DAC-Less and Amplifier-Less Generation and Transmission of 16QAM Signals Using a Sub-Volt Silicon Photonic Modulator

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Abstract *We demonstrate generation and transmission of QPSK and 16QAM signals by directly interfacing highly efficient silicon-organic hybrid (SOH) modulators to GTH ports of an FPGA. Peak-to-peak voltages amount to only 0.41* V_{pp}*. Neither digital-to-analog converters (DAC) nor drive amplifiers are required.*

Introduction

High-capacity optical interconnects are key to overcome transmission bottlenecks in information-processing systems. In this context, intimate co-integration and direct interfacing of photonic and electronic circuitry[1] is indispensable to realize low-cost transceiver modules with high throughput, low power consumption, and the capability of using wavelength division multiplexing. At the same time, optimized spectral efficiency is becoming increasingly important not only for telecommunications but also for optical interconnects, where the transmission medium emerges as one of the most costly parts of the system. This calls for higher-order modulation formats[2] such as quadrature phase-shift keying (QPSK) or *M*-ary quadrature amplitude modulation (*M*-QAM). However, the technical complexity, cost and power consumption of the associated photonic-electronic interface still appears prohibitive for optical interconnects: The generation of higher-order modulation formats usually relies on high-speed digital-to-analog converters (DAC) and linear electrical amplifiers that are suited for driving common electro-optic modulators. The associated energy consumption is considerable: Operating a 3-bit power DAC[3] at a peak-to-peak voltage of 3.2 V_{pp} and a symbol rate of 42 GBd, the energy consumption in the electronic output stage amounts to 15.8 pJ/bit. This is ill-suited for highly integrated optical interconnects, where direct low-power interfaces between optical modulators and digital CMOS electronics are essential.

For conventional on-off-keying (OOK), amplifier-less interfaces have been demonstrated between the outputs of standard field-programmable gate arrays (FPGA) and silicon photonic microring modulators[4]. The line rate was 2.5 Gbit/s at a driving voltage of 1.2 V_{pp}, where the resonant structure was necessary to overcome the usually high driving voltage requirement of conventional depletion-type modulators. However, this concept cannot be directly transferred to higher-order modulation formats. Moreover, the scheme requires careful matching of the carrier wavelength and the modulator's resonance wavelength by, e.g., heaters, which come along with additional power consumption.

As an alternative, we recently showed that non-resonant and yet highly efficient Mach-Zehnder modulators (MZM) can be realized by silicon-organic hybrid (SOH) integration[5]. These devices are well suited for amplifier-less operation directly from the 270 mV_{pp} output ports of an FPGA, thereby generating OOK and binary phase shift keying signals[6]. However, directly FPGA-driven signaling with higher-order modulation formats has not yet been demonstrated.

In this paper, we show for the first time that higher-order modulation formats, namely QPSK and 16QAM, can be generated using an SOH IQ modulator directly interfaced with standard GTH ports of an FPGA. We combine binary FPGA outputs to form four-level signals that directly drive the modulators such that neither DAC nor driver amplifiers are required. The peak-to-peak amplitude of the drive signals amounts to 0.41 V_{pp}, corresponding to an electronic power consumption of 18 fJ/bit – far below that of current photonic-electronic interfaces for QAM modulation[3]. For the case of QPSK, we demonstrate error-free transmission over 100 km. For transmission of 16 QAM signals over the same distance, the bit error ratios (BER) are still below the limit of today's hard-decision forward error correction (FEC) algorithms with 7 % overhead[7].

We believe that DAC-less and amplifier-less interfaces between digital circuitry and highly efficient SOH modulators can enable a novel class of highly scalable optical interconnects with unprecedented energy efficiency.

SOH Electro-Optic IQ Modulator

The SOH IQ-modulator combines conventional silicon-on-insulator slot waveguides with organic

