Integrated nanophotonics for next-generation information science and sensing

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Lab: Nano-optoelectronic Integrated System Engineering (EEB-039)
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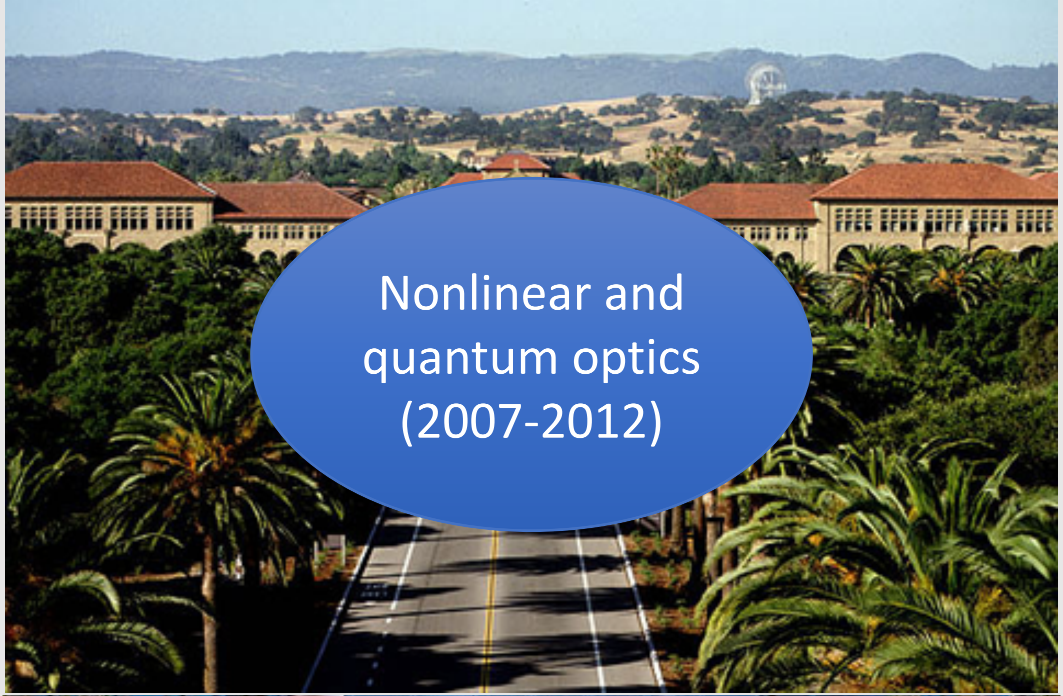
Graduate Courses: Applied Nanophotonics (EE539: Offering Fall)

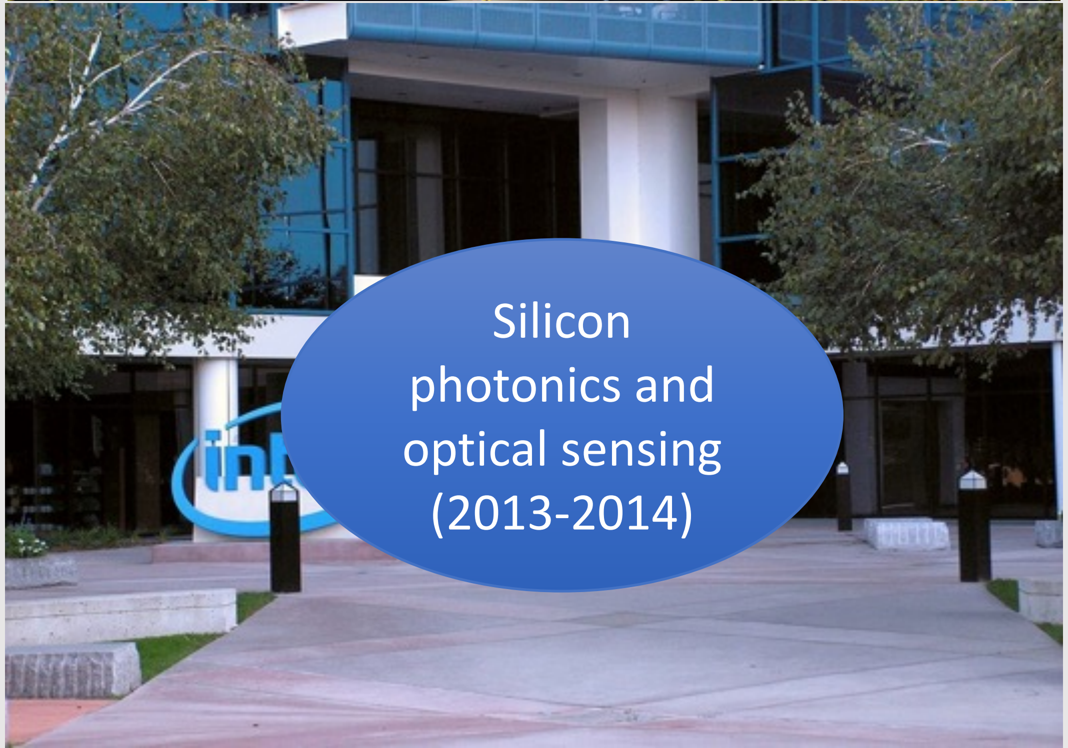
Undergraduate Course: Intro. To Nanotechnology (EE299: Offering Spring)

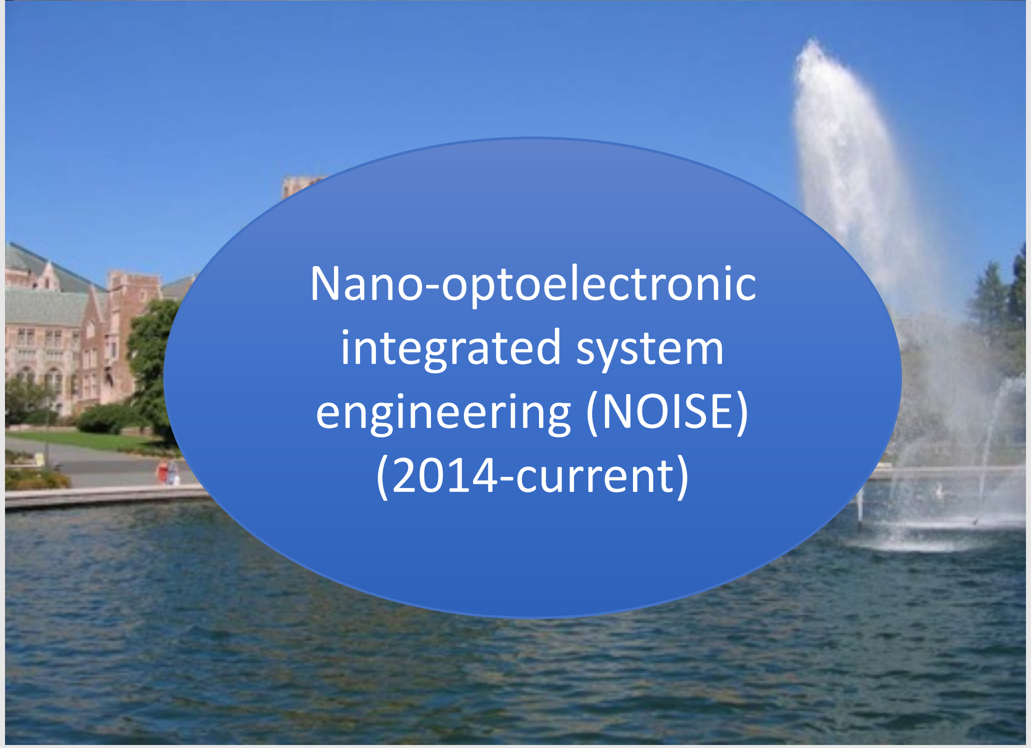
Undergraduate from India

Worked on Radio-frequency integrated circuits to make better cell-phone.
Did not know any quantum mechanics or solid-state physics.
Have very little exposure to electromagnetics (Transmission Line).


Nonlinear and quantum optics (2007-2012)

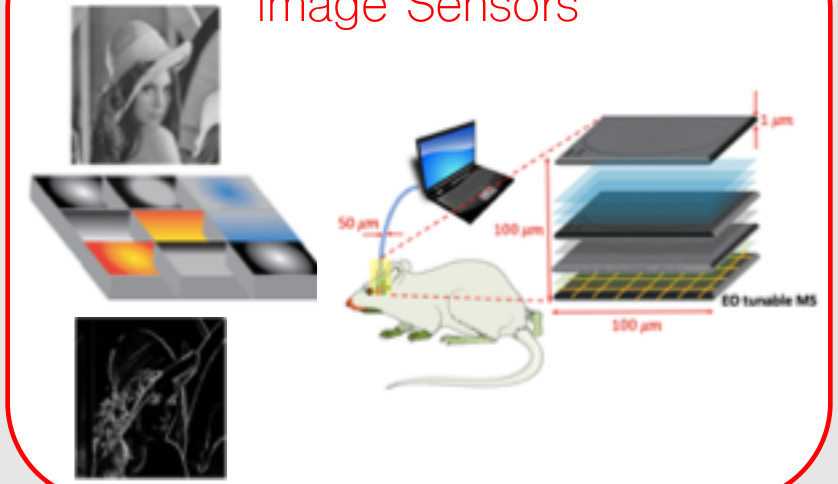

New materials: Monolayer material (2012-2013)


Silicon photonics and optical sensing (2013-2014)

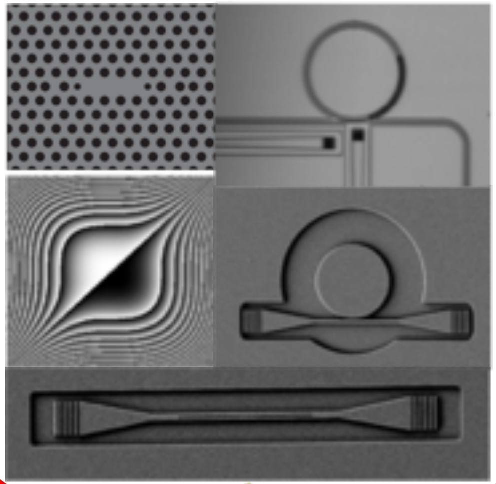

Nano-optoelectronic integrated system engineering (NOISE) (2014-current)

Nano-Optoelectronic Integrated System Engineering (NOISE) Lab
(Electrical Engineering + Physics)

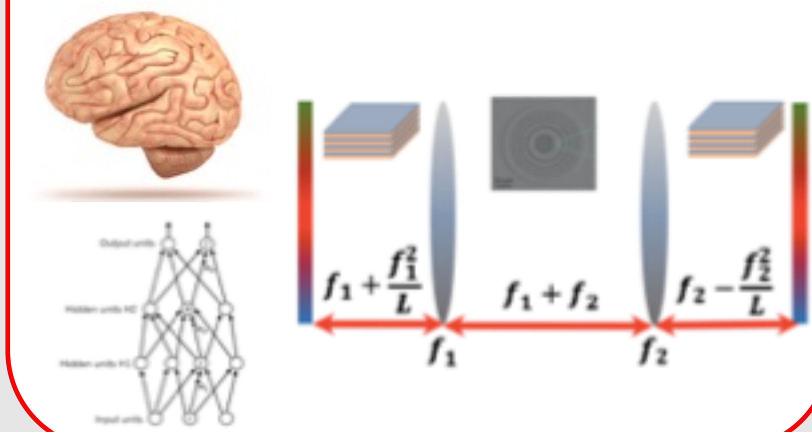
Nanophotonic Computational Image Sensors



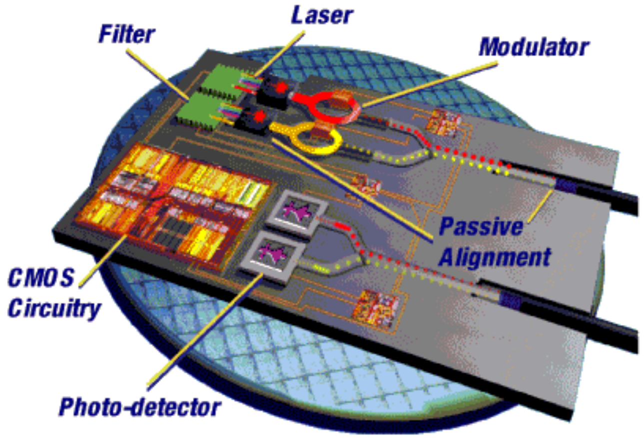
Light



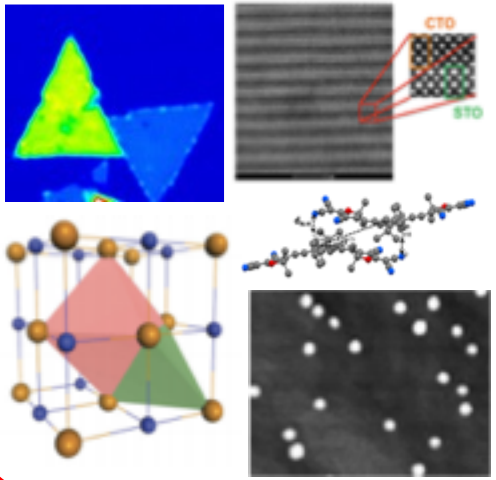
Nonlinear Image Processing and Monolithic Optical Neuron



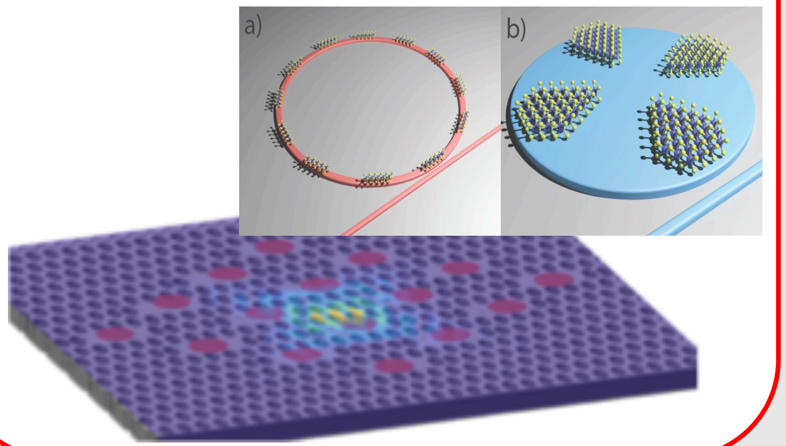
Hybrid Integrated Photonics



Matter

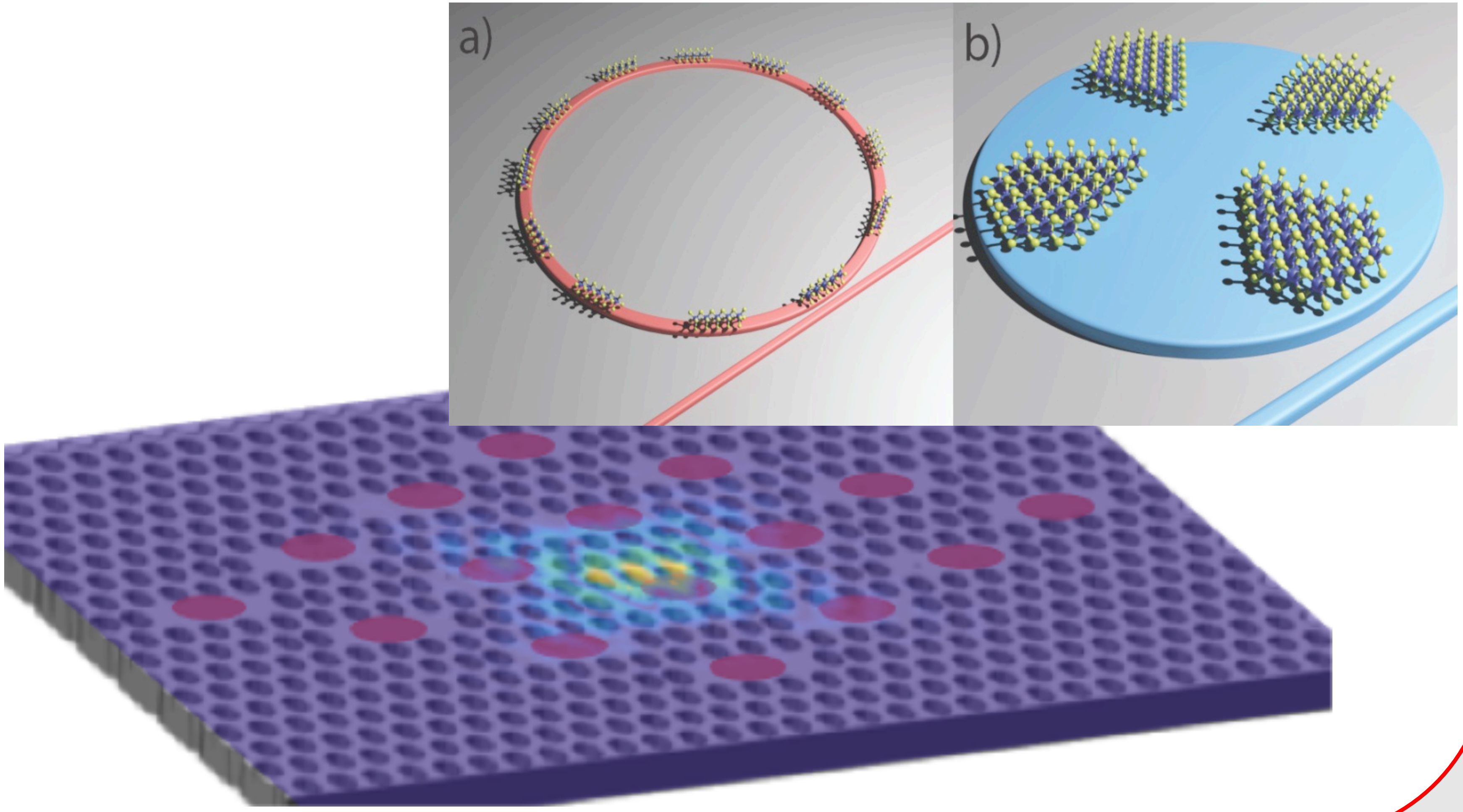


Quantum many-body simulation with photons

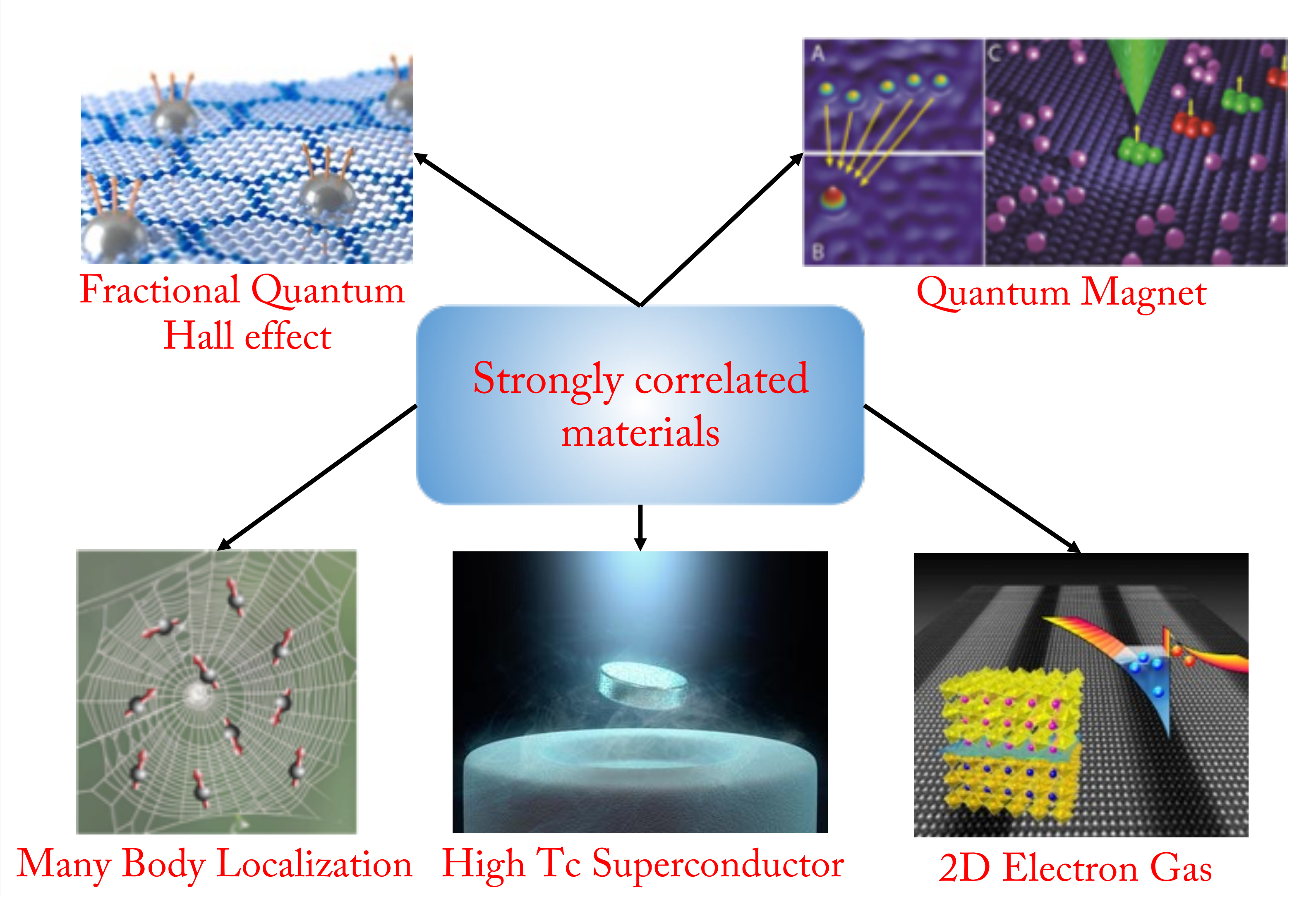


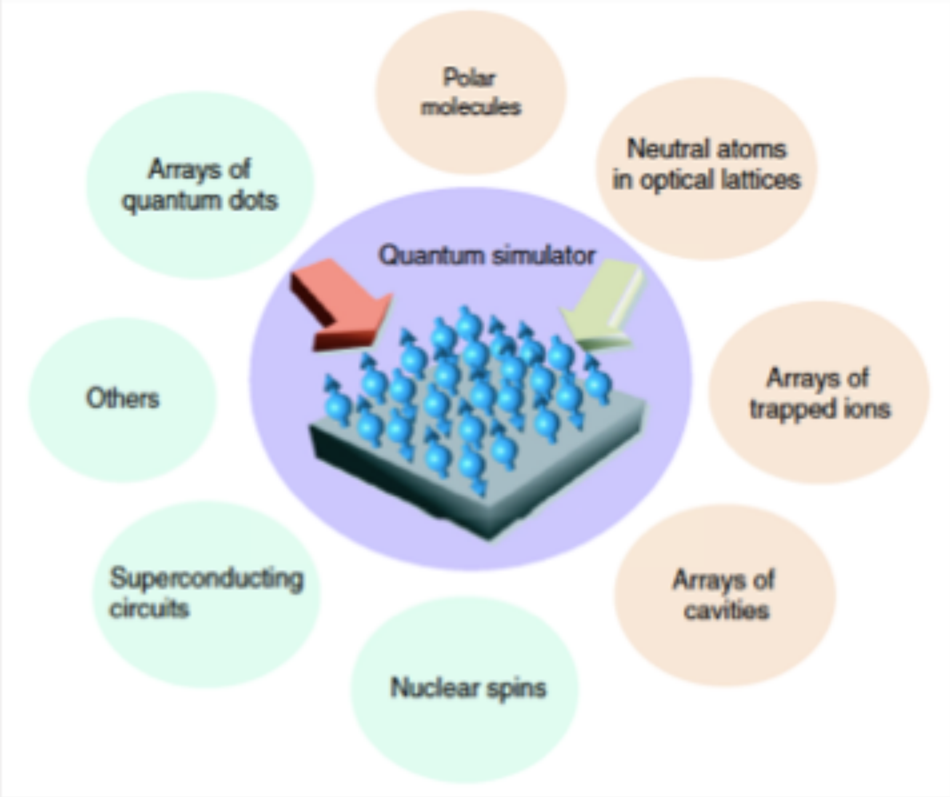
Sorger & Majumdar, Fundamental Scaling Laws in Nanophotonics, Scientific Reports 6, Article number: 37419, (2016).

