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Session IW3B - Modulators

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

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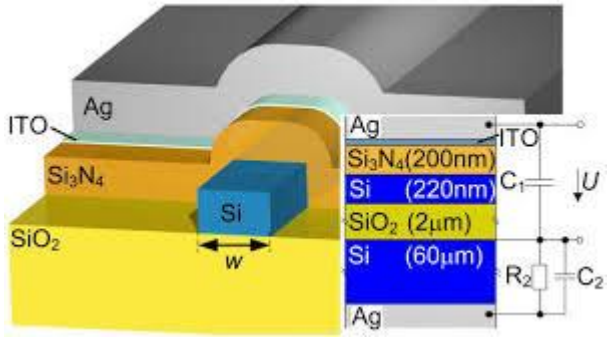
Presentation Outline

- **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**

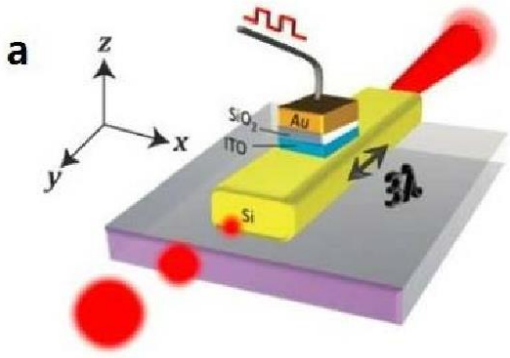
State-of-the-art, Motivation & Main objectives

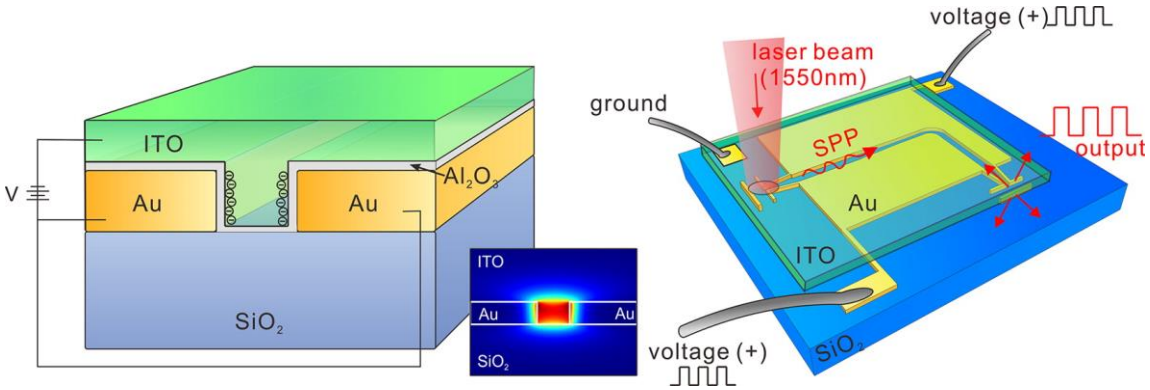
Introduction

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

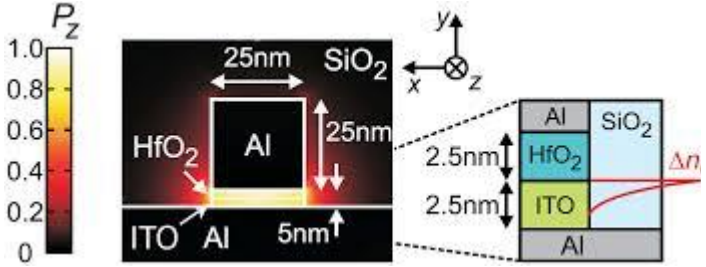


Melikyan, *Optics Express* **19**, 8855-8869, 2011

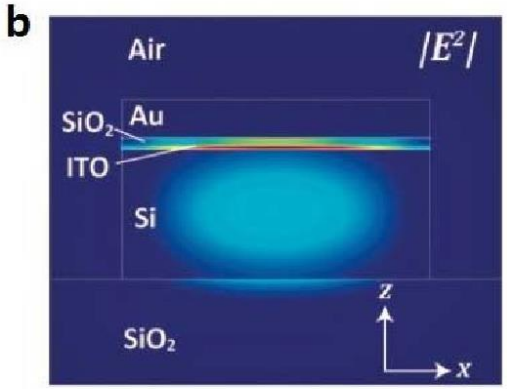




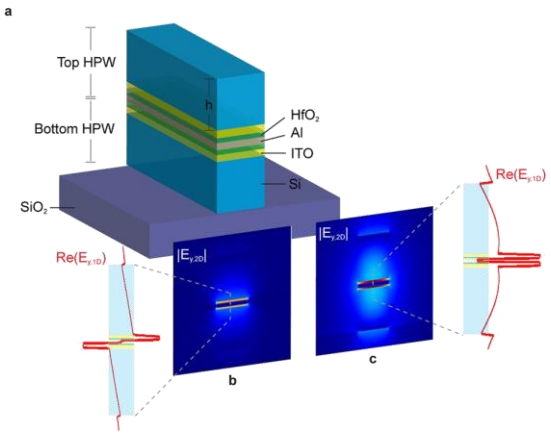
Lee, *Nano Lett.* **14** (11), 6463–6468, 2014



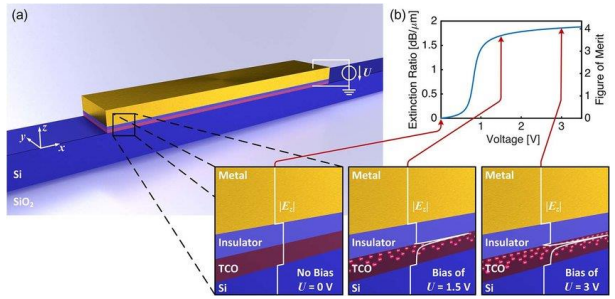
Krasavin, *Phys. Rev. Lett.* **109**, 053901, 1-5, 2012



Sorger, *Nanophotonics* **1**(1), 17-22, 2012

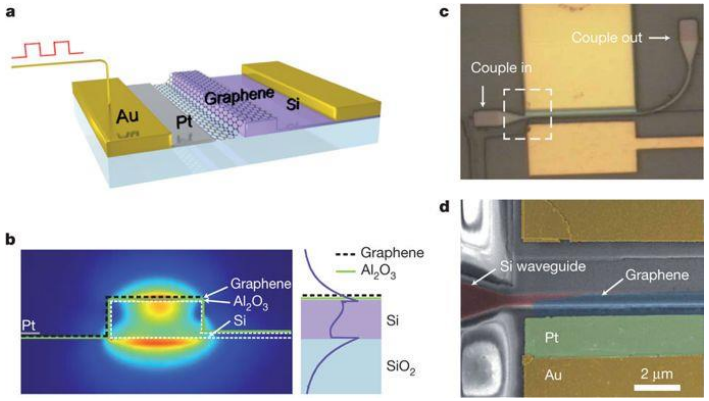


Lin, *Sci. Rep.* **5,** 12313, 2015

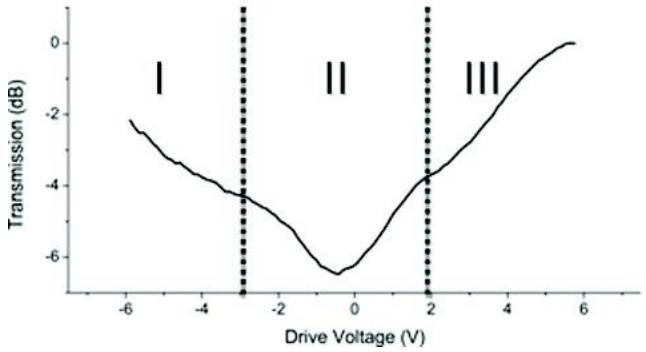


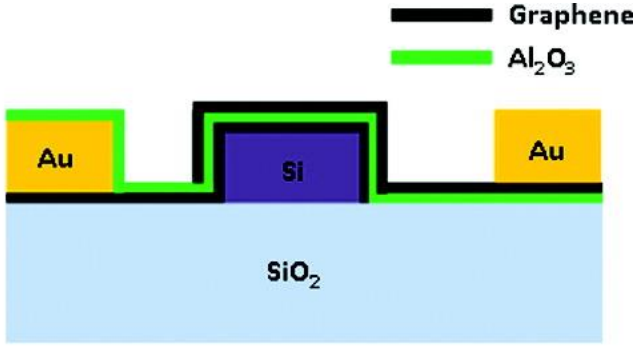
Koch, *IEEE Photonics J.* **8**(1), 2016

State-of-the-art on Graphene modulators

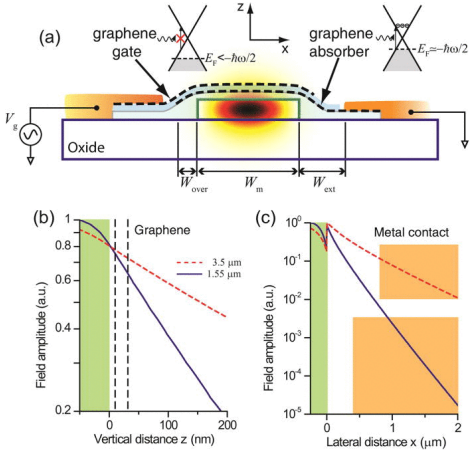


Liu, *Nature* **474,** 64–67, 2011

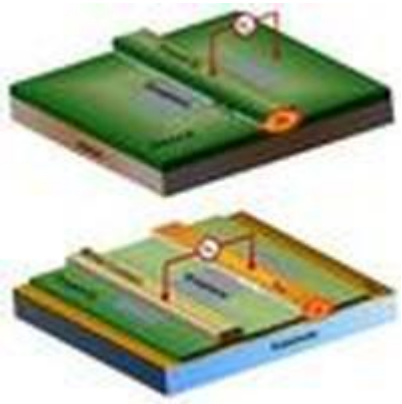




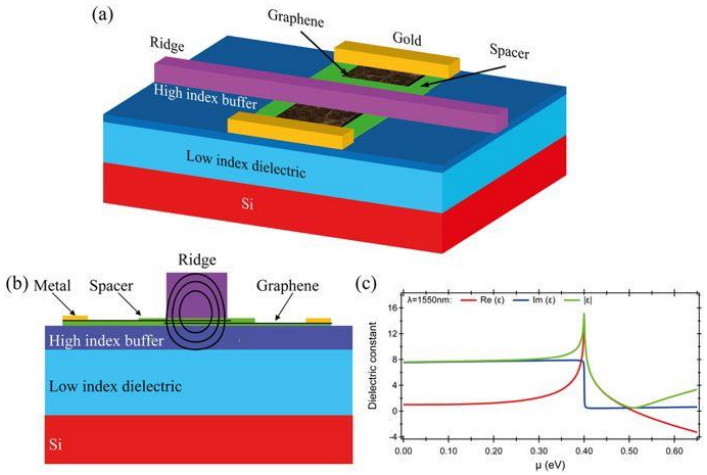
Liu, *Nano Lett.* **12,** 1482–1485, 2012



Koester, *Appl. Phys. Lett.* **100,** 171107, 2012



Lu, *J. Opt. Soc. Am. B* **29,** 1490–1496, 2012



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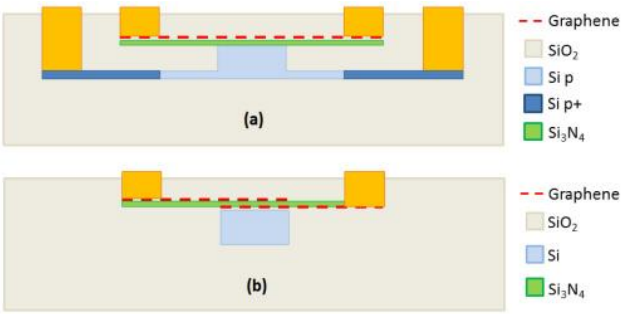


Sorianello, *Optics Express* **23**(5), 6478-6490, 2015

Motivation & Main objectives

❑ Motivation

☑ Demand for **high-performing nanophotonic modulators**, envisioned by advances in materials science

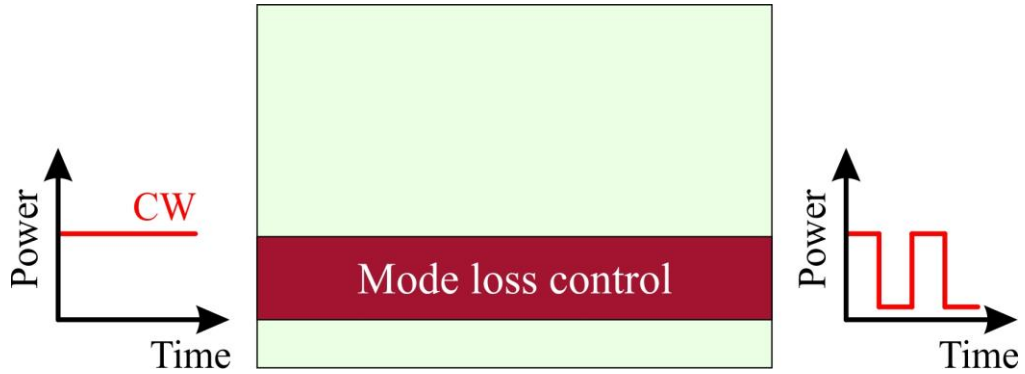
☑ **Addressable** & **versatile TCO properties** in the near-infrared (NIR)

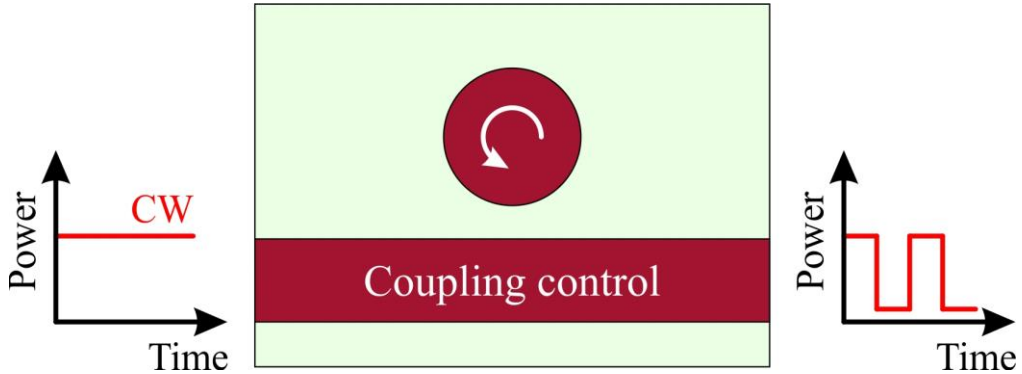
☑ **Tunable NIR graphene properties** along with its **two-dimensional (2D) nature**

❑ 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



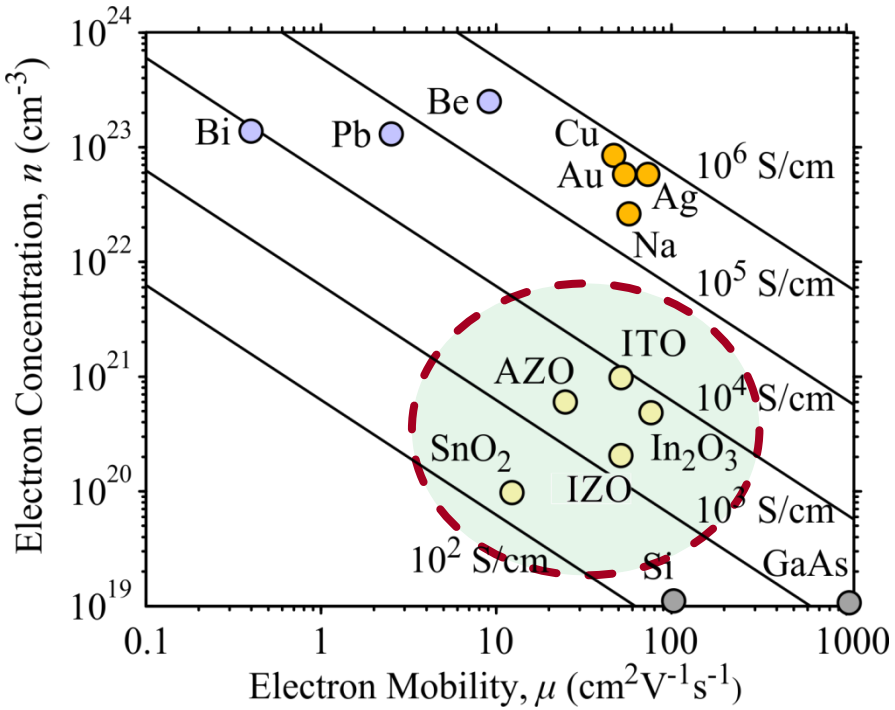


TCOs, Graphene, Physical systems

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**

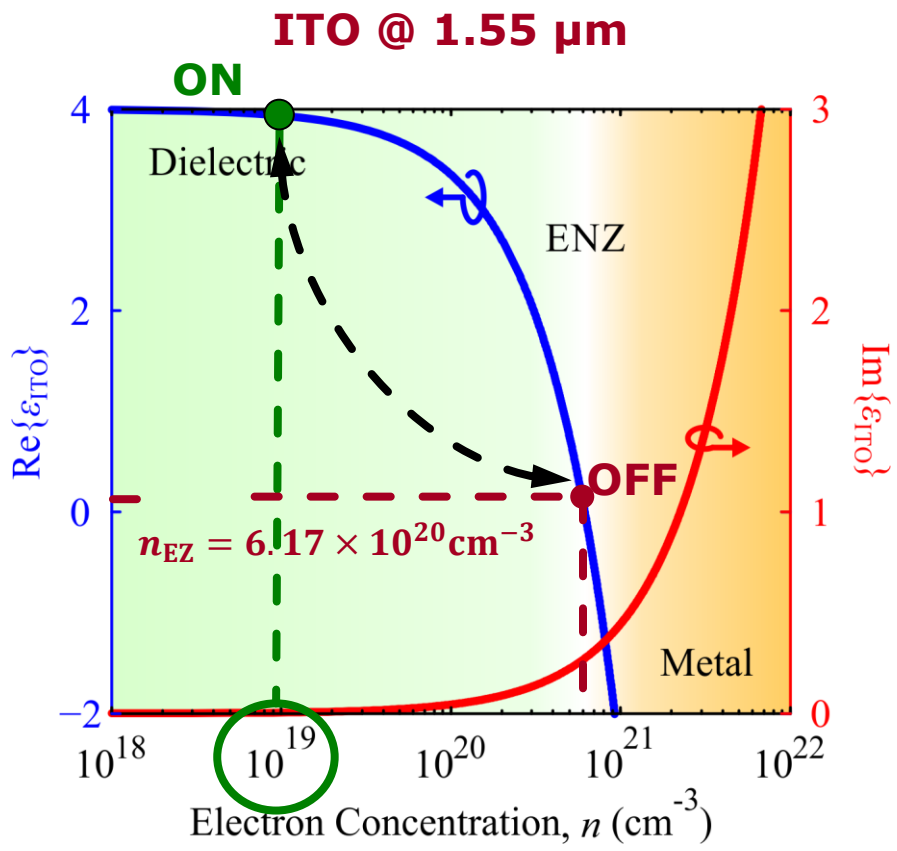
- Drude permittivity function
- Plasma frequency ω_p lies in the NIR region
  → $\mathrm{Re}\{\varepsilon(\omega_p)\} \approx 0$ **in the NIR**

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

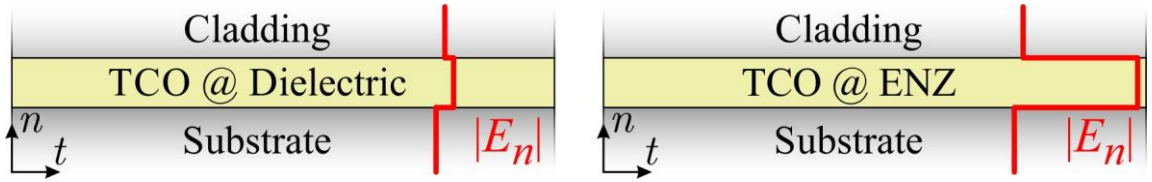
$$\omega_p(n) \sim \sqrt{\frac{n}{\varepsilon_{\text{opt}}}}$$