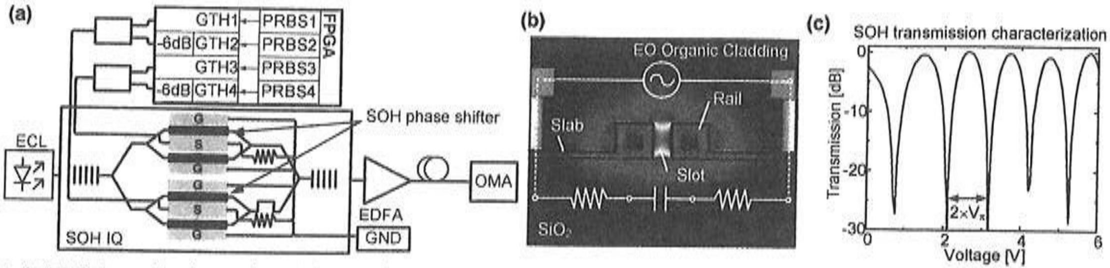

Fig. 1: (a) Schematic of experimental setup for DAC-less generation of 16QAM. The silicon-organic hybrid (SOH) IQ modulator consists of two 1.5 mm long Mach-Zehnder modulators (MZM) that are driven by a ground-signal-ground (GSG) transmission line that is contacted via bias-T and microwave probes (not shown), and terminated with a 50 Ω impedance. An intentional imbalance in the parent MZM allows to adjust a π/2 phase shift between I and Q via wavelength tuning. To generate the four-level drive signal for each MZM, the PRBS signals from two GTH ports with independent output voltages differing by 6 dB are combined in a power combiner. The resulting 4-level signal is applied to the modulator electrodes. An external cavity laser (ECL) is used as an optical source, and an erbium-doped fiber amplifier (EDFA) compensates the optical insertion loss of the device before the signal is fed to the optical modulation analyzer (OMA). The local oscillator is derived from the transmitter laser for homodyne detection (not shown). (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 *n*-doped slabs. (c) DC-Transmission curve of one MZM modulator. The voltage for a π-phase shift is V_π = 0.53 V, measured at a DC of more than 2 V to avoid screening by free charges in the electro-optic cladding[5].

electro-optic cladding materials[8,9]. The device consists of two nested MZM, each of which is operated in push-pull mode, see Fig 1(a). The cross-section of a typical SOH phase shifter is depicted in Fig 1(b). For quasi-TE polarization, the field in the slot waveguide is strongly enhanced due to the discontinuity of the normal electric field component at the interface to the silicon rails[9], see Fig. 1(b). The two rails are electrically connected to a ground-signal-ground (GSG) transmission line via thin *n*-doped silicon slabs. Any applied electrical voltage thus drops mainly across the narrow slot of each phase shifter, leading to a strong overlap of the modulating field with the optical mode in the slot. Push-pull operation of the MZM is achieved by suitable alignment of the electro-optic chromophores in the cladding in a dedicated poling step[5]. To increase the modulation bandwidth, a static gate field of 0.05 V/nm is applied between the bulk silicon and the SOI device layer, such increasing the conductivity of the thin silicon slabs by an electron accumulation layer[8,10]. The commercially available material SEO100 from Soluxra, LLC is used as electro-optic cladding. It features high electro-optic coefficients and is specified for operating temperatures up to 85°C. Both 1.5 mm-long SOH MZM in the IQ-modulator exhibit a π-voltage of 0.53 V at DC. A transmission characterization of one SOH MZM is depicted in Fig 1(c).

Experimental Setup

The setup consists of an FPGA-based transmitter using four standard GTH lines which are directly connected to the SOH IQ-modulator. For generating the I and Q drive signals in the 16QAM experiment, we combine two GTH lines by using a power coupler. The 6 dB power attenuation required for a 4-level signal is realized by reducing the output voltage of two ports via the FPGA software. Furthermore, the independent output levels of the FPGA can be used to compensate the nonlinear transfer function of the push-pull MZM. The resulting 4ASK signals are connected to the GSG I- and Q-lines of the modulator via microwave probes. The optical insertion loss is compensated by an erbium-doped fiber amplifier (EDFA). After transmission, the signal is fed to an optical modulation analyzer (OMA). We set up a homodyne receiver by splitting the external cavity laser (ECL) output in a signal and a local oscillator (LO) path.

For the experiment, we use a Xilinx XC7VH580T FPGA on a VC7222 evaluation board. A PRBS of length 2^{31}-1 is generated on the FPGA and output by the GTH ports that are operating at 13 GBd. This symbol rate leads to an aggregate data rate of 26 Gbit/s and 52 Gbit/s for the QPSK and 16QAM formats, respectively. We measure a drive voltage of 0.28 V and 0.41 V before the bias-Ts for 2-level or 4-level signals, respectively, see Fig. 2(a). The signal quality is impeded by the power couplers, which are specified to work in the range of 1-18 GHz only.