Quantum many-body simulation with photons



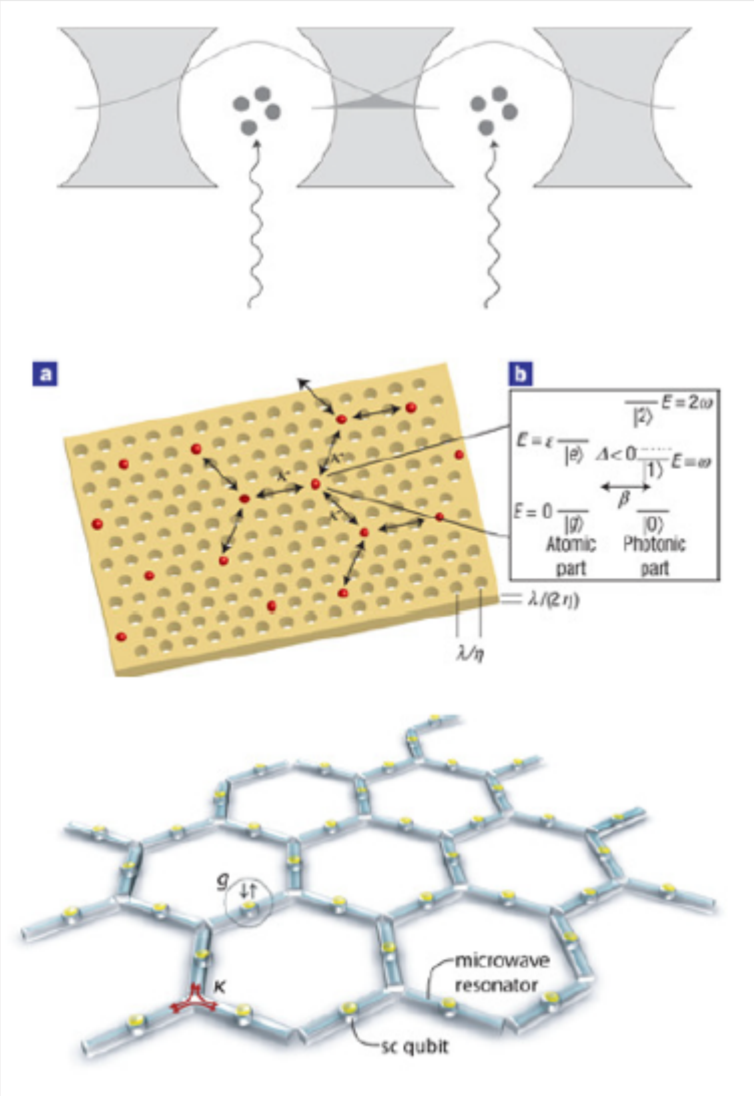
Non-equilibrium quantum many-body simulation



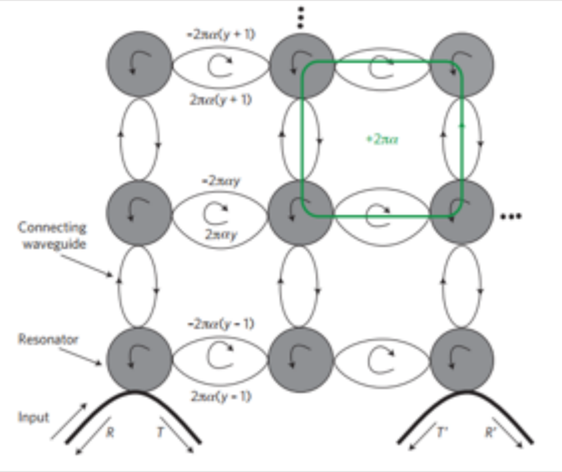


Quantum Simulation, Rev. Mod. Physics, Vol. 86, January–March 2014

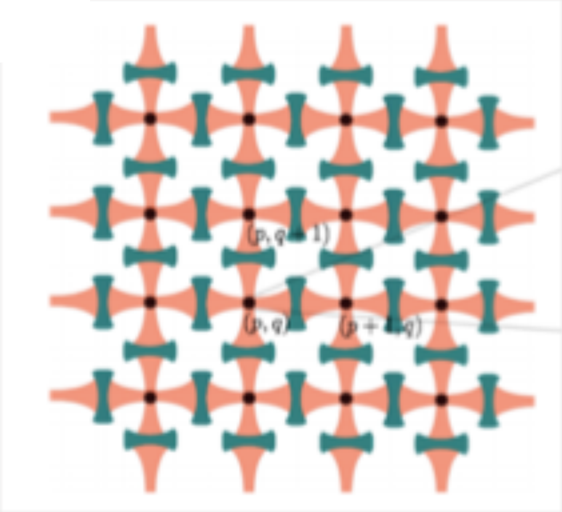
Quantum simulation with correlated light



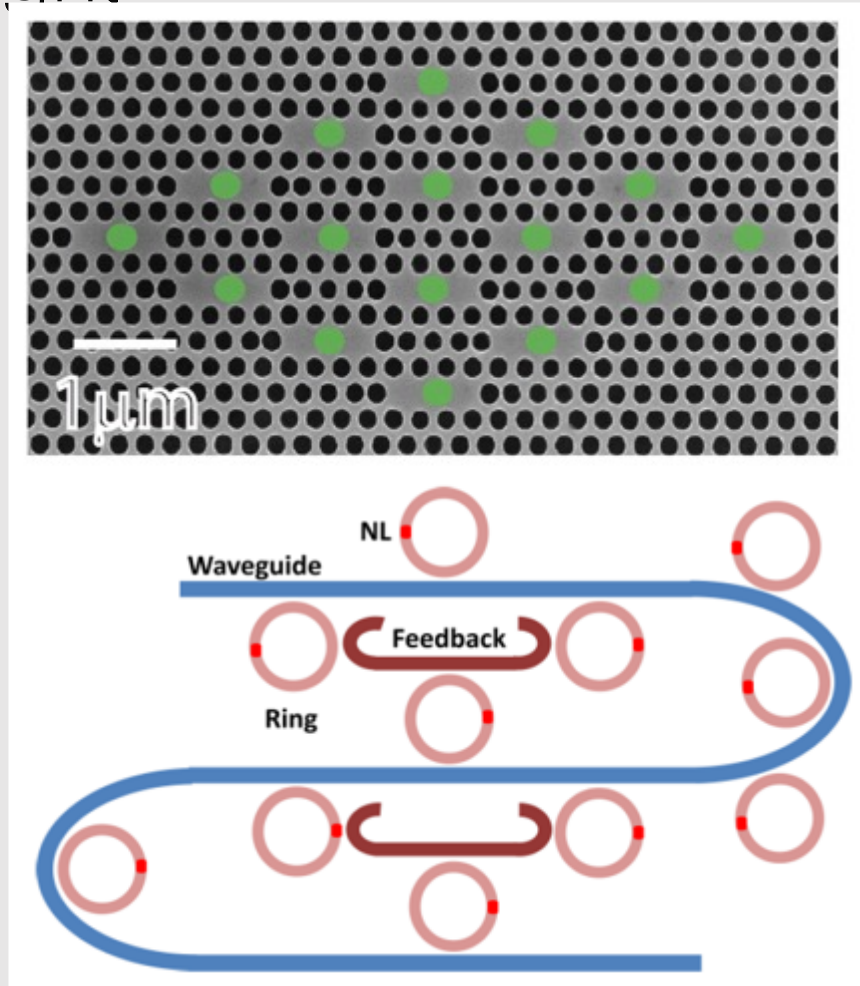
Quantum fluids of light, Rev. Mod. Phys. 85, 299 (2013)



Nature Physics 7, 907–912 (2011)



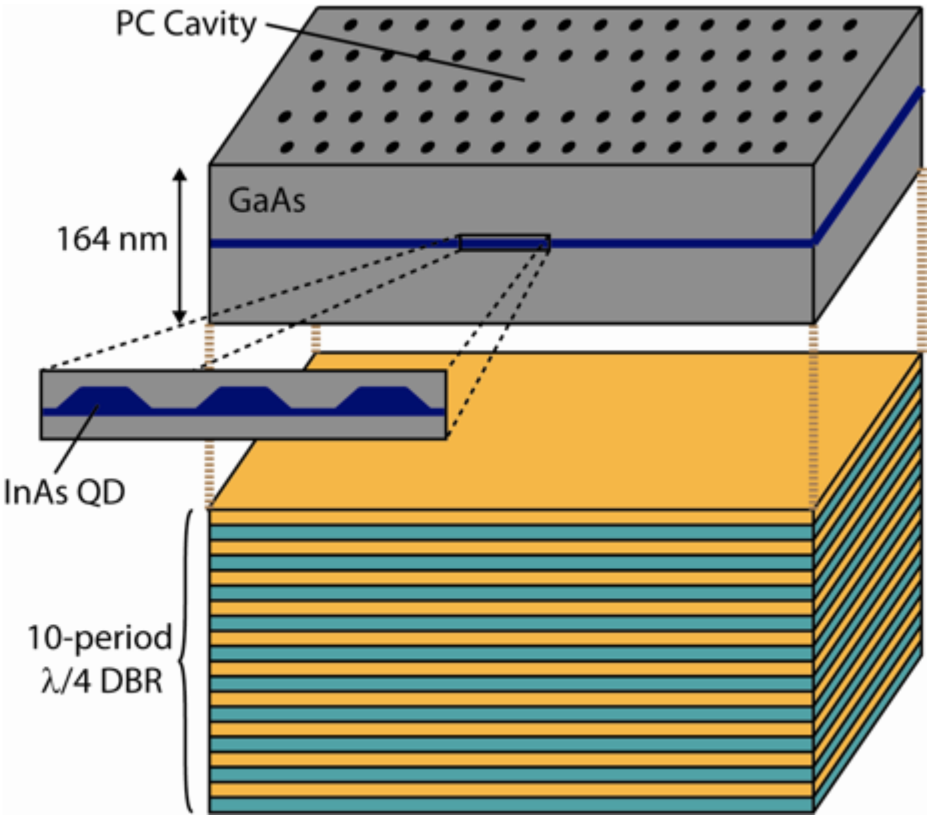
Report of Progress in Physics, 80, 016401 (2016)



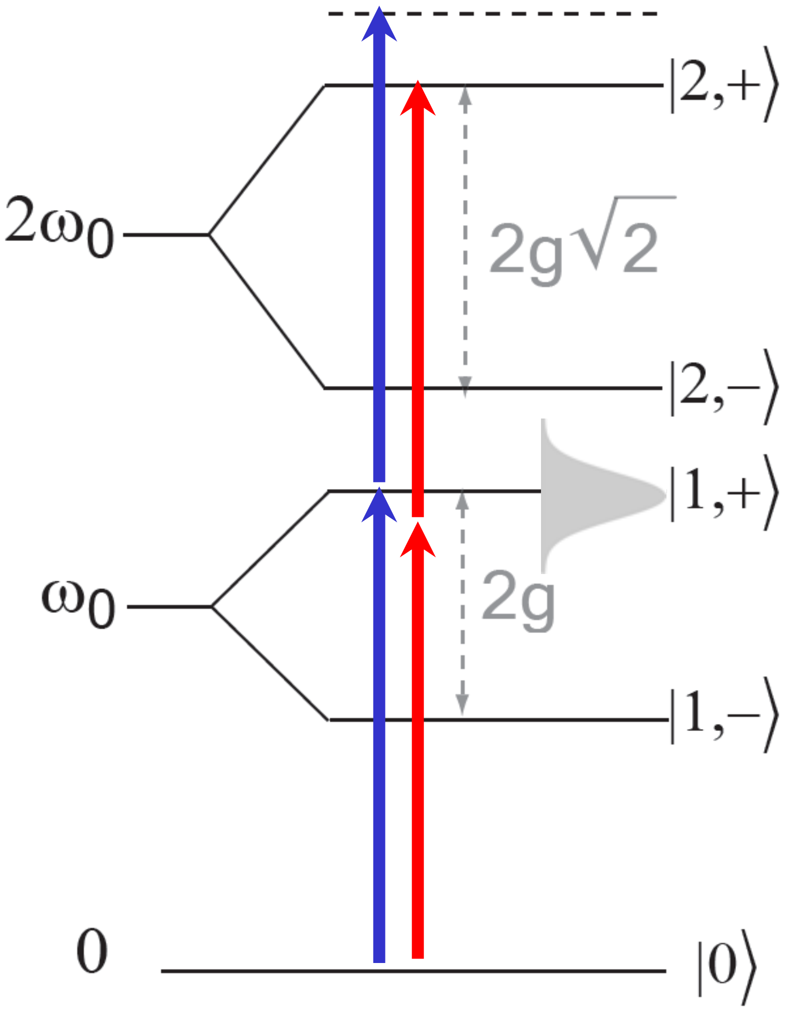
- Driven-dissipative nature provide a platform to study non-equilibrium quantum systems.
- Easy to measure multi-photon correlations.

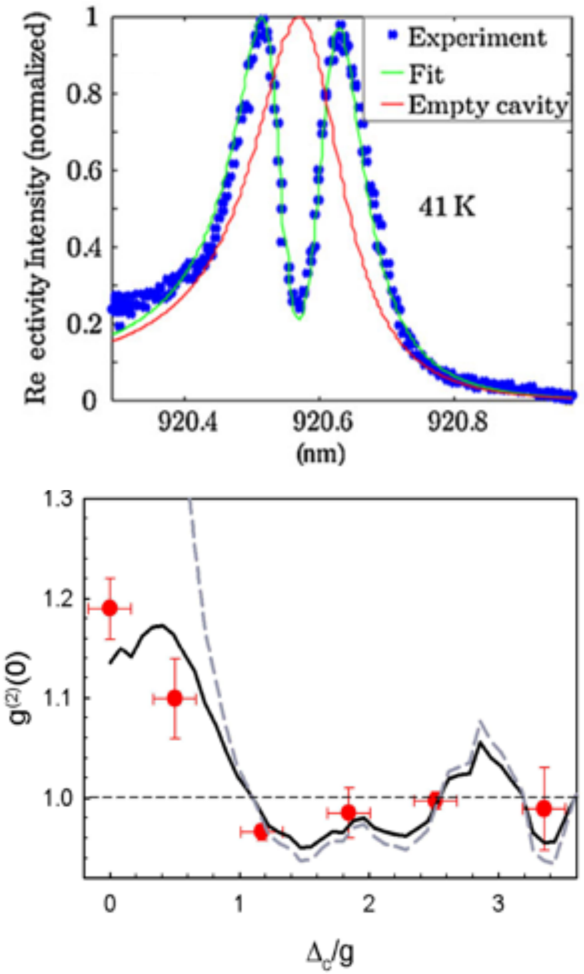
Lack of scalable single photon nonlinearity remains a big challenge to realize photonic quantum simulators.

Single photon nonlinearity: self-assembled quantum dots in nano-cavity



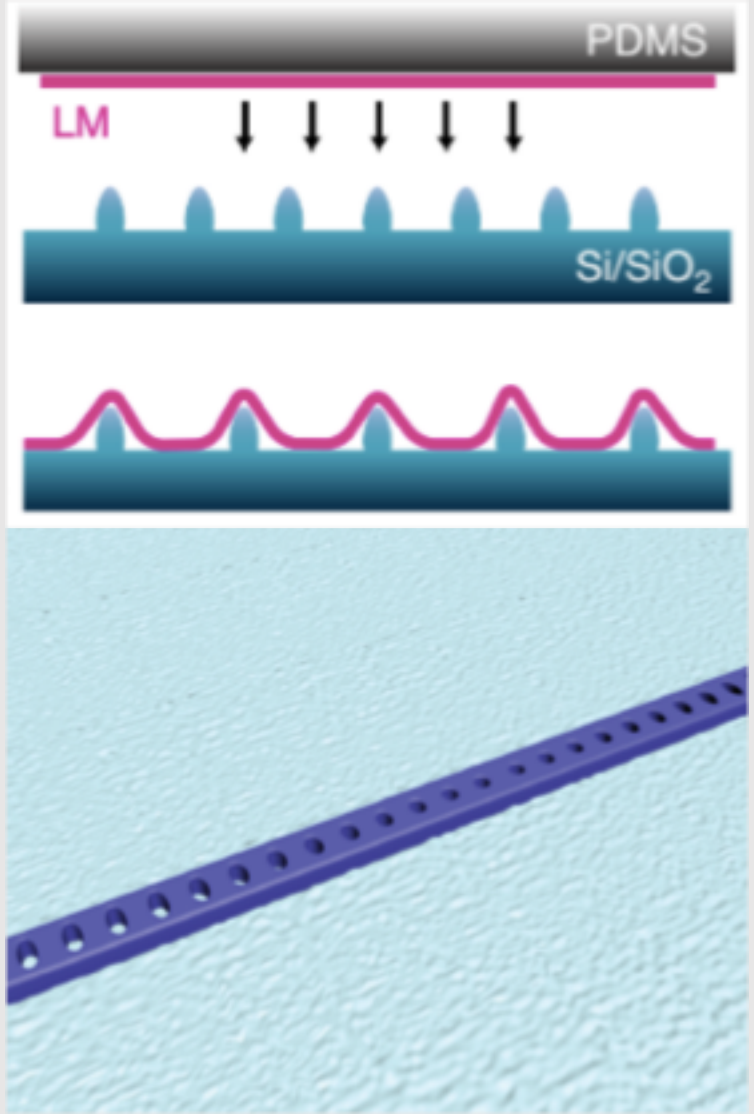
Majumdar, Englund, Faraon, Vuckovic
Also: Waks, Imamoglu



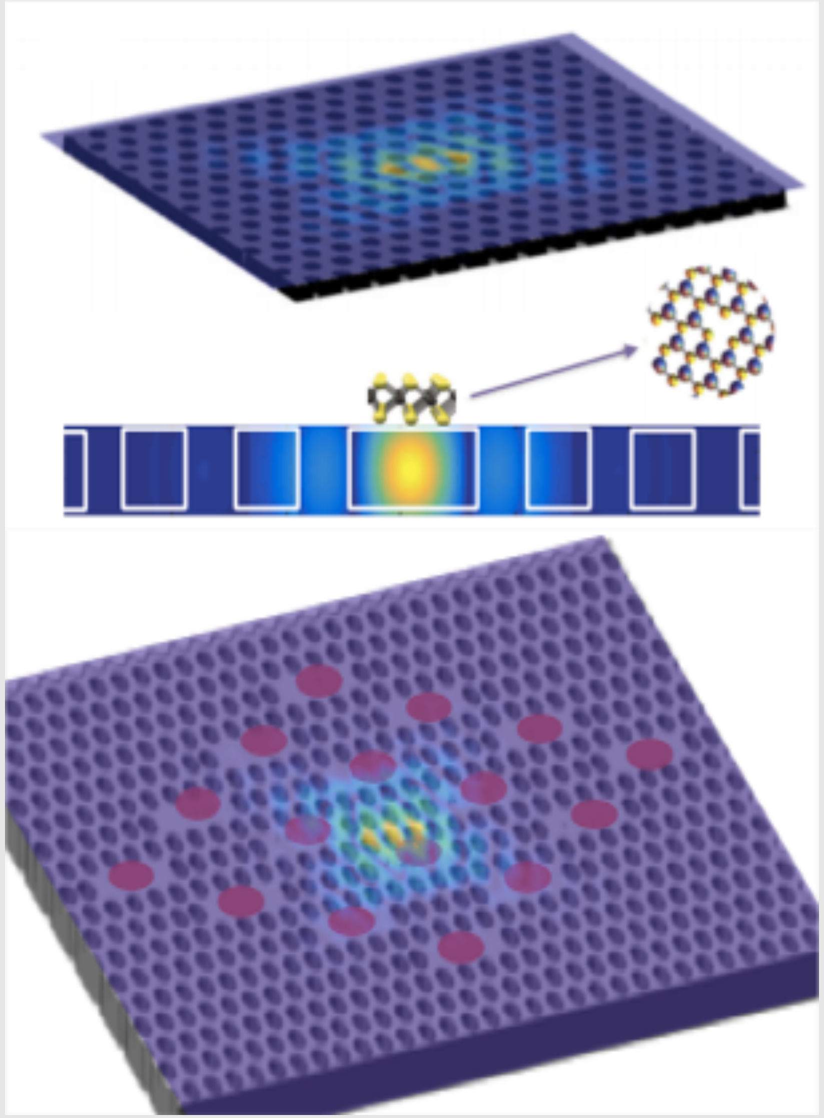


- Strongly coupled quantum dot-cavity system: Jaynes-Cummings Nonlinearity
- Spectral and spatial matching remains problem
- The largest number of coupled cavities with dots is only two

