Electro-optic phase modulators based on transparent-conducting-oxide loaded silicon waveguides

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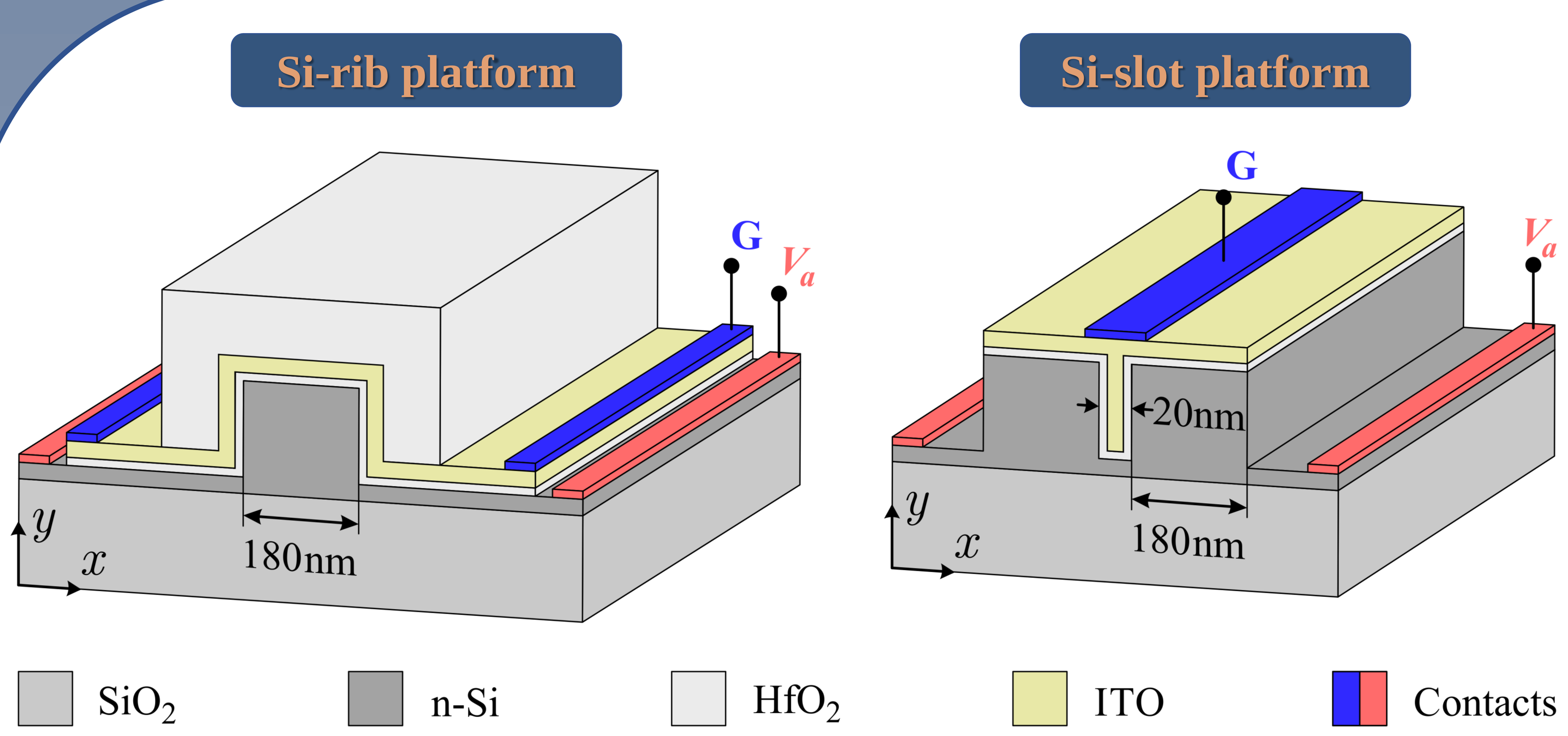
I Introduction

