Silicon-photonic electro-optic modulators based on graphene and epsilon-near-zero materials

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Introduction
- State-of-the-art
- Motivation & Main objectives

Materials & Platforms
- Transparent conducting oxides (TCOs)
- Graphene
- Physical systems

Waveguide amplitude modulators
- Methods
- TCO-based in-line modulators
- Graphene in-line modulators

Resonator amplitude modulators
- Methods
- TCO-based resonator modulators
- Graphene resonator modulators

Summary & Conclusions
State-of-the-art, Motivation & Main objectives

Introduction
State-of-the-art on TCO-based modulators

Melikyan, *Optics Express* **19**, 8855-8869, 2011


Lee, *Nano Lett.* **14** (11), 6463-6468, 2014


State-of-the-art on Graphene modulators


Sorianello, *Optics Express* **23**(5), 6478-6490, 2015
Motivation & Main objectives

**Motivation**

- Demand for high-performing nanophotonic modulators, envisioned by advances in materials science
- Addressable & versatile TCO properties in the near-infrared (NIR)
- Tunable NIR graphene properties along with its two-dimensional (2D) nature

**Main Objectives**

- Rigorously design high-end TCO-loaded & graphene modulators on silicon-photonics platforms, based on either in-line or resonator modulation schemes using computationally efficient tools
- Performance comparison between TCO- & graphene-loaded modulators, highlighting the conditions for increasing the interaction between the dynamically configurable medium & the guided wave
TCOs, Graphene, Physical systems

Materials & Platforms
Transparent conducting oxides (TCOs) (I)

- **Compounds of metals and oxides** e.g. ITO (Indium Tin Oxide), AZO (Aluminum Zinc Oxide)
- **Highly conductive** ($n\mu_n \uparrow$) & **transparent** ($E_g \sim 3\text{eV}$) in the visible & near-infrared (NIR) spectrum
- **Tailored** electrical & optical properties by controlling the fabrication conditions

- **Epsilon-near-zero (ENZ) values in NIR**
  - Drude permittivity function
  - Plasma frequency $\omega_p$ lies in the NIR region
  \[ \text{Re}\{\varepsilon(\omega_p)\} \approx 0 \text{ in the NIR} \]

\[ \varepsilon(\omega_0, n) = \varepsilon_{\text{opt}} \left(1 - \frac{\omega_p^2}{\omega_0^2 - j\Gamma\omega_0}\right) \]

\[ \omega_p(n) \sim \sqrt{\frac{n}{\varepsilon_{\text{opt}}}} \]

<table>
<thead>
<tr>
<th>Material</th>
<th>$n$ (cm$^{-3}$)</th>
<th>$\lambda_p$ (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>$5.86 \times 10^{22}$</td>
<td>0.14</td>
</tr>
<tr>
<td>ITO</td>
<td>$6.17 \times 10^{20}$</td>
<td>1.55</td>
</tr>
<tr>
<td>n-InSb</td>
<td>$4.00 \times 10^{18}$</td>
<td>14.0</td>
</tr>
</tbody>
</table>
Transparent conducting oxides (II)

**ENZ Effect** → Transformation of a conventional nanophotonic mode to a highly confined mode in the ENZ layer (electric-field enhancement due to the discontinuous permittivity profile).

**ENZ Condition** → Principal polarization normal to the TCO layer

**Modulation principle** → Modulate the TCO permittivity by changing the free-carrier concentration in the TCO through changes in its Fermi level

- **ON state** → Dielectric region, $n_{on} = 10^{19} \text{ cm}^{-3}$
- **OFF state** → ENZ region, $n_{off} \sim 6 \times 10^{20} \text{ cm}^{-3}$
Graphene

- **Two-dimensional (2D) material** → atomic layer of graphite

- Graphene is modelled as a **surface current**, $J_s = \hat{n} \times (H_2 - H_1) = \sigma E ||$ → interaction with tangential electric field components

- Unique **optical** properties described by its **surface conductivity** $\sigma$ → contribution from both interband & intraband transitions

