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High-Performance Sub-Lambda Silicon Plasmonic Modulator

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THE GEORGE WASHINGTON UNIVERSITY

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Final Report

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14. ABSTRACT
The objective of this research program is to develop the first sub wavelength scale integrated electrooptic modulators for ultra low power communi cation links. In the proposed research, hybrid switching approaches utilizing positive synergies of photonics and plasmonics at the nanoscale will be investigated. By utilizing enhanced light latter interactions and conductive oxides as functional active materials, the performance frontier of switching devices will be pushed towards the THz regime while reducing their power consumption at the same time. These waveguide based electro optical transistors will blend seamlessly into silicon waveguiding platforms and will constitute the backbone of future photonic integrated circuits. Approach: To approach to demonstrate the first sub long, high performing plasmonic based EOM is based on a waveguide integrated design that seamlessly blends a plasmonic EOM node into a Silicon on Insulator data routing platform. A gate stack comprised of the active material, Indium Tin Oxide (ITO) will be sandwiched between the top metal and the silicon waveguide core forming a deep subwavelength hybrid plasmon polariton mode. A thin gate oxide prevents electrical shorting through this Metal Oxide Semiconductor (MOS) capacitor

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plasmonics, modulator

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Final Report

High-Performance Sub-Lambda Silicon Plasmonic Modulator

Volker J. Sorger

for

Dr. Gernot Pomrenke (AFOSR)

Personal Highlights

Publications	
#Citations	5532
h	23

Table 1. Publication summary. Source: Google Scholar

- **About 1100 Citations per Year** (2017 forecasted)
- **h-factor climbed to 23**
- **Broke the 5500 Citations barrier**
- **Filed 9x Patents**
- **Delivered 75x invited talks at Conferences and Top Institutions**
- **Won 8x prestigious Awards**
- **Early Tenure Promotion**
- **Nominated to be Division Chair for OSA 'Photonics and Optoelectronics'**
- **Invited to serve at SPIE Symposium and Scholarship Committee**
- **Nominated to be Editor-in-Chief of Nanophotonics**
- **Served on over 30x Conference Committees**
- **3T: started 2^nd^ Optics student chapter for SPIE at GWU, Published 2x papers at STEM conferences**

A. 250 Summary for FA9550-14-1-0378

In this effort we focused on electro-optic modulators, as they perform a key function in data communication. Furthermore, modulators also show potential in photonic analogue computing; for instance they could be used as analogue optical tuning element in photonic neuromorphic computing providing non-linearity of the perceptions output. In this program, we delivered a holistic performance-tradeoff analysis of modulators to date. We showed how critical physical parameters such as the active material, the optical mode overlap, the optical mode confinement, and the material broadening determine the modulator performance. We find that the strong binding energy in 2D materials enables efficient absorption in charge-driven modulators, while TCOs are unique candidates for phase-shifters. In short, we develop a set of guiding principles for attojoule-per-bit efficient transfer functions. We also find that the small mode overlap of 2D materials outperforms Silicon due to strong index modulation. However, we experimentally demonstrate the optimizing the optical mode for 2D materials by squeezing the mode area using slot-plasmon waveguides, delivers record-efficient modulators requiring just 100's of aJ/bit. We further show that the plasmonic metal is also critical to form the electrical capacitor right over the active device region and to deliver small contact resistances – a challenge that photonic modulators needs a tradeoff design. Further, we reveal the impact of a cavity feedback on EOM and EAMs, and show how the tradeoff between loss and feedback can be harnessed. We experimentally demonstrate a hybrid plasmon Graphene-based modulator just requiring 0.5V to switch on a silicon platform.

B. Scholarly Work Summaries

Indium-Tin-Oxide for High-performance Electro-optic Modulation

Advances in opto-electronics are often led by discovery and development of materials featuring unique properties. Recently, the material class of transparent conductive oxides (TCO) has attracted attention for active photonic devices on-chip. In particular, indium tin oxide (ITO) is found to have refractive index changes on the order of unity. This property makes it possible to achieve electrooptic modulation of sub-wavelength device scales, when thin ITO films are interfaced with optical light confinement techniques such as found in plasmonics; optical modes are compressed to nanometer scale to create strong light-matter interactions. Here we review efforts towards utilizing this novel material for high performance and ultra-compact modulation. While high performance metrics are achieved experimentally, there are open questions pertaining to the permittivity modulation mechanism of ITO.

Finally, we review a variety of optical and electrical properties of ITO for different processing conditions, and show that ITO-based plasmonic electro-optic modulators have the potential to outperform diffraction limited devices.

A Sub-λ-Size Modulator Beyond the Efficiency-Loss Limit

Electrooptic modulators (EOMs) are key devices in performing the conversion between the electrical and optical domains in data communication links. With respect to a road map for photonic computing, future EOMs are required to be highly scalable, should feature strong modulation performance, and must not consume much power during operation. In light of these requirements, here, we investigate indium–tin–oxide (ITO) as an electrooptic switching material. The results show that ITO is capable of changing its extinction coefficient by a factor of 136. Utilizing these findings, we analyze an ultracompact (i.e., sub- long ¼ 1310 nm) electroabsorption modulator based on a plasmonic MOSmode design. In our analysis, we investigate the performance, i.e., the extinction ratio and insertion loss of the device as a function of various geometric parameters of the device. The optimized device is 0.78 long and features an extinction ratio and on-chip insertion loss of about 6 dB=m and 0.7 dB, respectively. Furthermore, we suggest a metric to benchmark electroabsorption modulators and show that silicon plasmonics has potential for high-end switching nodes in future integrated photonic circuits.

Ultra-compact Graphene-based Electro-optic Modulators on a Silicon-on-Insulator Platform

Electro-optic modulators (EOM) convert electronic signals into high bit-rate photonic data. Its on-chip design plays an important role for the integration of electronic and photonic components for various types of applications, including photonic computing and telecommunication. Graphene is an emerging material allowing the design of ultra-compact EOMs due to its extraordinary electro-optic properties, addressing the trade-offs between a high bandwidth and modulation strength. Two Graphene-based EOM designs are presented for (a) an absorption and (b) a phase-shifter device. The high performance Graphene-based absorption modulator is analyzed numerically demonstrating an extinction ratio and insertion loss of 7.77 dB/μm and 0.75 dB, respectively. This sub-wavelength compact (0.78λ long) absorption modulator is capable of a broadband operation over 500 nm bandwidth. The second design, a Mach-Zehnder modulator formed by push-pull Graphene-based phase shifter, exhibits an insertion loss of ~2.7 dB/μm with a 5.6 μm arm shifter length operating at telecom wavelength (1.55μm). These EOMs performance results have the potential to become essential building blocks for optical interconnects in future integrated optoelectronic systems.

Silicon Plasmon Modulators: Breaking Photonic Limits

Emerging communication applications anticipate a photonic roadmap leading to ultra-compact photonic integrated circuits. The objective is to design integrated on-chip electro-optic modulators (EOM) that can combine both high modulation efficiency and low switching energy. While silicon-based EOMs have been demonstrated, they have large device footprints of the order of millimeters as a result of weak non-linear electro-optical properties. By deploying a high-Q resonator the modulation strength can be increased, however with the trade-off of bandwidth. Here we review some of our recent work and future prospects of hybrid plasmonic EOMs. We demonstrate a high-performance ITO-EOM in a plasmonic silicon-on-insulator (SOI) hybrid design. Remarkably, results show that an ultra-compact (3λ) hybrid EOM deploying enhanced light- matter-interactions (LMI) is capable of delivering an extinction ratio (ER) of about 1 dB/μm. This is possible due to a change of the ITO's extinction coefficient by a factor of 136 leading. Furthermore, a metric to benchmark electro- absorption modulators is provided, which shows that silicon Figure 1. In this paper we focus on a hybrid integration technique low-loss, CMOS compatible Silicon-on-Insulator (SOI) with (LMI) plasmonics, which allows synergistic design via multi-functional utilization of the deployed metal. Plasmonics has potential for high-end switching nodes in future integrated hybrid photonic circuits.

Review and perspective on ultrafast wavelength-size electro-optic modulators

As electronic device feature sizes scale-down, the power consumed due to on chip communications as compared to computations will increase dramatically; likewise, the available bandwidth per computational operation will continue to decrease. Integrated photonics can offer savings in power and potential increase in bandwidth for on hip networks. Classical diffraction-limited photonics currently utilized in photonic integrated circuits (PIC) is characterized by bulky and inefficient devices compared to their electronic counterparts due to weak light–matter interactions (LMI). Performance critical for the PIC is electro-optic modulators (EOM), whose performances depend inherently on enhancing LMIs. Current EOMs based on diffraction-limited optical modes often deploy ring resonators and are consequently bulky, photon-lifetime modulation limited, and power inefficient due to large electrical capacitances and thermal tuning requirements. In contrast, wavelength-scale EOMs are potentially able to surpass fundamental restrictions set by classical (i.e. diffraction-limited) devices via (a) high index modulating materials, (b) non resonant field and density of-states enhancements such as found in metal optics, and (c) synergistic on chip integration schemes. This manuscript discusses challenges, opportunities, and early demonstrations of nanophotonic EOMs attempting to address this LMI challenge, and early benchmarks suggest that nanophotonic building blocks allow for densely integrated high-performance photonic integrated circuits.