- **Objective** → Impress an electrical signal onto the phase of an optical carrier towards realizing **on-chip electro-optical phase-modulation schemes.**
- **Motive** → Achieve **more advanced and sophisticated** modulation formats compared to the more frequently employed amplitude modulation solutions.
- **Design** → Exploit the **epsilon-near-zero (ENZ) behavior of transparent conducting oxides (TCOs)** in the near-infrared (NIR) [1] along with well-established **silicon-waveguide platforms.**

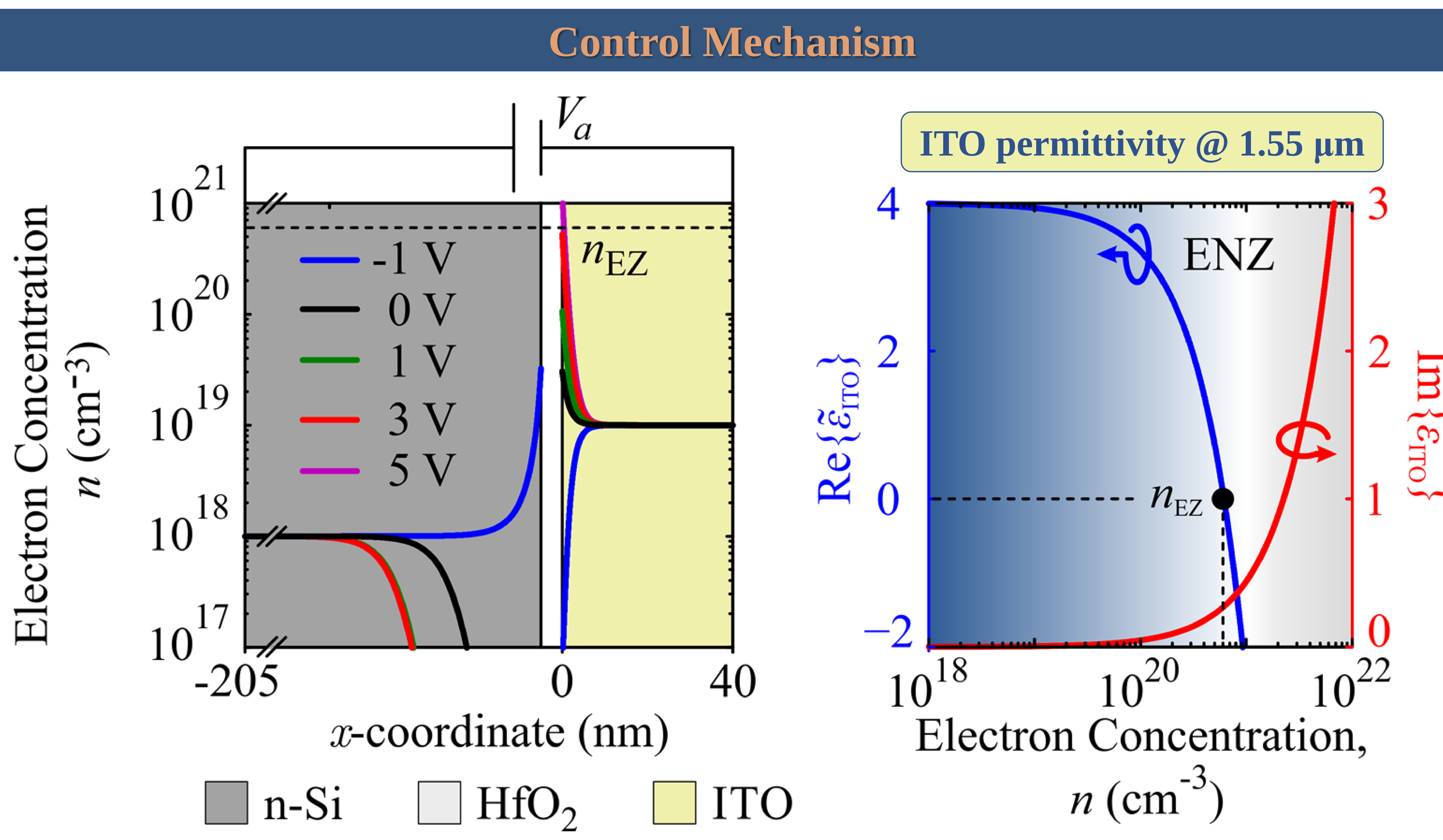
II Physical platforms



❖ In both platforms, the waveguide is conformally coated by two successive layers of **HfO$_2$ (5 nm) & ITO (10 nm),** forming a capacitor-like structure for controlling the ITO properties through the **field-effect**.