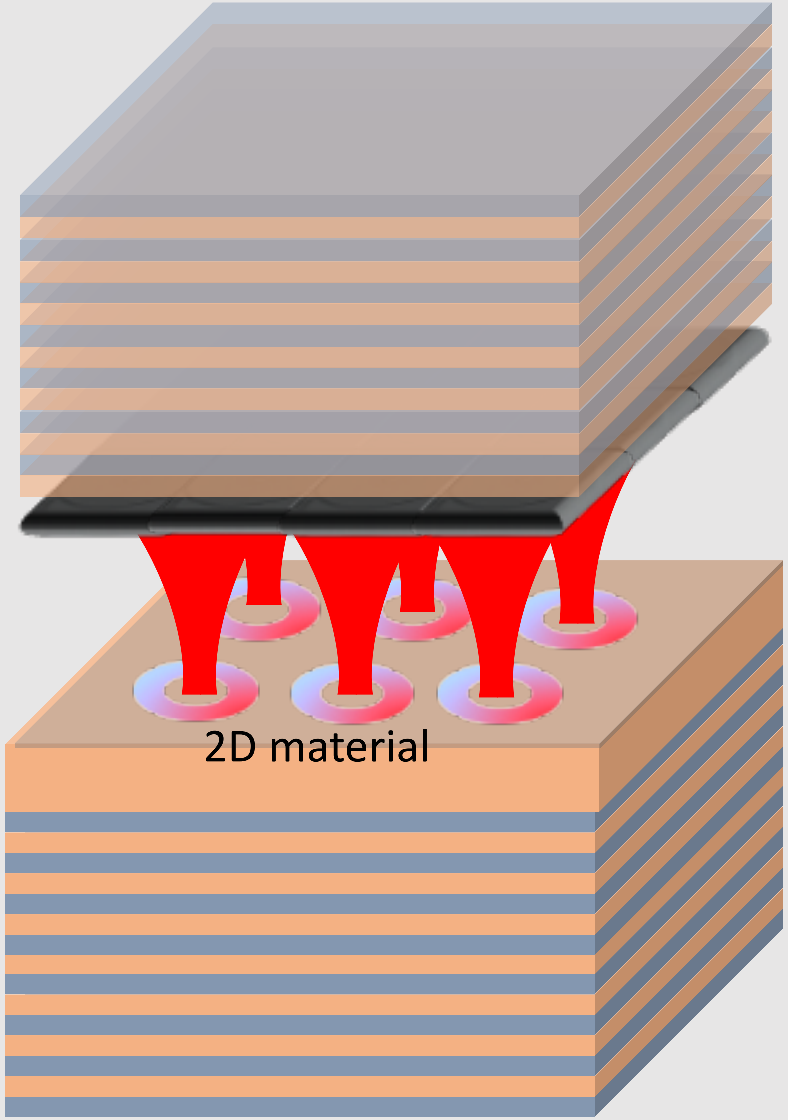
Quantum many-body simulation with photons



Deterministically localize single emitters in 2D materials

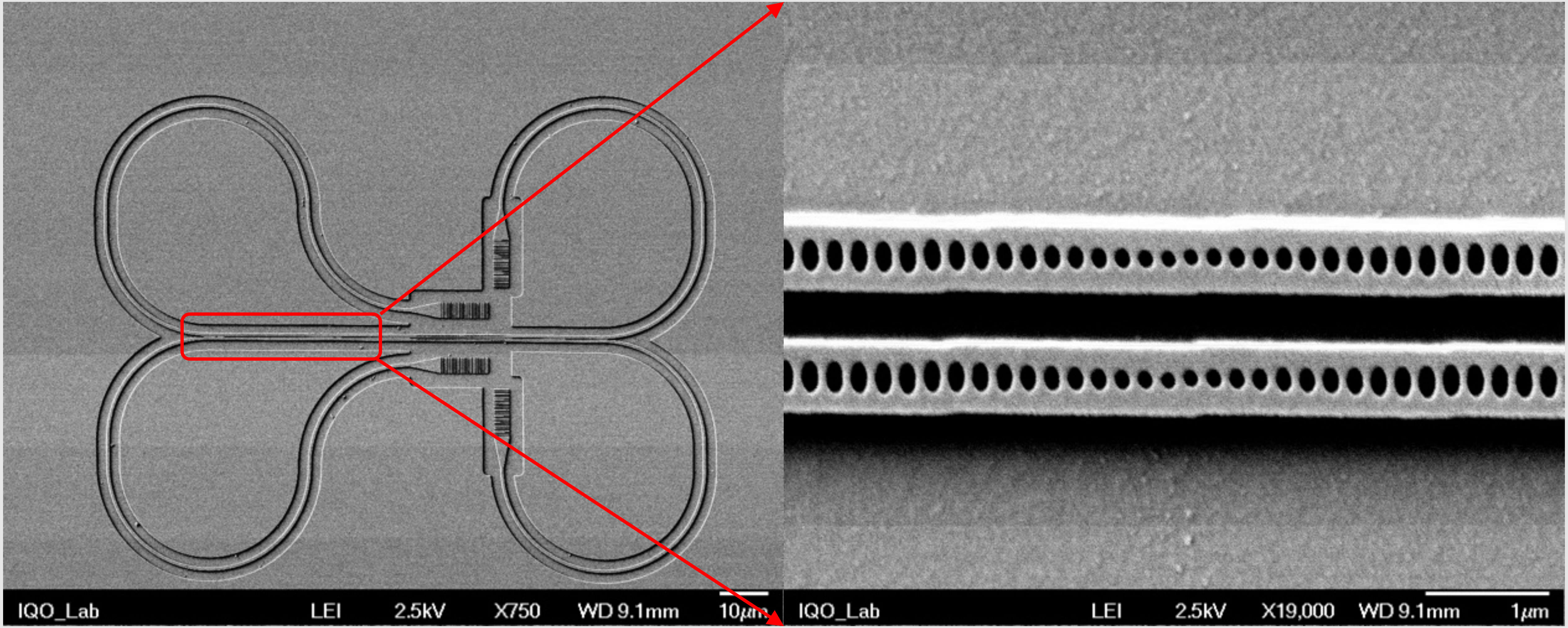


Pattern 2D material to enhance the polariton-polariton interaction

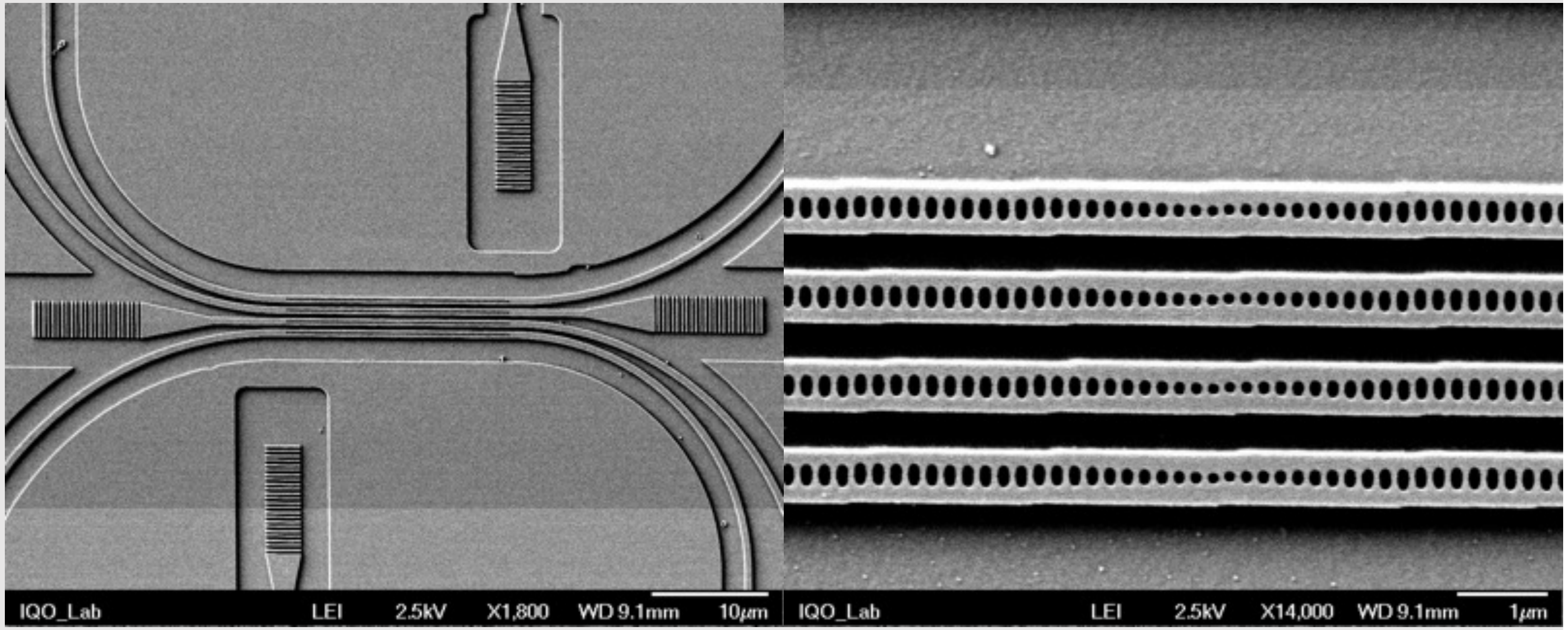


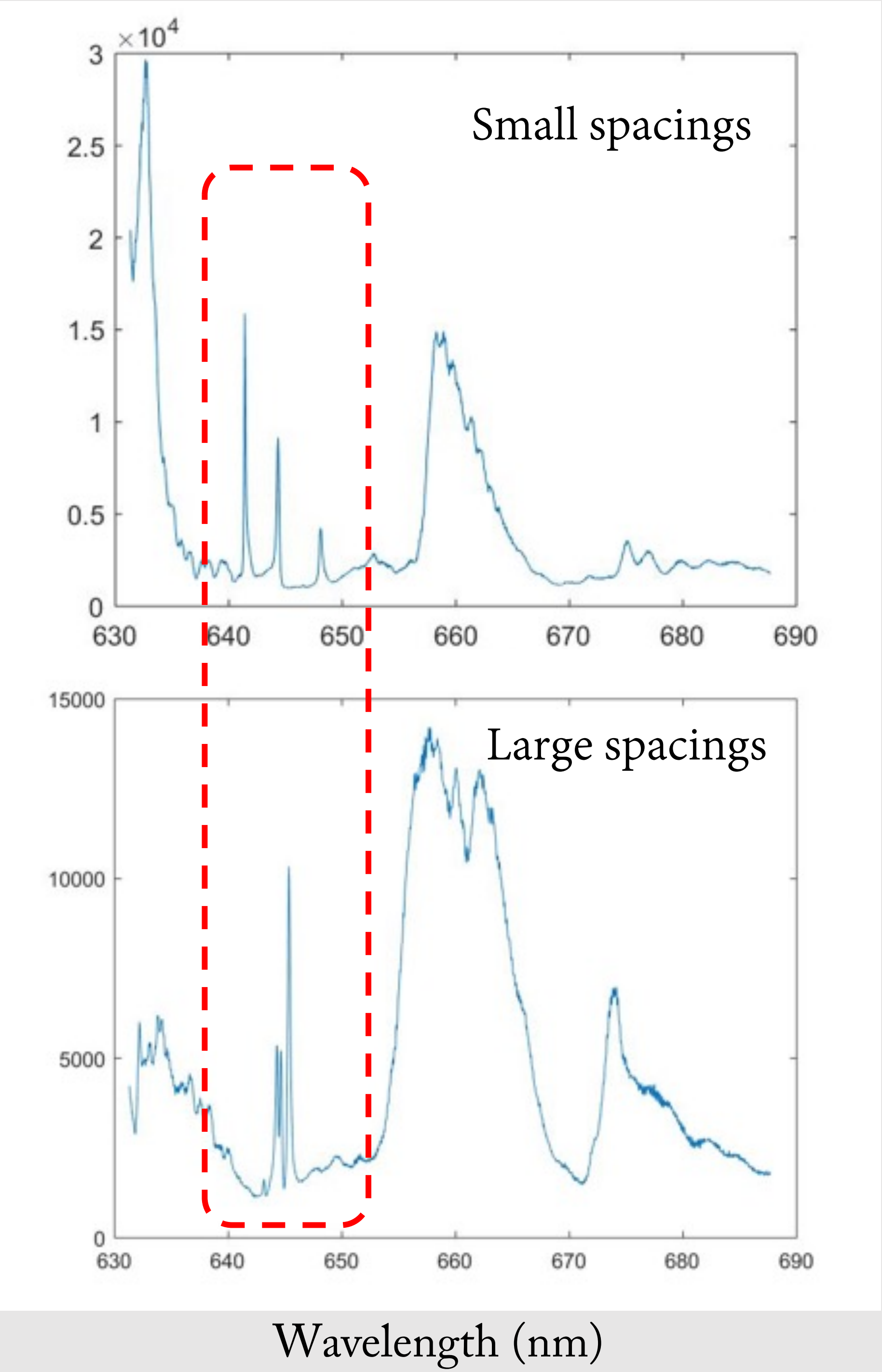
Metasurface optics inside DBR cavities can create local potential

Coupled cavity array: photonic molecule

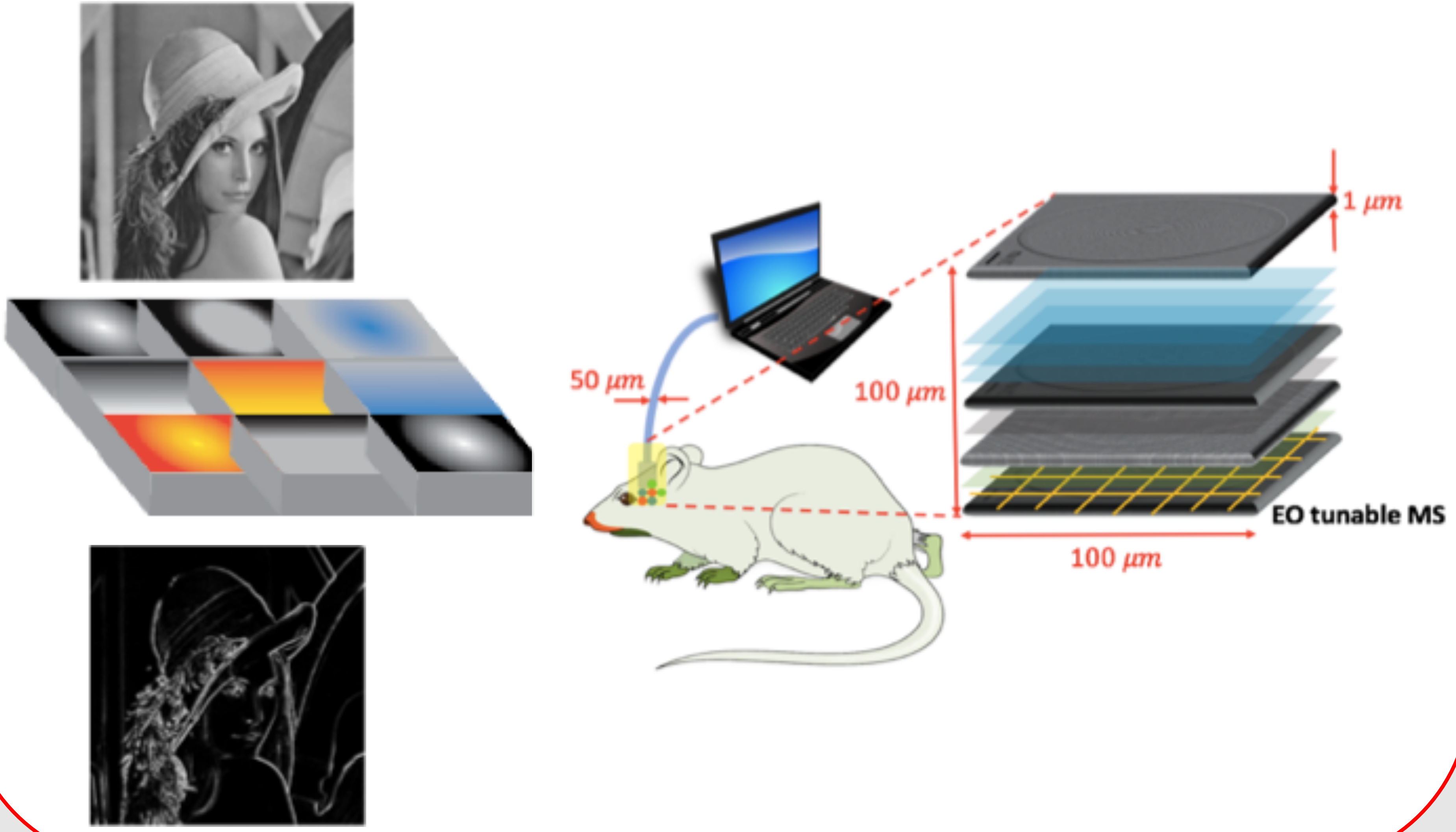


Coupled cavity array

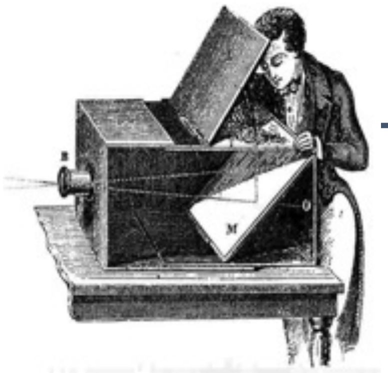




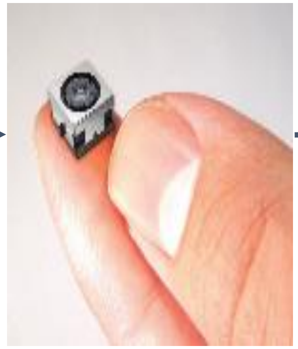
Nanophotonic Computational Image Sensors



Smaller sensors and display

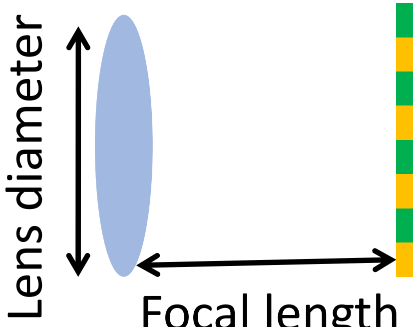


Old camera



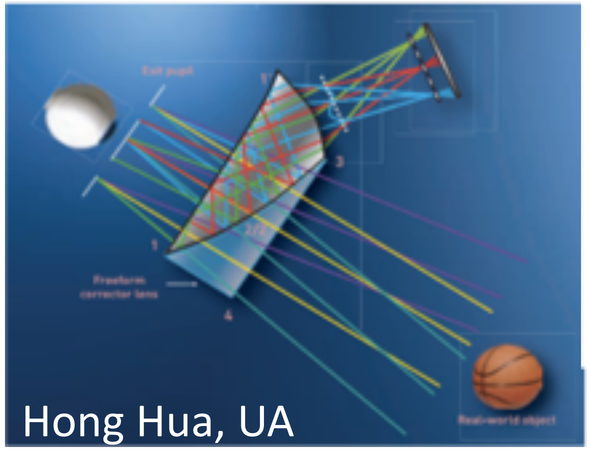
Mobile camera

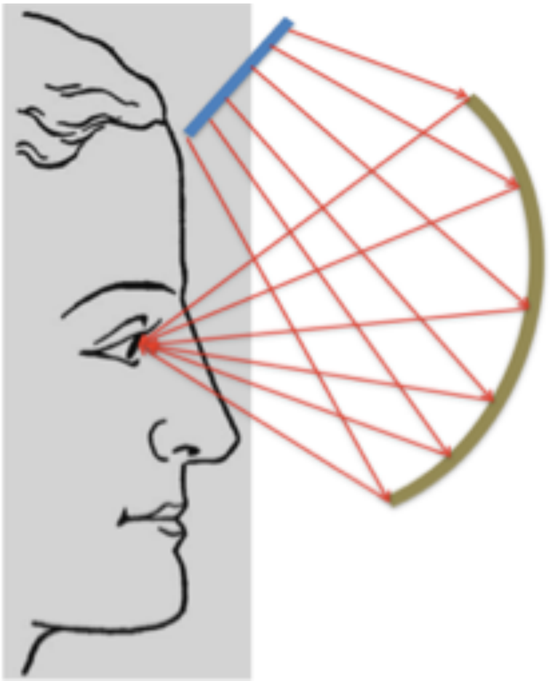
→ ? Smaller sensors (IoT, MV, bio-imaging)



- Volume of a camera is fundamentally limited by a lens
- A compact short focal length lens is difficult to make

