THE GEORGE WASHINGTON UNIVERSITY

WASHINGTON, DC

aJ/bit Modulators and Photonic Neuromorphic Computing

Volker Sorger

14th NSF-Korea Nanotechnology Forum 2017

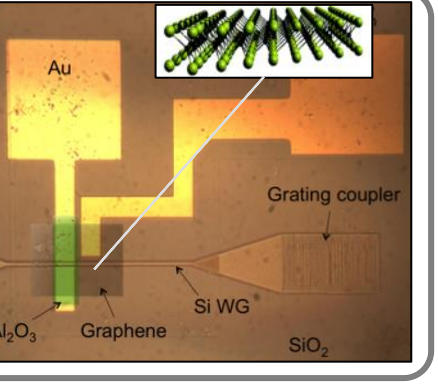
Orthogonal Physics Enabled Nanophotonics (OPEN) lab

OPEN Lab
Prof. Sorger

Today

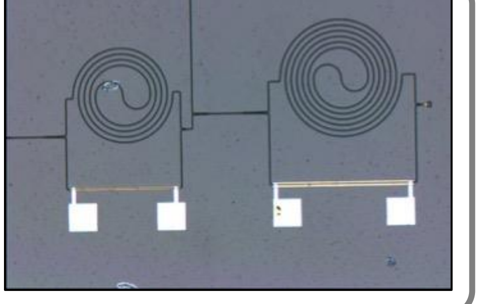
Atto-Joule Optoelectronics

Sorger, Zhang lab, *Nature Photonics* (2008)
Sorger, Zhang lab, *Nature* (2009)
Sorger lab , *IEEE Photonics* (2013)
Sorger lab, Altug lab, *Nature Nanotech.* (2015)
Sorger lab, Majumdar Lab, *Sci. Reports* (2016)
Sorger lab, *Optics Letters* (2016)
Sorger lab, *IEEE STQE* (2014 & 2017)



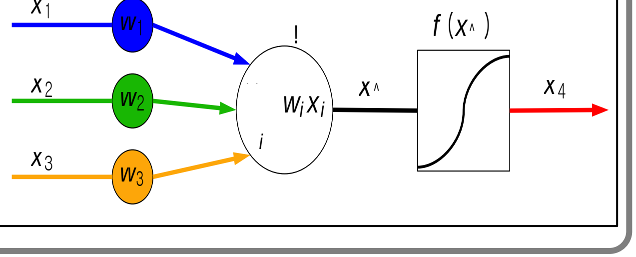
Photonic Functions

Sorger lab, *IEEE Photonics* (2015)
Sorger lab, *Nanophotonics* (2016)
Sorger lab, *Optics Letters* (2016)
Sorger lab, El-Ghazawi lab, *IPCC* (2017)
Sorger lab, El-Ghazawi lab, *Mircoprocess. & MS* (2017)
Sorger lab, *Frontiers in Optics* (2017)



Analogue Computing

Sorger lab, *Nanophotonics* (2017)
Sorger Lab, Grace lab, *Biofabrication* (2017)
Sorger lab, *IEEE Rebooting Computing* (2017)
Prucnal lab, Sorger lab, (in preparation)



OPEN Lab
Prof. Sorger

Modulators = Optical Transistors

- 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

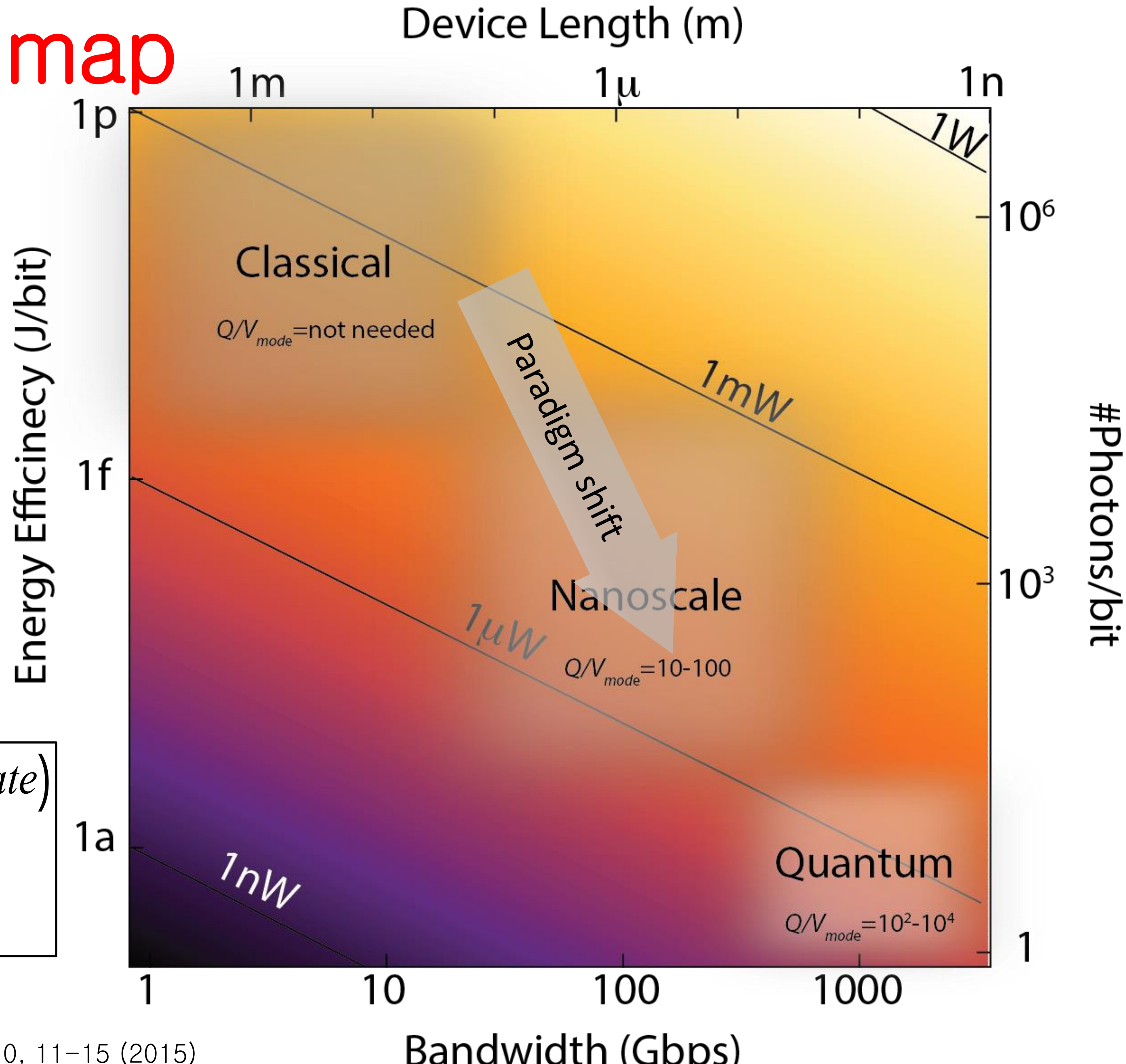
$$\frac{R_{on/off}}{\Delta V}$$ (=SS@FET)