- **Si-rib platform:** **Weak-waveguiding conditions** are adopted for the fundamental TE-mode in order to enhance the interaction with the superimposed ITO layer. The waveguide is cladded on top by a lossless 200-nm thick HfO$_2$ layer, aiding waveguiding.
- **Si-slot platform:** **Strong-waveguiding conditions,** enhancing the light-matter interaction in the 20-nm wide slot.

Control Mechanism



- **Field-effect** induced carrier-concentration changes in ITO modulate its NIR permittivity, as described by the **Drude model** [2].
- An initial **10^{19} cm^{-3}** free-electron concentration is selected for the ITO layer.
- At **n_{EZ} = 6.17 x 10^{20} cm^{-3}**, ITO crosses into the ENZ region for a threshold bias equal to **V_a ~ 3 V**.

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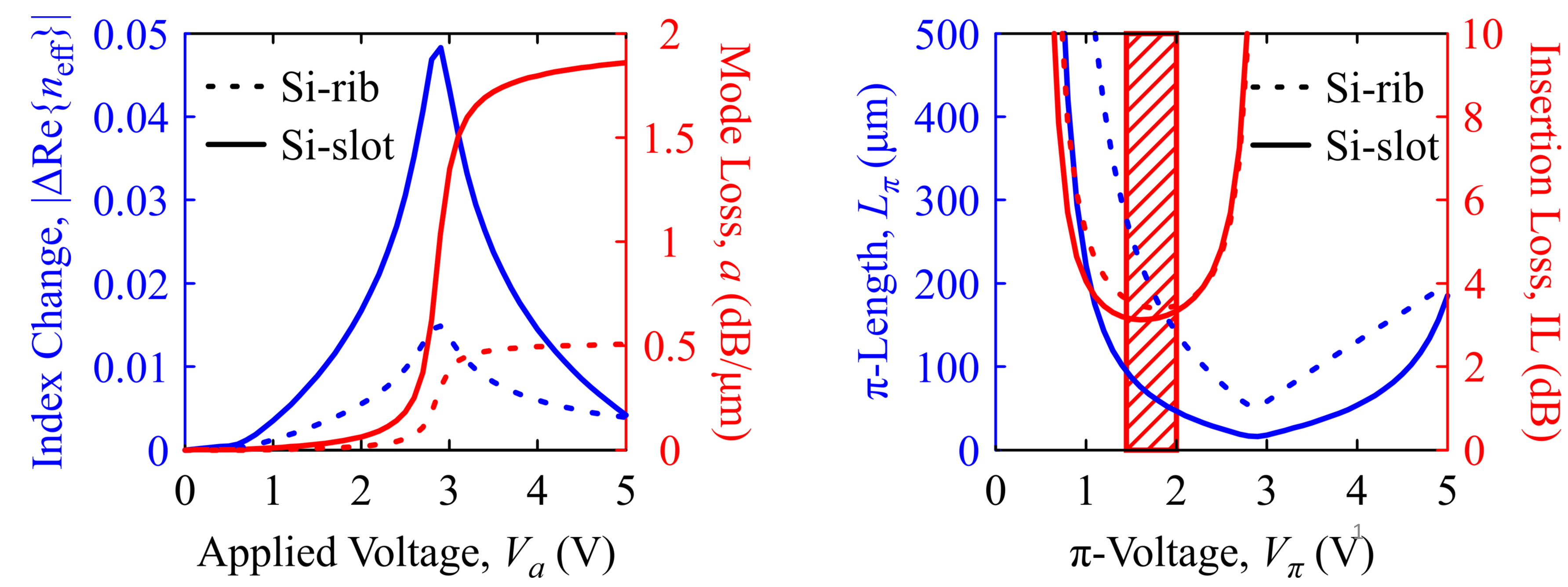
III Methods & Results

