THE GEORGE WASHINGTON UNIVERSITY

WASHINGTON, DC

aJ/bit Modulators and Photonic Neuromorphic Computing

Volker Sorger

14th NSF-Korea Nanotechnology Forum 2017

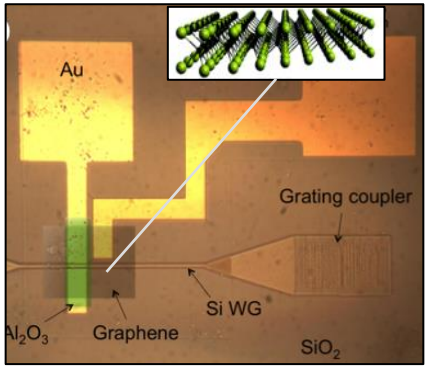
OPEN Lab
Prof. Sorger

Orthogonal Physics Enabled Nanophotonics (OPEN) lab

Today

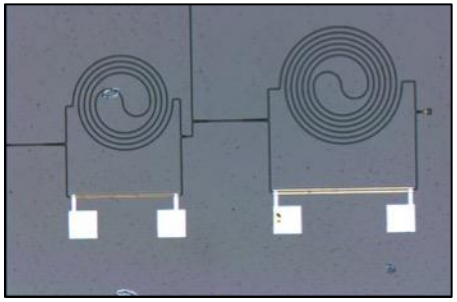
Atto-Joule Optoelectronics

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)



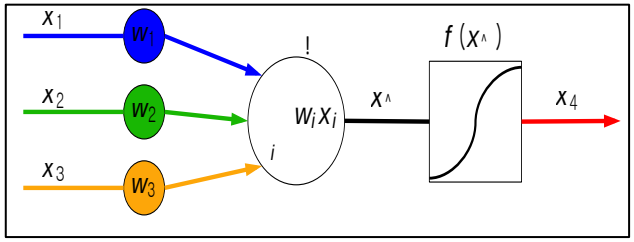
Photonic Functions

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)



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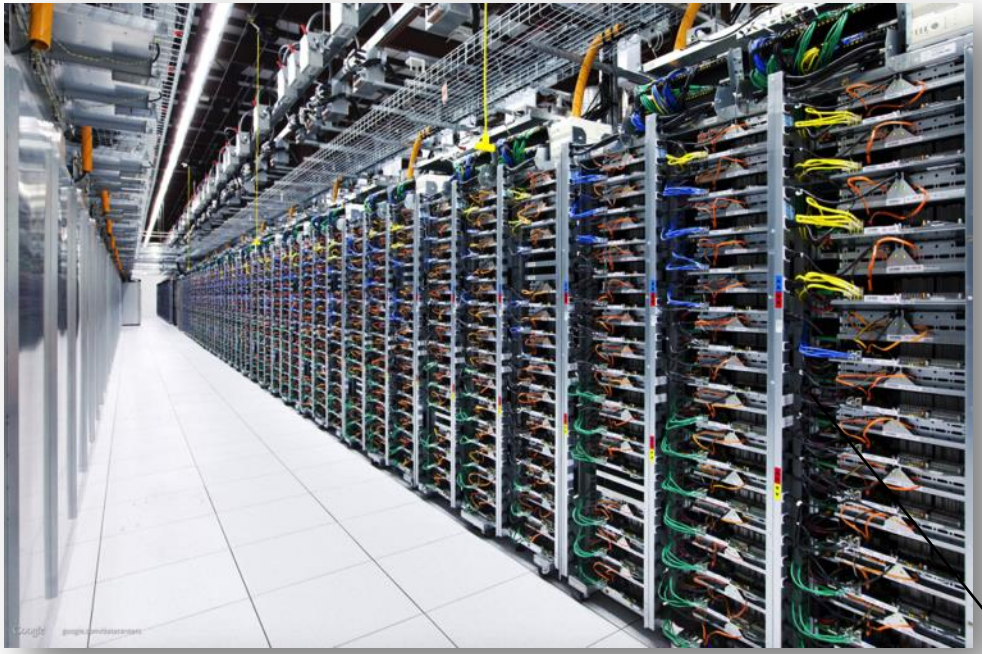
Modulators = Optical Transistors



- Contrast ratio

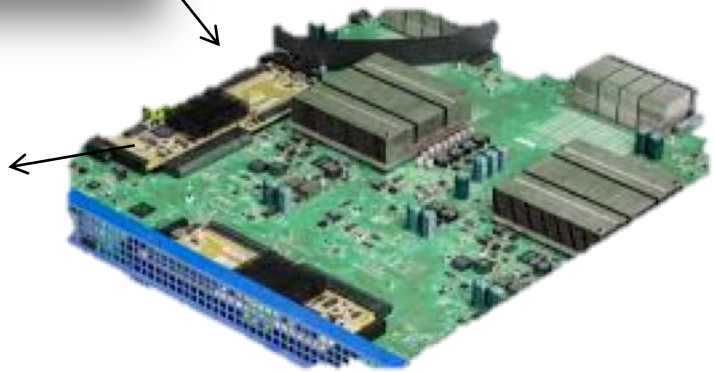
$$R_{on/off} = \frac{P_{out}(V_{off})}{P_{out}(V_{on})}$$

