

SOH Mach-Zehnder Modulators for 100 GBd PAM4 Signaling With Sub-1 dB Phase-Shifter Loss

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Abstract: We demonstrate 280 μm -long silicon-organic hybrid (SOH) modulators with optical phase-shifter losses of 0.7 dB and π -voltages of 1.5 V. We show OOK and PAM4 signaling at 100 GBd with a BER below the 7% HD-FEC limit. © 2020 The Author(s)

1. Introduction

Electro-optic (EO) Mach-Zehnder modulators (MZM) should combine small π -voltage U_π with small device length L , while offering low optical loss in the underlying phase shifters. These quantities are subject to various trade-offs, which can be described by two figures of merit: The π -voltage-length-product $U_\pi L$ and the loss-efficiency product $aU_\pi L$, where a is the phase-shifter propagation loss measured in dB/mm. In practical devices, it is difficult to simultaneously minimize both quantities. Recently, ultra-low loss-efficiency products of 0.5 VdB were achieved in thin-film lithium niobate (LN) modulators [1]. While this is an impressive result, the efficiency of these modulators is fundamentally limited by the low EO coefficient of LN resulting in large $U_\pi L$ products of 28 Vmm. Thus, low drive voltages can be only achieved in rather bulky, cm-long devices. The device length can be greatly reduced by using semiconductor-based MZM. On the indium-phosphide platform, MZM with $aU_\pi L$ products down to 0.9 VdB have recently been reported [2], but the $U_\pi L$ products still amount to 6 Vmm, such that sub-mm devices are hard to realize. At the other extreme, plasmonic-organic hybrid (POH) EO modulators with $U_\pi L$ products down to 0.05 Vmm have been shown [3]. These devices offer unprecedented bandwidths [4], but suffer from high absorption in the plasmonic phase shifters leading to $aU_\pi L$ products of more than 20 V dB [3]. For practical applications, a modulator technology combining low drive voltage with small optical loss along with low footprint would be highly desirable.

In this paper, we expand on our recent research [5], and show silicon-organic hybrid (SOH) MZM combining low $U_\pi L$ products of 0.41 Vmm with $aU_\pi L$ products of 1.0 VdB. The MZM have a small footprint with 280 μm long phase shifters and the optical phase shifter insertion loss amounts to only 0.7 dB. To the best of our knowledge, this is the lowest phase-shifter insertion loss reported so far for a high-speed MZM on the SiP platform. The high-speed performance of the modulator is demonstrated by generating OOK and PAM4 signals at symbol rates of 100 GBd, resulting in a line rate (net data rate) of up to 200 Gbit/s (187 Gbit/s) with a bit error ratio (BER) below the 7% HD-FEC limit. To the best of our knowledge, this is the highest PAM4 data rate so far reported with a sub-1 mm SiP modulator [6,7].

2. SOH modulator principle

Figure 1(a) shows a false-colored micrograph of an SOH MZM in top-view. The aluminum (Al) coplanar ground-signal-ground (GSG) transmission line is colored yellow, and the optical path is indicated in blue. Light is coupled to and from the SiP chip with grating couplers (GC). Two multimode interference couplers (MMI, not visible) equally split and recombine light of the two MZM arms. The photonic and metal structures are fabricated in a commercial silicon foundry, while the OEO material JRD1 [8] (green) is locally applied to the SOH MZM in a post-processing step. Figure 1(b) shows a schematic cross section of the two MZM arms at position A-A' indicated in Fig. 1(a). Each arm contains an SOH slot waveguide, which is formed by 220 nm high Si rails separated by the 130 nm wide slot. The rails are electrically connected to the transmission line by n -doped Si slabs. Both the electrical and the optical mode are highly confined to the OEO material in the slot resulting in a strong field overlap and a highly efficient phase modulation. Macroscopic EO activity is induced in a poling step, in which the OEO material is heated to the glass transition temperature and the EO chromophores are aligned by applying a poling field (green arrows) via a DC voltage U_{pol} . The orientation is preserved by removing U_{pol} only after the device has cooled down. When a radio frequency (RF) drive voltage U_d is applied, the electric fields in the slots (red arrows) point in opposite directions resulting in push-pull operation of the MZM. The smallest U_π of the poled devices amounts to 1.48 V, which results in a $U_\pi L$ product of only 0.41 Vmm. For the OEO material JRD1 used in this experiment, the glass transition temperature of 82 °C is rather low, which prevents operation at elevated temperatures. However, the chromophores may be modified by reactive side groups, which enable cross linking after the poling step. For similar classes of OEO materials, this approach increased the glass transition temperature to 250 °C [9] such that thermally induced relaxation of the poling-induced order can be neglected.