Experimental Results

To quantify the signal quality, we generate QPSK and 16QAM signals and measure the error vector magnitude (EVM_m)[11] and the bit error ratio (BER). We record the signals with real-time oscilloscopes and perform offline signal analysis which includes post-equalization. Within our record length of 800k symbols, we do not measure any errors for the back-to-back (b2b) QPSK signal. This is in good agreement with the measured EVM_m values of 13.3 % which indicates[11] a BER well below 10^{-9}. For 16QAM transmission, we measure BER = 3.5×10^{-4} and EVM_m = 10.2 % (estimating[11] BER = 4×10^{-4}) in the b2b case. We then performed transmission experiments with fiber spans of 10 km, 50 km

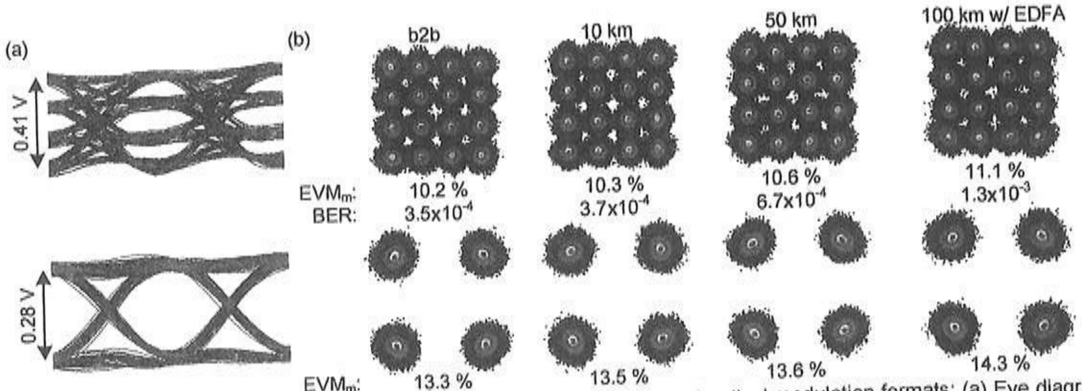

Fig. 2: Experimental results of DAC-less amplifier-less generation of advanced optical modulation formats: (a) Eye diagram for electrical drive signals for 16QAM (top) and QPSK signals (bottom), directly measured at the output of the power coupler. Drive electrical drive signals with sub-Volt peak-to-peak swings are sufficient to operate the SOH device. (b) Optical constellation diagrams of optical 16QAM (top) and QPSK (bottom) signals generated (b2b) and transmitted over fiber spans of 10 km, 50 km and 100 km length. An erbium-doped fiber amplifier (EDFA) at the receiver side was only used for a transmission distance of 100 km. The influence of transmission distance on signal quality is small: For QPSK signals, the EVM$_m$ of 14.3% after 100 km still suggests BER values well below 10^{-9}. For 16QAM, the measured BER increases from 3.5×10^{-4} to 1.2×10^{-3}, which is still below the 3rd generation FEC limit with 7 % overhead[7].

and 100 km. The results of the signal quality analysis are listed in Tab. 1, and the constellation diagrams are depicted in Fig. 2(b). An additional optical amplifier at the receiver side is used only for transmission over 100 km. For distances larger than 10 km, digital compensation of chromatic dispersion is applied. The influence of transmission on signal quality of QPSK signals is negligible, as the EVM$_m$ is still 14.3 % for a transmission distance of 100 km. No errors were found in the recording, and we estimate a BER < 10^{-9} from the EVM$_m$. Hence, we consider the signal error-free. For the transmission of 16QAM signals, there is no significant change in EVM$_m$ or BER for a 10 km fiber span. Even for transmission over up to 100 km, the BER of the 16QAM signal is 1.3×10^{-3}, still below the hard-decision limit of 4.5×10^{-3} for 3rd generation FEC coding with an overhead[7] of 7%.

Summary

We successfully demonstrated DAC-less and amplifier-less generation of higher order modulation formats by directly driving an SOH modulator from the binary outputs of an FPGA. We demonstrate error-free transmission for 26 Gbit/s QPSK signals as well as transmission of 52 Gbit/s 16QAM signals over distances of up to 100 km. In all cases, the signal quality was well within the hard decision FEC limits. These results show that SOH IQ-MZM enable direct photonic-electronic interfaces even when higher-order modulation formats are to be generated.

Tab. 1: EVM$_m$ values for QPSK and 16QAM transmission. No bit errors were measured for QPSK, and BER values relate to 16QAM signals. A receiver amplifier is used for compensating transmission losses for 100 km only.

	QPSK EVM$_m$	16QAM EVM$_m$ (BER)
b2b	13.3 %	10.2 % (3.5×10^{-4})
10 km	13.5 %	10.3 % (3.7×10^{-4})
50 km	13.6 %	10.6 % (6.7×10^{-4})
100 km	14.3 %	11.1 % (1.3×10^{-3})

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