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Breaking Photonic Limits- light-matter-interaction enhanced devices for atto-jou

Volker Sorger
THE GEORGE WASHINGTON UNIVERSITY

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Final Report

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14. ABSTRACT

Advancing the data bandwidth and security of communication systems is critical in this fast paced information age. Particular critical to the war fighter, other high end military machinery, and command infrastructure are to develop technological solutions for interconnect technology that propels the U.S. Air Force ahead of the competition. The long term research goal of this AF YIP effort is to unite the fields of electronics and optics by creating a distinct research branch of opto electronic devices with unprecedented data modulation performance for both the defense and civilian markets. In pursuit of this goal, the research objective of this effort is to test the hypothesis that strong lightmatter interactions in optical transistors, i.e. electroptic modulators & switches, result in a significant performance boost beyond classically known limits. The target is to enable nanoscale device footprints for unprecedented photonic on chip integration, and surpassing both the fundamental modulation efficiency loss and speed power tradeoffs. In pursuit of this objective, the technical approach takes on the challenge to design and demonstrate electro optic modulators and switches with performance metrics (i.e. footprint, power, speed) far beyond those set by classical (i.e. diffraction limited) photonic solutions. Key research elements

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Final Report

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 2nd Optics student chapter for SPIE at GWU, Published 2x papers at STEM conferences**

A. 250 Summary for FA9550-14-1-0215 (YIP)

With photonic devices being fundamentally challenged to deliver strong light-matter-interactions, we set out to explore devices, materials, and effects that allow increasing this weak interaction. In this context we explored emerging materials with remarkable high index tunability such as Graphene or TCO materials, we considered resonators and showed devices based on microrings, Fabry-Perots, plasmon, photonic crystal-based resonators. Here the focus was to consider the Purcell enhancement, namely volume reduction in addition to Q enhancement. Beyond cavities, a main task was to define scaling laws for nanophotonic devices to include lasers, modulators, detectors, and all-optical switching devices. Together with IBM we investigated heterogeneous integrated III-V on-Silicon nanolasers and LEDs for optical interconnects. We also solved the laser rate equations, and showed that carbon materials can exhibit ultra-fast switching due to the short intrinsic lifetime. We then explored Purcell enhancements in 2D material nanocavities and showed that a monomer performs equally well as a dimer for 2D material emission. We developed an ITO material process to deliver ENZ behavior. We used this then to design ultra-compact 2x2 routing switches in Silicon photonics. We next demonstrated an electrical-driven plasmon light source based on inelastically scattering electrons operating on Silicon at room temperature. Lastly, we used the coincidence properties of leaky-integrate-and-fire neurons to show a neuromorphic engine to directly identify mirror symmetry of images. Taken together, we developed new materials, explored physical effects, and demonstrated nanophotonic devices all with high relevance to the mission of the Air Force such as communication and image processing.

B. Scholarly Work Summaries

Fundamental Scaling Laws in Nanophotonics

The success of information technology has clearly demonstrated that miniaturization often leads to unprecedented performance, and unanticipated applications. This hypothesis of "smaller-is-better" has motivated optical engineers to build various nanophotonic devices, although an understanding leading to fundamental scaling behavior for this new class of devices is missing. Here we analyze scaling laws for optoelectronic devices operating at micro and nanometer length-scale. We show that optoelectronic device performance scales non-monotonically with device length due to the various device tradeoffs, and analyze how both optical and electrical constrains influence device power consumption and operating speed. Specifically, we investigate the direct influence of scaling on the performance of four classes of photonic devices, namely laser sources, electro-optic modulators, photodetectors, and all-optical switches based on three types of optical resonators; microring, Fabry-Perot cavity, and plasmonic metal

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nanoparticle. Results show that while microrings and Fabry-Perot cavities can outperform plasmonic cavities at larger length-scales, they stop working when the device length drops below 100 nanometers, due to insufficient functionality such as feedback (laser), index-modulation (modulator), absorption (detector) or field density (optical switch). Our results provide a detailed understanding of the limits of nanophotonics, towards establishing an opto-electronics roadmap, akin to the International Technology Roadmap for Semiconductors.

Monolithic III–V on Silicon Plasmonic Nanolaser Structure for Optical Interconnects

Monolithic integration of III–V semiconductor lasers with Si circuits can reduce cost and enhance performance for optical interconnects dramatically. We propose and investigate plasmonic III–V nanolasers as monolithically integrated light source on Si chips due to many advantages. First, these III–V plasmonic light sources can be directly grown on Si substrates free of crystallographic defects due to the submicron cavity footprint (250nm×250nm) being smaller than the average defect free region size of the heteroepitaxial III–V material on Si. Secondly, the small lateral and vertical dimensions facilitate process co-integration with Si complementary metal-oxide-semiconductor (CMOS) in the front end of the line. Thirdly, combining with monolithically integrated CMOS circuits with low device capacitance and parasitic capacitance, the nano-cavity optoelectronic devices consume orders of magnitude less power than the conventional lasers and reduce the energy consumption. Fourthly, the modulation bandwidth of the plasmonic light-sources is enhanced to significantly higher than conventional lasers due to enhanced photon state density and transition rate. In addition, we show that these device performance are very robust after taking into account the surface recombination and variations in device fabrication processes.

Integrated Nanocavity Plasmon Light Sources for On-Chip Optical Interconnects

Next generation on-chip light sources require high modulation bandwidth, compact footprint, and efficient power consumption. Plasmon-based sources are able to address the footprint challenge set by both the diffraction limited of light and internal laser physics such as plasmon utilization. However, the high losses, large plasmonic-momentum of these sources hinder efficient light coupling to on-chip waveguides, thus, questioning their usefulness. Here we show that plasmon light sources can be useful devices; they can deliver efficient outcoupling power to on-chip waveguides and are able to surpass modulation speeds set by gain-compression. We find that waveguide-integrated plasmon nanocavity sources allow to transfer about ~60% of their emission into planar on-chip waveguides, while sustaining a physical small footprint of ~0.06 μm^2. These sources are able to provide output powers of tens of microwatts for microamp-low injection currents and reach milliwatts for higher pump rates. Moreover, the direct modulation bandwidth exceeds that of classical, gain compression-limited on-chip sources by more than 200%. Furthermore, these novel sources feature high power efficiencies (~1 fJ/bit) enabled by both minuscule electrical capacitance and efficient internal photon utilization. Such strong light–matter interaction devices might allow redesigning photonic circuits that only demand microwatts of signal power in the future.

Monolithically Integrated III-V NanoLED on Si for Optical Interconnects

With the recent advances in nanoscale light sources, there is a tantalizing opportunity to integrate optical interconnects monolithically on Si CMOS. However, one key issue is whether the output power of the nanoscale sources is sufficient for next generation optical interconnect technology. The output power of such miniscule-sized sources is, at best, orders of magnitude lower than the conventional lasers with a size of hundreds of microns. We analyze this question and envision that high-speed interconnects (~40 Gbps) using these emerging sources is possible for inter-chip communication with the following realistic assumptions: (i) 70% optical coupling efficiency from the nano-LED into the waveguide, (ii) a light emission efficiency of EQE of ~20% with a photon energy of ~1 eV, (iii) a low-loss (0.3 dB/cm) SOI waveguide yielding <10% loss for waveguide transmission of 1 cm distance, (iv) an ultra-low capacitance photodetector, e.g. Ge metal cavity photodiode (30 aF) with high efficiency (50% EQE), and (v) 0.3V circuit drive voltage. These result in a required emitter power of 125 photons/bit, corresponds to an energy per bit of <200 aJ, and a LED drive current of 5 μA for 40 Gbps data rates. The average optical power in the waveguide is 0.8 μW, which is a factor of 10^2-10^3 smaller than that required for the state-of-the-art integrated chip source. In cases where higher optical power is needed, multiple LEDs can be used in parallel. If optoelectronic circuits are to reach integration densities comparable to electronics of the 1990, high power dissipation leads to thermal budget constrains during operation. This demands the device energy-per-bit functions to be reduced to the sub-femtojoule per-bit regime.