- Insertion loss

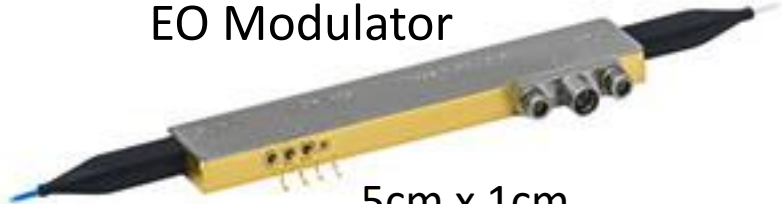
$$Loss = \frac{P_{in} - P_{out}(V_{off})}{P_{in}}$$

- Modulation efficiency

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



EO Modulator



5cm x 1cm

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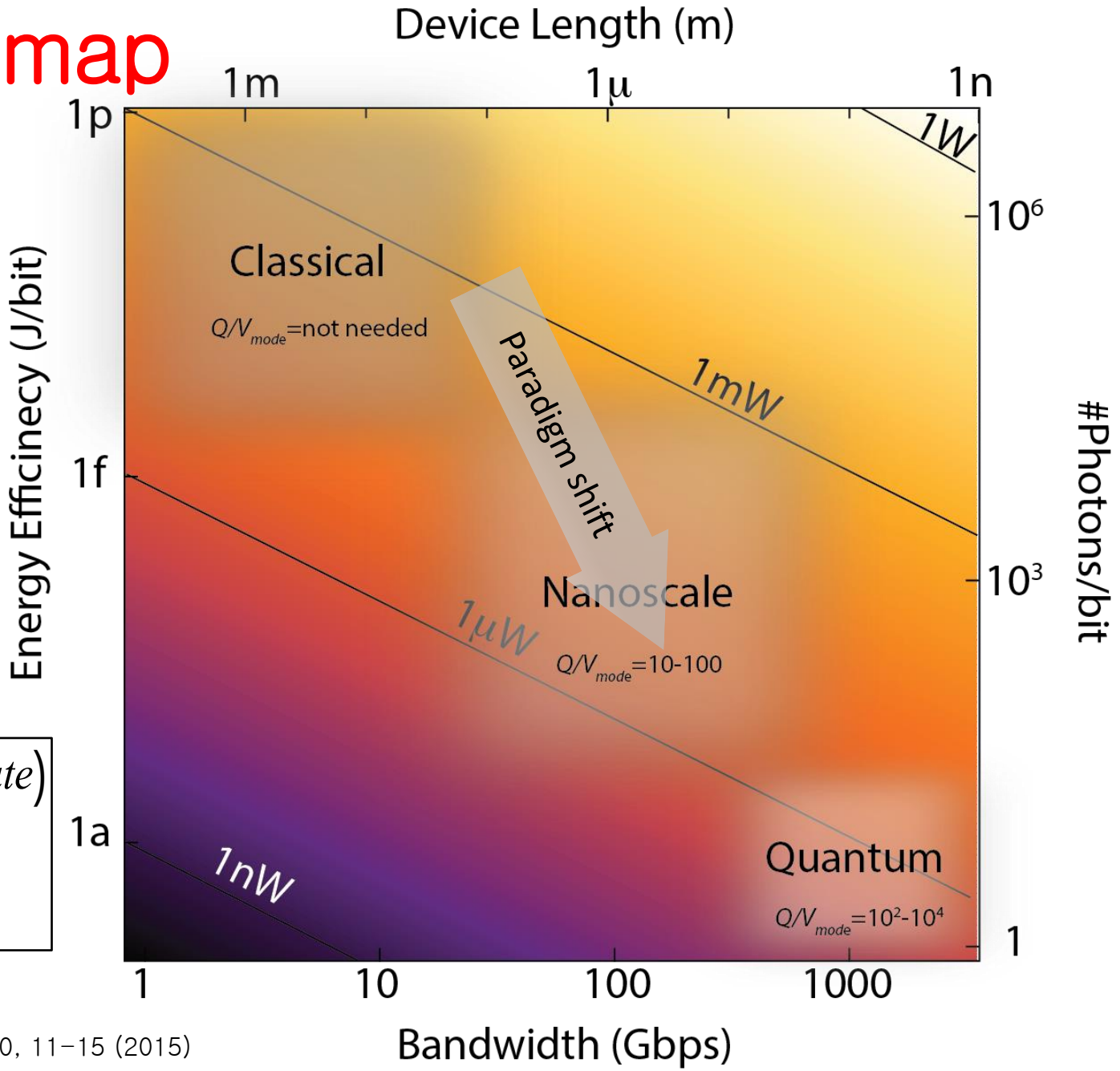
Power-BW Roadmap



