

Beyond 110 GHz Silicon-Organic Hybrid Modulator

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Abstract First-time demonstration of 3dB bandwidth larger than 110GHz for a vertical silicon organic hybrid electro-optical (EO) modulator without back gating. For the same Pockels coefficient, the new configuration shows a two times reduced $V_{\pi}L$ compared to classical SOH devices.

Introduction

Electro-optical (EO) modulators with bandwidths exceeding 100 GHz are critical components for next-generation telecommunication systems [1]. Pockels materials are promising candidates for such high-speed applications due to their intrinsic femtosecond-scale response times [2]. However, integrating these materials into photonic waveguide architectures introduces bandwidth limitations. In traveling-wave modulators, optical and radiofrequency (RF) walk-off effects constrain performance. In lumped-element modulators, it is the RC time constants instead. Current state-of-the-art devices achieve bandwidths up to approximately 110 GHz [3]. Higher bandwidth, for both approaches, require material with a large ratio of the effective Pockels coefficient (r_{eff}) to the relative dielectric permittivity (ϵ_r) to facilitate shorter devices and thus reduce the device capacitance. Synthetic organic electro-optic (OEO) materials exhibit particularly favourable properties (e.g., $r_{33} \approx 300$ pm/V, $\epsilon_r \approx 5$) [4] compared to lithium niobate (LiNbO_3 , $r_{33} \approx 31$ pm/V, $\epsilon_r \approx 30$) [2] and barium titanate (BaTiO_3 , $r_{42} \approx 800$ pm/V, $\epsilon_r \approx 1000$) [5].

OEO materials can be deposited solution based enabling the integration within photonic and plasmonic slot-waveguide configurations, whereas the slots are typically <150 nm enabling phase shifters voltage length products of 0.64 V mm and 0.18 V mm [4, 6], respectively. POH devices, see Figure 1(a), comprise highly-conductive metallic slot waveguides that maximizes RF and optical field confinement [6] and offer bandwidths >500 GHz [6]. However, intrinsic plasmonic losses exceed hundreds of dB/mm leading to a $\alpha V_{\pi}L$ of 100 VdB and above [6]. Loss minimization requires gold which is not CMOS compatible. In silicon-organic-hybrid (SOH) devices (Figure 1 (b)), doped silicon is employed instead of metals to balance the trade-off between 3 dB bandwidth (i.e. ~40 GHz) and optical propagation loss (i.e. >4 dB/mm [4]). To introduce an electrical signal, a thin silicon slab rail (typically 60 nm to 70 nm) is used to connect the metals to the silicon slot waveguide. However, the thickness of this rail must be optimized to balance optical confinement, which in turn gives a larger electrical resistance. A common solution is to add a back gating voltage of hundreds of volts between the Si

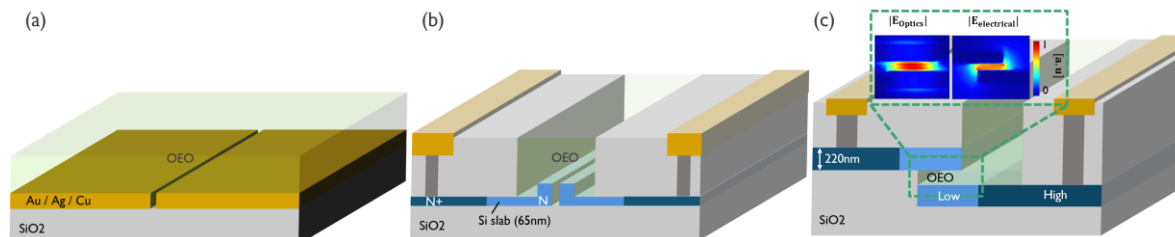


Fig. 1: (a) Plasmonic-organic hybrid modulator: metals are employed to be electrodes and slot waveguide. (b) Conventional silicon-organic hybrid (SOH) modulator: slot waveguide are made of doped silicon. (c) Our work introduces a **new configuration of a vertical SOH modulator** which allows us to break the trade-off between mode confinement and bandwidth typically associated with SOH modulators.