Roadmap on Atto-Joule per Bit Modulators

Electro-optic modulation performs the conversion between the electrical and optical domain with applications in data communication for optical interconnects, but also for novel optical compute algorithms such as providing non-linearity at the output stage of optical perceptrons in neuromorphic analogue optical computing. While resembling an optical transistor, the weak light-matter-interaction makes modulators 105 times larger compared to their electronic counterparts. Since the clock frequency for photonics on-chip has a power-overhead sweet-slot around 10's of GHz, ultrafast modulation may only be required in long-distance communication, but not for short on-chip links. Hence the search is open for power-efficient on-chip modulators beyond the solutions offered by foundries to date. Here we show a roadmap towards atto-Joule per bit efficient modulators on-chip as well as some experimental demonstrations of novel plasmon modulators with sub-1fJ/bit efficiencies. Our parametric study of placing different actively modulated materials into plasmonic vs. photonic optical modes shows that 2D materials overcompensate their miniscule modal overlap by their unity-high index change. Furthermore, we reveal that the metal used in plasmonic-based modulators not only serves as an electrical contact, but also enables low electrical series resistances leading to near-ideal capacitors. We then discuss the first experimental demonstration of a photon-plasmon-hybrid Graphene-based electroabsorption modulator on silicon. The device shows a sub-1V steep switching enabled by near-ideal electrostatics delivering a high 0.05dB/V-µm performance requiring only 110 aJ/bit. Improving on this design, we discuss a plasmonic slot-based Graphene modulator design, where the polarization of the plasmonic mode matches with Graphene's in-plane dimension. Here a push-pull dual-gating scheme enables 2dB/V-µm efficient modulation allowing the device to be just 770 nm short for 3dB small signal modulation. Lastly, comparing the switching energy of transistors to modulators shows that modulators based on emerging material-based, plasmonic-Silicon hybrid integration perform on-par relative to their electronic counter parts. This in turn allows for a device-enabled two orders-ofmagnitude improvement of electrical-optical co-integrated network-on-chips over electronic-only architectures. The latter opens technological opportunities in cognitive computing, dynamic data-driven applications system, and optical analogue compute engines to include neuromorphic photonic computing.

A deterministic guide for material and mode dependence of on-chip electro-optic modulator performance

Electro-optic modulation is a key function in optical data communication and possible future optical computing engines. The performance of modulators intricately depends on the interaction between the actively modulated material and the propagating waveguide mode. While high-performing modulators were demonstrated before, the approaches were taken as ad-hoc. Here we show the first systematic investigation to incorporate a holistic analysis for high-performance and ultra-compact electro-optic modulators on-chip. We show that intricate interplay between active modulation material and optical mode plays a key role in the device operation. Based on physical tradeoffs such as index modulation, loss, optical confinement factors and slow-light effects, we find that bias-material-mode regions exist where high phase modulation and high loss (absorption) modulation is found. This work paves the way for a holistic design rule of electro-optic modulators for on-chip integration

2D material-based mode confinement engineering in electro-optic modulators

The ability to modulate light using 2-dimensional (2D) materials is fundamentally challenged by their small optical cross-section leading to miniscule modal confinements in diffraction-limited photonics despite intrinsically high electro-optic absorption modulation (EAM) potential given by their strong exciton binding energies. However the inherent polarization anisotropy in 2D-materials and device tradeoffs lead to additional requirements with respect to electric field directions and modal confinement. A detailed relationship between modal confinement factor and obtainable modulation strength including definitions on bounding limits are outstanding. Here we show that the modal confinement factor is a key parameter determining both the modulation strength and the modulator extinction ratio-to-insertion loss metric. We show that the modal confinement and hence the modulation strength of a single-layer modulated 2D material in a plasmonically confined mode is able to improve by more than 10x compared to diffraction-limited modes. Combined with the strong-index modulation of graphene the modulation strength can be more than 2-orders of magnitude higher compared to Silicon-based EAMs. Furthermore modal confinement was found to be synergistic with performance optimization via enhanced light-matter-interactions. These results show that there is room for scaling 2D material EAMs with respect to modal engineering towards realizing synergistic designs leading to high-performance modulators.

Active material, optical mode and cavity impact on nanoscale electro-optic modulation performance

Electro-optic modulation is a key function in optical data communication and possible future optical compute engines. The performance of modulators intricately depends on the interaction between the actively modulated material and the propagating waveguide mode. While a variety of high-performance modulators have been demonstrated, no comprehensive picture of what factors are most responsible for high performance has emerged so far. Here we report the first systematic and comprehensive analytical and computational investigation for high-performance compact on-chip electro-optic modulators by considering emerging active materials, model considerations and cavity feedback at the nanoscale. We discover that the delicate interplay between the material characteristics and the optical mode properties plays a key role in defining the modulator performance. Based on physical tradeoffs between index modulation, loss, optical confinement factors and slow- light effects, we find that there exist combinations of bias, material and optical mode that yield efficient phase or amplitude modulation with acceptable insertion loss. Furthermore, we show how material properties in the epsilon near zero regime enable reduction of length by as much as by 15 times. Lastly, we introduce and apply a cavity-based electro-optic modulator figure of merit, $\Delta\lambda/\Delta\alpha$, relating obtainable resonance tuning via phase shifting relative to the incurred losses due to the fundamental Kramers-Kronig relations suggesting optimized device operating regions with optimized modulation-to-loss tradeoffs. This work paves the way for a holistic design rule of electro- optic modulators for high-density on-chip integration.

2D Materials in Electro-optic Modulation: energy efficiency, electrostatics, mode overlap, material transfer and integration

Here we discuss the physics of electro-optic modulators deploying 2D materials. We include a scaling laws analysis showing how energy-efficiency and speed change for three underlying cavity systems as a function of critical device length scaling. A key result is that the energy-per-bit of the modulator is proportional to the volume of the device, thus making the case for submicron-scale modulators possible deploying a plasmonic optical mode. We then show how Graphene's Pauli-blocking modulation mechanism is sensitive to the device operation temperature, whereby a reduction of the temperature enables a 10x reduction in modulator energy efficiency. Furthermore, we show how the high index tunability of Graphene is able to compensate for the small optical overlap factor of 2D-based material modulators, which is unlike classical Silicon-based dispersion devices. Lastly we demonstrate a novel method towards a 2D material printer suitable for cross- contamination free and on-demand printing. The latter paves the way to integrate 2D materials seamlessly into taped-out photonic chips.

Temperature Dependence of a Sub-wavelength Compact Graphene Plasmon- Slot Modulator

We investigate a plasmonic electro-optic modulator with an extinction ratio exceeding 1 dB/∫m by engineering the optical mode to be in-plane with the graphene layer, and show how lowering the operating temperature enables steeper switching.

λ-Size ITO and Graphene-Based Electro-Optic 2 Modulators on SOI

One of the key devices that convert electronic signals into high bit-rate photonic data is the electro-optic modulator (EOM). Its on-chip design plays an important role for the integration of electronic and photonic devices for various types of applications including photonic computing and telecommunication. Recently, indium tin oxide (ITO) and graphene have attracted significant attention primarily due to their extraordinary electro-optic properties for the design of ultra-compact EOMs to handle bandwidth and modulation strength trade-off. Here we show design details of a high-performance ITO-EOM in a plasmonic silicon- on-insulator hybrid structure. Results show that ITO is capable of changing its extinction coefficient by a factor of 136 leading to λ- short devices with an extinction ratio of about 1dB/μm. Further numerical device optimizations demonstrate the feasibility for an extinction ratio and on-chip insertion loss of about 6 dB/μm and 0.25 dB, respectively, for a sub-wavelength compact (0.78 λ) EOM design using ITO. Utilizing graphene as an active switching material in a similar ultra-compact plasmonic hybrid EOM design yields enhanced light-matter interaction, in which extinction-ratio is 9 times larger than the insertion-loss for a 0.78 λ short device. Both ITO and graphene EOMs are capable of broadband operations (>500 nm) since no resonator is deployed.

Simulation of two-dimensional design of trench-coupler based Silicon Mach-Zehnder thermo-optic switch
Optical switches are key components for routing of light transmission paths in data links. Existing waveguide-based Mach-Zehnder interferometer (MZI) switches occupy a significant amount of real estate on-chip. Here we propose a compact Silicon MZI thermo-optic 2×2 photonic switch, consisting of two frustrated total internal reflection (TIR) trench couplers and TIR mirror-based 90^{o} waveguide bends, forming a rectangular MZI configuration. The switch allows for reconfigurable design footprints due to selected control of the optical signal being transmitted and reflected at the 90^{o} crosses and bends. Our simulation results show that the switch exhibits a chip size of 42 µm × 42 µm, the extinction ratio of ~14 dB, the rise and fall time of 20 µs and 16 µs, and the low switching voltage and power of 0.35 V and 26 mW, respectively. This device configuration can readily scale its pattern at the two-dimensional directions, making them attractive for Silicon photonic integrated circuits.