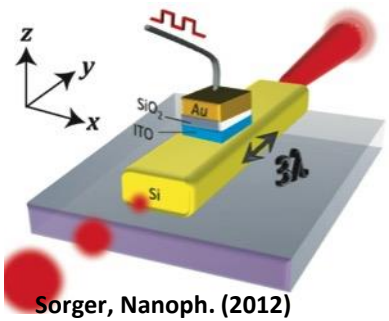
$$Power = (E/bit)\cdot(Bitrate)$$

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

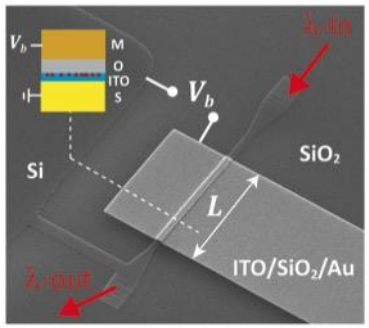
V. J. Sorger, *Nature Nanotech.*, 10, 11–15 (2015)

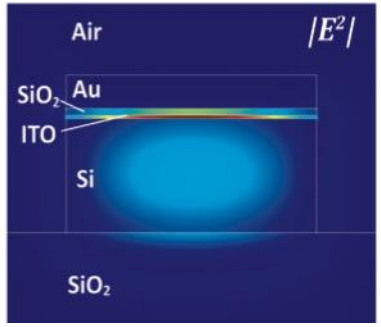
GW EO Modulators

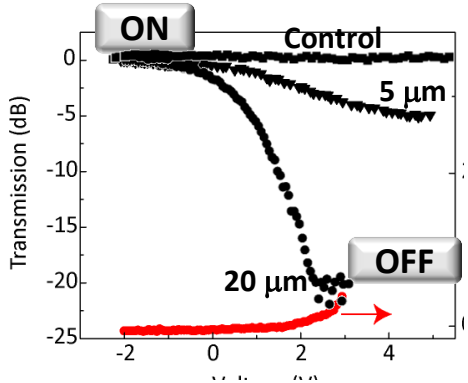
E/bit (fJ)



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







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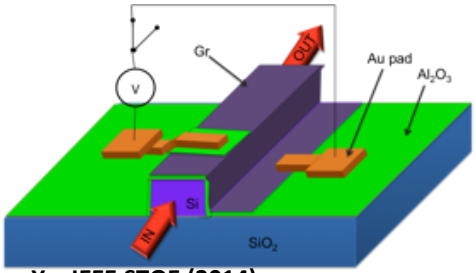
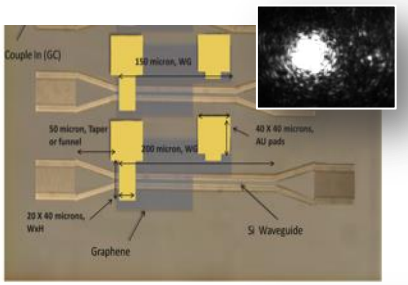
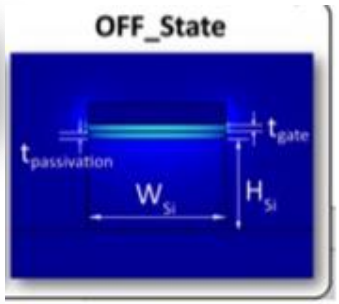
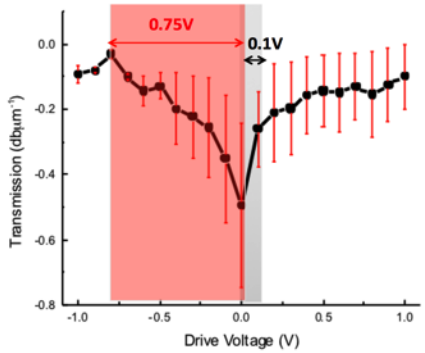


Ye, IEEE STQE (2014)
Khan, (under review)

