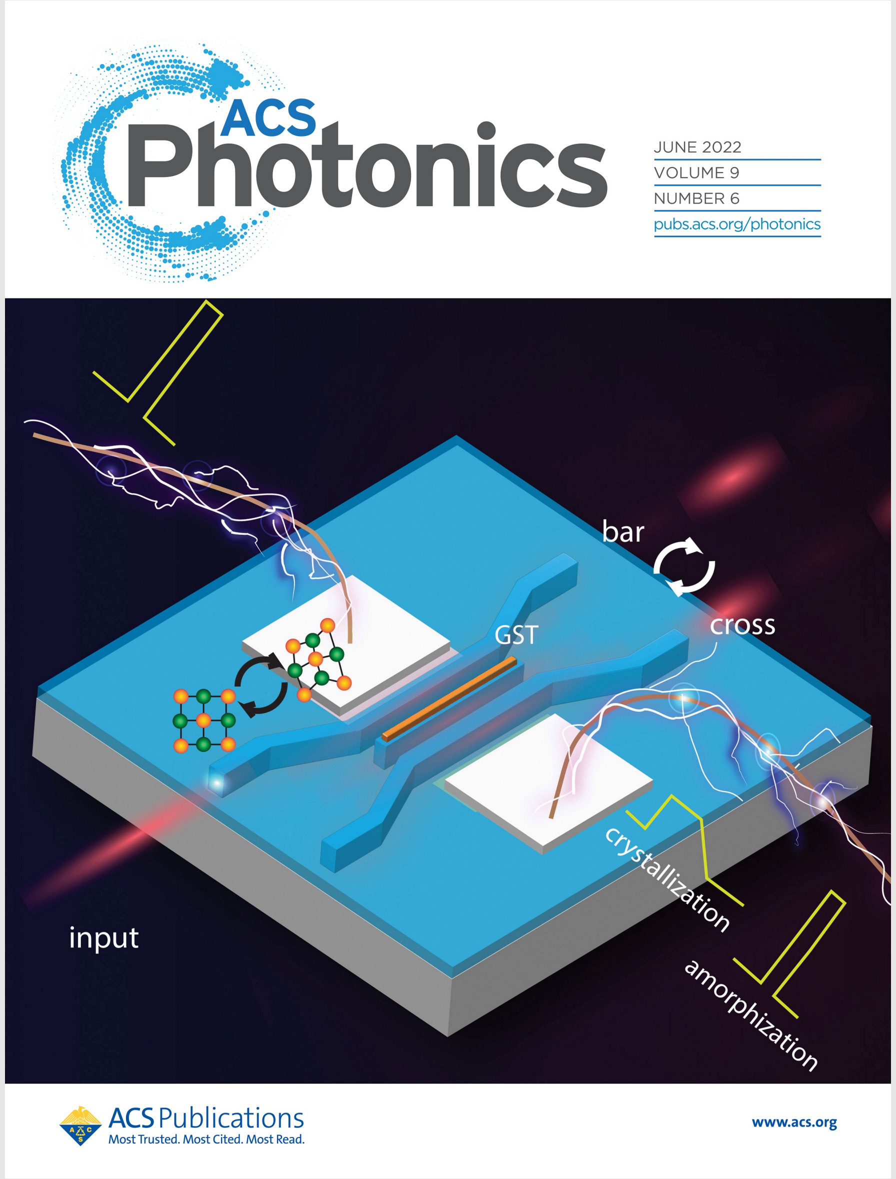
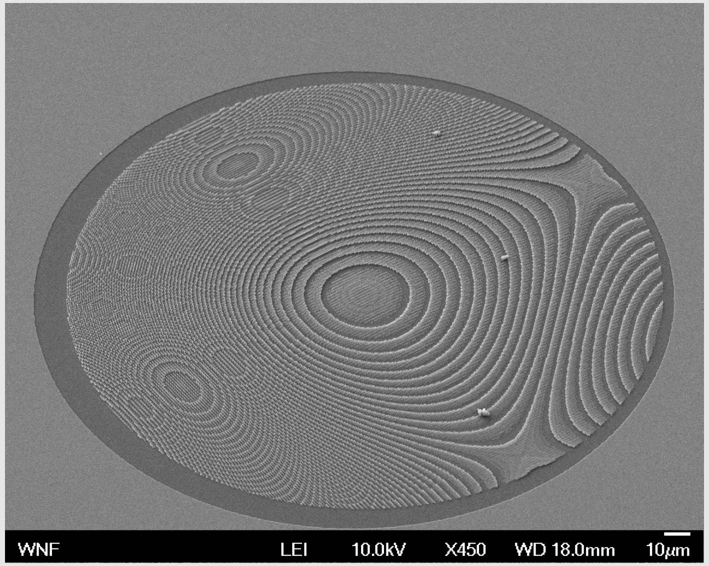
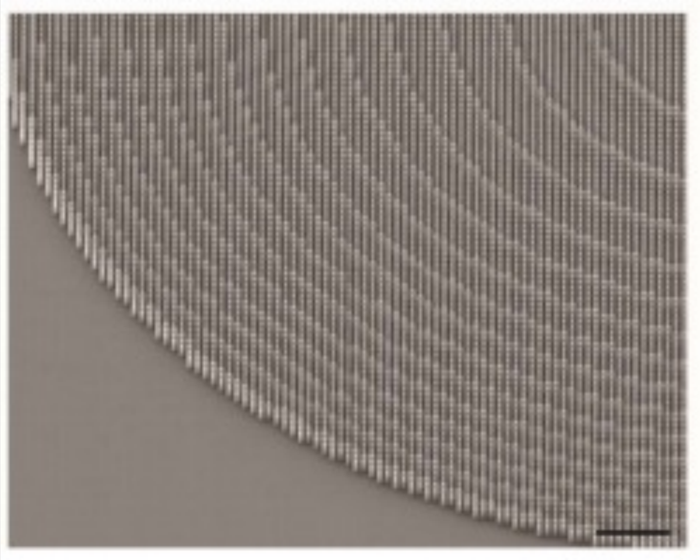
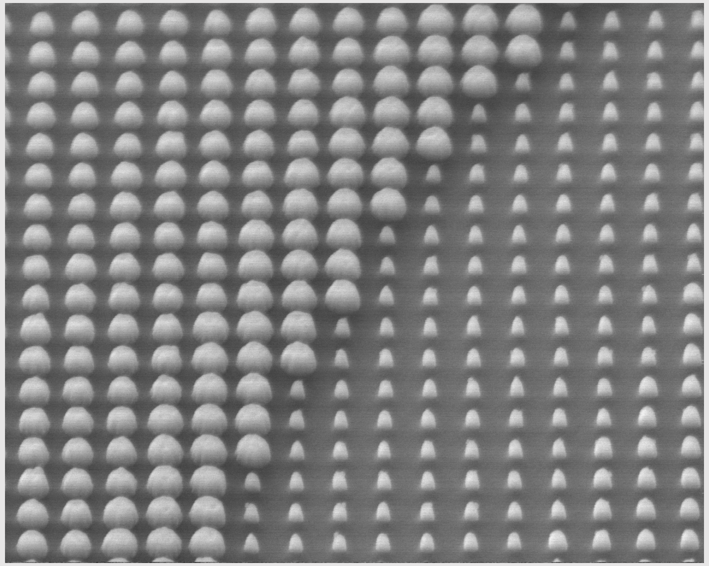
Nanophotonic Technology for Optical Neural Network









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Team and Funding

Christmas, 2020:
Current Group + Alumni

My team at UW:
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Rui Chen

Alumni:
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Elyas Bayati (in Tunoptix)
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Albert Ryou (in Atom Computing)
Jiajiu Zheng (in Analog Photonics)

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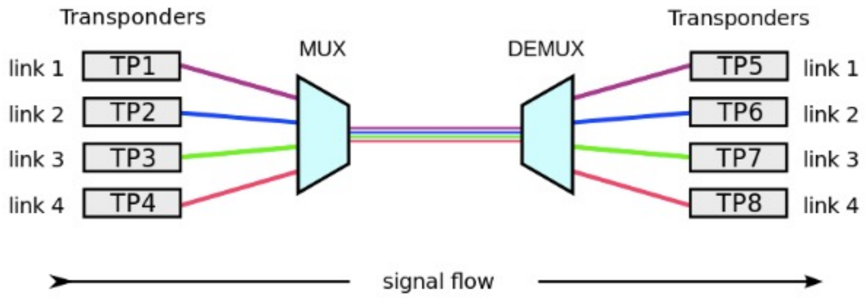
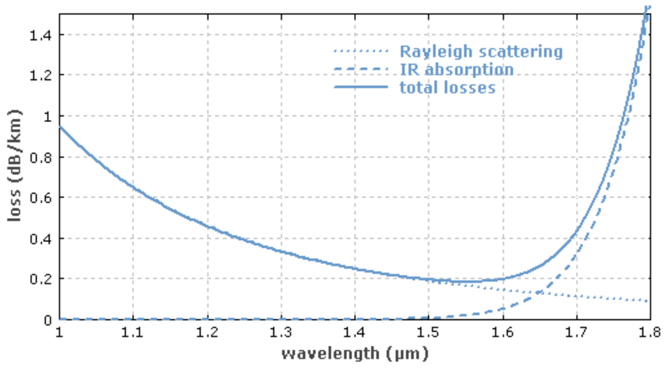
Eli Shlizerman (UW)
Karl Bohringer (UW)
Felix Heide (Princeton)
Steven Johnson (MIT)

Why Photonics for computing?

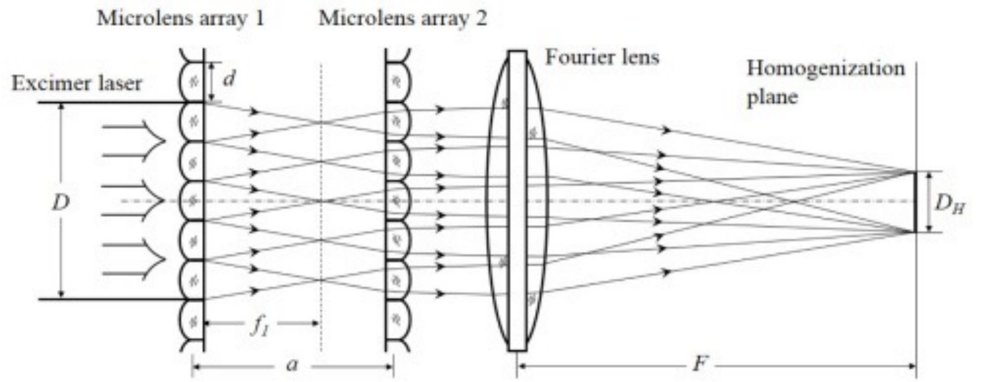
Light provides an enormous bandwidth, possibility of wavelength division multiplexing



Communication through optical waveguides can be almost lossless

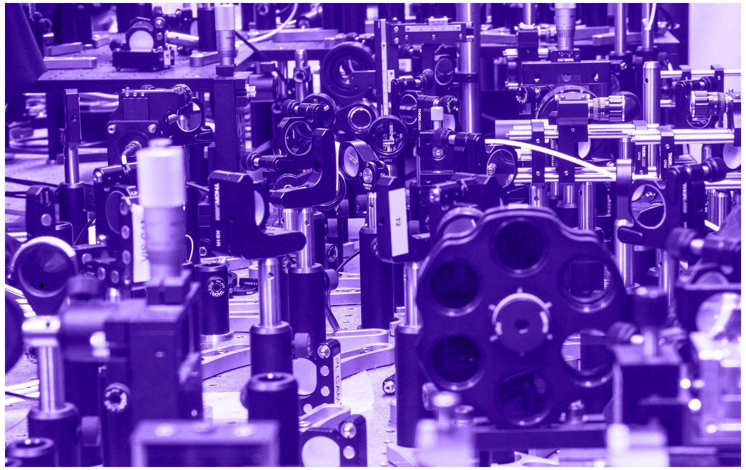


Light does not interact with other light: there is an inherent parallelism offered by light

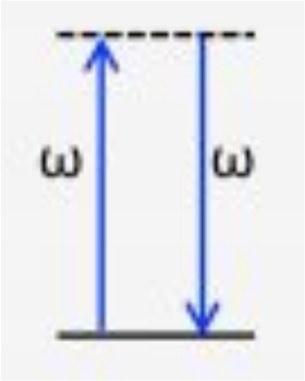


Why optical computing failed: Intrinsic and extrinsic reason

Large size and misalignment

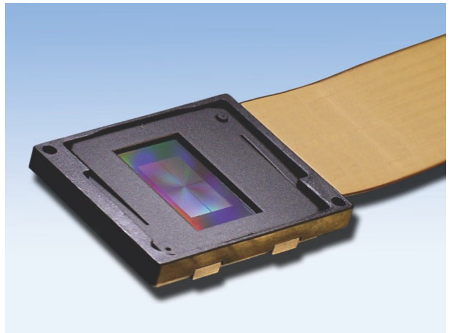


Lack of nonlinearity



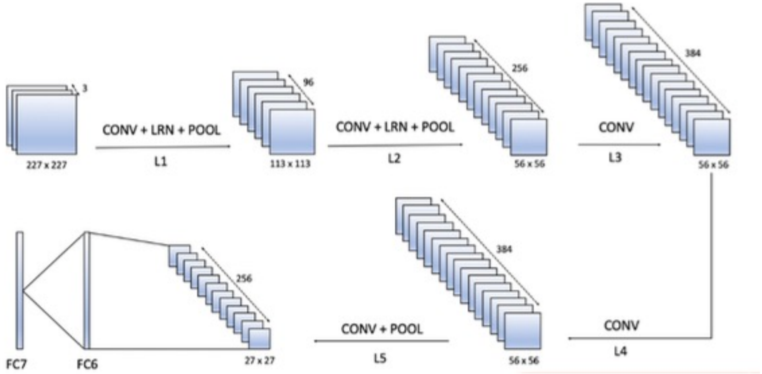
Light does not interact easily: the input-output relation is generally linear.

Lack of tunability



Fast tuning of optical phase by 2π with low power is difficult!!

Skepticism about neural network

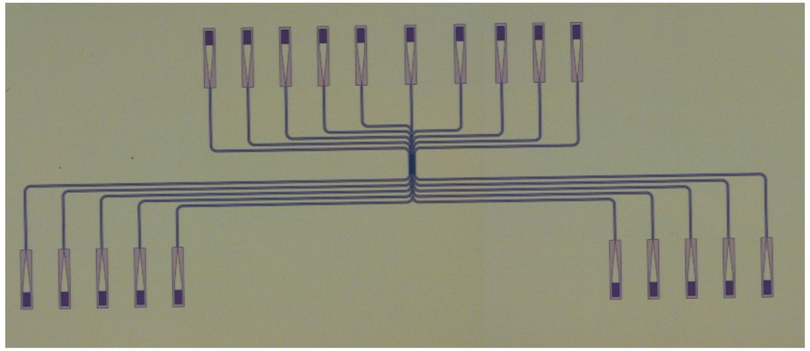


The surge in ANN is recent phenomenon

Electronic computers and software

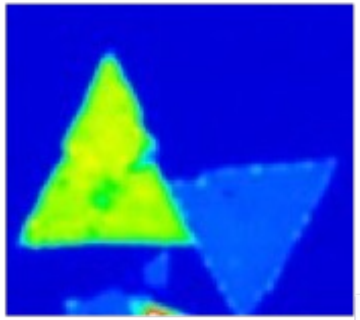
Opportunities for today

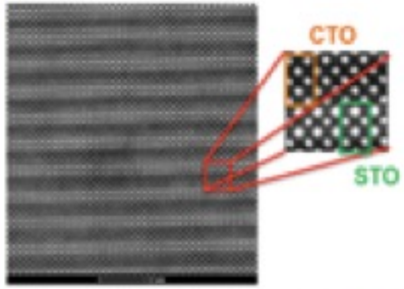
Nanophotonics and metaphotonics

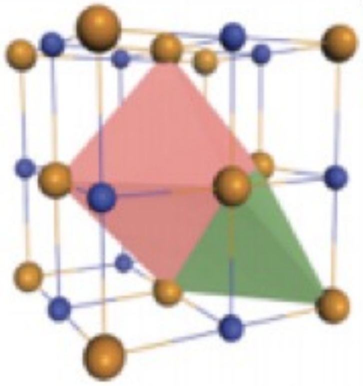


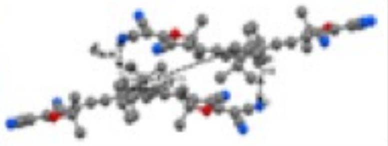
- Large computational resources for design
- Sophisticated nano-fabrication technology

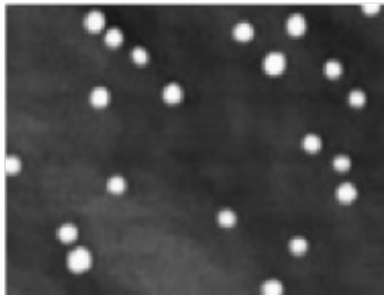
Emerging material systems for tunable photonics





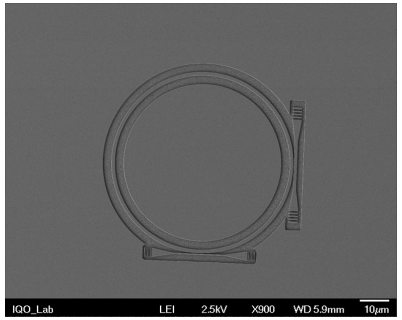


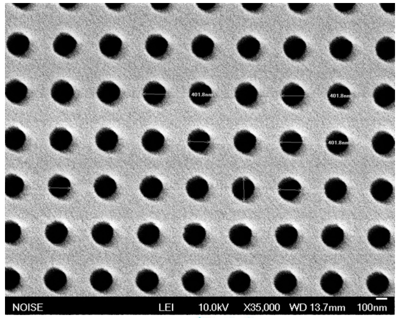


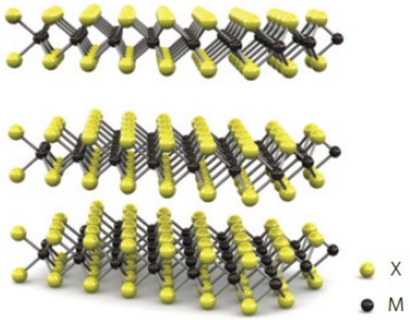


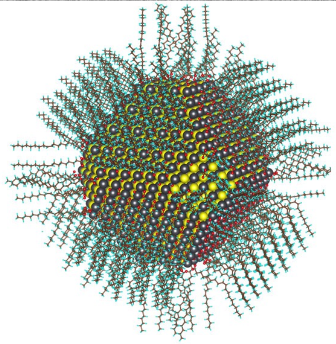
Quantum-confined structures, solution-processed materials, atomically thin materials, phase-change materials

Emerging material systems for nonlinear photonics





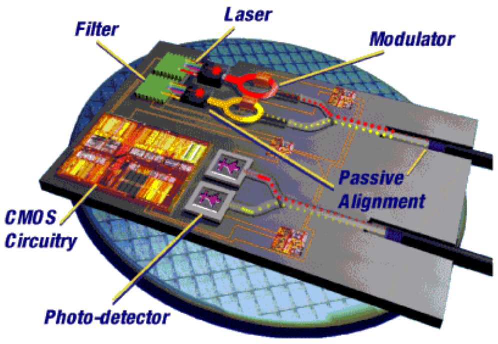




- Novel resonator structure (multimode)
- Nonlinear materials: AlN, LiNbO3, 2D materials
- Organic materials

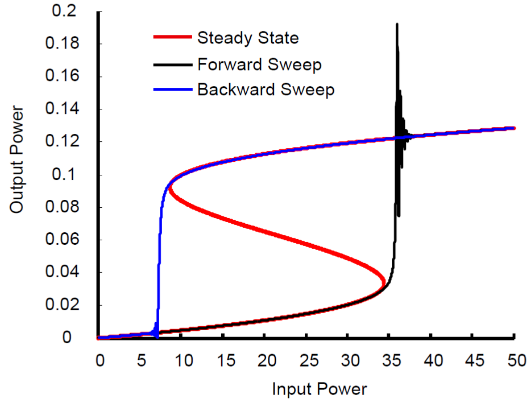
Photonics in computing

Optics as interconnect for high performance computing



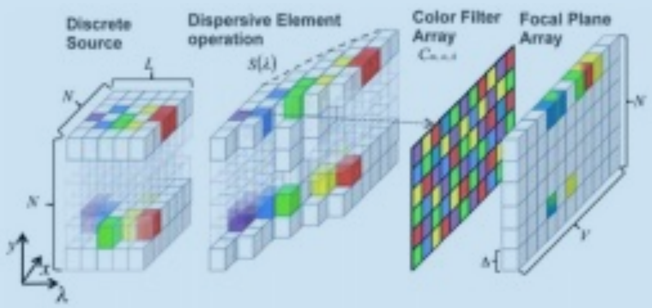
Optics as signal carrier: already commercialized

Digital logic with optics



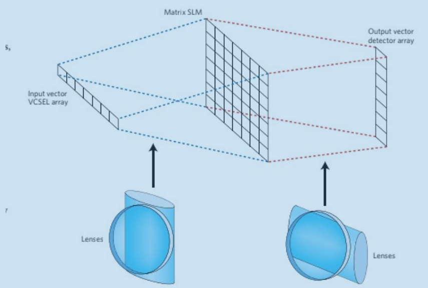
Binary logic with Optics

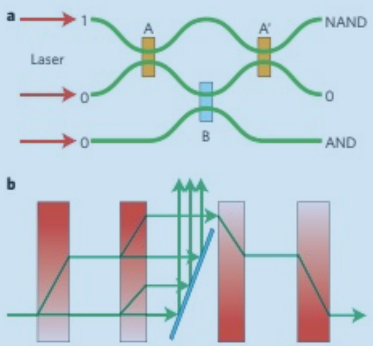
Computational imaging and computer vision with nanophotonics



- Capture image with existing camera and software processing to extract features
- Capture information in a non-canonical basis, and with software create image
- Very little innovation in photonic devices.