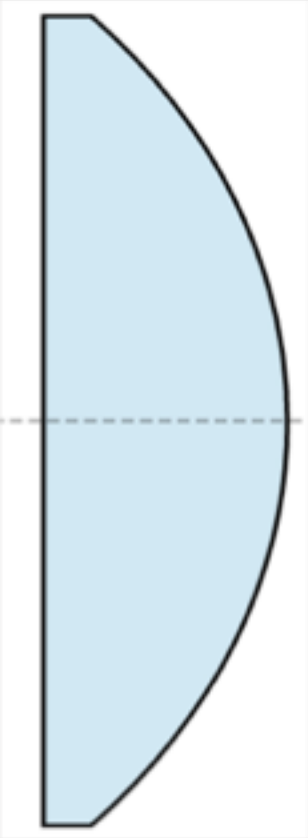
Image Sensors



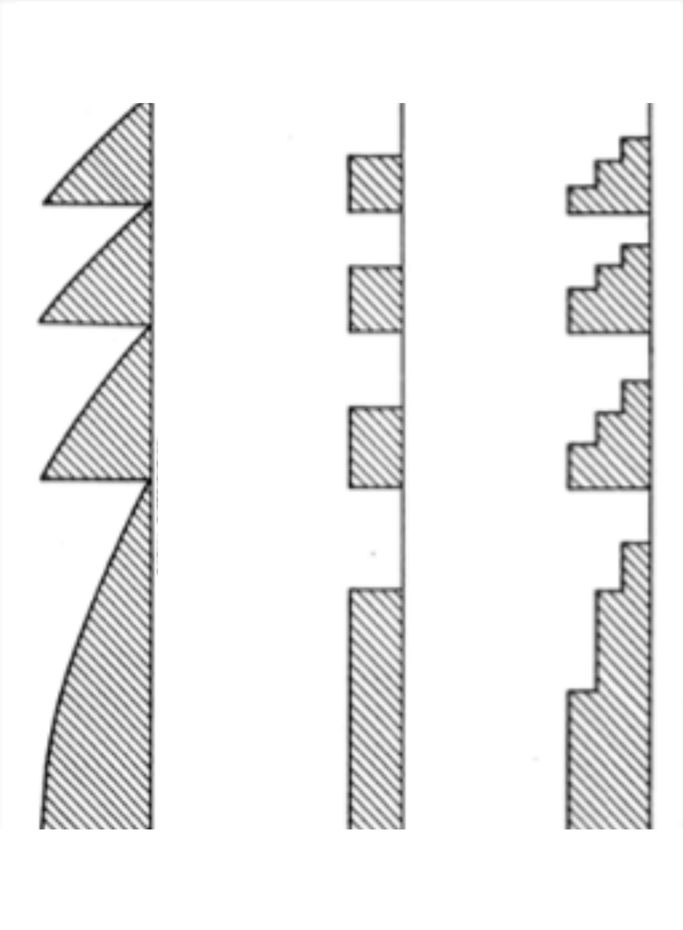


Compact Display/Near-eye visors

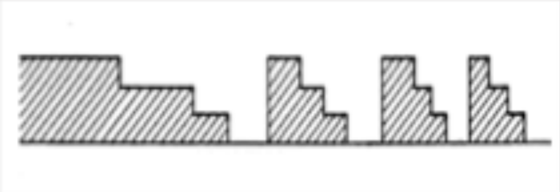
Dielectric Metasurface

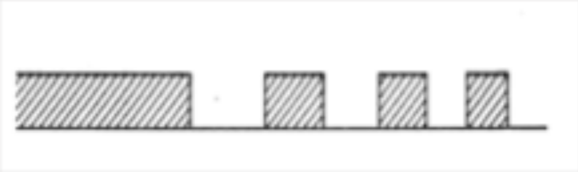


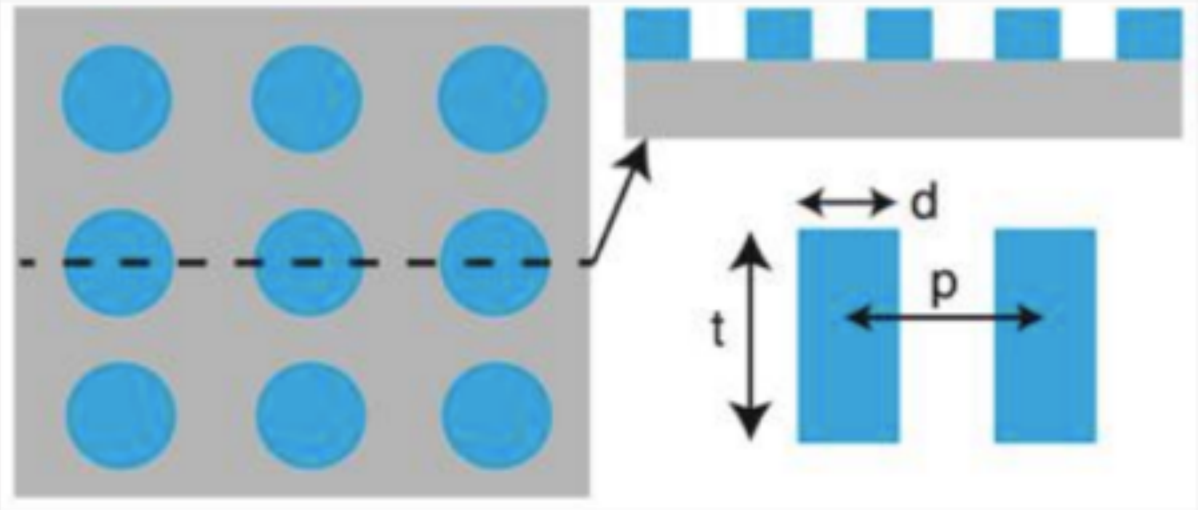
Refractive

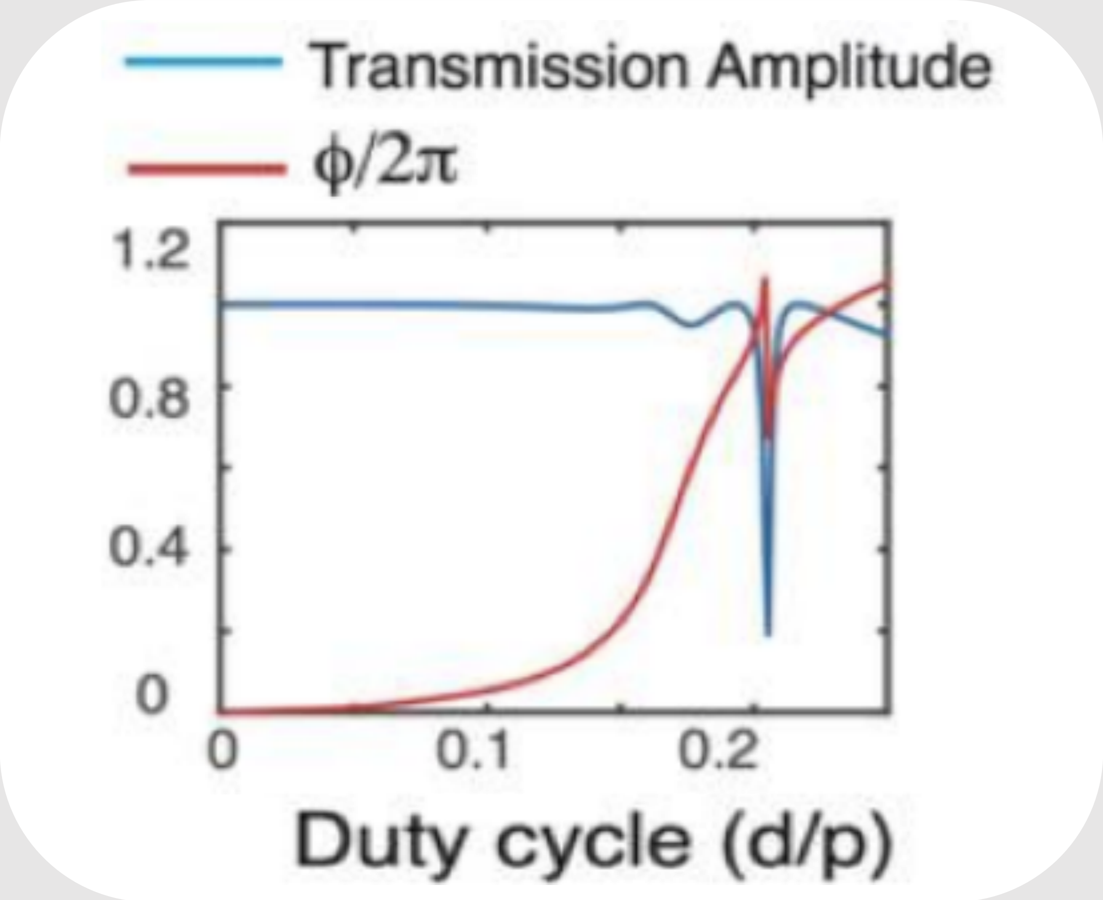


Multi-level diffractive optics

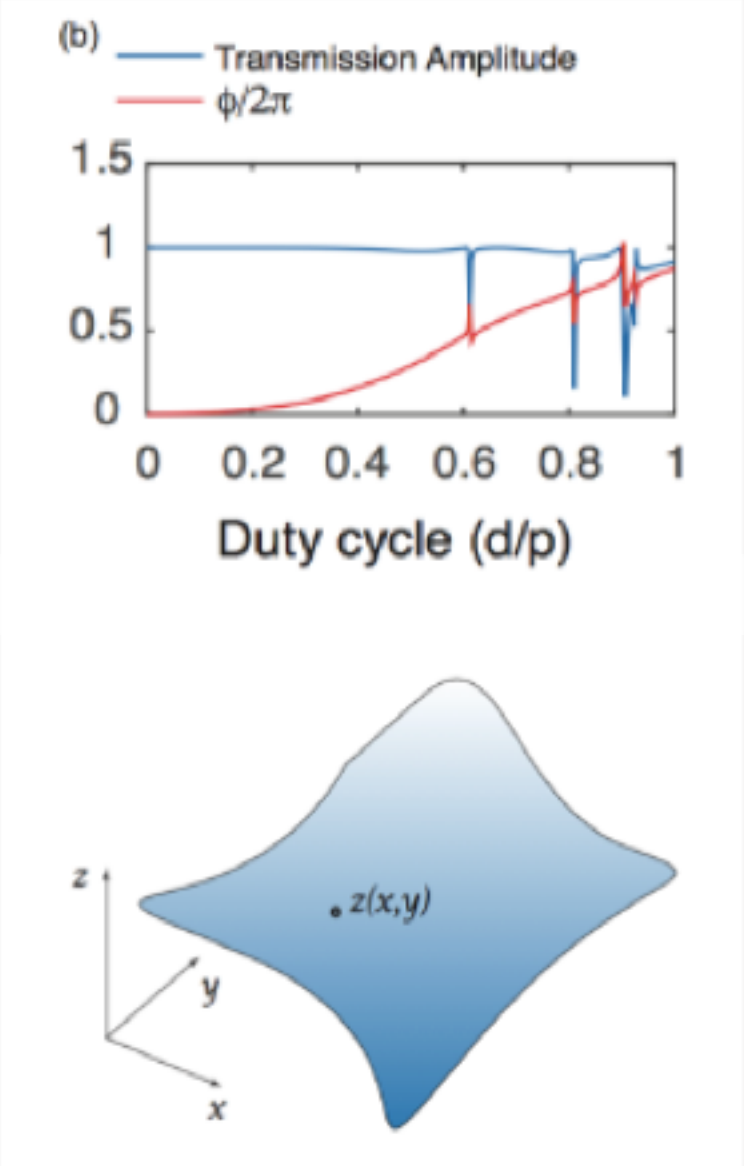




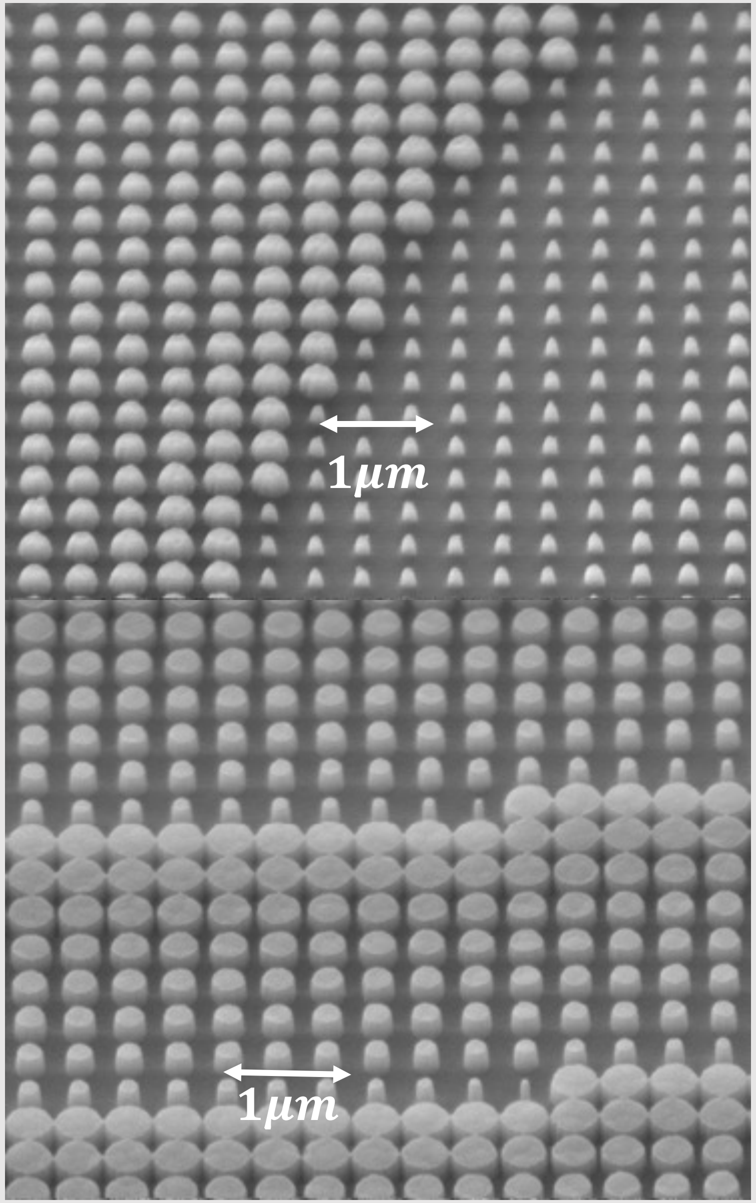




Freeform optics using metasurface

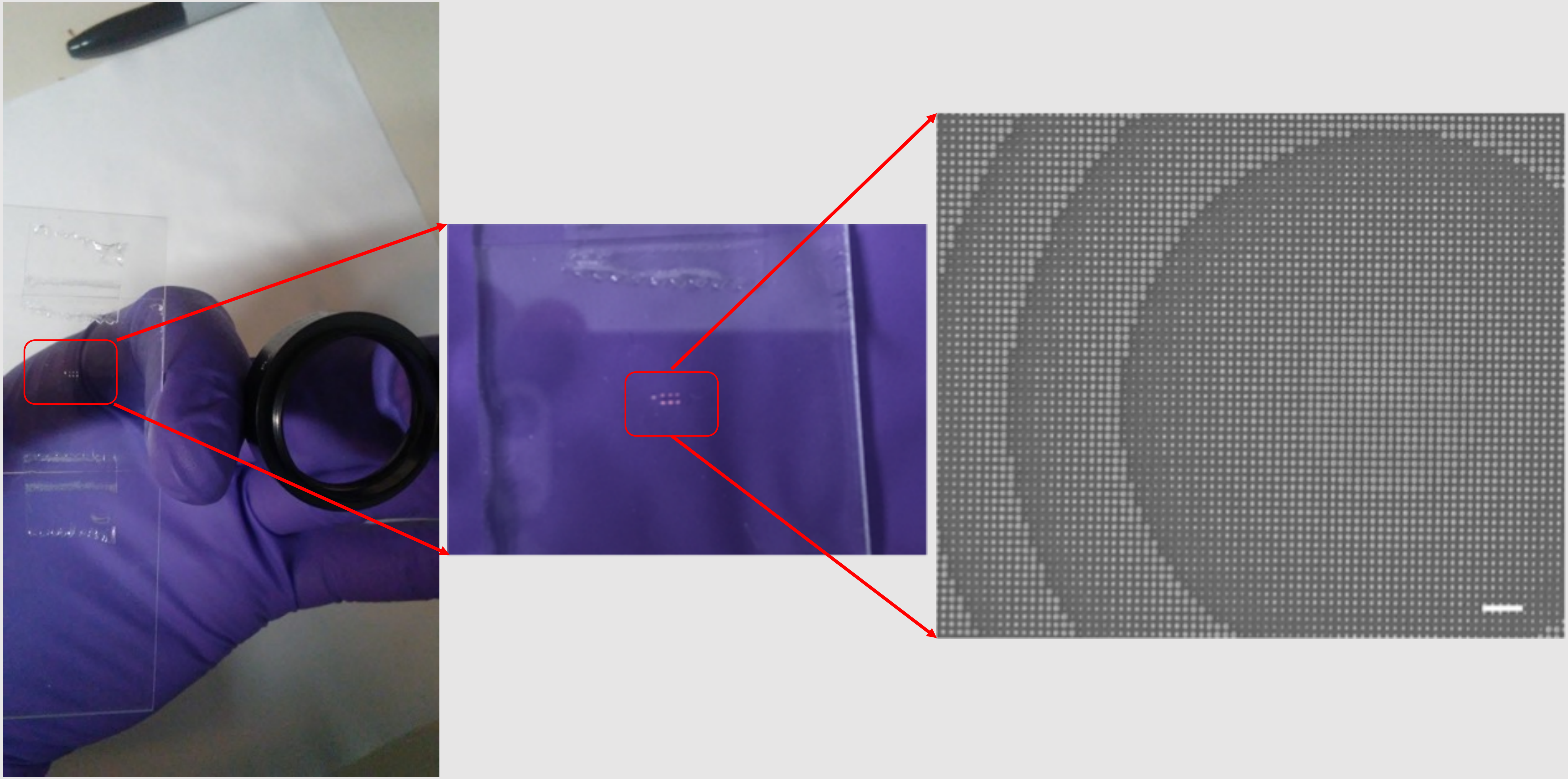


Identify the phase distribution

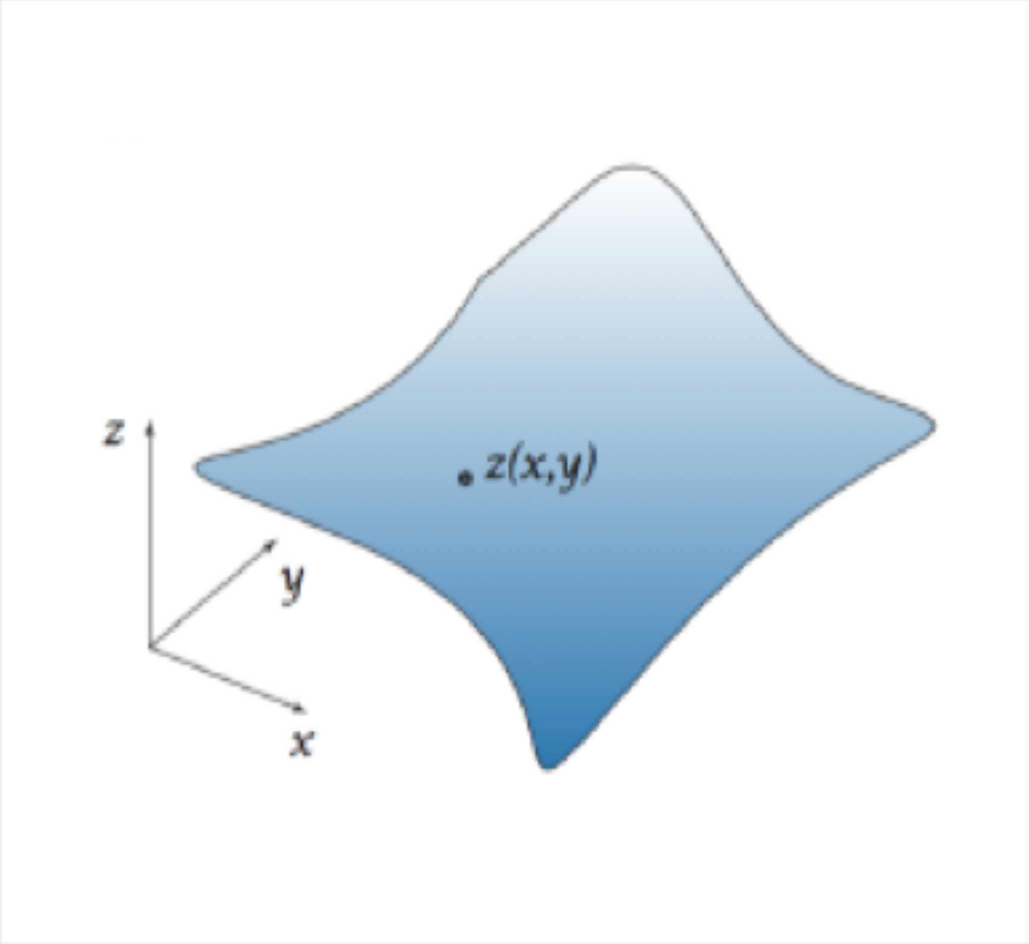


Choose the appropriate grating to mimic the phase

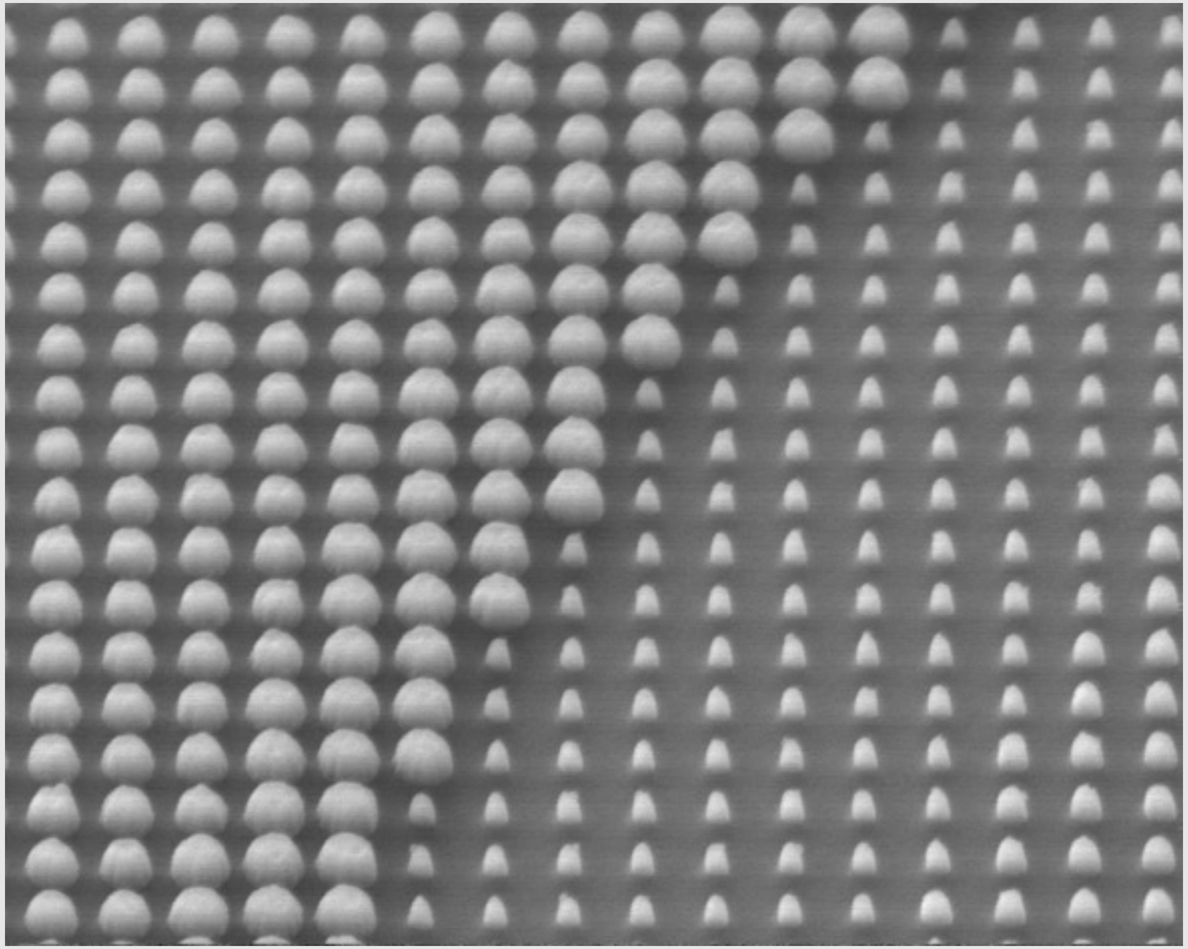
Comparison with conventional lenses



Inverse problems in metasurface

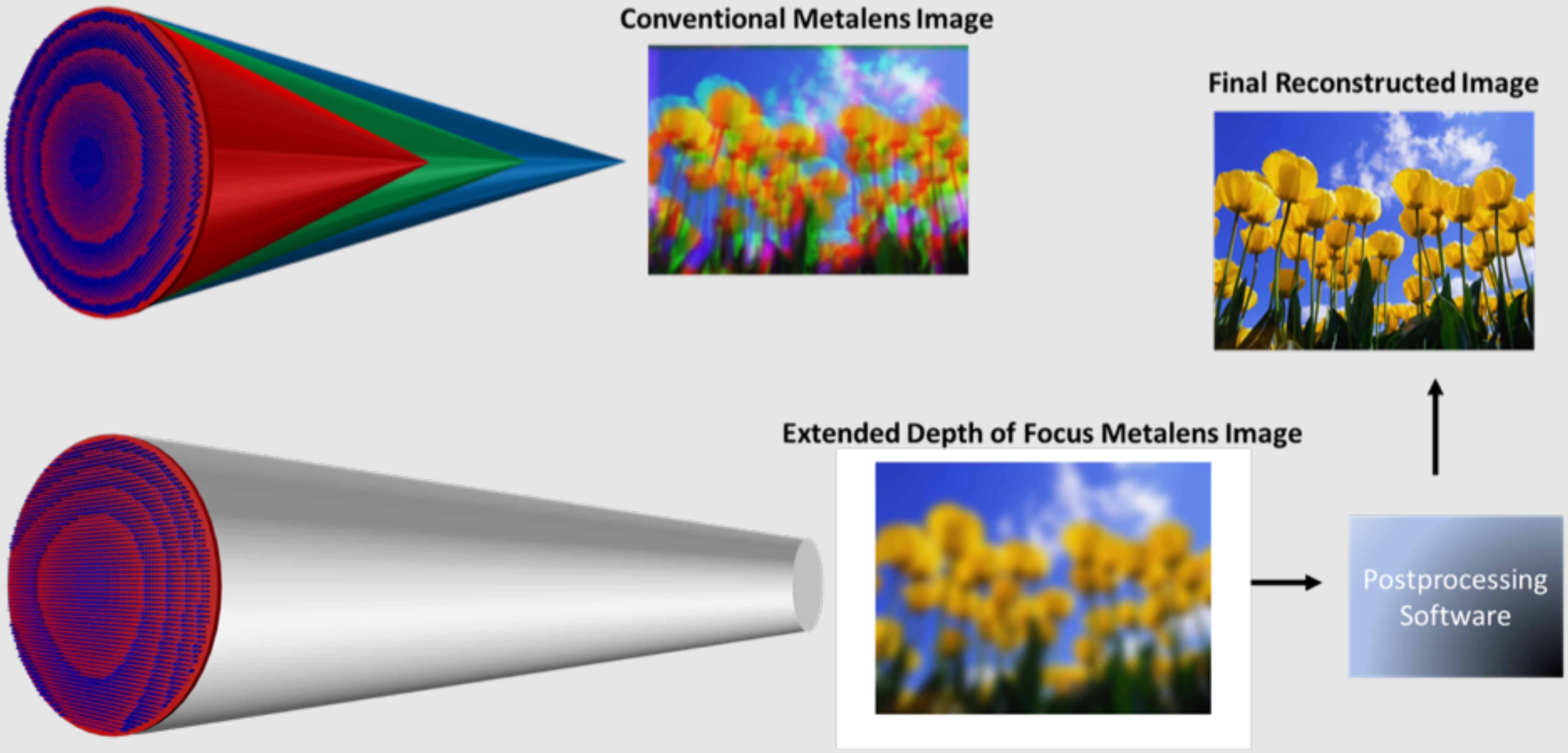


Given an application how do you identify the desired phase distribution?