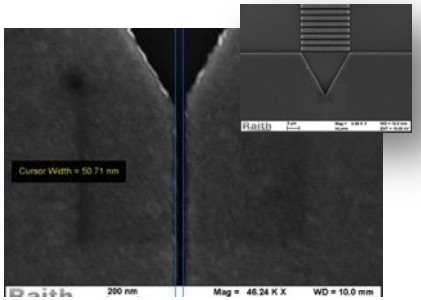


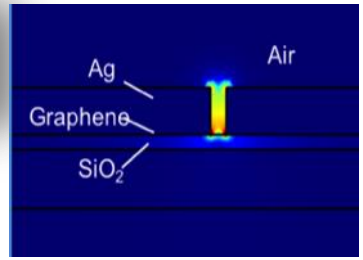


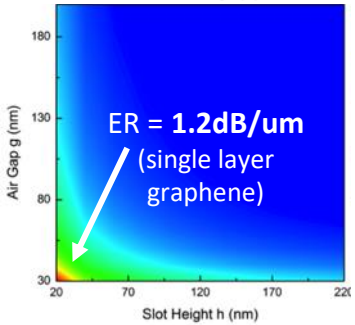


3.4

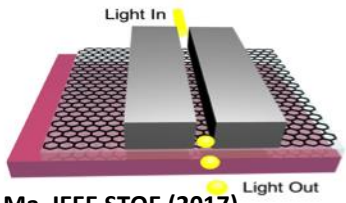
0.3



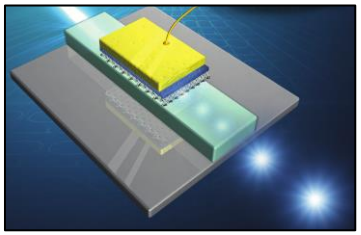




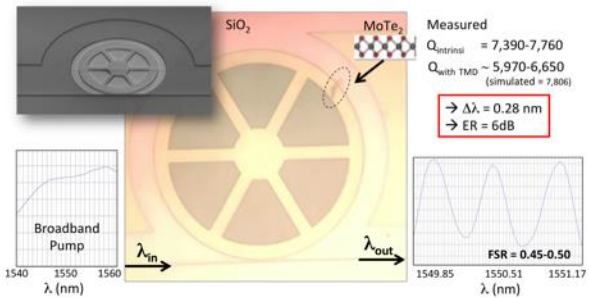
2.4
(0.16)

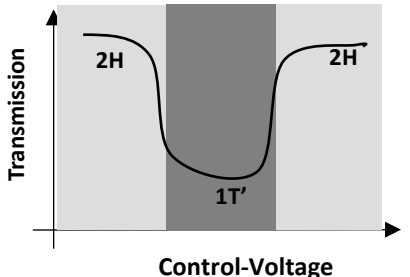


Ma, IEEE STQE (2017)