Analog computing (all-optical)

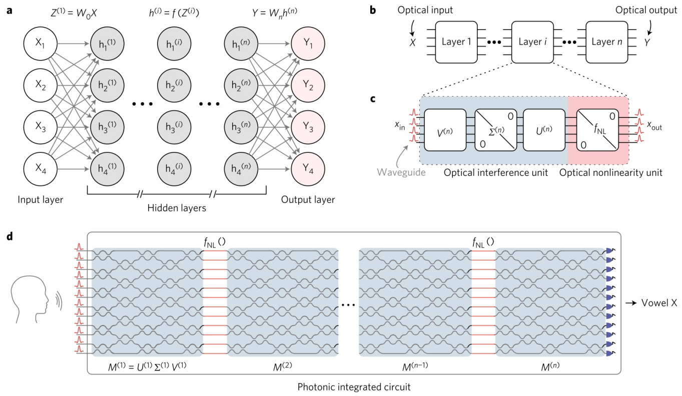




Nature Photonics, 2010

No explicit signal transduction

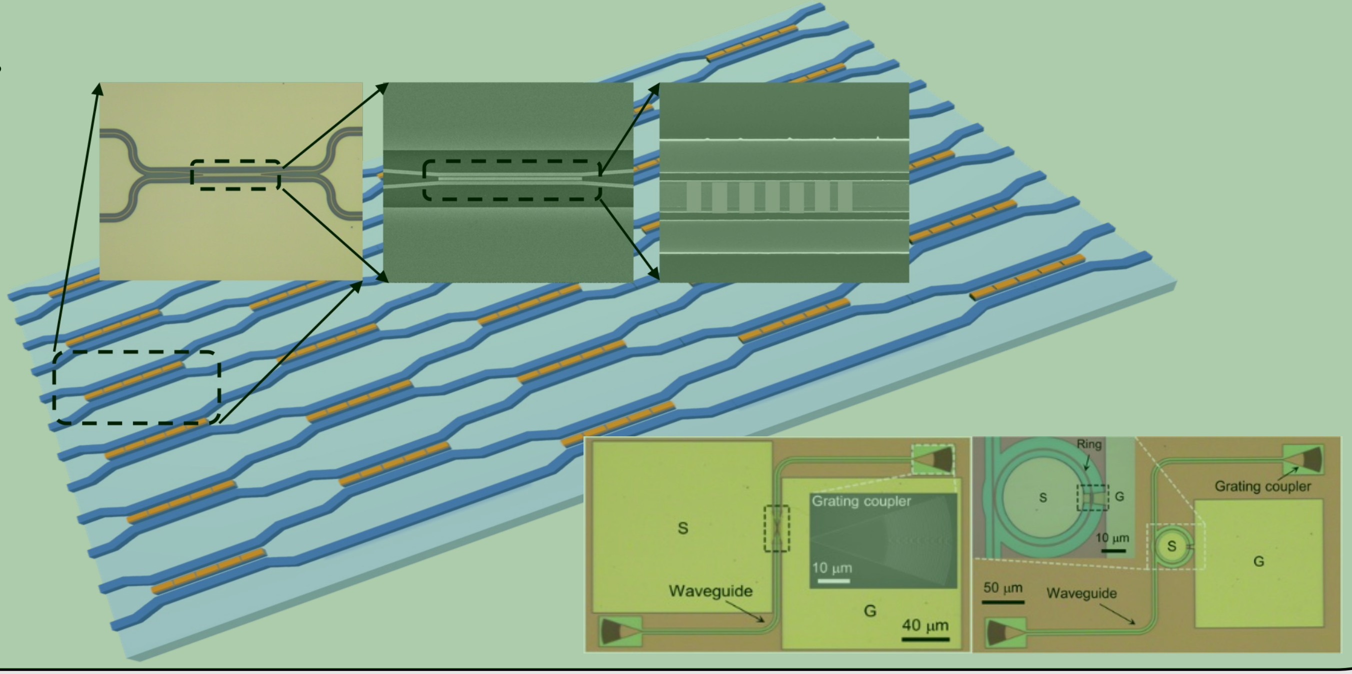
Hybrid Electro-photonics computing



Nature Photonics, 2017

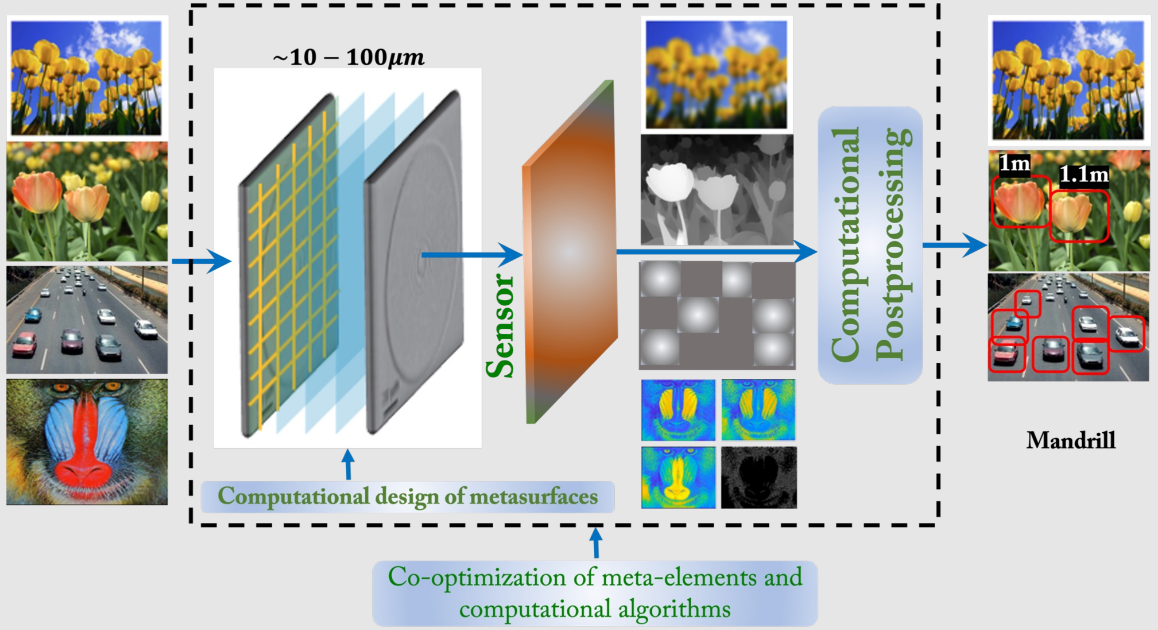
Hybrid integrated photonics for VMM and nonlinear activation

Majumdar et al., Optics Letter, 2014
Zheng et al., Optical Material Express, 2018
Zheng et al., ACS Photonics, 2019
Zheng et al., Advanced Materials 2020
Chen et al., ACS Photonics 2022

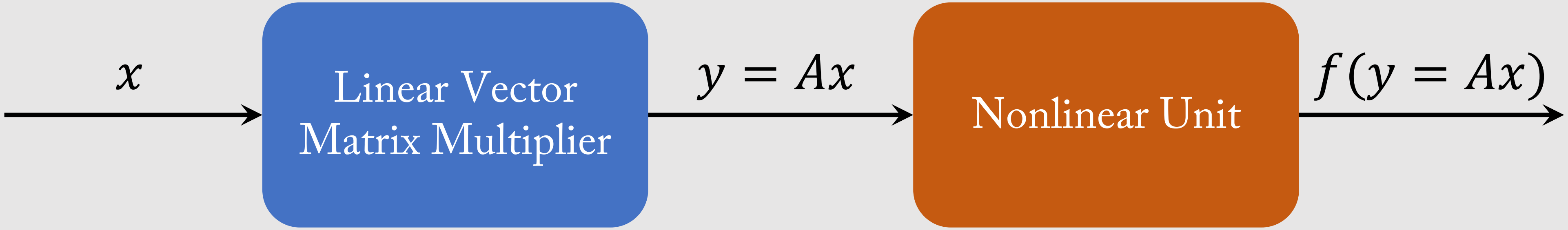


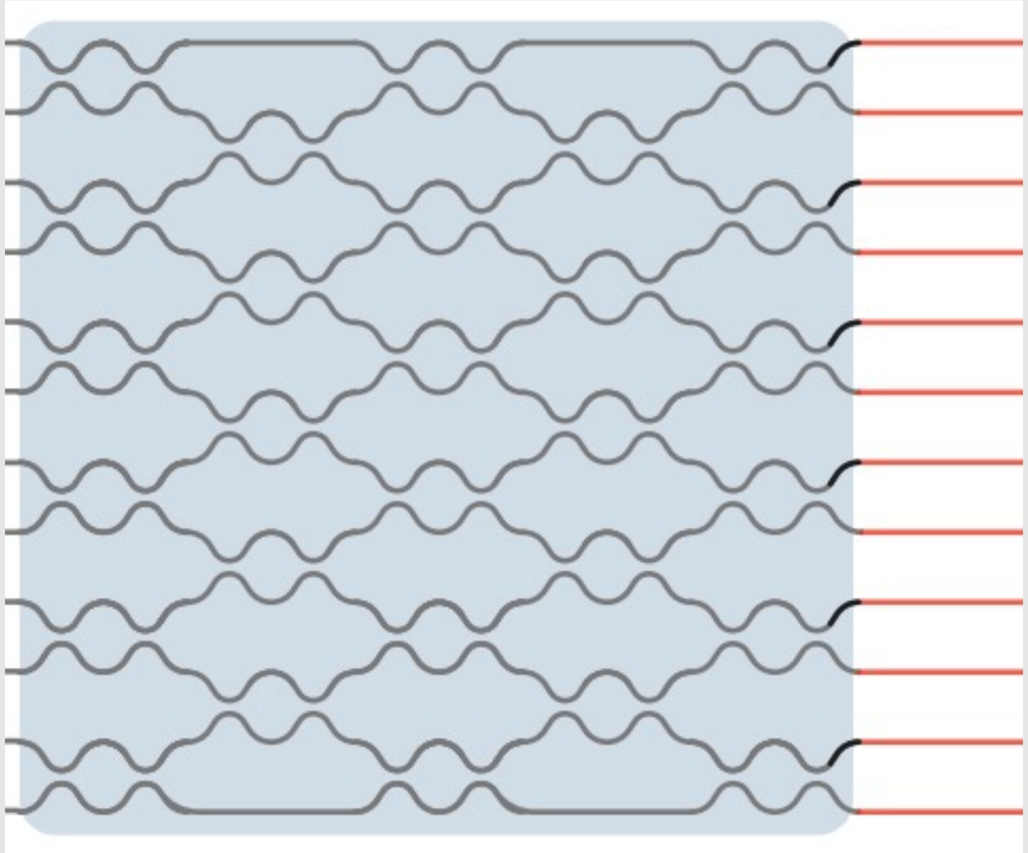
Meta-optical information processing

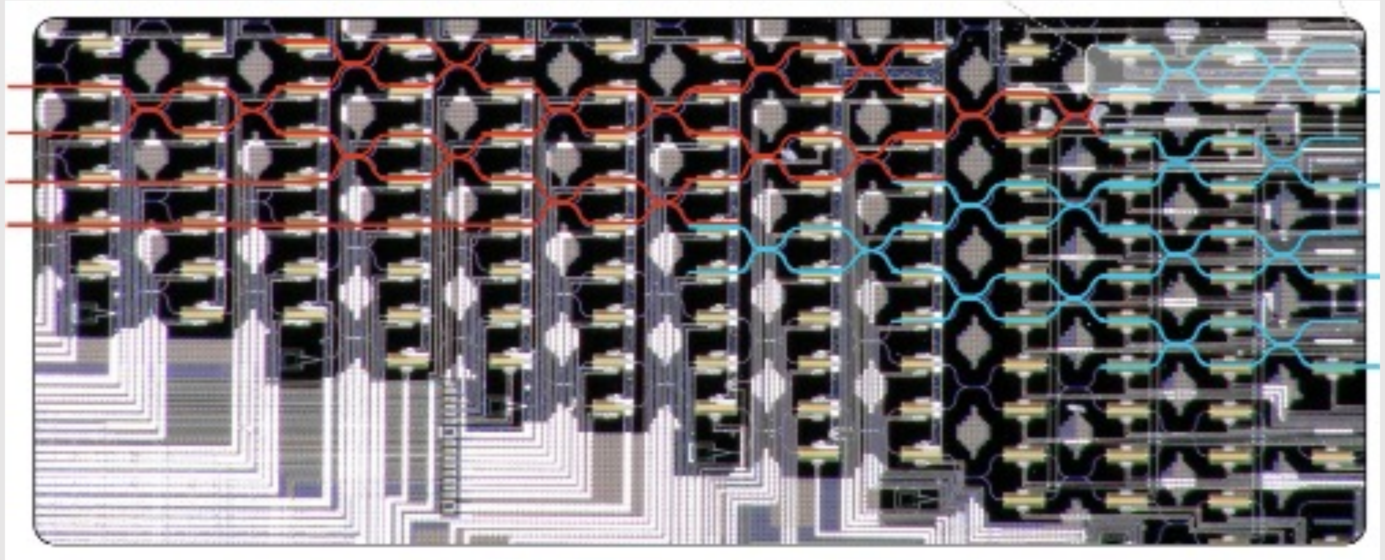
Colburn et al., Science Advances, 2018
Colburn et al., ACS Photonics, 2019
Zhan et al., Applied Optics, 2018
Zhan et al., Science Advances, 2019
Zhelyeznyakov et al, Optics Communication, 2020
Ryou et al., PRA, 2020
Colburn et al., Applied Optics, 2019
Tseng et al., Nature Communications 2021



Basic block of neural network



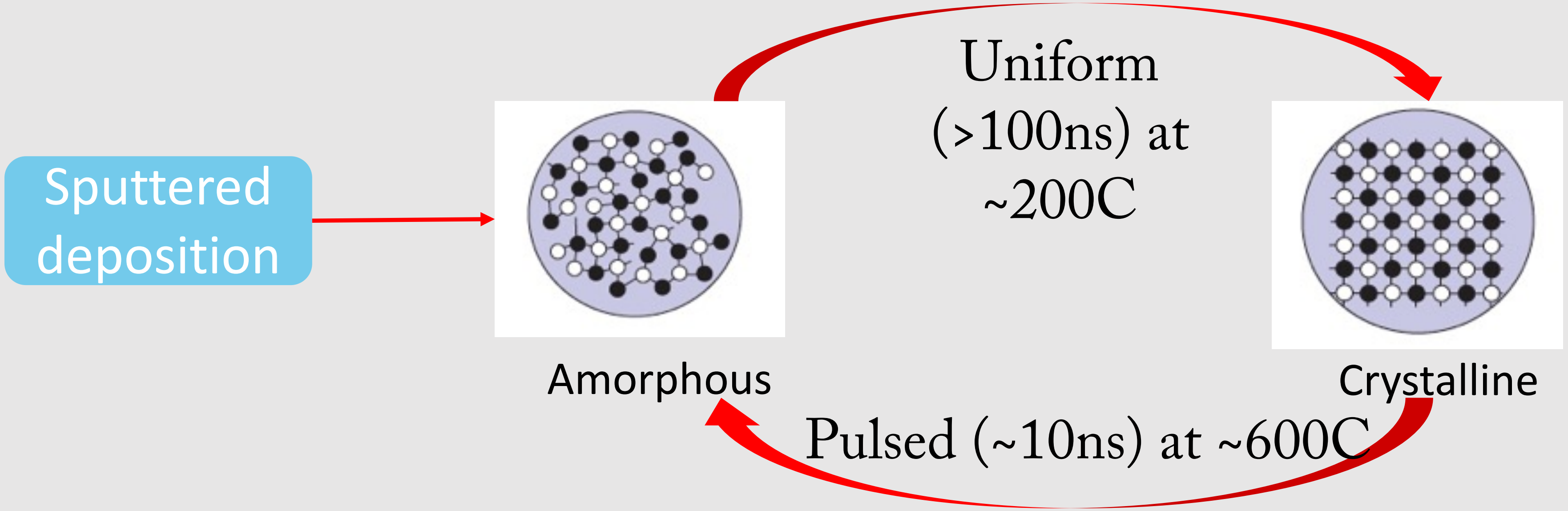


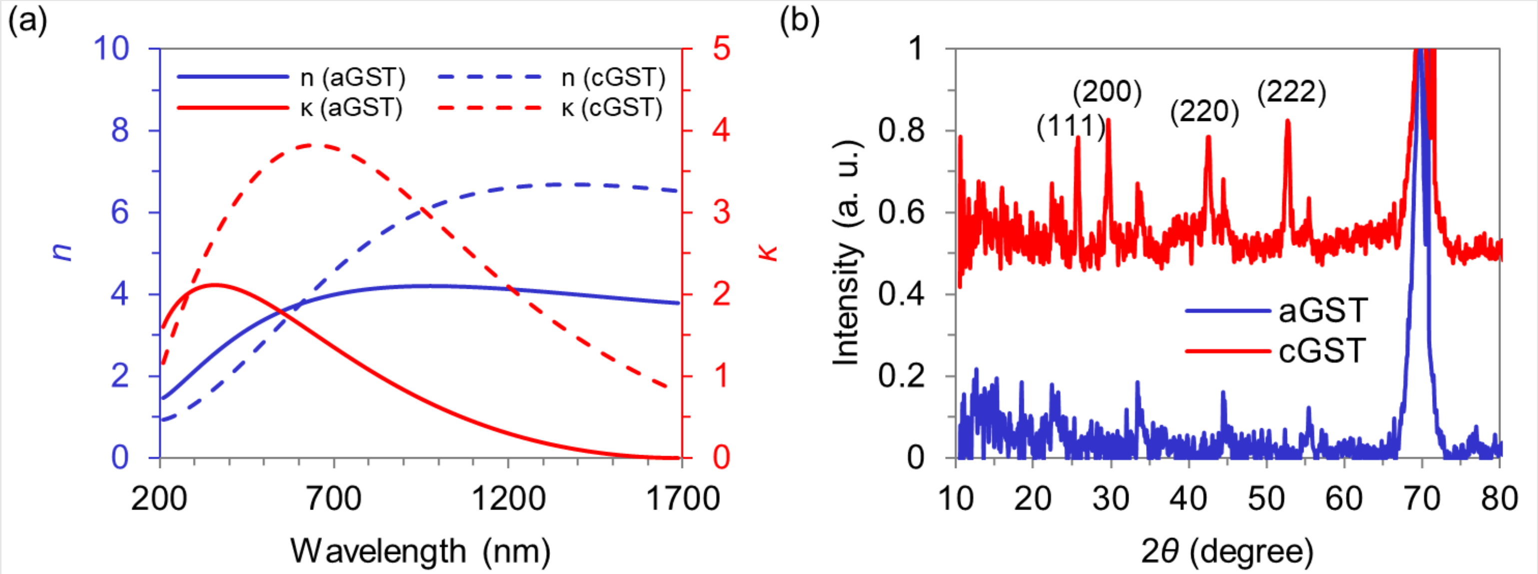


Volatile thermal control of the MZIs: power-hungry and limit scalability: $\mathbf{\Delta n < 0.001}$

Englund, Soljacic, 2017

Non-volatile phase-change materials (PCMs): GST





Ellipsometry **X-ray diffraction (XRD)**

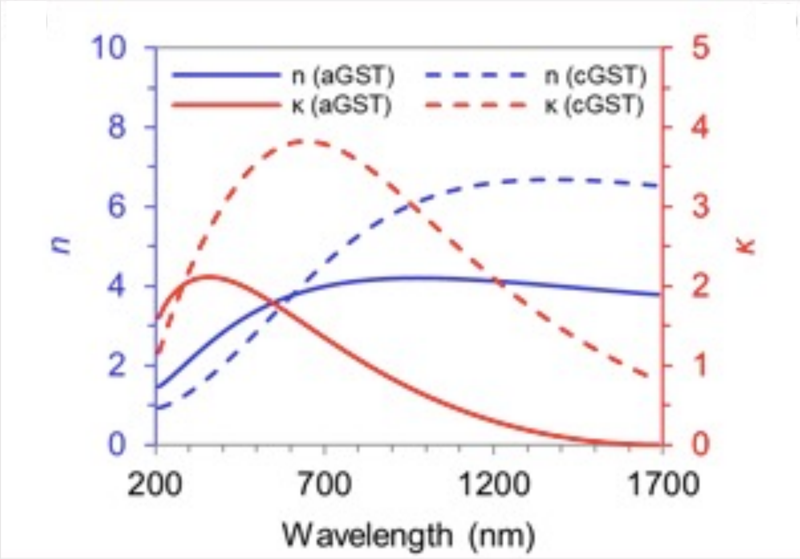
- Extremely large index change
- Reversible phase transition
- High loss

Zheng, J. et al. Opt. Mater. Express ***8****(6) (2018).*

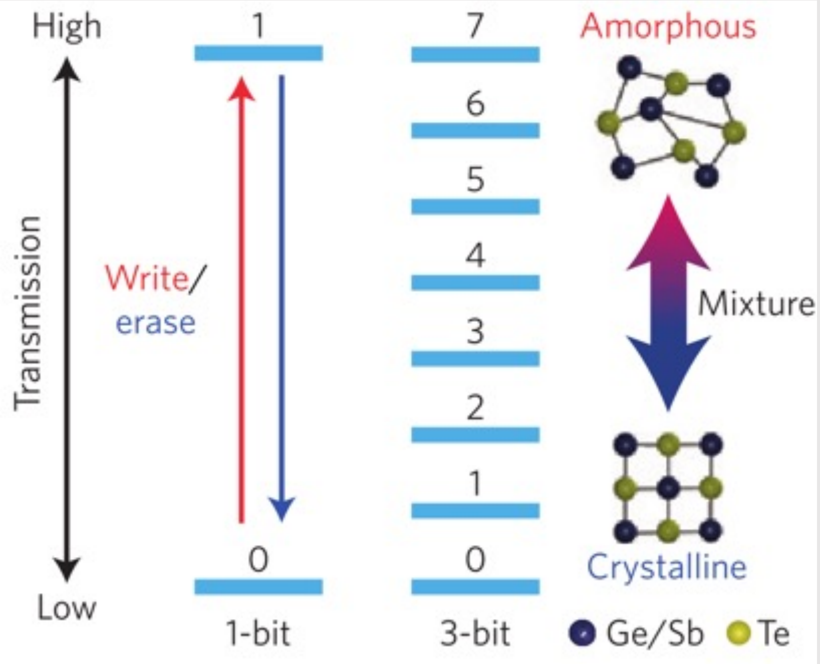
Pros & Cons of PCM

- Non-volatility: ~10 years. No external power supply needed!!
- High contrast between two states ($\Delta n > 1$)
- Multi-level operation potentially possible
- Fast reconfiguration (~ ps – sub-ns for amorphization, ~sub-ns – ns for crystallization).
- Low-energy (fJ/bit): fundamental limit $\sim 1.2\ aJ/nm^3$
- Excellent scalability: large scale and shrunk to nanoscale, easy to deposit on any substrate; CMOS compatible
- Is not limited by Kramers-Kronig relation!!