- Energy band diagram → Dirac cone, $E_g = 0$

- Fermi level $E_f$ → surface carrier density

\[
\sigma = \sigma_{\text{intra}} + \sigma_{\text{inter}}
\]

\[
\sigma_{\text{intra}}(E_f) = \frac{-je^2 k_B T}{\pi \hbar^2 (\omega - j/\tau_1)} \left[ \frac{E_f}{k_B T} + 2 \ln(e^{-E_f/k_B T} + 1) \right]
\]

\[
\sigma_{\text{inter}}(E_f) = \frac{-je^2}{4\pi \hbar} \ln \left[ \frac{2|E_f|-\hbar(\omega - j/\tau_2)}{2|E_f|+\hbar(\omega - j/\tau_2)} \right] \quad \tau_1 \approx 10 \text{ fs} \\
\tau_2 \approx 1.2 \text{ ps}
\]

Hanson, *J. Appl. Phys.* **103**, 064302, 2008
Graphene

\[ J_s = J_{s,\text{intra}} + J_{s,\text{inter}} = (\sigma_{\text{intra}} + \sigma_{\text{inter}})E_{\|} \]

- **Symmetric** change around Dirac point \((\mu_C = 0)\)

- **Step behavior** for \(\text{Re}\{\sigma\}\) at \(E_f = \pm 0.4\ \text{eV} \) & \(\lambda = 1.55\ \mu\text{m}\)

- **Modulate surface conductivity by tuning** \(E_f\)

\[ \sigma = \sigma_{\text{intra}} + \sigma_{\text{inter}} \]
Materials & Platforms

Physical systems (I)

- $10^{18}$ cm$^{-3}$ n-doped Si
- Thin layer (5 nm) of high-k dielectric (HfO$_2$) → energy consumption reduction
- $10^{19}$ cm$^{-3}$ ITO layer (10 nm)

- Modulation mechanism: Externally applied bias $V_a$ attracts/repels carriers, forming accumulation/depletion layers due to the electric field developed in capacitor-like formed structures (field effect) →
  - Semi/Insulator/Semi (SIS)
  - Graphene/Insulator/Graphene (GIG)

- GIG structure → uniform change in $\sigma$, graphene effect enhancement
- Graphene workfunction, $W_f = 4.5$ eV
- Metal contacts → Ideal ohmic
Physical systems (II)

\[-\nabla \cdot (\varepsilon_0 \varepsilon_r \nabla \phi) = \rho = q(N_D^+ - n)\]

\[n = 2 \left( \frac{m^*_n}{2\pi \hbar^2} \right)^{3/2} F_{1/2}(E_f)\]

\[J_n = -q\mu_n n \nabla \phi + qD_n \nabla n\]

\textbf{Semi/Insulator} \quad \phi = \text{cont.}, \quad \hat{n}J_n = 0

\[n_s = \frac{2}{\pi \hbar^2 v_F^2} \left[ F_1(E_f) + F_1(2E_f) \right]\]

\[E_f \gg k_B T \rightarrow |n_s| = \frac{(q\phi)^2}{\pi (\hbar v_F)^2}\]

\[F_i(E_f) = \frac{1}{\Gamma(i+1)} \int_0^\infty \frac{x^i dx}{1 + e^{(x-E_f)/k_B T}}\]

\[\Gamma(n) = (n-1)!\]

Sinatkas, J. Appl. Phys. 121 (2), 023109, 2017
Hanson, J. Appl. Phys. 103, 064302, 2008
Fang, Appl. Phys. Lett. 91, 092109, 2007
Physical systems (II)

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Fang, Appl. Phys. Lett. 91, 092109, 2007
Methods, TCO-based & graphene in-line designs

Waveguide amplitude modulators
Methods

Finite Element Method (FEM) Platform

Solid-State Physics
- Electrostatic calculations of
  - Electron concentration $n$ in TCOs
  - Fermi level $E_f$ in graphene

Wave Physics
- Maxwell Equations
  - Conventional 2D eigenmode solver
  - $\text{Im}\{n_{\text{eff}}\} \rightarrow$ Mode Loss

NIR Material Models
- TCOs $\rightarrow$ Dielectric permittivity $\tilde{\varepsilon}(n)$
- Graphene $\rightarrow$ Surface conductivity $\sigma(E_f)$
TCO-based in-line modulators – TE operation

- SiO₂
- n-Si
- HfO₂
- ITO
- Contacts

Waveguide AMs

<table>
<thead>
<tr>
<th>x-coordinate (nm)</th>
<th>y-coordinate (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-150 - 150</td>
<td>0 - 250</td>
</tr>
</tbody>
</table>

$|E_x|_{TE}$

$|E_y|_{TE}$

Electric field, $|E_x|$ (a.u.)

Electric field, $|E_y|$ (a.u.)