C. Publication List

Notes:

- Conference proceedings papers are omitted here. List in order of summary discussion in Section **B**.
- arXiv papers are in peer review
- All papers can be downloaded at sorger.seas.gwu.edu/publications

Z. Ma, Z. Li, K. Liu, C. Ye, V. J. Sorger, “Indium-Tin-Oxide for High-performance Electro-optic Modulation”, *Nanophotonics*, 4, 1 (2015).

C. Huang, S. Pickus, R. Lamond, Z. Li, V. J. Sorger, “A Sub-λ Size Modulator Beyond the Efficiency-Loss Limit” *IEEE Photonics Journal* 5, 4 (2013).

C. Ye, S. Pickus, V. J. Sorger, “Ultra-compact Graphene-based Electro-optic Modulators on a Silicon-on-Insulator Platform” *Intl J. M. Eng.* (2014).

S. K. Pickus, S. Khan, C. Ye, Z. Li, and V. J. Sorger, “Silicon Plasmon Modulators: Breaking Photonic Limits” *IEEE Photonic Society*, 27, 6 (2013).

K. Liu, C.R. Ye, S. Khan, V. J. Sorger, “Review and perspective on ultrafast wavelength-size electro-optic modulators” *Laser & Photonics Review,* 9, 2, p.172-194 (2015) - Cover

V. J. Sorger, R. Amin, J. B. Khurgin, Z. Ma, S. Khan, “Roadmap on Atto-Joule per Bit Modulators”, *arXiv*:1710.00046 (2017).

R. Amin, C. Suer, Z. Ma, J. Khurgin, R. Agarwal, V. J. Sorger, “A Deterministic Guide for Material and Mode Dependence of On-Chip Electro-Optic Modulator Performance”, *Solid-State Electronics,* 136, 92-101 (2017).

Z. Ma, M. H. Tahersima, S. Khan and V. J. Sorger, "Two-Dimensional Material-Based Mode Confinement Engineering in Electro-Optic Modulators," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 23, no. 1, 1-8 (2017).

R. Amin, C. Suer, Z. Ma, J. Khurgin, R. Agarwal, V. J. Sorger, “Active Material, Optical Mode and Cavity Impact on electro-optic Modulation Performance”, *arXiv:*1612.02494. Accepted at *Nanophotonics* (8-2017).

Z. Ma, R. Hemnani, L. Bartels. R. Agarwal, V. J. Sorger, “2D Materials in Electro-optic Modulation: energy efficiency, electrostatics, mode overlap, material transfer and integration”, *arXiv*:1708.05986 (2017).

Z. Ma, R. Amin, S. Khan, M. Tahersima, V. J. Sorger, "Temperature Dependence of a Sub-wavelength Compact Graphene Plasmon-Slot Modulator", *arXiv*: 1709.01465 (2017).

C. Ye, S. Khan, Z.R. Li, E. Simsek, V. J. Sorger, "λ-Size ITO and Graphene-based Electro-optic Modulators on SOI" *IEEE Selected Topics in Quantum Electronics*, 4, 20 (2014).

K. Liu, *C.* Zhang, S. Mu, S. Wang, V. J. Sorger, "Trench-coupler based Silicon Mach-Zehnder Thermo-optic Switch with Flexible Two-dimensional Design" *Optics Express*. 24, 14, 15845-15853 (2016).

High-Performance Sub-λ Silicon Plasmonic Modulator

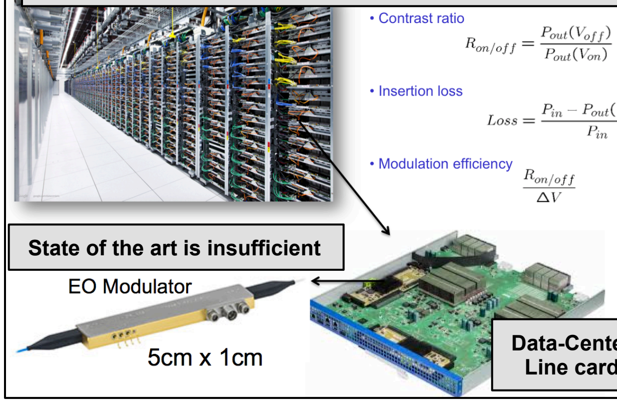
- Volker Sorger (PI)
- FA-9550-14-0378
- Time: 9/30/2014-8/31/2017

Objective
- Demonstrate a CMOS-compatible high-performance plasmonic EOM on SOI
- Develop fundamental understanding of light-matter-interaction, and create strategies to enhance them

Approach
- Utilize strong light-matter-interaction
- Analyze and apply EOM laws
- Integrate Si-Photonics with novel materials.
- Switching Materials: TCO or Graphene

Deliveries
- ✓ Derived electro-optic modulator scaling vectors
- ✓ Demonstrated Hybrid Plasmon Graphene Modulator on Silicon
- ✓ Demonstrated Plasmon Slot Graphene Modulator

The *Need* for high-performing Modulators



- Contrast ratio

$$R_{on/off} = \frac{P_{out}(V_{off})}{P_{out}(V_{on})}$$

- Insertion loss

$$Loss = \frac{P_{in} - P_{out}(V_{off})}{P_{in}}$$

- Modulation efficiency

$$\frac{R_{on/off}}{\Delta V}$$

State of the art is insufficient

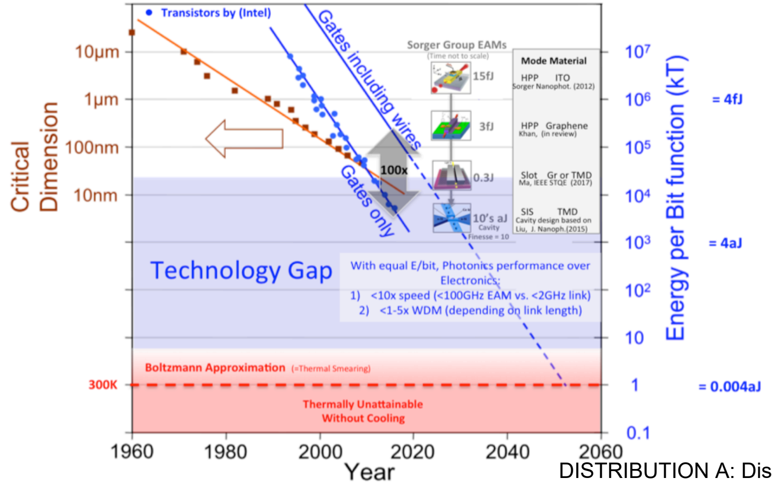
Data-Center Line card

Amin, et al. ***Solid-State Electr.*** (2017)

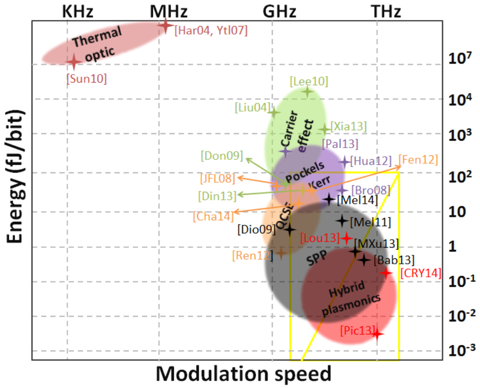
Plasmonics over SOI mode ~0.1-5x | 2D&TCO over Silicon 10^3-10^4x | Plasmonics 2-5x

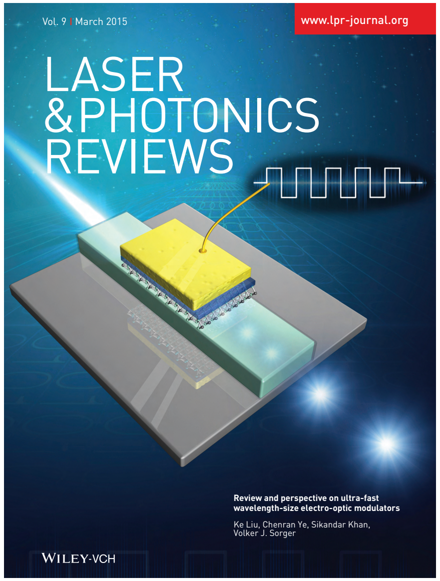
$$\Delta n_{eff} = \Gamma \cdot \frac{\Delta n_{\mathrm{mat}}}{n_{\mathrm{mat}}} \cdot n_{group}$$

Overlap Factor | Material | Slow-Light



V. J. Sorger, R. Amin, J. B. Khurgin, Z. Ma, S. Khan "Roadmap on Attojoule per Bit Modulators" ***arXiv***:1710.00046 (2017) in review at ***J. Opt.***