Given a phase distribution how do you identify the correct distribution of pillars?

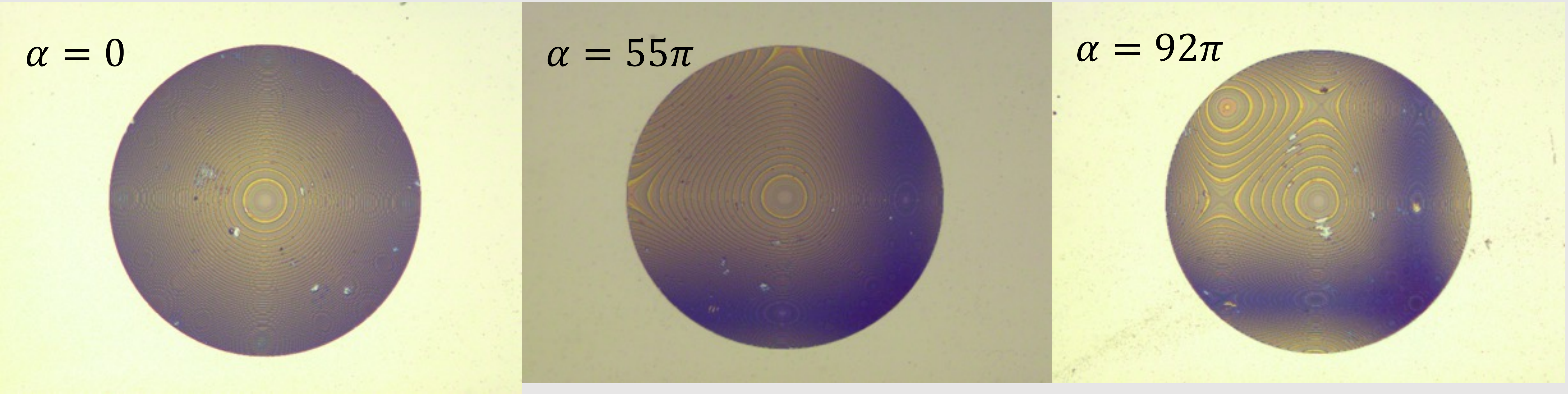
Solution of the chromatic aberrations



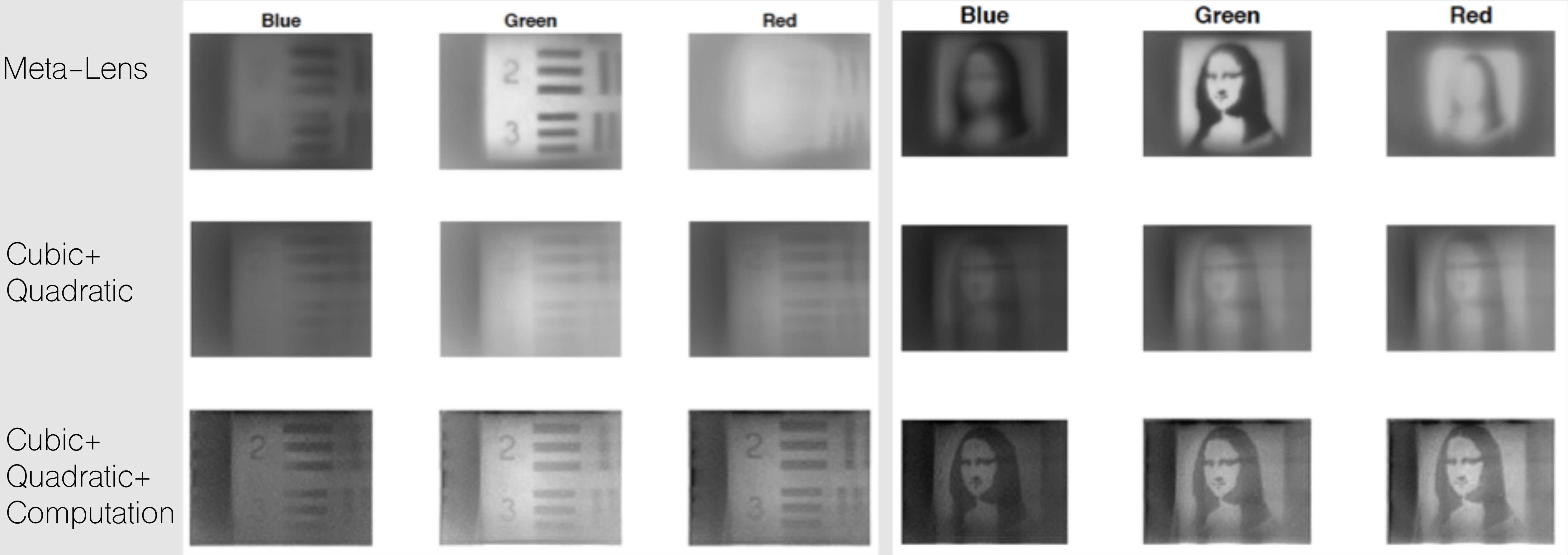
Cubic + Quadratic metasurface

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

$\boldsymbol{\alpha}$ is a design parameter for the combined metasurface



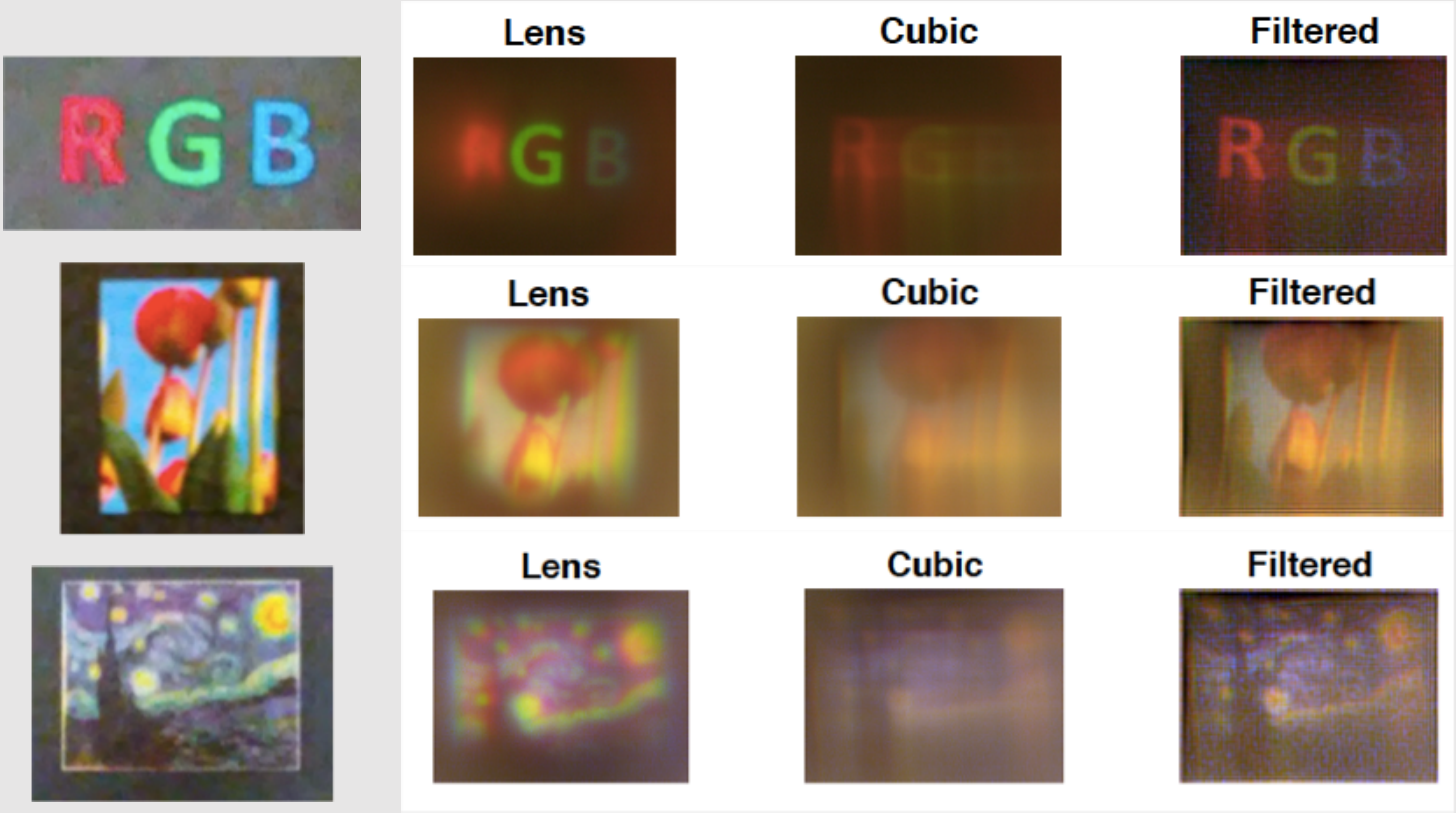
Imaging with red, green and blue LEDs (MS-sensor separation of 200 micron)



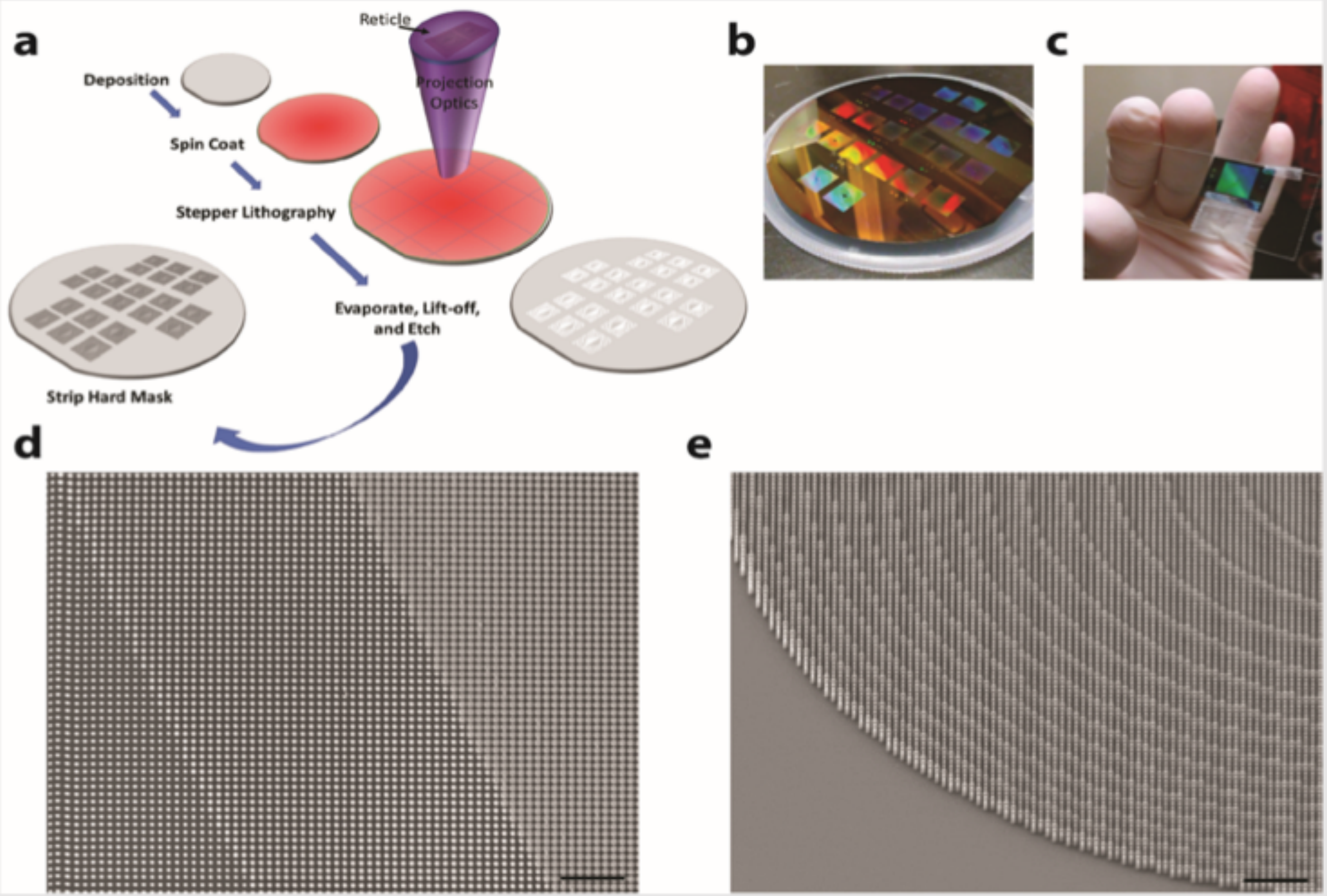
Structural Similarity (SSIM): for metalens: ~ 0.7 ; our approach: ~ 0.9

Computational algorithm is Wiener deconvolution: $O(Nlog\,N)$

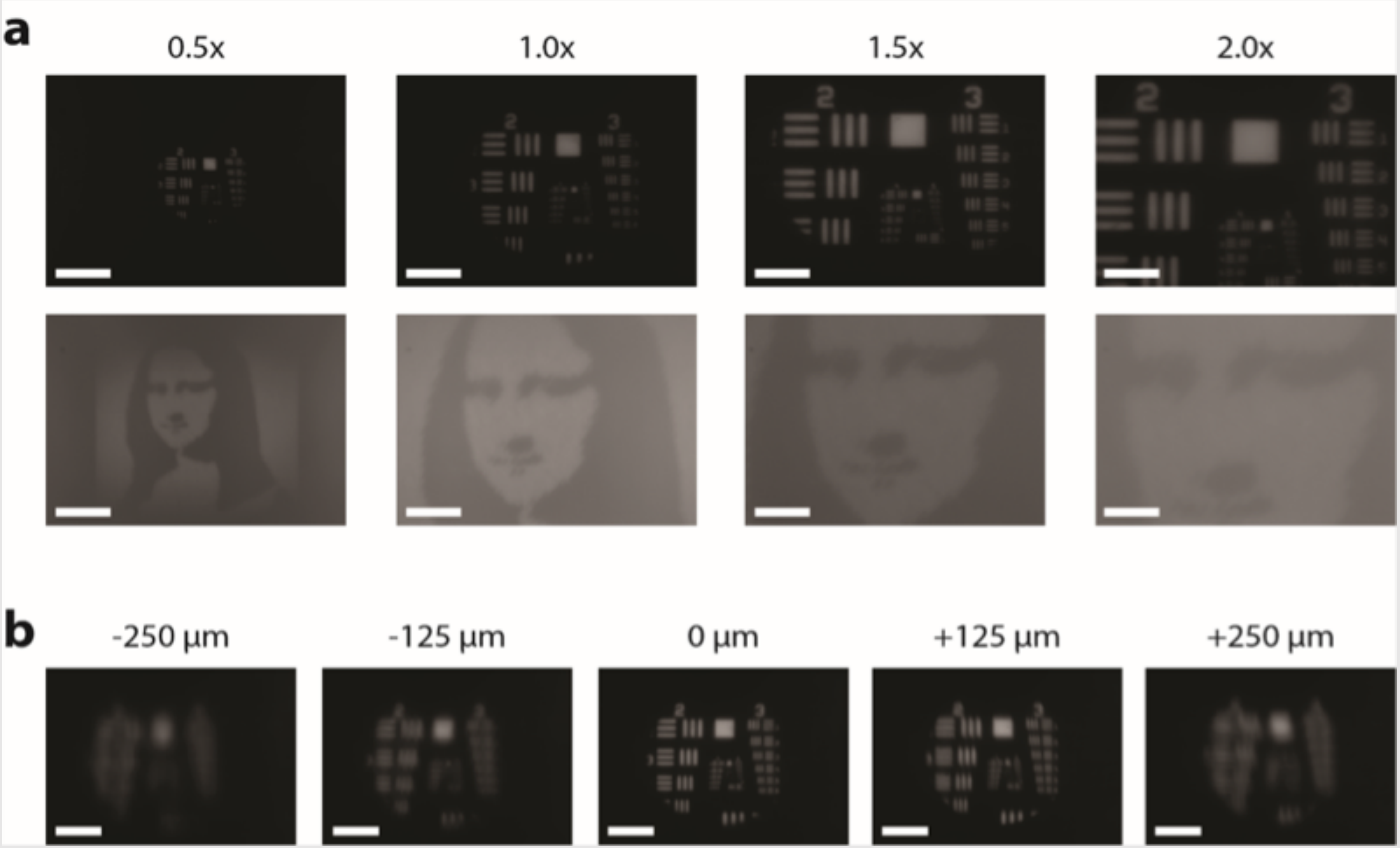
White light imaging (MS-sensor separation of 200 micron)



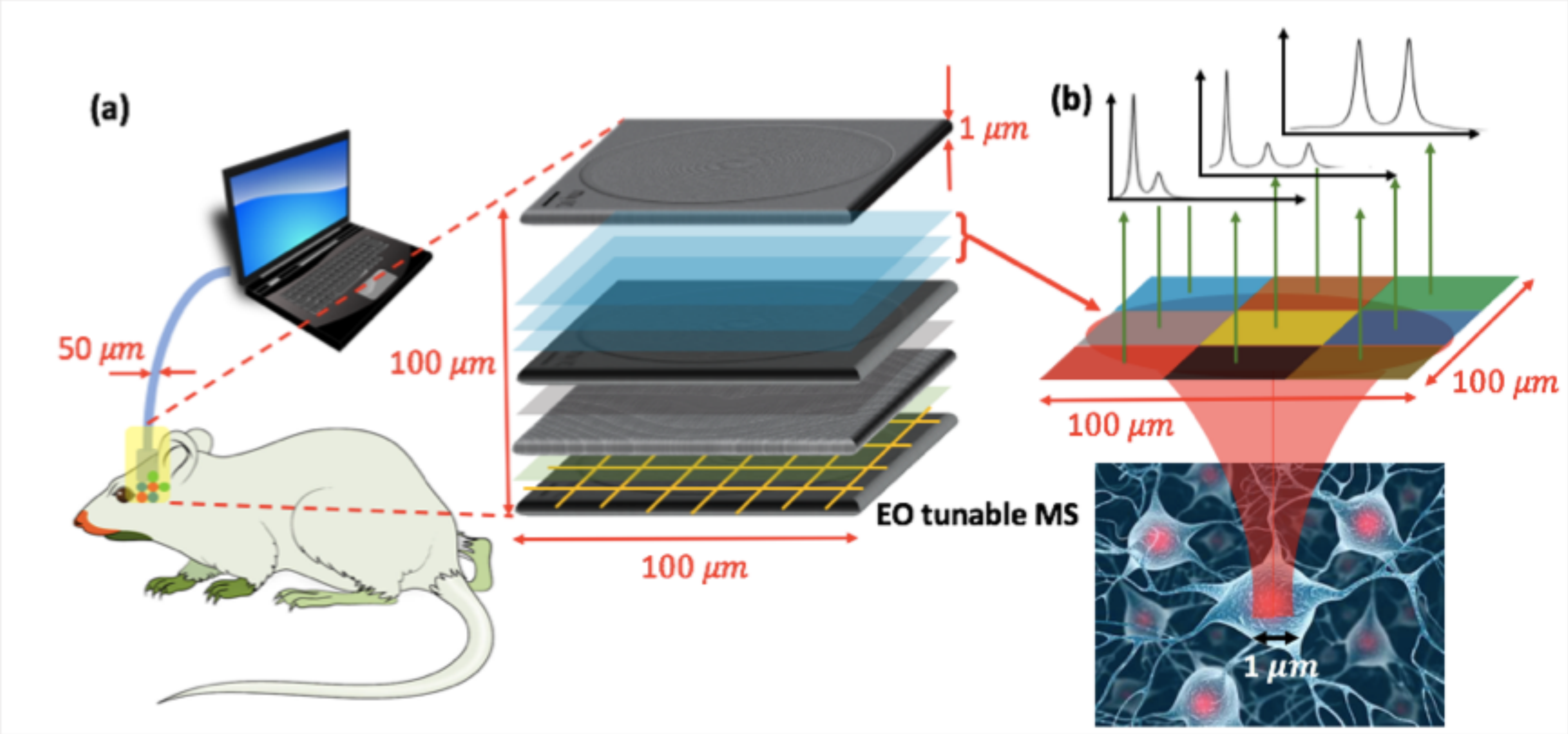
Large area metasurfaces



Imaging with metasurface (no other optical element)