Electron concentration, $n$ (cm$^{-3}$)

NIR permittivity, Re{$\varepsilon$} (a.u.)

$N_{E2} = 6.2 \times 10^{20}$ cm$^{-3}$

Re{$\varepsilon$} = 0

ENZ effect

Electric-field peak shift
TCO-based in-line modulators – TE operation

- \( w \times h = 180 \text{ nm} \times 220 \text{ nm} \),
- \( t_h = t_w = 150 \text{ nm} \)

\[ n < n_{EZ} \quad \text{for} \quad V_a < V_{th} \approx 3 \text{ V} \]
\[ n > n_{EZ} \quad \text{for} \quad V_a > V_{th} \approx 3 \text{ V} \]

Sinatkas, J. Appl. Phys. 121 (2), 023109, 2017
TCO-based in-line modulators – TE operation

- Waveguide AMs
  - \( w \times h = 180 \text{ nm} \times 220 \text{ nm} \),
  - \( t_h = t_w = 150 \text{ nm} \)
  - \( \text{ER} = 0.35 \text{ dB/μm}, \text{IL} = 3 \times 10^{-3} \text{ dB/μm} \)

Sinatkas, *J. Appl. Phys.* **121** (2), 023109, 2017
TCO-based in-line modulators – TM operation

- $w \times h = 400 \text{ nm} \times 20 \text{ nm}$,
  - $t_h = 300 \text{ nm}$ $t_w = 150 \text{ nm}$
- ER = 0.29 dB/μm, IL = 3 x 10^{-3} dB/μm

Sinatkas, *J. Appl. Phys.* **121** (2), 023109, 2017
Graphene in-line modulators – TE operation

- \( w \times h = 340 \text{ nm} \times 220 \text{ nm} \)
- \( \text{ER} = 0.23 \text{ dB/µm}, \text{IL} = 0.02 \text{ dB/µm} \)
Graphene in-line modulators – TE operation

- $w \times h = 340 \text{ nm} \times 220 \text{ nm}$
- ER = $0.23 \text{ dB/\mu m}$, IL = $0.02 \text{ dB/\mu m}$
Graphene in-line modulators – TM operation

- $w \times h = 450 \text{ nm} \times 260 \text{ nm}$
- ER $= 0.28 \text{ dB/μm}$, IL $= 0.02 \text{ dB/μm}$
TCO-based & Graphene in-line modulators for ER = 10 dB

<table>
<thead>
<tr>
<th>Platform</th>
<th>Mode</th>
<th>$w \times h$ (nm x nm)</th>
<th>$L$ (µm)</th>
<th>IL (dB)</th>
<th>Bias swing</th>
<th>Intrinsic BW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TE</td>
<td>180 x 220</td>
<td>29</td>
<td>0.10</td>
<td>0 V ↔ 4 V</td>
<td>~ 150 GHz</td>
</tr>
<tr>
<td></td>
<td>TM</td>
<td>400 x 200</td>
<td>34</td>
<td>0.10</td>
<td>0 V ↔ 4 V</td>
<td>~ 150 GHz</td>
</tr>
<tr>
<td></td>
<td>TE</td>
<td>340 x 220</td>
<td>43</td>
<td>0.86</td>
<td>0.5 V ↔ 2 V</td>
<td>Externally limited</td>
</tr>
<tr>
<td></td>
<td>TM</td>
<td>450 x 260</td>
<td>35</td>
<td>0.78</td>
<td>0.5 V ↔ 2 V</td>
<td></td>
</tr>
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Methods, TCO-based & graphene resonator designs

Resonator amplitude modulators
Methods (I)

**FEM Platform**

**Solid-State Physics**
- Electrostatic 2D calculations of
  - Electron concentration $n$ in TCOs
  - Fermi level $E_f$ in graphene

**NIR Material Models**
- TCOs $\rightarrow$ Dielectric permittivity $\tilde{\epsilon}(n)$
- Graphene $\rightarrow$ Surface conductivity $\sigma(E_f)$

**Coupled Mode Theory (CMT)**
- Calculate the power transmission $T$

**Wave Physics**
- **Maxwell Equations**
  - Axisymmetric 2D eigenmode solver
  - $n_{\text{eff}}$ of the bent waveguide
Resonator AMs

Methods (II) – Axisymmetric eigenmode solver

**Resonator radius**

\[ R = \frac{m\lambda_0}{2\pi \text{Re}\{n_{\text{eff}}\}} \]

