Electro-Optic Plasmon Modulators: Breaking Photonic Limits

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Active Material

is a key component of any electro-optic modulator design. A combination of both modulation ability and light-matter-interaction response are critical for increased efficiency and device performance. Here we examine the free carrier and dispersive index tuning ability of two emerging active materials (Graphene and Indium Tin Oxide (ITO)) and the way we use these materials to modulate a light signal.

Refractive Index

can be compared to the more recognized electrical imedance equation. The the formula for the complex refractive index ($\tilde{n}$) also has two parts:

The Lossy Factor

$$\tilde{n} = n + ki \qquad Z = R + j\omega X$$

The Phase Factor

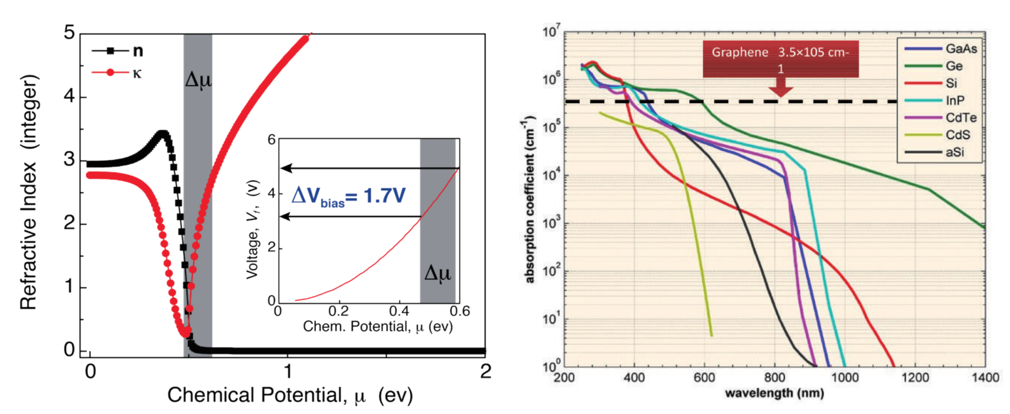
The real part of the refractive index (n) indicates the speed of the light's propogating phase, while the imaginary part of the refractive index quantifies the optical absorption (i.e., loss) of the media. Changing the optical loss is the key mechanism for these proposed electro-optic modulators. We are able to acheive this by altering the electrical carrier density of the device via an applied voltage bias. The refractive index of a medium can be related to its complex relative dialetric constant, $\hat{\epsilon_r}$.

$$\tilde{\epsilon_r} = \epsilon_1 + i\epsilon_2 \quad \begin{cases} \epsilon_1 = n^2 - \kappa^2 \\ \epsilon_2 = 2n\kappa \end{cases}$$

Graphene

$$\varepsilon_{eff}(\mu_c) = 1 - \frac{\sigma_v}{j\omega\varepsilon_0} = 1 - \frac{\sigma_g}{j\omega\varepsilon_0\Delta}$$

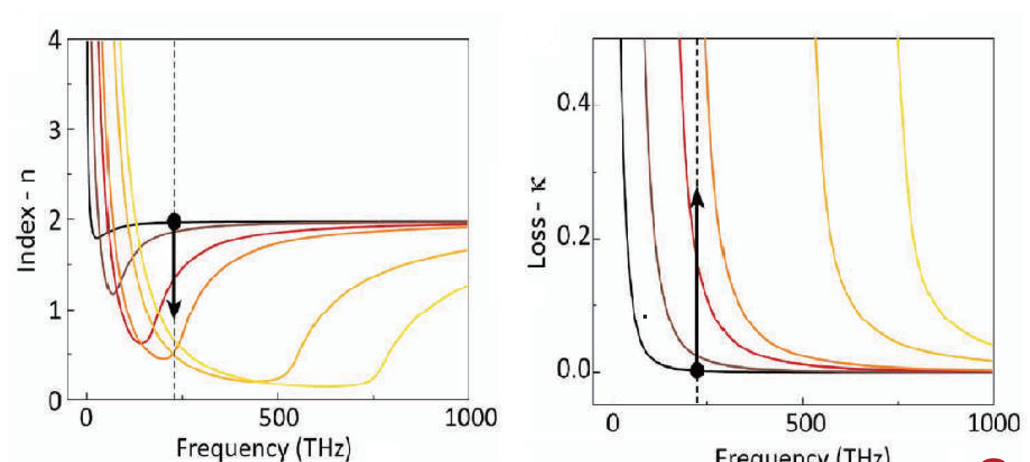
Δ=effective thickness of graphene
σ =electrical conductivity
ε_0 =permitivity of free space
ω =light angular frequency