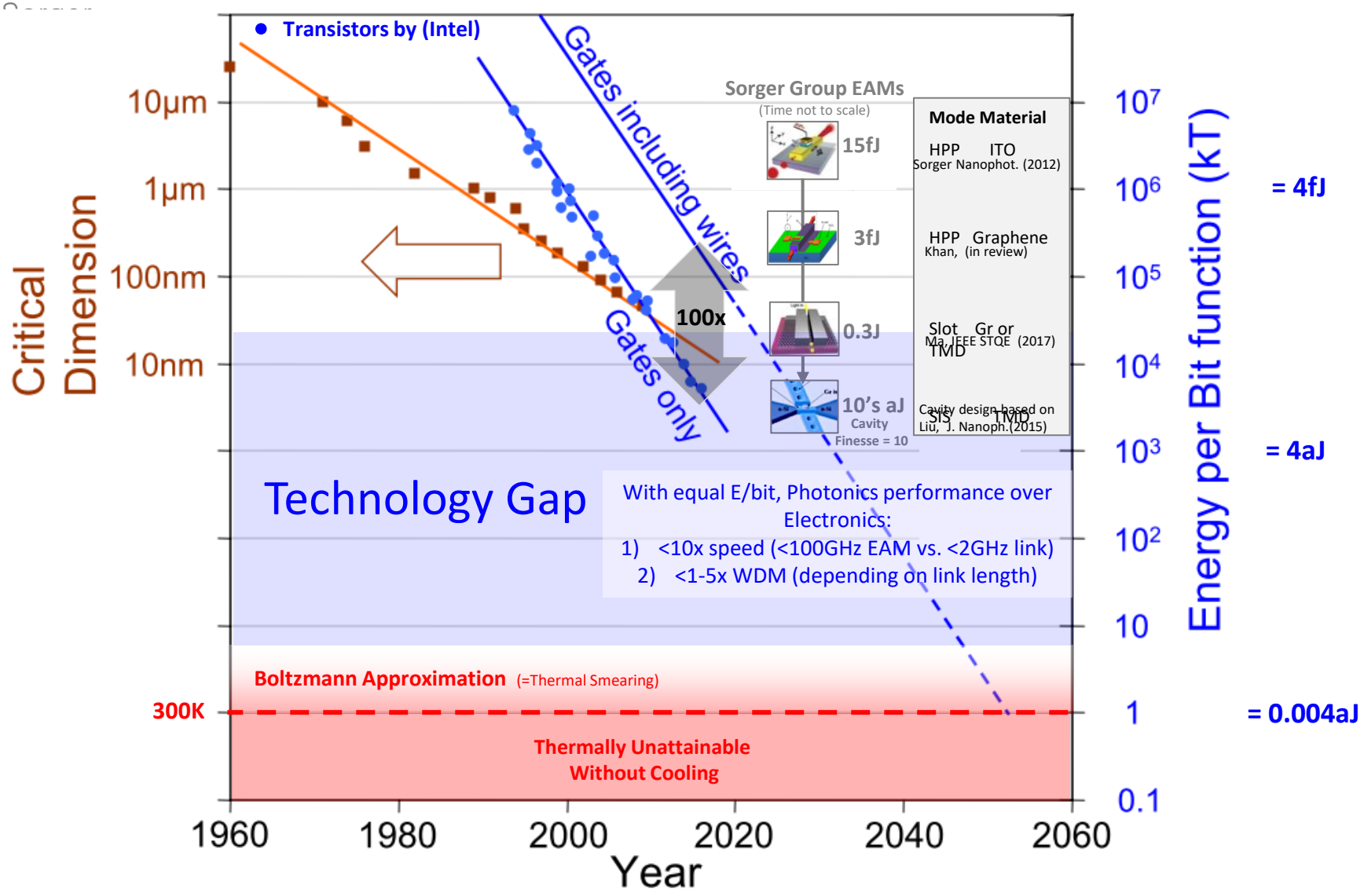


Sarpkaya, (in prep)





E/bit Scaling: FET vs. EAM



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

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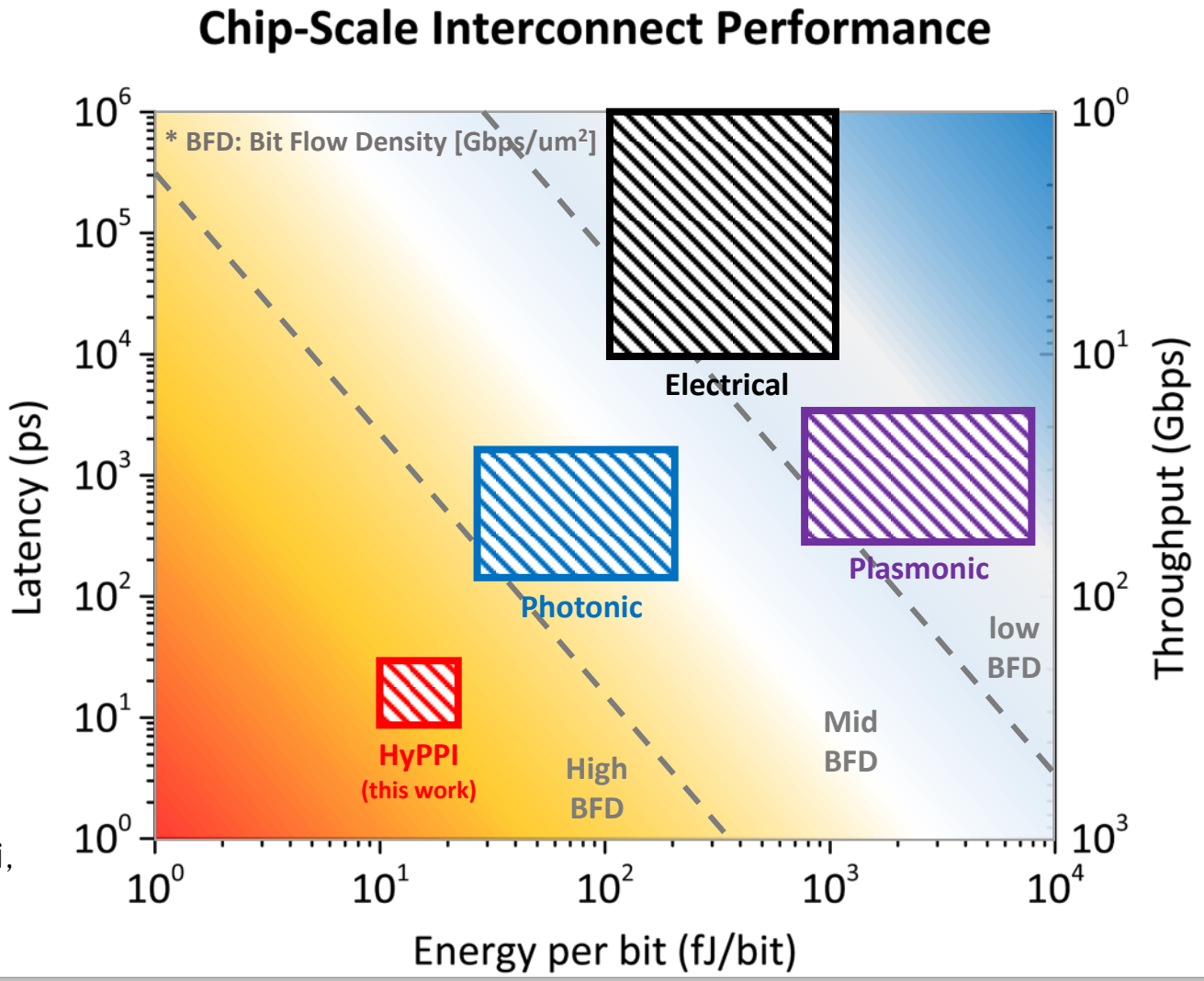
HyPPI: Hybrid Plasmon Photonics Interconnect