Vol. 9 March 2015

www.lpr-journal.org

LASER & PHOTONICS REVIEWS

Review and perspective on ultra-fast wavelength-size electro-optic modulators

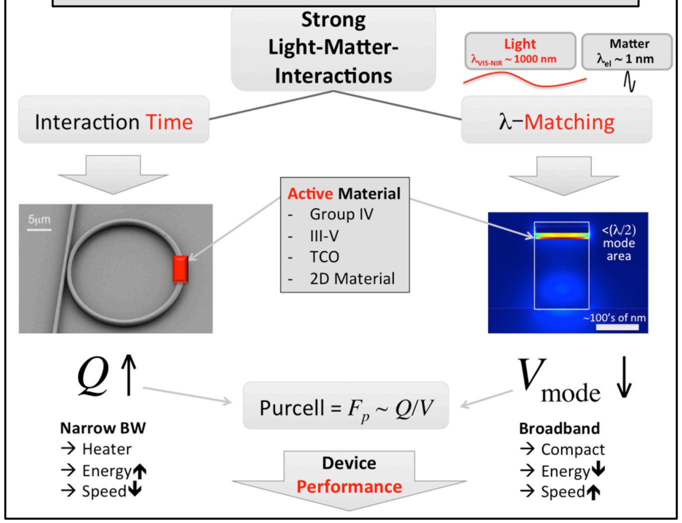
Ke Liu, Chenran Ye, Sikandar Khan, Volker J. Sorger

WILEY-VCH

K. Liu, Z.R. Li, S. Khan, C. Ye, V. J. Sorger, Ultra-fast electro-optic modulators for high-density photonic integration ***LPR*** 10, 1, p.11-15 (2015)

Design Vectors of Modulators

Fundamental Challenge of Modulators



Strong Light-Matter-Interactions

Interaction Time

λ−Matching

Active Material
- Group IV
- III-V
- TCO
- 2D Material

$Q \uparrow$

Purcell = $F_p \sim Q/V$

$V_{\text{mode}} \downarrow$

Narrow BW
→ Heater
→ Energy↑
→ Speed↓

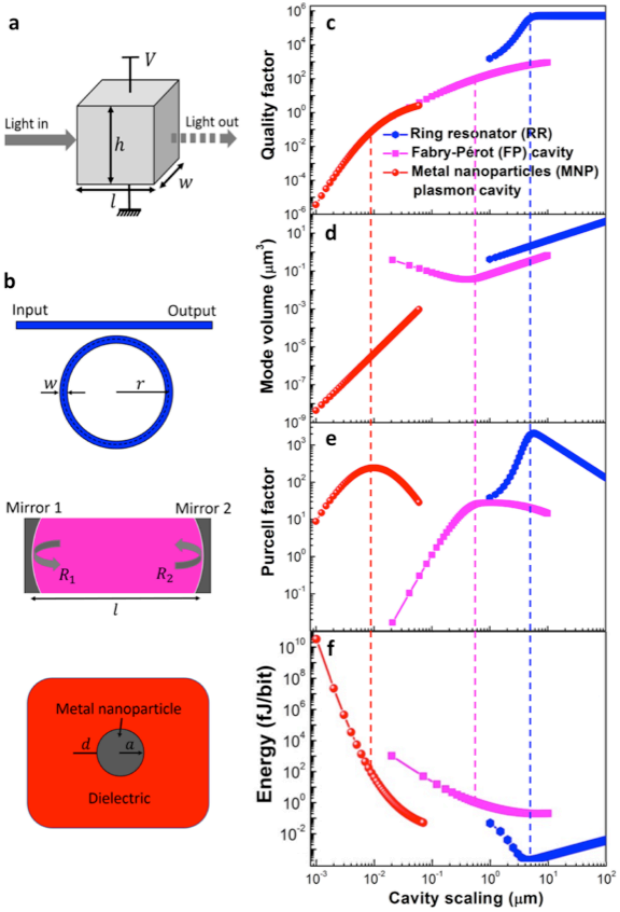
Device Performance

Broadband
→ Compact
→ Energy↓
→ Speed↑

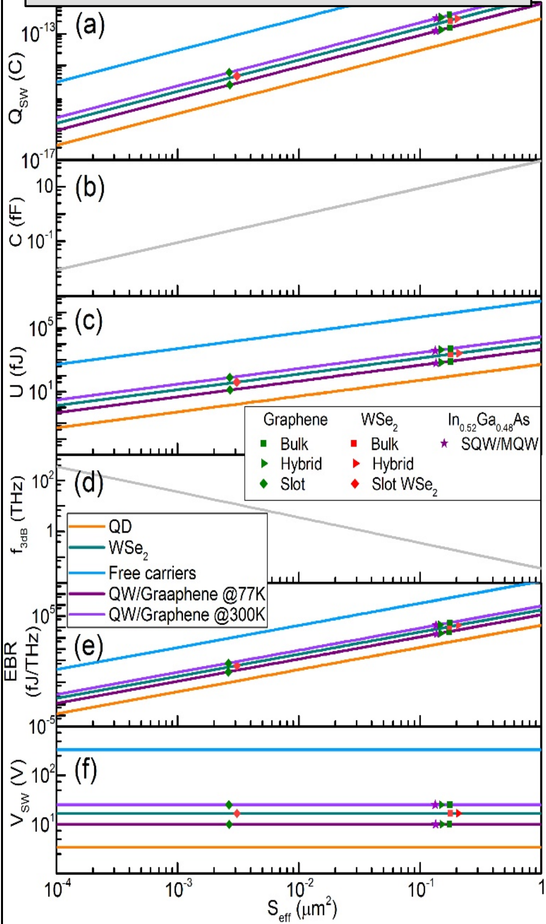
Performance Governing Equation

$$\delta k = \delta\omega_0 \frac{\partial k}{\partial \omega} = \frac{\delta n}{n}\omega_0 \frac{\partial k}{\partial \omega} = \frac{\delta n}{n} k_0 c \frac{\partial k}{\partial \omega} = \delta n k_0 \frac{n_g}{n}$$

Modulator Scaling-Laws



Charge-Driven EAM Performance



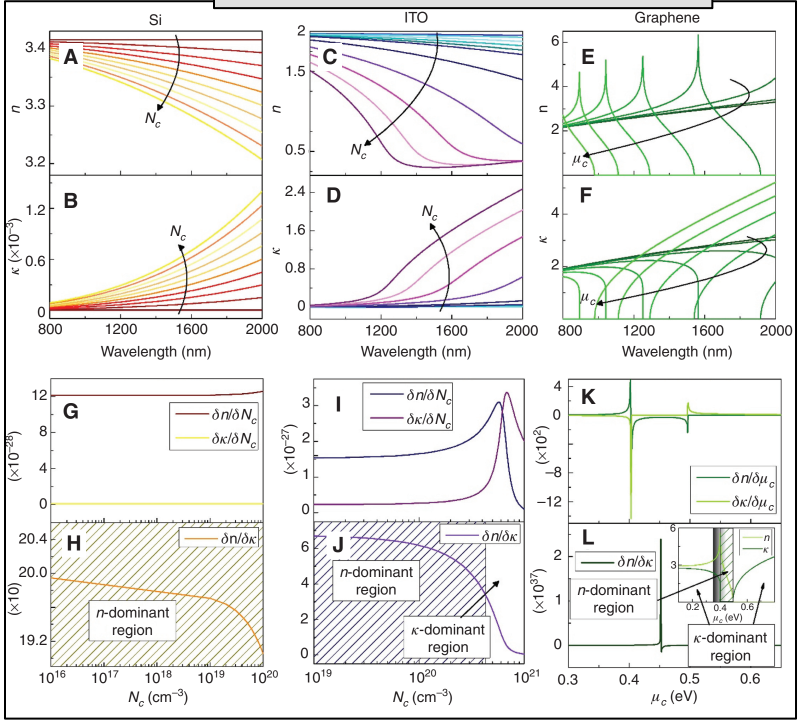
V. J. Sorger, R. Amin, J. B. Khurgin, Z. Ma, S. Khan, "Roadmap on Atto-Joule per Bit Modulators", ***arXiv***:1710.00046 (2017)

R. Amin, J. Khurgin, V. J. Sorger "Electro-Absorption Modulator Performance Study: Charge, Voltage, Energy and Bandwidth Analysis" in preparation, (2017)

DISTRIBUTION A: Distribution approved for public release.