Finite Element Method (FEM) Computational Framework

Solid-State Physics — Electron Concentration, n → **NIR Material Models** — Dielectric permittivity $\tilde{\varepsilon}(n)$ → **Wave Physics Maxwell Equations**
- Eigenmode Solver
- Re{n_{eff}} → Phase Shift
- Im{n_{eff}} → Mode Loss

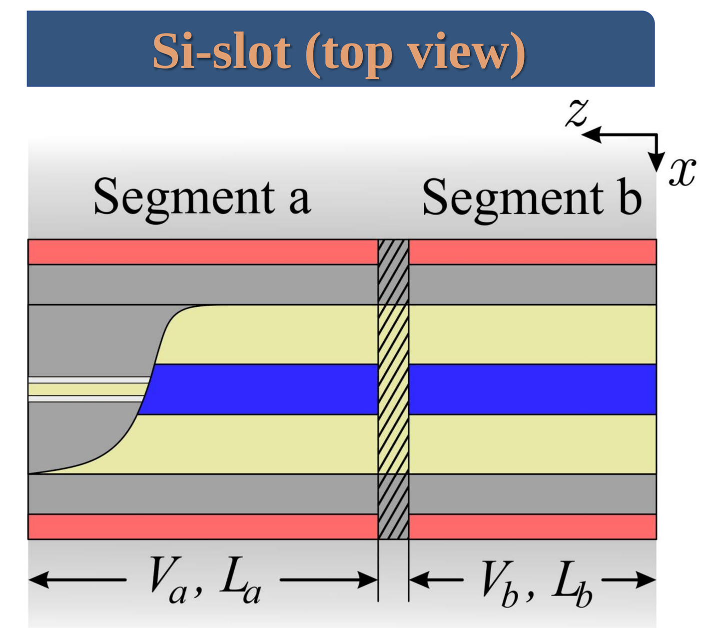


- **The mode loss maintains high values for V_a > 3 V** due to the ENZ effect → already investigated for amplitude modulation formats [3].
- The change of the effective mode index shows a peak at **V_a ~ 3 V,** where Re{$\tilde{\varepsilon}_{ITO}$} → 0.
- **The Si-slot platform achieves enhanced ENZ performance** as a result of the increased light-matter interaction in the slot.
- For both designs, **the total IL** for achieving a π-phase shift obtains its minimum value at **V_a ~ 1.5 V**, calculated **in the order of 3 dB.**
- The **Si-slot** platform demands less than a half length for achieving the π-phase shift, compared to its **Si-rib** counterpart **(76 μm vs 176 μm)**.
- Shorter π-lengths can be achieved, reaching a low at **V_a ~ 3 V,** though with a high penalty on the total IL.

BPSK & QPSK Modulation Formats

- A **BPSK modulator** can be directly realized by **equalizing the loss levels of a π-phase shifter**. This is achieved by combining **a couple of independently controlled** waveguide segments in cascade architecture, separated by an electrically insulating and arbitrarily long junction.
- The same design allows for implementing **QPSK modulation formats** as well.

Si-slot (top view)



BPSK

IL = 3.2 dB	
L_a (μm)	L_b (μm)
79.2	1.3
V_a (V)	V_b (V)
0.0	5.0
1.5	0.0

QPSK

IL = 4.7 dB	
L_a (μm)	L_b (μm)
118.7	2.0
V_a (V)	V_b (V)
0.00	5.00
0.85	2.96
1.18	2.76
1.50	0.00

IV Conclusions

SOI-based phase modulators are presented by exploiting free-carrier effects in TCO semiconductors. The proposed designs provide very reduced footprints, **outcompeting their conventional, mm-long, silicon counterparts**[4], experiencing ultra-high switching speeds and a pJ/bit energy consumption [3].

V References

[1] E. Feigenbaum, et al., Nano Lett., vol. 10, pp. 2111-2116, 2010.
[2] V. E. Babicheva, et al., Nanophotonics, vol. 4, pp. 165-185, 2015.
[3] G. Sinatkas, et al., J. Appl. Phys., vol. 121, 2017.
[4] A. Liu, et al., Nature, vol. 427, pp. 615-619, 2004.