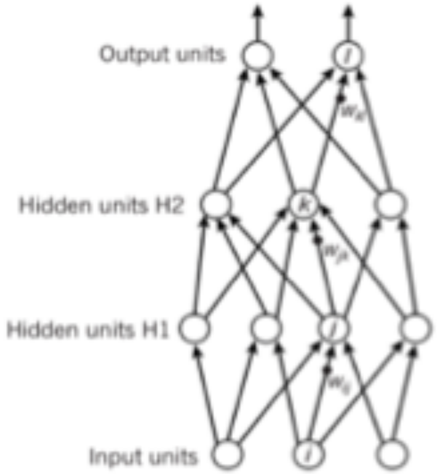


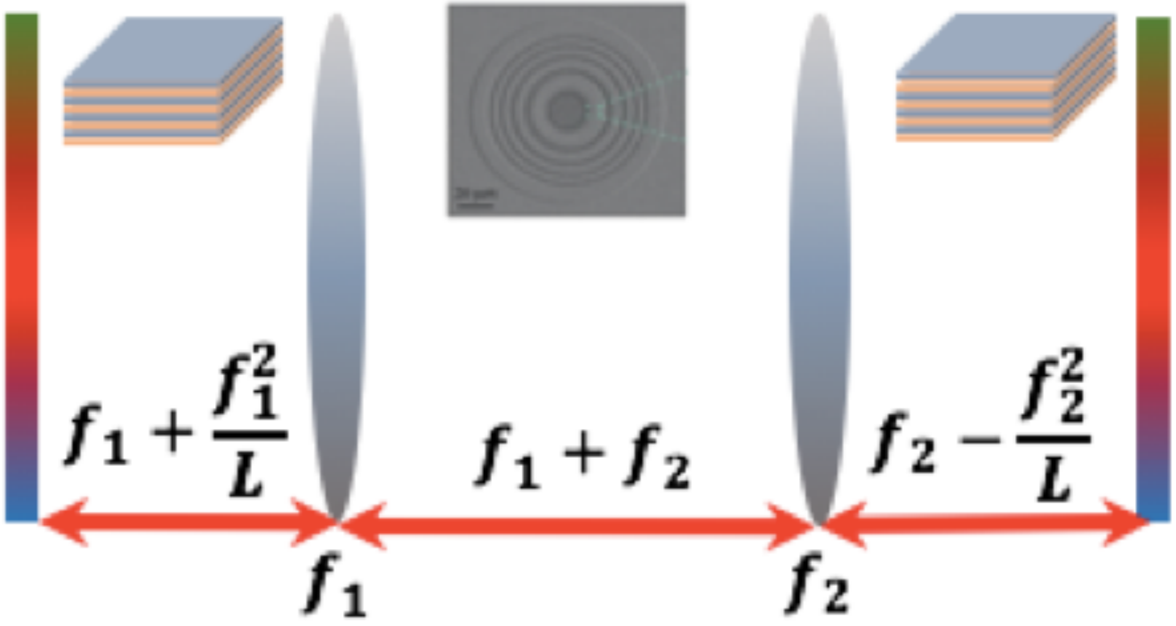
Implantable microscope



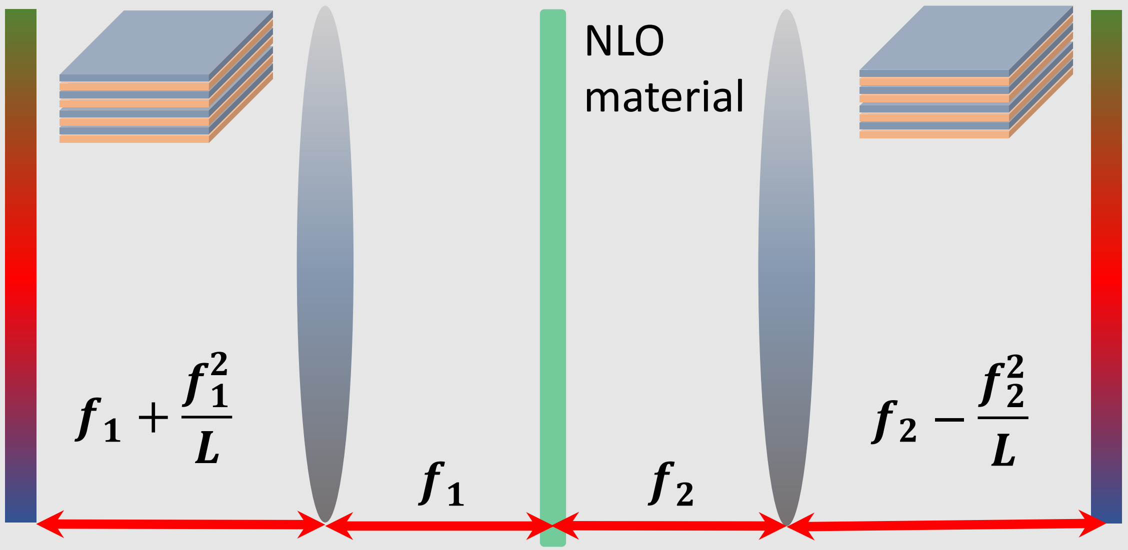
Spatial to spectral mapping for wide-field microcopy with meta-photonic elements

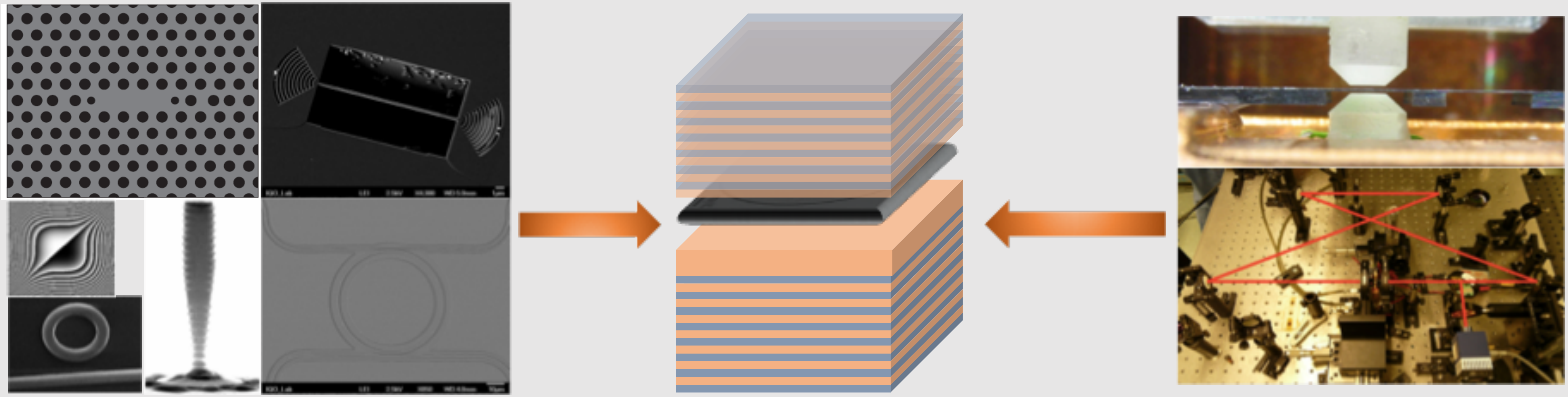
Nonlinear Image Processing and Monolithic Optical Neuron





Nonlinear image processing



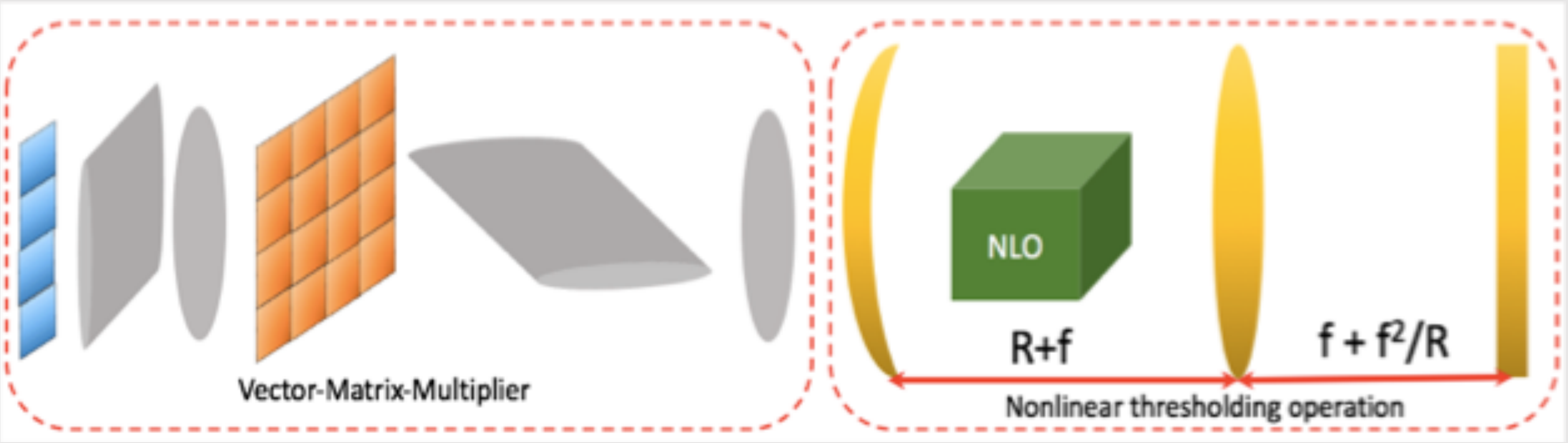


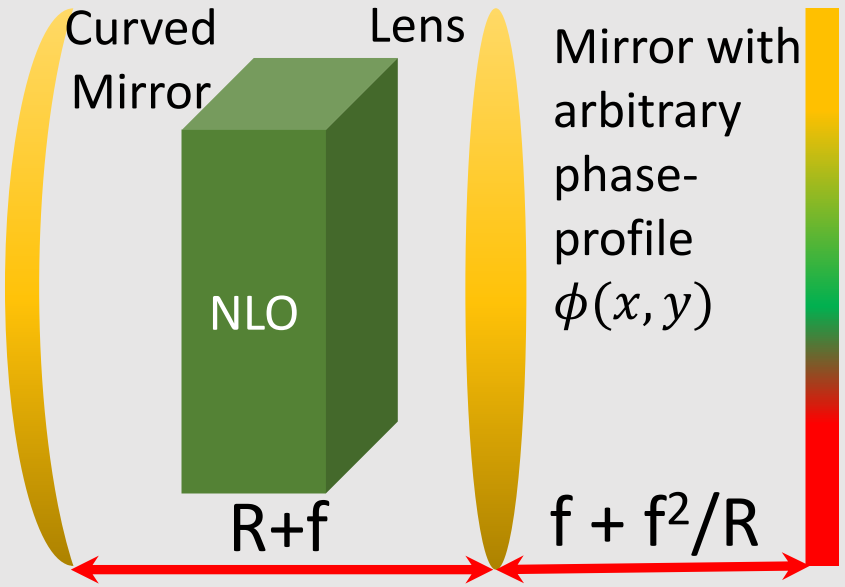
Nanophotonics and optical resonators

Metasurface-DBR cavity

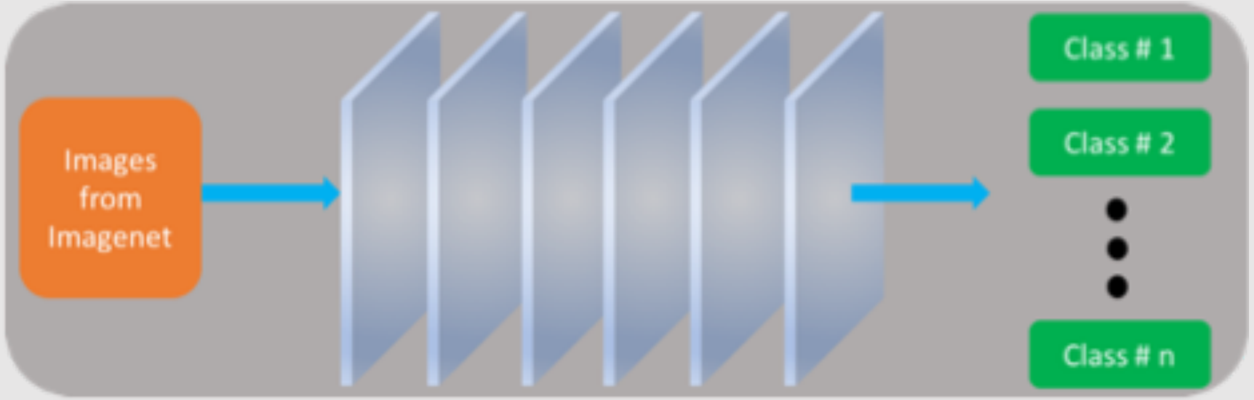
Macroscopic atomic physics cavity

Monolithic Optical Neuron

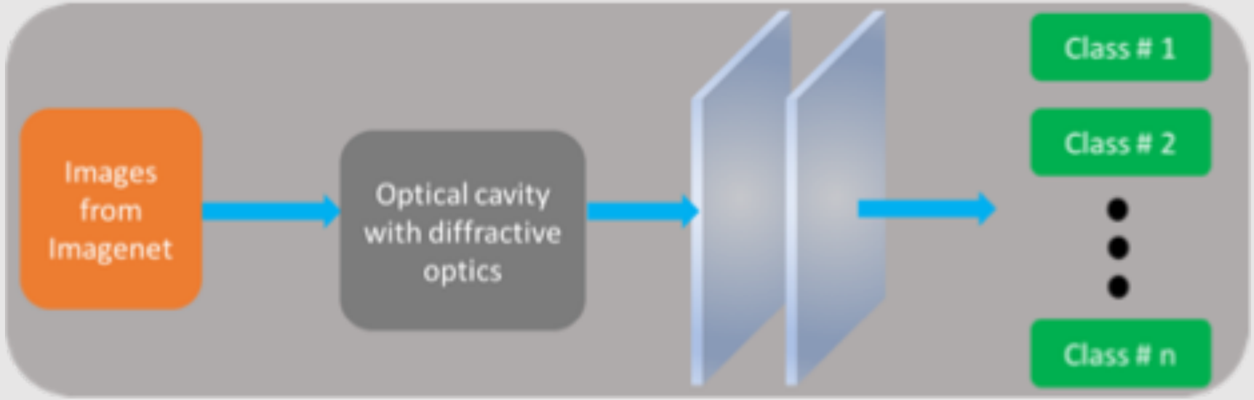




Metasurface and solid state photonic devices provide an opportunity for monolithic integration



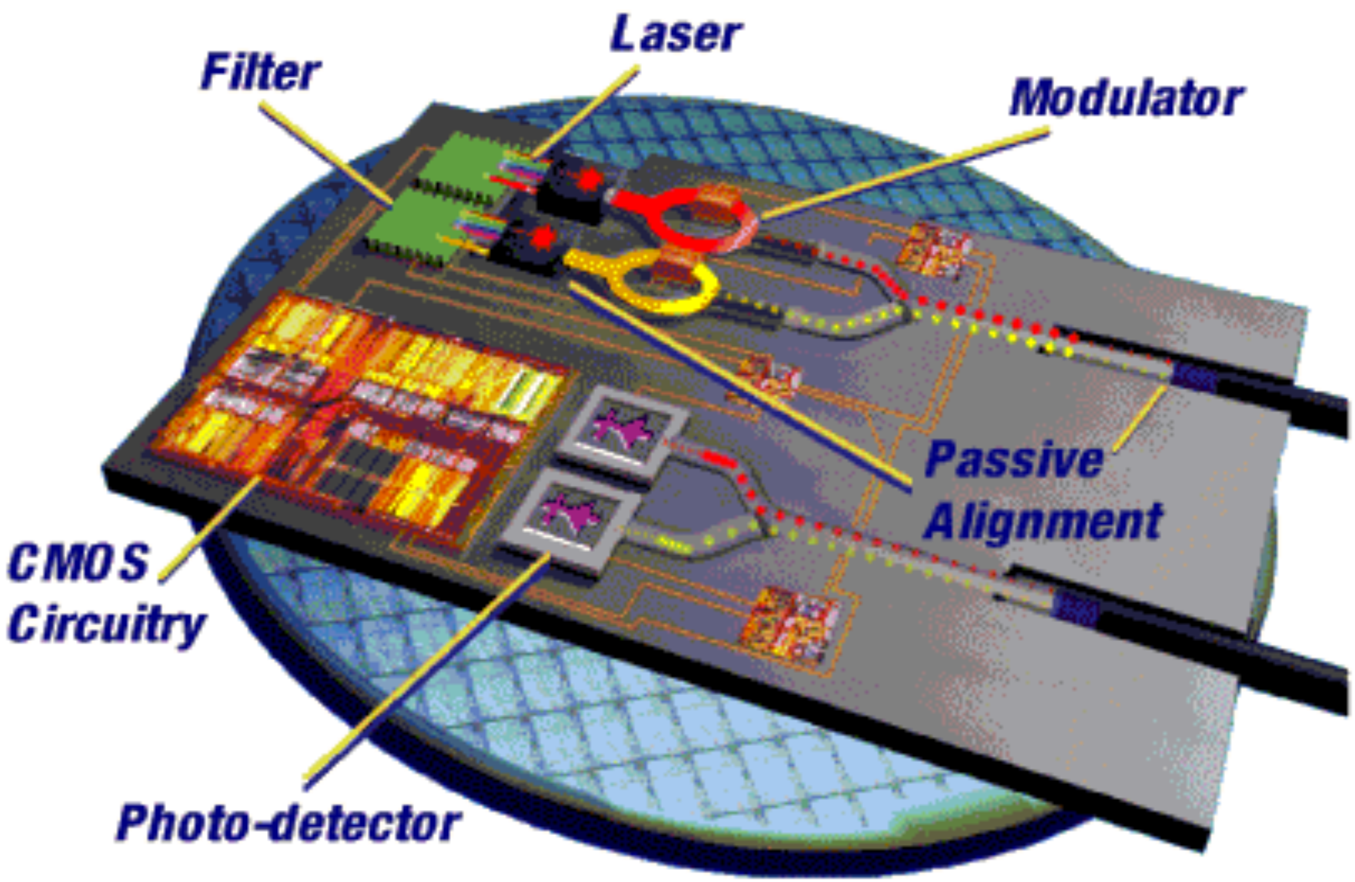
Conventional Deep Neural Network



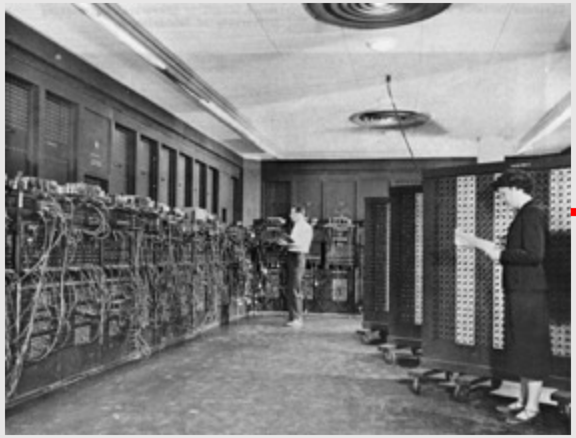
Hybrid Optical Deep Neural Network

- Simplify the geometry: can we make a VMM using an arbitrary phase profile inside the cavity?
- How can we reuse the layers?
- Is this network mimicking recurrent neural network?

Hybrid Integrated Photonics



Evolution of computing



Eniac

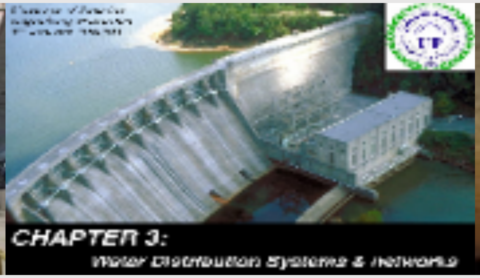
1980 computer

Moore's law (for CMOS transistors) will end!!

Replace CMOS?