EAM Design:
Material, Mode, Overlap Factor

Material Index Change Potential

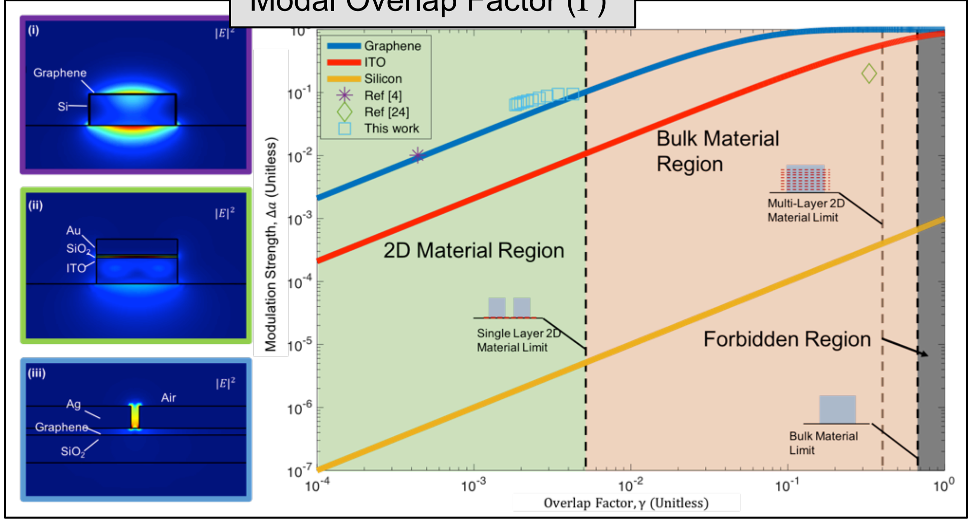


Ma, et al ***IEEE STQE*** (2017)

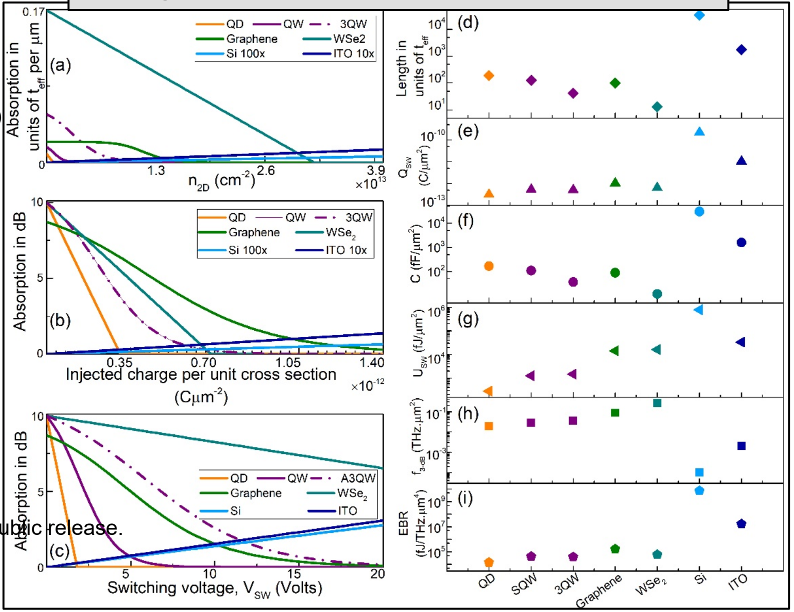
Amin, et al ***Nanophot.*** (2017)

Amin, et al ***Opt. Exp.*** (in review)

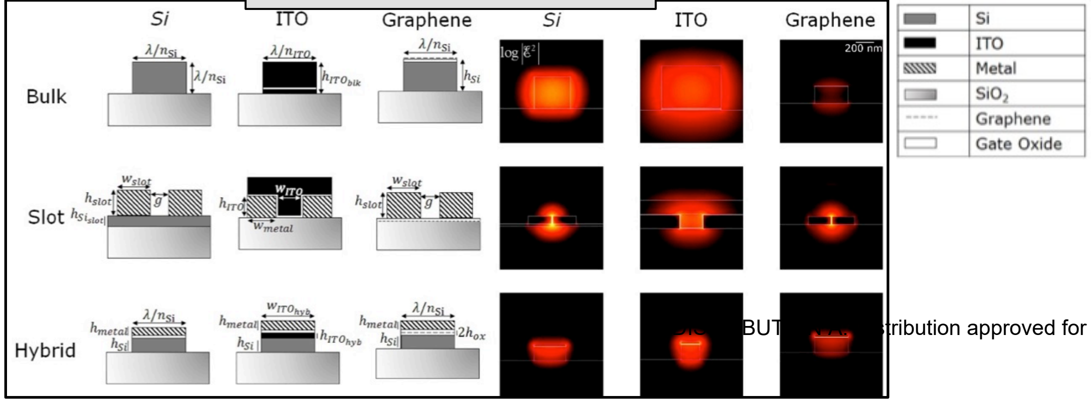
Modal Overlap Factor (Γ)



Charge-driven Materials for EO Modulation



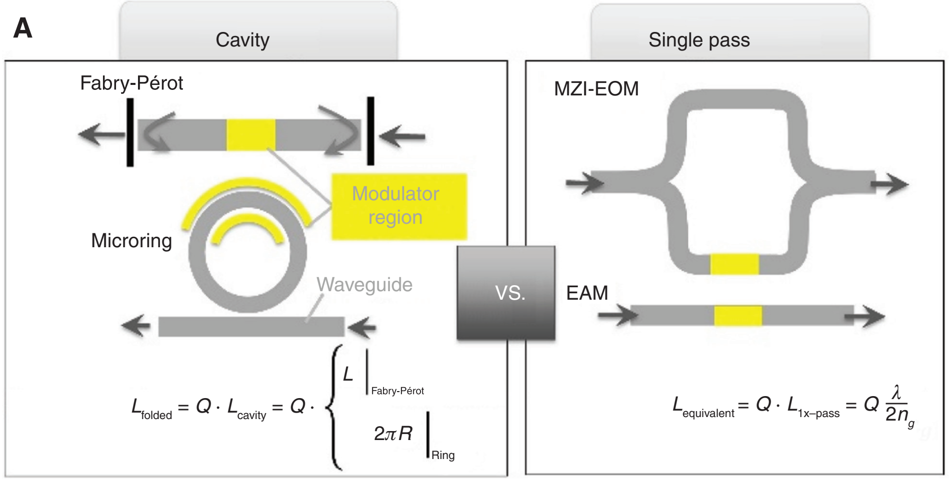
Waveguide Mode Options



Cavity Impact on Modulators

Linear vs. Cavity Modulators: Case Footprint saving

A



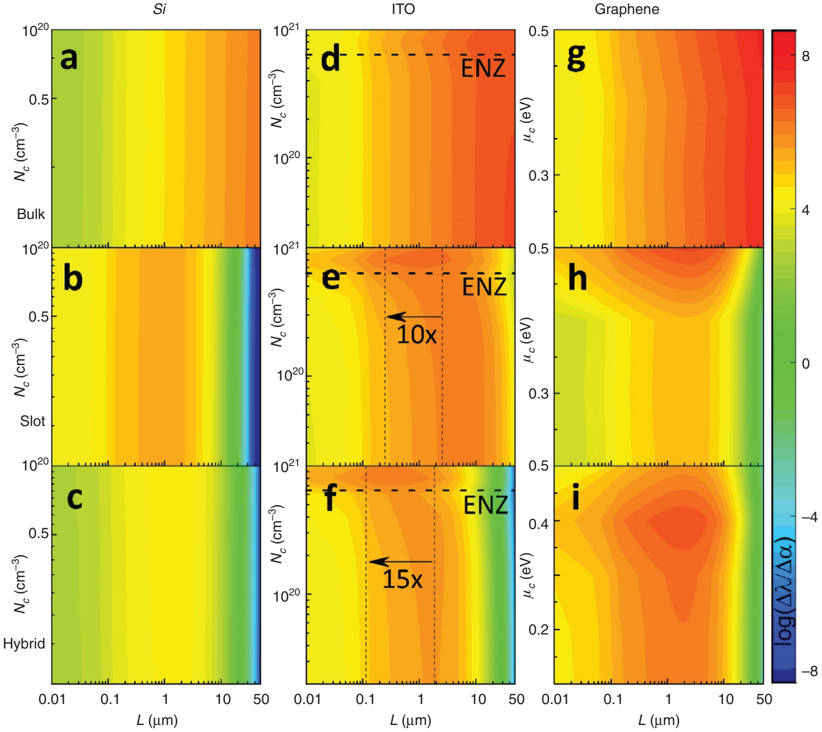
$$L_{\text{folded}} = Q \cdot L_{\text{cavity}} = Q \cdot \begin{cases} L \,\big|_{\text{Fabry-Pérot}} \\ 2\pi R \,\big|_{\text{Ring}} \end{cases}$$

$$L_{\text{equivalent}} = Q \cdot L_{1\text{x-pass}} = Q\,\frac{\lambda}{2n_g}$$

B

$$\text{Footprint saving} = \text{Cavity enhancement} = \frac{L_{\text{equivalent}}}{L_{\text{cavity}}} = \frac{Q\lambda}{2n_g \cdot 2\pi R} = \frac{1}{2}\,\frac{\Delta\nu_{\text{FSR}}}{\Delta\nu_{\text{FWHM}}} = \frac{1}{2}\,F$$

Cavity-Modulator $FOM = \delta\alpha/\delta\kappa$ Scaling Performance



Fabry-Perot Cavity-Modulator Equation Set

$$T_{\text{loss}} = \alpha_{\text{abs\_total}} + \alpha_{\text{pen}}$$

$$Q = -\frac{2\pi}{\lambda}\,\frac{2n_{\text{eff}}L}{\log[R_1R_2(1-T_{\text{loss}})^2]}$$

$$\alpha_{\text{abs\_total}} = 1 - e^{-\alpha_{\text{abs}}L}$$

$$\Delta\lambda = \frac{2L}{m}\left|n_{\text{eff,ON}} - n_{\text{eff,OFF}}\right|$$

$$\alpha_{\text{abs}} = \frac{4\pi\kappa_D}{\lambda}$$

$$(f_{3\text{dB}})_{\text{ring}} \approx \frac{1}{2\pi\tau_{ph}} = \frac{\nu}{Q}$$

$$\alpha_{\text{pen}} = \left(\frac{4\pi\kappa_m}{\lambda}\right)\delta_s \cdot \frac{2\delta_s}{2\delta_s + L}$$