Material	n (cm^{-3})	λ_p (μm)
Ag	5.86×10^{22}	0.14
ITO	**6.17×10^{20}**	**1.55**
n-InSb	4.00×10^{18}	14.0

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**

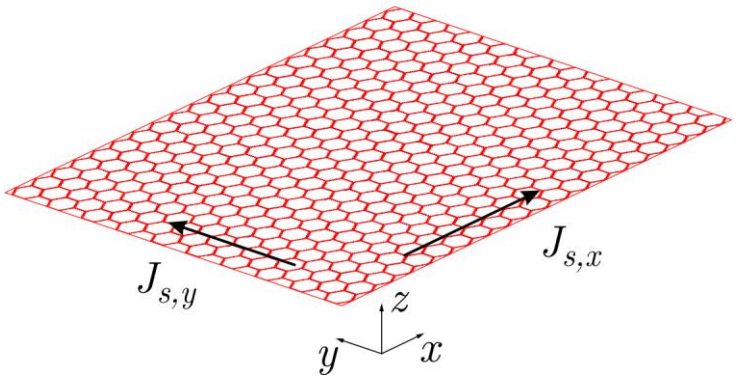
Modulation principle → Modulate the TCO permittivity by changing the free-carrier concentration in the TCO through changes in its Fermi level

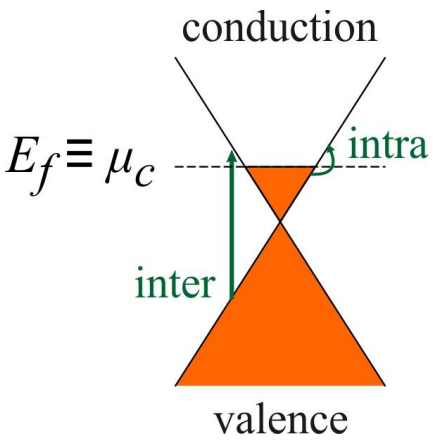
ON state → Dielectric region, $n_{on} = 10^{19}$ cm^{-3}

OFF state → ENZ region, $n_{off} \sim 6 \times 10^{20}$ cm^{-3}

Graphene

$$\mathbf{J}_s = \mathbf{J}_{s,\text{intra}} + \mathbf{J}_{s,\text{inter}} = (\sigma_{\text{intra}} + \sigma_{\text{inter}})\mathbf{E}_{||}$$





- **Two-dimensional (2D) material** → atomic layer of graphite
- Graphene is modelled as a **surface current,** $\mathbf{J}_S = \hat{\mathbf{n}} \times (\mathbf{H}_2 - \mathbf{H}_1) = \sigma \mathbf{E}_{||}$ → **interaction with tangential electric field components**
- Unique **optical** properties described by its **surface conductivity** σ → contribution from both **interband** & **intraband transitions**

- Energy band diagram → Dirac cone, $E_g = 0$
- Fermi level E_f → surface carrier density

$$\sigma = \sigma_{\text{intra}} + \sigma_{\text{inter}}$$

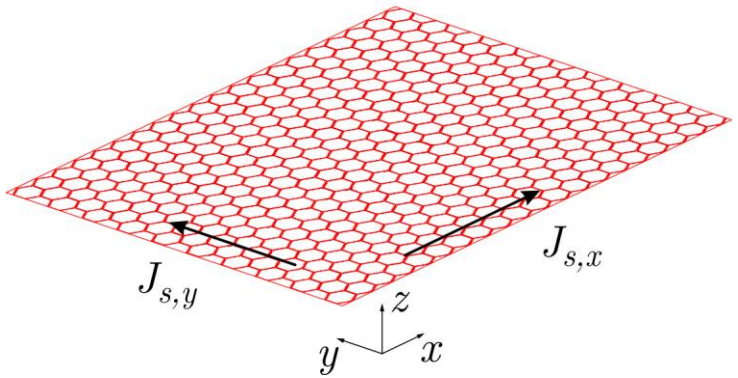
$$\sigma_{\text{intra}}(E_f) = \frac{-je^2 k_B T}{\pi\hbar^2(\omega - j/\tau_1)}\left[\frac{E_f}{k_B T} + 2\ln(e^{-E_f/k_B T} + 1)\right]$$

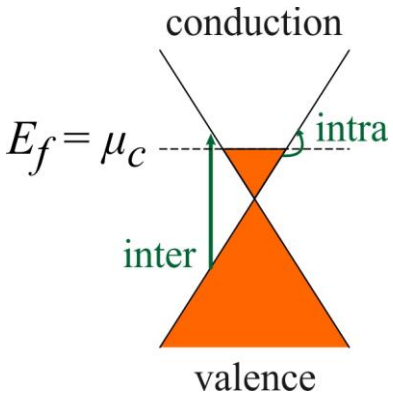
$$\sigma_{\text{inter}}(E_f) = \frac{-je^2}{4\pi\hbar}\ln\left[\frac{2|E_f| - \hbar(\omega - j/\tau_2)}{2|E_f| + \hbar(\omega - j/\tau_2)}\right] \qquad \tau_1 \approx 10 \text{ fs} \quad \tau_2 \approx 1.2 \text{ ps}$$

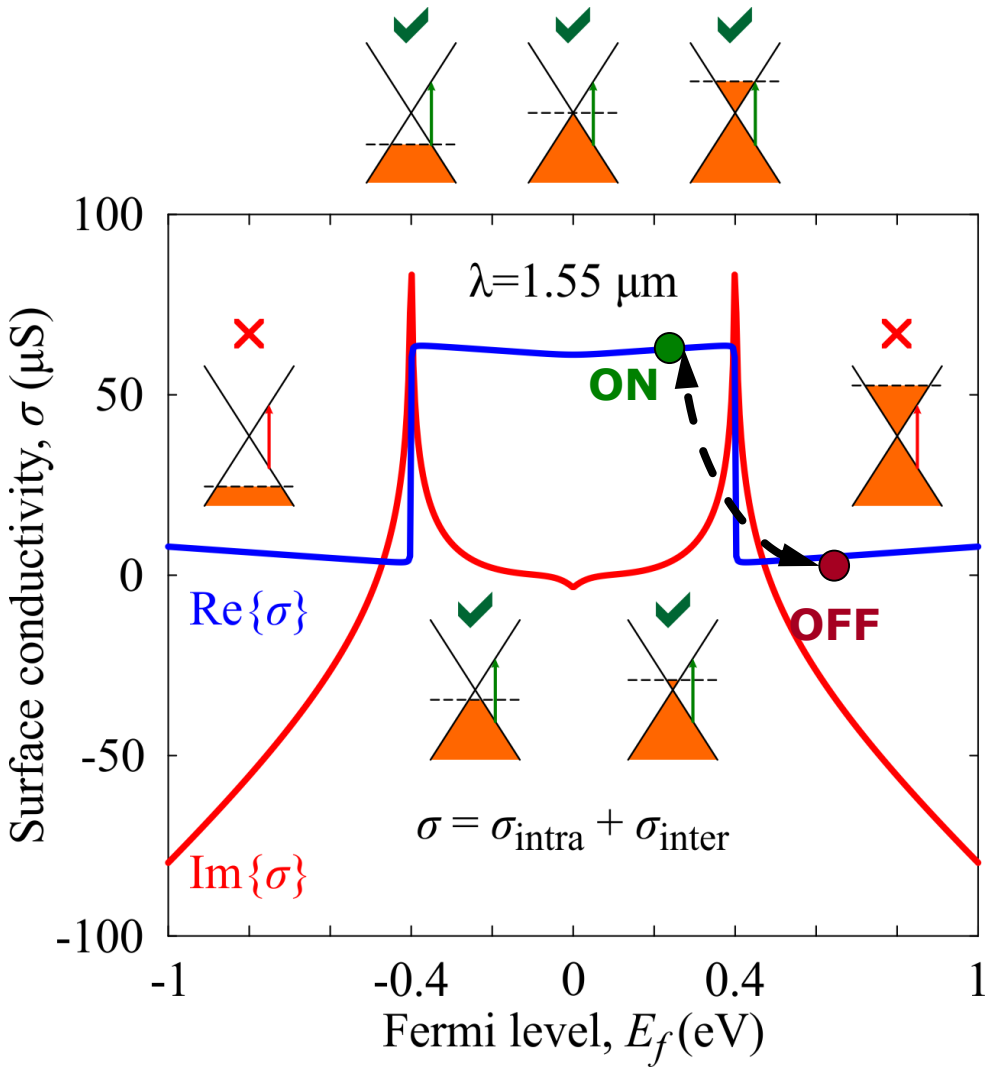
Hanson, *J. Appl. Phys.* **103**, 064302, 2008

Graphene

$$\mathbf{J}_s = \mathbf{J}_{s,\text{intra}} + \mathbf{J}_{s,\text{inter}} = (\sigma_{\text{intra}} + \sigma_{\text{inter}})\mathbf{E}_{||}$$

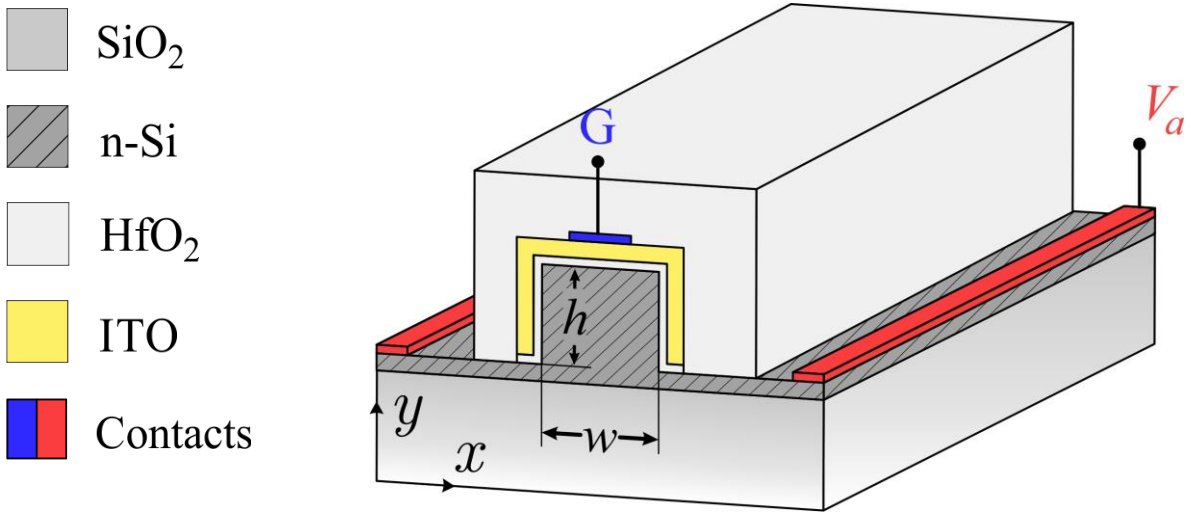


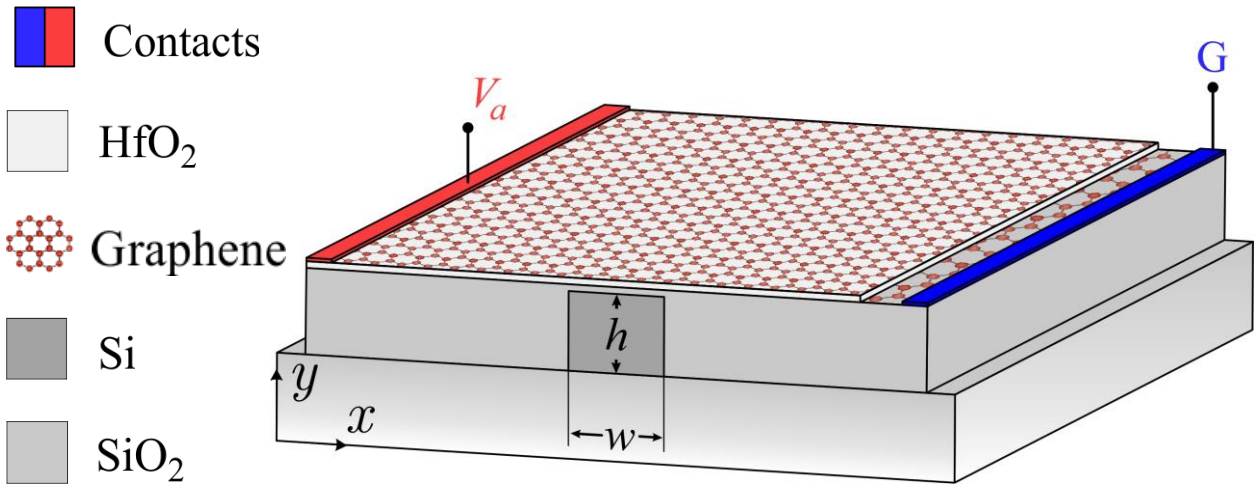




- **Symmetric** change around Dirac point ($\mu_c = 0$)
- **Step behavior** for $\text{Re}\{\sigma\}$ at $E_f = \pm 0.4$ eV & $\lambda = 1.55$ μm
- **Modulate surface conductivity by tuning E_f**

Physical systems (I)



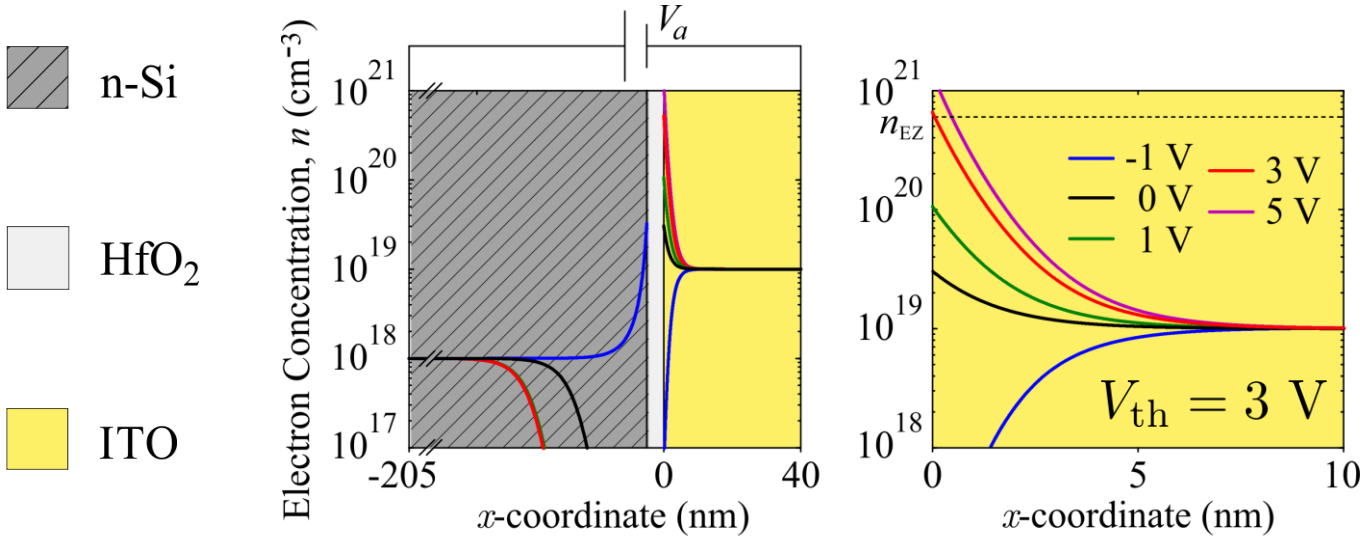


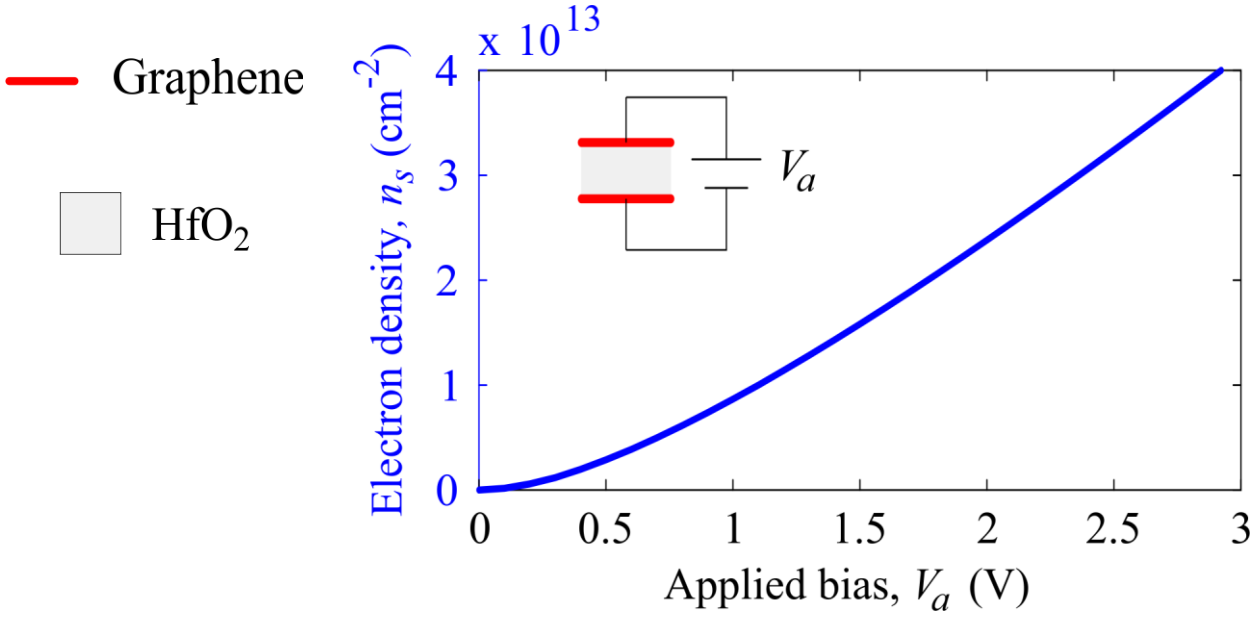
- **10^{18} cm^{-3} n-doped Si**
- Thin layer (5 nm) of high-k dielectric (HfO_2) **→ energy consumption reduction**
- **10^{19} cm^{-3} ITO layer** (10 nm)

- **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 σ, graphene effect enhancement**
- Graphene workfunction, $W_f = 4.5$ eV
- Metal contacts **→ Ideal ohmic**

Physical systems (II)





$$-\nabla \cdot (\varepsilon_0 \bar{\varepsilon}_r \nabla \phi) = \rho = q(N_D^+ - n)$$

$$n = 2\left(\frac{m_n^*}{2\pi\hbar^2}\right)^{3/2} \mathcal{F}_{1/2}(E_f)$$

$$\mathbf{J}_n = -q\mu_n n \nabla\phi + qD_n \nabla n$$

Semi/Insulator → $\phi = \text{cont.},\ \hat{\mathbf{n}}\mathbf{J}_n = 0$

$$n_s = \frac{2}{\pi\hbar^2 v_F^2}\left[\mathcal{F}_1(E_f) + \mathcal{F}_1(2E_f)\right]$$

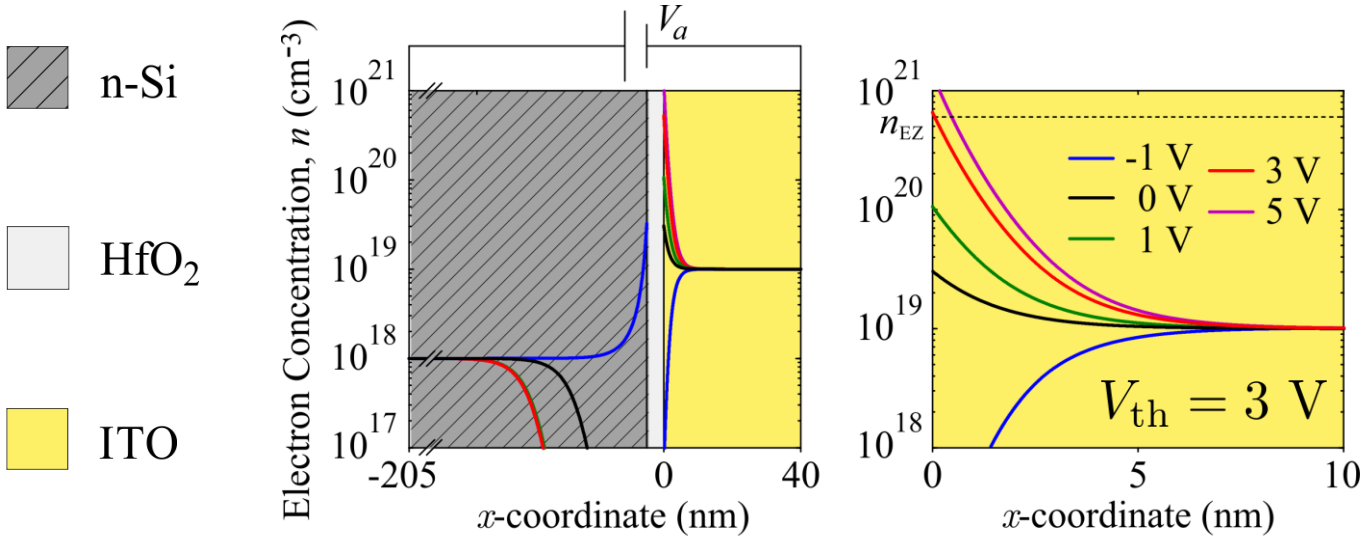
$$E_f >> k_B T \rightarrow |n_s| = \frac{(q\phi)^2}{\pi(\hbar v_F)^2}$$