- Phase transition conditions can be difficult to identity
- Low cyclability: potentially possible over 10^{15} cycles; in practice 10^{9} cycles
- Multi-level operation is stochastic
- High optical loss for most PCMs, including GST

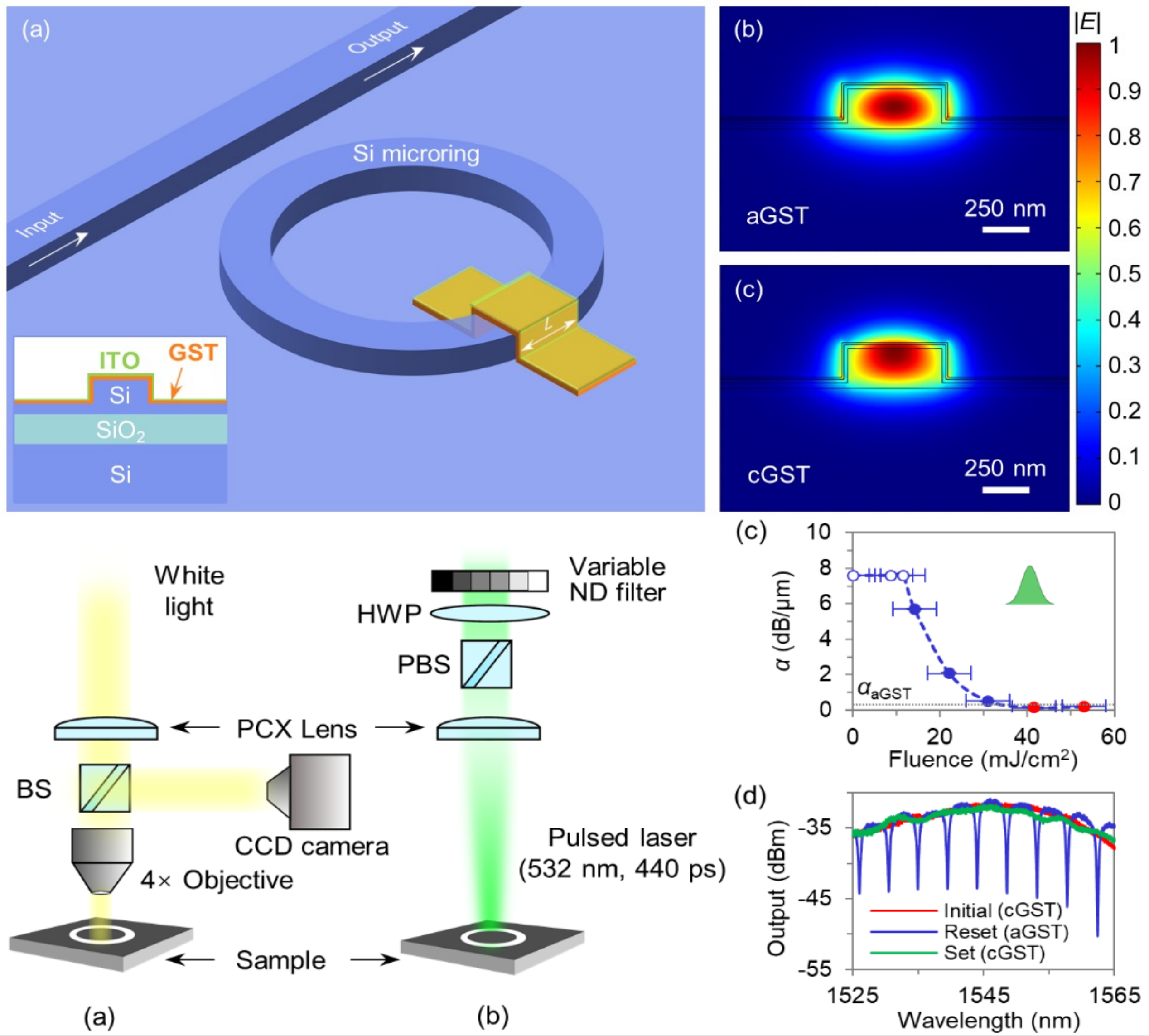


Zheng, J. et al. Opt. Mater. Express **8**(6) (2018).



Kuramochi, E. et al. Nat. Photon. **9**(11) (2015).

Integration of GST with silicon photonics and optical switching



Reset (amorphization)

- A single pulse of ~31 mJ/cm².
- Equivalent energy: ~9 aJ/nm³ (~620 pJ for GST on waveguide)
- Fundamental limit: 1.2 aJ/nm³

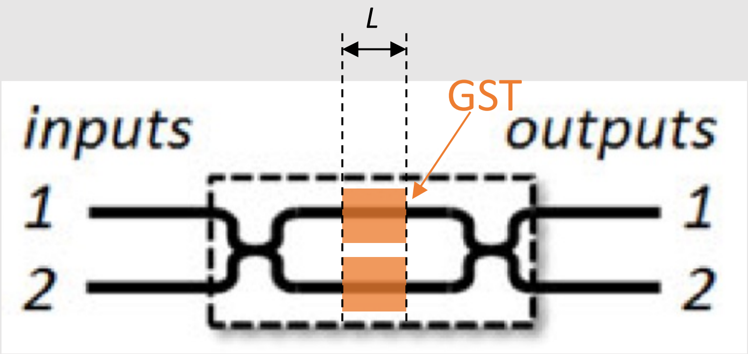
Set (crystallization)

- 450 numbers of pulses with ~10 mJ/cm² at 50 kHz.
- Equivalent energy: ~3 aJ/nm³ (~200 pJ for GST on waveguide).

Zheng, J. et al. Opt. Mater. Express ***8****(6) (2018).*

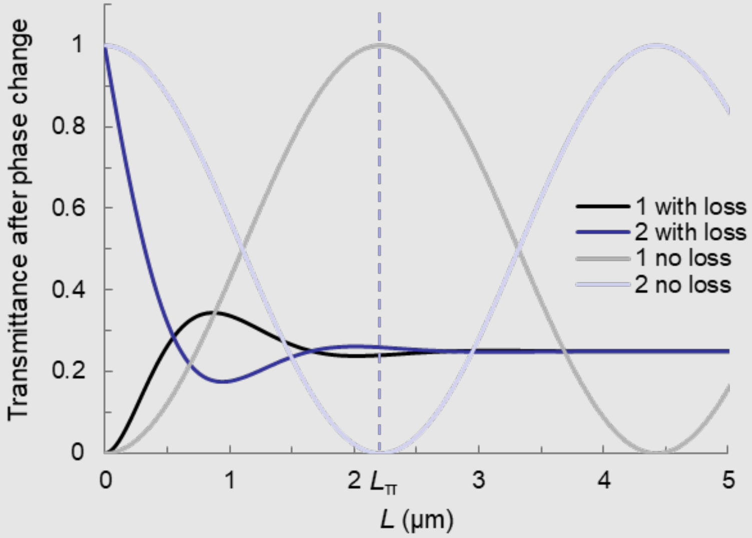
Consideration of the design of broadband switches

Traditional MZI switch ☹



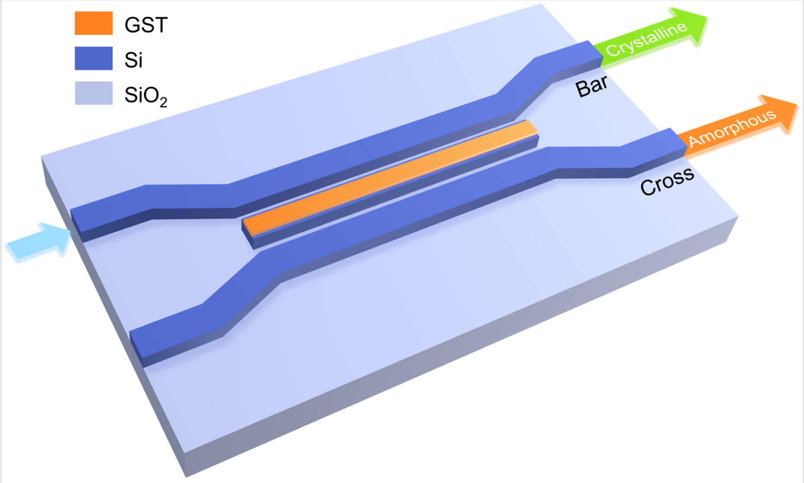
$$L_\pi = \frac{\lambda}{2\Delta n_{eff}} \approx 2.2\ \mu\text{m}$$

When $L = L_\pi$, change the phase of one arm, the light will switch port.



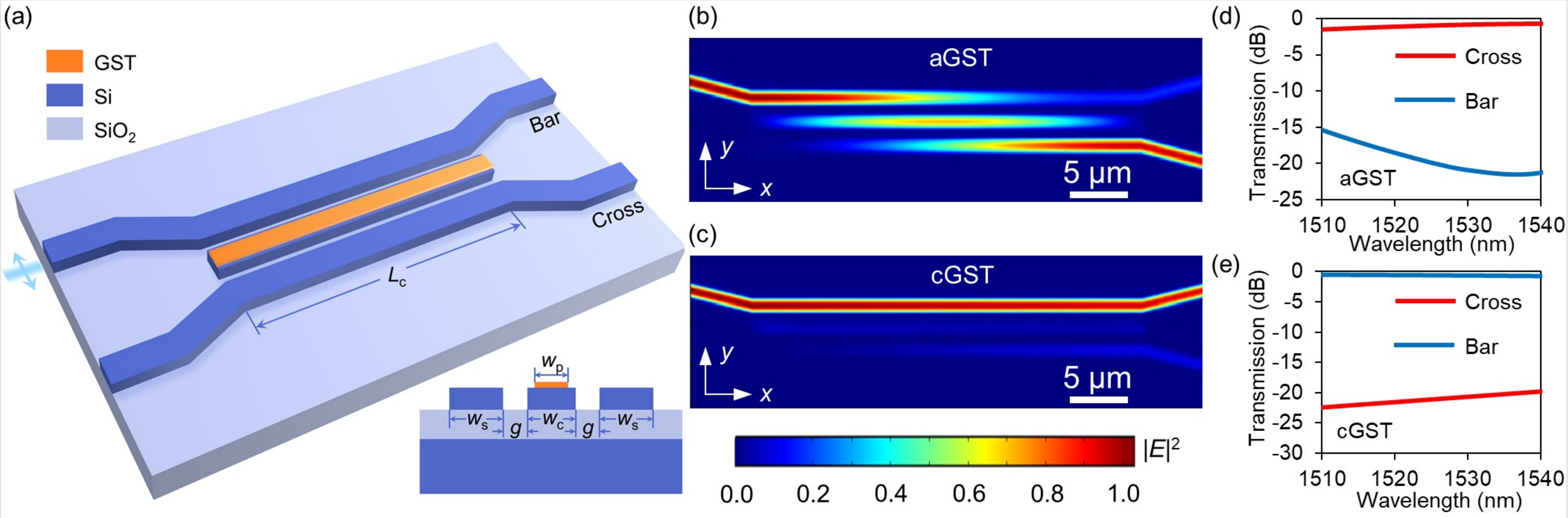
Large insertion loss and cross talk!

Directional coupler (DC) switch ☺

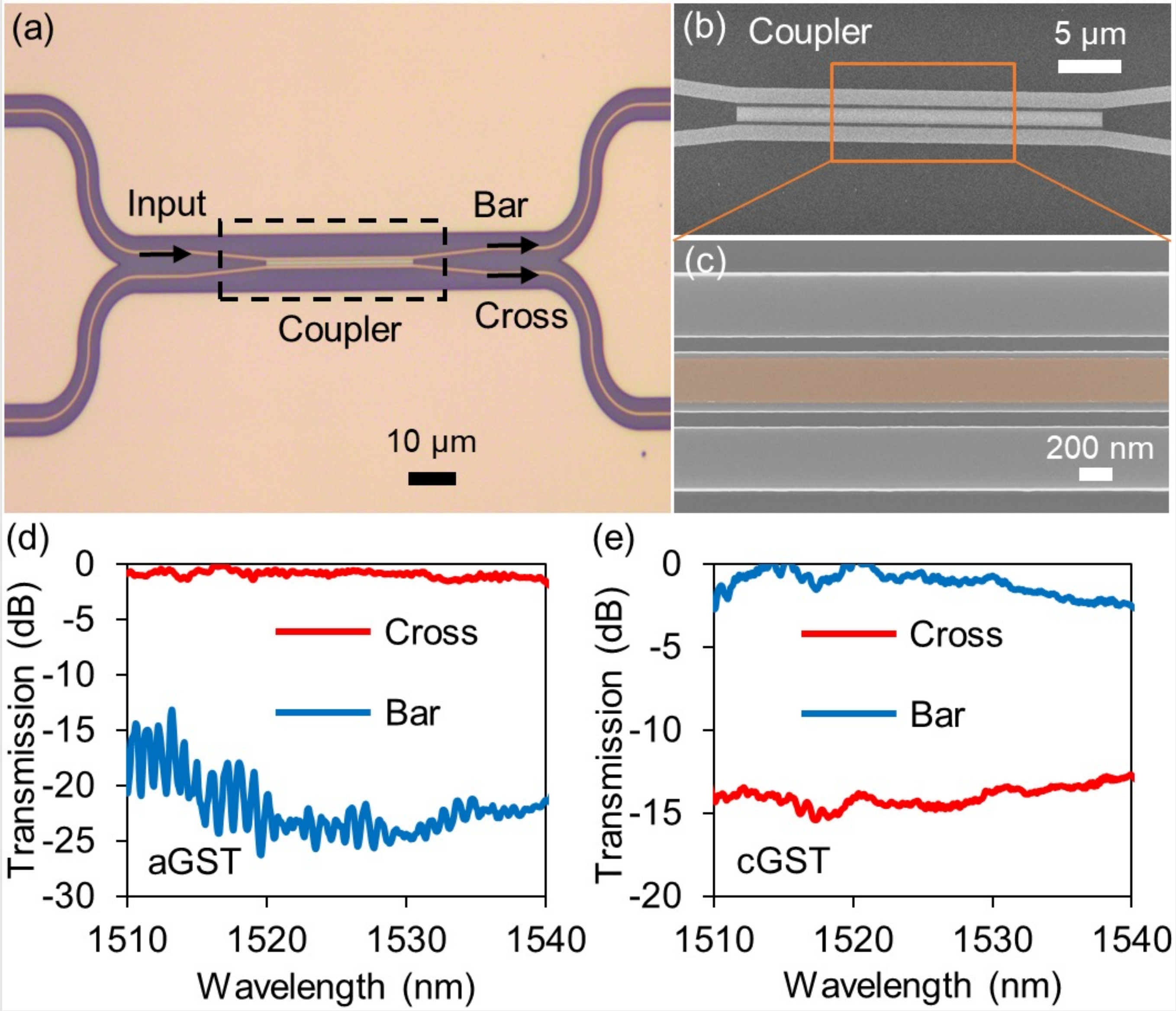


High loss associated with cGST is circumvented!

Low loss broadband switch



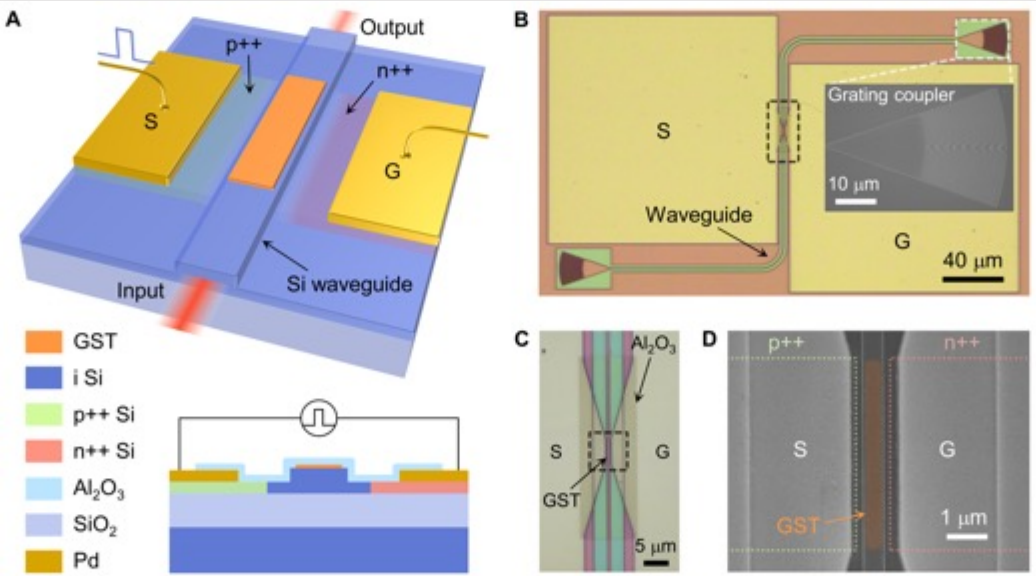
Phase-change 2 × 2 DC switch: experiment

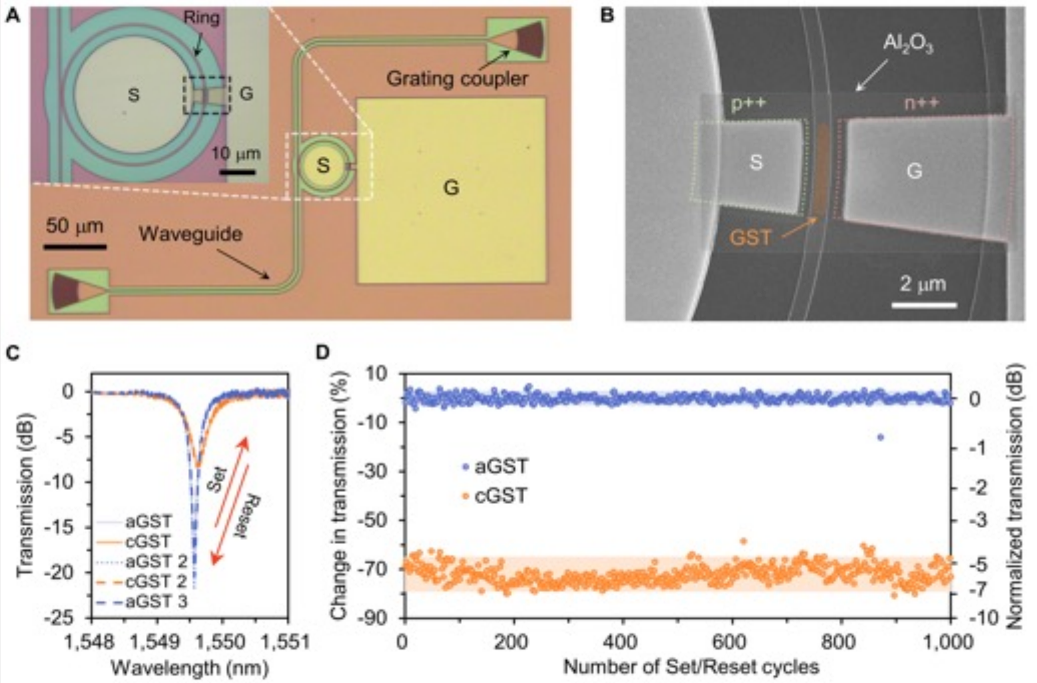


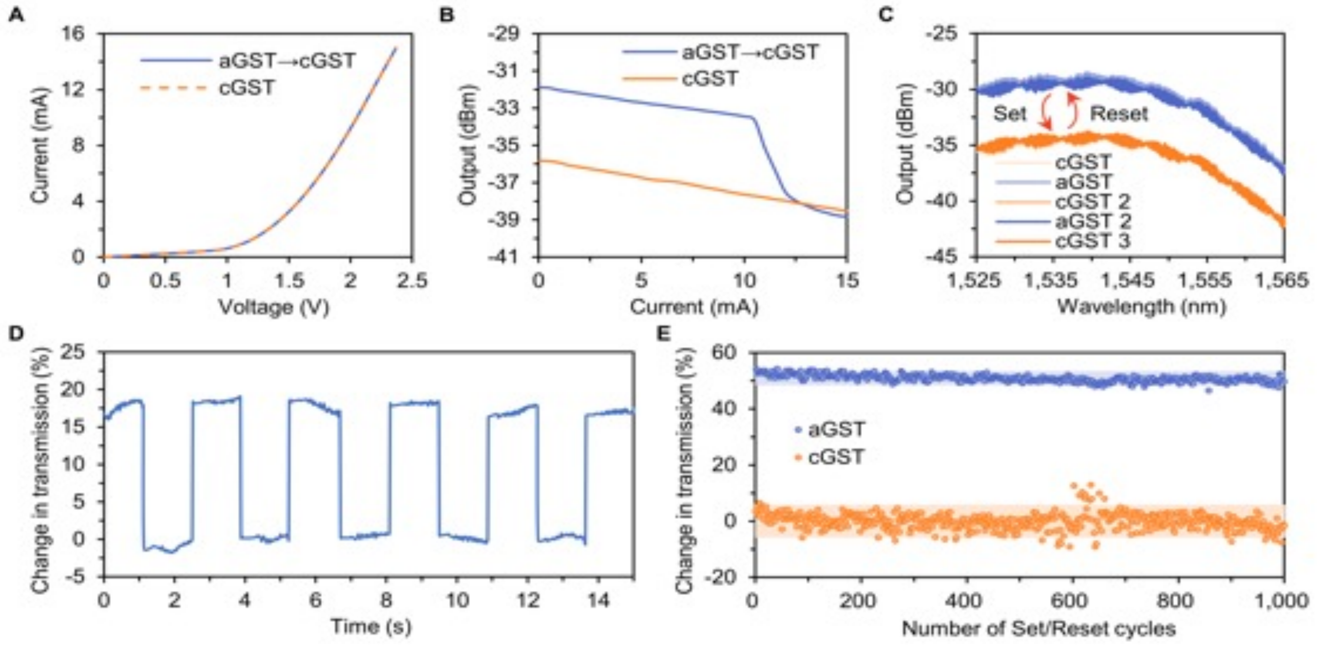
Zheng, J. et al. ACS Photonics, 2019

<1dB insertion loss even when the material loss is very high.