Indium Tin Oxide

$$\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)}; \quad \omega_p^2 = \frac{n_c e^2}{\varepsilon_0 m^*}$$

ε_∞ =long-angular-momentum-limit permitivity
ε_0 =permitivity of free space
ω =angular momentum (rad/s)
γ =electron scattering rate



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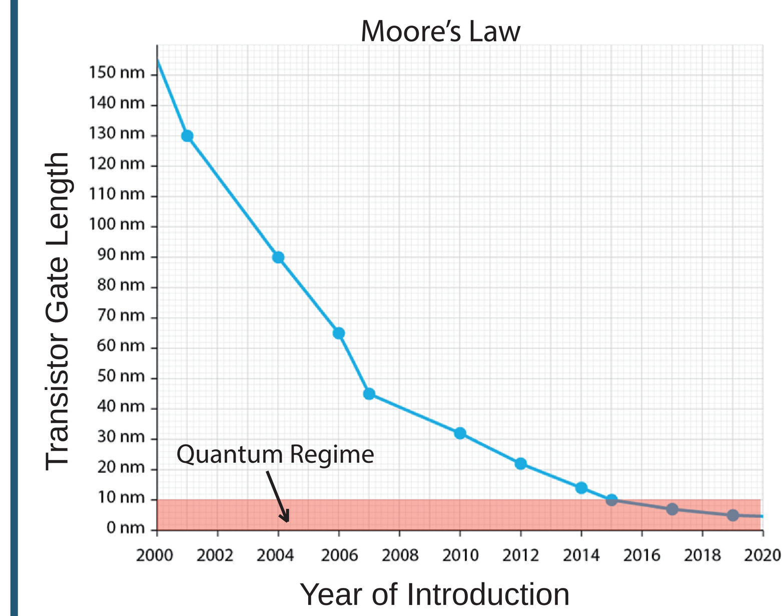
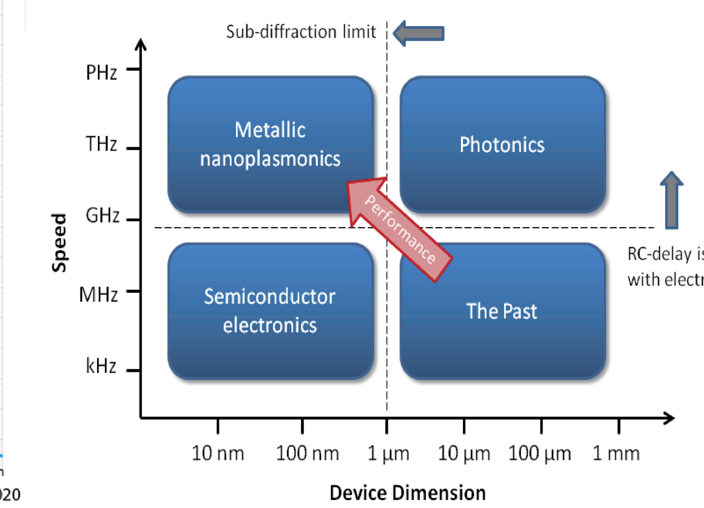
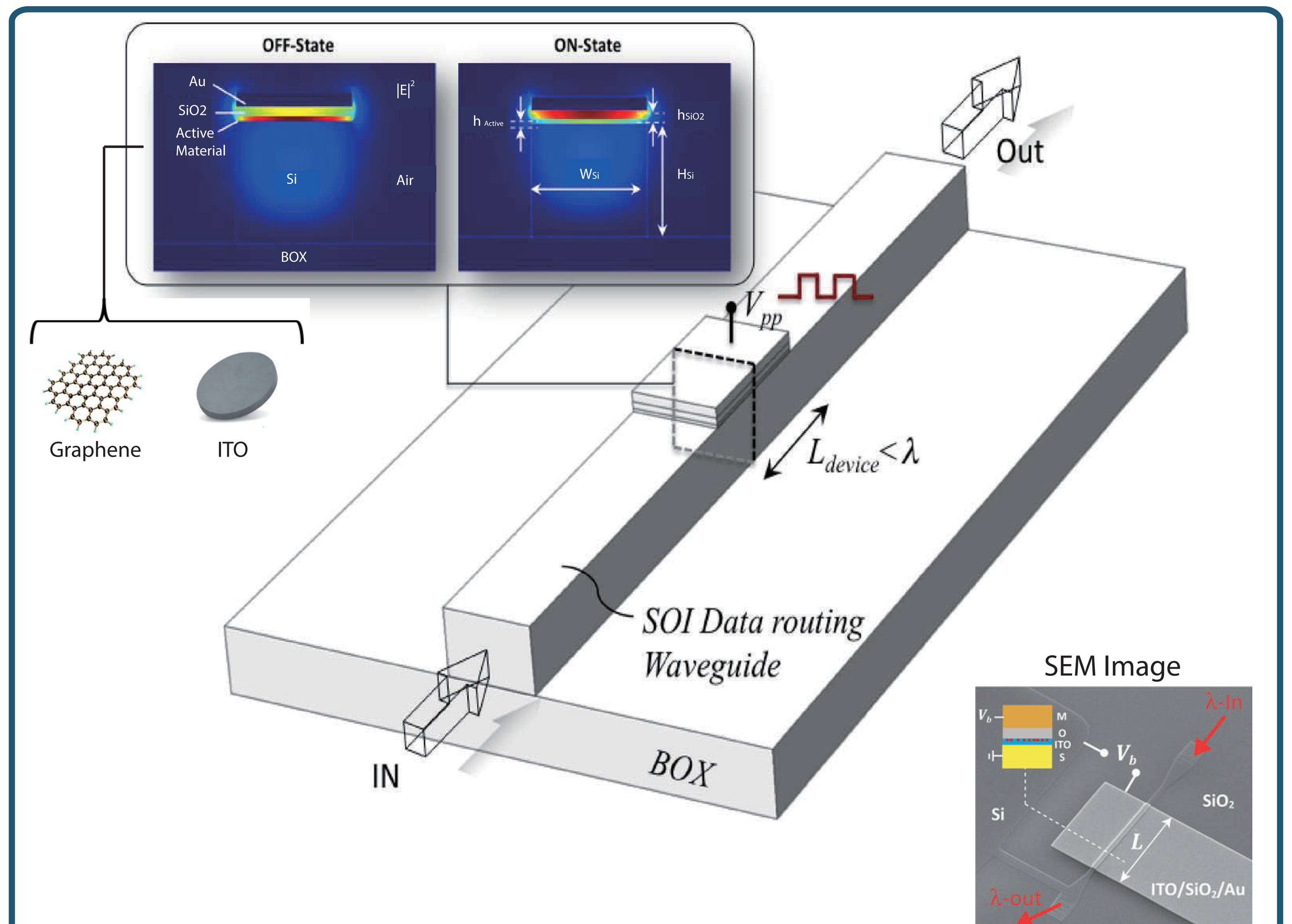
Motivation