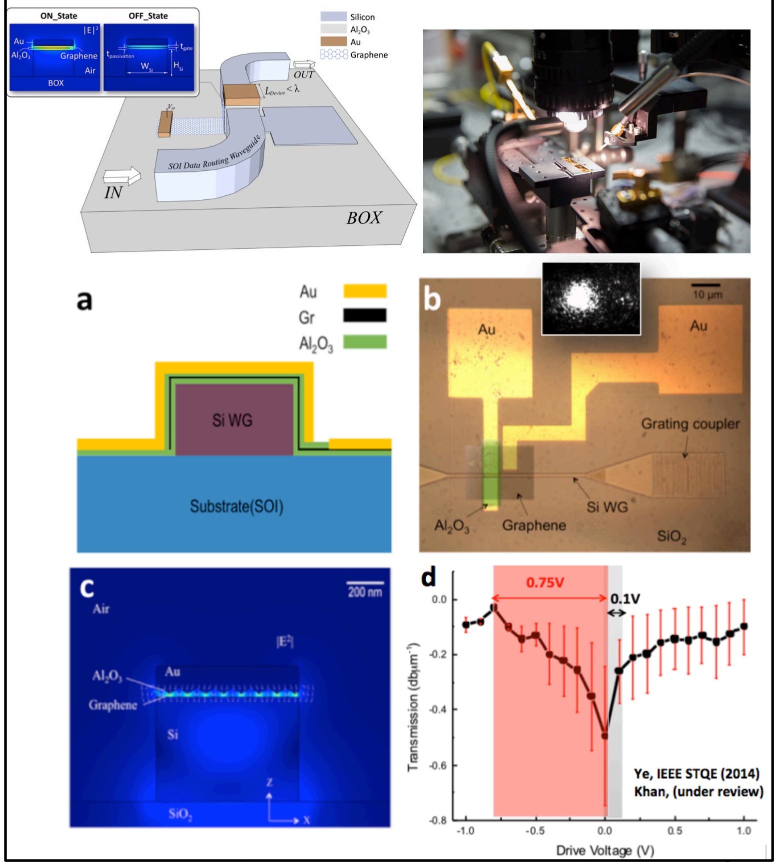
$$(f_{3\text{dB}})_{MZ} = 0.44 \cdot \frac{1}{T_{\text{trans}}} \approx \frac{1}{2T_{\text{trans}}} = \frac{1}{2n_g L} = \frac{\nu}{Q}.$$

R. Amin, C. Suer, Z. Ma, J. Khurgin, R. Agarwal, V. J. Sorger, “A Deterministic Guide for Material and Mode Dependence of On-Chip Electro-Optic Modulator Performance”, ***Solid-State Electronics***, 136, 92-101 (2017)**.**

R. Amin, C. Suer, Z. Ma, J. Khurgin, R. Agarwal, V. J. Sorger, “Active Material, Optical Mode and Cavity Impact on electro-optic Modulation Performance”, ***arXiv:***1612.02494. Accepted at ***Nanophotonics*** (2017)**.**

Hybrid Plasmon Graphene Modulator on Silicon Photonics

Demonstration of Hybrid Plasmon Graphene Modulator



C. Ye, S. Khan, Z.R. Li, E. Simsek, V. J. Sorger, "λ-Size ITO and Graphene-based Electro-optic Modulators on SOI" ***IEEE Sel. Top. Quant. Elect.*** (2014)

V. J. Sorger, R. Amin, J. B. Khurgin, Z. Ma, S. Khan "Roadmap on Atto-Joule per Bit Modulators" ***arXiv***:1710.00046 (2017)

S. Khan, Z. Ma, C.J. Lee, V. J. Sorger, "Sub-voltage Graphene-plasmon Based Electro-absorption Modulator (in prep)

Graphene's Doping dependent Conductivity →Index Tuning

In-plane conductivity of Graphene:

$$\sigma_{\parallel}(\omega,\mu_c,\tau,T)=\frac{-ie^2(\omega+i\tau^{-1})}{\pi\hbar^2}\left[\frac{1}{(\omega+i\tau^{-1})^2}\int_0^\infty \xi\left(\frac{\partial f_d(\xi)}{\partial\xi}-\frac{\partial f_d(-\xi)}{\partial\xi}\right)d\xi-\int_0^\infty\frac{f_d(-\xi)-f_d(\xi)}{(\omega+i\tau^{-1})^2-4(\xi/\hbar)^2}d\xi\right]$$

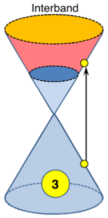
Performance
ER = 5.8dB
IL = 0.83dB
C = 470aF
f_{3dB} = 320+GHz (RC-Delay)
E/bit = 230aJ

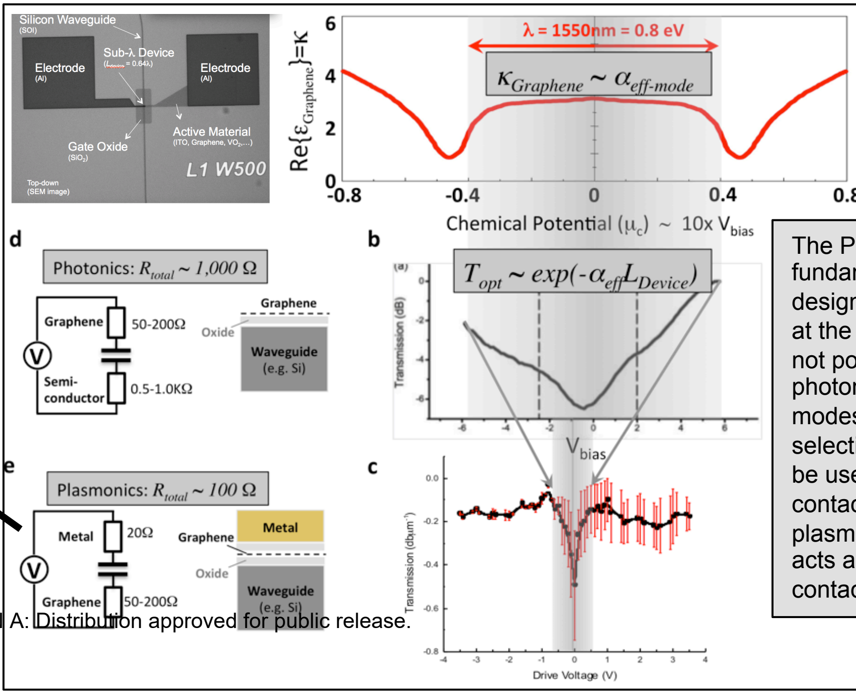
$$f_d(\xi)=1/\{\exp[(\xi-\mu_c)/k_BT]+1\}$$

$$|\mu_c|=\hbar v_F\sqrt{\pi a_o|V_g-V_{Dirac}|}$$

In-plane refractive index

$$n_g=\sqrt{1+i\sigma_{\parallel}/(w\varepsilon_0\Delta)}$$

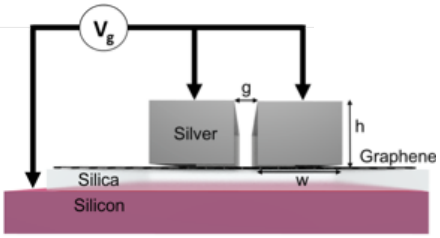


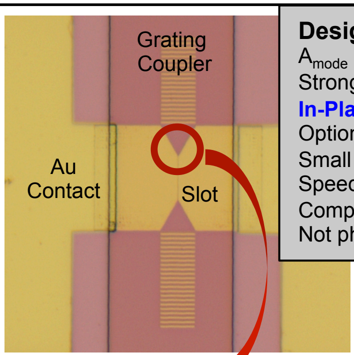


The Plasmonic Metal fundamentally allows designing the capacitor at the device. This is not possible for photonics (e.g. SOI modes), where selective doping has to be used to lower the contact resistance. The plasmon metal further acts as a electrical contact and heat sync.