Electrical Control of GST-SOI platform

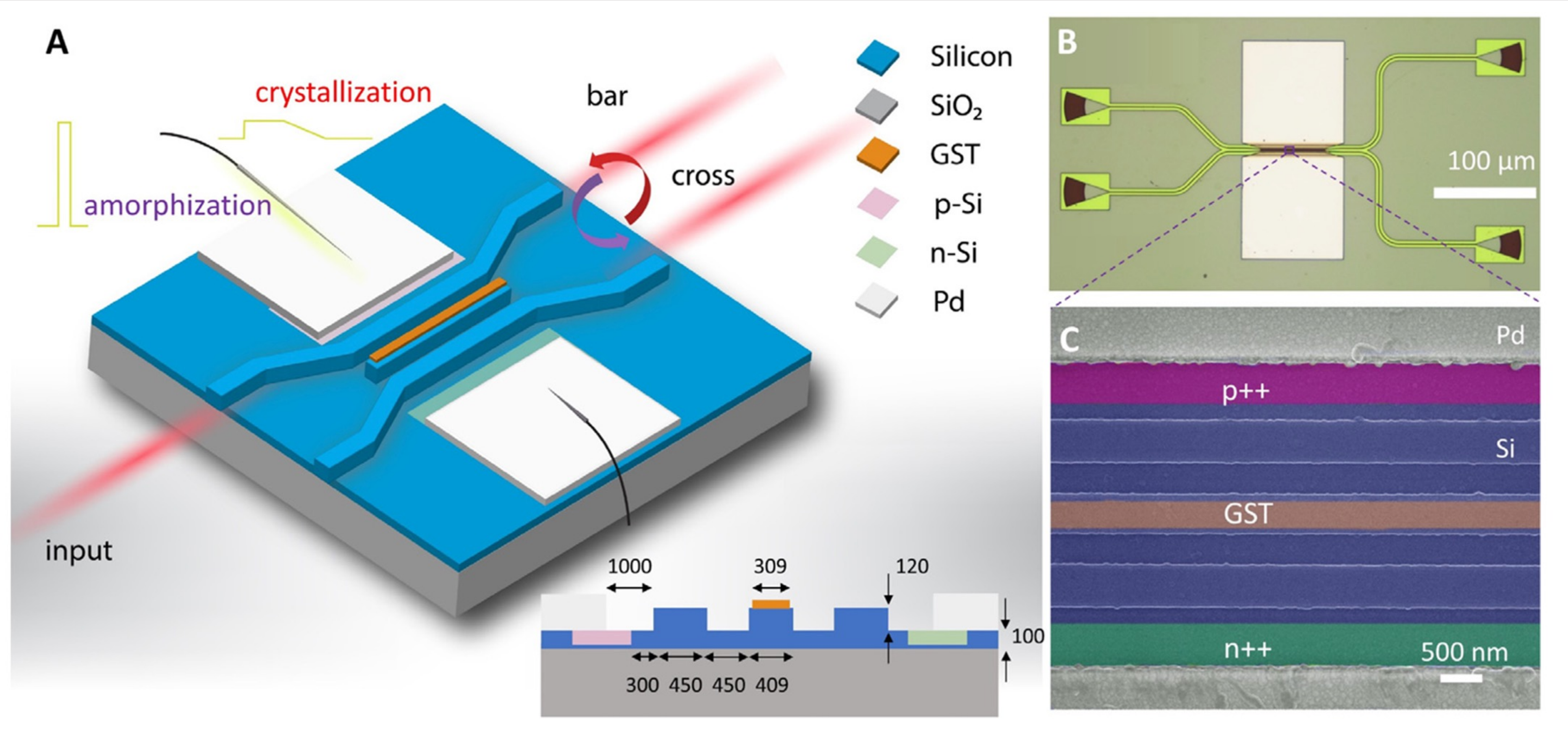




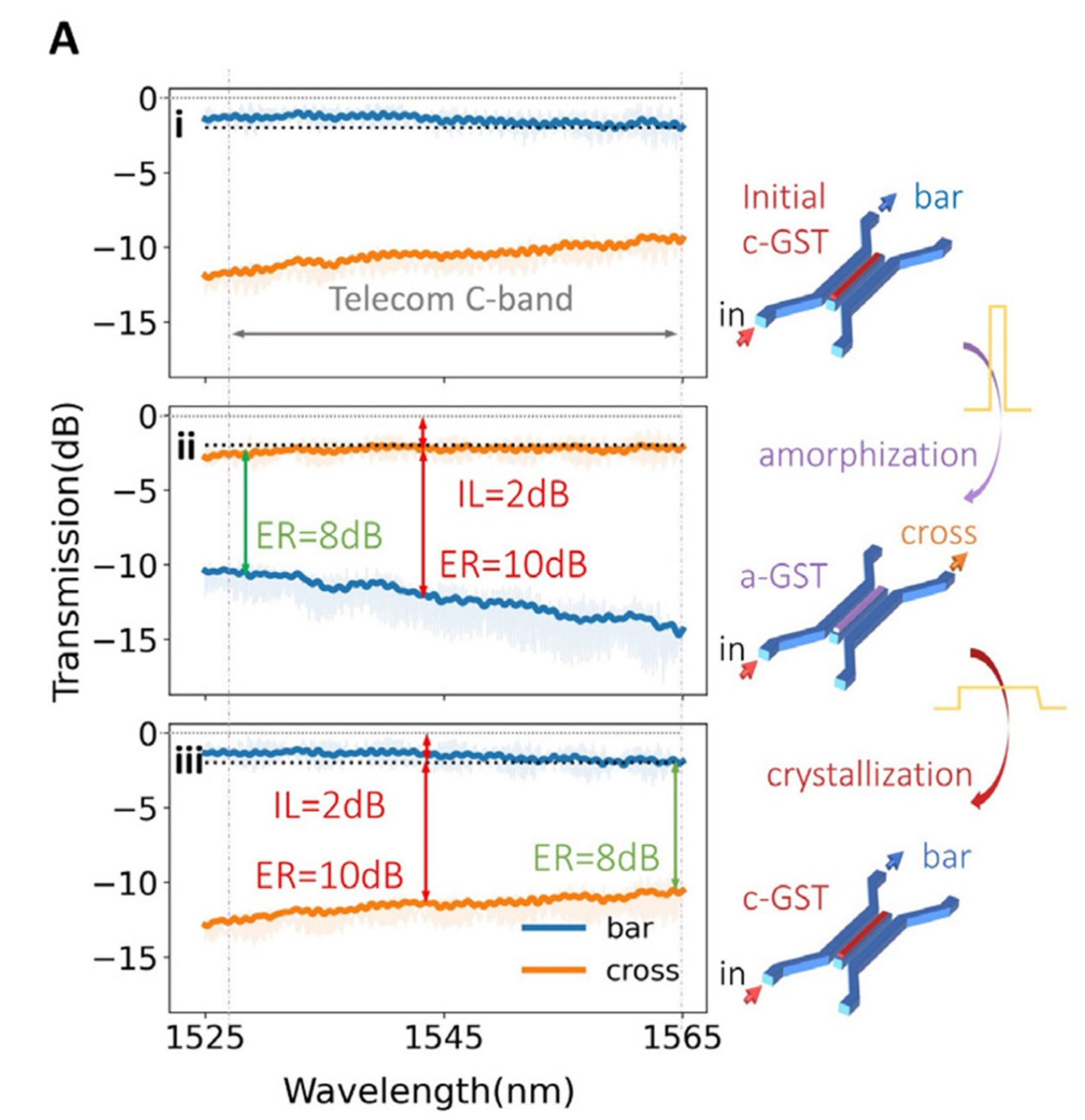


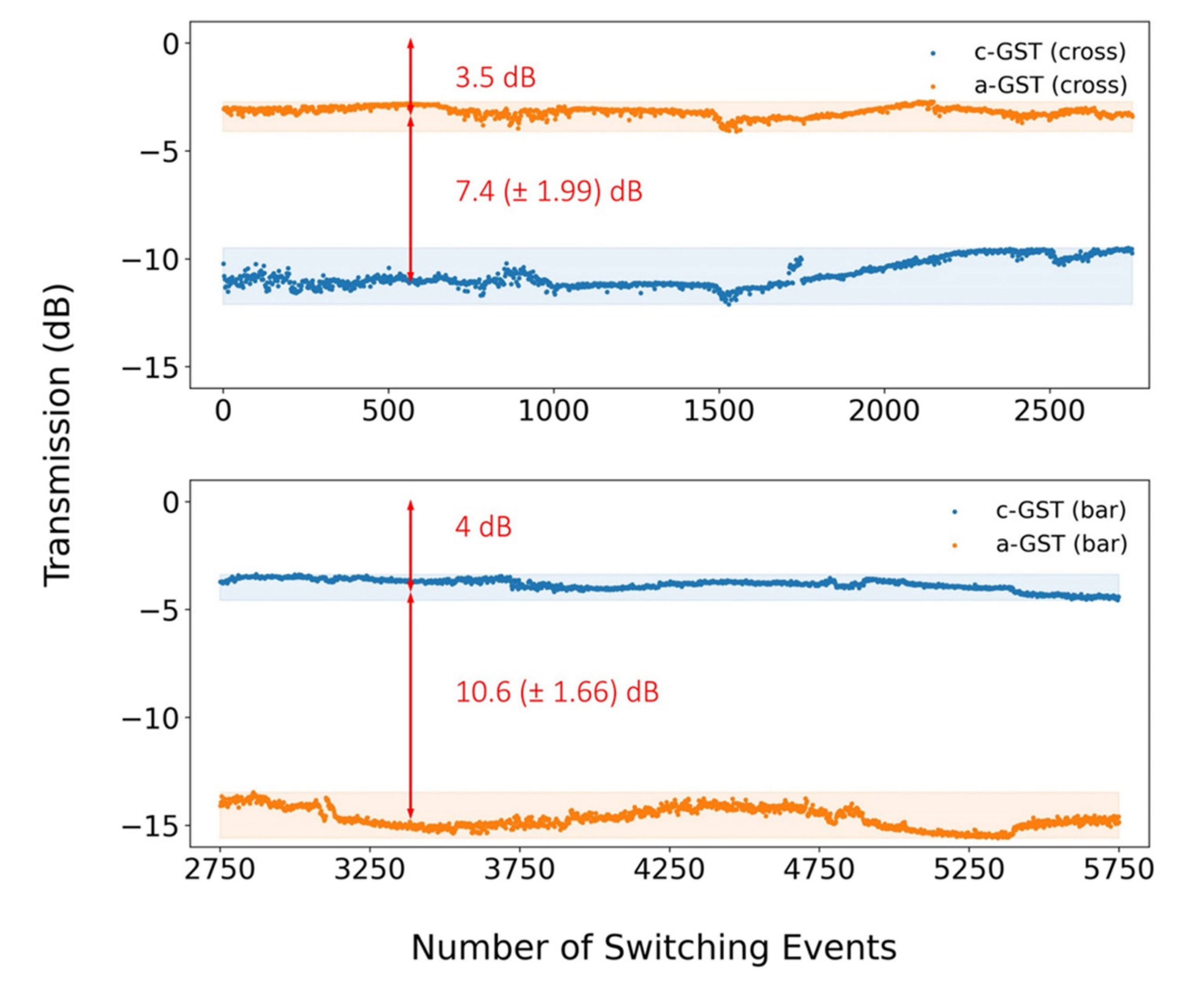
- Silicon p-i-n junction is used as a heater to actuate the phase transition of GST
- Demonstrate high extinction ratio switching using ring resonator and waveguide
- More than 1000 cycles are observed.

Broadband electrically controlled programmable unit

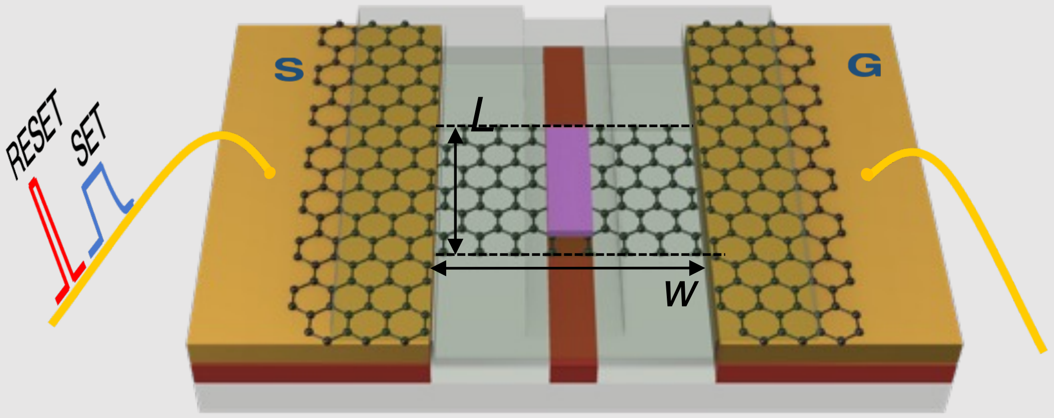


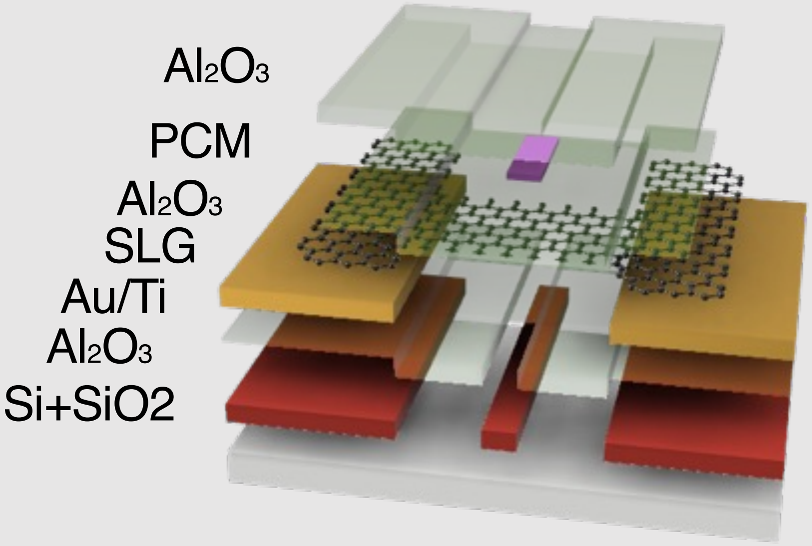
High endurance and broadband operations demonstrated



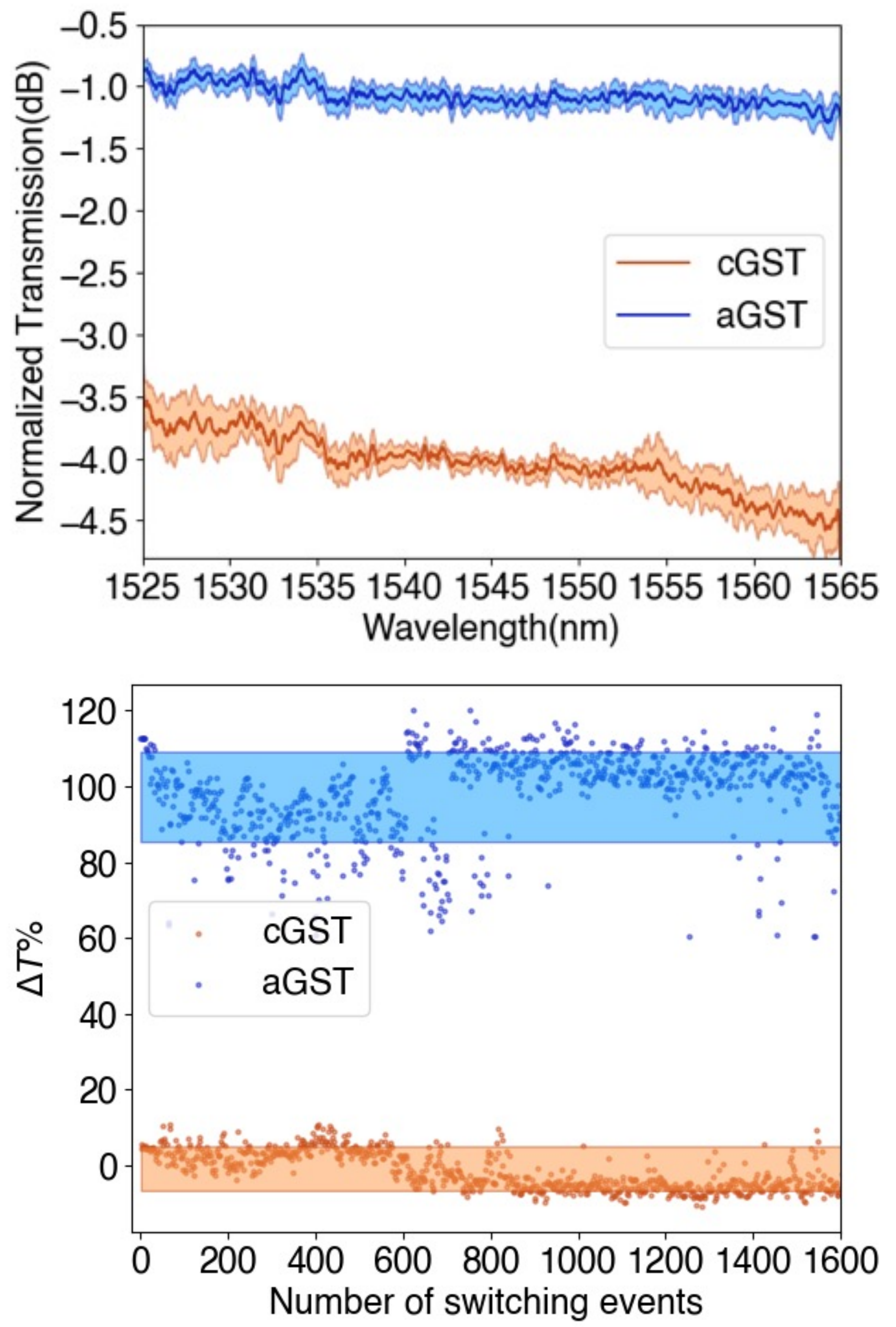


Phase transition actuated via graphene heater: Reaching fundamental energy-efficiency

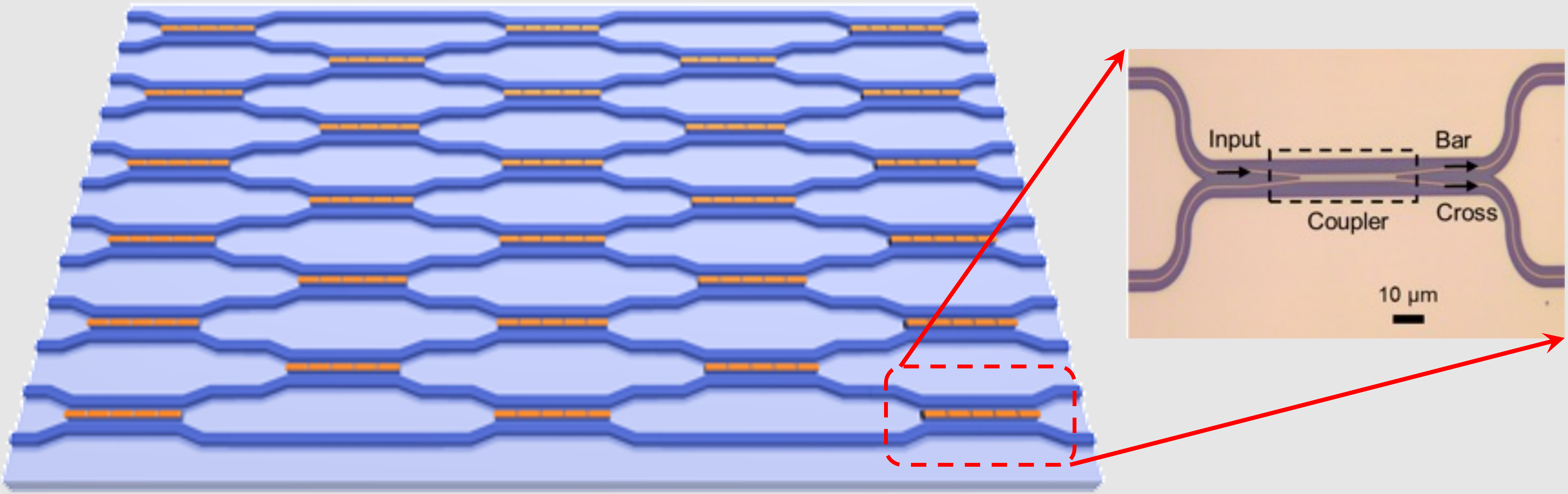


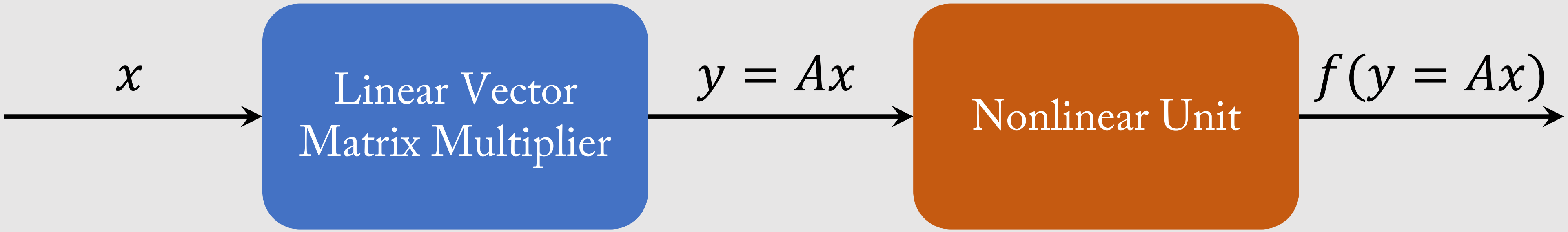


Energy: $\sim\mathbf{10}\,\boldsymbol{aJ/nm^3}$

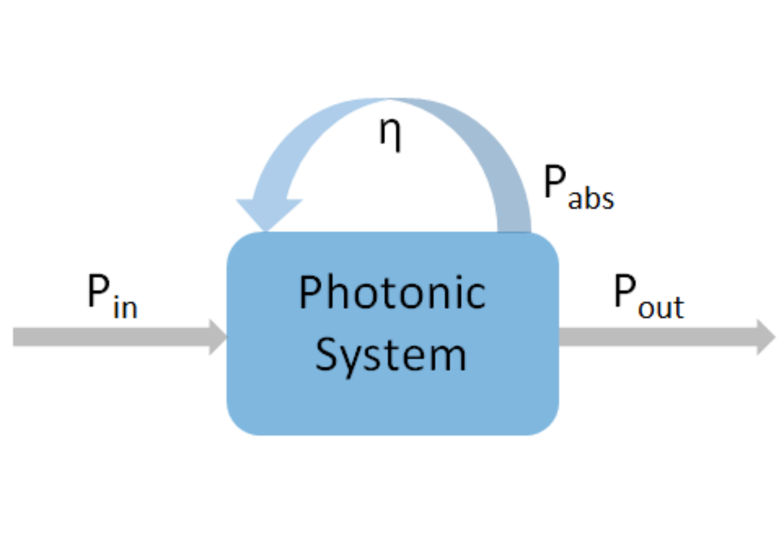


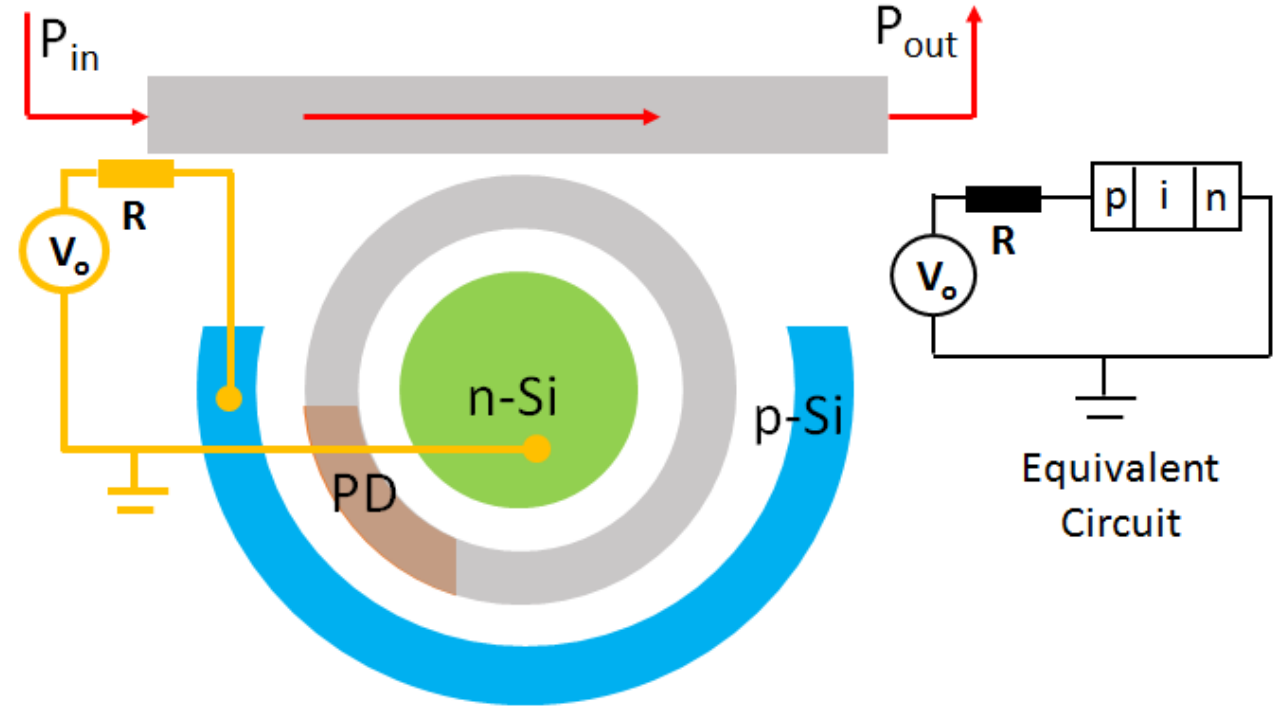
PCM integrated Silicon Photonic Switch for neural network