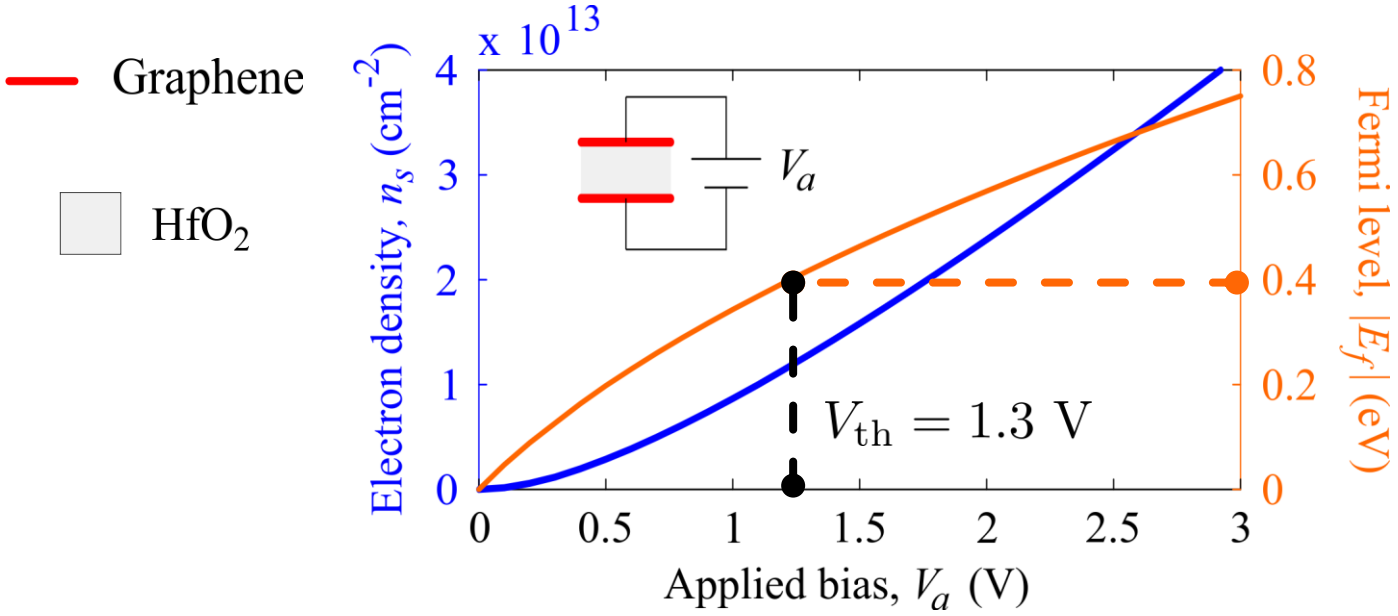
$$\mathcal{F}_i(E_f) = \frac{1}{\Gamma(i+1)} \int_0^\infty \frac{x^i \mathrm{d}x}{1 + e^{(x-E_f)/k_B T}}$$

$$\Gamma(n) = (n-1)!$$

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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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

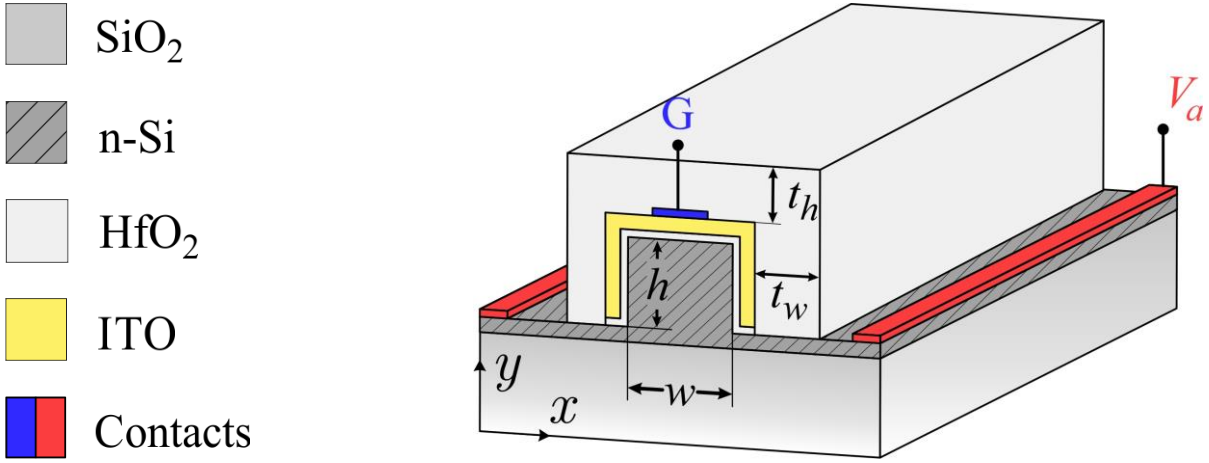
Maxwell Equations

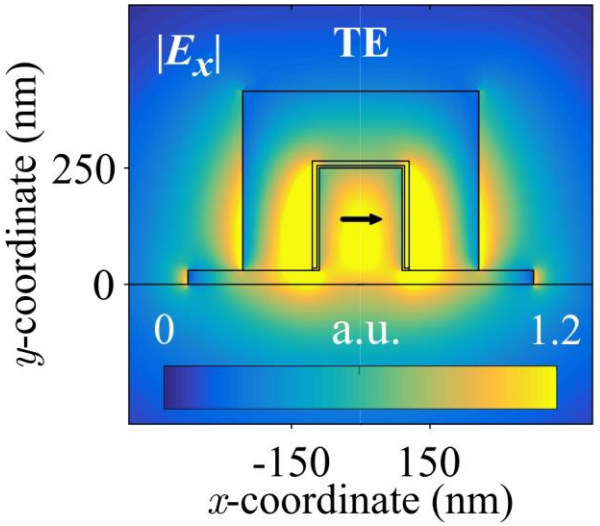
- Conventional 2D eigenmode solver
- $\mathrm{Im}\{n_{\mathrm{eff}}\} \rightarrow$ Mode Loss

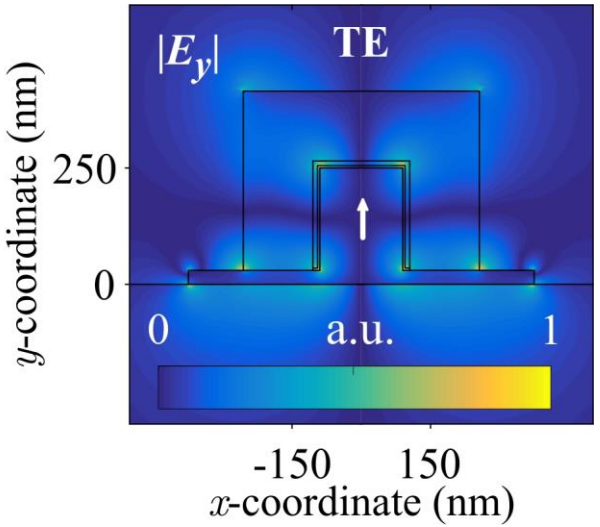
NIR Material Models

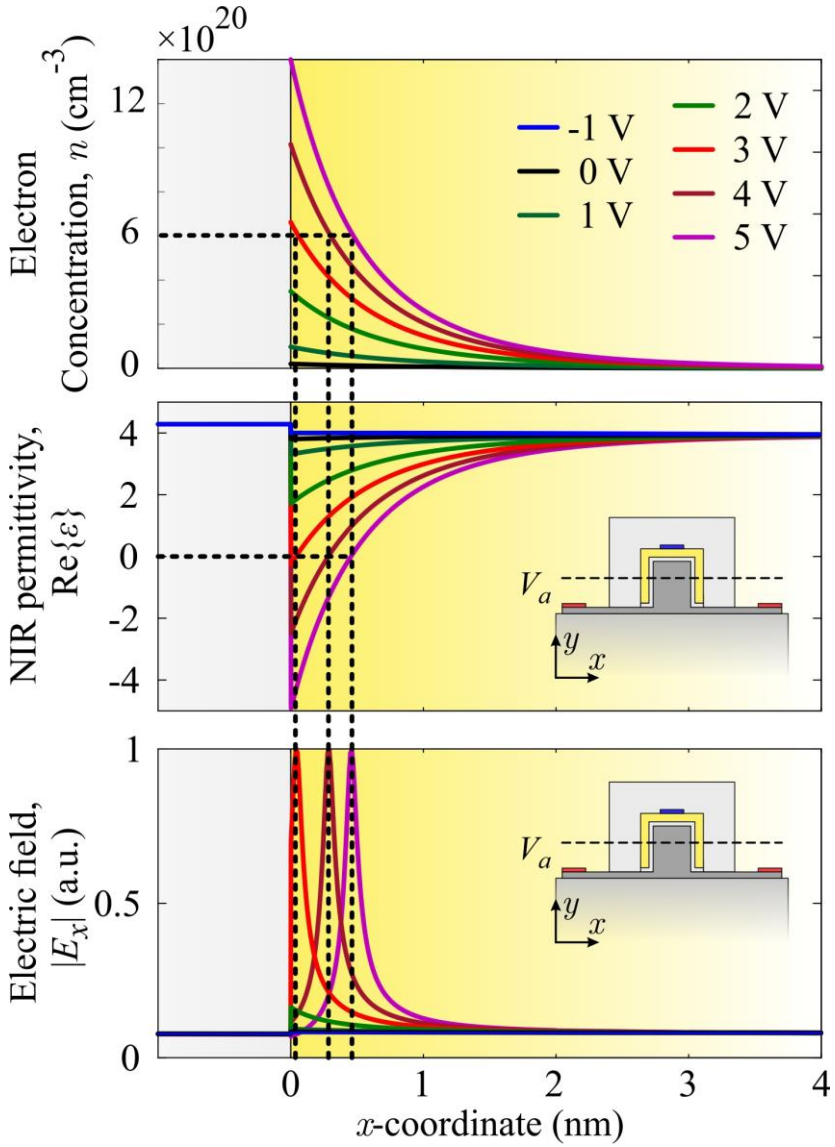
TCOs $\rightarrow$ Dielectric permittivity $\tilde{\varepsilon}(n)$
Graphene $\rightarrow$ Surface conductivity $\sigma(E_f)$

TCO-based in-line modulators – TE operation









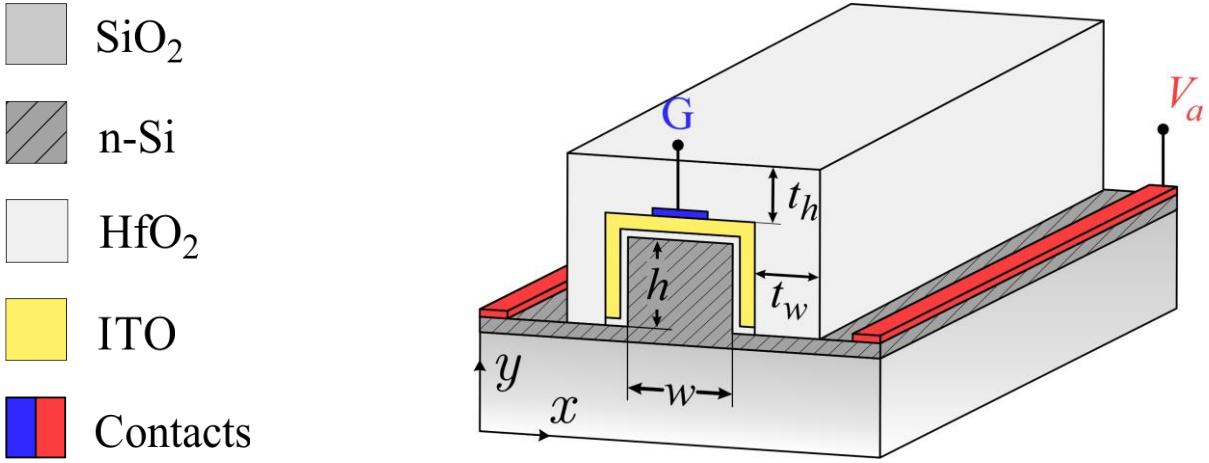
$$n_{\mathrm{EZ}} = 6.2 \times 10^{20}\mathrm{cm}^{-3}$$

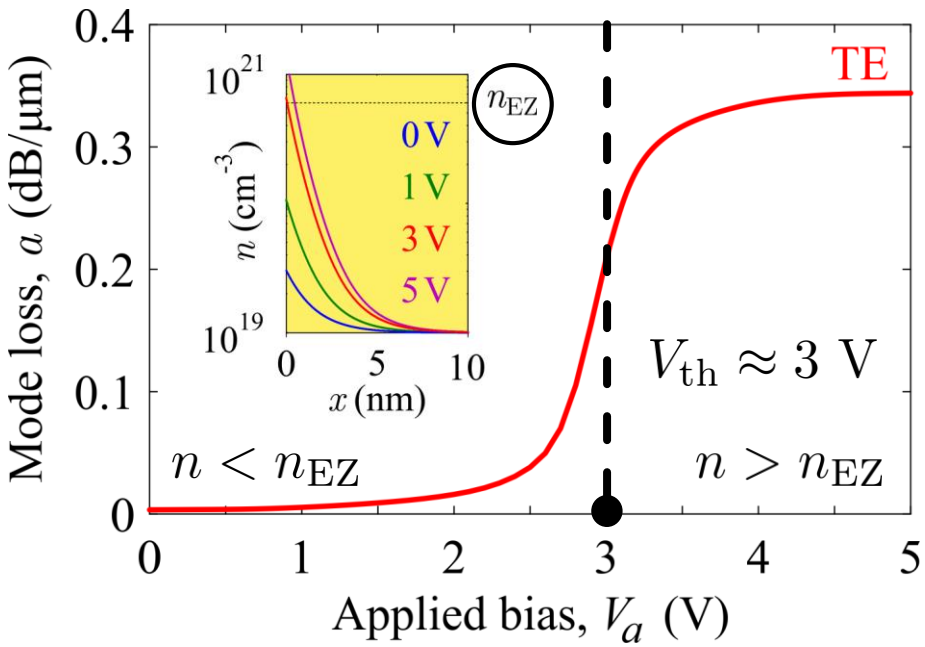
$$\mathrm{Re}\{\tilde{\varepsilon}\} = 0$$

