

Vertical Silicon Organic Hybrid (SOH) Modulators for Record Low $V_{\pi}L$ of $375V\mu m$

Conglin Sun^{1,2*}, Michiel Debaets^{1,3*}, Minkyu Kim¹, Chiara Marchese¹, Adam Barzanji^{1,3}, Peter Verheyen¹, Pol Van Dorpe^{1,2}, Francky Catthoor^{1,4}, Wim Bogaerts^{1,3}, Joris Van Campenhout¹, Christian Haffner^{1**}

**Authors contributing equally*

imec Kapeldreef 75, Leuven, B-3001, Belgium

2 Department of Physics and Astronomy Research unit Quantum Solid-State Physics KU Leuven, Leuven B-3001, Belgium

3 Department of Information Technology (INTEC), Photonics Research Group, Ghent University; B-9052 Ghent, Belgium

4 Zografou Campus National (Metsovian) Technical University of Athens 9, Iroon Polytechniou str15772 Zografou

Abstract: Demonstration of a vertical stack SOH phase shifter with record low voltage length product of $375 V\mu m$ achieved by enhancing the electro-optical interaction factor to near 50 percent.

1. Introduction

Organic electro-optic (OEO) materials exhibit extremely high Pockels coefficients (>300 pm/V) [1]. When integrated within ~ 100 nm wide slot waveguides, they achieve the highest modulation efficiency per length among phase modulators, corresponding to the smallest $V_{\pi}L$ [2]. The low permittivity of organic EO materials also minimizes device capacitance, supporting high modulation bandwidths. Two main platforms dominate organic electro-optic (EO) modulators: Silicon-Organic Hybrid (SOH) [1] and Plasmonic-Organic Hybrid (POH) [3]. Both use slot waveguides but differ in electrode materials—SOH employs doped silicon, while POH uses metals. SOH offers Complementary Metal-Oxide-Semiconductor (CMOS) compatibility and low optical loss, though its $V_{\pi}L$ of $640 V\mu m$ with the configuration in Figure 1 (a) is typically larger than that of POH device ($V_{\pi}L$ of $140 V\mu m$) using the same material (JRD-1 [1]).

We demonstrate a novel SOH architecture (Figure 1 (b)) featuring a vertically stacked slot waveguide formed by two doped silicon slabs (220 nm) and JRD-1 based on our conceptional work [5]. We experimentally confirm that this design improves the EO interaction factor from $\sim 20\%$ to $\sim 50\%$ reducing the $V_{\pi}L$ to a record low $375 V\mu m$ two times lower than state-of-the-art [1].

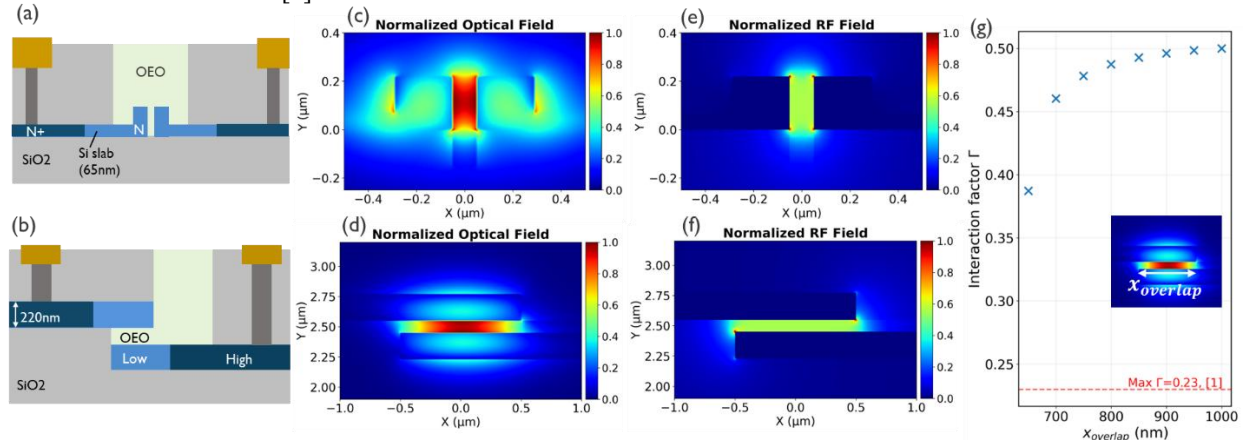


Figure 1(a) Conventional SOH configuration. (b) vertical stack SOH configuration with the slab thickness of 220 nm and the slot gap of 160 nm. (c), (d) normalized optical field of both configurations. (e), (f) normalized RF field of both configurations. (g), (h) cosine value of angle between optical and RF field.

2. Analysis

The waveguide geometry impacts the $V_{\pi}L$ most dominantly with the electro-optical interaction factor (Γ) as $V_{\pi}L \propto \Gamma^{-1}$ [1]. Γ is largest when electrical and optical field are confined and interacting within the electro-optical material in the slot waveguide. Figure 1(c) – (f) show the simulation results of the RF field and the optical field of both conventional configuration and our new vertical stack. In conventional slot waveguide designs, high-index silicon rails tend to attract optical energy away from the slot region, where the RF field is nearly absent, leading to reduced electro-optic interaction. This optical leakage significantly limits modulation efficiency because the overlap between the optical and RF fields is compromised. The vertical stack configuration effectively addresses this issue by maintaining strong optical confinement within the slot, thereby maximizing the spatial overlap with the RF field. As a result, this architecture enhances modulation efficiency without sacrificing optical mode integrity.