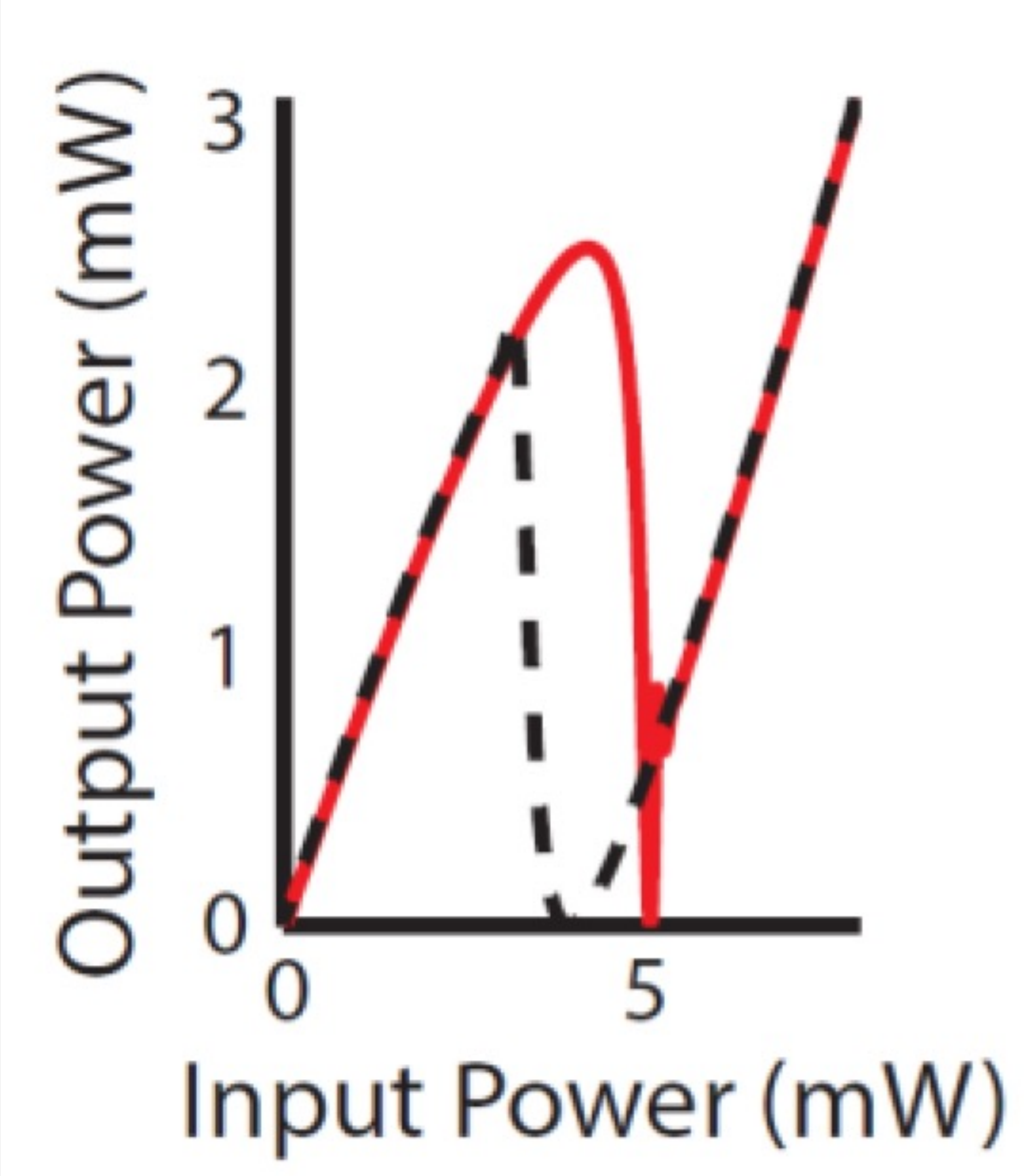




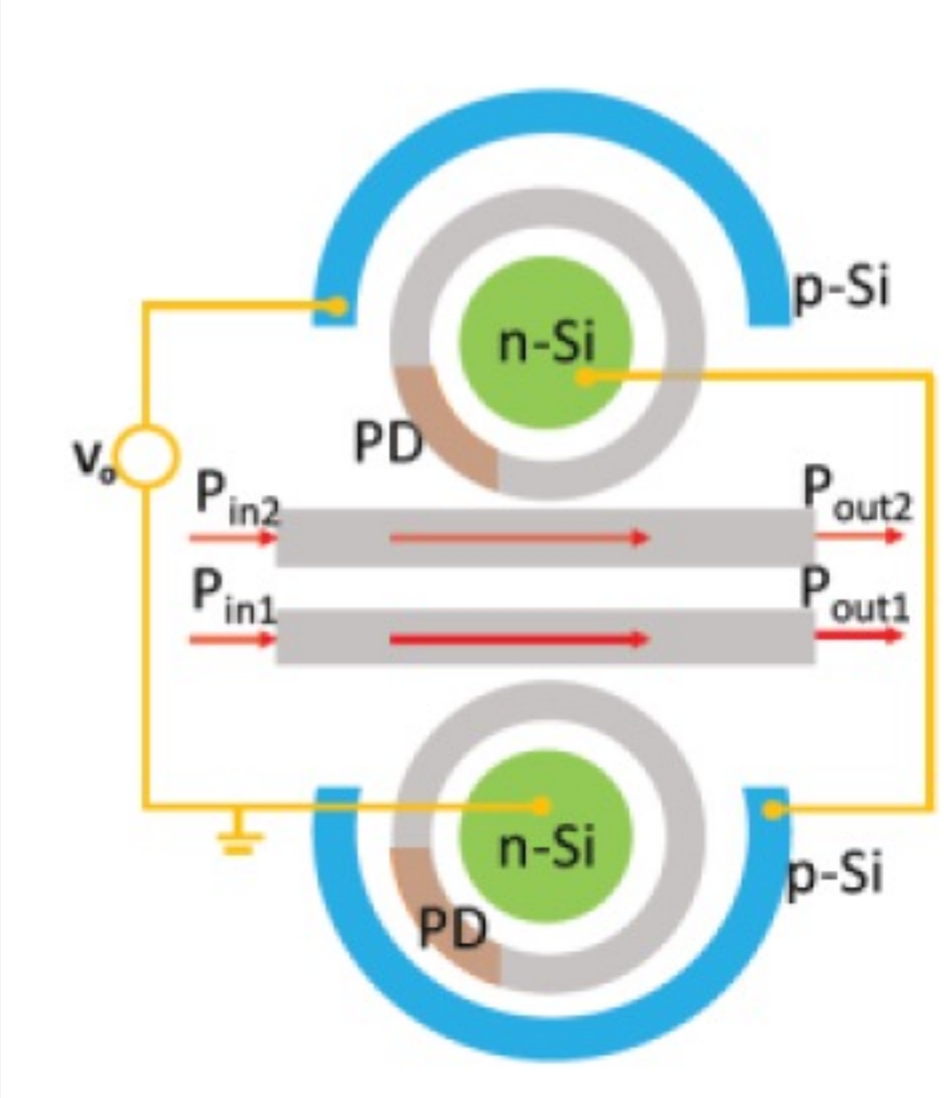
Nonlinear activation function: Self-electro-optic effect

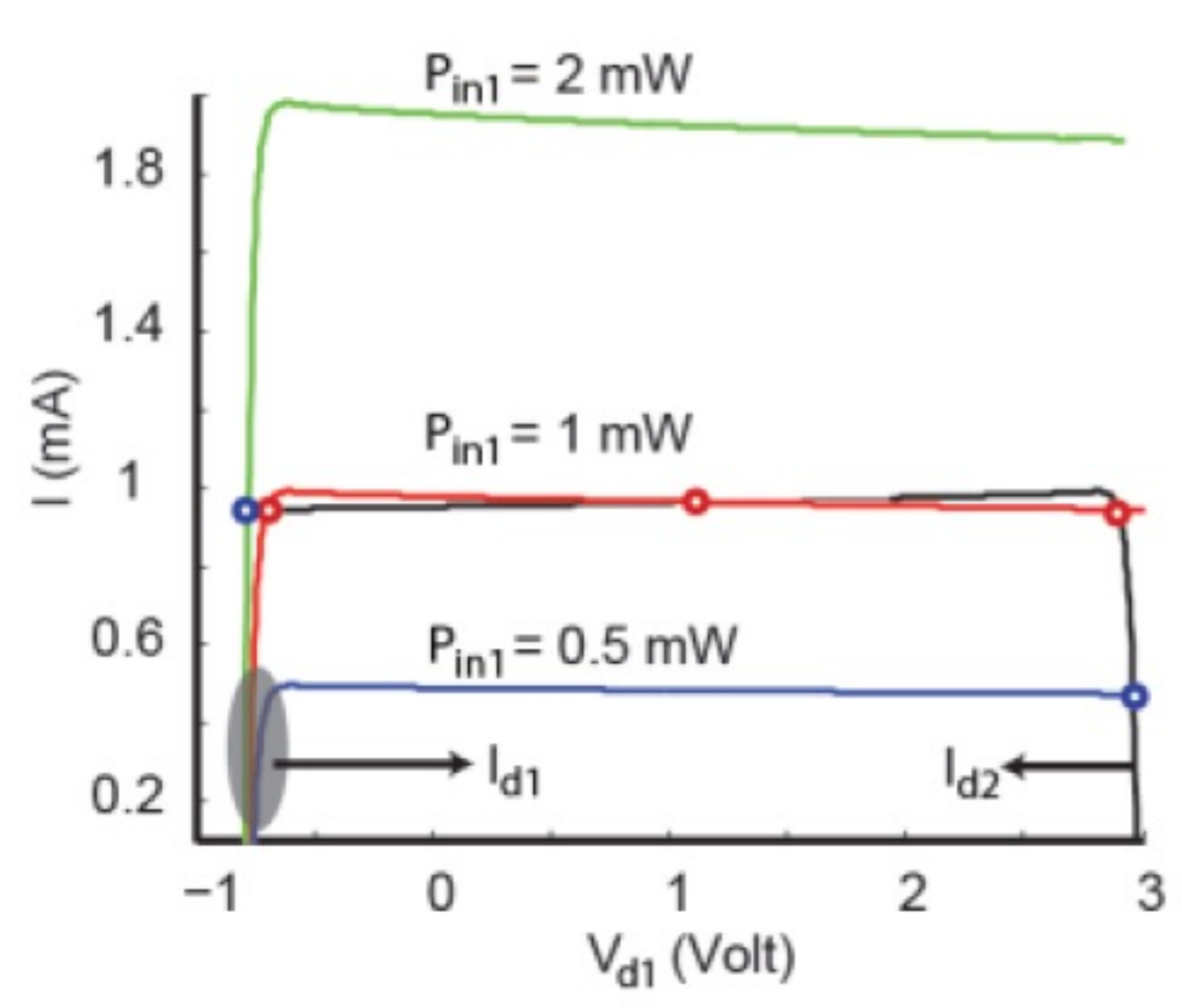






Symmetric self-electro-optic device





Majumdar et al., Optics Letter, 2014

Is integrated photonics the way to go?

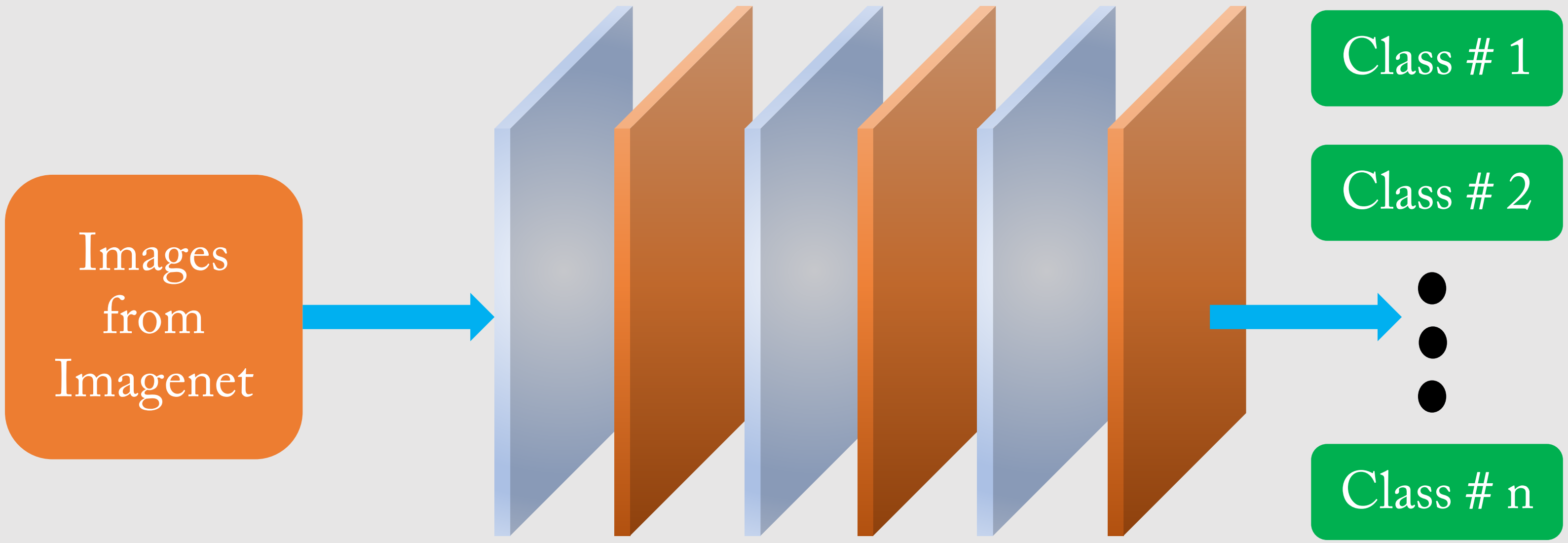
Pros:

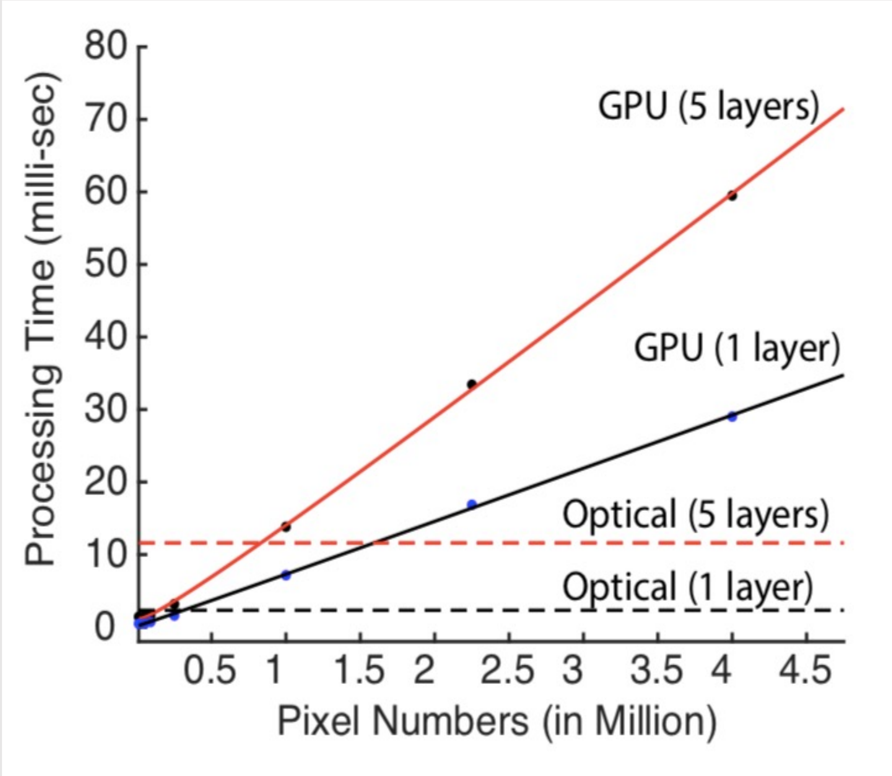
- Long travel path and resonant structures: reconfigurability and nonlinearity
- On-chip, compact footprint
- Alignment can be performed during lithography with sub-wavelength resolution

Cons:

- Scalability will be an issue: number of waveguides will be same as number of input data points ($N \sim 1000$)
- Number of MZI or switches ($N^2 \sim 10^6$)
- Resonant structures can require significant power and control circuits to stabilize: a serious problem for WDM
- Reconfigurability and nonlinearity still very power hungry
- May not be suitable to capture signal which are already in optical domain (generally free space)

Can we do deep network?



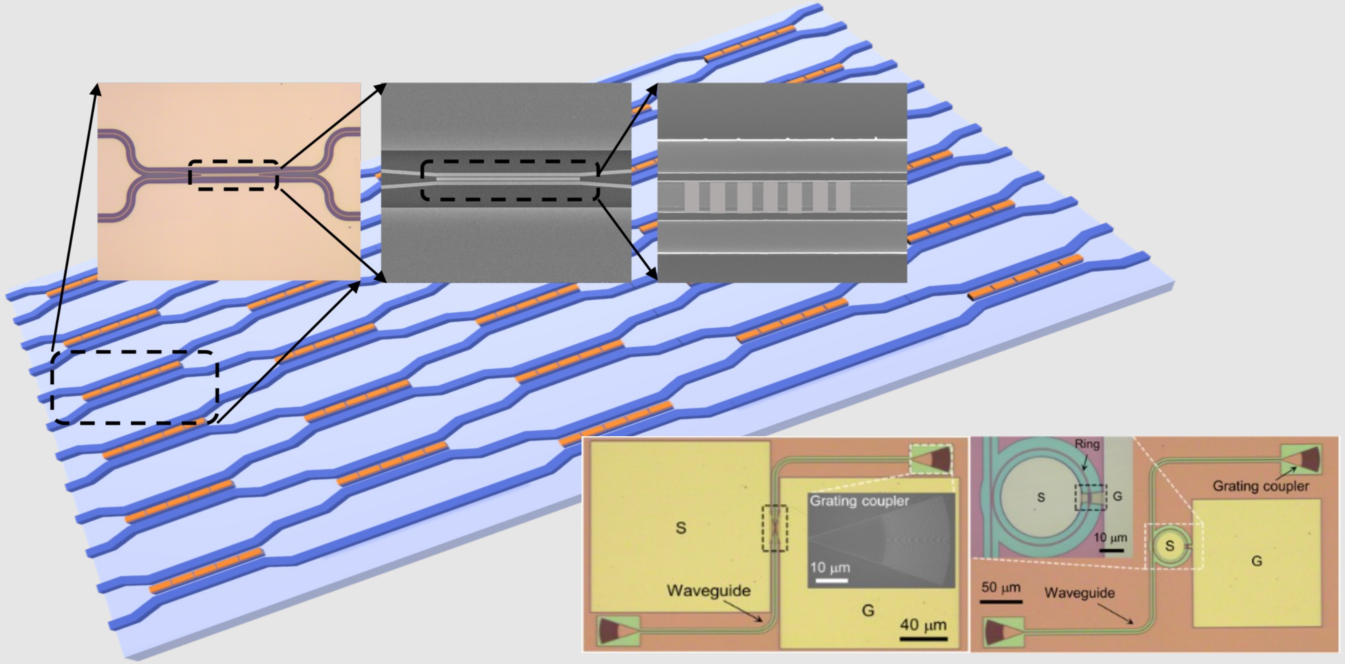


Colburn, Applied Optics, 2019

- Hybrid approach: Each signal transduction consumes energy and add latency
- All optical approach: how do we regenerate signal as it propagates?