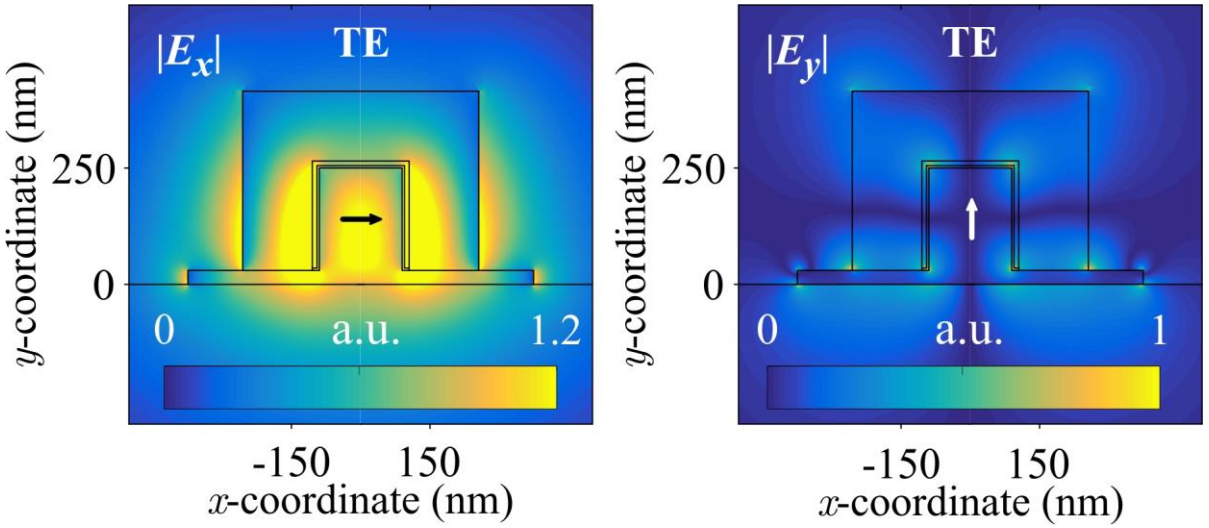
ENZ effect

Electric-field peak shift

TCO-based in-line modulators – TE operation



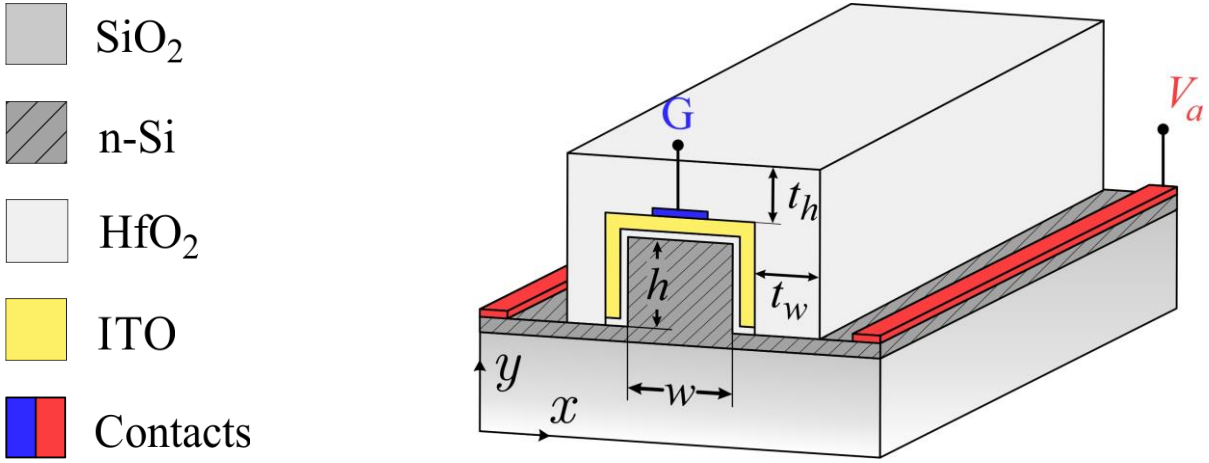


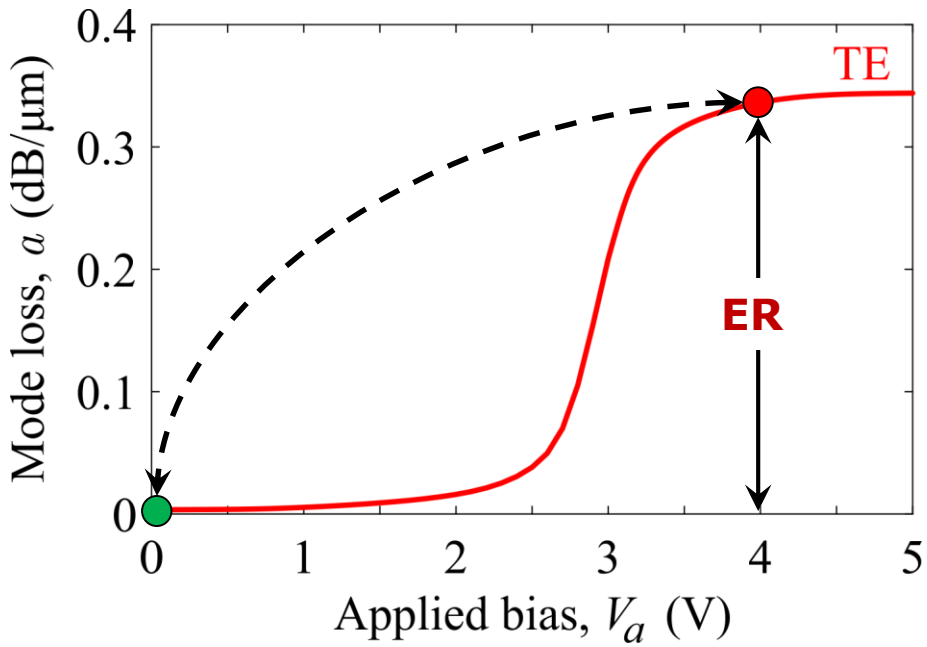


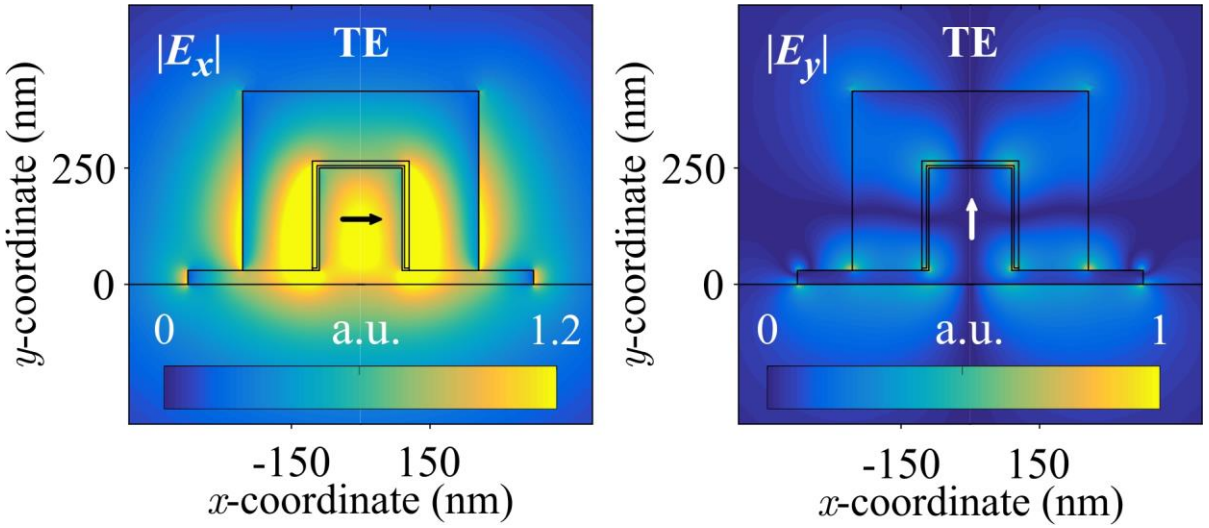
- w x h = 180 nm x 220 nm,
  $t_h = t_w$ = 150 nm

Sinatkas, *J. Appl. Phys.* **121** (2), 023109, 2017

TCO-based in-line modulators – TE operation



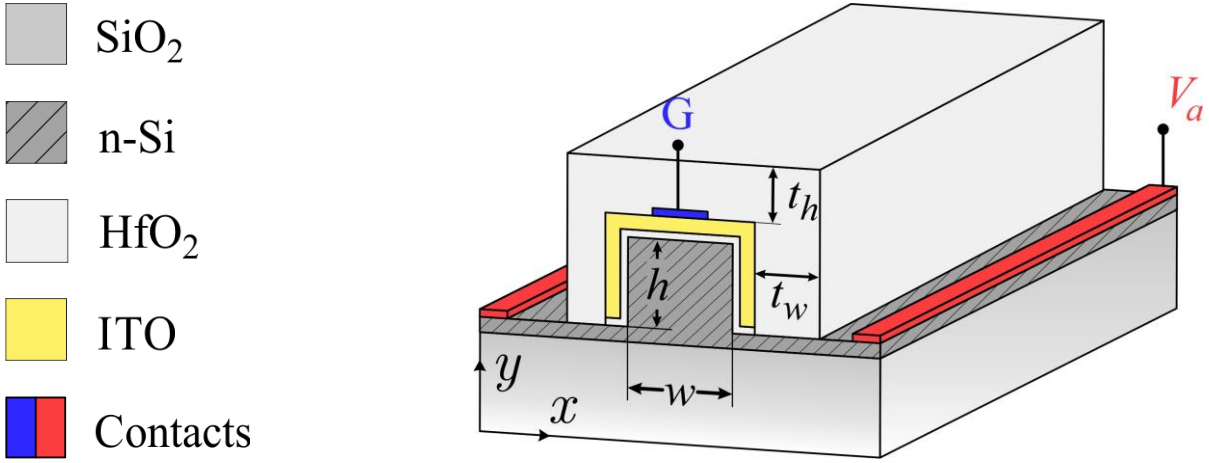


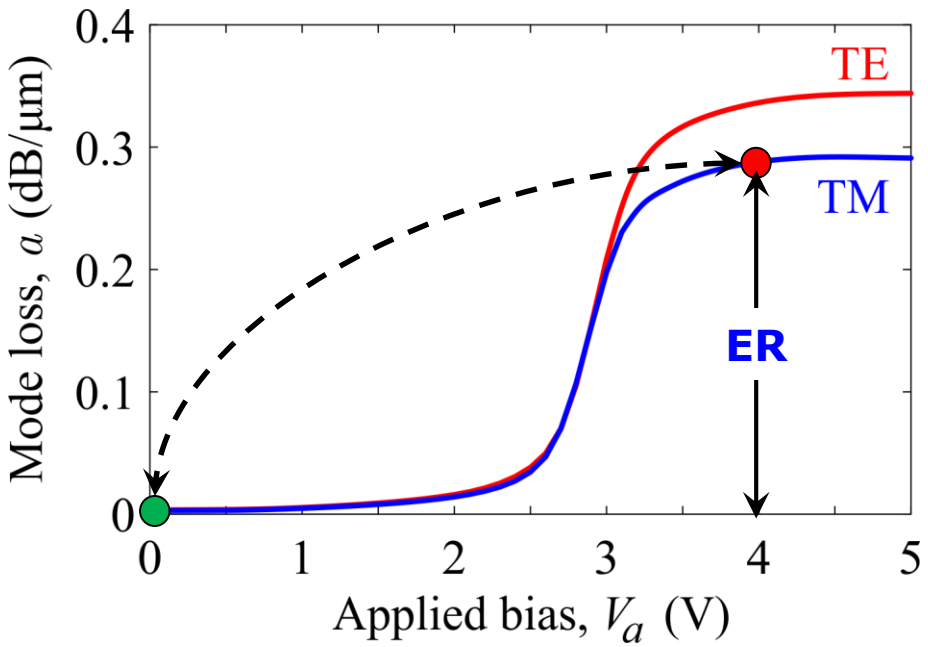


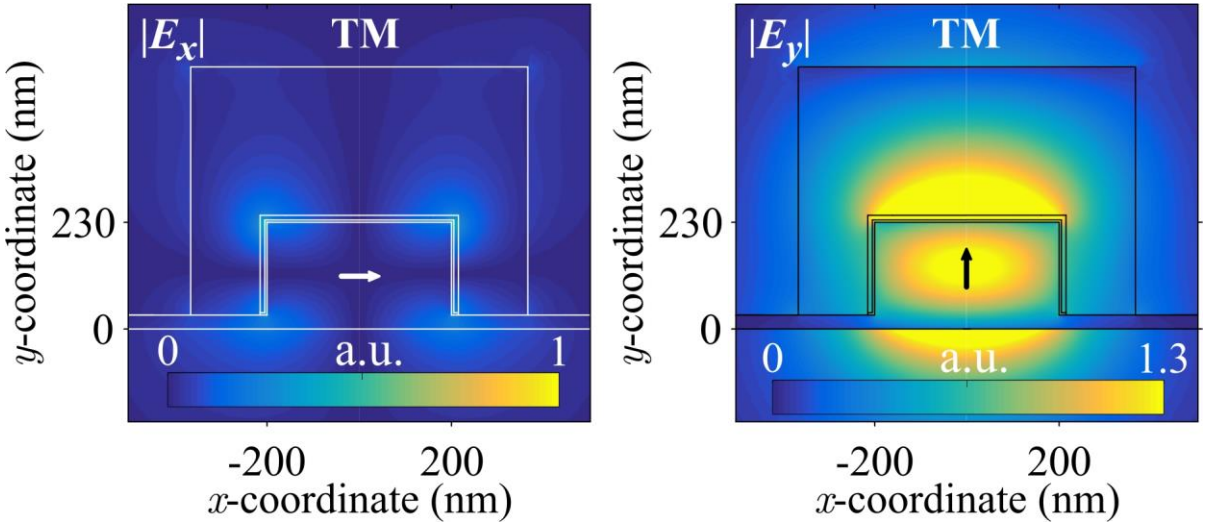
- w x h = 180 nm x 220 nm, $t_h = t_w$ = 150 nm
- **ER = 0.35 dB/μm, IL = 3 x 10^{-3} dB/μm**

Sinatkas, *J. Appl. Phys.* **121** (2), 023109, 2017

TCO-based in-line modulators – TM operation



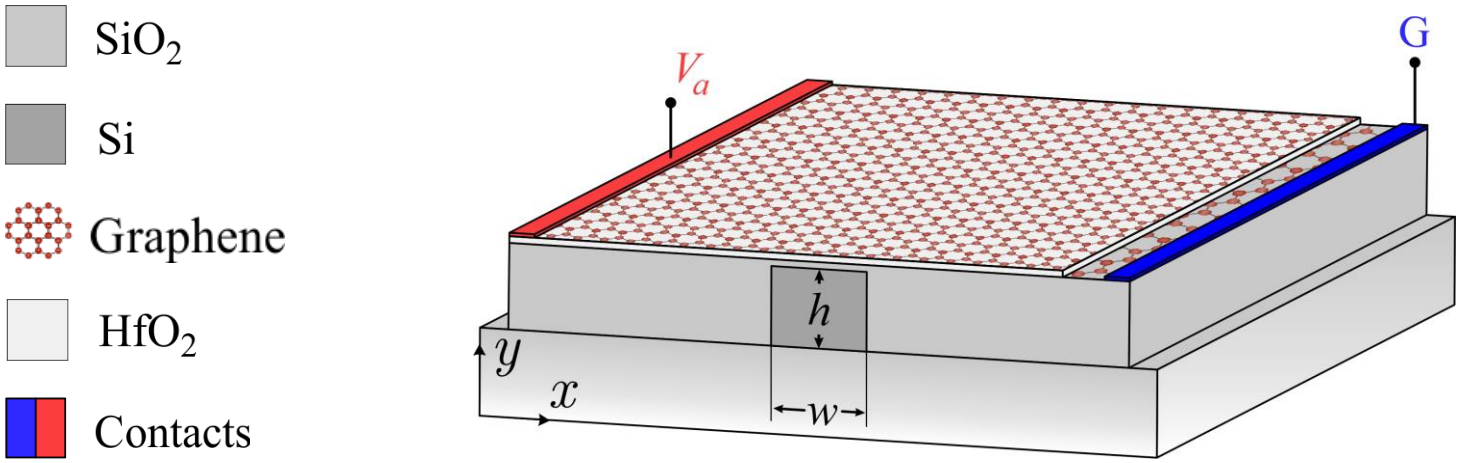


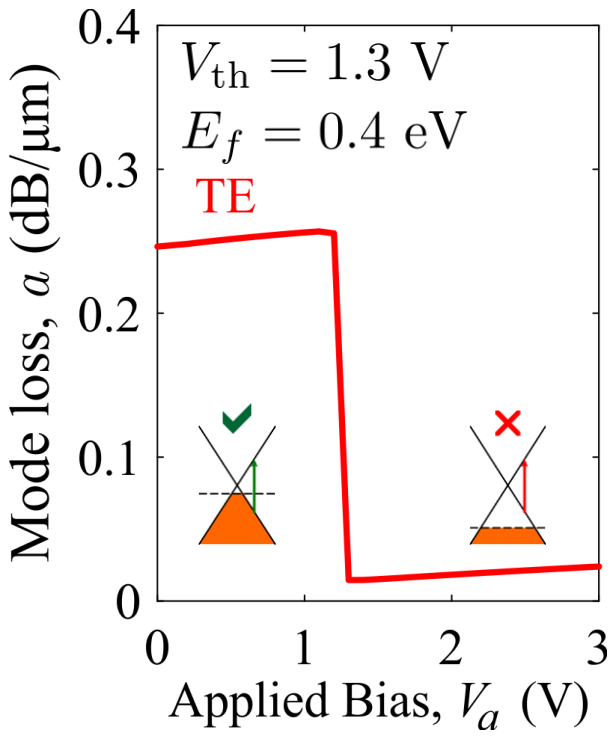


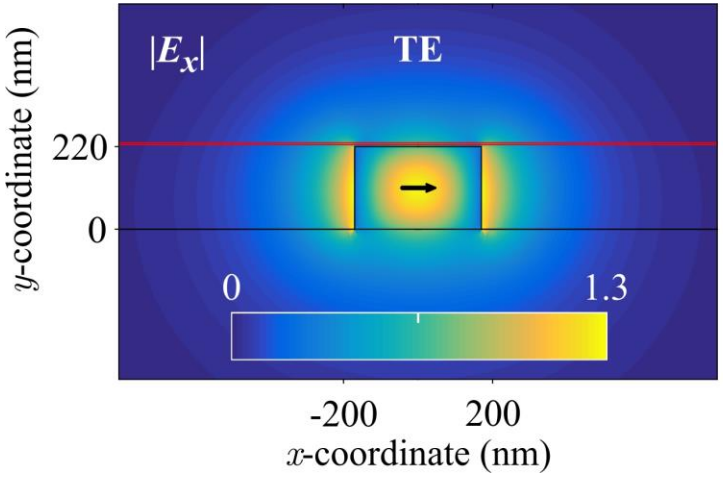
- w x h = 400 nm x 20 nm,
  t_h = 300 nm t_w = 150 nm
- **ER = 0.29 dB/μm, IL = 3 x 10^{-3} dB/μm**

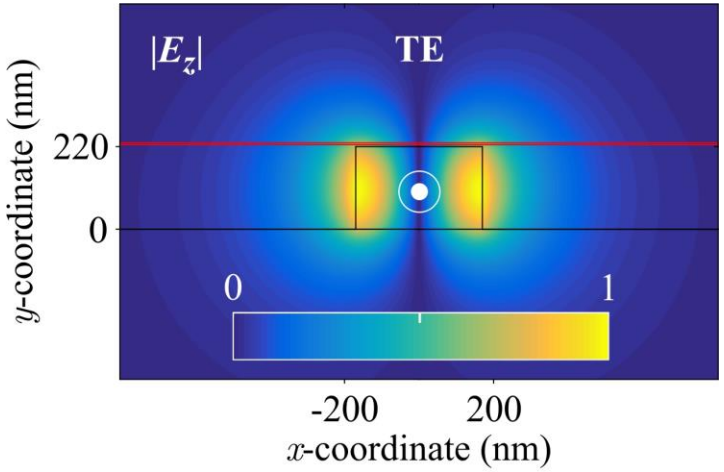
Sinatkas, *J. Appl. Phys.* **121** (2), 023109, 2017

Graphene in-line modulators – TE operation



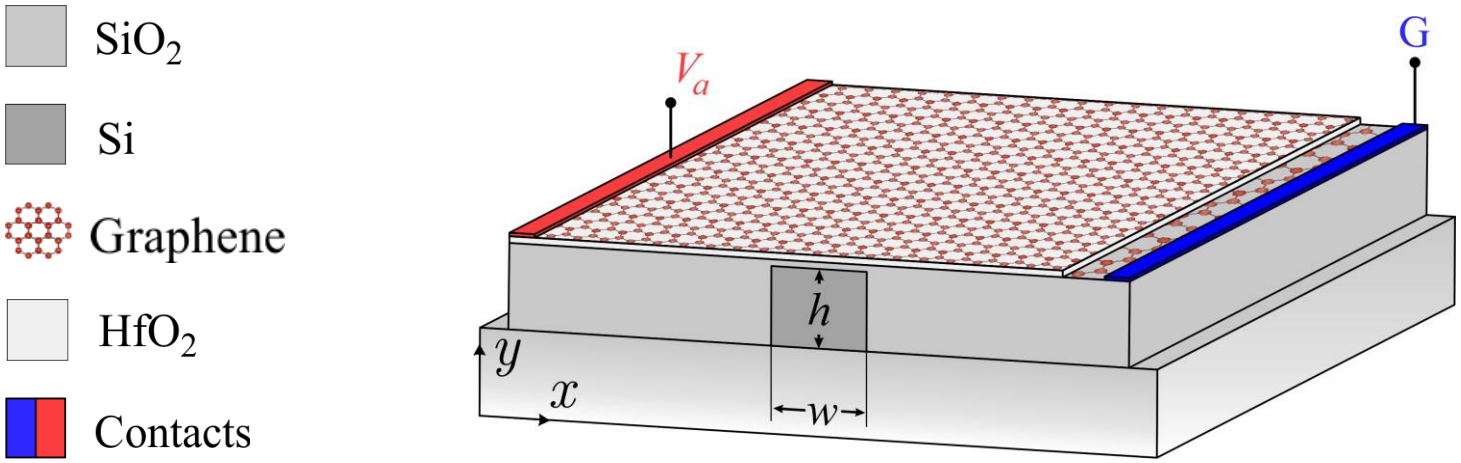


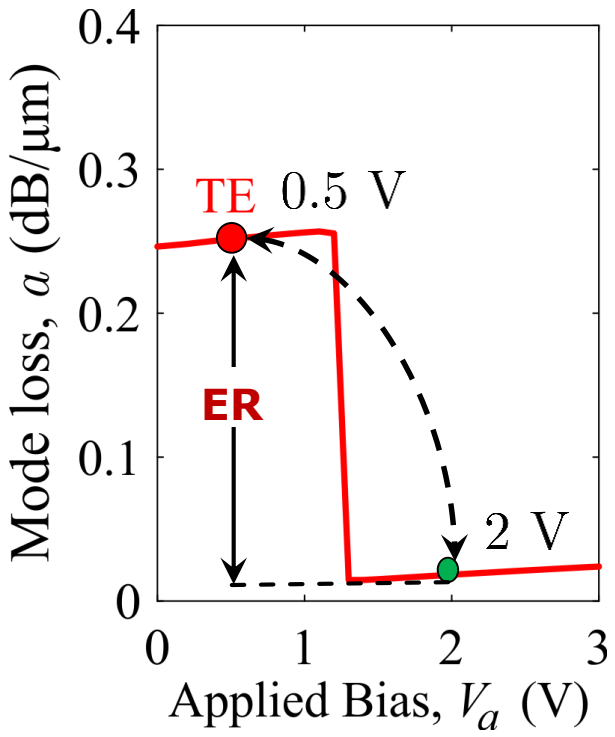


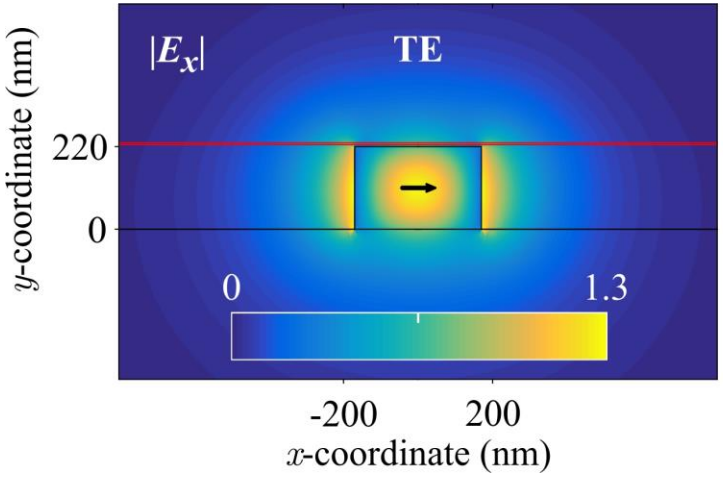


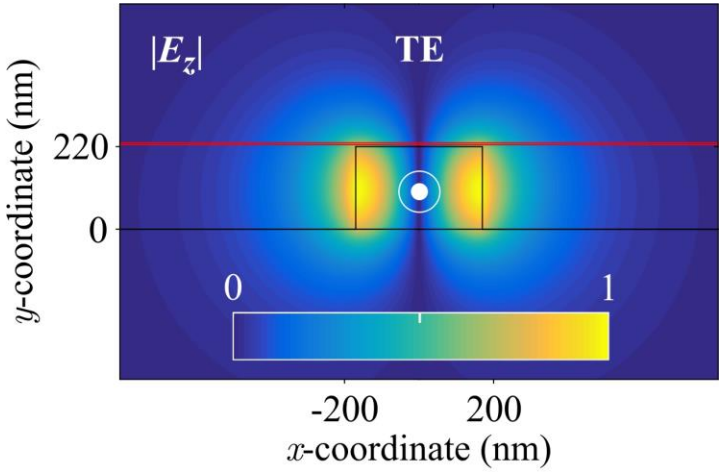
- w x h = 340 nm x 220 nm
- **ER = 0.23 dB/μm, IL = 0.02 dB/μm**