EO Modulator

5cm x 1cm

OPEN Lab
Prof. Sorger

Power–BW Roadmap



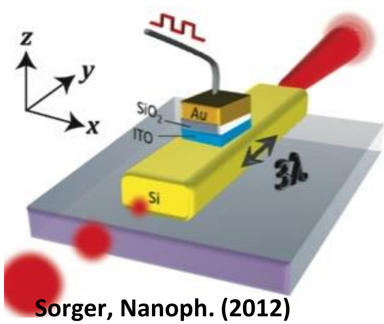
$$Power = (E/bit)\cdot(Bitrate)$$

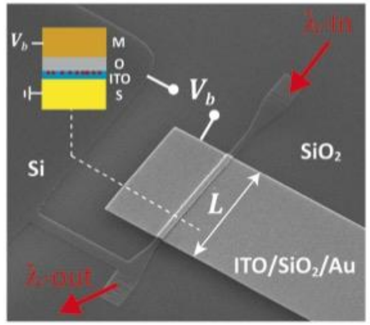
$$\left[\frac{J}{bit}\frac{bit}{s} = \frac{J}{s} = W\right]$$

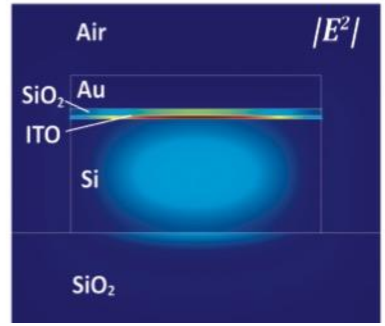
V. J. Sorger, *Nature Nanotech.,* 10, 11–15 (2015)

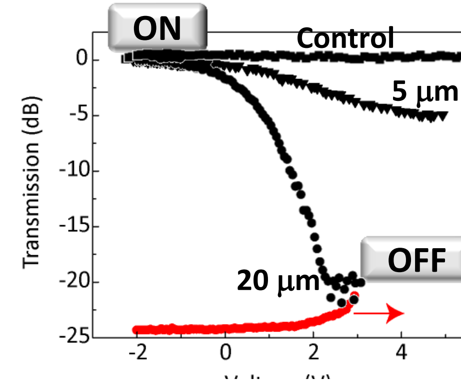
EO Modulators

E/bit (fJ)



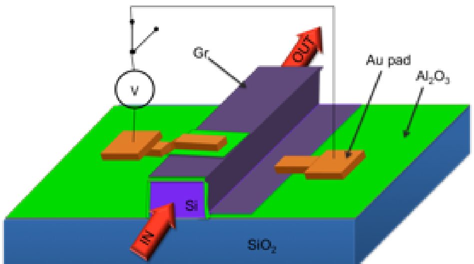


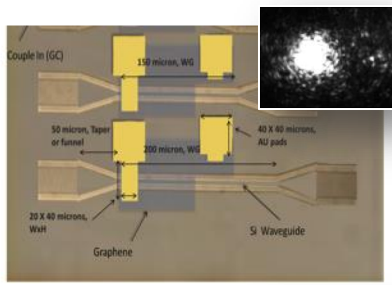


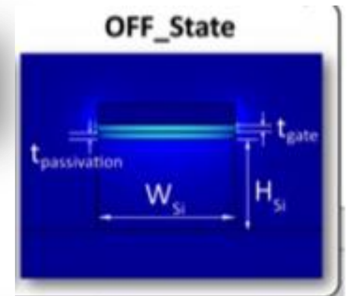


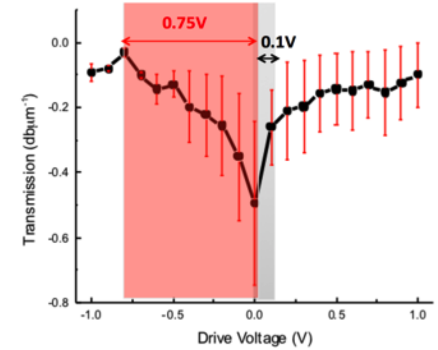
15

Sorger, Nanoph. (2012)
Huang, IEEE Phot. (2013)





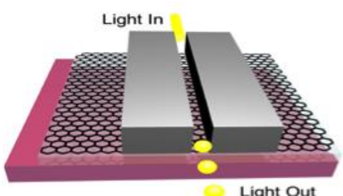


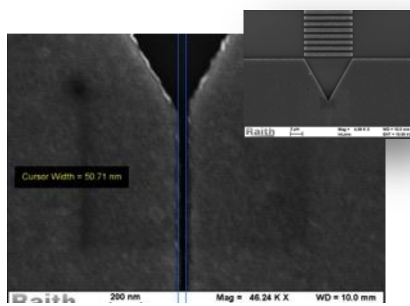


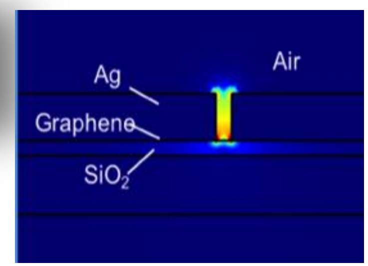
3.4

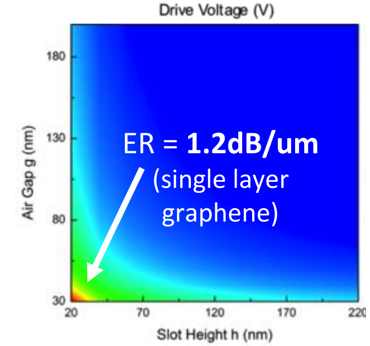
0.3

Ye, IEEE STQE (2014)
Khan, (under review)