Plasmonic Optical Modulator based on Adiabatic Coupled Waveguides

In atomic multi-level systems, adiabatic elimination is a method used to minimize complicity of the system by eliminating irrelevant and strongly coupled levels by detuning them from one another. Such a three-level system, for instance, can be mapped onto physical in form of a three waveguide system. Actively detuning the coupling strength between the respective waveguide modes allows modulating light propagating through the device, as proposed here. The outer waveguides act as an effective two- photonic-mode system similar to ground- and excited states of a three-level atomic system, whilst the center waveguide is partially plasmonic. In adiabatic elimination regime, the amplitude of the middle waveguide oscillates much faster in comparison to the outer waveguides leading to a vanishing field build up. As a result, the middle waveguide becomes a "dark state" and hence a low insertion-loss of 8 dB is expected to keep when achieving the modulation depth as high as 70 dB despite the involvement of a plasmonic waveguide in the design presented here. The modulation mechanism relies on switching this waveguide system from a critical coupling regime to adiabatic elimination condition via electrostatically tuning the free-carrier concentration and hence the optical index of a thin ITO layer residing in the plasmonic center waveguide. This alters the effective coupling length and the phase mismatching condition thus modulation in each of outer waveguides. Our results show a modulator energy efficiency as low as 40 atto-joule per bit and an extinction ratio of 50 2 dB. Given the miniscule footprint of the modulator, the resulting lumped-element limited RC delay is expected to exceed 200 GHz. Such expected performance is a direct result of both the unity-strong tunability of the plasmonic optical mode in conjunction with utilizing ultrasensitive modal coupling between the critically-coupled and the adiabatic elimination regimes. Taken together, this new class of modulators paves the way for next-generation both energyand speed conscience optical short-reach interconnects.

Electrically-driven carbon nanotube-based plasmonic laser on silicon

Photonic signal processing requires efficient on-chip light sources with higher modulation bandwidths. Today's conventional fastest semiconductor diode lasers exhibit modulation speeds only on the order of a few tens of GHz due to gain compression effects and parasitic electrical capacitances. Here we theoretically show an electrically-driven carbon nanotube (CNT)-based laser utilizing strong light-matter-interaction via monolithic integration into Silicon photonic crystal nanobeam (PCNB) cavities. The laser is formed by single-walled CNTs inside a combo-cavity consisting of both a plasmonic metal-oxide-semiconductor hybrid mode embedded in the one dimensional PCNB cavity. The emission originates from interband recombinations of electrostatically-doped nanotubes depending on the tubes' chirality towards matching the C-band. Our simulation results show that the laser operates at telecom frequencies resulting in a power output > 3 (100) μW and > 100 (1000)'s GHz modulation speed at 1 × (10 ×) threshold. Such monolithic integration schemes provide an alternative promising approach for light source in future photonic integrated circuits.

Testbeds for Transition Metal Dichalcogenide Photonics: Efficacy of Light Emission Enhancement in Monomer vs Dimer Nanoscale Antennae

Monolayer transition metal dichalcogenides (TMDs) are materials with unique potential for photonic and optoelectronic applications. They offer well-defined tunable direct band gaps in a broad electromagnetic spectral range. The small optical path across them naturally limits the light–matter interactions of these two-dimensional (2-D) materials, due to their atomic thinness. Nanoscale plasmonic antennae offer a substantial increase of field strength over very short distances, comparable to the native thickness of the TMD. For instance, it has been demonstrated that plasmonic dimer antennae generate hot-spot field enhancements by orders of magnitude when an emitter is positioned exactly over the middle of their gap. However, 2-D materials cannot be grown or easily transferred, to reside midgap of the metallic dimer cavity. Hence, it is not plausible to simply take the peak intensity as the emission enhancement factor. Here we show that the emission enhancement generated in a 2-D TMD film by a monomer antenna cavity rivals that of dimer cavities at a reduced lithographic effort. We rationalize this finding by showing that the emission enhancement in dimer antennae depends not on the peak of the field enhancement at the center of the cavity but rather from the average field enhancement across a plane located beneath the optical cavity where the emitting 2-D film is present. We test multiple dimer and monomer antenna geometries and observe a representative 3-fold emission enhancement for both monomer and dimer cavities as compared to the intrinsic emission of chemical vapor deposition (CVD)-synthesized WS2 flakes. This finding suggests facile control and enhancement of the photoluminescence yield of 2-D materials based on engineering of light–matter interactions that can serve as a testbed for their rapid and detailed optical characterization.

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-λ long 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/um 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.

A compact plasmonic MOS-based 2×2 electro-optic switch

We report on a three-waveguide electro-optic switch for compact photonic integrated circuits and data 5 routing applications. The device features a plasmonic metal-oxide-semiconductor (MOS) mode for enhanced light-matter-interactions. The switching mechanism originates from a capacitor-like design where the refractive index of the active medium, Indium-Tin-Oxide, is altered via 10 shifting the plasma frequency due to carrier accumulation inside the waveguide-based MOS structure. This light manipulation mechanism controls the transmission direction of transverse magnetic polarized light into either a CROSS or BAR waveguide port. The extinction ratio of 18 dB (7) dB 15 for the CROSS (BAR) state, respectively, is achieved via a gating voltage bias. The ultrafast broadband fJ/bit device allows for seamless integration with Silicon.

On-chip Integrated All-Optical Fast Fourier Transform: Design and Sensitivity Analysis

The Fast Fourier Transform (FFT) algorithm is a universal function in signal processing. It characterizes the magnitude and phase of a signal, or is used in combination with other operations to perform more complex computations such as convolution and correlation. Electronic FFTs are limited by serial processing and the charging of wires resulting in delay and data processing bottlenecks. A fiber optical temporal FFT has demonstrated high data bandwidth enabled by wavelength division multiplexing and delays only limited by the propagation of the optical signal. Thus, the delay can be significantly improved when integrated photonics is being used instead. Here we show a design of an optical FFT in Silicon photonics and analyze its performance with respect to variations in phase and amplitude. We discuss the impact of the deployed devices on the FFT's transfer function's quality defined by the transmission output power as a function of frequency, detuning phase, optical delay (loss). Our results show that the instability of the phase delay critically depend on the correct probe frequency and temperature, but can be relatively stable using heaters considering state-of-the-art Silicon photonics process conditions. We further show how loss imbalances in the deployed interferometers can be design-compensated via added delay lines. This on-chip FFT is anticipated to handle 2.56 bit/s per single wavelength channel. A temporal FFT capable of 10^3 times higher data rates enables real-time nonlinear cyclostationary and convolutional processing, and with applications in optical electromagnetic signal environmental surveillance.

Towards On-Chip Optical FFTs for Convolutional Neural Networks

Convolutional neural networks have become an essential element of spatial deep learning systems. In the prevailing architecture, the convolution operation is performed with Fast Fourier Transforms (FFT) electronically in GPUs.

The parallelism of GPUs provides an efficiency over CPUs, however both approaches being electronic are bound by the speed and power limits of the interconnect delay inside the circuits. Here we present a silicon photonics based architecture for convolutional neural networks that harnesses the phase property of light to perform FFTs efficiently. Our all-optical FFT is based on nested Mach-Zender Interferometers, directional couplers, and phase shifters, with backend electro-optic modulators for sampling. The FFT delay depends only on the propagation delay of the optical signal through the silicon photonics structures. Designing and analyzing the performance of a convolutional neural network deployed with our on-chip optical FFT, we find dramatic improvements by up to 10^2 when compared to state-of-the-art GPUs when exploring a compounded figure-of-merit given by power per convolution over area. At a high level, this performance is enabled by mapping the desired mathematical function, an FFT, synergistically onto hardware, in this case optical delay interferometers.

