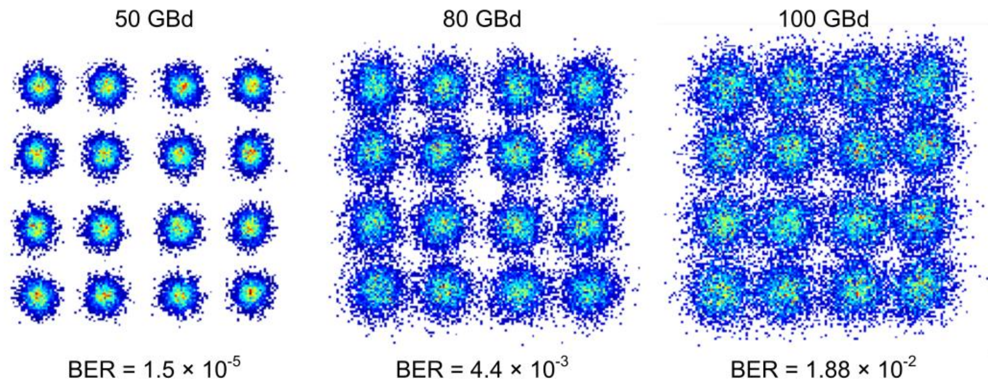

Fig. 2: Experimental results. 16QAM constellation diagrams received at 50 GBd (200 Gbit/s, left), 80 GBd (center), and 100 GBd (right). For 50 GBd and 80 GBd (320 Gbit/s), the measured values for the bit error ratio (BER) are 1.5×10^{-5} and 4.4×10^{-3}, respectively. Both values are within the threshold for forward error correction (FEC) with 7% overhead, leading to net data rates of 186 Gbit/s and 299 Gbit/s. At 100 GBd, the measured BER is 1.88×10^{-2}. Considering a FEC with 20% overhead, the net data rate is 333 Gbit/s.

semiconductor-based device reported so far. Considering the peak-to-peak drive voltage of 1.5 V_{pp} for the 400 Gbit/s data signal, we find an electrical energy consumption of 30 fJ/bit which is the lowest value achieved for modulators of its class.

4. Conclusion

Using an SOH IQ modulator, we generate 16QAM data streams at symbol rates of up to 100 GBd, resulting in line rates of up to 400 Gbit/s on a single polarization. This represents the highest values reported for modulators integrated on a semiconductor substrate to date, thereby paving the path towards highly integrated coherent transmitters with unprecedented data rate and energy efficiency. Based on these results, we believe that the SOH technology is a promising candidate for single-wavelength transmission of data rates approaching or even exceeding 1 Tbit/s.

Acknowledgements

We acknowledge support from Tektronix for lending the optical receiver and high-speed real-time oscilloscopes and from Jingdong Luo and Alex Jen from Soluxra for providing the electro-optic polymer. We acknowledge support by the European Research Council (ERC Starting Grant 'EnTeraPIC', 280145), the EU-FP7 projects PhoxTroT and BigPipes, the Alfried Krupp von Bohlen und Halbach Foundation, the Helmholtz International Research School for Teratronics (HIRST), the Karlsruhe School of Optics and Photonics (KSOP), and the Karlsruhe Nano-Micro Facility (KNMF).

References

[1] G. Raybon *et al.*, "Single Carrier High Symbol Rate Transmitter for Data Rates up to 1.0 Tb/s," in *Optical Fiber Communication Conference*, 2016, p. Th3A.2.

[2] M. Y. S. Sowailem *et al.*, "770-Gb/s PDM-32QAM Coherent Transmission Using InP Dual Polarization IQ Modulator," *IEEE Photonics Technol. Lett.*, vol. 29, no. 5, pp. 442–445, Mar. 2017.

[3] Y. Fang *et al.*, "Silicon IQ Modulator Based 480km 80x453.2Gb/s PDM-eOFDM Transmission on 50GHz Grid with SSMF and EDFA-only Link," in *Optical Fiber Communication Conference*, 2015, p. M3G.5.

[4] J. Geyer *et al.*, "Practical Implementation of Higher Order Modulation Beyond 16-QAM," in *Optical Fiber Communication Conference*, 2015, p. Th1B.1.

[5] D. Petousi *et al.*, "High-Speed Monolithically Integrated Silicon Photonic Transmitters in 0.25 μm BiCMOS Platform," *ECOC 2016; 42nd Eur. Conf. Opt. Commun.*, pp. 604–606, 2016.

[6] C. Koos *et al.*, "Silicon-Organic Hybrid (SOH) and Plasmonic-Organic Hybrid (POH) Integration," *J. Lightw. Technol.*, vol. 34, no. 2, pp. 256–268, Jan. 2016.

[7] S. Koeber *et al.*, "Femtojoule electro-optic modulation using a silicon–organic hybrid device," *Light Sci. Appl.*, vol. 4, no. 2, p. e255, Feb. 2015.

[8] M. Lauermann *et al.*, "40 GBd 16QAM Signaling at 160 Gb/s in a Silicon-Organic Hybrid Modulator," *J. Lightw. Technol.*, vol. 33, no. 6, pp. 1210–1216, Mar. 2015.

[9] S. Wolf *et al.*, "An Energy-Efficient 252 Gbit/s Silicon-Based IQ-Modulator," in *Optical Fiber Communication Conference*, 2016, p. Th3J.2.

[10] M. Lauermann *et al.*, "Low-power silicon-organic hybrid (SOH) modulators for advanced modulation formats," *Opt. Express*, vol. 22, no. 24, pp. 29927–29936, Nov. 2014.

[11] S. Wolf *et al.*, "DAC-less Amplifier-less Generation and Transmission of QAM Signals Using Sub-Volt Silicon-organic Hybrid Modulators," *J. Lightw. Technol.*, vol. 33, no. 7, pp. 1425–1432, 2015.

[12] 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, pp. 9389–9396, May 2016.

[13] G. Raybon *et al.*, "180-Gb/s (90-GBd QPSK) Single Carrier Transmitter Using a Thin Film Polymer on Silicon I/Q Modulator," in *ECOC 2016; 42nd European Conference on Optical Communication*, 2016, pp. 31–33.

[14] H. Huang, J. Yang, Y. Yue, Y. Ren, S. R. Nuicco, and R. Dinu, "100-Gbit/s Amplitude and Phase Modulation Characterization of a Single-Drive, Low-Vπ Polymer Mach-Zehnder Modulator," in *Optical Fiber Communication Conference and Exposition (OFC/NFOEC)*, 2012, p. OW4F.5.

[15] S. Shahin, S. Mehravar, P. Gangopadhyay, N. Peyghambarian, R. a. Norwood, and K. Kieu, "Multiphoton microscopy as a detection tool for photobleaching of EO materials," *Opt. Express*, vol. 22, no. 25, p. 30955, Dec. 2014.

[16] L. Alloatti *et al.*, "100 GHz silicon–organic hybrid modulator," *Light Sci. Appl.*, vol. 3, no. 5, p. e173, May 2014.

[17] K. Schuh *et al.*, "100 GSa/s BiCMOS DAC Supporting 400 Gb/s Dual Channel Transmission," in *ECOC 2016; 42nd European Conference on Optical Communication*, 2016, pp. 37–39.

[18] F. Chang, K. Onohara, and T. Mizuochi, "Forward error correction for 100 G transport networks," *Commun. Mag. IEEE*, vol. 48, no. 3, pp. 48–55, 2010.