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

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

Photonic Reconfigurable Computing

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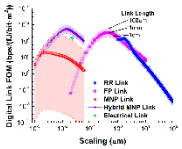
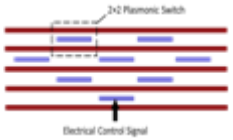
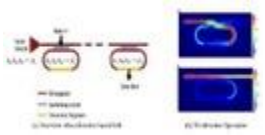
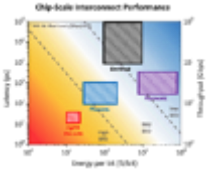
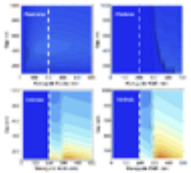
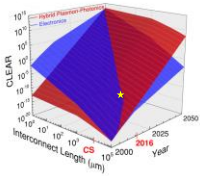
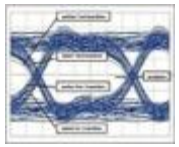
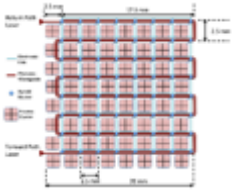
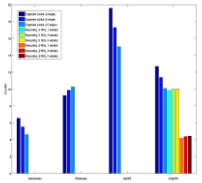
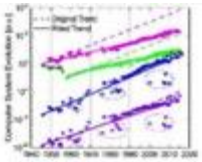
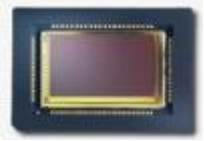
	2015	2016	2017
DEVICE		 Fundamental Scaling Law	 5x5 Optical Router	 MoDetector
LINK	 HyPPI	 BFD  Link-CLEAR	 Noise HyPPI
NETWORK	 MorphoNoC	 HyPPI NoC  Dynamic-CHyPPI	
SYSTEM & APPLICATION		 Universal CLEAR	 D-CHyPPI based Camera Sensor

G. Pomrenke
F. Darema

El-Ghazawi & Sorger Groups

Optical on-chip FFT

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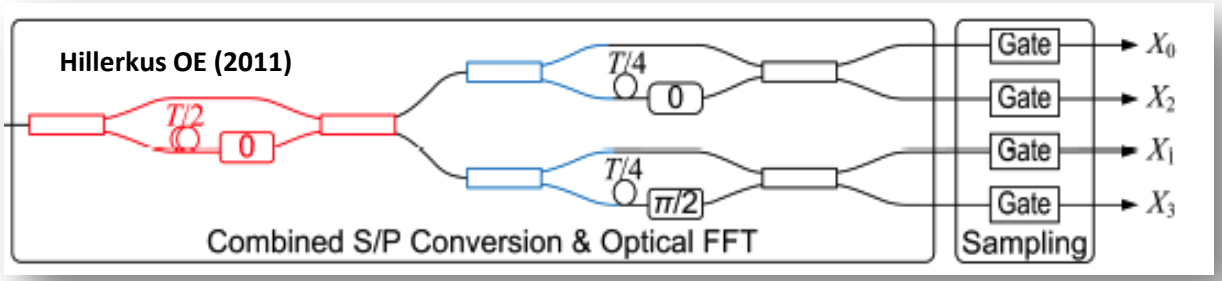
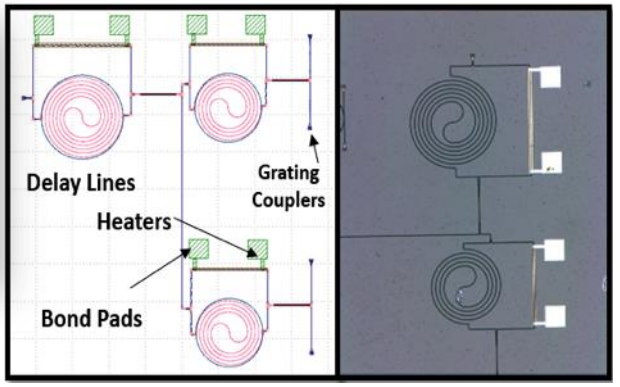
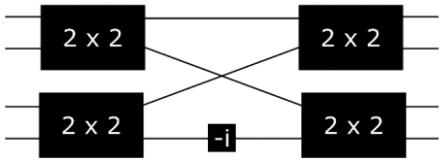




Cooley-Tukey Method



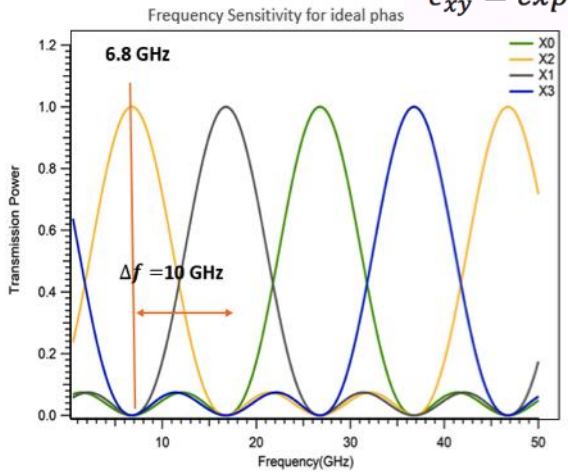
Addition

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

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

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)