Paper Mill

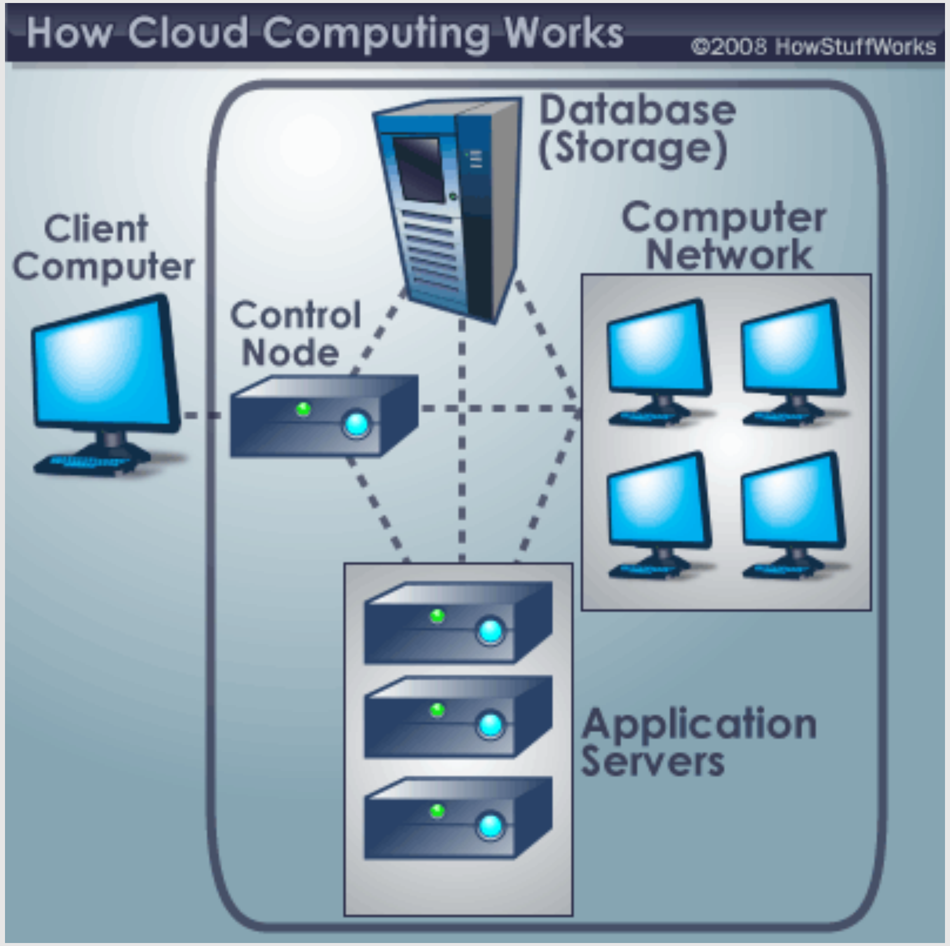
Water Distribution



Electric Grid

Increased connectivity

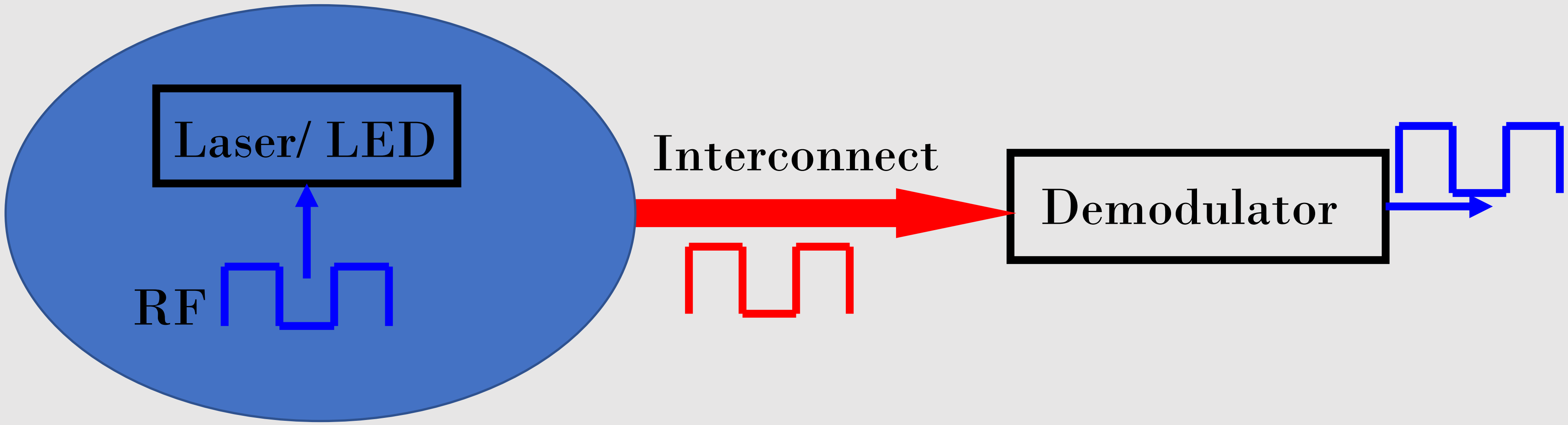
- Future : cloud computing; parallel computing; ubiquitous computing: more communications
- Massive data centers



More communication channels required.

Low power optoelectronics

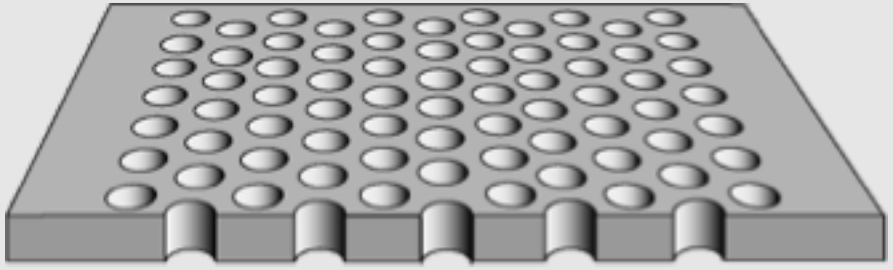
- Switching energy in electronics: 100’s of fJ
- Metallic interconnects are lossy at high frequency
- Huge energy consumption: environmental sustainability issue

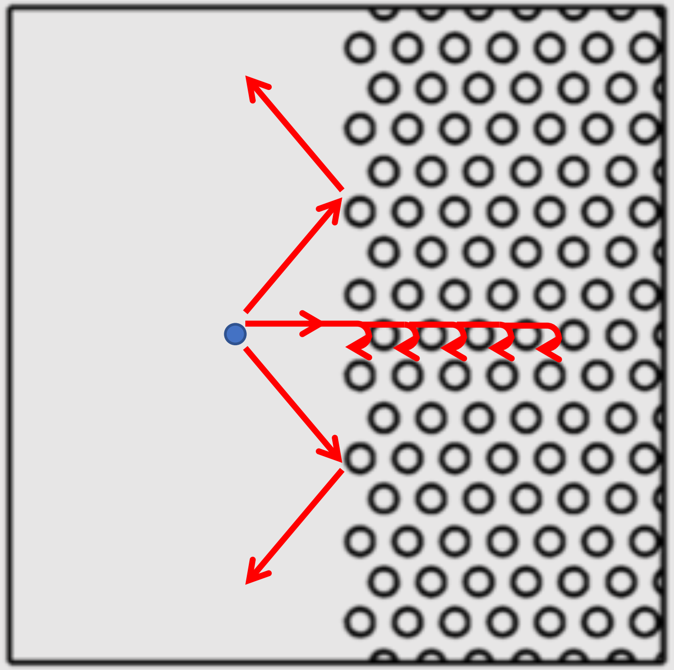


- Use optical signal along with electronic signal
- Efficient (low energy, fast) modulator and (sensitive, fast) detector
- To bring optics to chip scale: energy required attojoule (~10 photons)

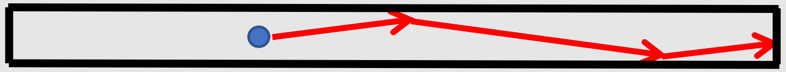
David Miller, Proc. IEEE Special Issue on Silicon Photonics, 2009.