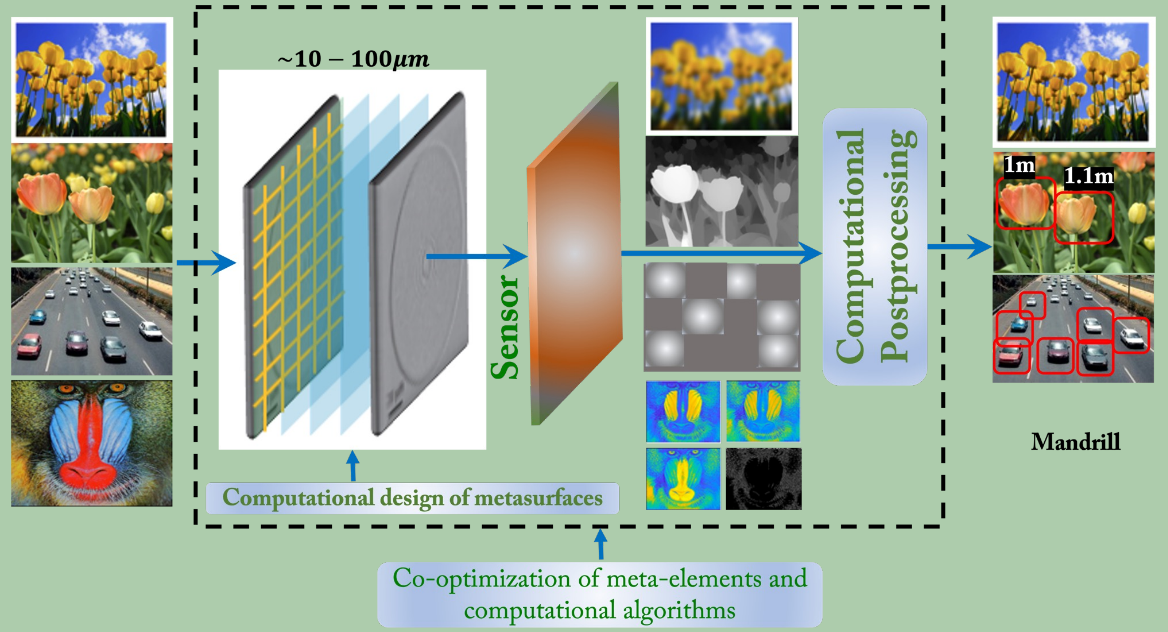
Hybrid integrated photonics for VMM and nonlinear activation

Majumdar et al., Optics Letter, 2014
Zheng et al., Optical Material Express, 2018
Zheng et al., ACS Photonics, 2019
Zheng et al., Advanced Materials 2020
Chen et al., ACS Photonics 2022

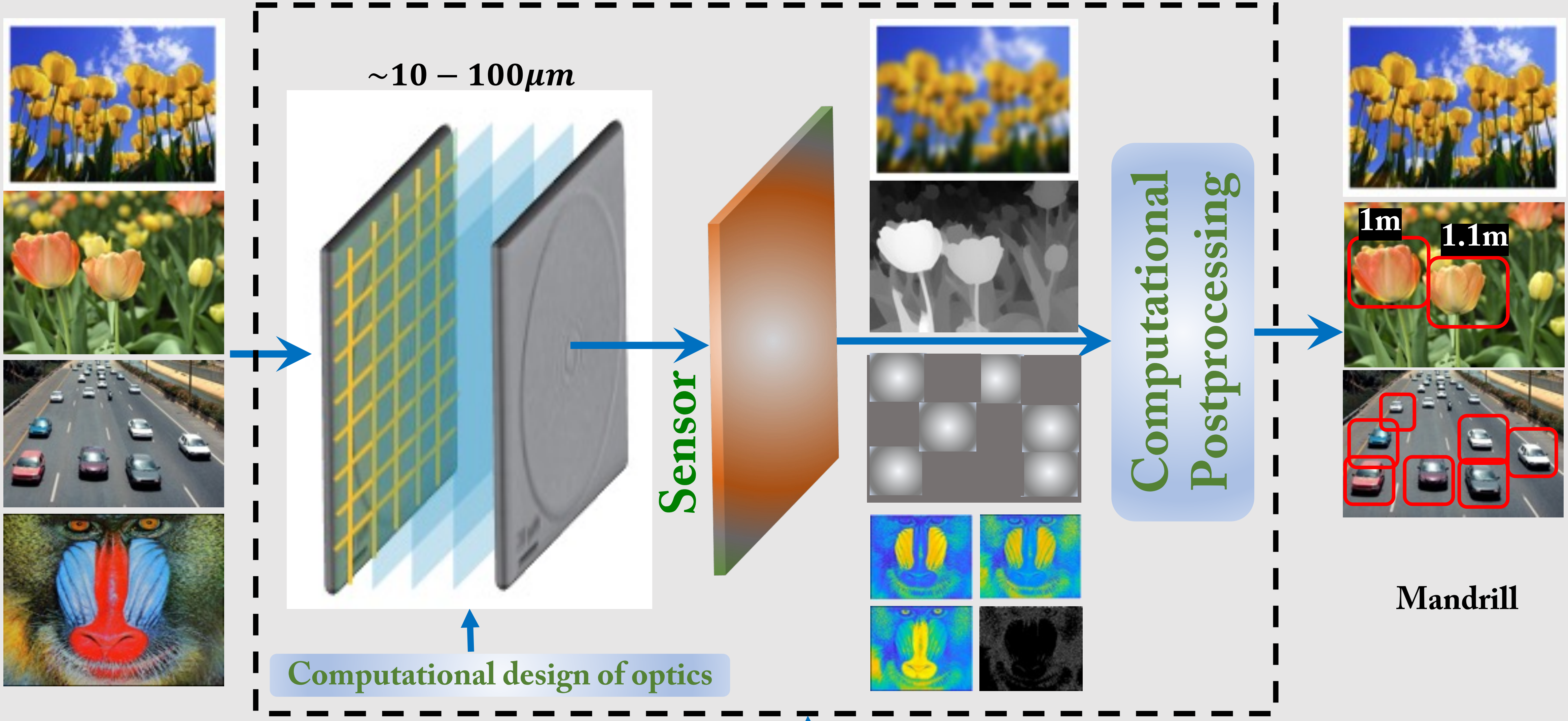


Meta-optical information processing

Colburn et al., Science Advances, 2018
Colburn et al., ACS Photonics, 2019
Zhan et al., Applied Optics, 2018
Zhan et al., Science Advances, 2019
Zhelyeznyakov et al, Optics Communication, 2020
Ryou et al., PRA, 2020
Colburn et al., Applied Optics, 2019
Tseng et al., Nature Communications 2021



Reduce Computational Complexity using Free-space Optics

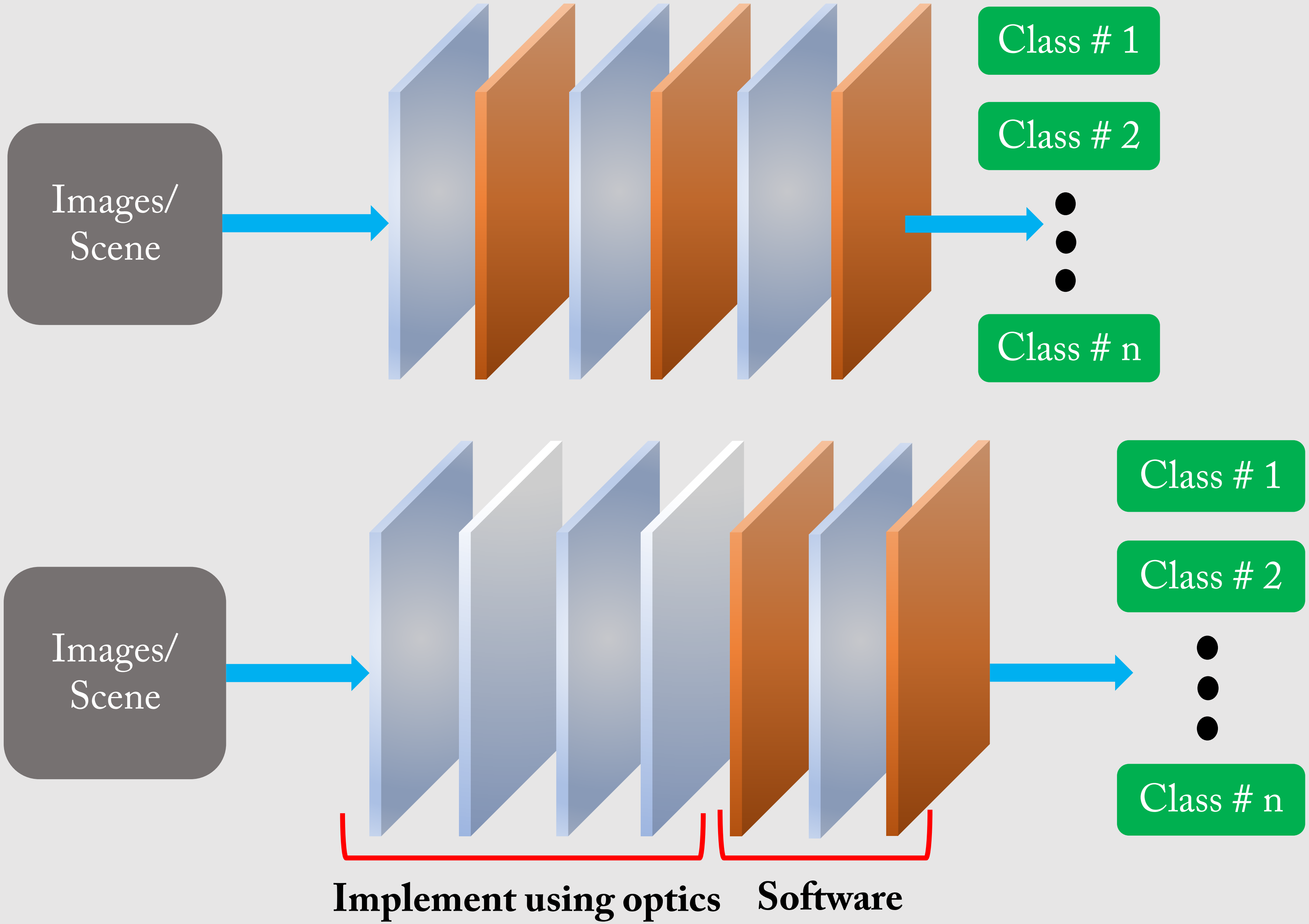


Co-optimization of optics and computational algorithms

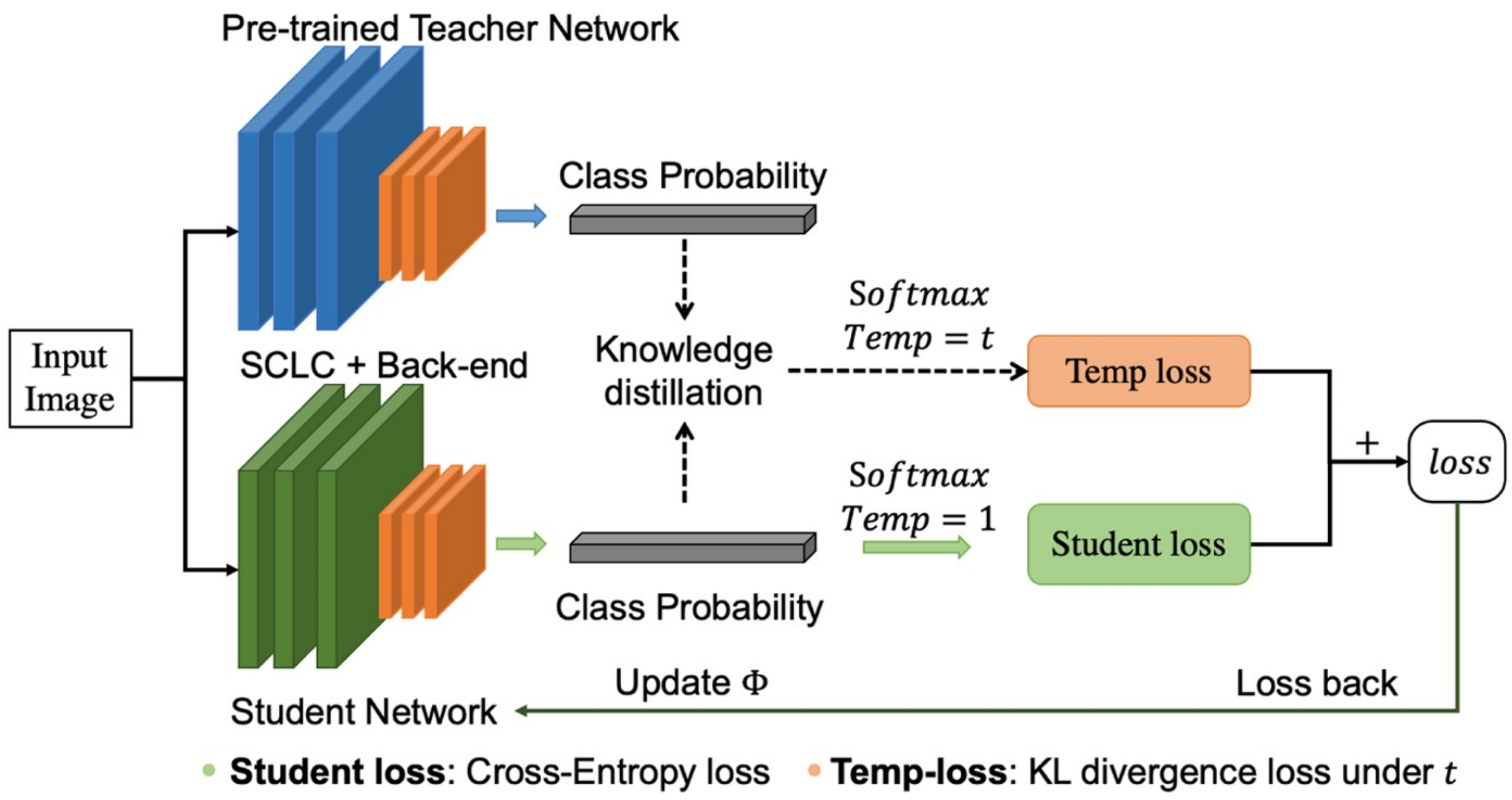
Can we also simplify optics using computing?

See: Stork and Robinson, Applied Optics Vol. 47, Issue 10, pp. B64-B75 (2008)
Matic and Goodman, Journal of the Optical Society of America A Vol. 6, Issue 3, pp. 428-440 (1989)

Rethinking DNN architecture



Knowledge distillation to circumvent nonlinear activation: Spectral CNN Linear Counterpart (SCLC)



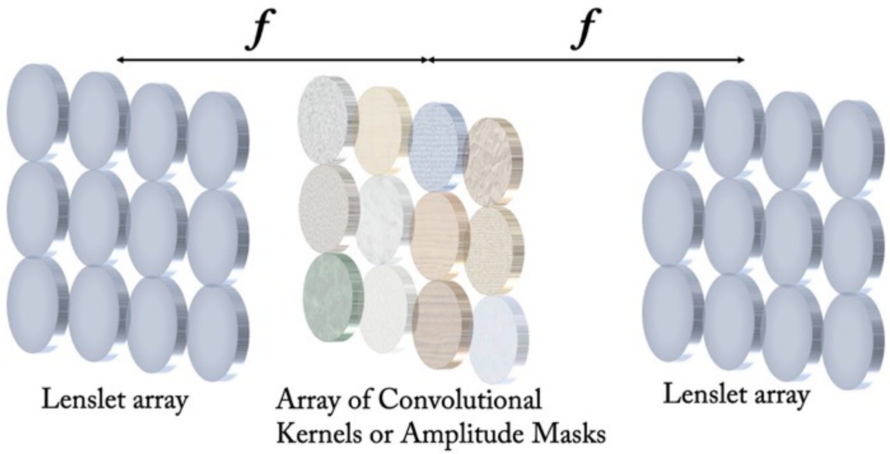
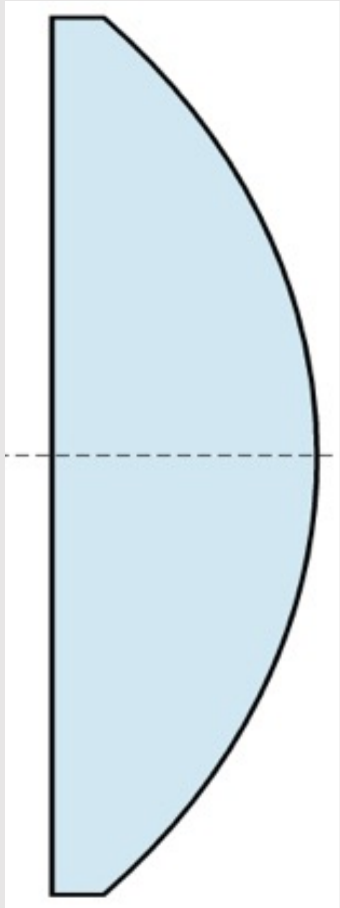


Table 4. Ablation Studies of Pooling Components, SCLC, Back End, and KD Training

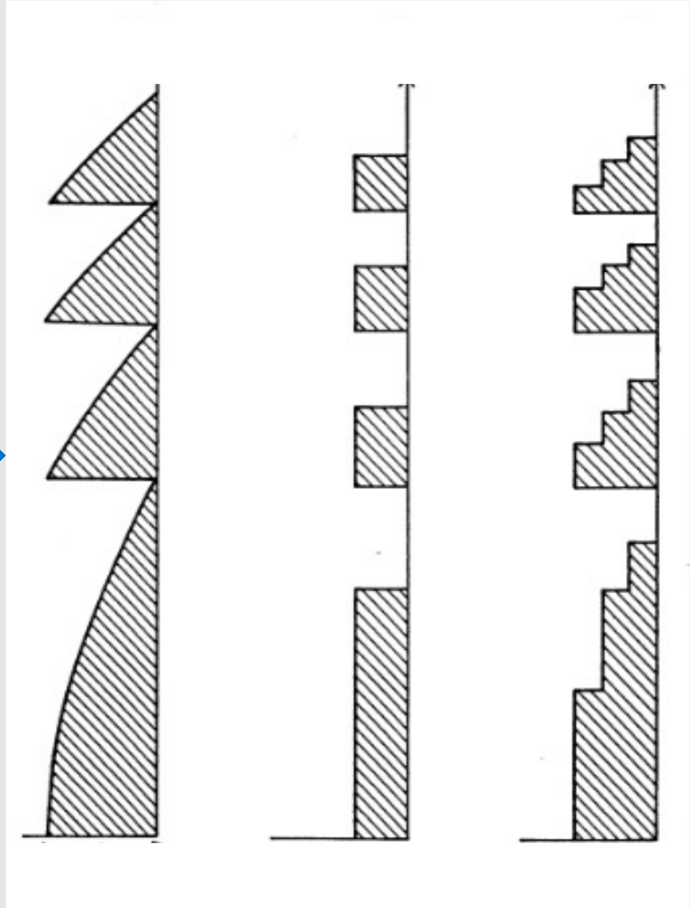
Structure	Accuracy
Max pooling	68.41%
Spectral pooling	70.12% (+1.71%)
Back end only	41.40%
SCLC (front end) + back end	70.12% (+28.72%)
SCLC (front end) + back end + KD	81.40% (+11.28%)

Xiang et al., Applied Optics, 2022

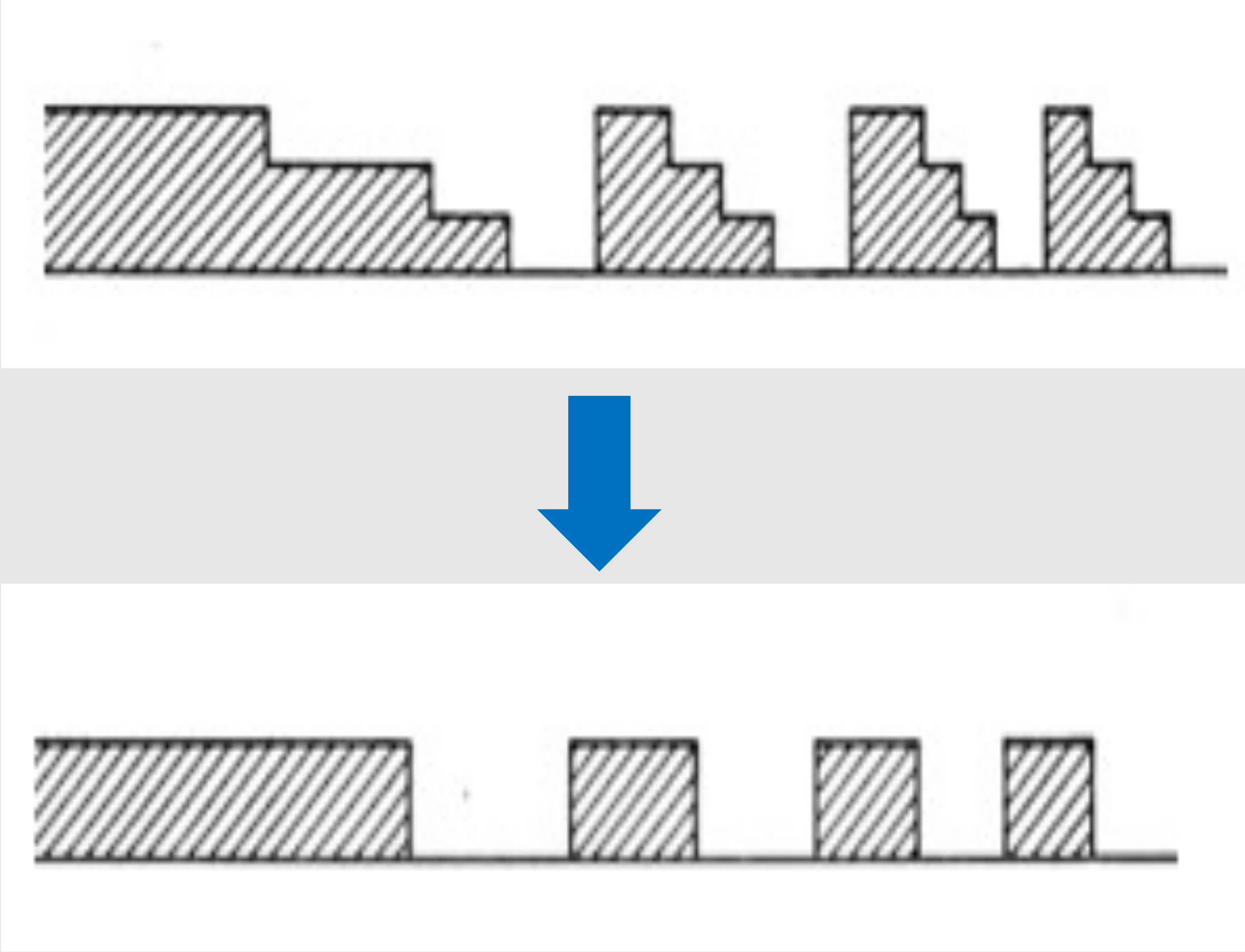
Dielectric Metasurface: sub-wavelength diffractive optics