Convolutional Neural Networks based-on Optical FTT

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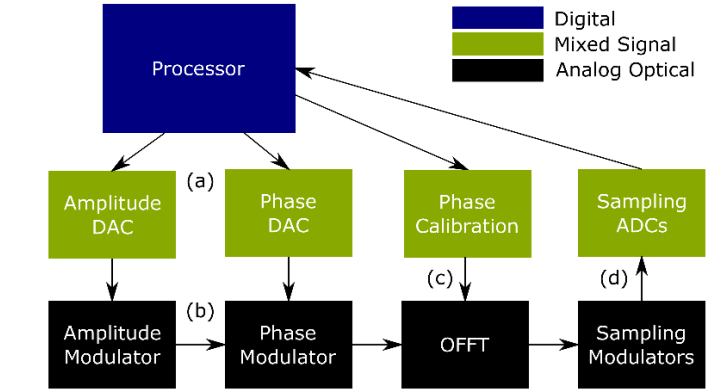
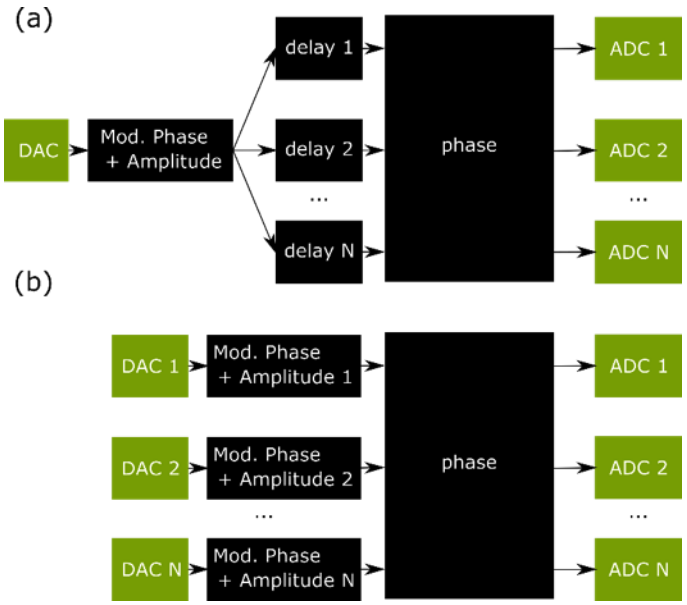
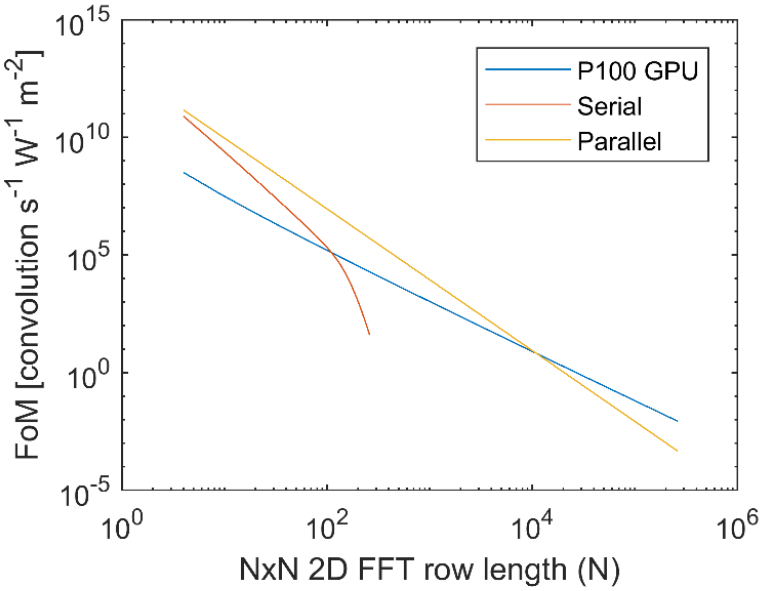




Description	Assumption
FLOPS per convolution	$20N^2log_2(N) + N^2$
ADC	56 GSa/s @ 2 W
DAC	100 GA/s @ 2.5 W
Optical loss first spiral	0.686 dB
Optical loss modulator	3.49 dB
Optical loss 2 x 2	0.99105 dB
Optical loss splitter	3 dB
Optical loss input grating coupler	4 dB



Sorger Group, IEEE Computing (2017)