Identifying Mirror Symmetry Density with Delay in Spiking Neural Networks

The ability to rapidly identify symmetry and antisymmetry is an essential attribute of intelligence. Symmetry perception is a central process in human vision and may be key to human 3D visualization. While previous work in understanding neuron symmetry perception has concentrated on the neuron as an integrator, here we show how the coincidence detecting property of the spiking neuron can be used to reveal symmetry density in spatial data. We develop a method for synchronizing symmetry-identifying spiking artificial neural networks to enable layering and feedback in the network. We show a method for building a network capable of identifying symmetry density between sets of data and present a digital logic implementation demonstrating an 8x8 leaky-integrate-and-fire symmetry detector in a field programmable gate array. Our results show that the efficiencies of spiking neural networks can be harnessed to rapidly identify symmetry in spatial data with applications in image processing, 3D computer vision, and robotics.

Graphene-based solitons for spatial division multiplexed switching

Spatial division multiplexing utilizes the directionality of the light's propagating k-vector to separate it into distinct spatial directions. Here, we show that the anisotropy of orthogonal spatial solitons propagating in a single graphene monolayer results in phase-based multiplexing. We use the self-confinement properties of spatial solitons to increase the usable density of states (DOS) of this switching system. Furthermore, we show that crossing two orthogonal soli- tons exhibits a low (0.035 dB) mutual disturbance from another enabling independent k-vector switching. The efficient utilization of the DOS and multiplexing in real space enables data processing parallelism with applications in optical networking and computing.

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

K. Liu, S. Sun, A. Majumdar, V. J. Sorger, "Fundamental Scaling Laws in Nanophotonics" *Nature: Scientific Reports*, 6, 37419 (2016).

K. Liu, N. Li, D. K. Sadana, V. J. Sorger, "Integrated nano-cavity plasmon light-sources for on-chip optical interconnects" *ACS Photonics*, 3. 233-242 (2016).

N. Li, K. Liu, D. K. Sadana, V. J. Sorger, "Monolithic III-V on Silicon Nanolaser structure for optical Interconnects", *Nature: Scientific Reports*, 5, 14067 (2015).

N. Li, K. Han, D. K. Sadana, V. J. Sorger, "Monolithically integrated III-V NanoLED on Silicon for optical Interconnects", *Optica*, (in review)

R. Wang, H. Dalir, X. Xu, Z. Pan, S. Sun, V. J. Sorger, R. T. Chen, "Atto-Joule, High-Speed and Compact Plasmonic Modulator based on Adiabatic Coupled Waveguides", *arXiv*: 1710.01689 (2017).

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K. Liu, V. J. Sorger, “Electrically-driven Carbon nanotube-based plasmonic laser on Silicon” *Optical Materials Express*, 5, 1910-1919 (2015).

M. H. Tahersima, M. Danang Birowosuto, Z. Ma, W. C. Coley, M. Valentin, I. Lu, K. Liu, Y. Zhou, A. Martinez, I. Liao, B. N. Davis, J. Martinez, S. Naghibi Alvillar, D. Martinez-Ta, A. Guan, A. E. Nguyen, C. Soci, E. Reed, L. Bartels, V. J. Sorger. “Testbeds for Transition Metal Dichalcogenide Photonics: Efficacy of Light Emission Enhancement in Monomer vs. Dimer Nanoscale Antennas”, *ACS Photonics,* 4, 1713-1721 (2017).

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).

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. Ye, K. Liu, R. Soref, and V. J. Sorger, “3-Waveguide 2x2 Plasmonic Electro-optic Switch” *Nanophotonics*, 4, 1, pp. 261-268 (2015).

H. Nejadriahi, D. Hillerkus, J. K. George, V. J. Sorger, “On-chip Integrated All-Optical Fast Fourier Transform: Design and Analysis”, (in preparation)

J. K. George, H. Nejadriahi, V. J. Sorger, "Towards On-Chip Optical FFTs for Convolutional Neural Networks". *arXiv*: 1708.09534. Accepted at *IEEE International Conference on Rebooting Computing 2017* (2017).

J. K. George, C. Soci, V. J. Sorger, " Identifying Mirror Symmetry with Delay in Spiking Neural Networks" *arXiv*: 1709.02684 (2017).

J. K. George, V. J. Sorger, “Graphene-based Solitons for Spatial Division Multiplexed Switching”, *Optics Letters* 42, 4, 787-790 (2017).

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YIP - Breaking Photonic Limits

light-matter-interaction enhanced devices for atto-joule &THz datalinks

- Volker Sorger (PI)
- FA-9550-14-0215
- Time: 7/15/2014-7/14/2017

Objective

- Demonstrate that strong light-matter-interactions in optoelectronic devices beyond classically known limits.

Approach

- Demonstrate next technology-level (=nanoscale regime) via high Q/V_m factors, cavities, and material selection
- Explore Hybrid Silicon-photonics or Hybrid III-V Photonics platforms, where able.

Deliveries

- Obtained First nanophotonic scaling laws analysis
- Designed and demonstrated nanoscale source with Si-III-V heterointegration
- Demonstrated E-driven plasmon source based on tunnel electrons
- Realized ENZ materials (ITO) and device integration

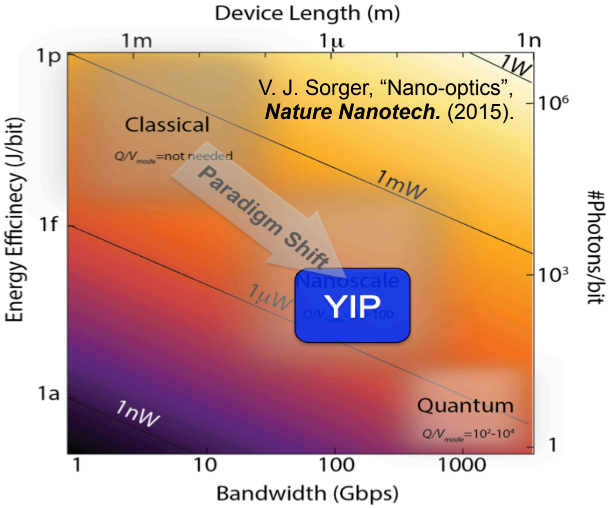
Technology Transition

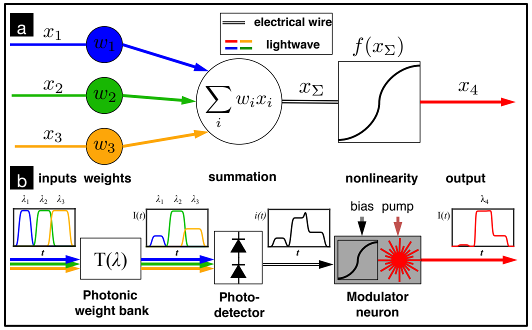
- Collaboration with IBM Watson and Nick Usechak (AFRL)
- 6 Patents filed (this includes FA-995-13-1-0378)
  - (#14/528,392): Silicon-Based, Broadband, Waveguide-Integrated Electro-Optical Switch.
  - (#14/941,100): Integrated nano-cavity plasmon laser light-sources. (IBM jointly filed).
  - (#62/146,590) 2D material-based Spiral Solar Cell.
  - (#62/461,889) Image Symmetry Detection via leaky-firing Spiking Neuromorphic Networks.
  - (#62/463,217) Graphene Sot-waveguide based Electro-optic Modulator.
  - (#62/553,440) 2D Material Printer.

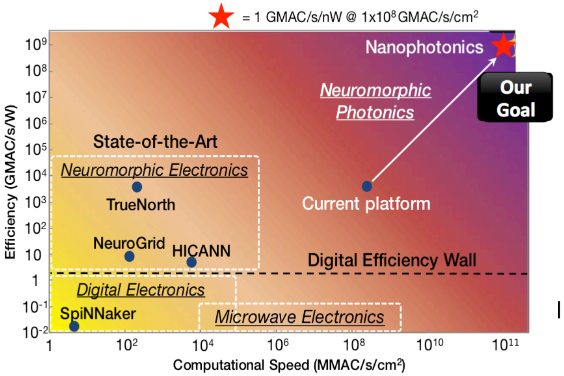
Sorger Lab: Reflection & Outlook

Summarizing our achievements over the last 3 year, we obtained the most holistic understanding of nanoscale light sources, electro-optic modulators, and other switching devices to date. Using this knowledge, we demonstrated attojoule-per-bit efficient modulators, and explored novel physical effects such as electron tunneling for plasmon creation.