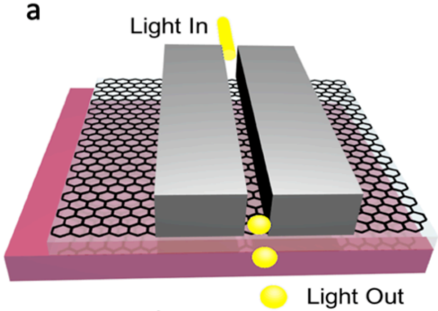
Graphene Plasmon Slot Modulator

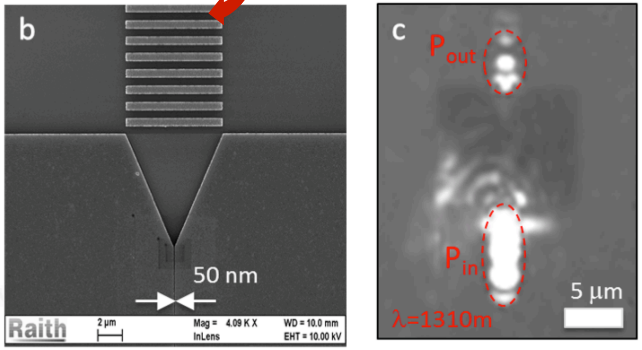
Demonstration of Graphene Plasmon Modulator



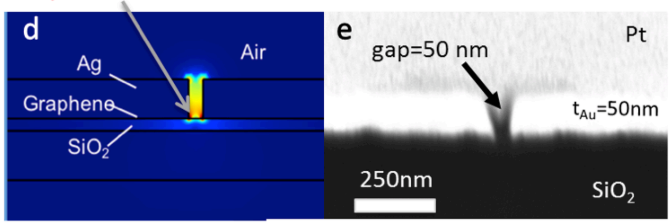


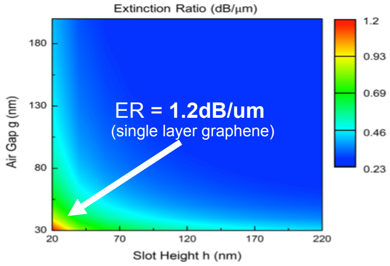
Design Features
$A_{mode} = 0.01\ (\lambda/2)^2$
Strong EO Modulation = 1.2dB/um
In-Plane benign mode design
Option to Interface w/ Silicon
Small capacitance → E/bit + Speed
Compact footprint
Not photon-lifetime limited

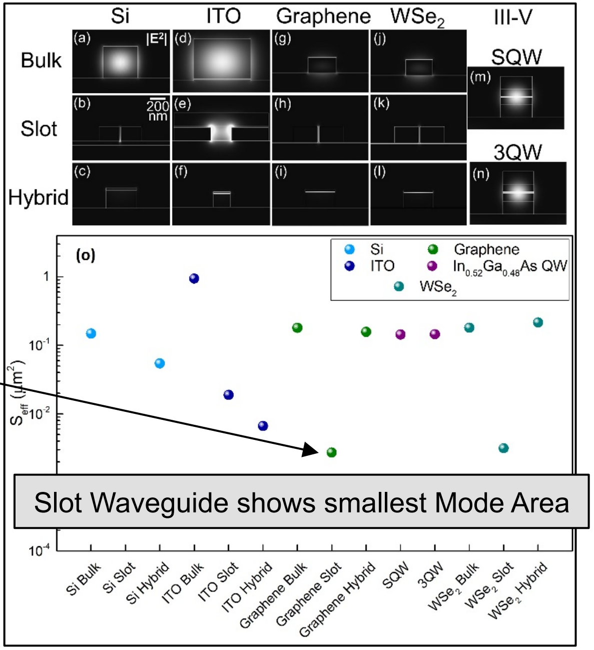




2D Material
in-plane E-Field



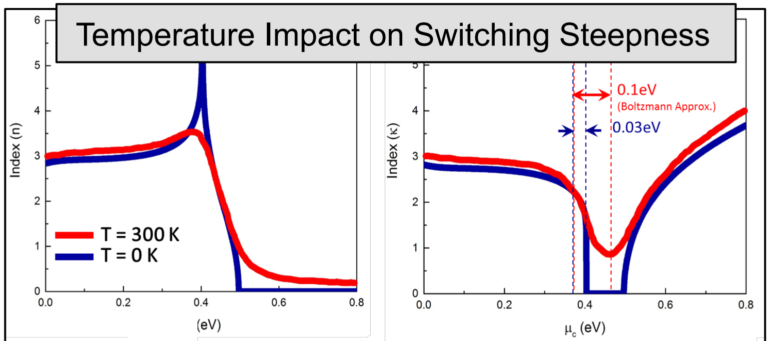




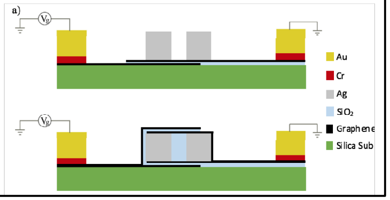
Slot Waveguide shows smallest Mode Area

R. Amin, J. Khurgin,
V. J. Sorger (in preparation)

Temperature Impact on Switching Steepness



#Graphene Layers	ER (dB/µm)	Device Length for ER = -3dB (µm)	E/bit $V_D = 0.75V$
1	1.2	2.5	540aJ
2	2.1	1.73	310aJ
4	3.9	0.77	170aJ



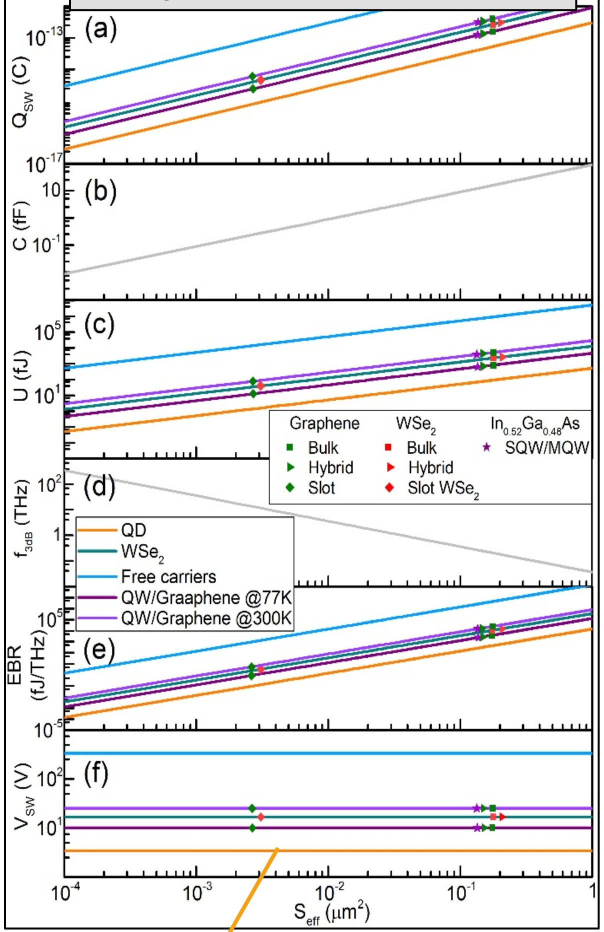
Z. Ma, M. Tahersima, S. Khan, V. J. Sorger, “2D material-based mode overlap engineering in electro-optic modulators” ***IEEE STQE*** (2016)

Z. Ma, H. Hong, H. Dalir, V. J. Sorger, (in preparation)

V. J. Sorger, R. Amin, J. B. Khurgin, Z. Ma, S. Khan “Roadmap on Atto-Joule per Bit Modulators” ***arXiv***:1710.00046 (2017)

Proposal:
Quantum Dot-based Plasmon Waveguide Modulators and Sources on Silicon Photonics

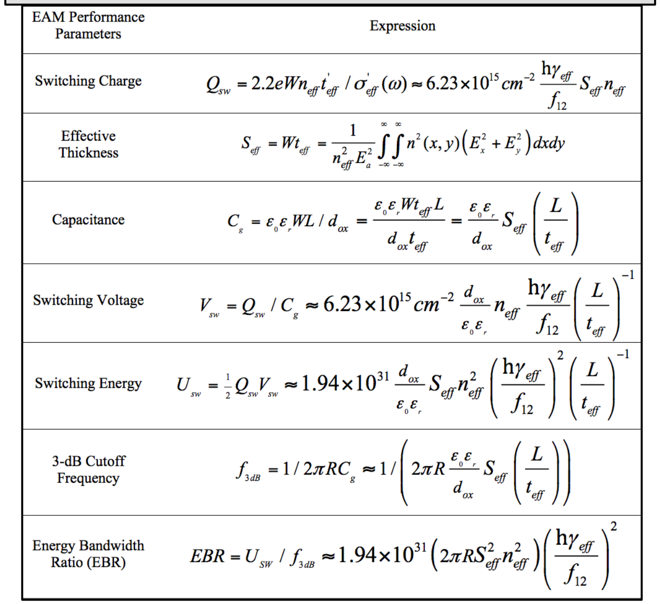
Charge-Driven EAM Performance



Quantum Dots have the lowest broadening (γ)
→ Least amount of switching voltage (V)
→ E/bit = ½ CV²

R. Amin, J. Khurgin, V. J. Sorger "Electro-Absorption Modulator Performance Study: Charge, Voltage, Energy and Bandwidth Analysis" in preparation, (2017)