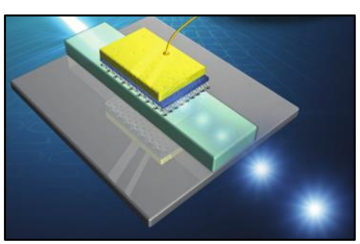




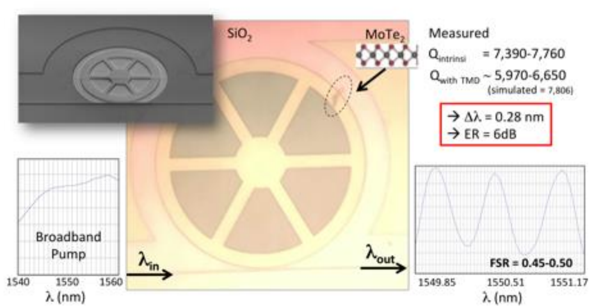


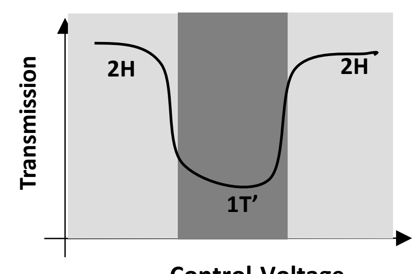
2.4
(0.16)

Ma, IEEE STQE (2017)



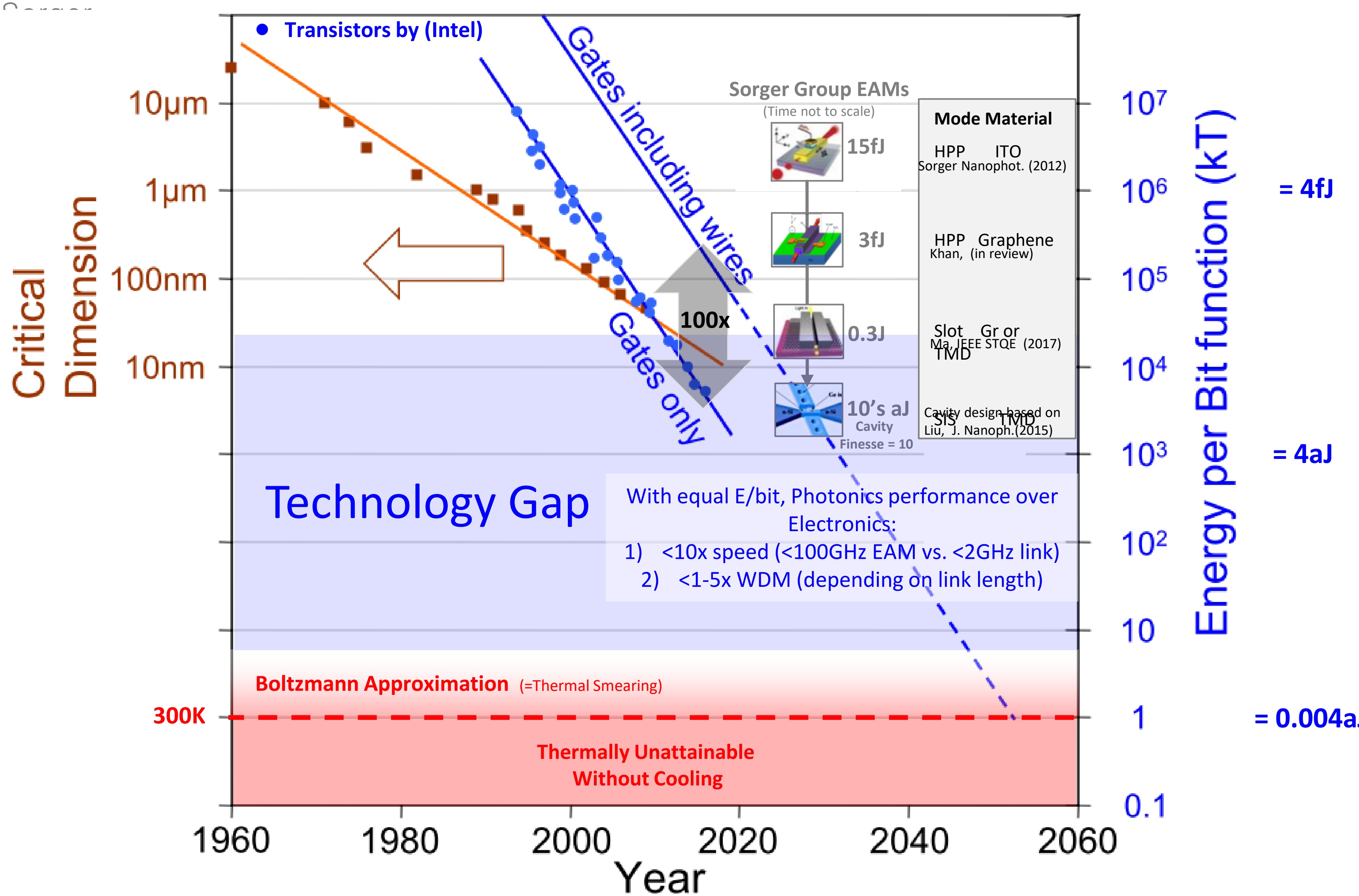
Sarpkaya, (in prep)