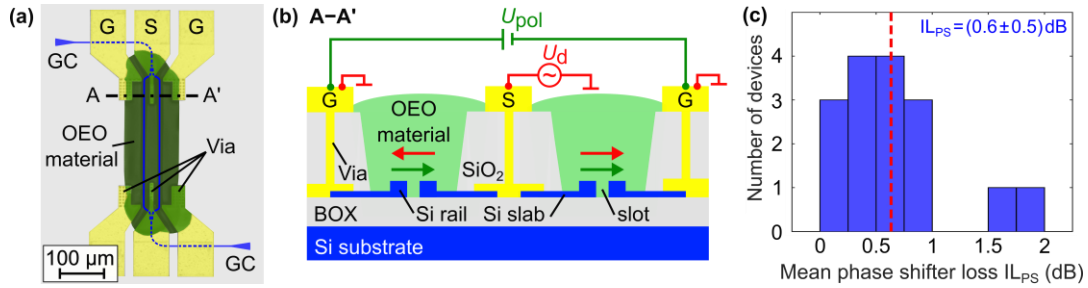


Fig. 1. SOH modulator schematic. **(a)** False-color top-view micrograph of an SOH MZM. Grating couplers (GC) and waveguides are drawn in blue, the coplanar GSG transmission line in yellow, and the OEO material in green. **(b)** Cross section A-A'. Each MZM arm contains a Si slot waveguide formed by two Si rails, which are electrically connected to the GSG transmission line by Si slabs. The slot is filled with the OEO material. The fields due to poling voltage U_{pol} and drive voltage U_d are indicated by green and red arrows, respectively. **(c)** Histogram of phase shifter loss IL_{PS} determined from 16 devices. The histogram mean amounts to 0.6 dB (red dashed line).

3. Determination of phase shifter insertion loss

To de-embed the phase shifter insertion loss, we subtract the insertion loss of the grating couplers, the feeding strip waveguides, the MMI couplers, and the strip-to-slot mode converters from the total fiber-to-fiber insertion loss. The insertion loss for the strip waveguides is calculated according to the manufacturer's specification. For all other components, we use suitable test structures on the fabricated wafer. Due to measurement inaccuracies, the calculated phase shifter insertion loss varies slightly (± 0.1 dB) in the investigated wavelength range between 1510 nm and 1580 nm. For that reason, we specify a wavelength-averaged phase shifter insertion loss IL_{PS} . To account for statistical variations, we investigate nominally identical dies from four different locations on the 8" wafer. Each die contains four SOH MZM with 280 μm-long phase shifters. A histogram with the phase shifter losses of all 16 devices is shown in Fig. 1(c). From the histogram, we obtain a phase shifter loss of $IL_{PS} = (0.6 \pm 0.5)$ dB. The rather high standard deviation is dominated by two outliers, which we attribute to the fact that the OEO material is filled into the slots by a manual process. We expect that an automated dispensing of the OEO material will improve these figures.

The currently used devices still suffer from a low doping level in the silicon slabs, which leads to high RC time constants and hence limits the bandwidth of the device. In the subsequent 100 GBd PAM-4 signaling experiments, we emulate an increased doping concentration by applying a so-called gate field between the Si substrate and the silicon device layer (colored blue in Fig. 1(b)). This induces an electron accumulation in the Si device layer and thereby increases the slab conductivity [10], but also increases the optical insertion loss of the devices by 0.8 dB for an applied gate field of 0.1 V/nm. Note, however, that this increase in insertion loss comprises the contributions of both the 280 μm-long phase shifter and the 1.3 mm-long access waveguides. Assuming approximately equal carrier-induced propagation losses in both sections, we estimate an increase of the phase shifter loss of approximately 0.14 dB, leading to a still acceptable phase-shifter insertion loss of around (0.7 ± 0.5) dB. To the best of our knowledge, this is the lowest phase-shifter insertion loss so far demonstrated for a high-speed MZM on the silicon photonic platform. Note also that the gate voltage and the associated loss can be avoided by using optimized doping profiles, which rely on high doping concentrations in the slabs outside the core region of the slot waveguide.

The phase shifter loss of $IL_{PS} = 0.7$ dB leads to a power propagation loss coefficient of 2.5 dB/mm. Based on theoretical considerations, we believe that these losses are mainly caused by surface roughness of the slot waveguides and that there is still significant potential for further reduction. In fact, slot waveguides with propagation losses down to 0.2 dB/mm were already shown [11]. With the loss coefficient of $a = 2.5$ dB/mm and the measured $U_{\pi}L$ product of 0.41 Vmm we calculate a loss-efficiency-product of $aU_{\pi}L = 1.0$ VdB.