Graphene in-line modulators – TE operation



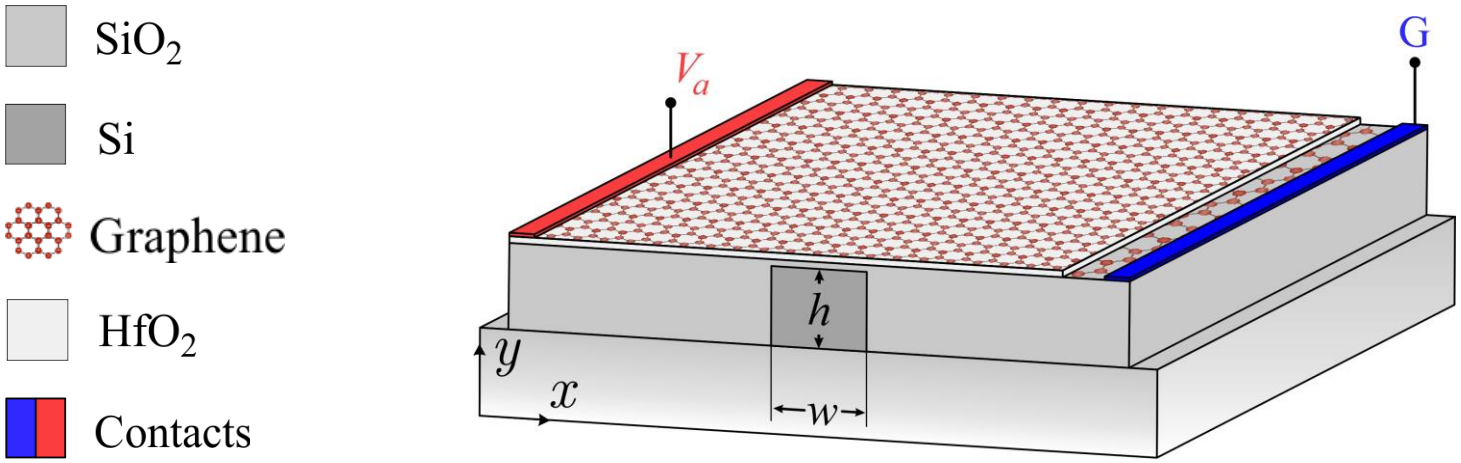


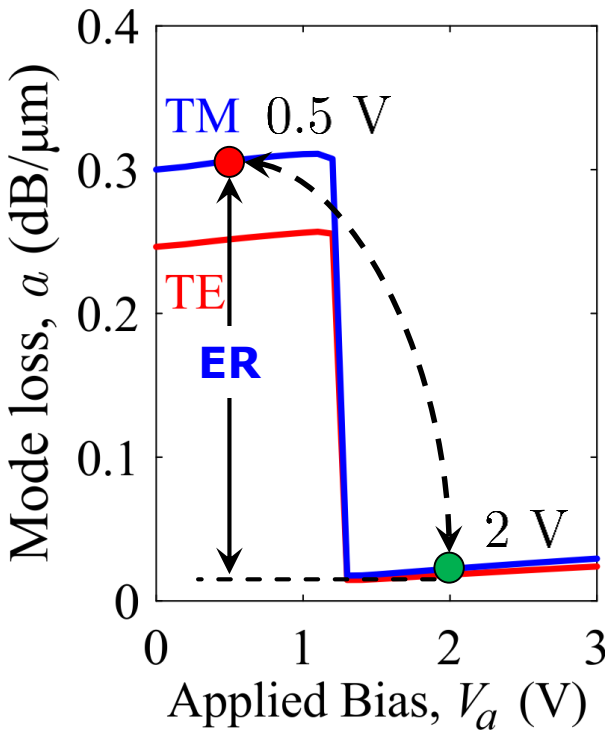


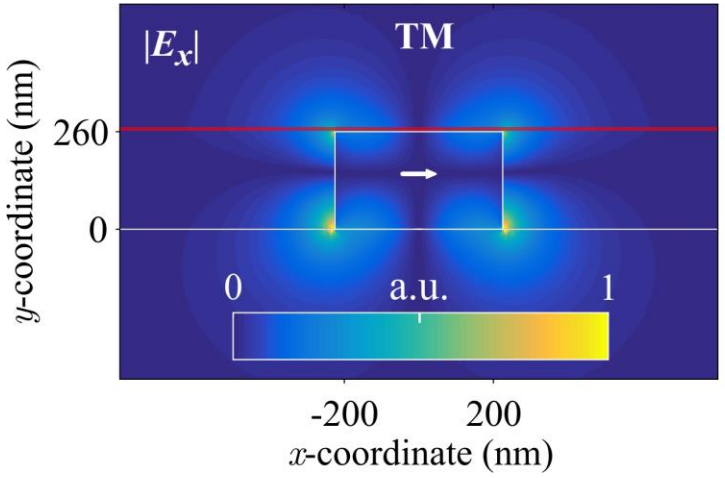


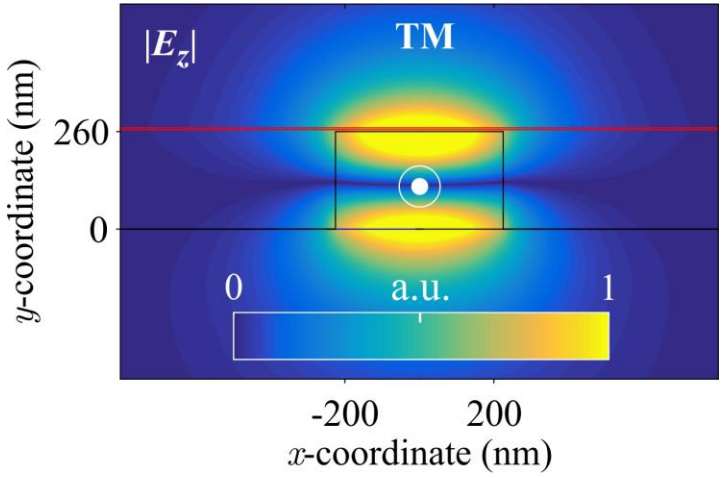
- w x h = 340 nm x 220 nm
- **ER = 0.23 dB/μm, IL = 0.02 dB/μm**

Graphene in-line modulators – TM operation



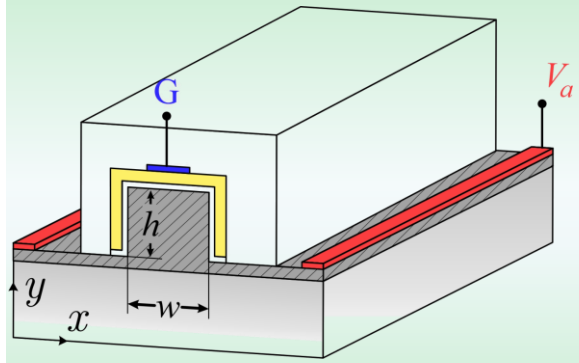
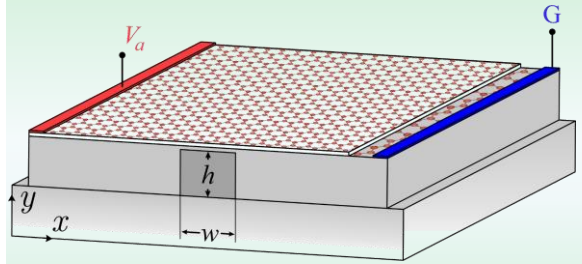






- w x h = 450 nm x 260 nm
- **ER = 0.28 dB/μm, IL = 0.02 dB/μm**

TCO-based & Graphene in-line modulators for ER = 10 dB

Platform	Mode	*w* x *h* (nm x nm)	*L* (μm)	IL (dB)	Bias swing	Intrinsic BW
	**TE**	180 x 220	29	0.10	0 V ↔ 4 V	~ 150 GHz
	TM	400 x 200	34	0.10	0 V ↔ 4 V	~ 150 GHz
	**TE**	340 x 220	43	0.86	0.5 V ↔ 2 V	Externally limited
	TM	450 x 260	35	0.78	0.5 V ↔ 2 V	

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 → Dielectric permittivity $\tilde{\varepsilon}(n)$
Graphene → Surface conductivity $\sigma(E_f)$

Wave Physics

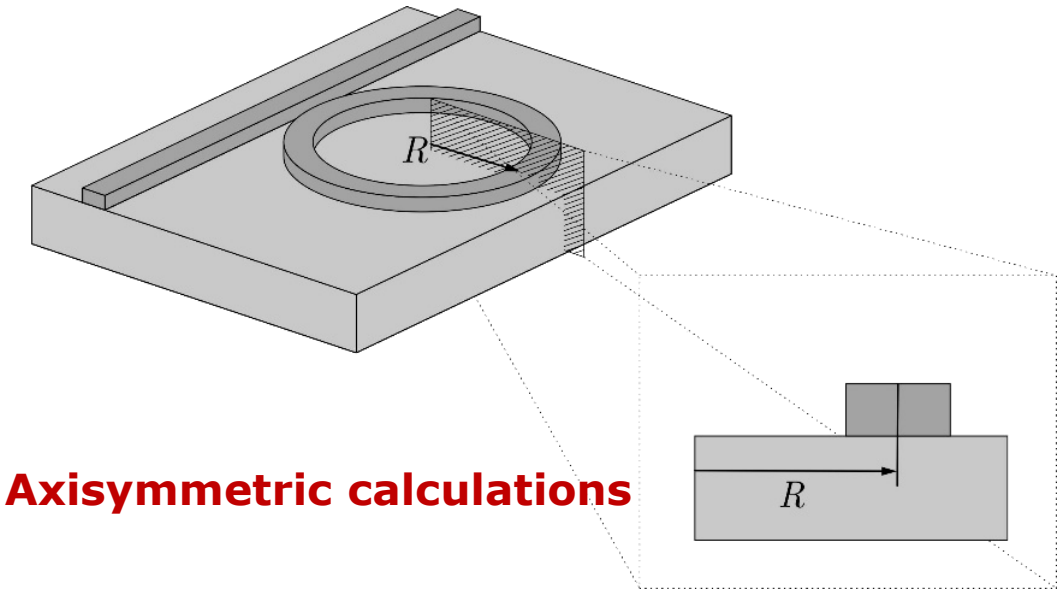
Maxwell Equations

- **Axisymmetric 2D eigenmode solver**
- n_{eff} of the bent waveguide

Coupled Mode Theory (CMT)

Calculate the power transmission T

Methods (II) – Axisymmetric eigenmode solver



Axisymmetric calculations

- Downgrades complex geometries
- Computationally cheap
- Highly accurate

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

Han, *Opt. Lett.* **38**, 1778-1780, 2013

Resonator radius

$$R = \frac{m\lambda_0}{2\pi \mathrm{Re}\{n_{\mathrm{eff}}\}}$$

m → azimuthal mode order

λ_0 → resonance wavelength

Quality factor

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

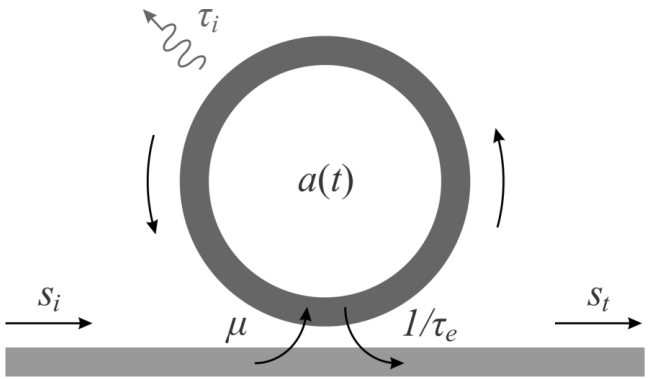
$n_g = \mathrm{Re}\{n_{\mathrm{eff}}\} - \lambda_0 \frac{\mathrm{dRe}\{n_{\mathrm{eff}}\}}{\mathrm{d}\lambda}$ → group index

$L = 2\pi R$ → resonator circumference

$a = \exp\{-\frac{2\pi}{\lambda_0}\mathrm{Im}\{n_{\mathrm{eff}}\}L\}$ → round-trip loss (resistive + radiation)

Bogaerts, *Laser Photonics Rev.* **6** (1), 47-73, 2012

Methods (III) – Coupled Mode Theory (CMT)



$$\frac{\mathrm{d}a}{\mathrm{d}t} = j\omega_0 a - \left(\frac{1}{\tau_i} + \frac{1}{\tau_e}\right) a + \mu s_i$$

$$s_t = s_i + \mu a$$

$a(t)$ → cavity amplitude, $|a|^2 \equiv W$

ω_0 → unperturbed resonance frequency

τ → photon lifetime, $\tau = 2Q/\omega_0$

μ → 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

Steady-state response

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

$$\mathrm{ER} = 10 \log \frac{T_{\text{high}}}{T_{\text{low}}} \to \infty$$

$$\mathrm{IL} = 10 \log T_{\text{high}} \to 0$$

$\delta = \tau_i(\omega - \omega_0)$ → normalized detuning

$r_Q = Q_i/Q_e$ → quality factor ratio

Low-power state

✓ Select low-loss state

- Input wave on resonance, $\delta = 0$
- Admit gap for critical coupling, $Q_i^{\text{low}} = Q_e \Longleftrightarrow r_Q = 1$

✓ $T_{\text{low}} = 0$

High-power state

✓ Modify resonance frequency, $\mathrm{Re}\{n_{\text{eff}}\}$, **and** losses, $\mathrm{Im}\{n_{\text{eff}}\}$

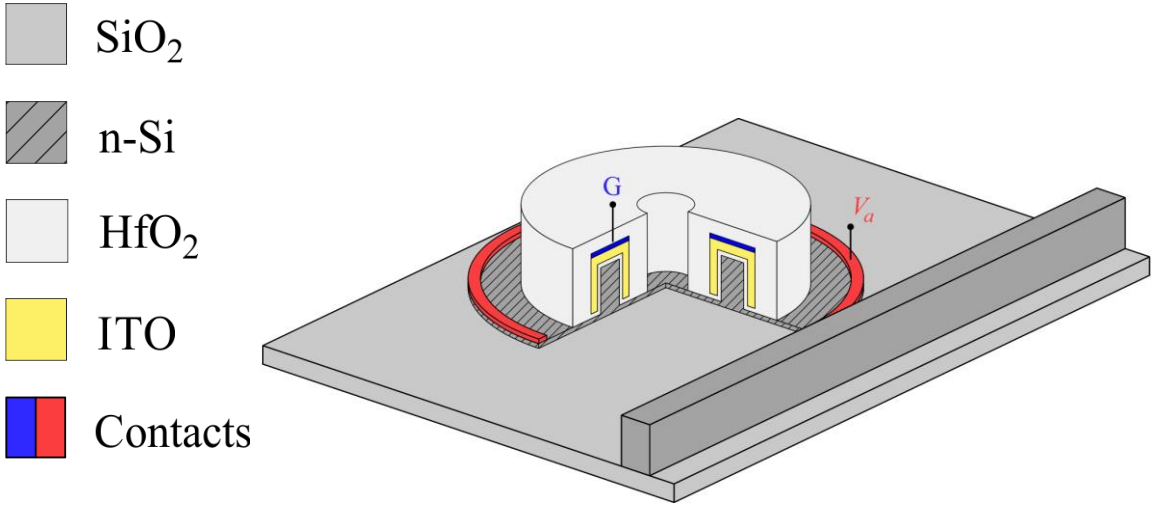
- Input wave (commonly) out of resonance $\delta \neq 0$
- Same gap → impair critical coupling, $Q_i^{\text{high}} << Q_i^{\text{low}} = Q_e$

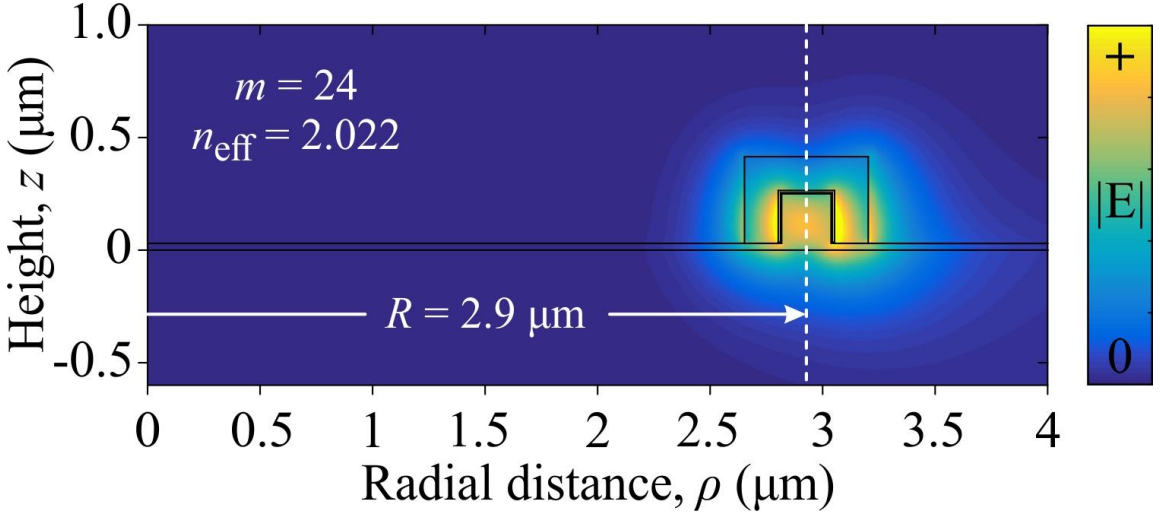
$(r_Q < 1)$

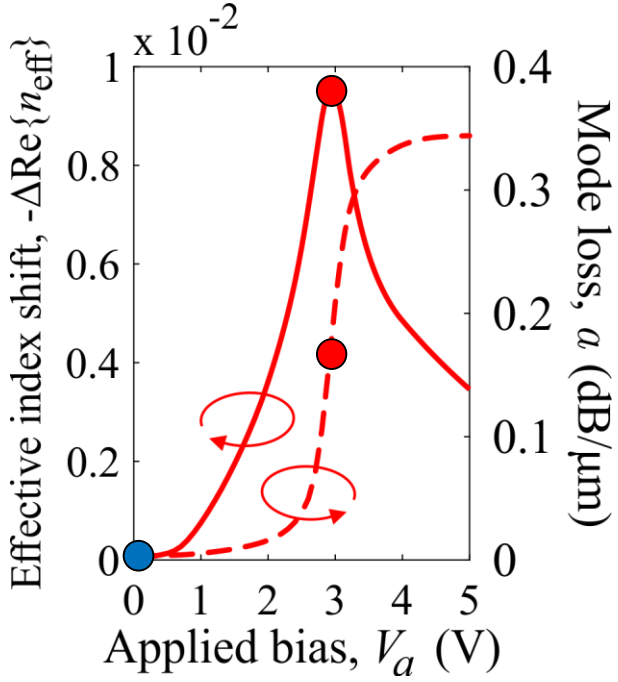
✓ $T_{\text{high}} \gg 0$

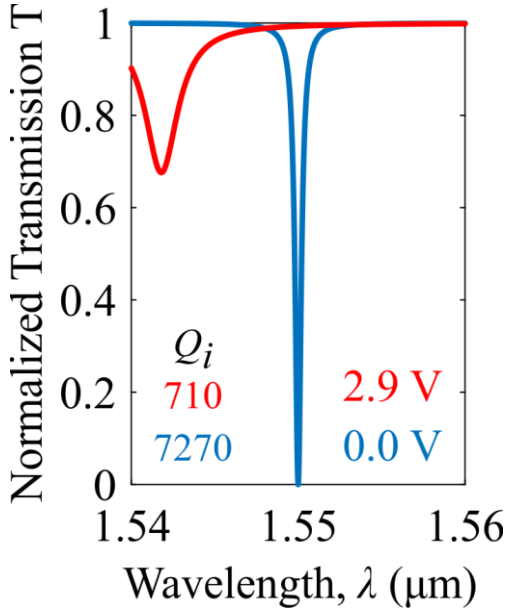
Christopoulos, *Phys. Rev. E* **94** (6), 062219, 2016
Tsilipakos, *J. Lightwave Technol.* **34** (4), 1333-1343, 2016