Device Performance

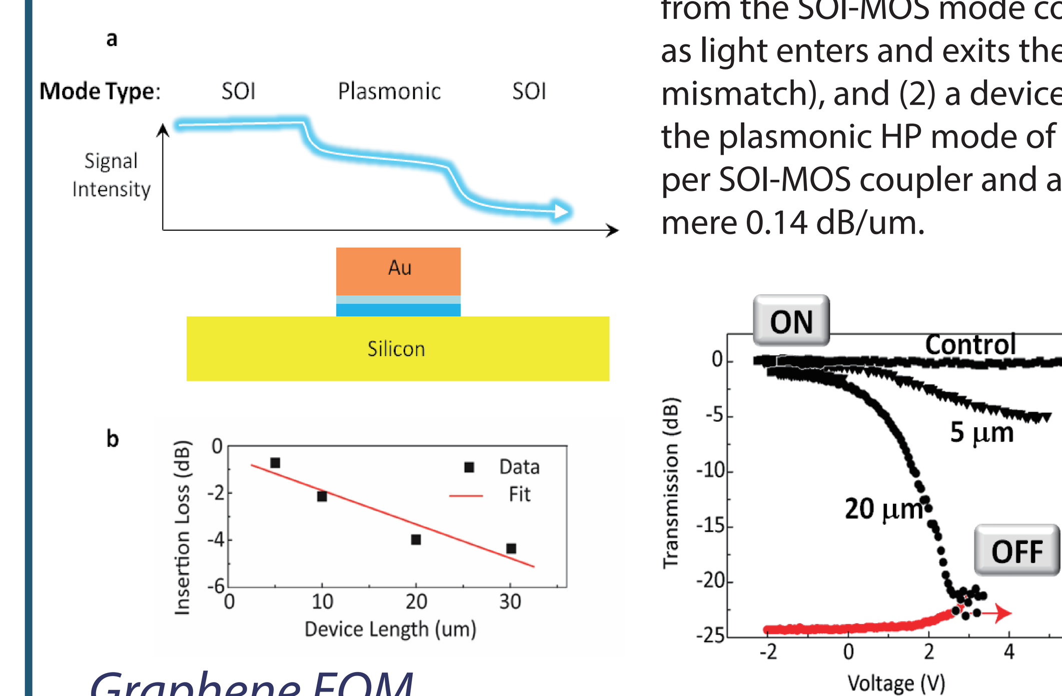
The key performance figures of an EOM are power consumption (i.e. E/bit) and 3dB bandwidth (i.e. speed). The performance optimization device dimensions include silicon waveguide core width and thickness, gate oxide thickness, the active material thickness, and the device length. Similarly, the modulor's extinction ratio (ER) and insertion loss (IL) performance depends on the plasmonic HP MOS mode, which can be modified by altering the geometric parameters of the EOM.

$$IL = \frac{P_{in} - P_{out}(V_b = V_{ON})}{P_{in}} = 1 - \frac{T(L, \alpha_{ON})}{T_0} = 1 - e^{-\alpha_{ON}L} = 1 - e^{\wedge}\left(-\frac{4\pi\kappa_{ON}}{\lambda}L\right)$$

$$ER = \frac{P_{out}(V_b = V_{OFF})}{P_{out}(V_b = V_{ON})} = \frac{T(L, \Delta\alpha)}{T_0} \rightarrow \eta_{mod} = \frac{ER}{V_{pp}}$$

Indium Tin Oxide EOM

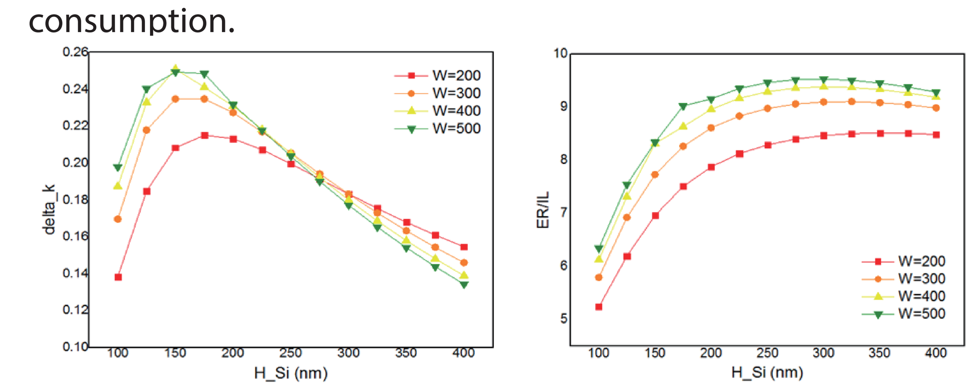
We verify a low insertion loss of a mere -1dB/um. The two loss contributions in this device are quantitatively depicted in Figure (a) (left); (1) a device length independent loss originating from the SOI-MOS mode coupling indicating a signal intensity drop as light enters and exits theplasmonic mode (due to impedance mismatch), and (2) a device length dependent loss originating from the plasmonic HP mode of the device. Measurements indicate 0.25dB per SOI-MOS coupler and a plasmonic MOS propogation loss of a mere 0.14 dB/um.