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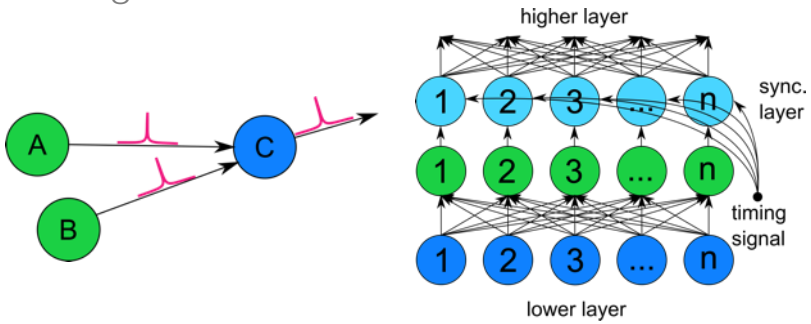
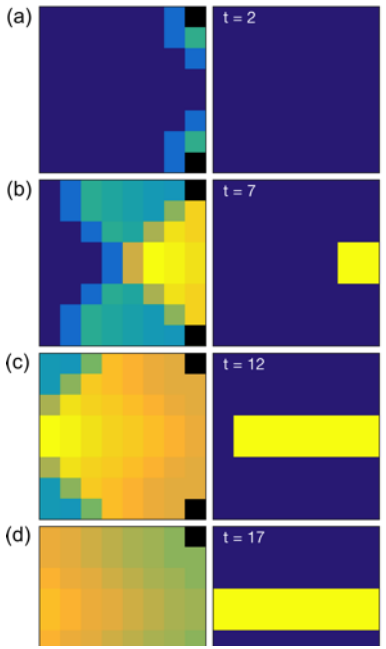
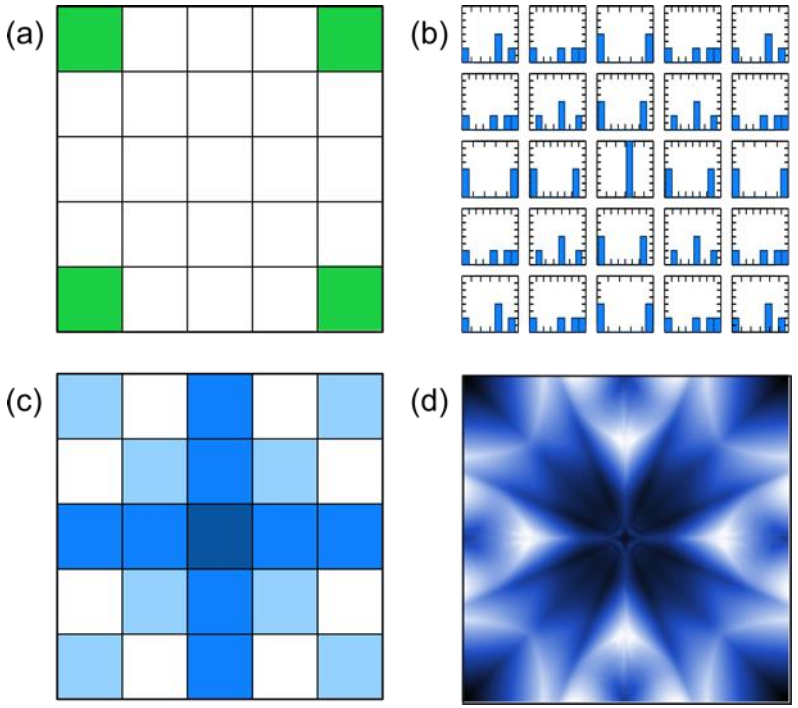
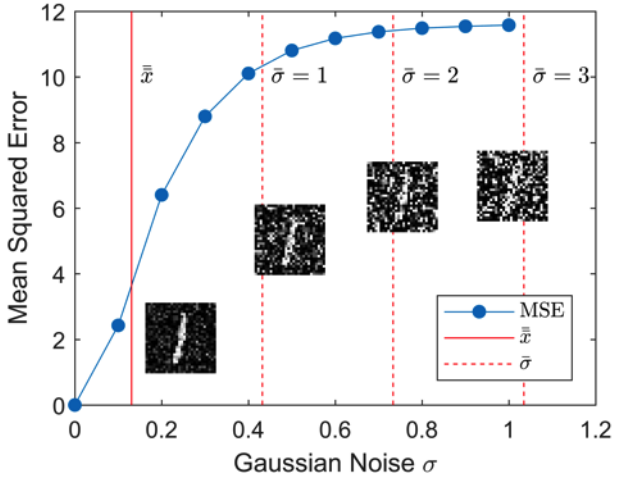
Mirror Symmetry Density with Delay in Spiking Neural Networks









Sorger Group. (2017) submitted

OPEN Sorger Team

Post Docs

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Dr. Hasan Goktas
Dr. Elnaz Akbari

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Matt Zhizhen
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Seyed Haghshenas
Rohit Hemnani

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D. D'Hemmecout
T. Weinshel
J. Crandall

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Prof. Reed (Stanford)
Prof. Bartels (UCR)
Prof. Lee (KU)
Prof. Prucnal (Princeton)
Prof. El Ghazawi (GWU)
Dr. Sadana (IBM Watson)
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