TCO-based resonator modulators – TE operation







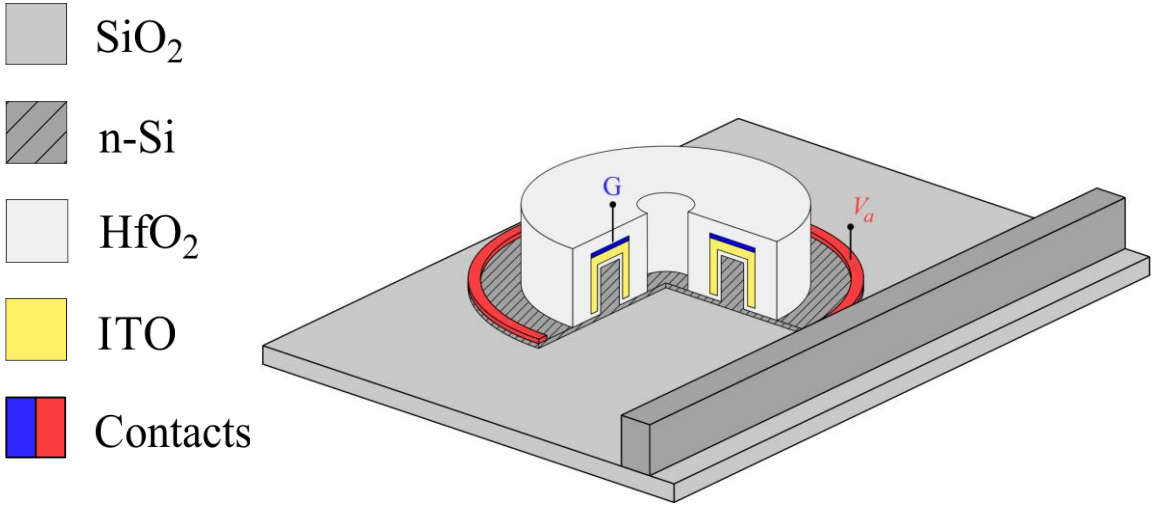


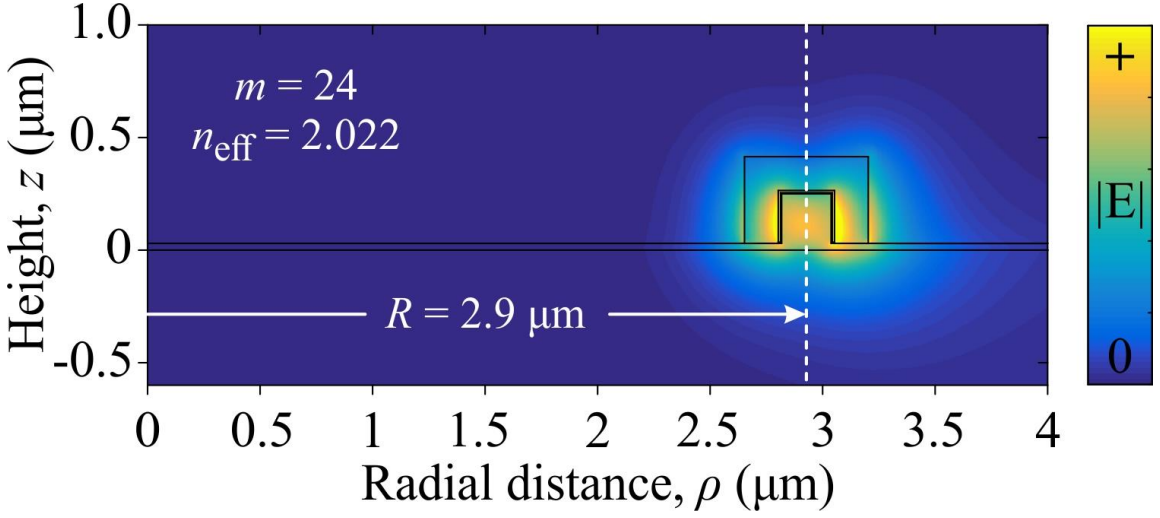
- w x h = 220 nm x 220 nm, $t_h = t_w$ = 150 nm
- Critical coupling at zero bias (low losses)
- Detuning + change in loss level

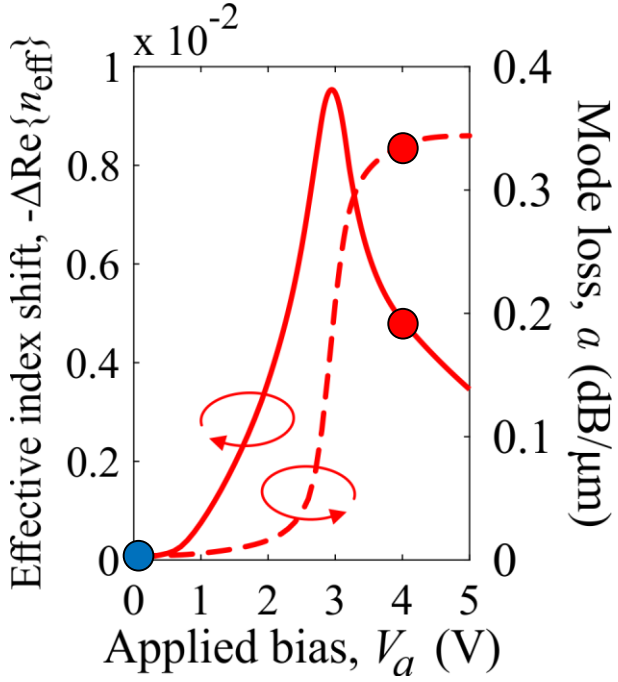
$$\lambda_{\mathrm{res}} = 1.550\ \mu\mathrm{m}$$

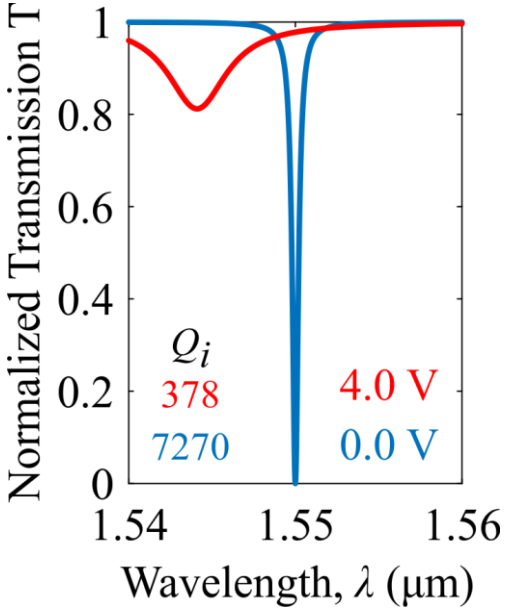
ER → ∞, IL = 0.03 dB

TCO-based resonator modulators – TE operation







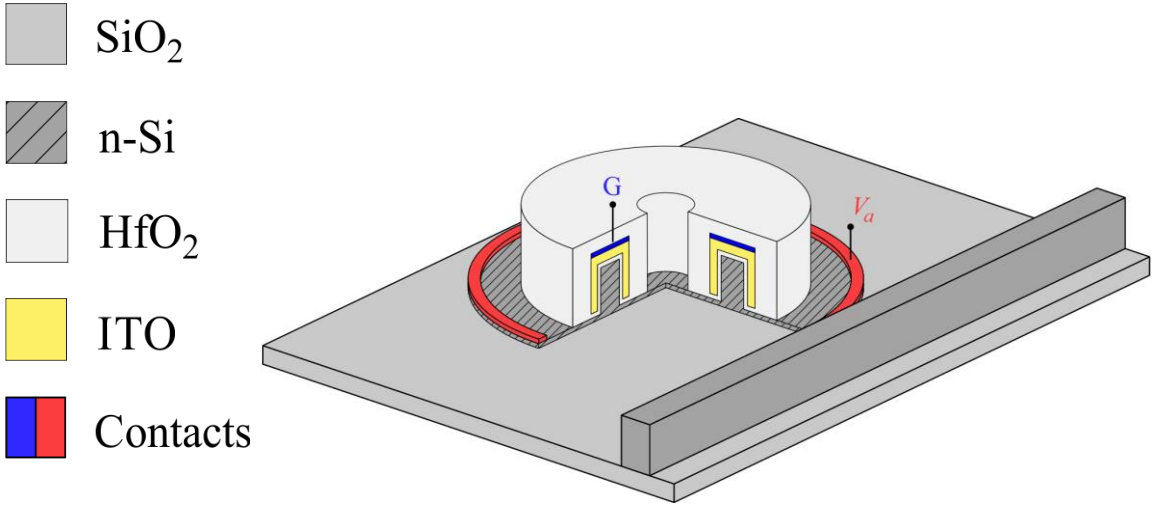


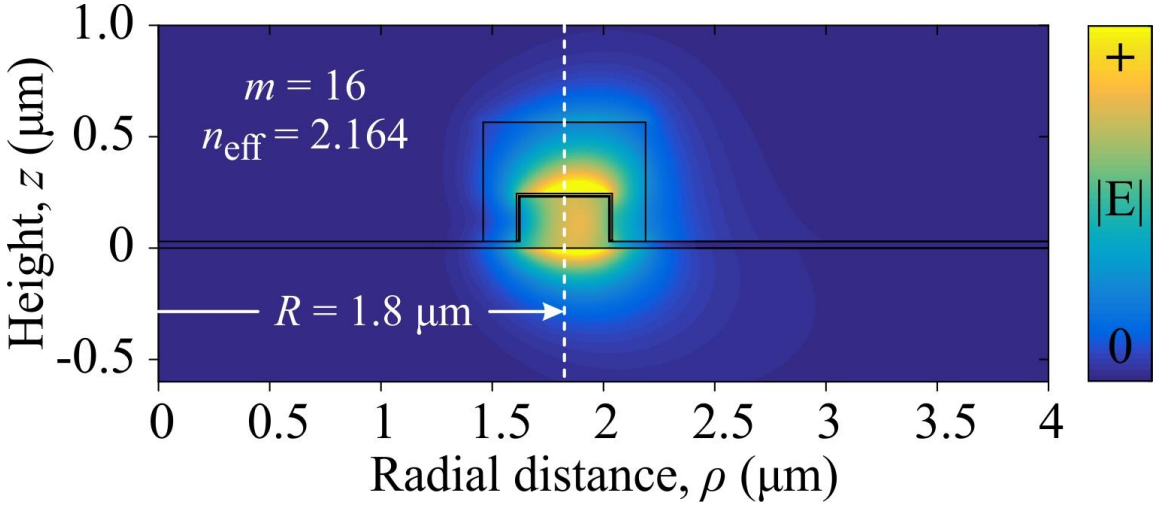
- w x h = 220 nm x 220 nm, $t_h = t_w$ = 150 nm
- Critical coupling at zero bias (low losses)
- Detuning + change in loss level

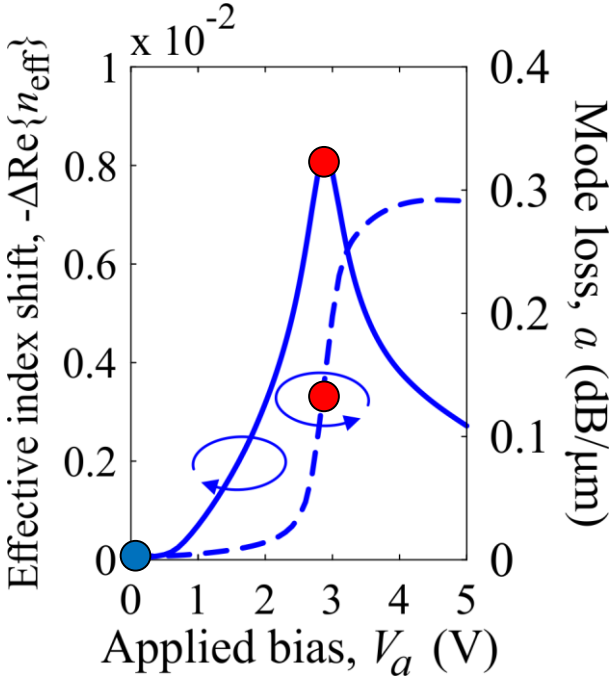
$$\lambda_{\text{res}} = 1.550\ \mu\text{m}$$

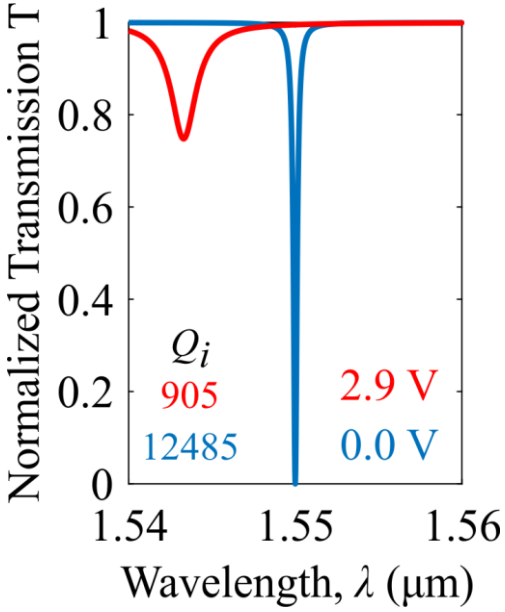
ER → ∞, IL = 0.10 dB

TCO-based resonator modulators – TM operation







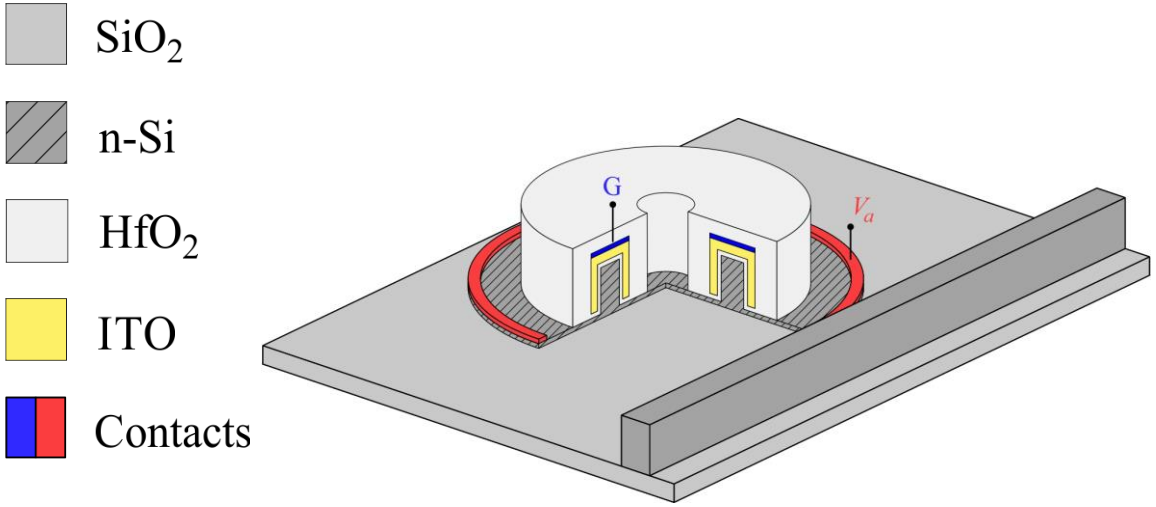


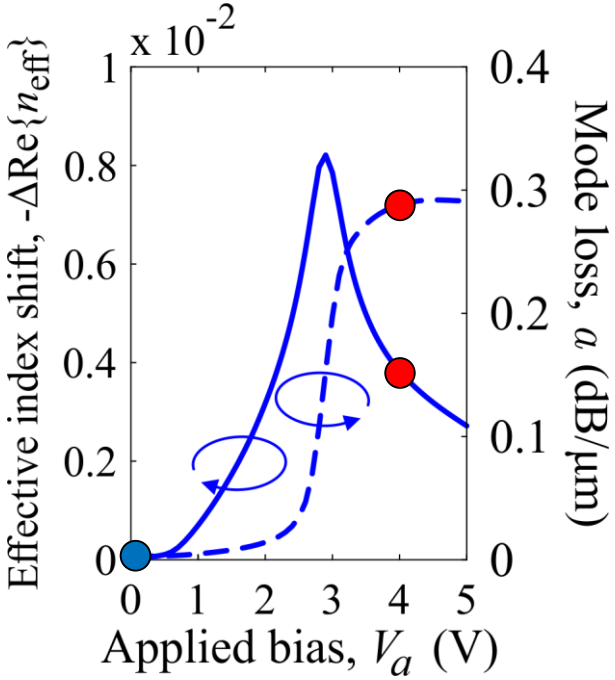
- w x h = 400 nm x 200 nm, t_h = 300 nm, t_w = 150 nm
- Critical coupling at zero bias (low losses)
- Detuning + change in loss level

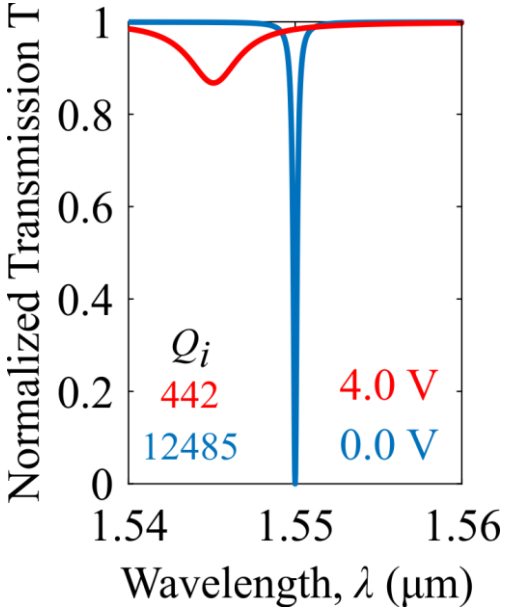
$$\lambda_{\text{res}} = 1.550\ \mu\text{m}$$