From here we are interested in the following directions; (i) to explore non-linearities in modulators for neuromorphic computing (see figure on right), (ii) to demonstrate on-demand quantum sources on-chip, (iii) to develop a TCO-based low-loss phase shifters on Silicon together with AIM Photonics, (iv) to demonstrated the first NP-complete oracle in Si-Photonics, and (v) to explored quantum-dot nanophotonic modulators and sources. (see proposals in slides below)







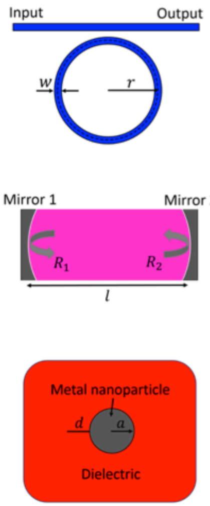
Nanophotonic Scaling Laws

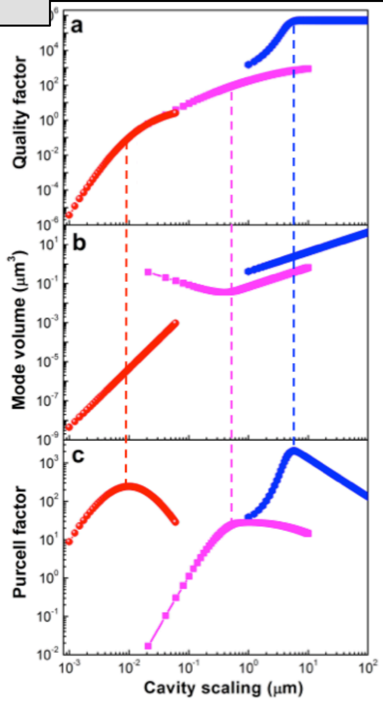
i.e. Is smaller = better?

Cavity Scaling Laws

Purcell Factor ~ Q/V$_{mode}$

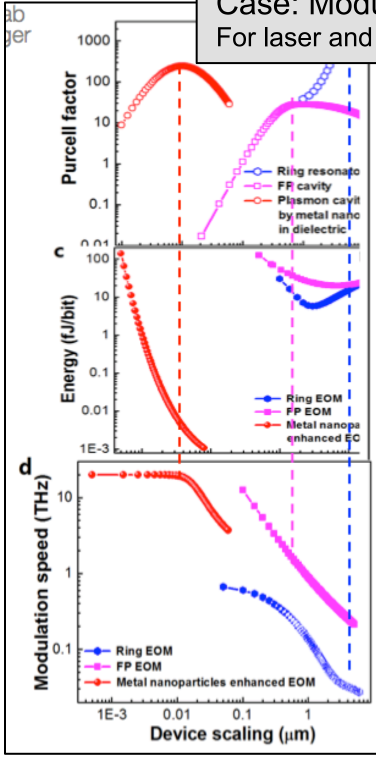
- Losses and mode Volumes
- Field penetration into metal mirror
- Mode Density ratio (SP/Continuum)

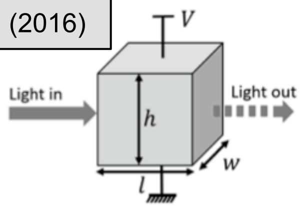




Case: Modulator

For laser and detector Liu, et al. Sci. Rep. (2016)





$$\frac{E}{bit} \propto \frac{1}{F_p Q}$$

$$E_{critical} = \frac{V_{bias}}{h}, \quad C = \varepsilon\frac{LW}{h}$$

The refractive index change is governed by an electric field $E_{critical}$.

$$\begin{aligned} Energy_{dissipate} &= \tfrac{1}{2}CV_{bias}^2 \\ &= \tfrac{1}{2}\left(\varepsilon\frac{WL}{h}\right)(h)^2 E_{critical}^2 \\ &= \tfrac{1}{2}\varepsilon\cdot E_{critical}^2\cdot(WLh) \\ &= \tfrac{1}{2}\varepsilon\cdot\left(\frac{2}{r_{EO}n^2Q}\right)^2\cdot(Volume) \end{aligned}$$

$$E_{critical} = \frac{\lambda\cdot BW}{\pi r_{EO} n^2 c}$$

*Lin et al. Opt Exp. (2012)

$$Q \equiv \frac{\omega}{\Delta\omega} = \frac{2\pi c}{\lambda\cdot BW}$$

K. Liu, S. Sun, A. Majumdar, V. J. Sorger, "Fundamental Scaling Laws in Nanophotonics" ***Nature: Scientific Reports***, *6, 37419* (2016)

Device Methodology

	Electric	Optic		
Energy →	$\frac{1}{2}CV^2$	& '*Effect*'	Threshold Extinction Ratio Responsivity	= Laser = EOM = Detector

Speed → $\frac{1}{RC}$ & $\frac{1}{\tau_p} \propto \frac{1}{Q}$

Elect. Opt. (photon Lifetime)

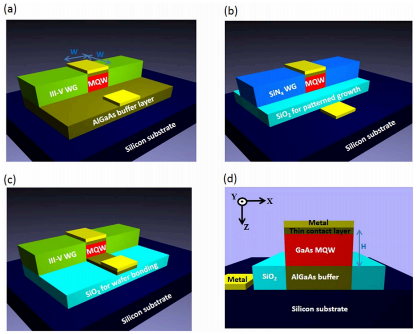
$$f_{3dB} = \frac{f_{Ph}\cdot f_{RC}}{\sqrt{f_{Ph}^2 + f_{RC}^2}}$$

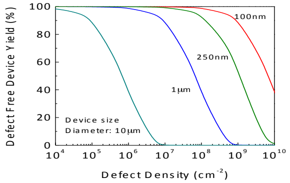
Conclusions

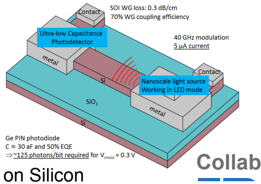
- Cavity quality (Purcell factor) impacts device performance
- Nanophotonic Device Performance scales generally ~(V_{mode}/Q)
- The laser threshold scales inversely with Purcell effect.
- Optical Non-linear devices have a stronger Q-dependency.
- The speed depends on both electrical RC-delay and the cavities photon lifetime (i.e. high-Q does not help).
- 100's aJ/bit modulators are possible for small optical modes.

Nanoscale Light Lasers and LEDs

Monolithic III-V Plasmon-Laser





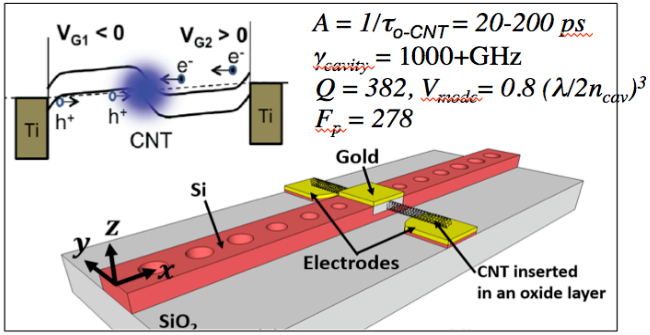


- N. Li, K. Liu, D. K. Sadana, V. J. Sorger, “Monolithic III-V on Silicon Nanolaser structure for optical Interconnects” ***Sci. Rep.***, 5, 14067 (2015).
- Sorger et al. Optica (in preparation)