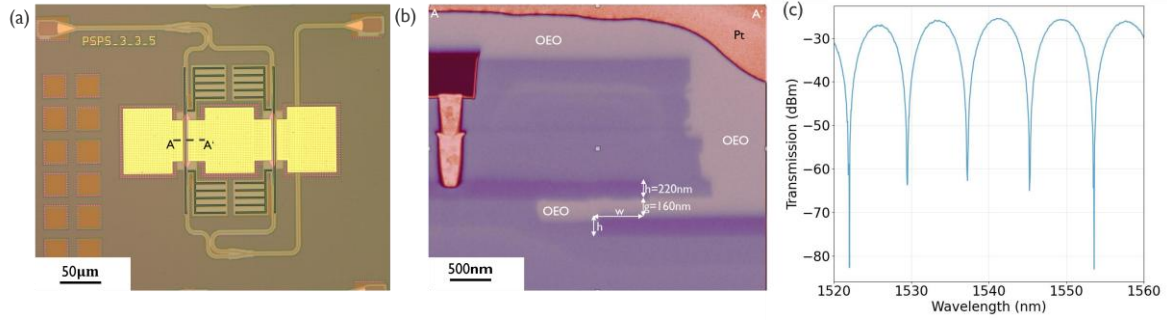


Fig. 2: (a) Top-view microscope image of an MZM with vertical SOH configuration (b) SEM cross section image of a filled slot (along A-A' line in (a)). The cross section was prepared by FIB. (c) Transmission spectrum of the filled MZM, where the losses are dominated by non-optimized doping profiles and couplers.

slab and the substrate enabling a 100 GHz bandwidth [7].

We demonstrate that switching from a horizontal to a vertical SOH device stack see Figure 1 (c) enables 1) a three-fold increased bandwidth; 2) no need for a high voltage back gating and 3) a more than two times reduced voltage length product inherent to the device architecture [8] and not originating from utilizing improved organic materials. We integrate this novel architecture in imec's 300 mm silicon photonic platform and fabricate lumped element modulators with a predicated bandwidth of 150 GHz limited by the 50ohm RF source impedance. In an initial experiment, we confirm a measured bandwidth beyond 110 GHz.

Device Fabrication

We integrated the vertical SOH phase shifter, introduced conceptionally in [9], into imec's 300mm silicon photonic platform. A fabricated device is shown in Figure 2(a). Figure 2 (b) presents a SEM cross section image of the left phase shifter arm comprising of a top polysilicon slab and a bottom crystalline silicon slab of thickness $h = 220$ nm, while the slot height is $g = 160$ nm. A highly doped region is formed for the metal connection, and a moderately doped silicon region was implemented to provide low RC-time constant. The moderately doped waveguide of width $W = 550$ nm confines the optical mode. Subsequently, the slot was filled with the organic electro-optic (OEO) material JRD-1 [3]. The OEO material forms a uniform film between the stacked silicon slabs, and no visible voids were observed within the slot. The transmission spectrum of the filled MZM is shown in Figure 2 (c). The propagation loss extracted by phase shifters cutback measurements is ~ 0.08 dB/μm, this is almost an order of magnitude smaller compared to POH modulators. While the latter are inherently limited by ohmic losses, further loss optimization of the SOH modulator is possible without significant reduction in bandwidth.

Measurement Result

Following the filling, the poling of the left arm of the 50 μm MZM is performed near the glass transition temperature (82 °C of JRD-1). After poling, we perform a fiber-to-fiber measurement, see Figure 3(a), while applying a 600 kHz 3 V AC signal to extract the $V_{\pi}L$ and Pockels coefficient. Figure 3(b) shows the photodetector signal projected onto the transmission spectrum of the device under test (DUT). The measured phase shift of 37.3° corresponds to a single arm $V_{\pi}L$ of 720 Vμm and an extract Pockels coefficient ~ 115 pm/V. Note, that JRD1 has reported Pockels coefficients of ~ 390 pm/V [4] and for different devices we achieved in-device pockels coefficients of 240 pm/V with a measured a $V_{\pi}L$ of ~ 375 Vμm [8] which is 40% less than the state of the art in the horizontal device configuration [3].