E/bit Scaling: FET vs. EAM

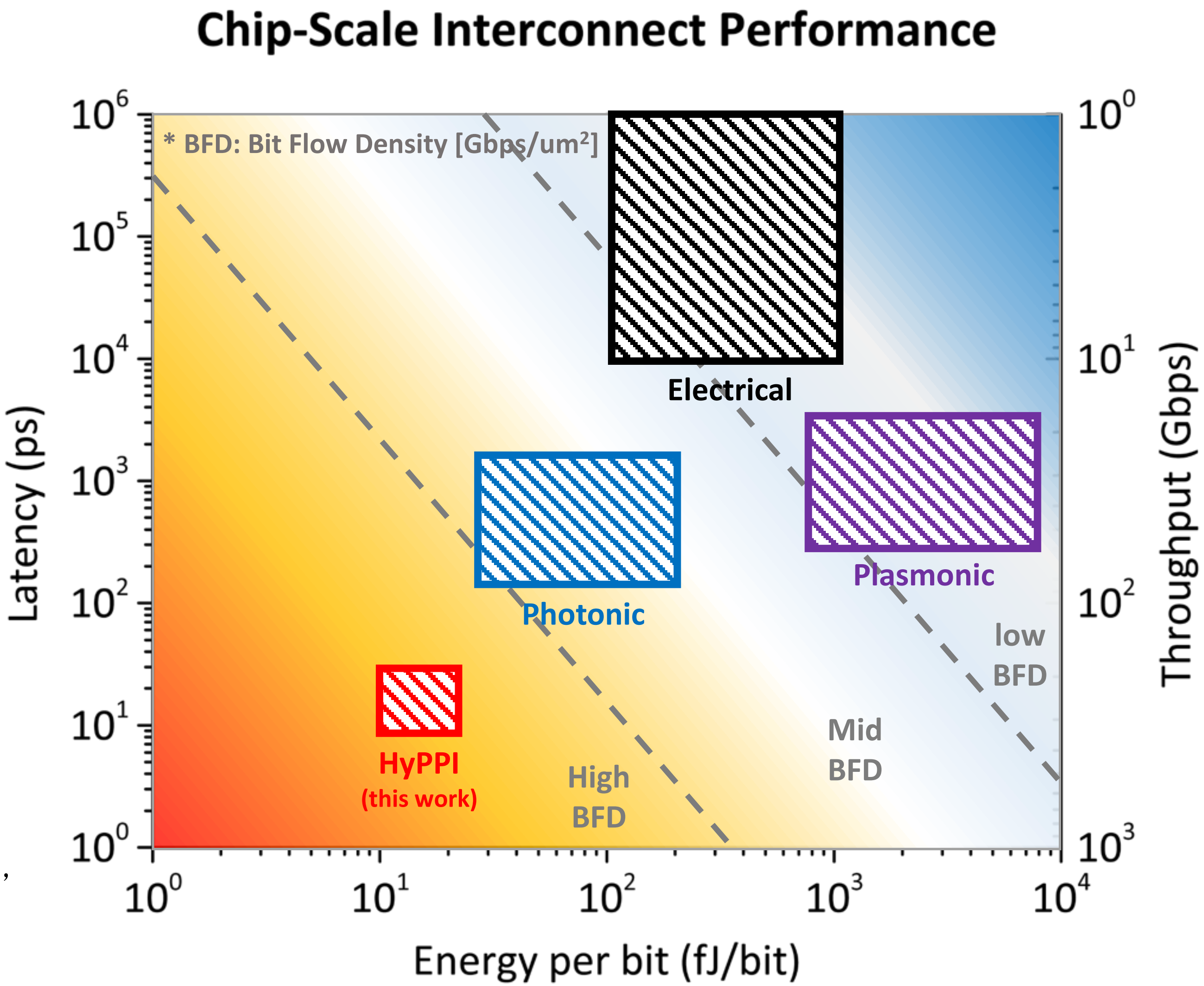
OPEN Lab
Prof. Sorger



Sorger Group, J. Opt., special issue (submitted)

HyPPI: Hybrid Plasmon Photonics Interconnect

OPEN Lab
Prof. Sorger



Sun, Badaway, Narayana, El-Ghazawi, Sorger, *IEEE Photonics*, 7,6 (2015)

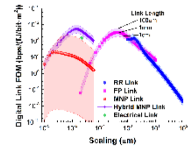
Physics & Material ← $(E/bit)_{Device}$ ← SNR @ Rx ← Desired BER