Collaboration

IBM

Carbon-based Silicon-Photonics Laser

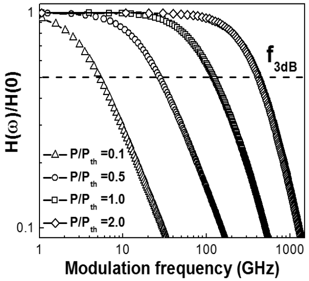


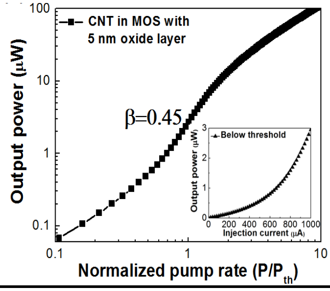
$A = 1/\tau_{o\text{-}CNT} = 20\text{-}200$ ps

$\gamma_{cavity} = 1000\text{+GHz}$

$Q = 382$, $V_{mode} = 0.8\ (\lambda/2n_{cav})^3$

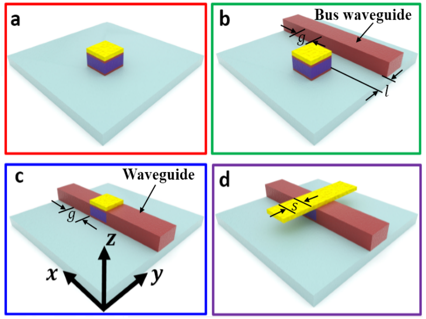
$F_p = 278$

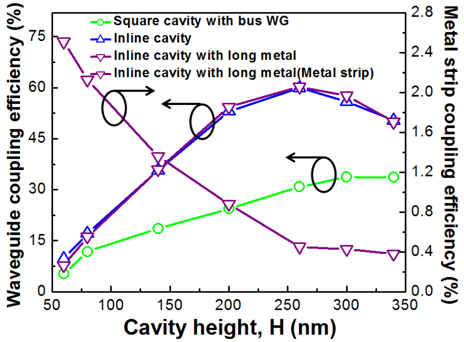


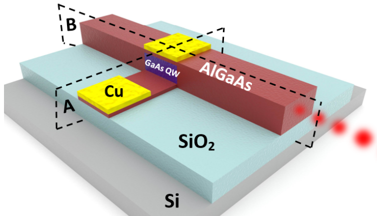


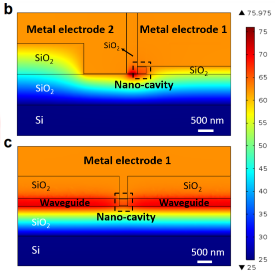
K. Liu, V. J. Sorger, “Electrically-driven Carbon nanotube-based plasmonic laser on Silicon” ***Opt. Mat. Exp.*** (2015).

Plasmon Nanolaser to-waveguide coupling & Temperature









Poly Si → $T_{operation}$ = 96C > CMOS

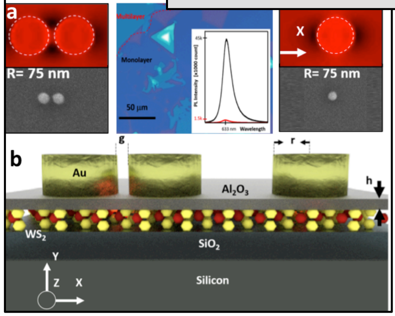
Metal → $T_{operation}$ = 65C < CMOS

Collaboration

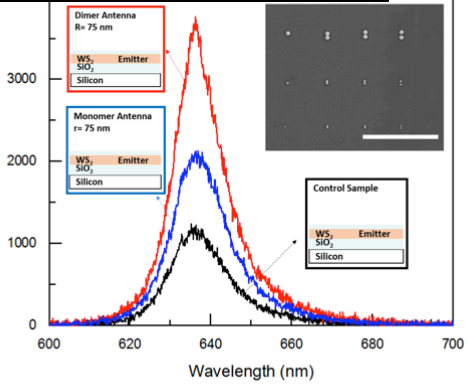
IBM

K. Liu, N. Li, D. K. Sadana, V. J. Sorger, “Integrated nano-cavity plasmon light-sources for on-chip optical interconnects” ***ACS Photonics***, 3. 233-242 (2016).

Nanocavity 2D Material Exciton Interaction

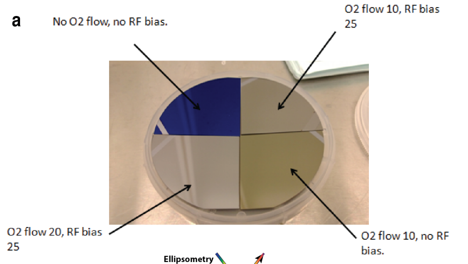


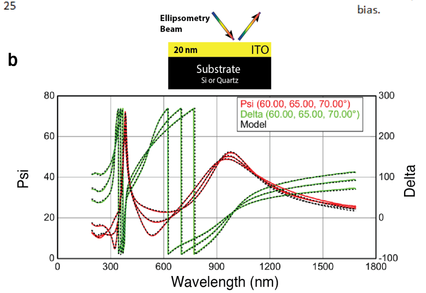
M. H. Tahersima, “Testbeds for Transition Metal Dichalcogenide Photonics: Efficacy of Light Emission Enhancement in Monomer vs. Dimer Nanoscale Antennas”, ***ACS Phot.*** (2017).

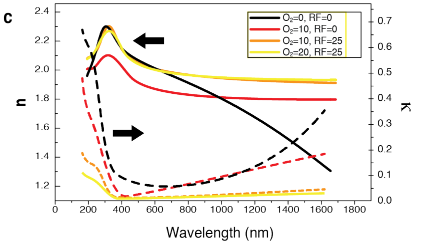


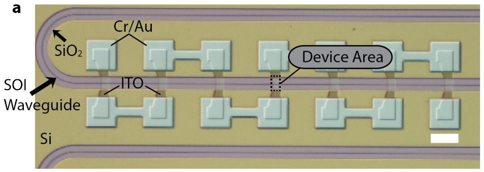
ITO for ENZ Materials and Devices

ITO Material Characterization









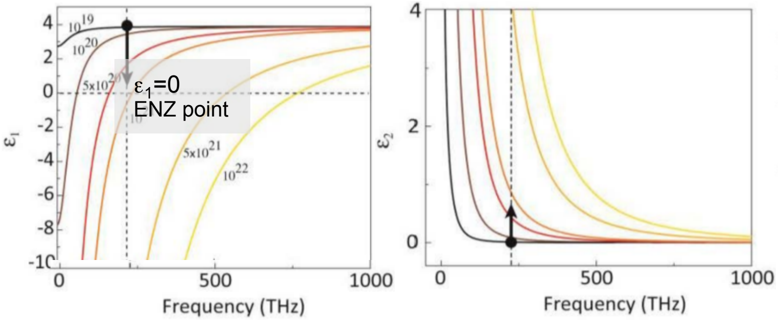
b

Sample	Si/ITO O_2=20 sccm Annealed = no Plasma = no	Si/ITO O_2=20 sccm Annealed = 300C, Plasma = no	Si/ITO O_2=20 sccm Annealed = no Plasma = Yes	Si/ITO O_2=20 sccm Annealed = 300C Plasma = Yes
Resistivity [Ω-cm]	[10^{-2}-10]	~10^{-3}	[10^{-4}-10^{-3}]	~10^{-4}

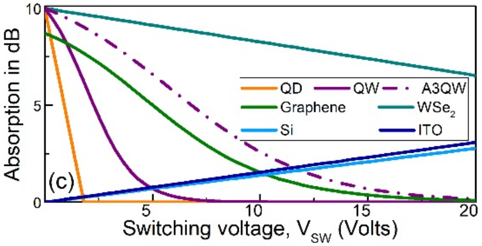
Z. Ma, Z. Li, K. Liu, C. Ye, V. J. Sorger, ***Nanophot.*** (2015)