Figure 1 (g) presents the simulated interaction factor Γ formalism defined in [1] (see the page footer of page 2 for the equation). The vertical stack configuration, demonstrating an increase in optical–RF overlap with Γ approaching 50%. For comparison, the state-of-the-art Γ of the conventional configuration is reproduced using the same equation and plotted by the red line in Figure 1(g). The results clearly illustrate a substantial improvement, with Γ rising from approximately 20 % to nearly 50 % when employing vertical stack architecture.

3. Device and Measurement

Asymmetric Mach–Zehnder modulators (MZMs) were fabricated using IMEC’s 300 mm silicon photonics pilot line based on the phase shifter concept introduced in [5]. Figure 2 (a) and (b) show the top Scanning Electron Microscope (SEM) of one MZM and its optical transmission spectrum. Figure 2 (c) shows a focused ion beam (FIB) cross section SEM image of one phase-shifter arm, which consists of a top polysilicon slab and a bottom crystalline silicon slab with a thickness of $h = 220 \text{ nm}$. The slot between them has a height of $g = 160 \text{ nm}$, width of 750 nm, and is filled with the OEO material JRD-1. The OEO material forms a uniform layer beneath the platinum coating from the inspection. FIB cross section SEM and optical inspection revealed no voids inside the slot, confirming successful EO material integration with the device. A low frequency (100 kHz) AC voltage of 20 V was applied to one arm of a $30 \mu\text{m}$ MZM after poling of that phase shifter. As shown in Figure 2 (d), an overmodulation of the optical transmission can be observed. We extract V_π of 12.5 V which leads to a $V_\pi L = 375 \text{ V}\mu\text{m}$ while the state of the art has a $V_\pi L$ of $640 \text{ V}\mu\text{m}$ for a phase shifter [1]. Note, the extract Pockels coefficient is around 240 pm/V, which is comparable to the r_{33} reported in [1].

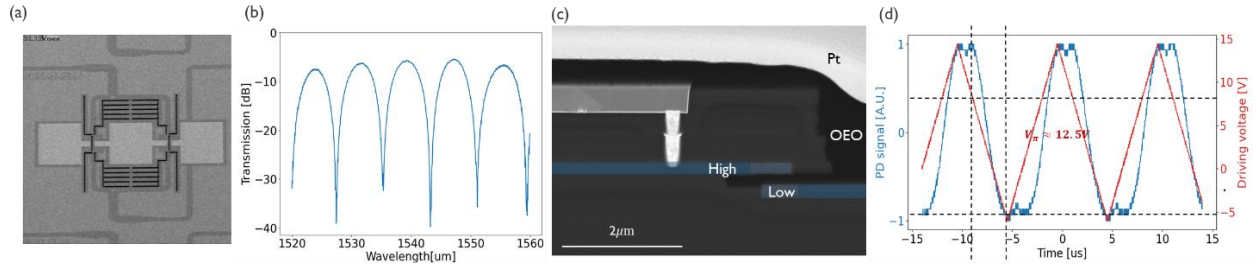


Figure 2 (a) Top SEM of the fabricated MZM. (b) Measured transmission of the fabricated MZM (c) Cross SEM of one arm of the fabricated MZM with OEO material filled in between silicon slabs. (d) The V_π measurement result on one arm MZM

4. Conclusion & Outlook

We demonstrated a new vertical stacked SOH device configuration that can lower the $V_\pi L$ of SOH phase shifter by around 50% to $375 \text{ V}\mu\text{m}$. The value can be further improved by optimizing the poling of JRD-1 and introducing OEO material with higher Pockels coefficient. Besides, it is also offering a larger bandwidth by lowering the resistance of silicon slabs by increasing the thickness from 65 nm to 220 nm [5]. It provides opportunities for SOH to compete with POH in modulation efficiency and bandwidth, while the propagation losses are in a more affordable region compared to the POH approach [5].

Acknowledgment

We acknowledge the collaboration with NLM Photonics providing the organic electro-optics material.

Reference

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$$\Gamma = \left(\frac{\epsilon_0 c n_{mat}}{2P} \cdot \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{\rho(x, y)}{|E_{RF}|_{slot} \cdot \frac{U}{g}} \cdot \left(\vec{E}_{RF}(x, y) \cdot \vec{E}_{opt}(x, y) \right)^2 dx dy \right)^{-1}$$

vacuum permittivity - ϵ_0 , the speed of light c , and the n_{mat} , normalized by the optical power P . The double integral evaluates the spatial overlap between the RF and optical fields, weighted by $\rho(x, y)$, which equals unity inside the EO material and zero elsewhere. The term $\vec{E}_{RF}(x, y) \cdot \vec{E}_{opt}(x, y)$ captures the vectorial alignment of the fields, while U/g corresponds to the applied voltage normalized by the electrode gap.