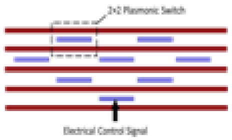
OPEN Lab
Prof. Sorger

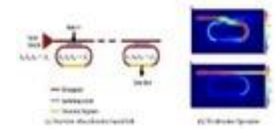
Photonic Reconfigurable Computing

2015 | 2016 | 2017

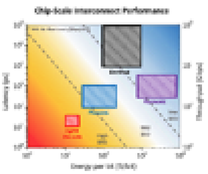
DEVICE

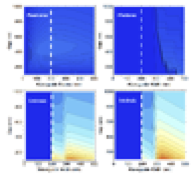

Fundamental Scaling Law

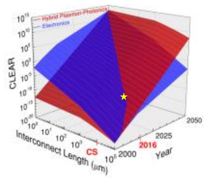

5x5 Optical Router

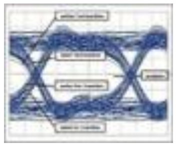

MoDetector

LINK

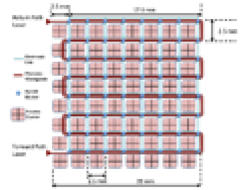

HyPPI

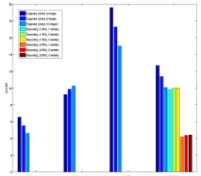

BFD


Link-CLEAR


Noise HyPPI

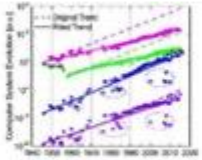
NETWORK

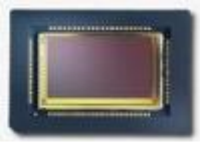

MorphoNoC


HyPPI NoC


Dynamic-CHyPPI

SYSTEM & APPLICATION


Universal CLEAR

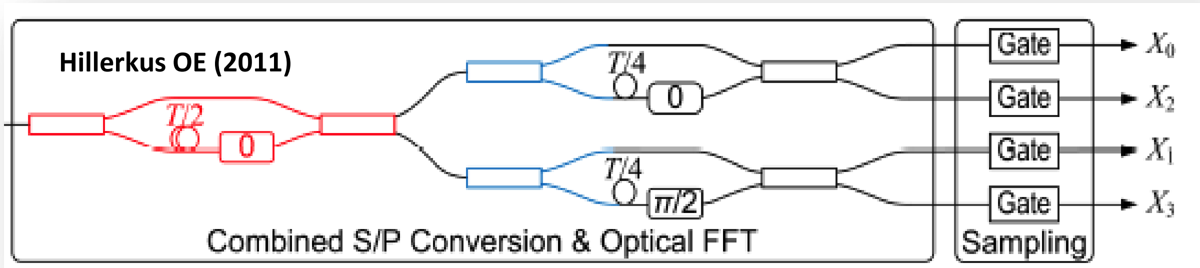

D-CHyPPI based Camera Sensor

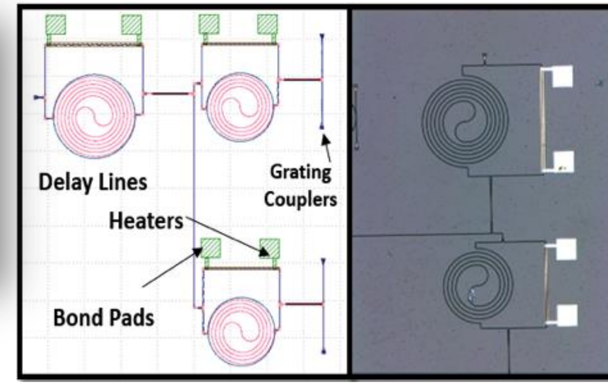
G. Pomrenke
F. Darema

El-Ghazawi & Sorger Groups

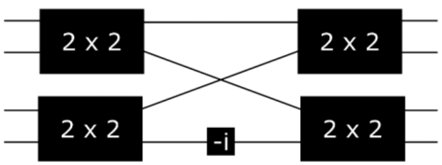
OPEN Lab
Prof. Sorger

Optical on-chip FFT





Cooley-Tukey Method



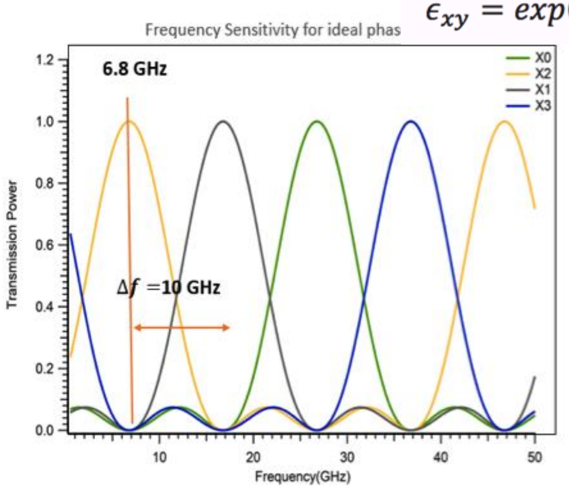
Addition

$$\beta_1 = \frac{1}{\sqrt{2}}(-\alpha_1 + \alpha_2)$$

$$\beta_2 = \frac{1}{\sqrt{2}}(\alpha_1 + \alpha_2)$$

Multiplication

$$\epsilon_{xy} = exp(-i2\pi xy/N)$$

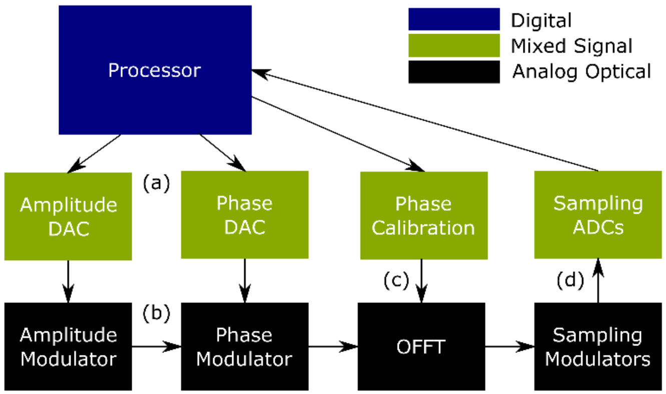


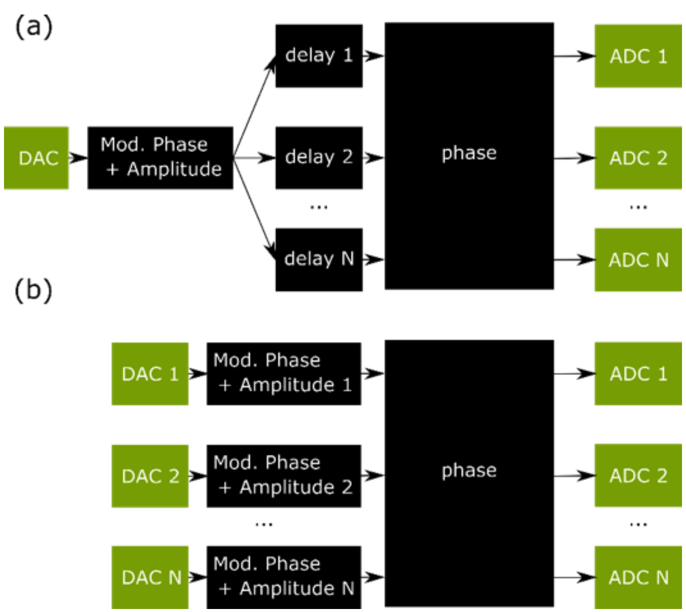
Metric	Electrical	OFFT (on-chip)
Operation Mode	Sequential	Continuous
Sampling Speed Device	GHz Slow ADC Conversion	10-100GHz short sampling window
Data BW	<10GFlop/s fftw.org/speed/CoreDuo-3.0GHz-icc/	10-100Tbps
Power	High Example: N=8 ~10-100W	Low 0.1-10W
Data/Power [GFlop/J]	1 Max 10 = CPU 'wall'	10^3-10^5 Assumed: 1Flop = 1 GHz
N Scaling	N^2	#Phases (physical arms) $N-1$ #Coupler = Complexity (C) $C_{DI} = 2(N-1)$
GVD (Group Velocity Dispersion)	N.A.	Low

Sorger Group, Frontiers in optics (2017)