ITO EOM	
Device Length	1 µm
V_{pp}	1V
Insertion Loss	0.7 dB
Extinction Ratio	6 dB/µm
E/bit	0.47-1.06 fJ

Graphene EOM

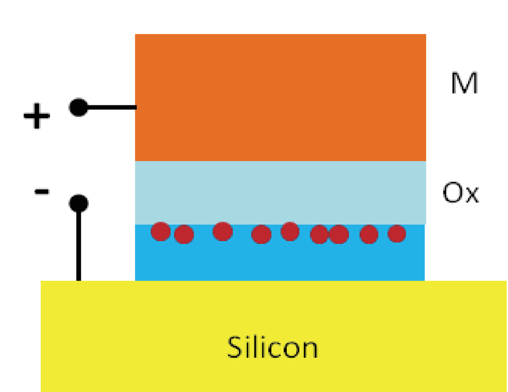
Using the values from the complex index of refaction of graphene, the MOS field distribution changes between the modulator absorbing OFF and light-through ON state were calculated using a numerical finite element solver (Comsol). Various geometrical parameters were swept within Comsol with the goal of producing an optimized device design that exhibited a high extinction ratio and low power consumption.

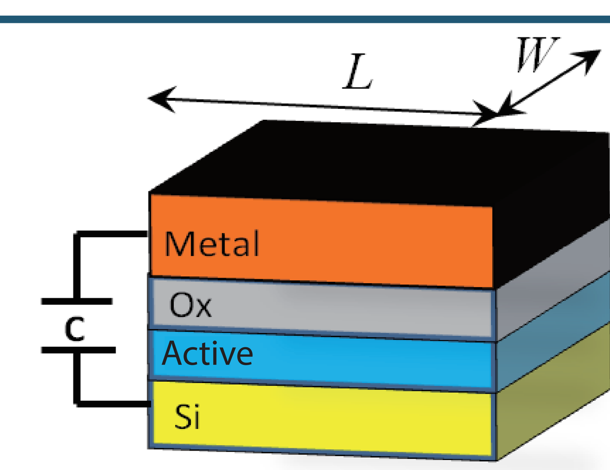


Graphene EOM	
Device Length	0.5 µm
V_{pp}	1-2V
Insertion Loss	0.53 dB
Extinction Ratio	4 dB/µm
E/bit	0.33-1.32 fJ