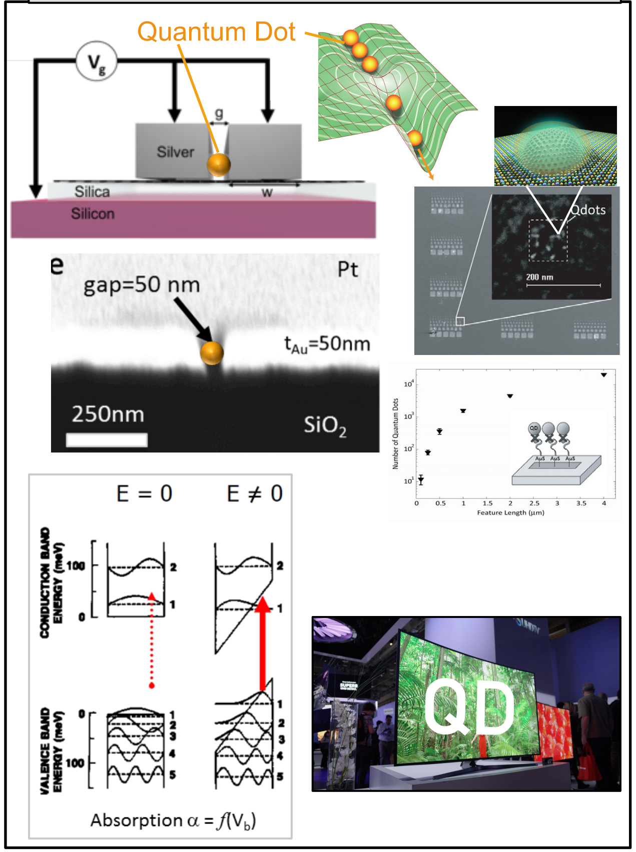
Low Broadening (γ) improves Performance



EAM Performance Parameters	Expression
Switching Charge	$Q_{sw} = 2.2eWn_{eff}t'_{eff} / \sigma'_{eff}(\omega) \approx 6.23\times10^{15}cm^{-2}\frac{h\gamma_{eff}}{f_{12}}S_{eff}n_{eff}$
Effective Thickness	$S_{eff} = Wt_{eff} = \frac{1}{n_{eff}^2E_a^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}n^2(x,y)\left(E_x^2+E_y^2\right)dxdy$
Capacitance	$C_g = \varepsilon_0\varepsilon_rWL / d_{ox} = \frac{\varepsilon_0\varepsilon_rWt_{eff}L}{d_{ox}t_{eff}} = \frac{\varepsilon_0\varepsilon_r}{d_{ox}}S_{eff}\left(\frac{L}{t_{eff}}\right)$
Switching Voltage	$V_{sw} = Q_{sw} / C_g \approx 6.23\times10^{15}cm^{-2}\frac{d_{ox}}{\varepsilon_0\varepsilon_r}n_{eff}\frac{h\gamma_{eff}}{f_{12}}\left(\frac{L}{t_{eff}}\right)^{-1}$
Switching Energy	$U_{sw} = \frac{1}{2}Q_{sw}V_{sw} \approx 1.94\times10^{31}\frac{d_{ox}}{\varepsilon_0\varepsilon_r}S_{eff}n_{eff}^2\left(\frac{h\gamma_{eff}}{f_{12}}\right)^2\left(\frac{L}{t_{eff}}\right)^{-1}$
3-dB Cutoff Frequency	$f_{3dB} = 1/2\pi RC_g \approx 1/\left(2\pi R\frac{\varepsilon_0\varepsilon_r}{d_{ox}}S_{eff}\left(\frac{L}{t_{eff}}\right)\right)$
Energy Bandwidth Ratio (EBR)	$EBR = U_{SW} / f_{3dB} \approx 1.94\times10^{31}\left(2\pi RS_{eff}^2n_{eff}^2\right)\left(\frac{h\gamma_{eff}}{f_{12}}\right)^2$

Quantum Dots (QD) have become of commercial grade such as used in display technology. QDs are also nearly perfect 2-level systems, resulting is a small broadening (γ). This means, that the required voltage for switching a QDs state is very small.

Proposed Devices: e.g. QD Modulator



We propose, to explore QD-based nanophotonic devices on a Silicon-platform. For instance, we will demonstrated the first plasmonic QD-based electro-optic modulator requiring only 100's of attojoule per bit. In fact, we aim to show the first single-quantum dot modulator where the active device region is just 10's of nanometer small, rivaling a modern FET. This project could also demonstrate efficient single quantum sources integrated in plasmonic-slot waveguides in Silicon photonics platform.

AFOSR Deliverables Submission Survey

Response ID:8799 Data

1.

Report Type

Final Report

Primary Contact Email
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sorger@gwu.edu

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Organization / Institution name

The George Washington University

Grant/Contract Title
The full title of the funded effort.

High Performance Sub-Lambda Silicon Plasmonic Modulator

Grant/Contract Number
AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-14-1-0378

Principal Investigator Name
The full name of the principal investigator on the grant or contract.

Volker Sorger

Program Officer
The AFOSR Program Officer currently assigned to the award

Dr. Gernot Pomrenke

Reporting Period Start Date

09/30/2014

Reporting Period End Date

09/29/2017

Abstract

In this effort we focused on electro-optic modulators, as they perform a key function in data communication. Furthermore, modulators also show potential in photonic analogue computing; for instance they could be used as analogue optical tuning element in photonic neuromorphic computing providing non-linearity of the perceptions output. In this program, we delivered a holistic performance-tradeoff analysis of modulators to date. We showed how critical physical parameters such as the active material, the optical mode overlap, the optical mode confinement, and the material broadening determine the modulator performance. We find that the strong binding energy in 2D materials enables efficient absorption in charge-driven modulators, while TCOs are unique candidates for phase-shifters. In short, we develop a set of guiding principles for attojoule-per-bit efficient transfer functions. We also find that the small mode overlap of 2D materials outperforms Silicon due to strong index modulation. However, we experimentally demonstrate the optimizing the optical mode for 2D materials by squeezing the mode area using slot-plasmon waveguides, delivers record-efficient modulators requiring just 100's of aJ/bit. We further show that the plasmonic metal is also critical to form the electrical capacitor right over the active device region and to deliver small contact resistances – a challenge that photonic modulators needs a tradeoff design. Further, we reveal the impact

of a cavity feedback on EOM and EAMs, and show how the tradeoff between loss and feedback can be harnessed. We experimentally demonstrate a hybrid plasmon Graphene-based modulator just requiring 0.5V to switch on a silicon platform.

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Archival Publications (published) during reporting period:

Z. Ma, Z. Li, K. Liu, C. Ye, V. J. Sorger, "Indium-Tin-Oxide for High-performance Electro-optic Modulation", Nanophotonics, 4, 1 (2015).

C. Huang, S. Pickus, R. Lamond, Z. Li, V. J. Sorger, "A Sub-λ Size Modulator Beyond the Efficiency-Loss Limit" IEEE Photonics Journal 5, 4 (2013).

C. Ye, S. Pickus, V. J. Sorger, "Ultra-compact Graphene-based Electro-optic Modulators on a Silicon-on-Insulator Platform" Intl J. M. Eng. (2014).

S. K. Pickus, S. Khan, C. Ye, Z. Li, and V. J. Sorger, "Silicon Plasmon Modulators: Breaking Photonic Limits" IEEE Photonic Society, 27, 6 (2013).

K. Liu, C.R. Ye, S. Khan, V. J. Sorger, "Review and perspective on ultrafast wavelength-size electro-optic modulators" Laser & Photonics Review, 9, 2, p.172-194 (2015) - Cover

V. J. Sorger, R. Amin, J. B. Khurgin, Z. Ma, S. Khan, "Roadmap on Atto-Joule per Bit Modulators", arXiv:1710.00046 (2017).

R. Amin, C. Suer, Z. Ma, J. Khurgin, R. Agarwal, V. J. Sorger, "A Deterministic Guide for Material and Mode Dependence of On-Chip Electro-Optic Modulator Performance", Solid-State Electronics, 136, 92-101 (2017).

Z. Ma, M. H. Tahersima, S. Khan and V. J. Sorger, "Two-Dimensional Material-Based Mode Confinement Engineering in Electro-Optic Modulators," IEEE Journal of Selected Topics in Quantum Electronics, vol. 23, no. 1, 1-8 (2017).

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Z. Ma, R. Hemnani, L. Bartels. R. Agarwal, V. J. Sorger, "2D Materials in Electro-optic Modulation: energy efficiency, electrostatics, mode overlap, material transfer and integration", arXiv:1708.05986 (2017).

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Compact Graphene Plasmon-Slot Modulator", arXiv: 1709.01465 (2017).

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K. Liu, C. Zhang, S. Mu, S. Wang, V. J. Sorger, "Trench-coupler based Silicon Mach-Zehnder Thermo-optic Switch with Flexible Two-dimensional Design" Optics Express. 24, 14, 15845-15853 (2016).

New discoveries, inventions, or patent disclosures:

Do you have any discoveries, inventions, or patent disclosures to report for this period?

Yes

Please describe and include any notable dates

1. (#62/463,217) Graphene Sot-waveguide based Electro-optic Modulator.
2. (#62/553440) 2D Material Printer.

Do you plan to pursue a claim for personal or organizational intellectual property?

Yes

Changes in research objectives (if any):

N.A.

Change in AFOSR Program Officer, if any:

N.A.

Extensions granted or milestones slipped, if any:

N.A.

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

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