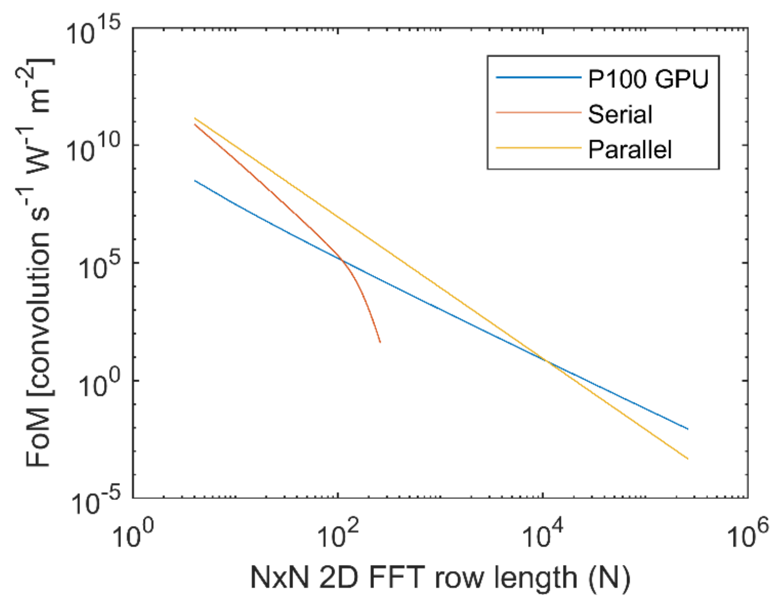
OPEN Lab
Prof. Sorger

Convolutional Neural Networks based-on Optical FTT





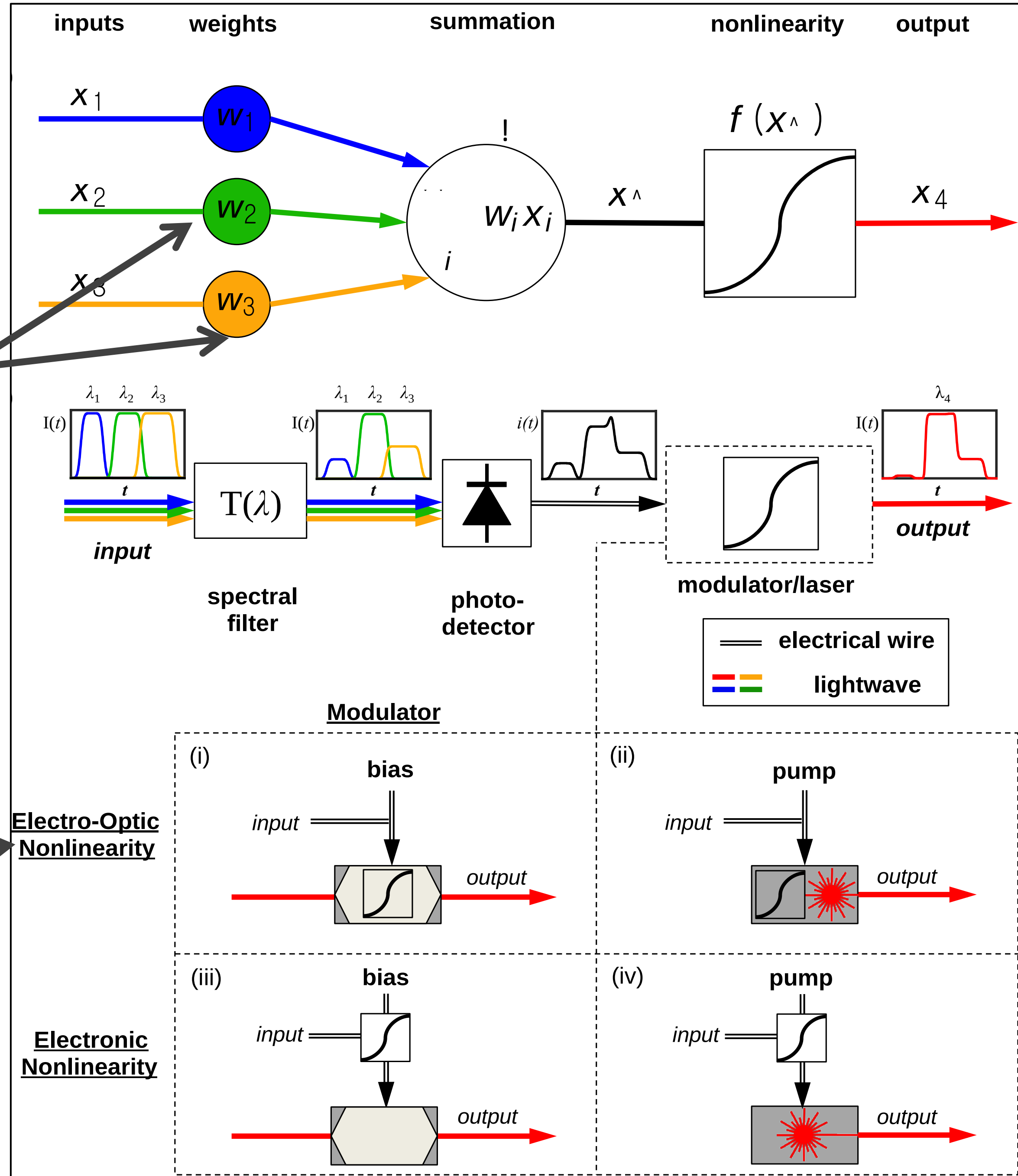
Description	Assumption
FLOPS per convolution	$20N^2 log_2(N) + N^2$
ADC	56 GSa/s @ 2 W
DAC	100 GA/s @ 2.5 W
Optical loss first spiral	0.686 dB
Optical loss modulator	3.49 dB
Optical loss 2 x 2	0.99105 dB
Optical loss splitter	3 dB
Optical loss input grating coupler	4 dB



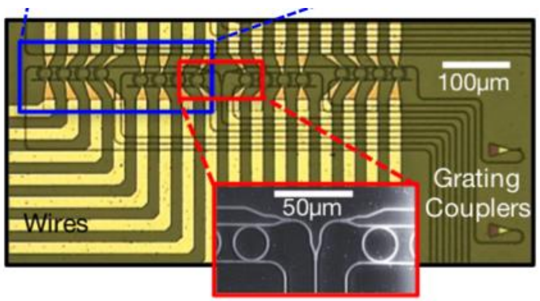
Sorger Group, IEEE Computing (2017)