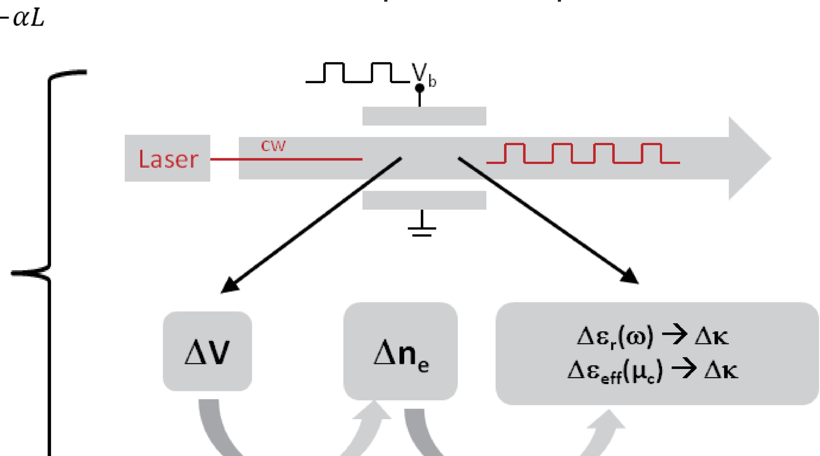
Device Structure

The structure of both of our hybrid plasmonic EOMs consists of an SOI waveguide and an a graphene/ITO - SiO2 - Au stack integrated on top. This specific configuration of materials forms a plasmonic HP mode and the Metal-Oxide-Semiconductor (MOS) capacitor, with the accumulation layer occuring at the active material's interface when a voltage bias is applied between the Gold and Silicon. Notice that this synergistic design allows for the triple use of the metal contact, namely (1) to form the HP mode, (2) to act as a heat sink, and (3) as an electrical electrode transporting the electrical data to the EOM gate, thus enabling for an ultra-compact design. Moreover, the overall length of the MOS stack is a mere 0.5um and 1um for the graphene - EOM and ITO - EOM, respectively. This compact device size is acheivable due to (1) the active materials ability to dramatically change its extinction coefficient (the imaginary part of the refractive index), and (2) the good overlap between the MOS mode and the active material. Notice that the peak of the electric field intensity across the MOS mode coincides per design directly with the area of the active material layer. Thus, when an electrical voltage is applied across our MOS capacitor, it forms an accumulation layer at the graphene/ITO-SiO2 interface, which in turn increases the active material's carrier density and, consequently, raises the extinction coefficient, k. This k-increase controls the optical absorption (i.e., the OFF-state) via Bear's law: $T(V) = Te^{-\alpha L}$