We then characterized the small signal EO bandwidth (S_{21} parameter) of the DUT using a VNA, Keysight N5222B, with a frequency extender (up to 110 GHz), Keysight N5293AX03 and a Lightwave component analyzer (LCA), Keysight N4372. The measured record 3 dB EO bandwidth of the device is greater than 110 GHz (Figure 3(c)) and at least twice as high as horizontal SOH modulator that are not utilizing back gating [4]. The estimated EO bandwidth from simulation based on the measure sheet resistance is 150 GHz

Conclusion and Outlook

This was the first demonstration of a 3dB EO bandwidth >110 GHz of a vertical configured SOH modulator. While the required π voltage of ~ 14.5 V is large, one should keep in mind operating the device in push pull and achieving higher poling efficiencies should reduce the drive voltage to approximately 2 V. Phase shifter propagation loss of ~ 4 dB is dominated by the non-optimized doping profile and the usages of a poly-

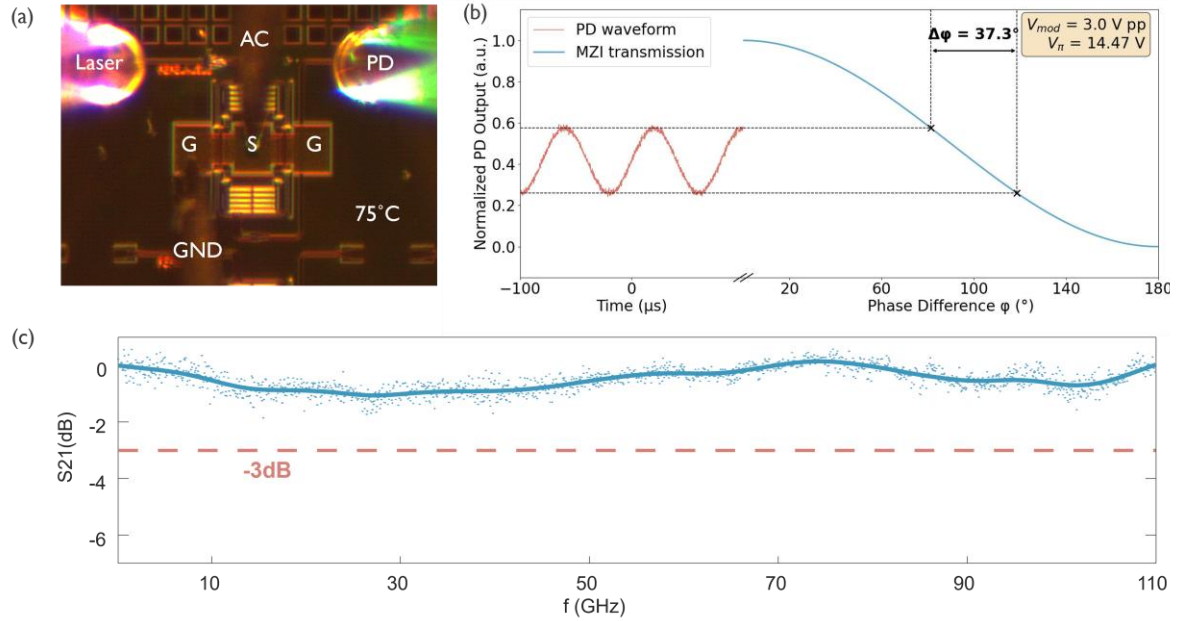


Fig. 3: (a) shows the DUT and measurement configuration of poling the OEO material with $V_{\pi}L$ extraction. (b) shows the projection of the modulated signal from the photodetector to the transmission spectrum of MZI in linear scale. The measured $V_{\pi}L$ of the device is $\sim 720 \text{ V}\mu\text{m}$. (c) shows the EO bandwidths (S_{21} parameter) of the MZM with lengths of $50 \mu\text{m}$. The 3 dB bandwidth of the device is beyond the measurement limit of the VNA (**110 GHz**).

silicon top slap that has intrinsically higher resistivity than crystalline silicon.

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