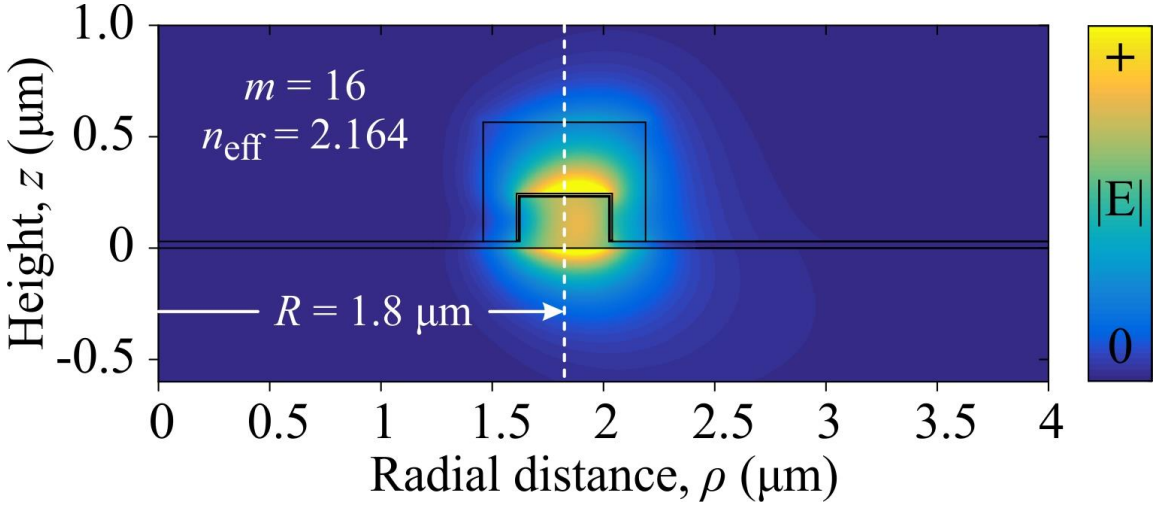
ER → ∞, IL = 0.02 dB

TCO-based resonator modulators – TM operation







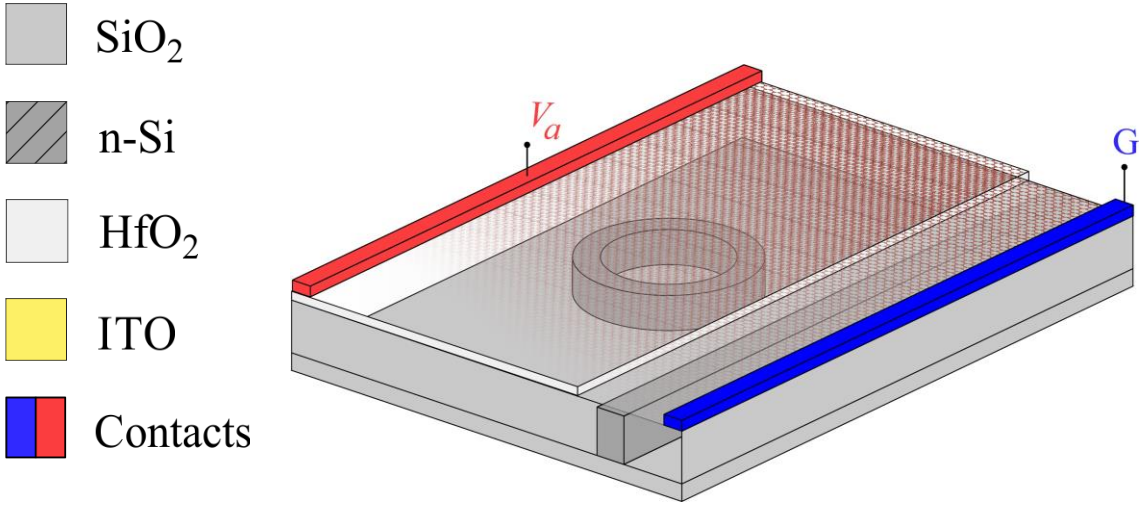


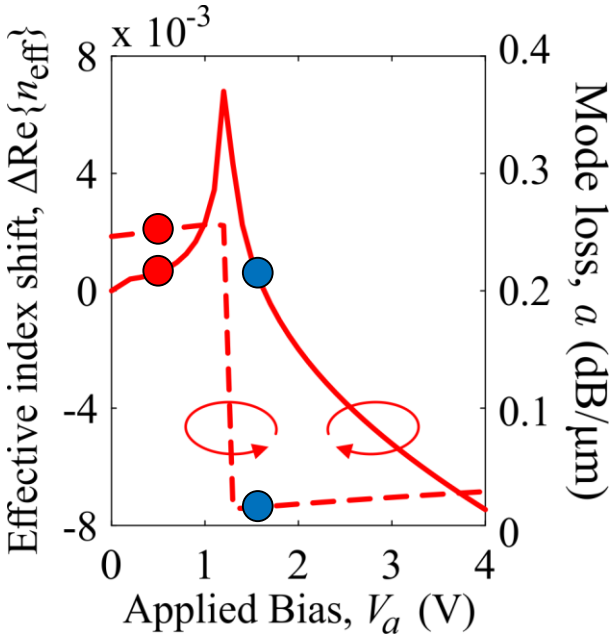
- w x h = 400 nm x 200 nm, t_h = 300 nm, t_w = 150 nm
- Critical coupling at zero bias (low losses)
- Detuning + change in loss level

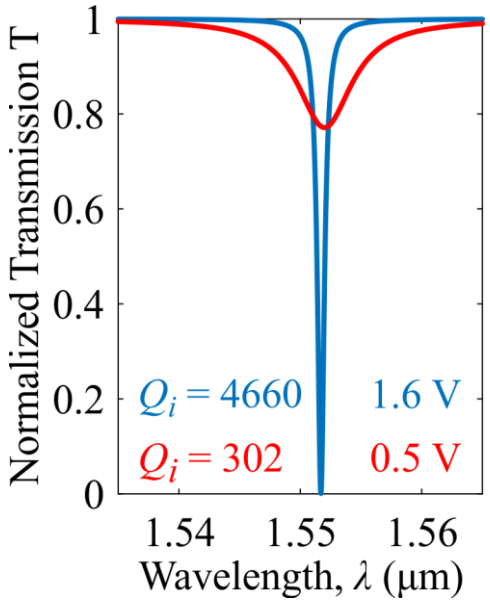
$$\lambda_{\text{res}} = 1.550\ \mu\text{m}$$

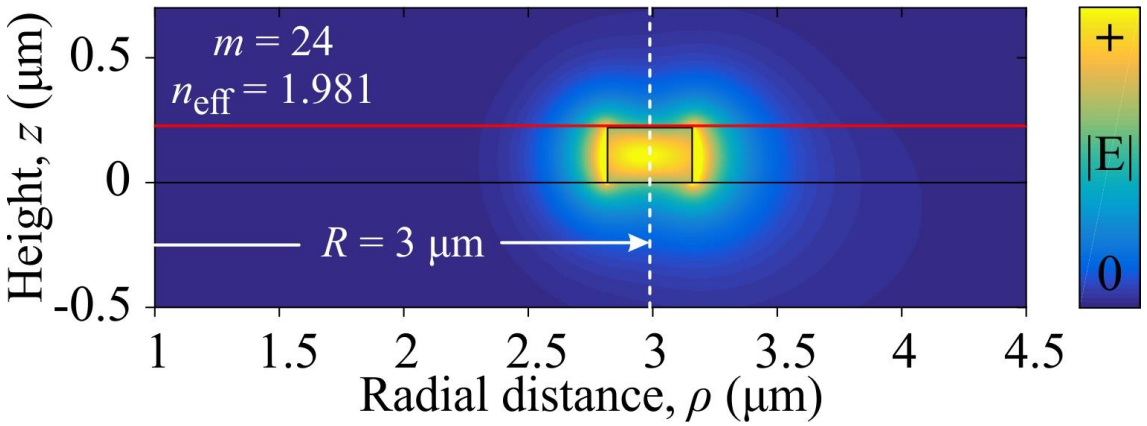
ER → ∞, IL = 0.07 dB

Graphene resonator modulators – TE operation







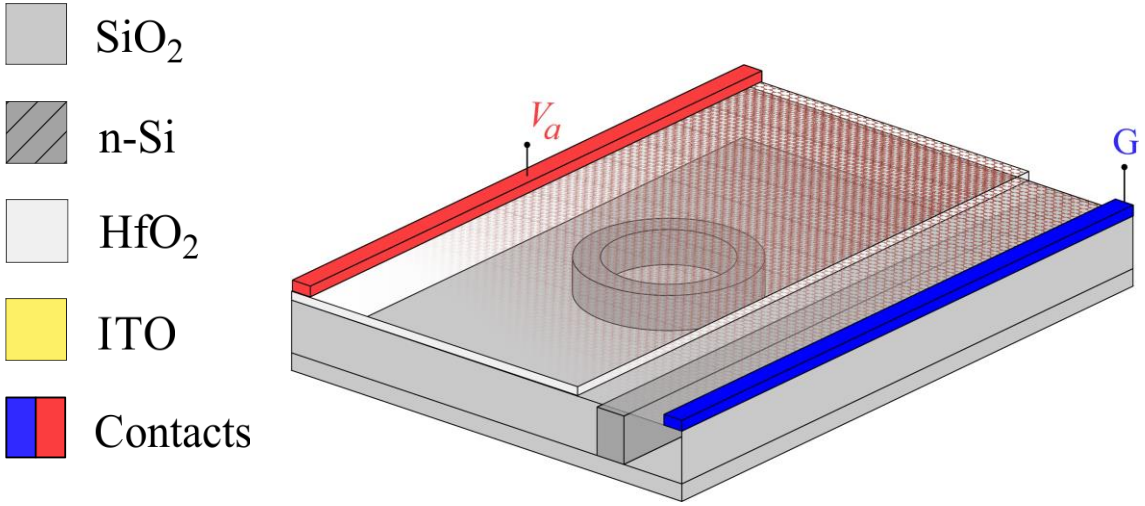


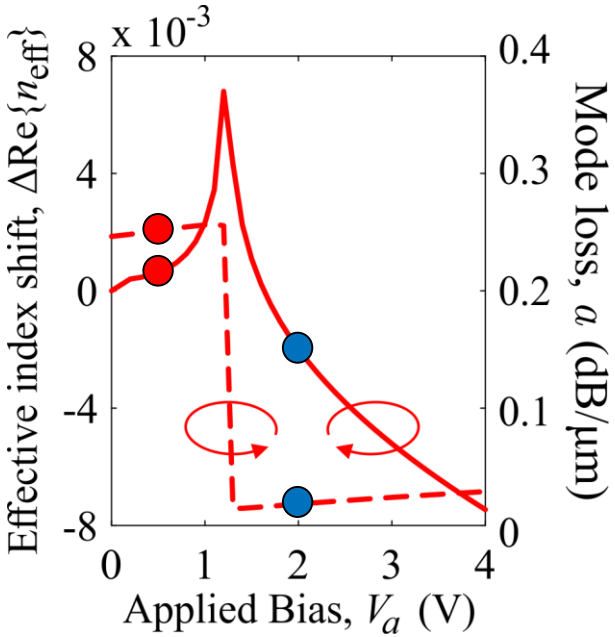
- w x h = 340 nm x 220 nm
- Critical coupling at high bias (low losses)
- No detuning, change in loss level

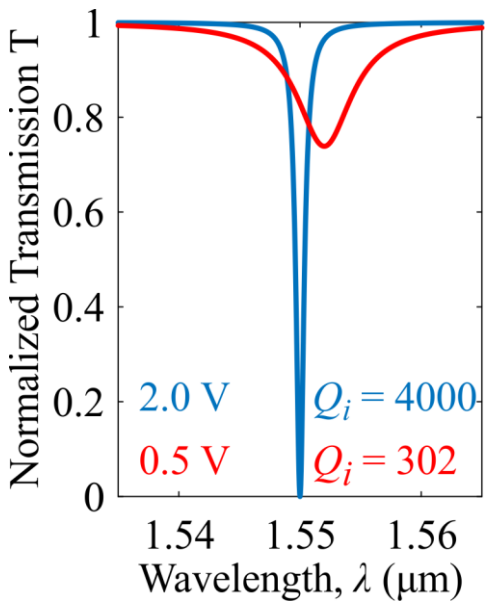
$$\lambda_{\text{res}} = 1.552\ \mu\text{m}$$

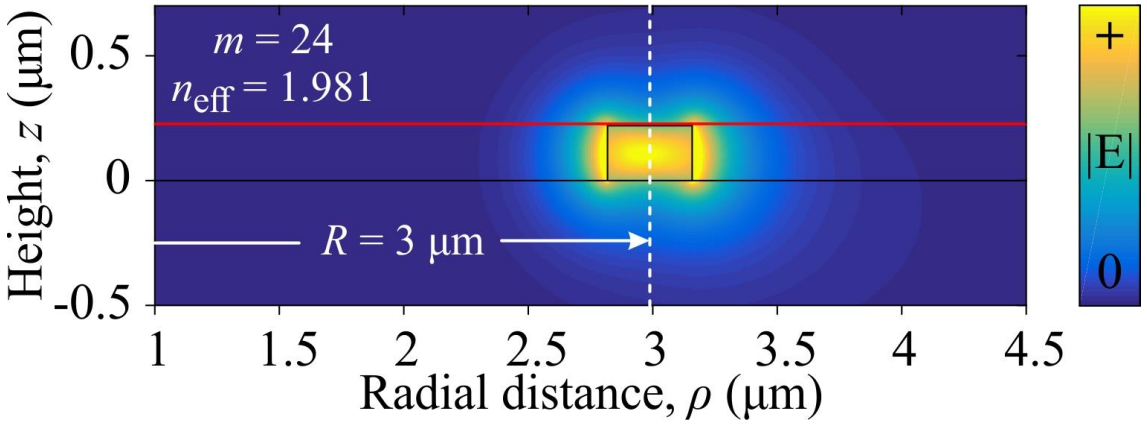
ER → ∞, IL = 1.11 dB

Graphene resonator modulators – TE operation







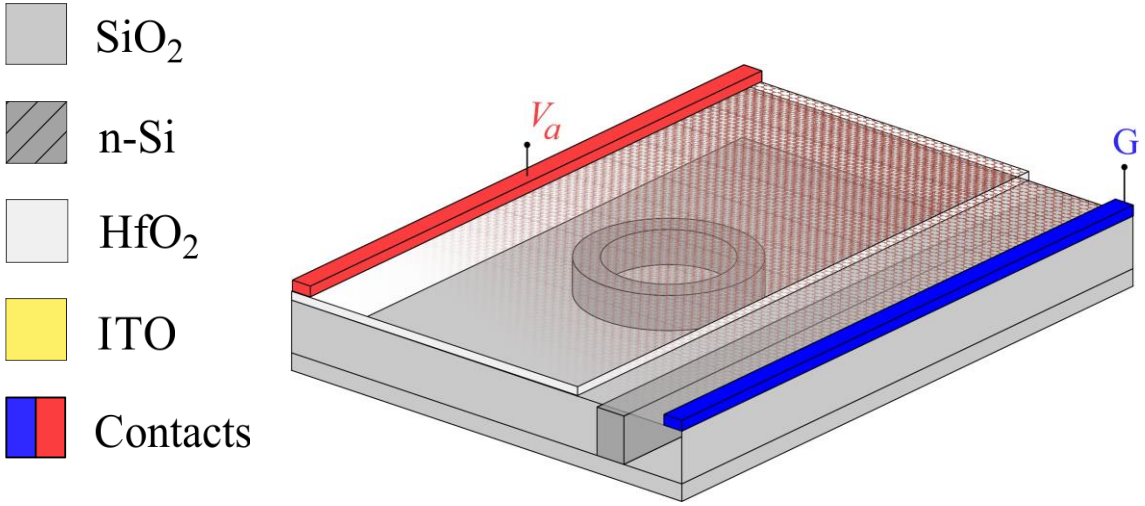


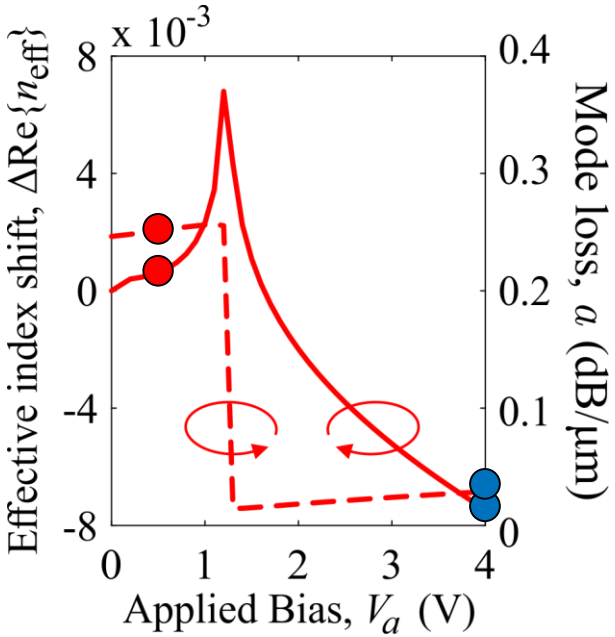
- w x h = 340 nm x 220 nm
- Critical coupling at high bias (low losses)
- Detuning + change in loss level

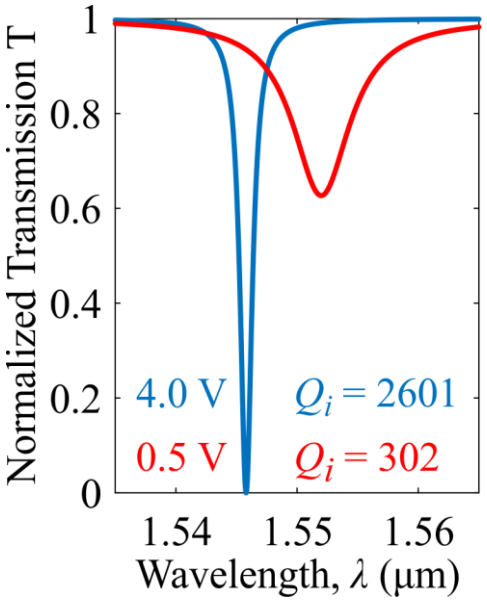
$$\lambda_{\mathrm{res}} = 1.550\ \mu\mathrm{m}$$

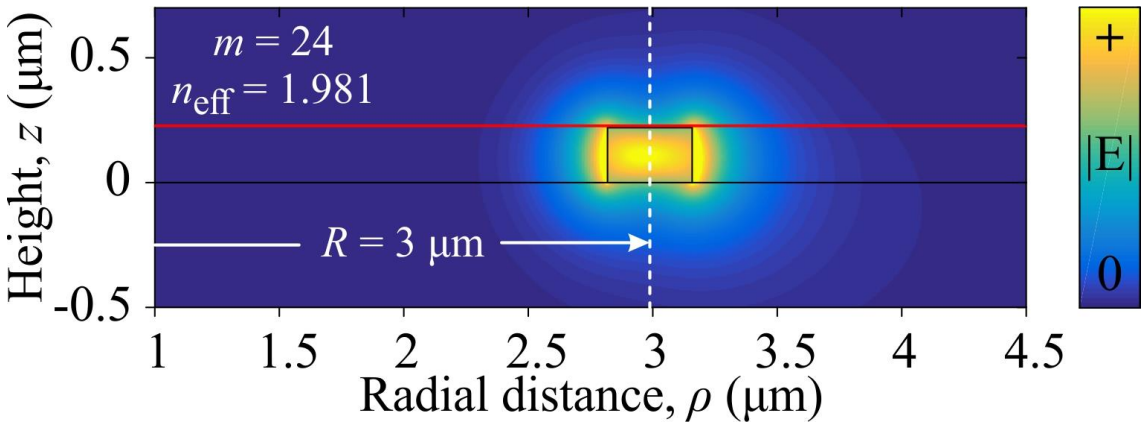
ER → ∞, IL = 0.81 dB

Graphene resonator modulators – TE operation







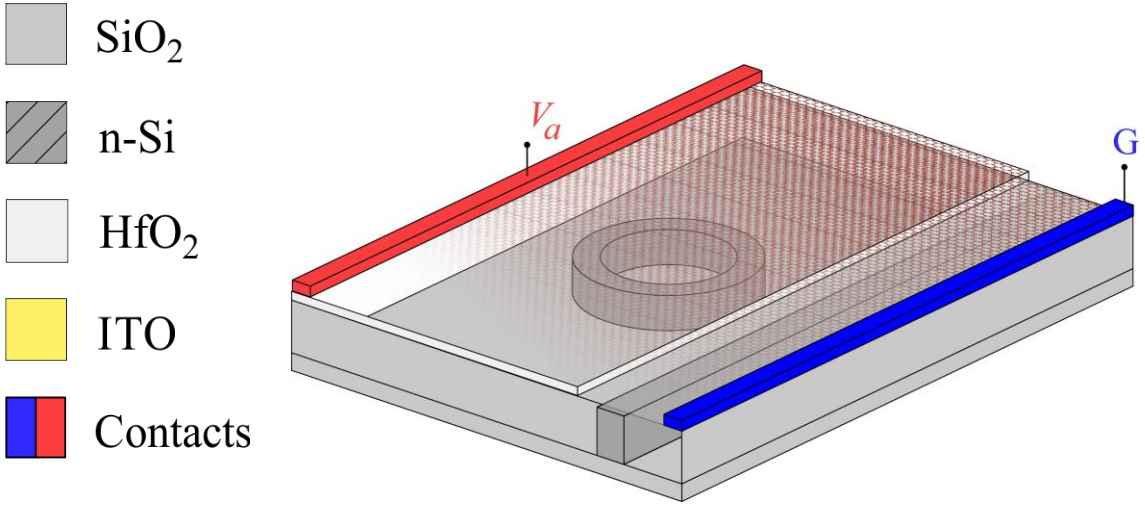


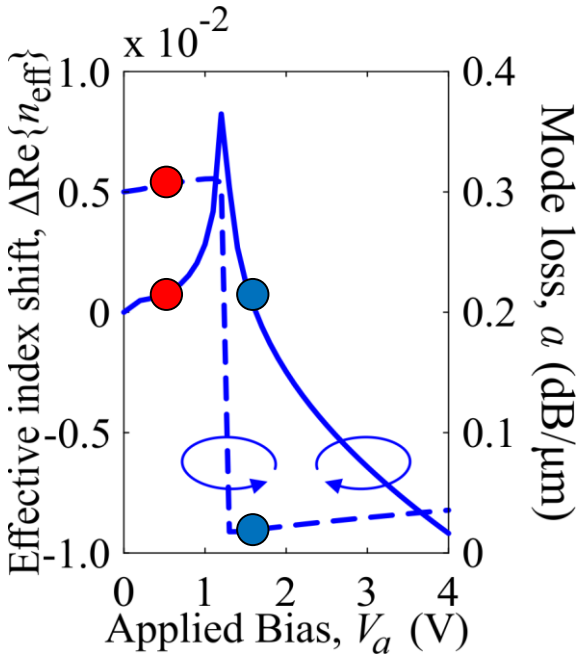
- w x h = 340 nm x 220 nm
- Critical coupling at high bias (low losses)
- Detuning + change in loss level