OPEN Lab
Prof. Sorger

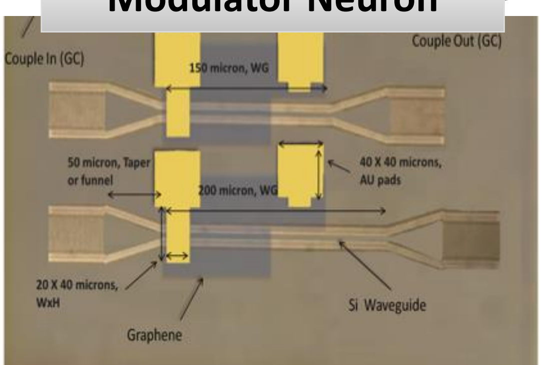
Example: *Photonic Analogue Perceptron*



Weight Bank = Partial Drop-Filter

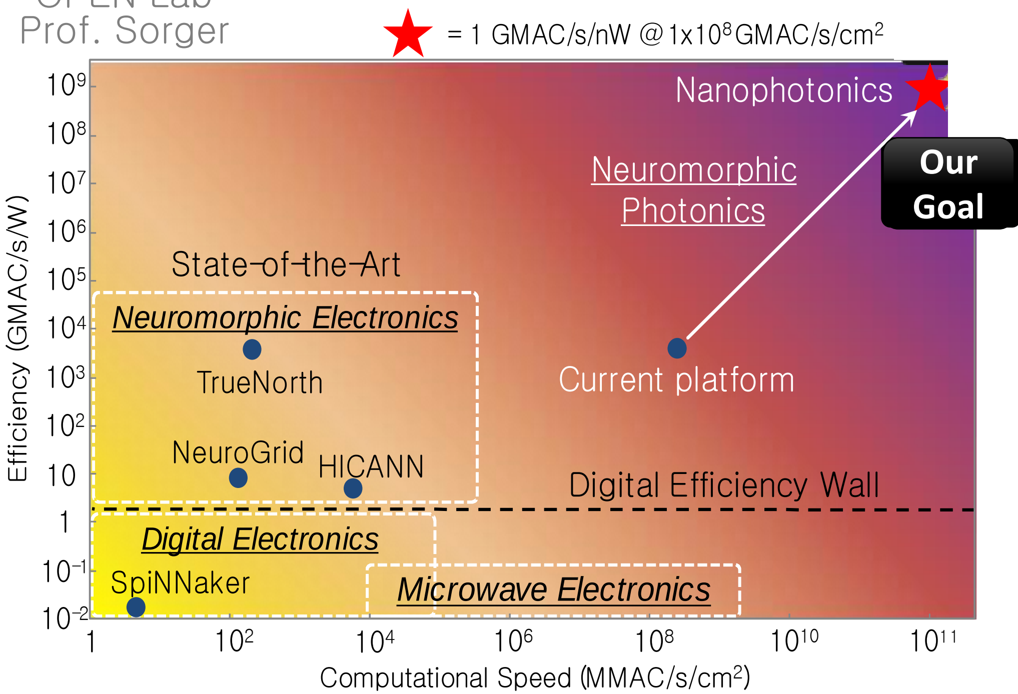


Modulator Neuron



Neuromorphic Photonics

OPEN Lab
Prof. Sorger



Vector Multiply Weighted Additions

For B. MAC/s per Neuron

$$\#MAC/s/neuron = N_{FI} \cdot f_{3dB},$$

$$f_{3dB} = (2\pi R_b C_{\mathrm{mod}})^{-1}$$

Computational Efficiency = J/MAC

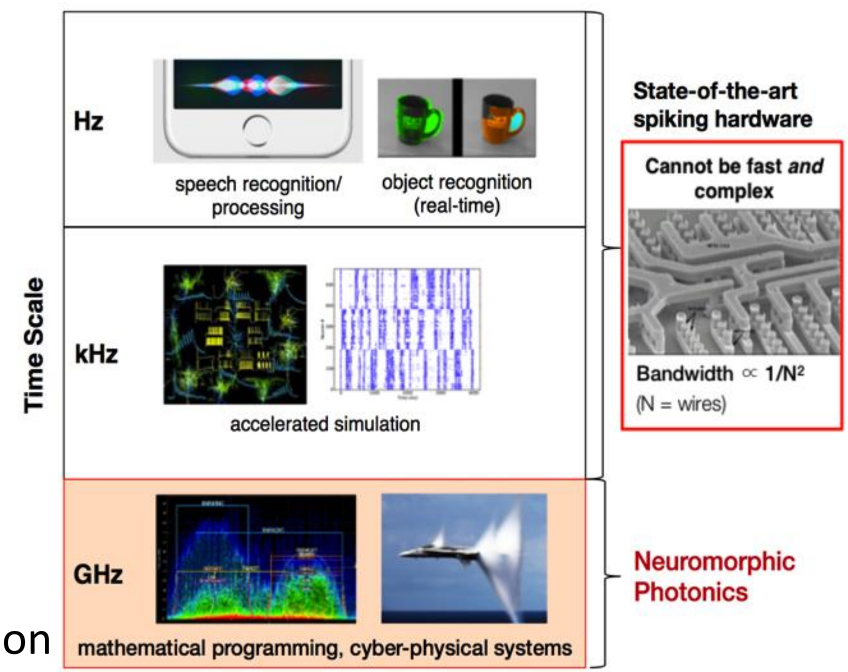
$$\eta_{MAC} \equiv \frac{\#MAC/s/neuron}{P_{total}/neuron} \leq \eta \cdot \left[\frac{N_{FI}}{N_{FO}}\right] \cdot \frac{e}{4h\nu}(V_\pi C_{\mathrm{mod}})^{-1}$$

Goal: 1GMAC/nJ → $V_\pi C_{EOM}$ = 1-10aC

Implementation Options

A. Spiking photonic laser neurons on III-V platform

B. Perceptron photonic neurons on Si platform



Applications

- Deep-Learning
- Real-time
- Non-linear Optimization

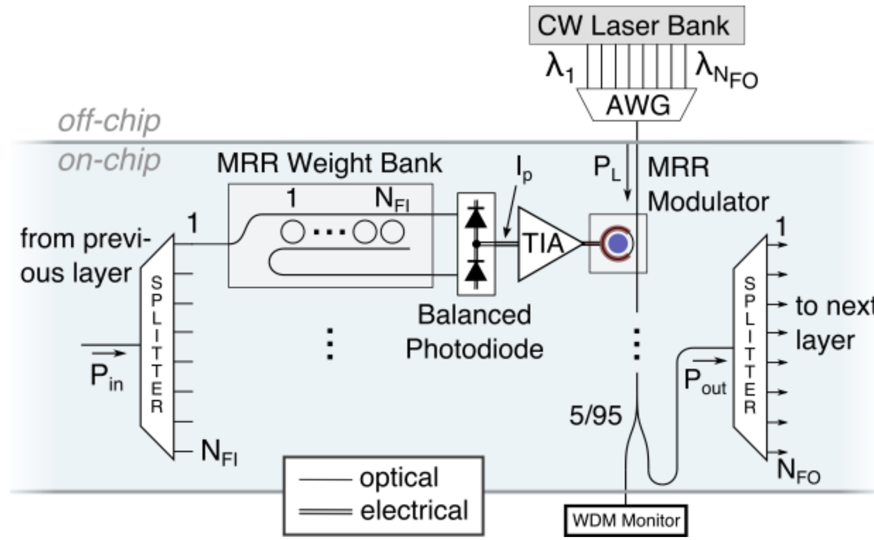
Prucnal, Sorger, El-Ghazawi, NSF E2CDA (2017)
Ferreira de Lima, Nanophot (2016)

OPEN Lab
Prof. Sorger

Neuromorphic Performance

Deep Learning

Reference	Efficiency (J/MAC)	Speed (MAC/s)
NVIDIA GPU [15]	3.4×10^{-7}	1.7×10^{7}
AlexNet FPGA [16]	2.6×10^{-10}	6.2×10^{10}
UPSIDE Crossbar [17]	1.3×10^{-10}	4.0×10^{10}
UTK Analog Engine [18]	1.0×10^{-12}	11.8×10^{6}
IBM TrueNorth [19]	2.6×10^{-11}	1.3×10^{6}
Nanophotonic Neuromorphic	**7.4×10^{-18}**	**2.0×10^{17}**



System Efficiency Vectors

Technology	Limitation	C_{total} (fF)	Quantum Efficiency	E_{MAC}
Silicon photonics (Eq. 1)	Gain	47	7%	5 pJ
Hybrid CMOS (Eq. 2)	Switching energy + noise	35	7%	2.1 fJ
Nanophotonics (Eq. 2)	**noise**	**0.1**	**16%**	**7.4 aJ†**