Refractive

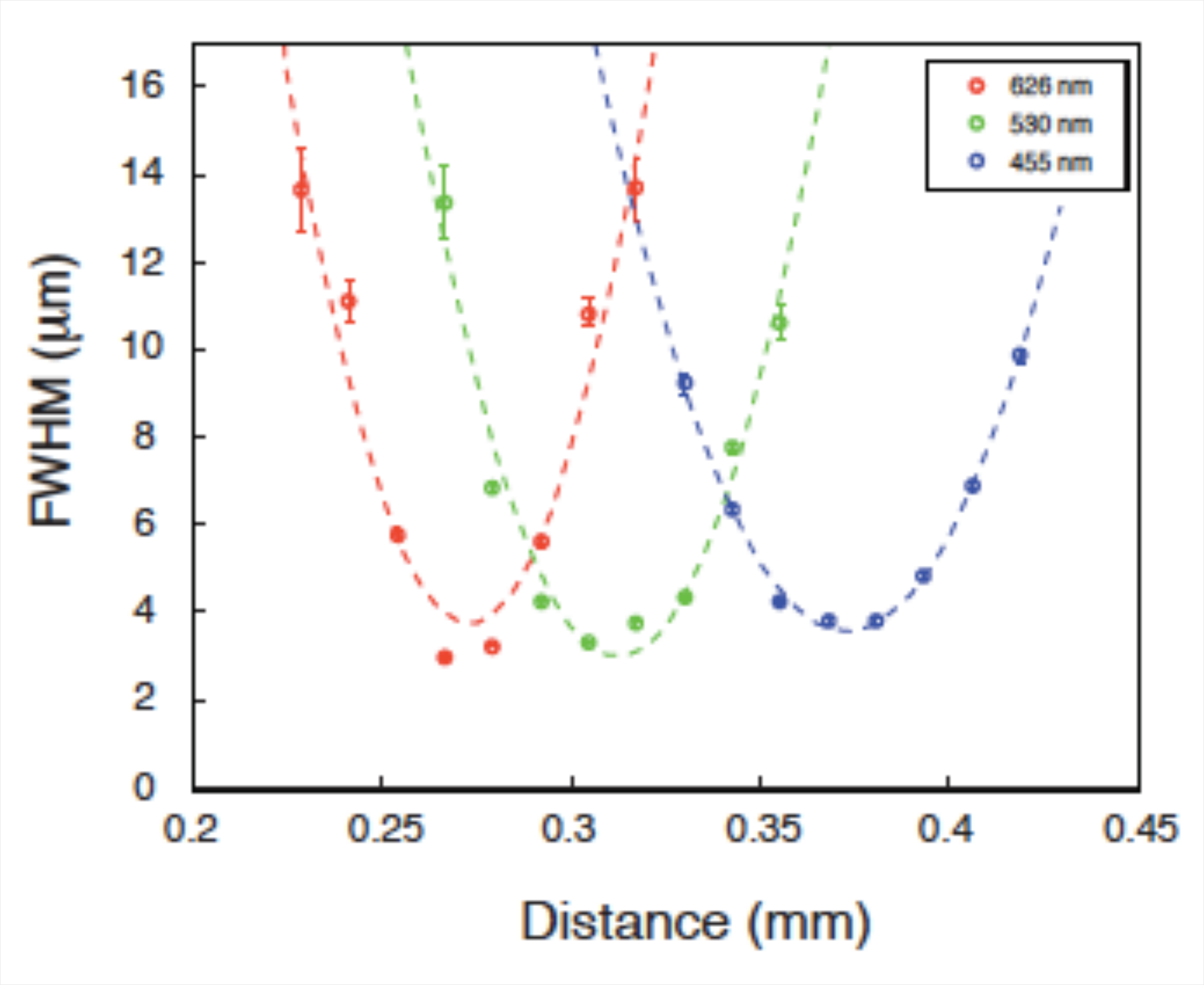


Multi-level diffractive optics

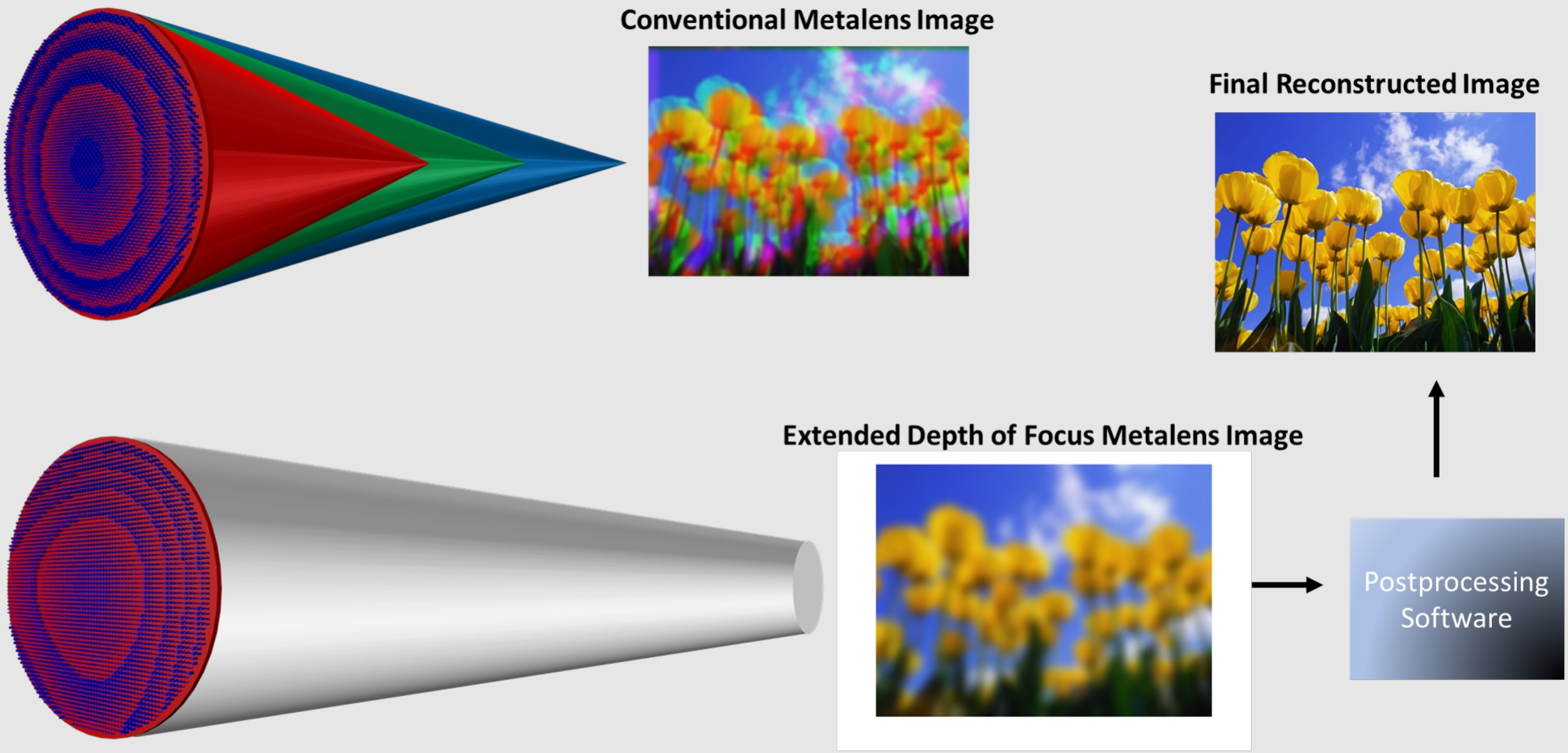


- Single stage lithography
- No higher order diffraction

Solving chromatic aberrations in metasurfaces



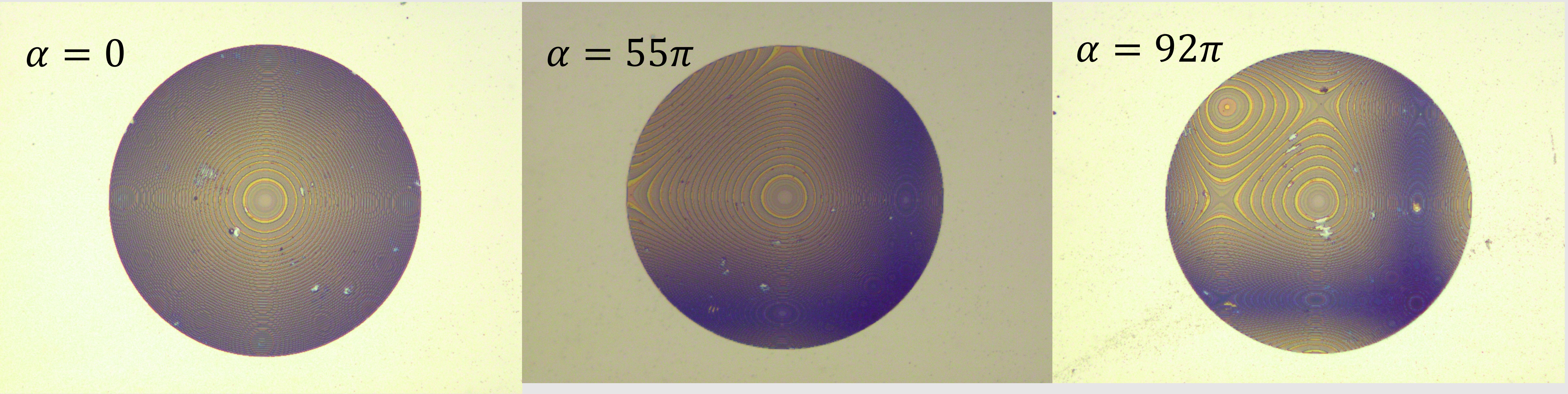
Novel metasurface + computational imaging



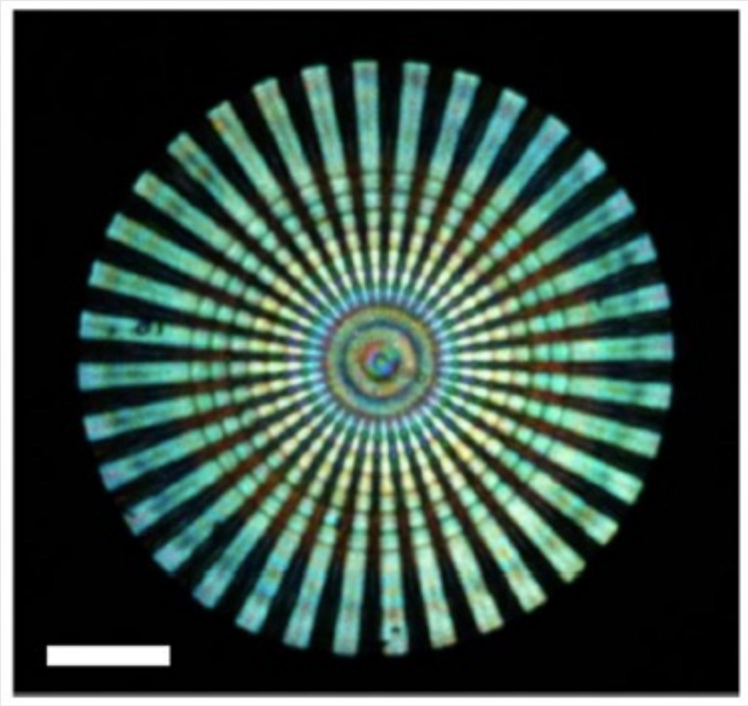
Cubic + Quadratic metasurface

$$\phi\,(x, y) = \frac{2\pi}{\lambda}\left(\sqrt{x^2 + y^2 + f^2} - f\right) + \frac{\alpha}{L^3}\,(x^3 + y^3)$$

α is a design parameter for the combined metasurface



Poor image quality: under broadband, ambient illumination

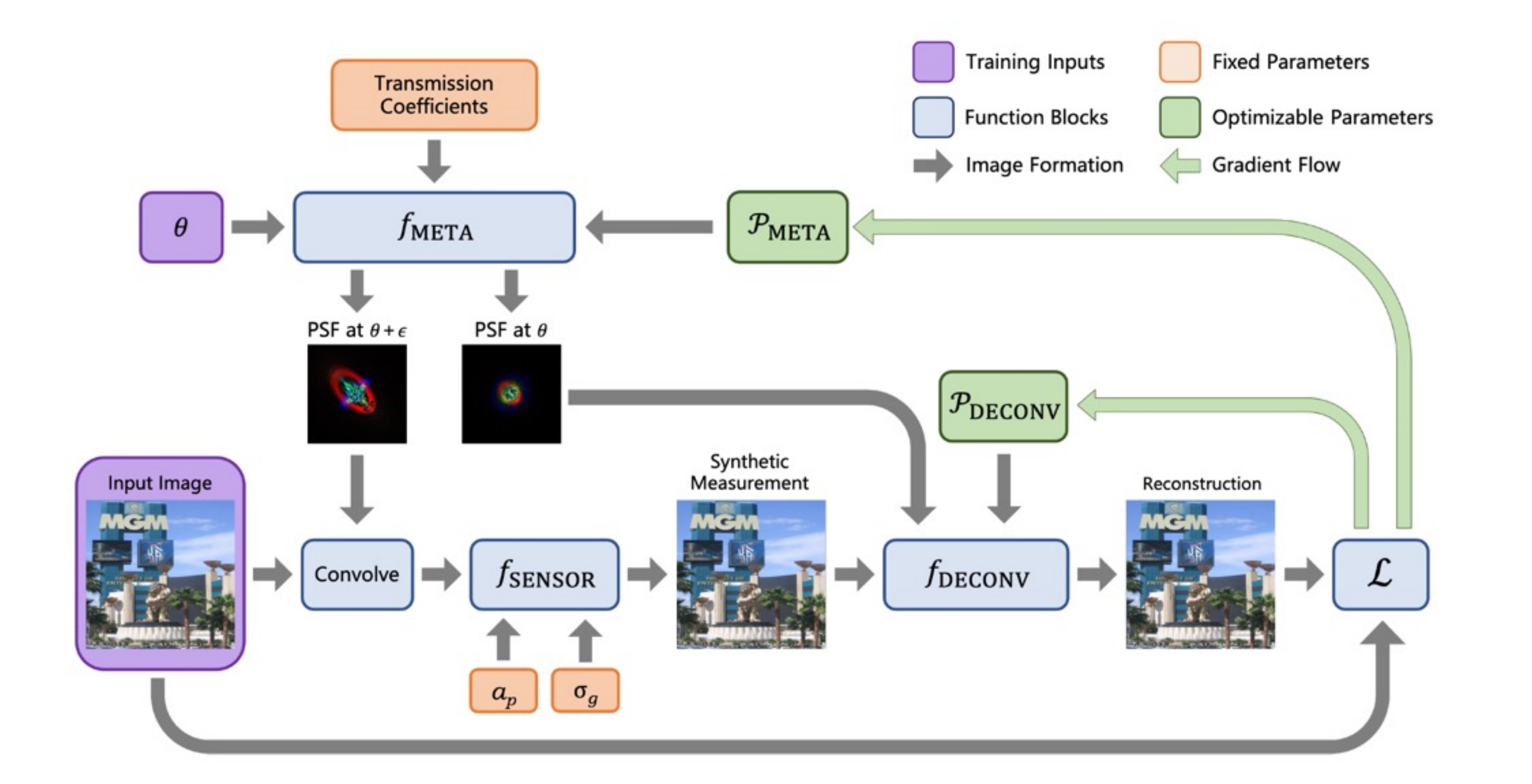


Capasso Group

Din Ping Tsai Group

Majumdar Group

Design strategy

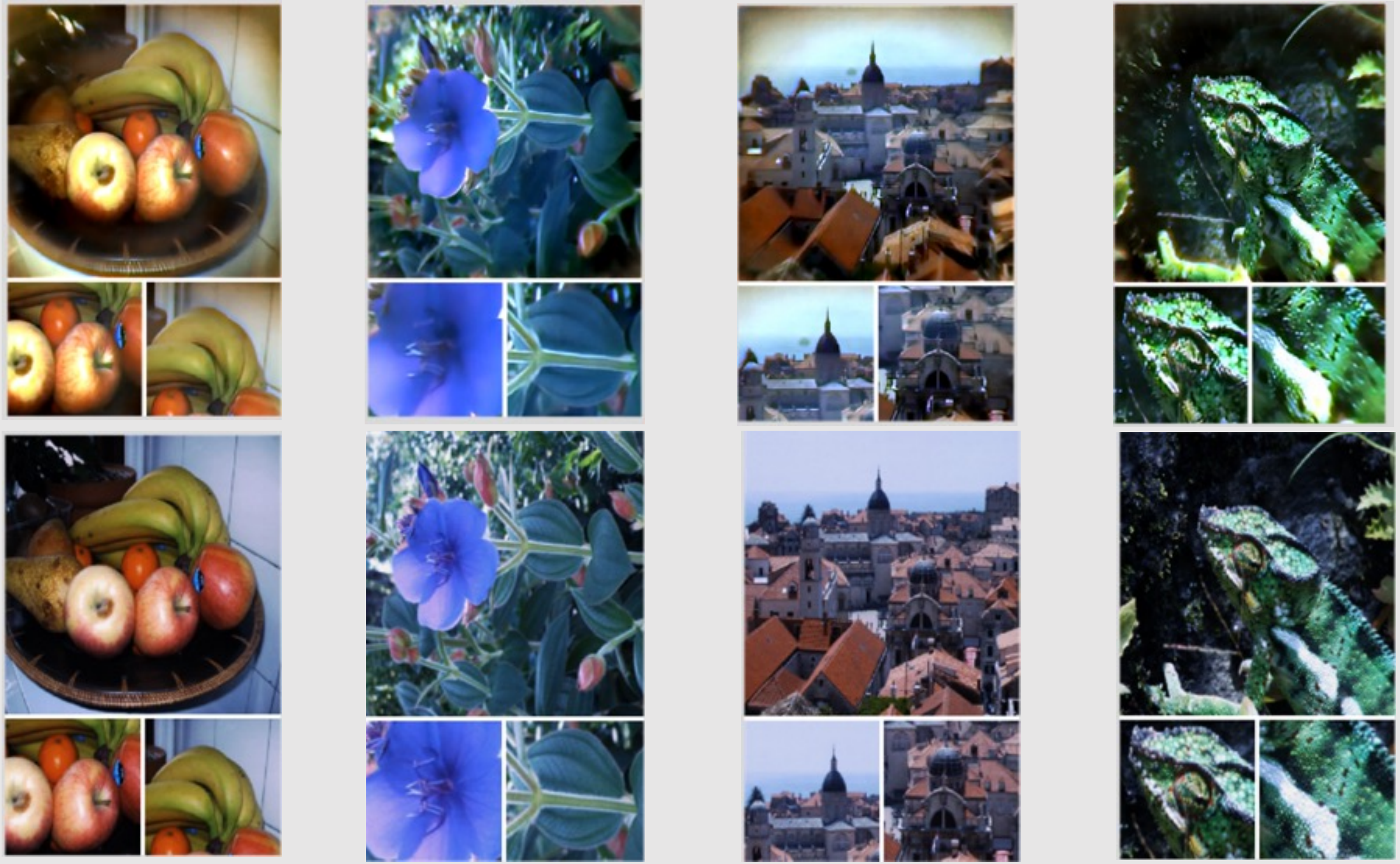


The computational backend uses neural network to train the parameters for the deconvolution algorithm.

High quality imaging: probably "good enough" quality?

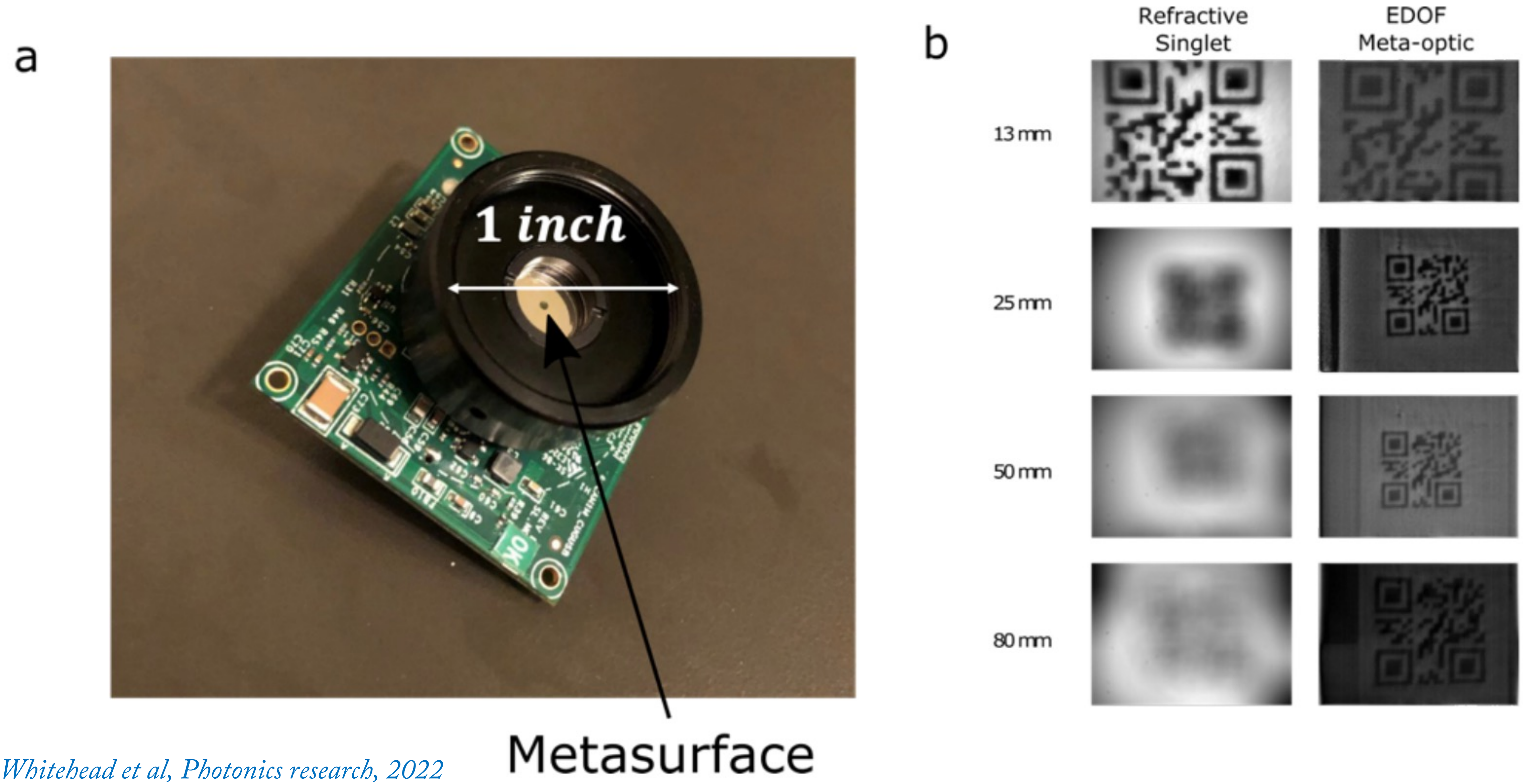
End-to-end designed meta-optics

Compound refractive lens consisting of 6 lenses



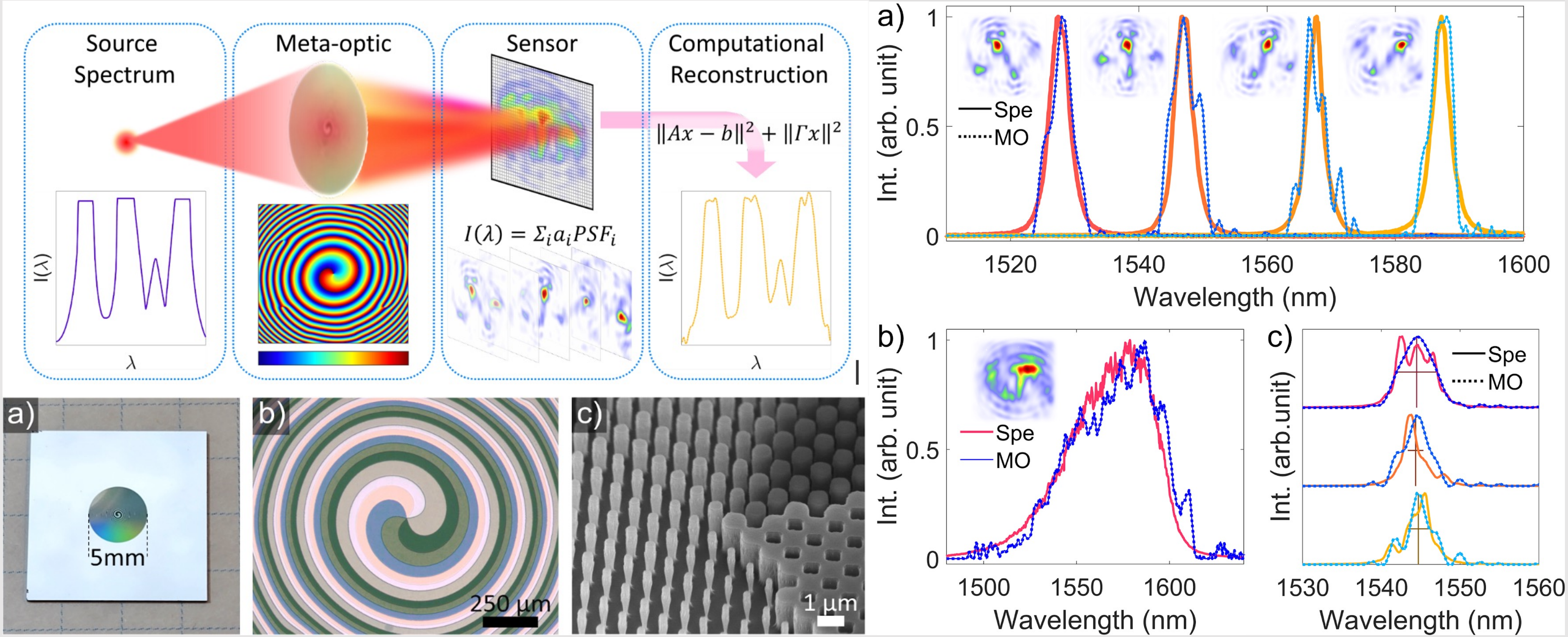
Comparable image quality is captured using a sensor with a volume 55,0000 times smaller.
500 μm aperture, f/2 lens, Field of View: 40^o, latency: 36ms
Can be scaled to 1 inch, f/1, Field of View: 30^o with latency of ~10ms