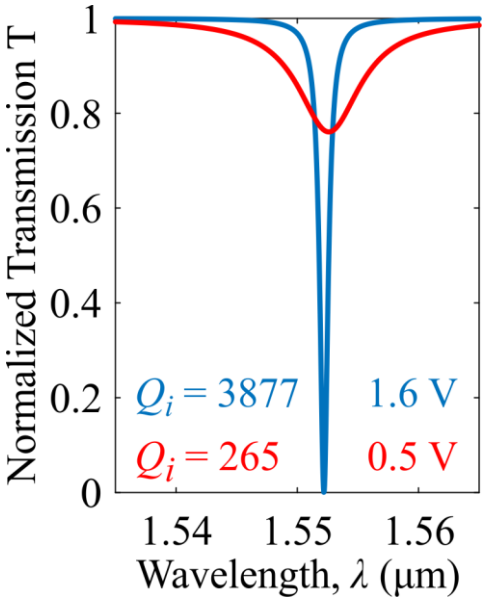
$$\lambda_{\text{res}} = 1.546\ \mu\text{m}$$

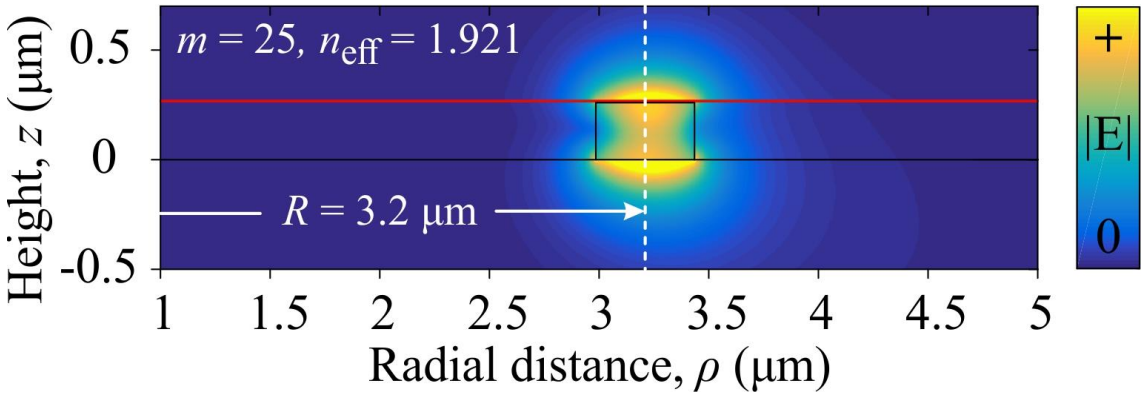
ER → ∞, IL = 0.30 dB

Graphene resonator modulators – TM operation







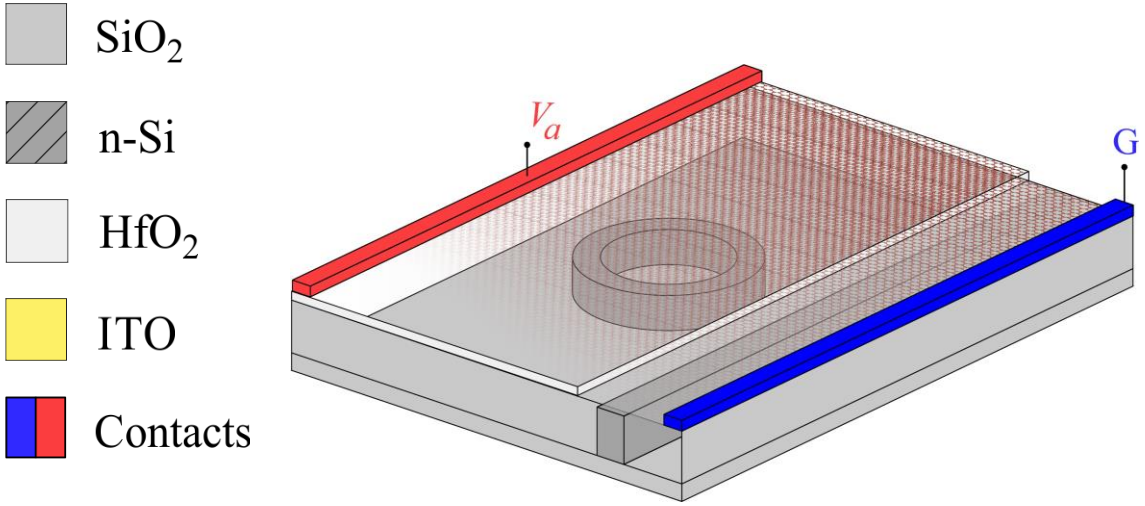


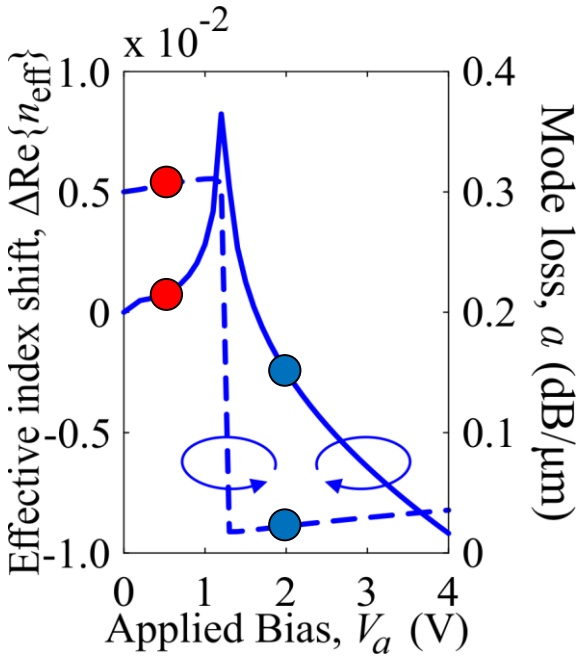
- w x h = 450 nm x 260 nm
- Critical coupling at high bias (low losses)
- No detuning, change in loss level

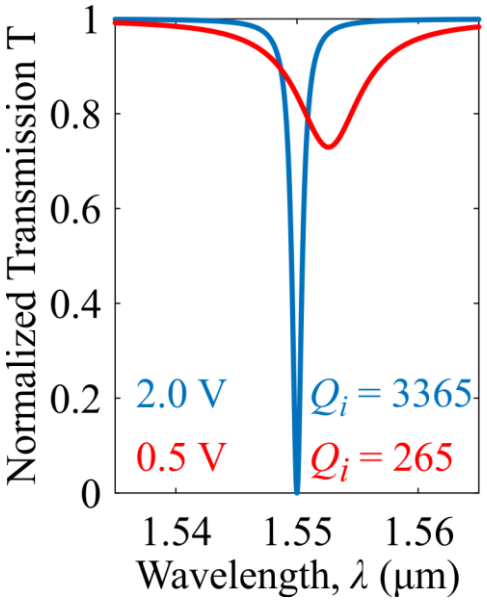
$$\lambda_{\mathrm{res}} = 1.552\ \mu\mathrm{m}$$

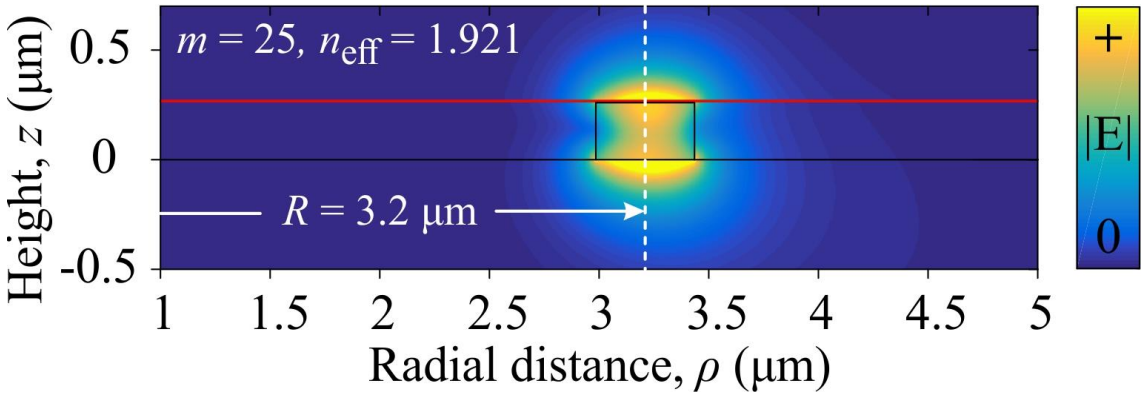
ER → ∞, IL = 1.18 dB

Graphene resonator modulators – TM operation







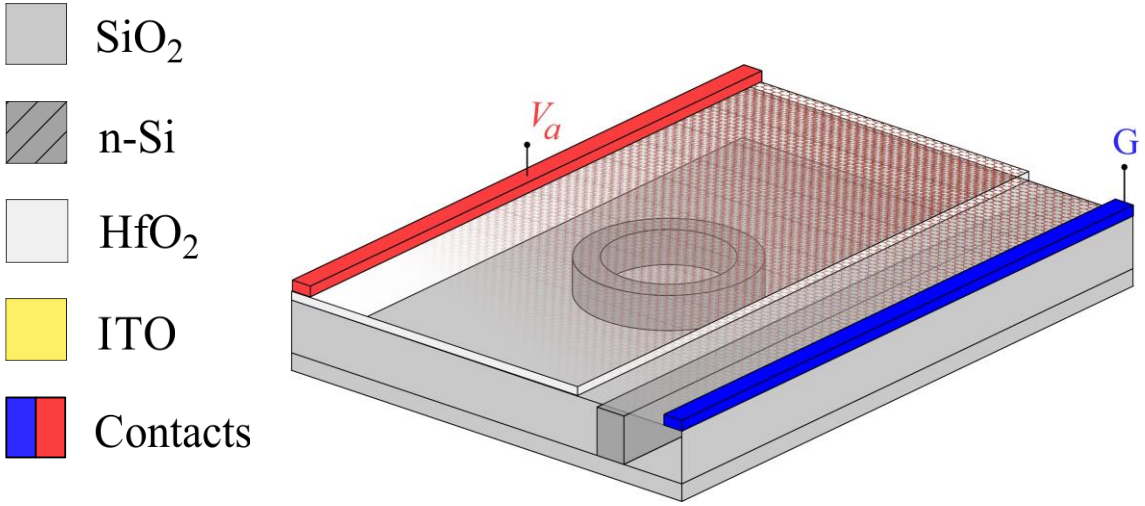


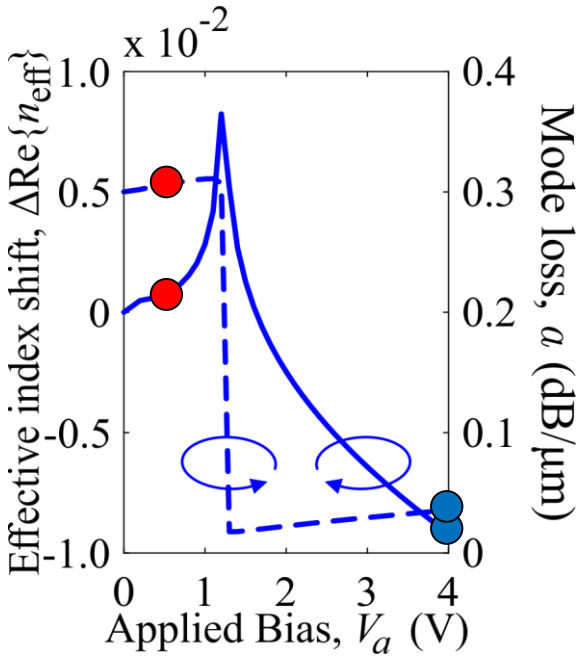
- w x h = 450 nm x 260 nm
- Critical coupling at high bias (low losses)
- Detuning + change in loss level

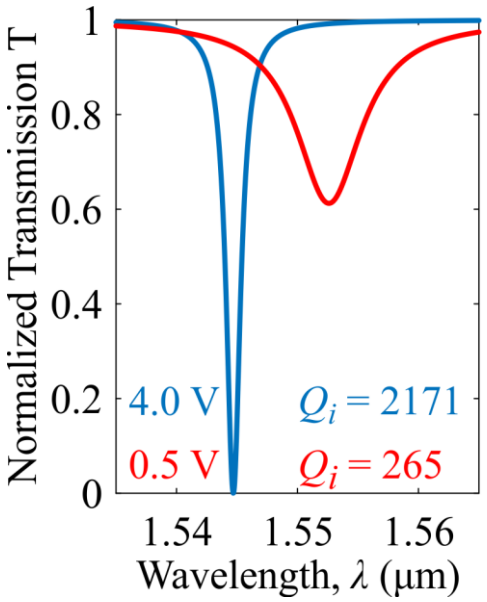
$$\lambda_{\mathrm{res}} = 1.550\ \mu\mathrm{m}$$

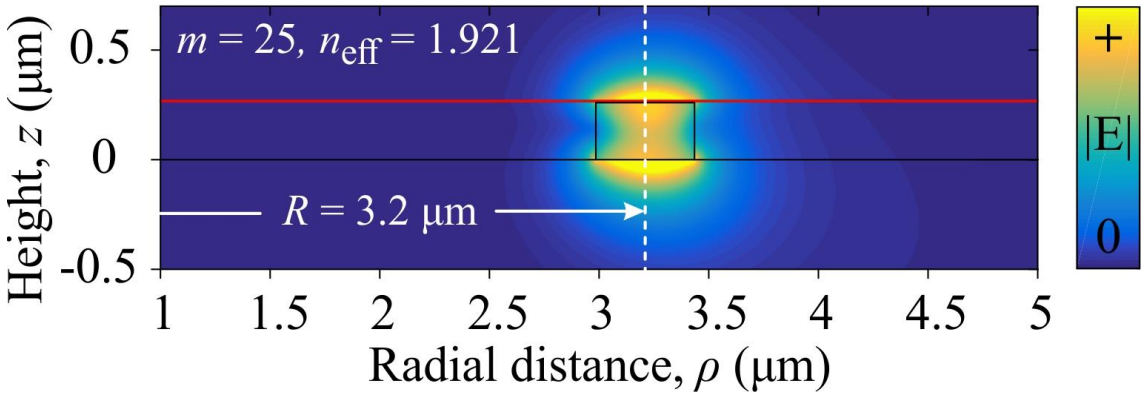
ER → ∞, IL = 0.78 dB

Graphene resonator modulators – TM operation









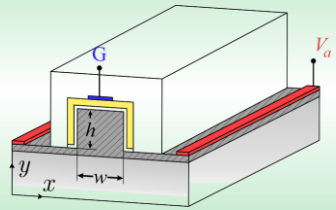
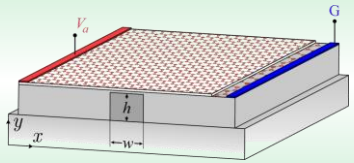
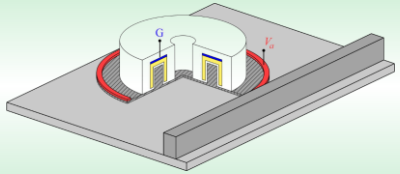
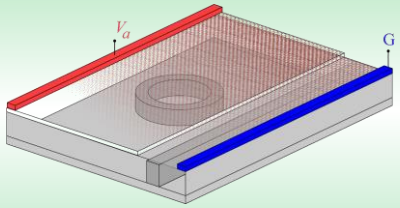
- w x h = 450 nm x 260 nm
- Critical coupling at high bias (low losses)
- Detuning + change in loss level

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

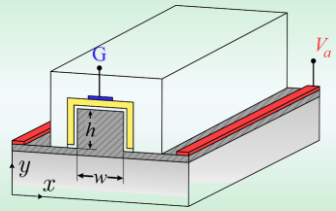
ER → ∞, IL = 0.27 dB

Summary & Conclusions

TCO-based & Graphene modulators comparison

Platform	Mode	Footprint (μm^2)	ER (dB)	IL (dB)	Bias swing	Intrinsic BW
	TE	14.5	10	0.10	0 V ↔ 4 V	~ 150 GHz
	TM	24.5	10	0.10	0 V ↔ 4 V	~ 150 GHz
	TE	14.6	10	0.86	0.5 V ↔ 2 V	Externally limited
	TM	15.8	10	0.78	0.5 V ↔ 2 V	Externally limited
	TE	26.4	Theoretically Inf.	0.03	0 V ↔ 2.9 V	~ 80 GHz
	TM	10.2	Theoretically Inf.	0.02	0 V ↔ 2.9 V	~50 GHz
	TE	28.3	Theoretically Inf.	0.30	0.5 V ↔ 4 V	~ 230 GHz
	TM	32.2	Theoretically Inf.	0.27	0.5 V ↔ 4 V	~ 280 GHz

TCO-based & Graphene modulators comparison

Platform	Mode	Footprint (μm^2)	ER (dB)	IL (dB)	Bias swing	Intrinsic BW
	TE	14.5	10	0.10	0 V ↔ 4 V	~ 150 GHz
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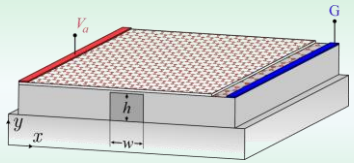	TE	14.6	10	0.86	0.5 V ↔ 2 V	Externally limited
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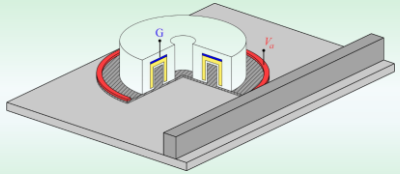	TE	26.4	Theoretically Inf.	0.03	0 V ↔ 2.9 V	~ 80 GHz
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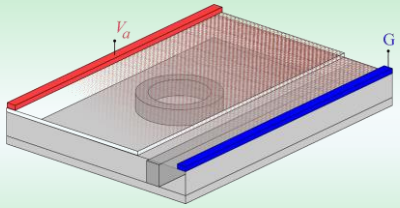	TE	28.3	Theoretically Inf.	0.30	0.5 V ↔ 4 V	~ 230 GHz
	TM	32.2	Theoretically Inf.	0.27	0.5 V ↔ 4 V	~ 280 GHz

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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Ευρωπαϊκή Ένωση
Ευρωπαϊκό Κοινωνικό Ταμείο

Επιχειρησιακό Πρόγραμμα
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Ειδική Υπηρεσία Διαχείρισης
Με τη συγχρηματοδότηση της Ελλάδας και της Ευρωπαϊκής Ένωσης

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