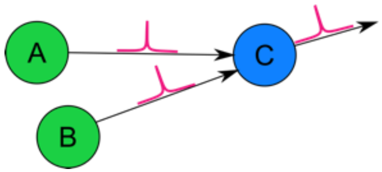
$$E_{MAC} \geq \underbrace{N_{FO}}_{\text{fan-out}} \cdot \underbrace{\frac{1}{\eta}}_{\text{quantum efficiency}} \cdot \underbrace{\frac{2^{2N_b+1}}{[illegible]}}_{\text{noise and resolution}} \cdot \underbrace{\frac{h\nu}{N_{FI}}}_{\text{photon energy/MAC}} + \underbrace{\frac{E_{bit}}{N_{FI}}}_{\text{switching energy/MAC}}$$

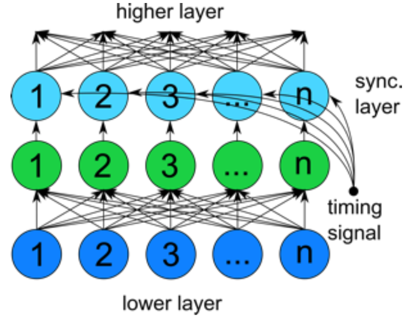
Comparison Neuromorphic Processors

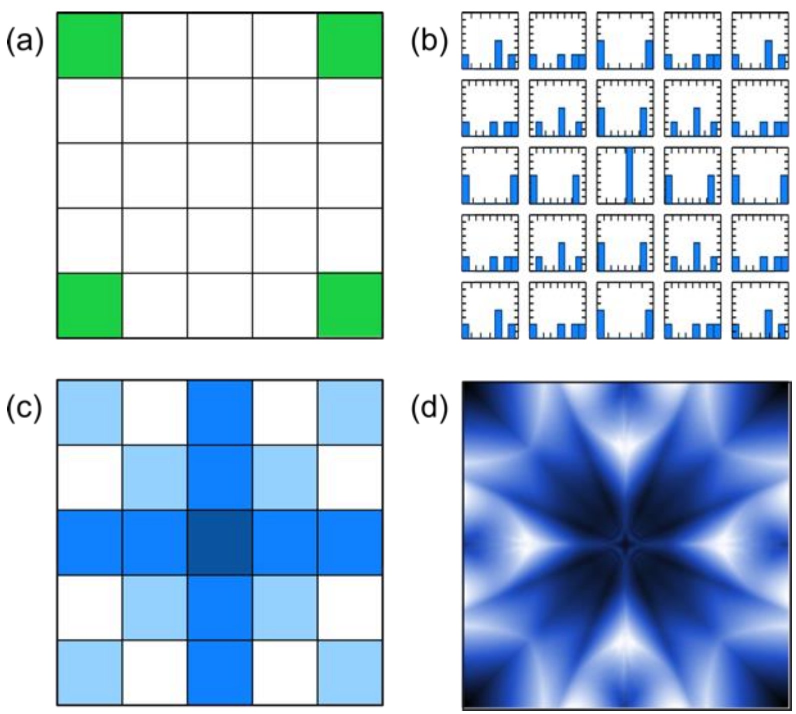
Chip	MAC Rate/ processor	Energy/ MAC	Processor fan-in	Area/MAC (μm^2)	MAC Rate/cm^2
Silicon Photonic (Princeton)	2 TMACs/s	5 pJ	56	20,000	1×10^{14}
Hybrid CMOS-Silicon Photonics	2 TMACs/s	2.1 fJ	148	5,000	4×10^{14}
Nanophotonic (This Project)	**2 TMACs/s**	7:4 aJ	**300**	**20**	**1×10^{17}**
TrueNorth (Electronic) [13]	2.5 kMACs/s	26 pJ	256	4.9	2×10^{8}

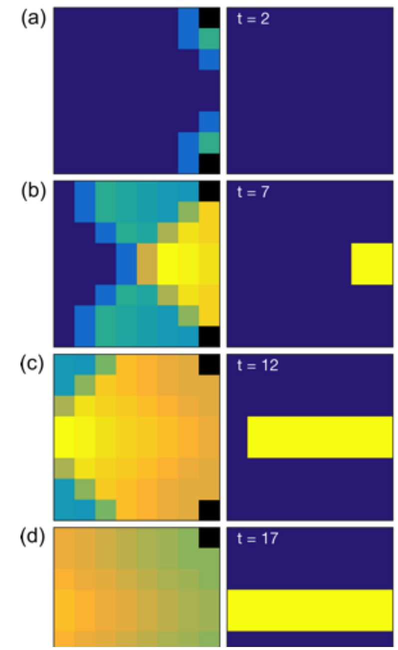
OPEN Lab
Prof. Sorger

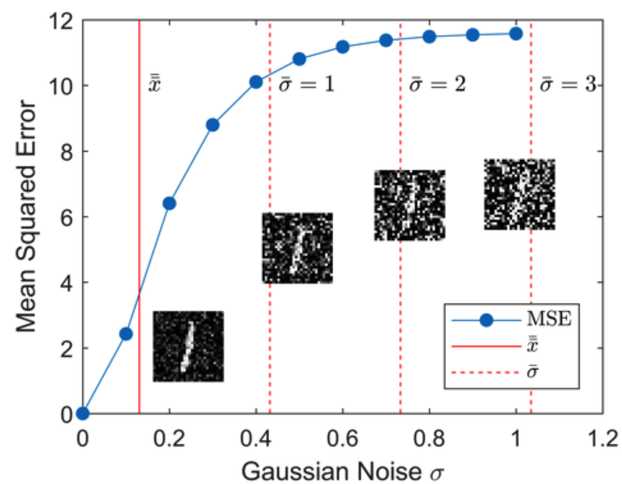
Mirror Symmetry Density with Delay in Spiking Neural Networks











Sorger Group. (2017) submitted

OPEN Sorger Team

Post Docs

Dr. I. Sarpkaya
Dr. Ke Liu
Dr. Hasan Goktas
Dr. Elnaz Akbari

Grad Students

Mohammad Tahersima
Sikandar Khan
Matt Zhizhen
Shuai Sun
Jonathan George
Rubab Amin
Hani Nejadriahi
Seyed Haghshenas
Rohit Hemnani

U-grads

D. D'Hemmecout
T. Weinshel
J. Crandall

Collaborators

Prof. Majumdar (UW)
Prof. Agarwal (UPenn)
Prof. Kimerling (MIT)
Prof. Reed (Stanford)
Prof. Bartels (UCR)
Prof. Lee (KU)
Prof. Prucnal (Princeton)
Prof. El Ghazawi (GWU)
Dr. Sadana (IBM Watson)
Prof. Cesare (NTU)

GW
Prof. Volker Sorger
sorger.seas.gwu.edu
sorger@gwu.edu