- \( m \rightarrow \) azimuthal mode order
- \( \lambda_0 \rightarrow \) resonance wavelength

**Quality factor**

\[ Q_i = \frac{\pi n_g L \sqrt{a}}{\lambda_0 (1-a)} \]

- \( n_g = \text{Re}\{n_{\text{eff}}\} - \lambda_0 \frac{d \text{Re}\{n_{\text{eff}}\}}{d\lambda} \rightarrow \) group index

- \( L = 2\pi R \rightarrow \) resonator circumference

- \( a = \exp\left\{-\frac{2\pi}{\lambda_0} \text{Im}\{n_{\text{eff}}\} L\right\} \rightarrow \) round-trip loss (resistive + radiation)

---

**Axisymmetric calculations**

- Downgrades complex geometries
- Computationally cheap
- Highly accurate

- EM field calculated using transformation optics → \( n_{\text{eff}} \) of the bent waveguide


Methods (III) – Coupled Mode Theory (CMT)

![Diagram of a resonator system with equations]

**Steady-state response**

\[
T \equiv \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{\delta^2 + (1-r_Q)^2}{\delta^2 + (1+r_Q)^2}
\]

\[\delta = \tau_i (\omega - \omega_0) \rightarrow \text{normalized detuning}\]

\[r_Q = Q_i/Q_e \rightarrow \text{quality factor ratio}\]

**Low-power state**

- Select low-loss state
- Input wave on resonance, \( \delta = 0 \)
- Admit gap for critical coupling, \( Q_i^{\text{low}} = Q_e \Leftrightarrow r_Q = 1 \)
- \( T_{\text{low}} = 0 \)

**High-power state**

- Modify resonance frequency, \( \text{Re}\{n_{\text{eff}}\}, \text{and losses}, \text{Im}\{n_{\text{eff}}\} \)
- Input wave (commonly) out of resonance, \( \delta \neq 0 \)
- Same gap \( \rightarrow \) impair critical coupling, \( Q_i^{\text{high}} < Q_i^{\text{low}} = Q_e \)
- \( T_{\text{high}} \gg 0 \)

\[ER = 10 \log \frac{T_{\text{high}}}{T_{\text{low}}} \rightarrow \infty\]
\[IL = 10 \log T_{\text{high}} \rightarrow 0\]

\(\tau_i\) – cavity amplitude, \(|a|^2 \equiv W\)

\(\omega_0\) – unperturbed resonance frequency

\(\tau\) – photon lifetime, \(\tau = 2Q/\omega_0\)

\(\mu\) – coupling coefficient, \(\mu = j\sqrt{2/\tau_e}\)

\(s(t)\) – w/g mode amplitude, \(|s|^2 \equiv P\)

Little, J. Lightwave Technol. 15 (6), 998 - 1005, 1997

Christopoulos, Phys. Rev. E 94 (6), 062219, 2016
TCO-based resonator modulators – TE operation

- $w \times h = 220 \text{ nm} \times 220 \text{ nm}$, $t_h = t_w = 150 \text{ nm}$
- Critical coupling at zero bias (low losses)
- Detuning + change in loss level

\[ \lambda_{\text{res}} = 1.550 \mu\text{m} \]
\[ \text{ER} \rightarrow \infty, \text{IL} = 0.03 \text{ dB} \]
TCO-based resonator modulators – TE operation

- $w \times h = 220 \text{ nm} \times 220 \text{ nm}$, $t_h = t_w = 150 \text{ nm}$
- Critical coupling at zero bias (low losses)
- Detuning + change in loss level

$\lambda_{\text{res}} = 1.550 \ \mu\text{m}$

ER $\rightarrow \infty$, IL $= 0.10 \ \text{dB}$
TCO-based resonator modulators – TM operation

- \( w \times h = 400 \text{ nm} \times 200 \text{ nm} \), \( t_h = 300 \text{ nm} \), \( t_w = 150 \text{ nm} \)
- Critical coupling at zero bias (low losses)
- Detuning + change in loss level

\[ \lambda_{\text{res}} = 1.550 \ \mu\text{m} \]

\( \text{ER} \to \infty, \ IL = 0.02 \ \text{dB} \)
TCO-based resonator modulators – TM operation

- $w \times h = 400 \text{ nm} \times 200 \text{ nm}$, $t_h = 300 \text{ nm}$, $t_w = 150 \text{ nm}$
- Critical coupling at zero bias (low losses)
- Detuning + change in loss level