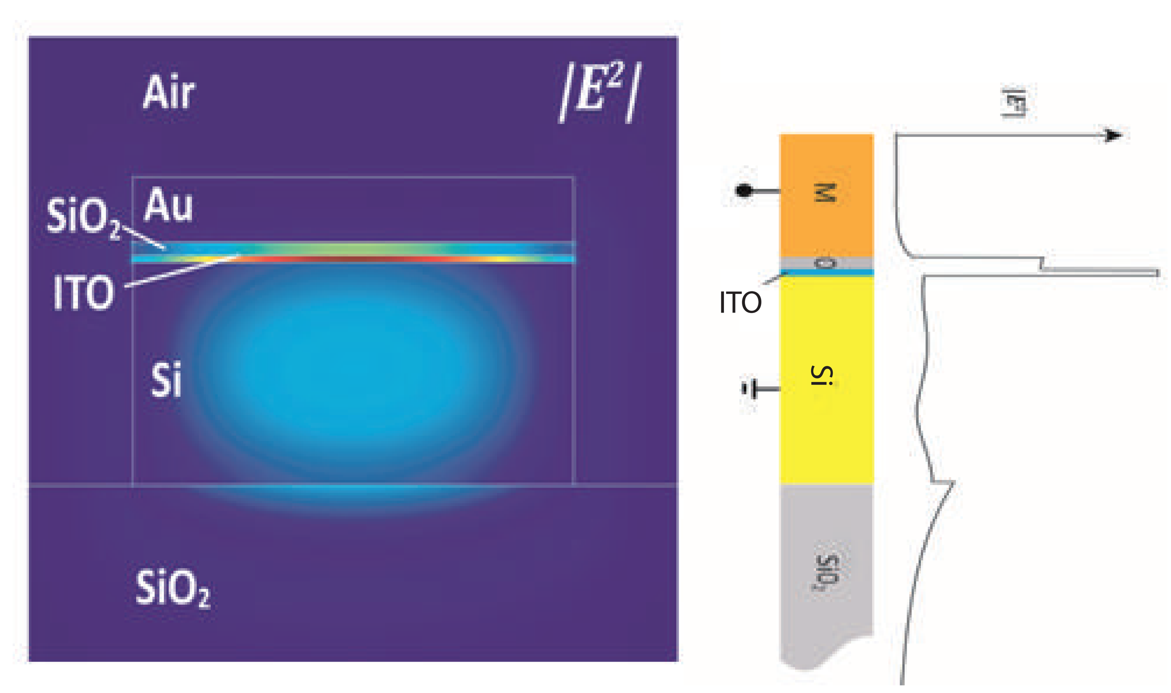


Modulation Mechanism



Advantages

- ✓ Ultra compact size
- ✓ Strong light-matter interaction
- ✓ Synergy: metal has multiple purposes
  - Confining optical field
  - Electrical contact
  - Heat sink



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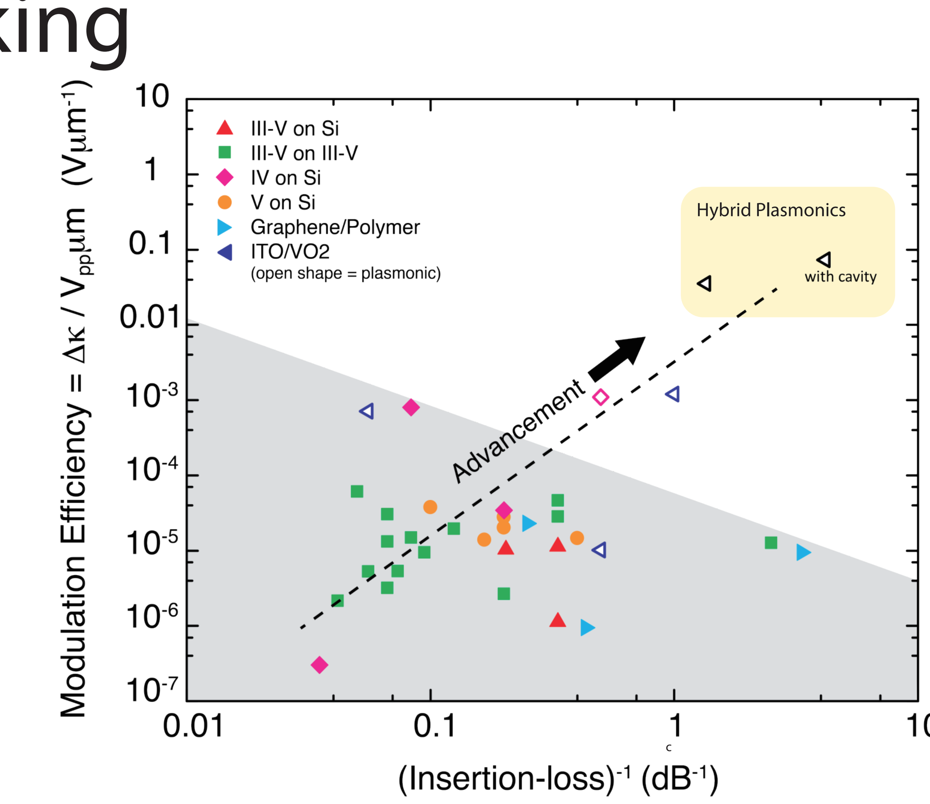
Device Benchmarking

Because EOMs play an integral role in the conversion between the electrical and optical domains in data communication links, factors such as the scalability, modulation performance, and power consumption of such devices need to be considered for future advancements in the field of high-speed photonic computing. In light of these factors, we have proposed a metric to benchmark EOMs in order to clearly demonstrate the stark contrast between traditional (i.e. diffraction limited) devices and those devices that incorporate emerging concepts (e.g., plasmonics) and/or materials (e.g., polymer, graphene, ITO, etc.) This Figure-of-Merit contrasts EOMs on the basis of modulation efficiency and power penalty.



$$FOM_{Physical} = \frac{\Delta\tilde{n}_{eff}(V_{pp})}{V_{pp} \cdot \mu m} \cdot \left(\frac{1}{IL}\right)_{on-chip, V=V_{on}}$$

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