Free-Carrier tunable TCO Material enabling ENZ

Black arrow = experimental switching data

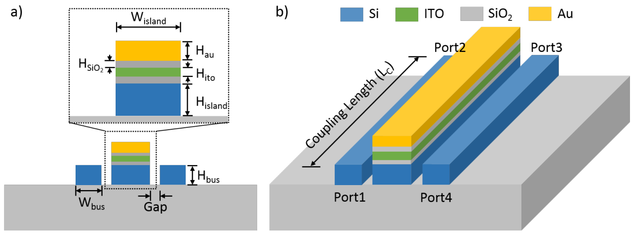


C. Huang, S. Pickus, R. Lamond, Z. Li, V. J. Sorger ***IEEE Phot. J.*** (2013)



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

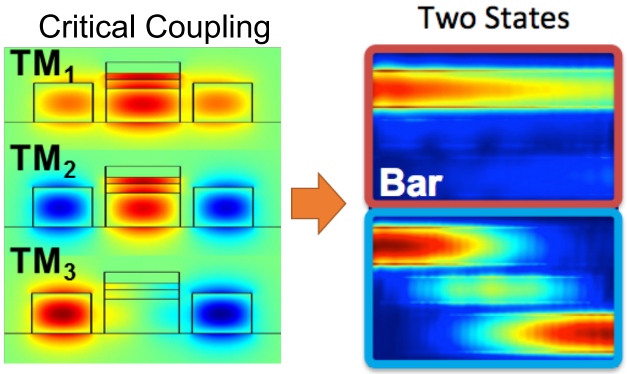
Proposed 2x2 Switches based on ITO Hybrid Silicon Plasmonics

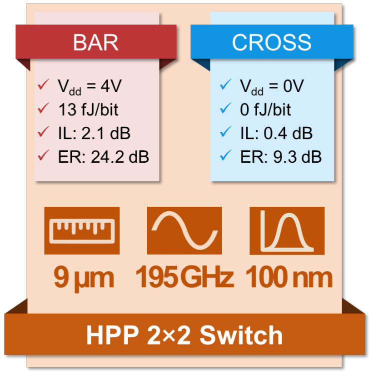


C. Ye, K. Liu, R. Soref, V. J. Sorger, ***Nanophot.*** (2015)

U.S. patent (#14/528,392): Plasmonic on-chip chip 2x2 switch.

S. Sun, V. K. Narayana, Ib. Sarpkaya, J. Crandall, R. A. Soref, T. El-Ghazawi, V. J. Sorger, ***IEEE Photonics Journal*** (2017).

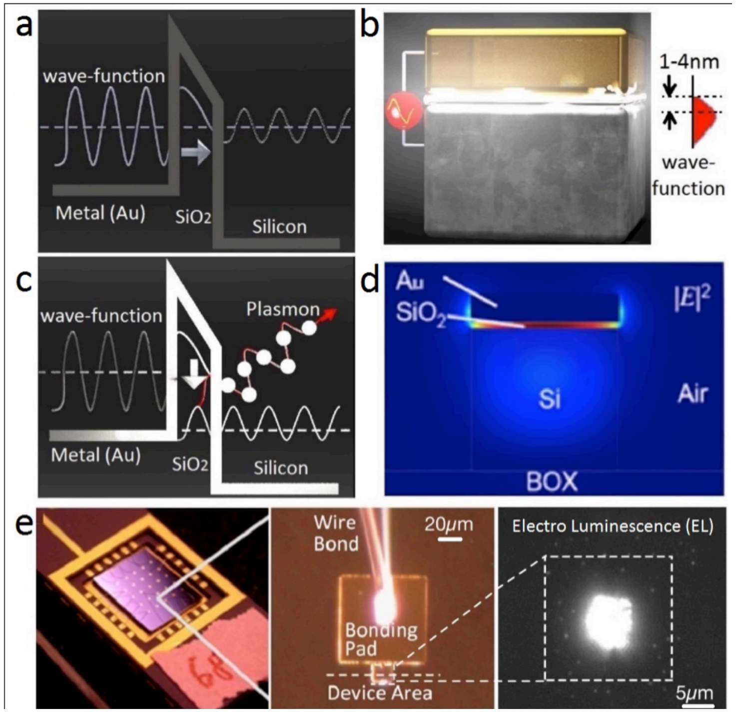


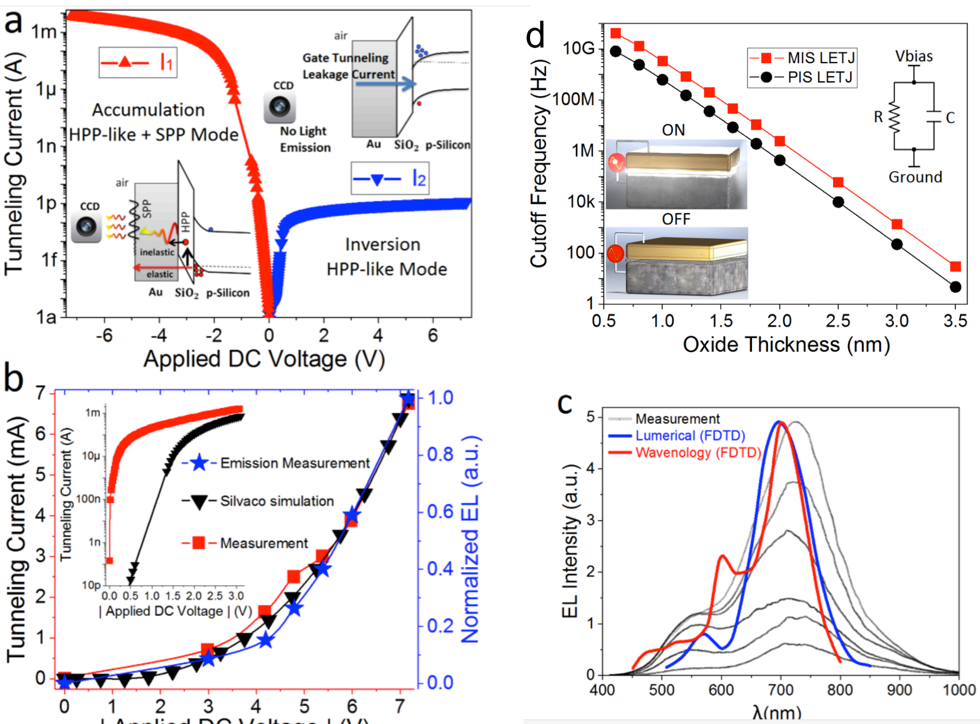


BAR	CROSS
✓ V_{dd} = 4V	✓ V_{dd} = 0V
✓ 13 fJ/bit	✓ 0 fJ/bit
✓ IL: 2.1 dB	✓ IL: 0.4 dB
✓ ER: 24.2 dB	✓ ER: 9.3 dB

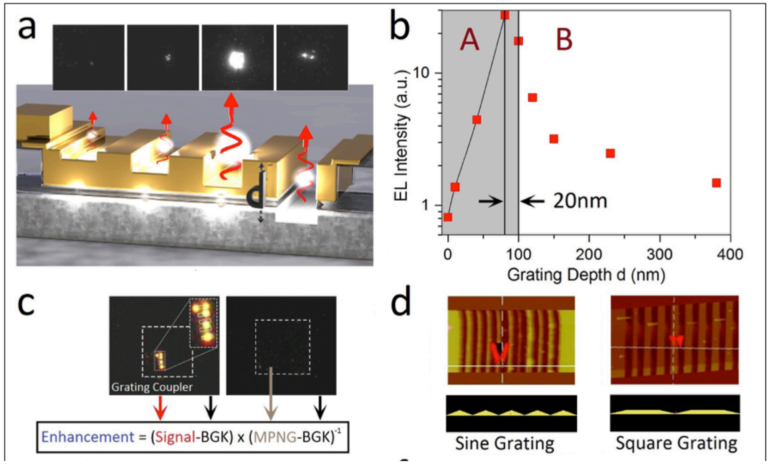
Proposal Option 1:

On-Demand Single Photon Sources based on Quantum Tunneling on Silicon





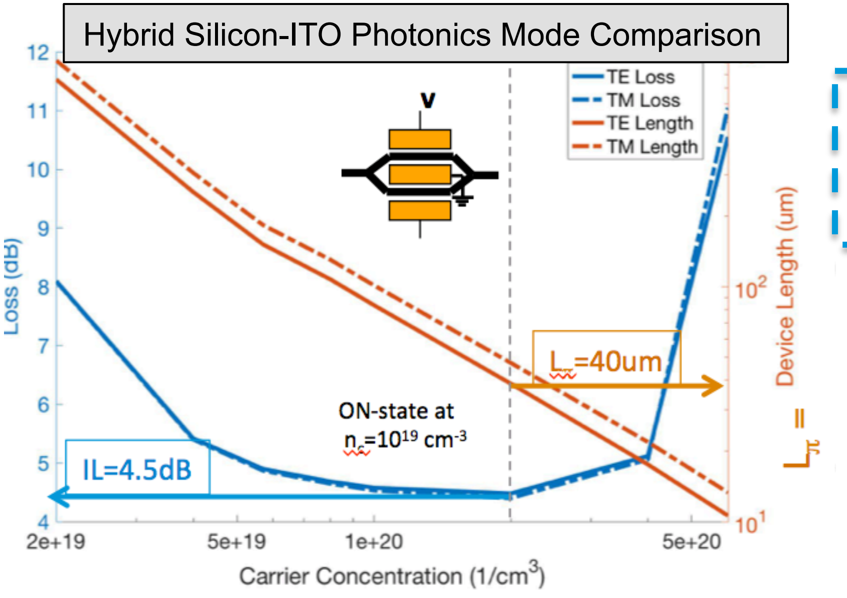
Sorger Lab (in preparation)



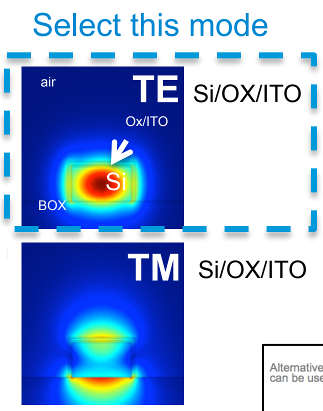
Inelastically scattering tunneling electrons are predicted to emit a photon (or plasmon) with up to 10% probability. This can be realized by biasing two Fermi-levels against each other creating a perfect inverted system. We recently demonstrated a silicon-based electrical driven, room-temperature Silicon compatible light (plasmon) source.

Based on these preliminary result we propose to, demonstrated single photon/plasmon creation on-demand by controlling the tunnel current accurately for application in quantum information processing. This device is novel because it is a novel light creation based-on quantum tunneling allows to be electrical-driven, room temperature, Silicon compatible.

Proposal Option 2:
ENZ TCO-based Phase-tunable Loss-Sensitive Silicon Hybrid Photonics



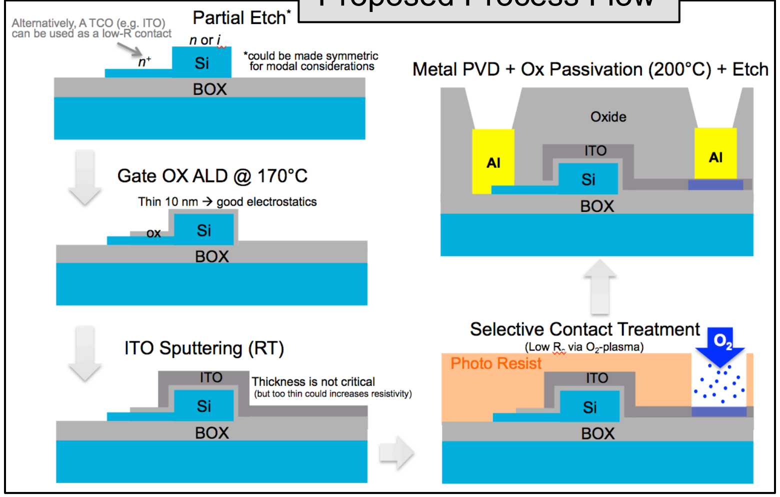
Sorger Lab, ***preliminary results*** (2017)



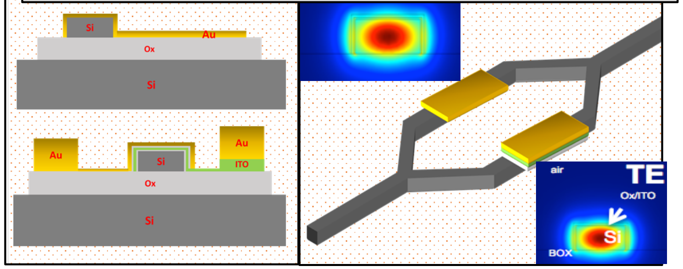
Si ITO TE mode has a lowest IL ~4dB at carrier concentration 4E20, with device length of 20um, RC-delay = 5GHz. **Options** (to reduce loss further): Change sputtering recipe (e.g. O_2 concentration or RF bias to engineer broadening γ), or use different ITO target composition. We used In_2O_3/SnO_2 (90/10).

$$\boxed{\gamma = \varepsilon_0 \rho \omega_p^2}$$

Proposed Process Flow



Proposed Low-loss Phase-tunable Devices

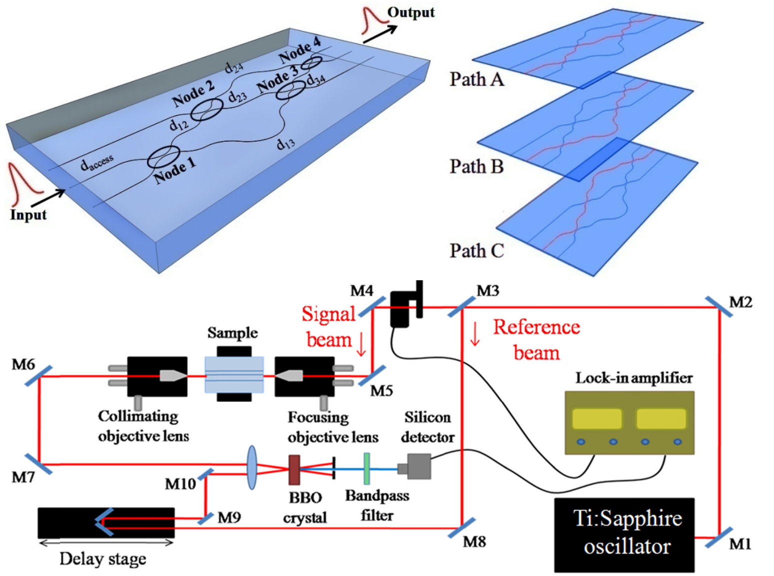


Transparent conductive oxides (TCO) have shown to have a strong index change near ENZ. While many demonstration show absorption modulation (imaginary part, loss), Kramers Kronig relations anticipate a strong real-part modulation as well, a feature not demonstrated to-date in integrated photonics with TCOs.

We propose to establish a comprehensive TCO-based Hybrid Silicon photonics platform for loss-conscious phase-tuning. We explore linear phase shifters for MZI-type and cavity (ring)-based modulators, and phased-waveguide arrays for beam steering. This will be in collaboration with AIM Photonics Foundry, and NRL for AZO and other TCO material depositions. ITO will be processed in-house.