- Effective index shift: $\Delta \text{Re}(n_{\text{eff}})$
- Mode loss: $\alpha (\text{dB}/\mu\text{m})$
- Normalized Transmission $T$

- $Q_i = 442$
- $12485$
- $0.0 \text{ V}$
- $4.0 \text{ V}$

- $\lambda_{\text{res}} = 1.550 \mu\text{m}$

ER $\rightarrow \infty$, IL = 0.07 dB
Graphene resonator modulators – TE operation

- $w \times h = 340 \text{ nm} \times 220 \text{ nm}$
- Critical coupling at high bias (low losses)
- No detuning, change in loss level

$$\lambda_{\text{res}} = 1.552 \ \mu\text{m}$$

$\text{ER} \to \infty$, $\text{IL} = 1.11 \ \text{dB}$
Graphene resonator modulators – TE operation

- $w \times h = 340 \text{ nm} \times 220 \text{ nm}$
- Critical coupling at high bias (low losses)
- Detuning + change in loss level

$\lambda_{\text{res}} = 1.550 \mu\text{m}$

ER $\to \infty$, IL = 0.81 dB
Graphene resonator modulators – TE operation

- $w \times h = 340 \text{ nm} \times 220 \text{ nm}$
- Critical coupling at high bias (low losses)
- Detuning + change in loss level

$\lambda_{res} = 1.546 \text{ } \mu\text{m}$

$\text{ER} \to \infty$, $\text{IL} = 0.30 \text{ dB}$
Graphene resonator modulators – TM operation

- $w \times h = 450 \text{ nm} \times 260 \text{ nm}$
- Critical coupling at high bias (low losses)
- No detuning, change in loss level
- $\lambda_{\text{res}} = 1.552 \ \mu\text{m}$
- $\text{ER} \rightarrow \infty$, $\text{IL} = 1.18 \ \text{dB}$
Graphene resonator modulators – TM operation

- $w \times h = 450 \text{ nm} \times 260 \text{ nm}$
- Critical coupling at high bias (low losses)
- Detuning + change in loss level

$\lambda_{\text{res}} = 1.550 \ \mu\text{m}$

$\text{ER} \rightarrow \infty, \ IL = 0.78 \text{ dB}$
Graphene resonator modulators – TM operation

- $w \times h = 450\,\text{nm} \times 260\,\text{nm}$
- Critical coupling at high bias (low losses)
- Detuning + change in loss level

$$\lambda_{\text{res}} = 1.545\,\mu\text{m}$$

$\text{ER} \to \infty, \text{IL} = 0.27\,\text{dB}$
Summary & Conclusions
<table>
<thead>
<tr>
<th>Platform</th>
<th>Mode</th>
<th>Footprint (µm²)</th>
<th>ER (dB)</th>
<th>IL (dB)</th>
<th>Bias swing</th>
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<tbody>
<tr>
<td></td>
<td>TE</td>
<td>14.5</td>
<td>10</td>
<td>0.10</td>
<td>0 V ↔ 4 V</td>
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<tr>
<td></td>
<td>TE</td>
<td>14.6</td>
<td>10</td>
<td>0.86</td>
<td>0.5 V ↔ 2 V</td>
<td>Externally limited</td>
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<tr>
<td></td>
<td>TM</td>
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<td>0.03</td>
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<td></td>
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<td>28.3</td>
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<td>0.30</td>
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<td>~ 230 GHz</td>
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<td>32.2</td>
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<td>0.27</td>
<td>0.5 V ↔ 4 V</td>
<td>~ 280 GHz</td>
</tr>
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</tbody>
</table>
Conclusions & Future directions

Conclusions

- **TCOs & graphene** → promising materials for compact, efficient, and ultra-high bandwidth on-chip optical modulation
- **In-line configurations** → bandwidth, footprint (low energy consumption), & low fabrication complexity
- **Resonator modulators** → theoretically infinite ER & lower ILs, bandwidth limited by photon lifetime
- **TE & TM polarization** → comparable performance metrics by proper engineering
  - TE → smaller footprint in general → lower energy consumption
- **Graphene modulators** → speed is theoretically limited by external factors such as the quality of the metal contacts and/or the photon lifetime in the case of resonator configurations

Future directions

- **Full-field three-dimensional (3D) verification** of the proposed analysis
- Investigate **higher order modulation formats**, including phase shift keying (PSK) schemes
- Investigation of **alternative switching mechanisms** such as current injection control & optical addressing
Thank you!

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