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

S. Wolf¹, H. Zwickel¹, C. Kieninger¹,², Y. Kutuvantavida¹,², M. Lauermann¹, J. Lutz³, L. Altenhain³, R. Schmidt³, W. Freude¹, C. Koos¹,², and S. Randel¹

(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) Micron Microelectronic GmbH, Bochum, Germany

Abstract: We generate record-high line rates of 400 Gbit/s (100 GBd 16QAM) using a silicon-based IQ modulator. With a BER=1.9x10⁻⁵ we transmit a net data rate of 333 Gbit/s, the highest value for a semiconductor-based modulator.

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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 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 Vnm [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 $U_{πL} = 1$ 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.
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 $1.5 \times 10^{-5}$. At 80 GBd (320 Gbit/s), the measured BER is $4.4 \times 10^{-7}$. Both measurements yield values below the threshold of $4.5 \times 10^{-5}$ 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 $1.88 \times 10^{-5}$. 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
semiconductor-based device reported so far. Considering the peak-to-peak drive voltage of 1.5 V peak 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 way 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.

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