Proposal Options 3 & 4:
Nanophotonics-based Algorithms

Photonics NP-Complete Solvers

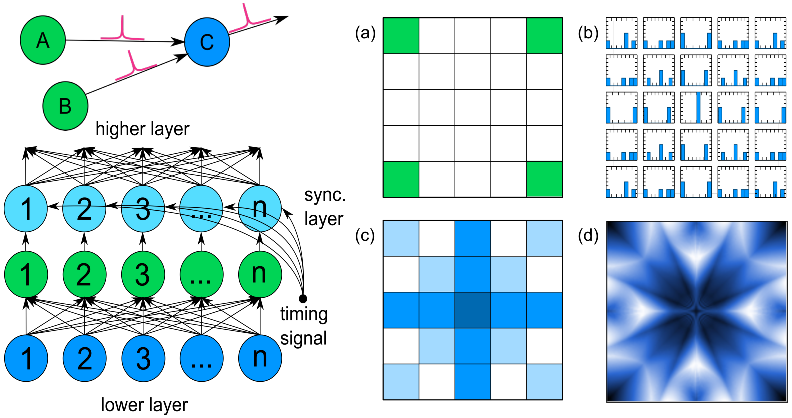


J. K. George, C. Soci, V. J. Sorger, ”Reconfigurable NP-Complete Oracle in Silicon-Photonics" (in preparation)

There are more than 2,000 non-deterministic polynomial time complete problems in our daily lives, such as the traveling salesmen problem. The time complexity of an algorithm defines the amount of time that the algorithm takes to be run and is a function of the input problem size. NP complete problems require exponential time complexity functions and are therefore compute demanding problems. A combinatorial graph problem with *N* nodes requires an execution time of 2^N times the clock time when solved through brute-force computing. A 60 node graph for example takes 10 years to solve.

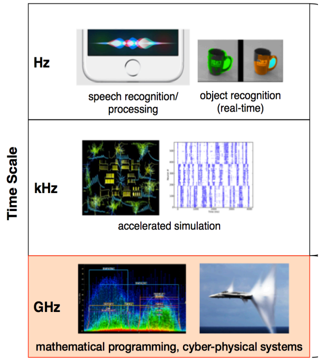
We propose, to optically solve NP-complete problems, and will demonstrate an optical oracle based on cascaded directional couplers in Silicon photonics, for the solution of the Hamiltonian path problem. We will further investigate reconfigurability of the network via tuning the couplers.

Photonic Spiking Neuromorphics for Mirror Symmetry Detection



J. K. George, C. Soci, V. J. Sorger, " Identifying Mirror Symmetry with Delay in Spiking Neural Networks" ***arXiv***: 1709.02684 (2017)

Symmetry is relevant to artificial intelligence as a mechanism for reducing dimensions. Over dimensioning is a constant problem in learning algorithms where distance between vectors, and consequently the ability to distinguish data clusters, decreases rapidly as the number of dimensions increases. This has AF relevance for real-time data processing, deep-learning or quantum optimization. Such processes



We propose, to demonstrate an optical image symmetry identification engine by utilizing the coincidence detection properties of neural-networks based on spiking leaky-integrated-and-fire neurons in both optical and photonic platform. We propose that the power efficiencies of spiking neural networks can be harnessed to rapidly identify symmetry in spatial data with applications in image processing, 3D computer vision, and robotics.

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1.

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The full title of the funded effort.

Breaking Photonic Limits: light-matter-interaction enhanced devices for atto-joule &THz datalinks

Grant/Contract Number
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FA9550-14-1-0215

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

07/15/2014

Reporting Period End Date

07/14/2017

Abstract

With photonic devices being fundamentally challenged to deliver strong light-matter-interactions, we set out to explore devices, materials, and effects that allow increasing this weak interaction. In this context we explored emerging materials with remarkable high index tunability such as Graphene or TCO materials, we considered resonators and showed devices based on microrings, Fabry-Perots, plasmon, photonic crystal-based resonators. Here the focus was to consider the Purcell enhancement, namely volume reduction in addition to Q enhancement. Beyond cavities, a main task was to define scaling laws for nanophotonic devices to include lasers, modulators, detectors, and all-optical switching devices. Together with IBM we investigated heterogeneous integrated III-V on-Silicon nanolasers and LEDs for optical interconnects. We also solved the laser rate equations, and showed that carbon materials can exhibit ultra-fast switching due to the short intrinsic lifetime. We then explored Purcell enhancements in 2D material nanocavities and showed that a monomer performs equally well as a dimer for 2D material emission. We developed an ITO material process to deliver ENZ behavior. We used this then to design ultra-compact 2x2 routing switches in Silicon photonics. We next demonstrated an electrical-driven plasmon light source based on inelastically scattering electrons operating on Silicon at room temperature. Lastly, we used the coincidence properties

of leaky-integrate-and-fire neurons to show a neuromorphic engine to directly identify mirror symmetry of images. Taken together, we developed new materials, explored physical effects, and demonstrated nanophotonic devices all with high relevance to the mission of the Air Force such as communication and image processing.

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Archival Publications (published) during reporting period:

K. Liu, S. Sun, A. Majumdar, V. J. Sorger, "Fundamental Scaling Laws in Nanophotonics" Nature: Scientific Reports, 6, 37419 (2016).

K. Liu, N. Li, D. K. Sadana, V. J. Sorger, "Integrated nano-cavity plasmon light-sources for on-chip optical interconnects" ACS Photonics, 3. 233-242 (2016).

N. Li, K. Liu, D. K. Sadana, V. J. Sorger, "Monolithic III-V on Silicon Nanolaser structure for optical Interconnects", Nature: Scientific Reports, 5, 14067 (2015).

N. Li, K. Han, D. K. Sadana, V. J. Sorger, "Monolithically integrated III-V NanoLED on Silicon for optical Interconnects", Optica, (in review)

R. Wang, H. Dalir, X. Xu, Z. Pan, S. Sun, V. J. Sorger, R. T. Chen, "Atto-Joule, High-Speed and Compact Plasmonic Modulator based on Adiabatic Coupled Waveguides", arXiv: 1710.01689 (2017).

K. Liu, V. J. Sorger, "Electrically-driven Carbon nanotube-based plasmonic laser on Silicon" Optical Materials Express, 5, 1910-1919 (2015).

M. H. Tahersima, M. Danang Birowosuto, Z. Ma, W. C. Coley, M. Valentin, I. Lu, K. Liu, Y. Zhou, A. Martinez, I. Liao, B. N. Davis, J. Martinez, S. Naghibi Alvillar, D. Martinez-Ta, A. Guan, A. E. Nguyen, C. Soci, E. Reed, L. Bartels, V. J. Sorger. "Testbeds for Transition Metal Dichalcogenide Photonics: Efficacy of Light Emission Enhancement in Monomer vs. Dimer Nanoscale Antennas", ACS Photonics, 4, 1713-1721 (2017).

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).

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. Ye, K. Liu, R. Soref, and V. J. Sorger, "3-Waveguide 2x2 Plasmonic Electro-optic Switch" Nanophotonics, 4, 1, pp. 261-268 (2015).

H. Nejadriahi, D. Hillerkus, J. K. George, V. J. Sorger, "On-chip Integrated All-Optical Fast Fourier Transform: Design and Analysis", (in preparation)

J. K. George, H. Nejadriahi, V. J. Sorger, "Towards On-Chip Optical FFTs for Convolutional Neural Networks". arXiv: 1708.09534. Accepted at IEEE International Conference on Rebooting Computing 2017 (2017).

J. K. George, C. Soci, V. J. Sorger, " Identifying Mirror Symmetry with Delay in Spiking Neural Networks" arXiv: 1709.02684 (2017).

J. K. George, V. J. Sorger, "Graphene-based Solitons for Spatial Division Multiplexed Switching", Optics Letters 42, 4, 787-790 (2017).

A. Fratalocchi, C. M Dodson, R. Zia, P. Genevet, E. Verhagen, H. Altug, V. J. Sorger, "Nano-optics gets practical: Plasmon Modulators", Nature Nanotechnology, 10, 11-15 (2015).

V. J. Sorger, "2D Material Nanowatt Threshold Lasing" Nature Asia Materials, 7, e200, (2015).

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. (#14/528,392): Silicon-Based, Broadband, Waveguide-Integrated Electro-Optical Switch.
2. (#14/941,100): Integrated nano-cavity plasmon laser light-sources. (IBM jointly filed).
3. (#62/555531) Integrated All Optical Fast Fourier Transform (OFFT) On Chip.
4. (#62/461,889) Image Symmetry Detection via leaky-firing Spiking Neuromorphic Networks.
5. (#62/146,590) 2D material-based Spiral Solar Cell.

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			

Report Document

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Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

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