Varifocal functionality via static meta-optics and computational imaging

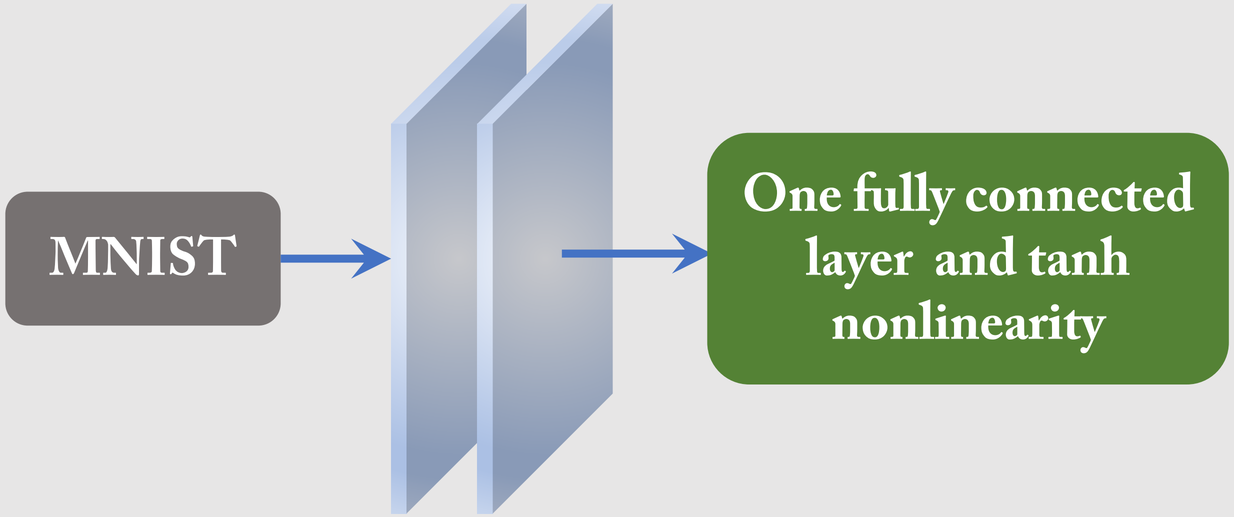


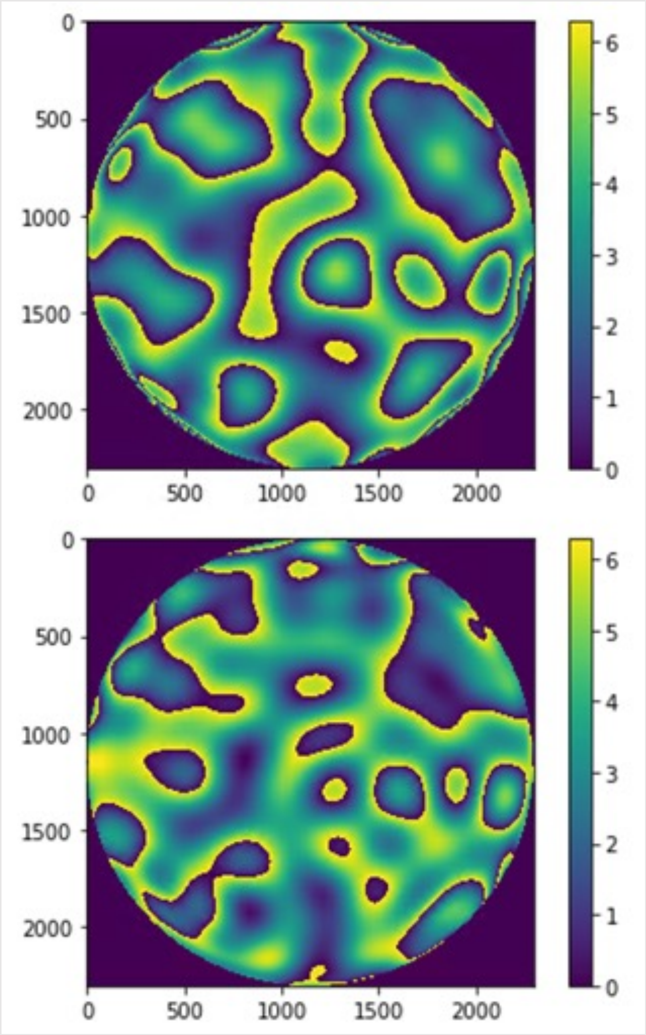
Whitehead et al, Photonics research, 2022

Computational Spectroscopy



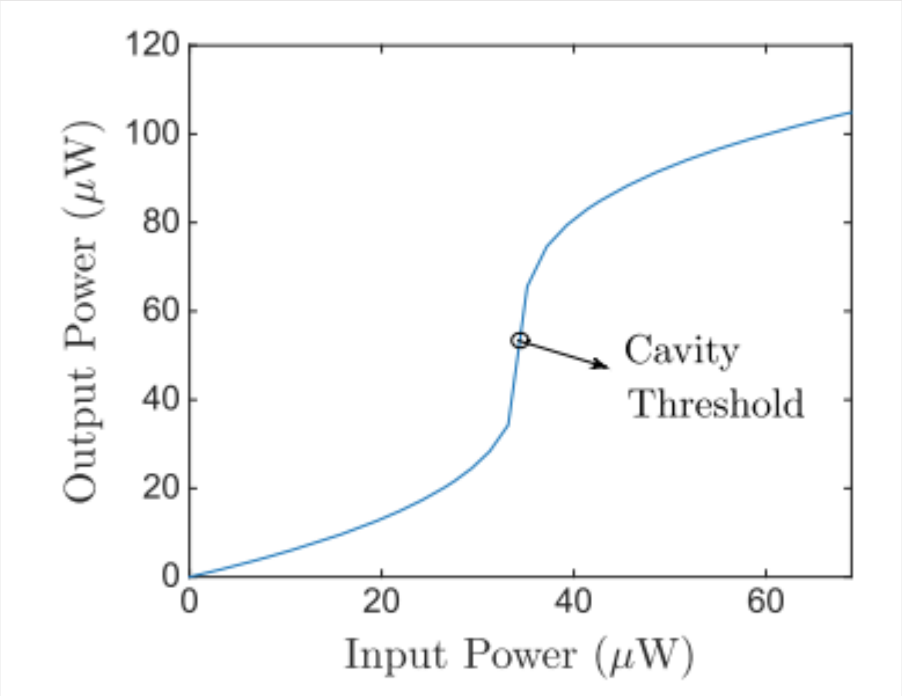
Object detection with meta-optical frontend and computational backend



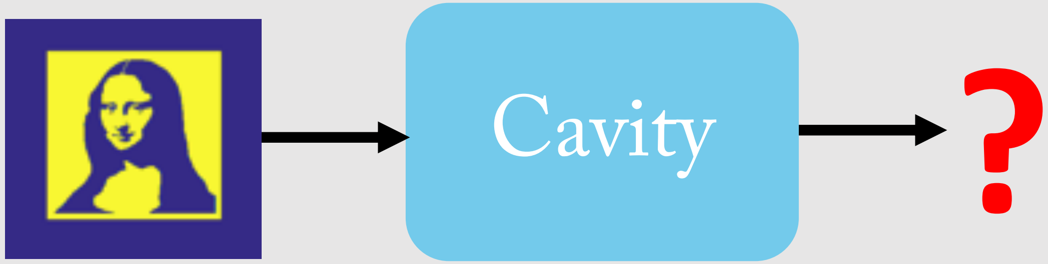


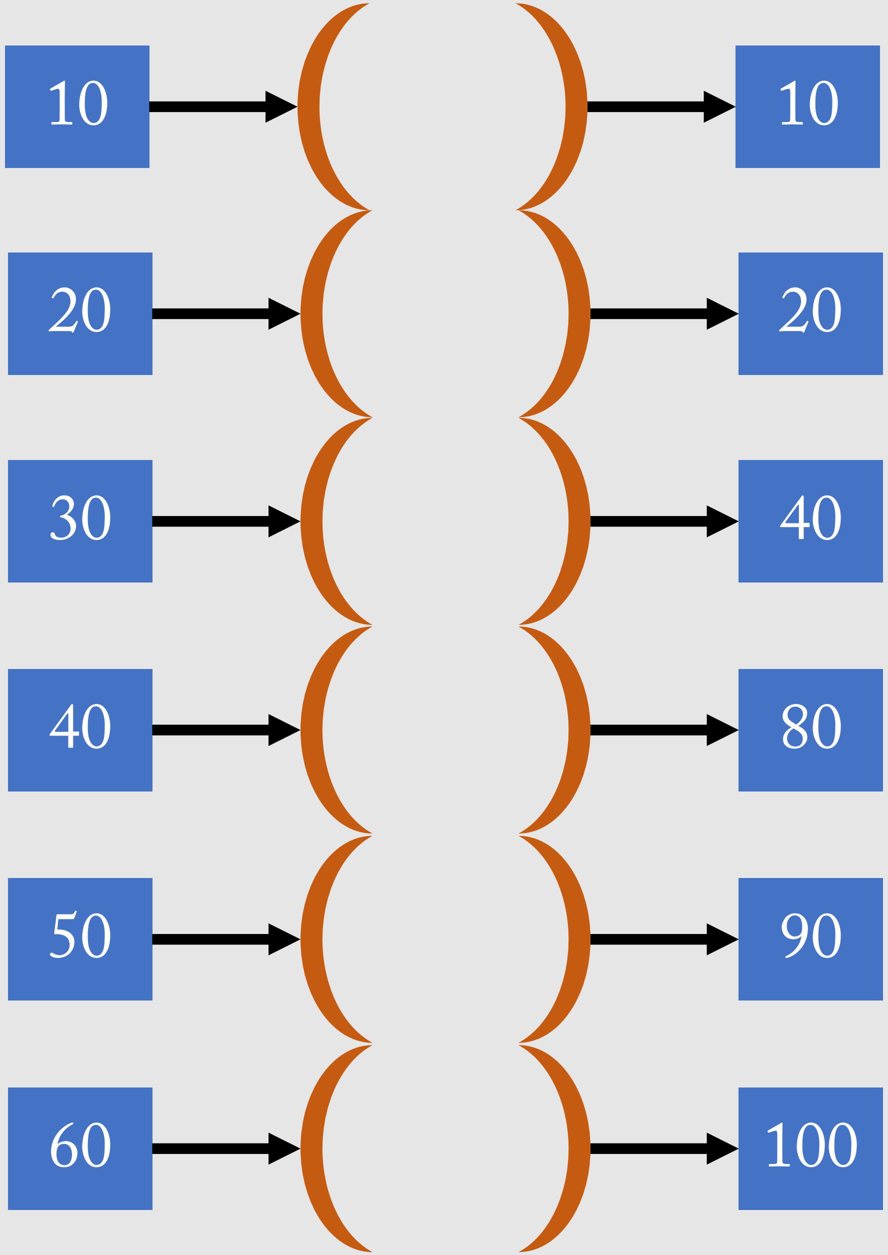
- Use incoherent light as the source
- High resolution input (1 million pixels) get reduced to 100 points that is fed to electronic layer
- Without meta-optical frontend (just electronic layer): 67% accuracy
- With meta-optical frontend : 95% accuracy

Need nonlinear processing of an image

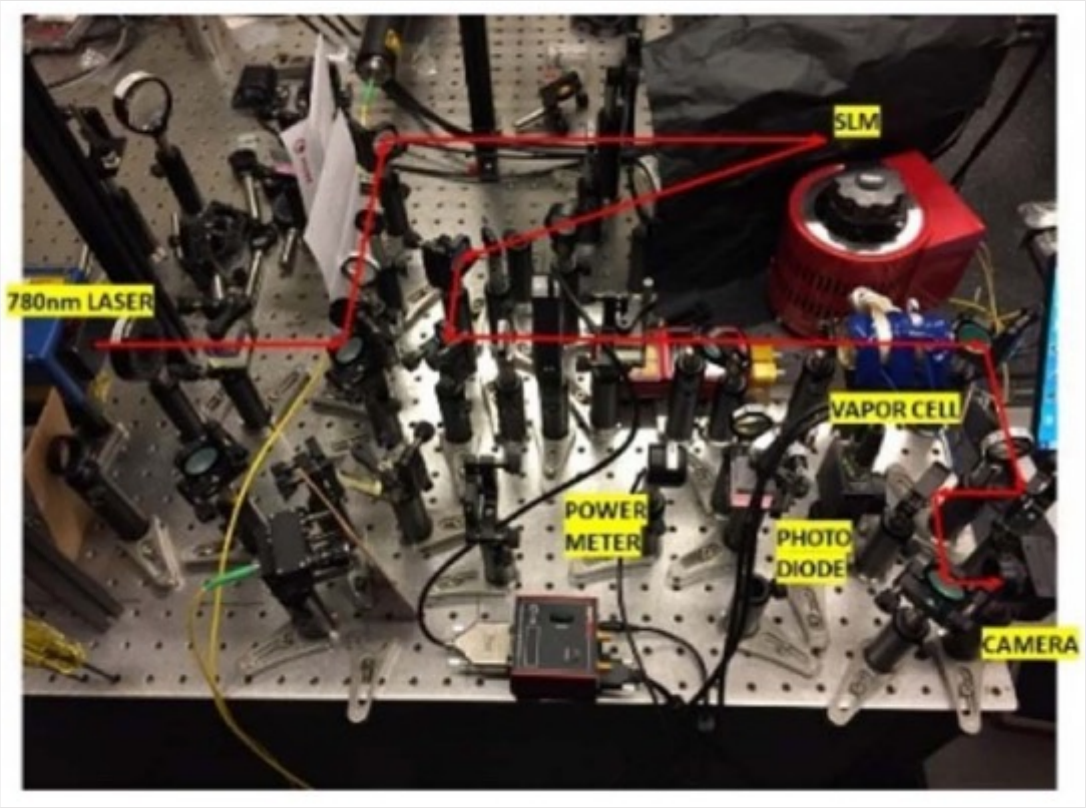


Majumdar Lab, Phys. Rev. Applied, 5, 054001, 2016





Nonlinear activation: slow but strong nonlinearity



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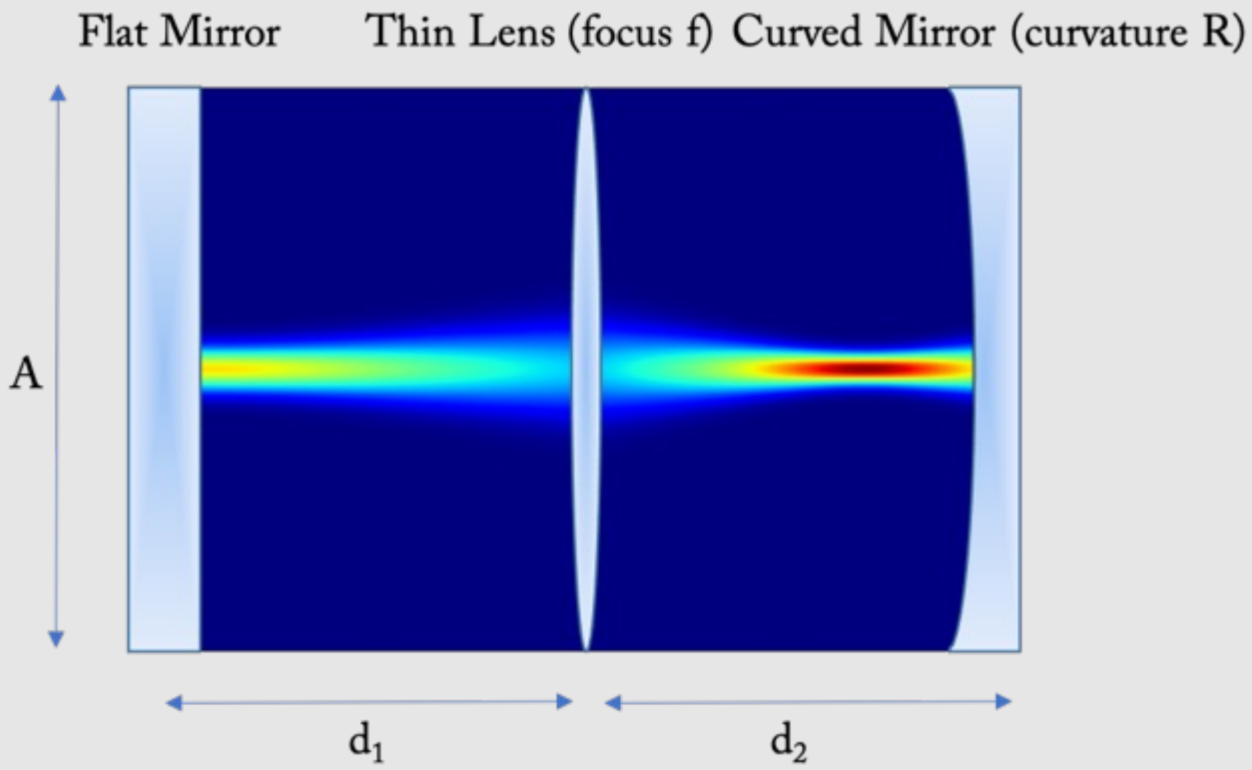
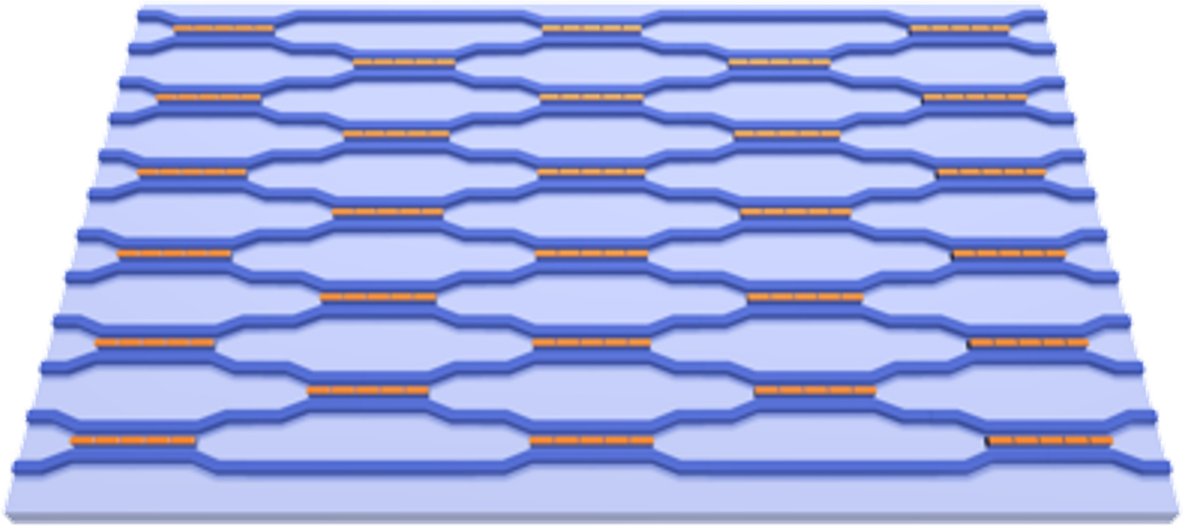


PHYSICAL REVIEW A 101, 013824 (2020)

- To exploit the parallelism of light we need to perform nonlinear operation in parallel
- Such parallel operation can provide large bit-rate, even with slow nonlinearity, like saturable absorption in thermal atoms.
- Can we exploit cavities that preserve the image integrity? Can we use flat-band in photonic structure?

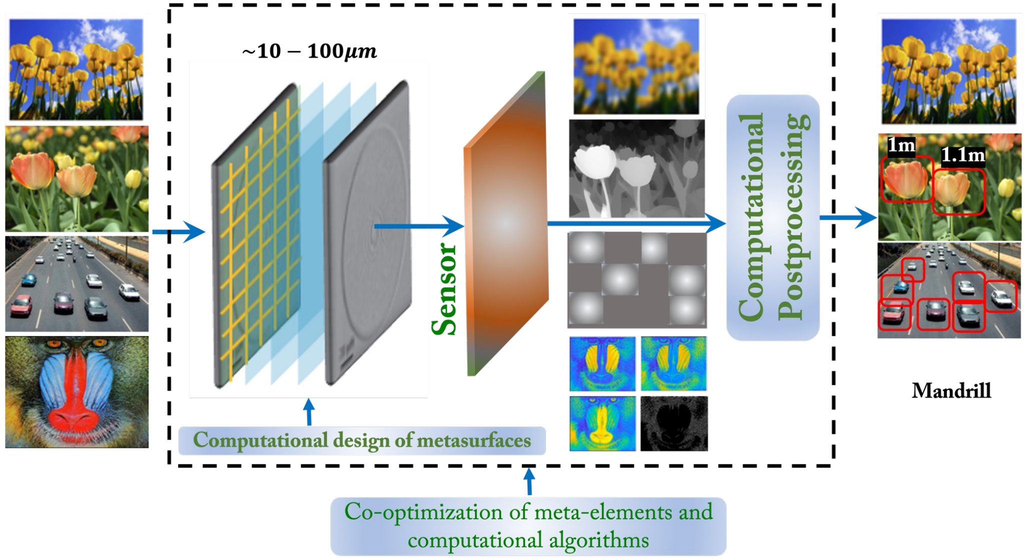
Summary

Integrated photonic based solution



- Phase-change material can significantly reduce the size and energy of the phase shifter.
- Self-electro-optic devices can provide optoelectronic nonlinearity.
- Scalability will remain a problem.
- Cascading is unclear.

Meta-optics-based optical computing



- **Object detection and classification using meta-optics and computational postprocessing.**
- **Post-processing can also mitigate fabrication error.**
- **Functionality can be improved with fast spatial light modulator and free-space nonlinearity.**

My take on Optical Information Processing: Game of Computing

Materials: Quantum Confined structures, 2D materials, Lithium Niobate

Devices: Ring resonator, photonic crystal, waveguide, grating, comb

Architecture: Free-space, WDM, Integrated photonics

Electronics

Software

Goal is not to build best optical computer, but rather to build one superior to its electrical implementation!! Need to remember history, focus on scalability, reliability, reconfigurability and nonlinearity.