4. Demonstration of 100 GBd PAM4 signaling

We demonstrate the high-speed performance of the modulator by generating on-off-keying (OOK) and 4-level pulse-amplitude modulation (PAM4) signals at symbol rates of 100 GBd. The experimental setup is shown in Fig. 2(a). An external-cavity laser (ECL) at 1560 nm with a power of 11.5 dBm provides the optical carrier, and an arbitrary-waveform generator (AWG) with a bandwidth of 45 GHz delivers the electrical drive signal. The signal is a pseudo random binary sequence of length $2^{11}-1$, which is mapped to OOK or PAM4 symbols with a raised-cosine spectrum (roll-off factor $\beta = 0.1$). An RF amplifier (RF amp) with 55 GHz bandwidth boosts the AWG output, which is coupled to the SOH device with a probe. An erbium-doped fiber amplifier (EDFA) compensates the loss of the GC (5.4 dB per side), and a band pass filter (BP) suppresses amplified spontaneous emission noise. With a variable optical attenuator (VOA) we adjust the power detected with a 70 GHz photodiode (PD). A real-time oscilloscope (RTO) with 63 GHz bandwidth records the PD output. The offline digital signal processing (DSP) chain includes resampling, timing recovery, blind adaptive time-domain equalization with 58 taps, and error counting.

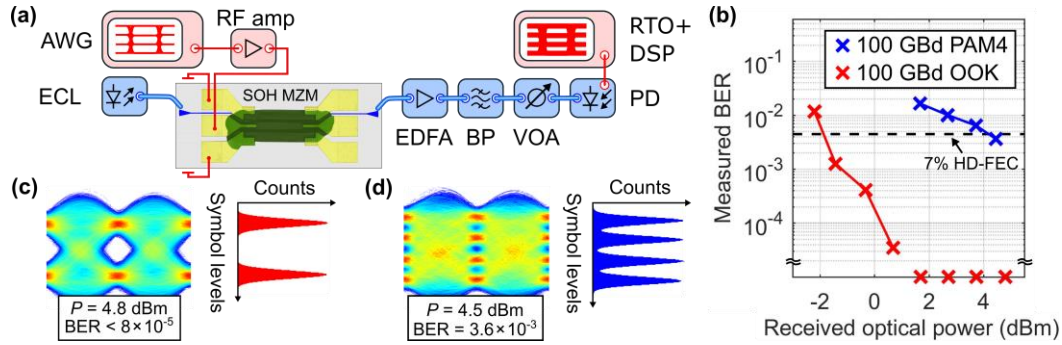


Fig.2. Data transmission experiment. (a) Experimental setup. External cavity laser (ECL), arbitrary waveform generator (AWG), RF amplifier (RF amp), erbium doped fiber amplifier (EDFA), bandpass filter (BP), variable optical attenuator (VOA), photo diode (PD), real time oscilloscope (RTO), digital signal processing (DSP). (b) Measured BER versus received optical power for 100 GBd OOK and PAM4. (c) and (d) Eye diagram and histogram for the highest received power P for OOK and PAM4.

For a gate field of 0.1 V/nm the SOH MZM has a 3 dB EO bandwidth of 40 GHz when terminating the GSG transmission line with a 50 Ω resistor. Note that the signaling experiment was done without device termination. By doing so, we gain modulation depth due to an inherent doubling of the drive voltage through reflection at the open end of the transmission line, while we sacrifice some of the device bandwidth. The peak-to-peak drive voltage amounts to 0.7 V. With a gate field of 0.1 V/nm and its corresponding overall excess loss of 0.8 dB, the used modulator has a total fiber-to-fiber insertion loss of (13.8+0.8) dB, and the phase shifter loss amounts to $IL_{PS} = (0.75+0.14)$ dB. Figure 2(b) shows the measured BER as a function of the received power. The dashed line indicates the BER threshold 4.45×10^{-3} for hard-decision forward error correction (HD-FEC) with a 7 % overhead.

For OOK and received powers > 1 dBm, we cannot detect any errors in our 12.5 μ s long recordings. For a received power of -1.4 dBm, the BER amounts to 1.2×10^{-3} , which is still well below the threshold for HD-FEC. Figure 2(c) shows that the eye-diagram for a received power of 4.8 dBm is well open as indicated by the histogram at the temporal sampling point in the center of the eye diagram. For PAM4 and a received optical power of 4.5 dBm, the BER amounts to 3.6×10^{-3} , which is just below the HD-FEC limit, see Figure 2(d) for the associated eye diagram and the histogram obtained at the sampling point in the center of the eye. To the best of our knowledge, this is the highest PAM4 data rate so far demonstrated with a sub-1 mm silicon photonic modulator [6,7].

4. Summary

We show SOH MZM with $U_{\pi}L$ products of 0.41 Vmm and $aU_{\pi}L$ products of 1.0 VdB. The compact devices have 280 μ m long phase shifters and the optical phase shifter loss amounts to only 0.7 dB. We demonstrate OOK and PAM4 signaling at 100 GBd with a BER below the 7% HD-FEC. We believe that our low-footprint devices are not only interesting for optical communications but may be also useful for applications requiring dense photonic integration of low-loss energy-efficient phase shifters such as in optical phased arrays and in the field of quantum optics.

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