Photonic Crystal Resonator

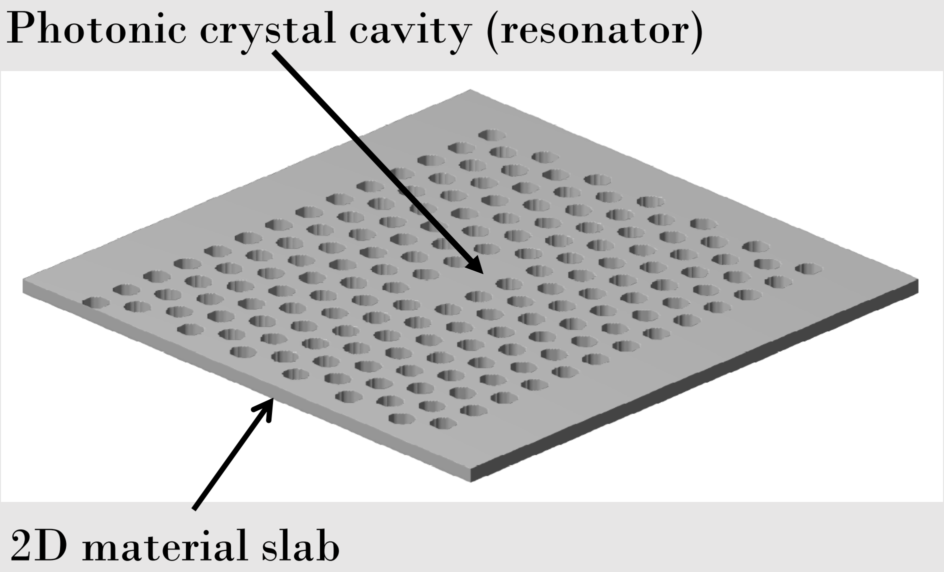


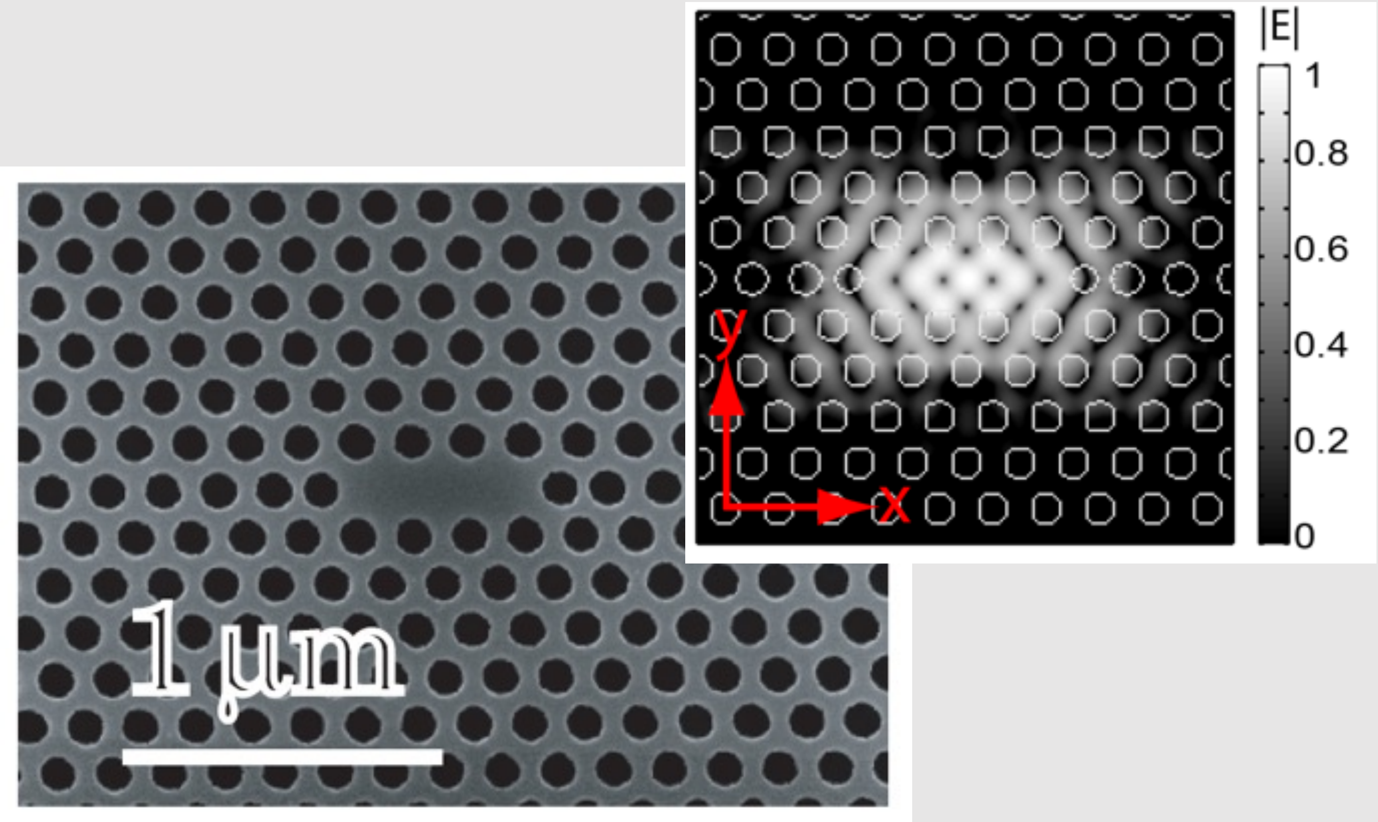


Distributed Bragg Reflection

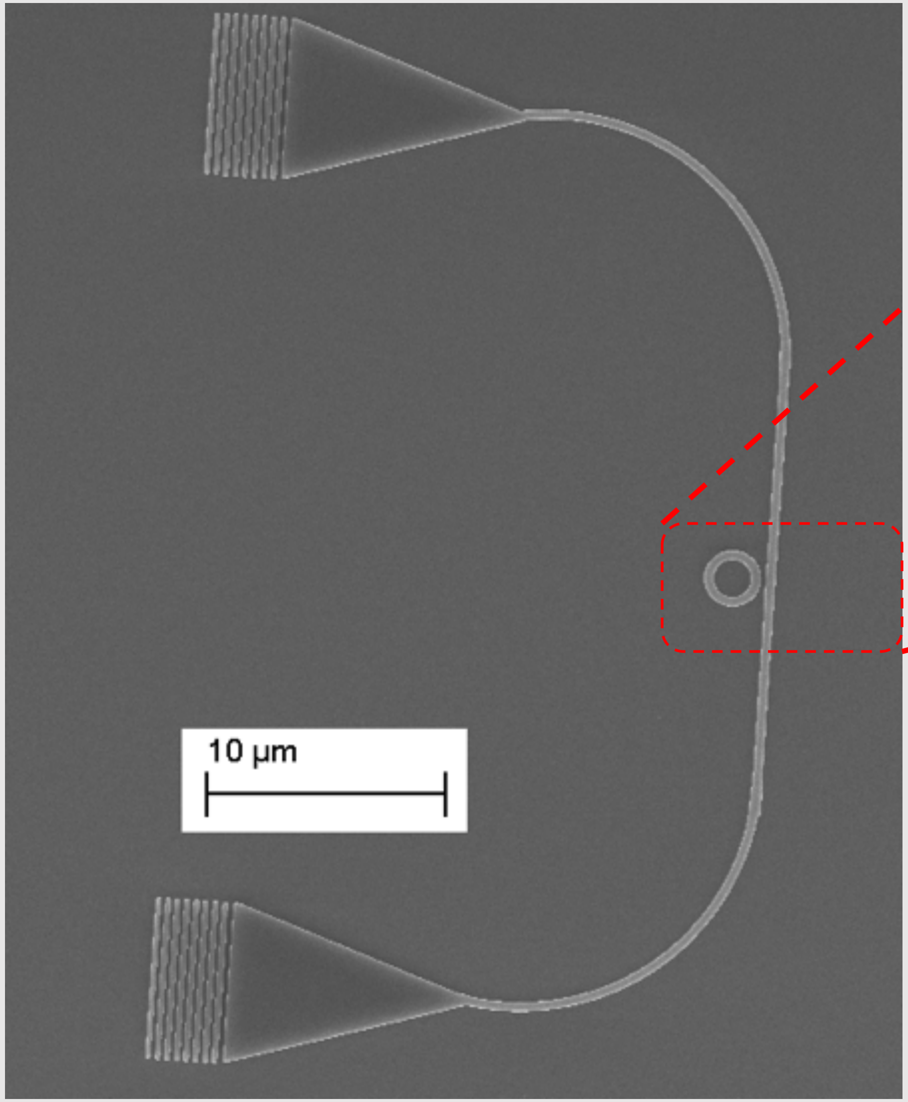


Total Internal Reflection

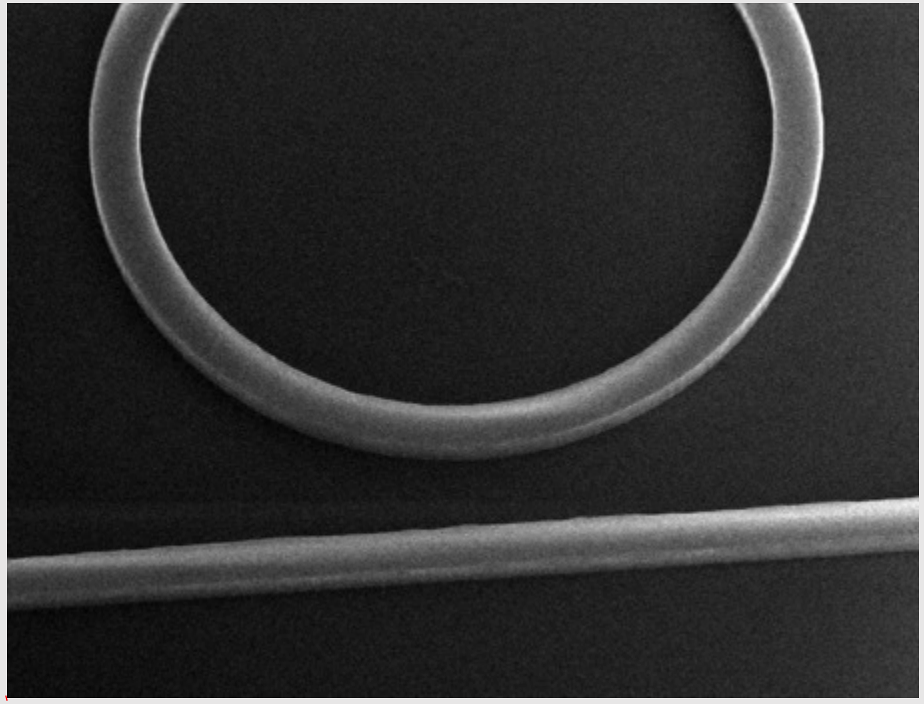


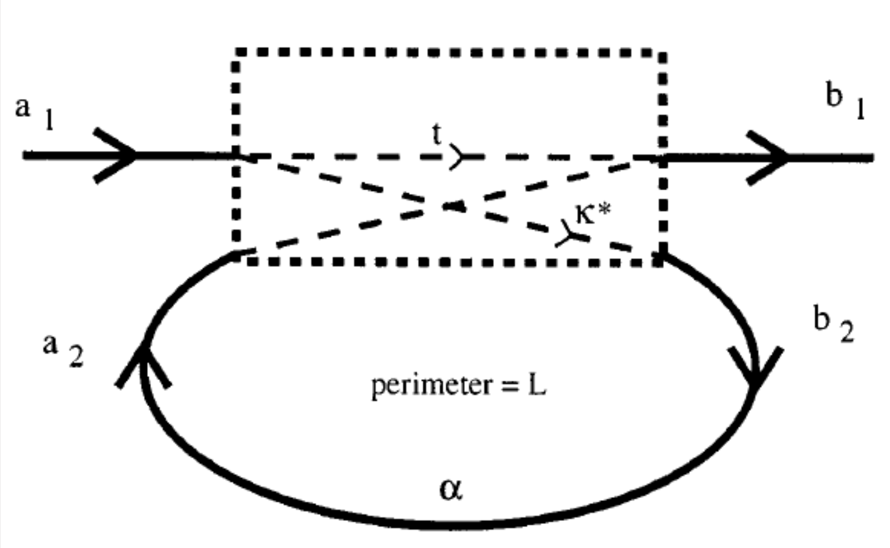


Whispering gallery mode resonator



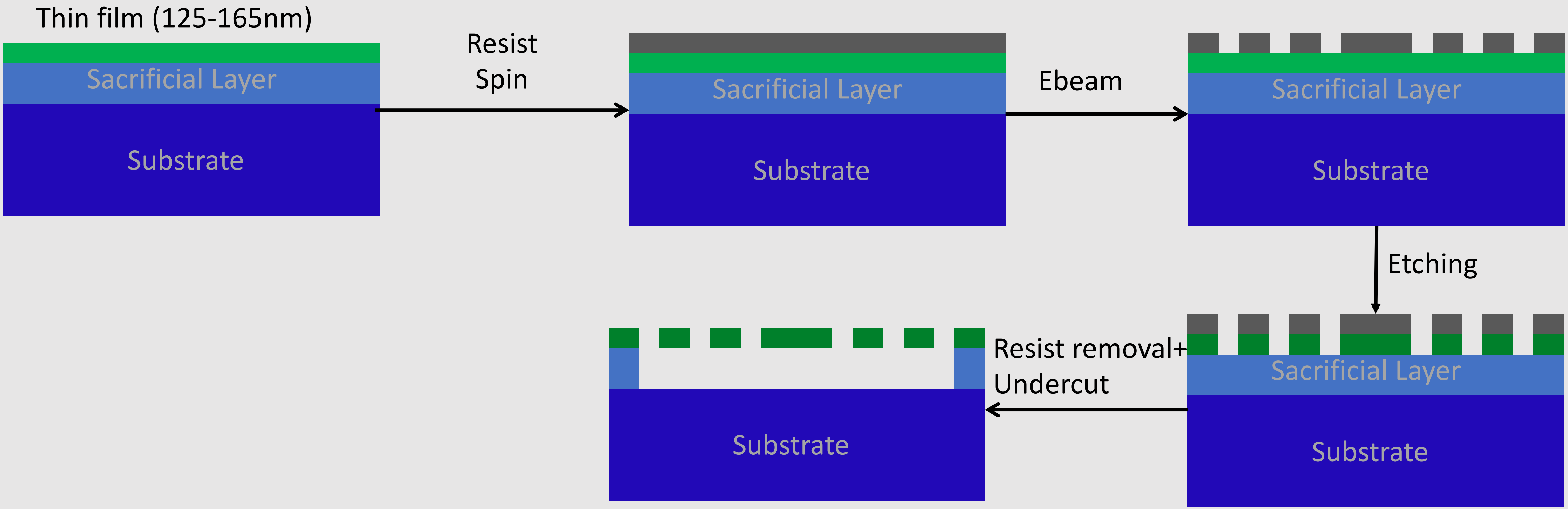
Travelling wave resonator



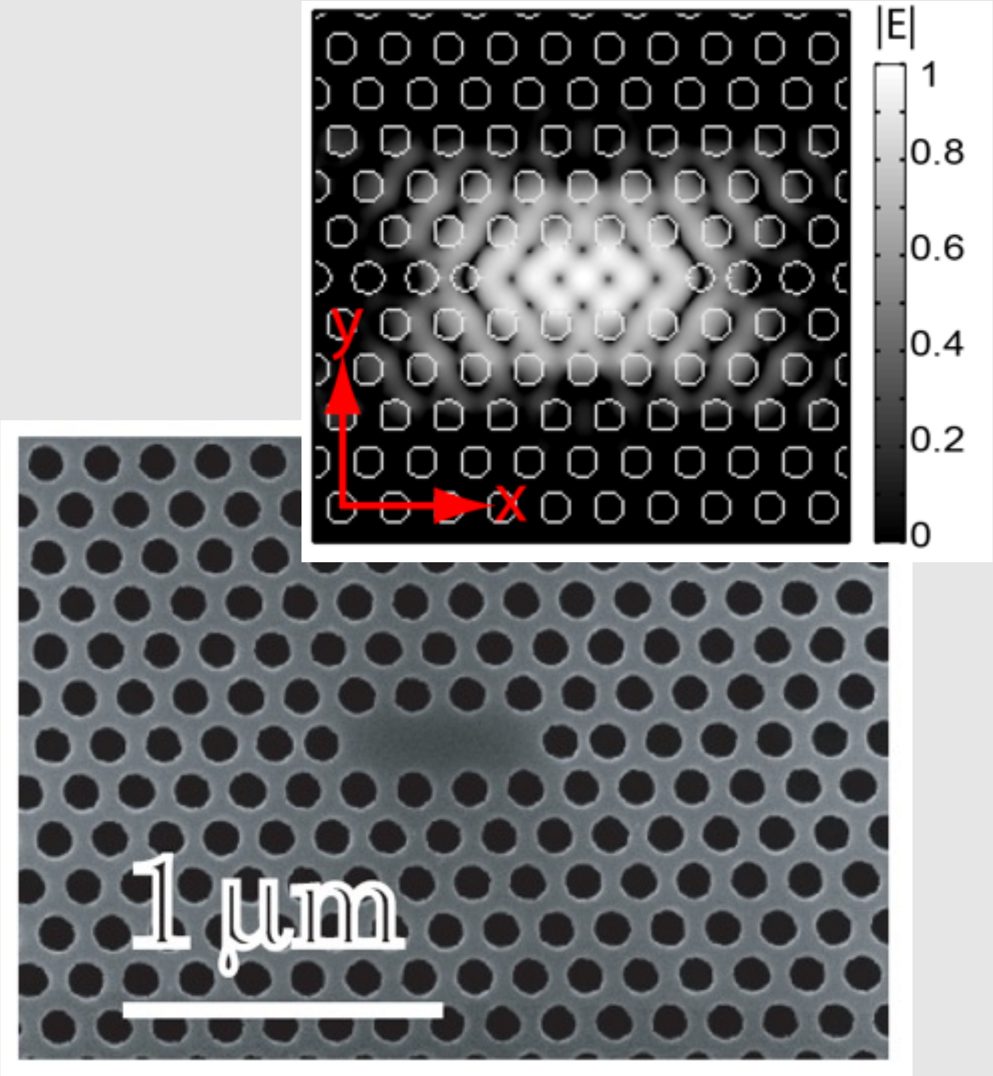


IEEE PTL, VOL. 14, NO. 4, APRIL 2002

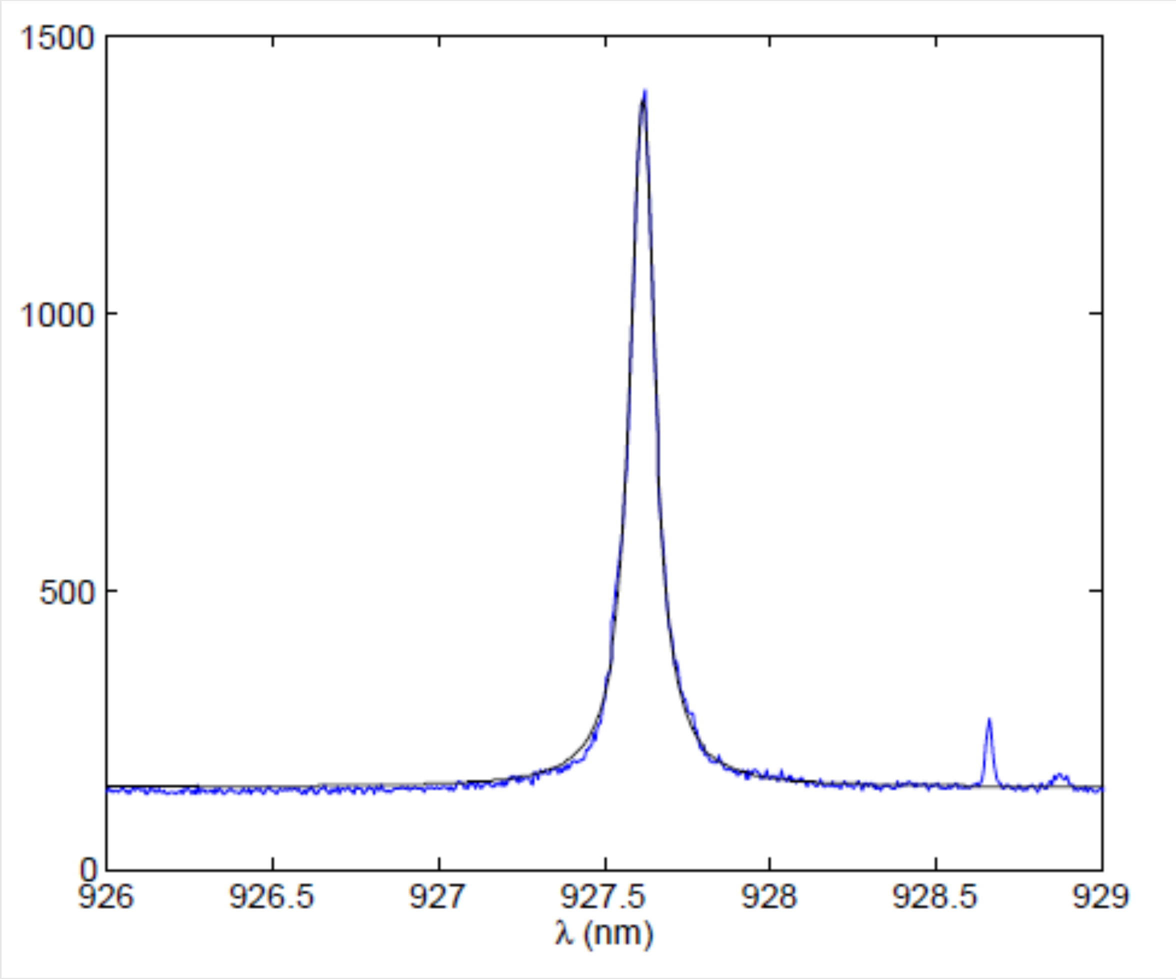
Cavity fabrication



Low mode volume (V) and high quality factor (Q) cavity



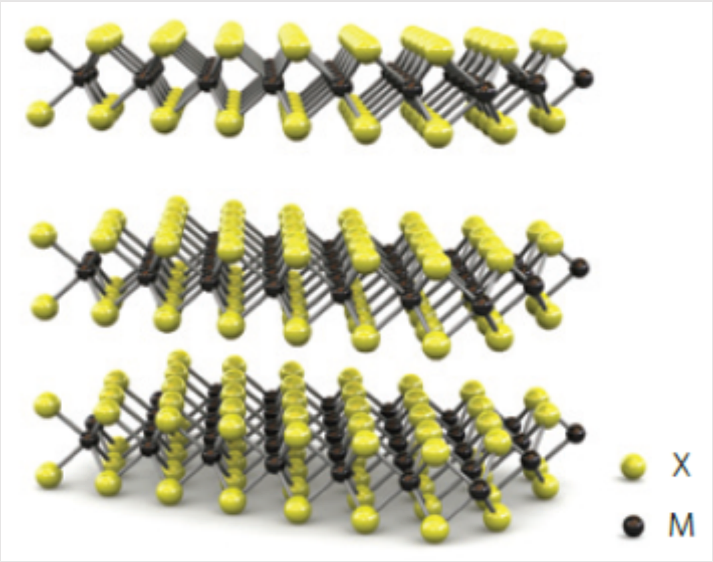
Confinement volume: 0.7 $(\lambda/n)^3$



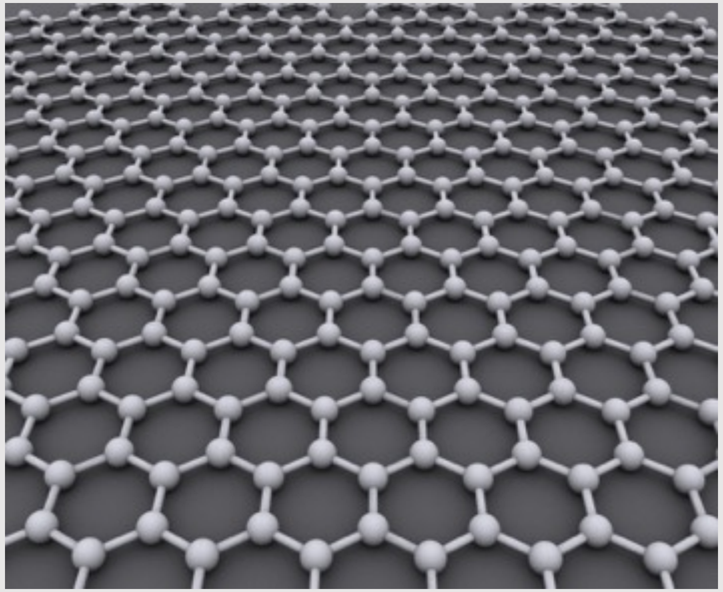
Quality Factor: 10000

Maximize Q/V

2D materials: Ideal material for hybrid photonics

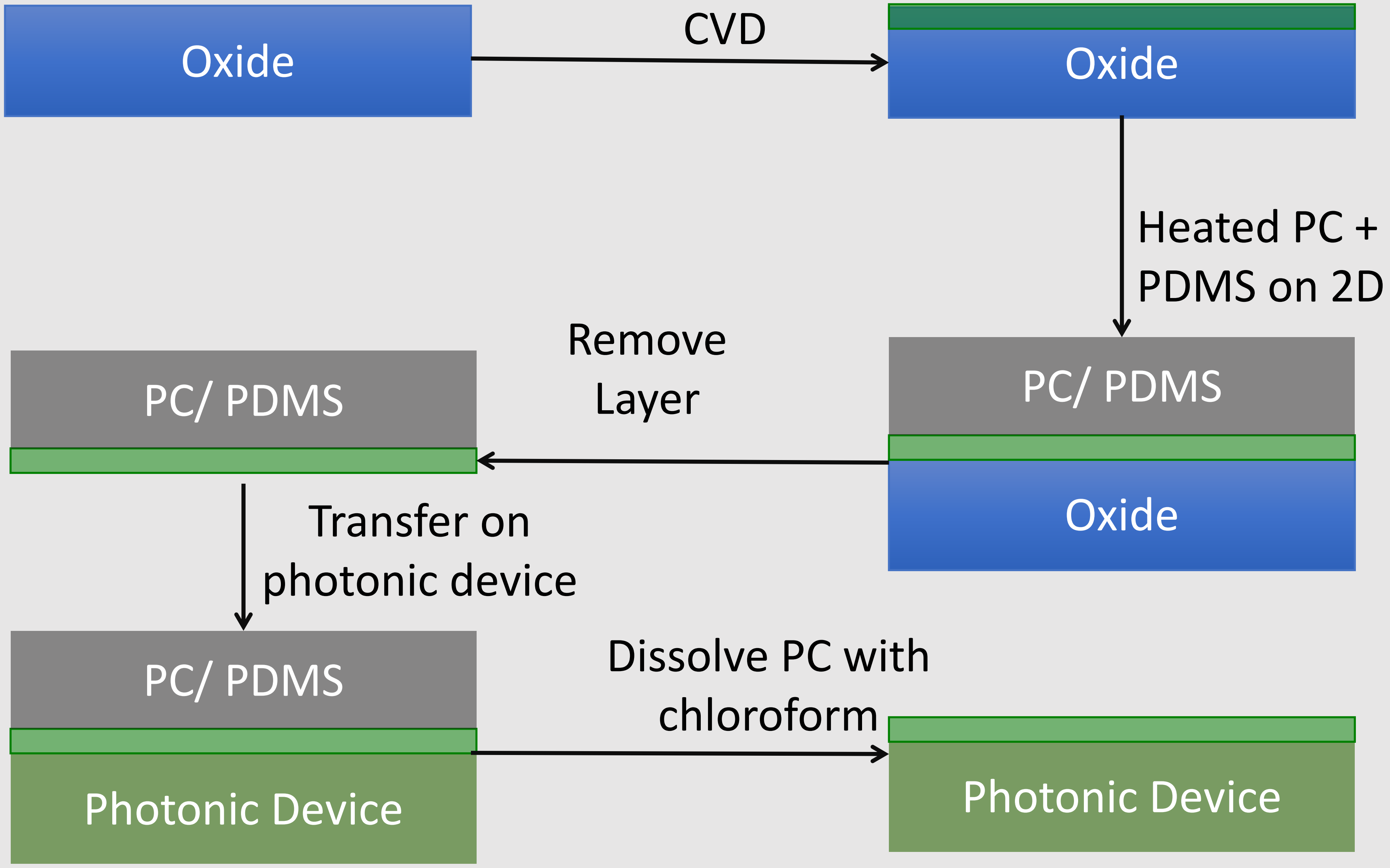


Nature nanotechnology, 7, 699, 2012

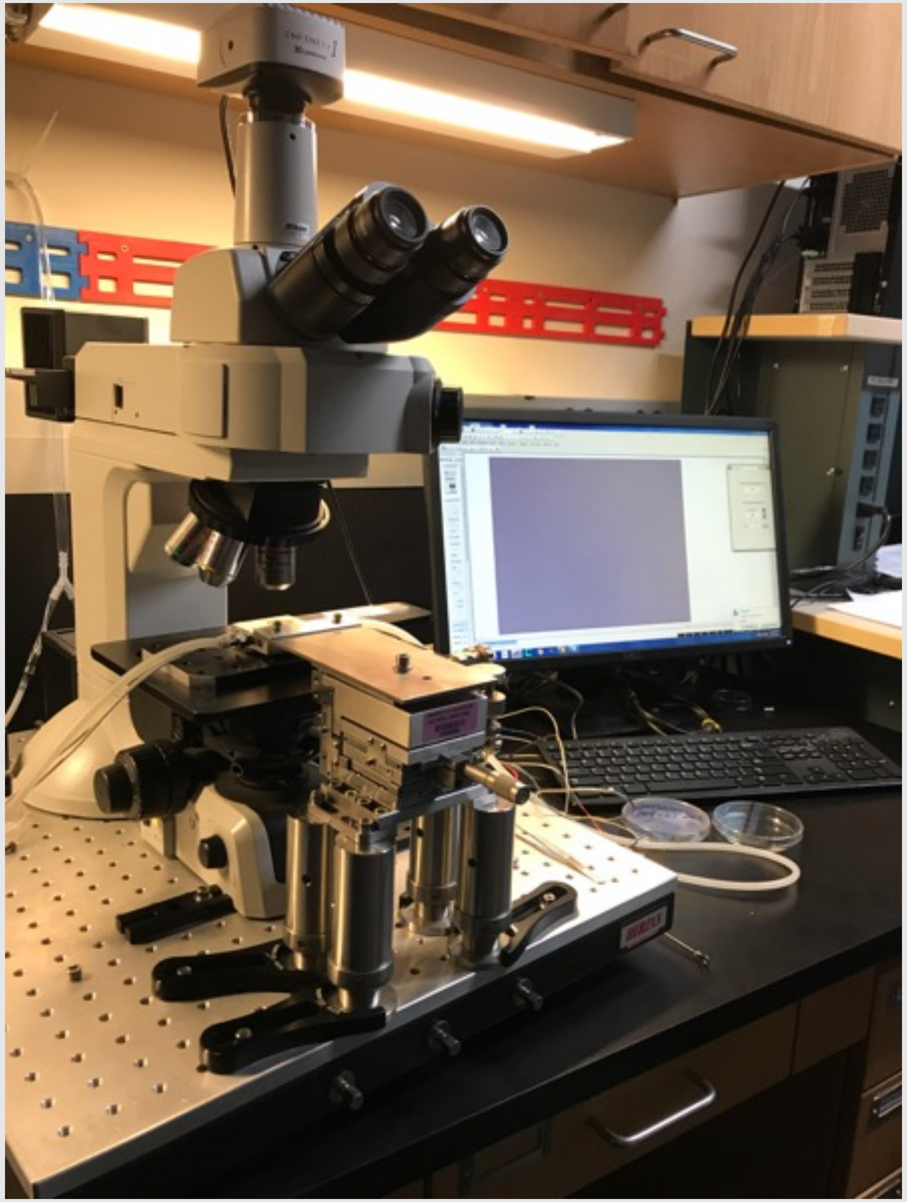


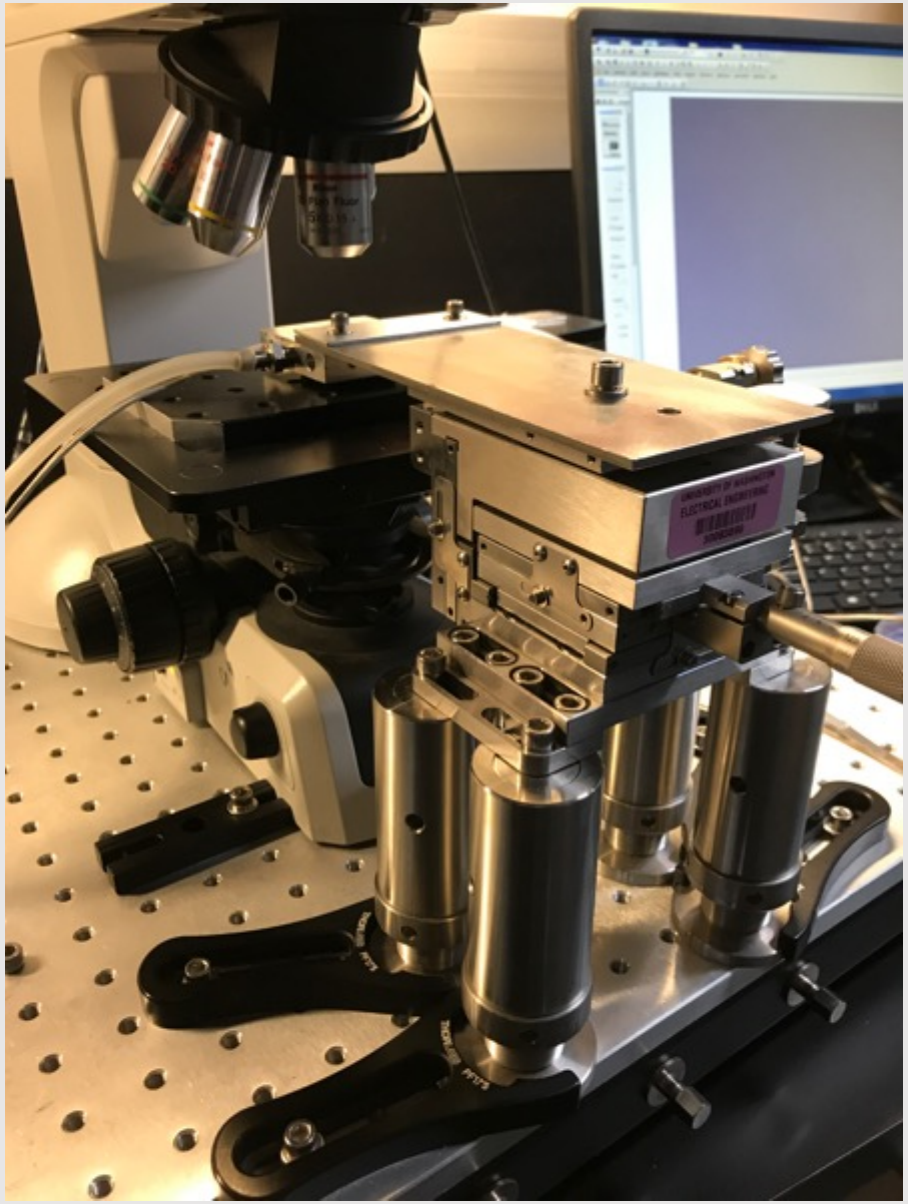
- Unique and advantageous properties
  - Graphene – extremely high carrier mobility
  - Transition metal dichalcogenides – strong emission and second-order nonlinearity
- Low control energy due to small active volume
- Enable quantum well like functionality.
- No explicit lattice matching is required and can be transferred on any material system.
- The thinness is ideal for evanescent coupling.
- Resonator provides an opportunity to enhance light-matter interaction

2D material transfer

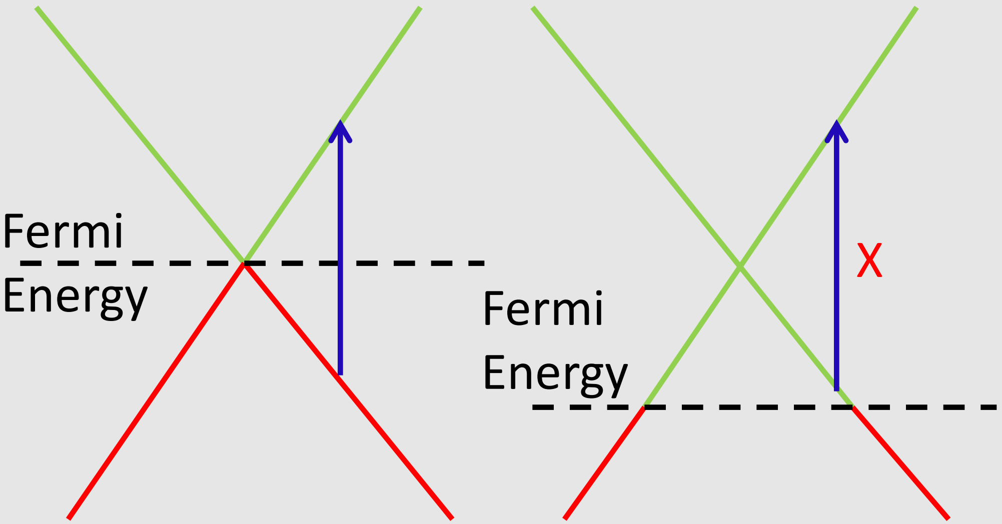


Transfer Stage





Electro-optics with graphene

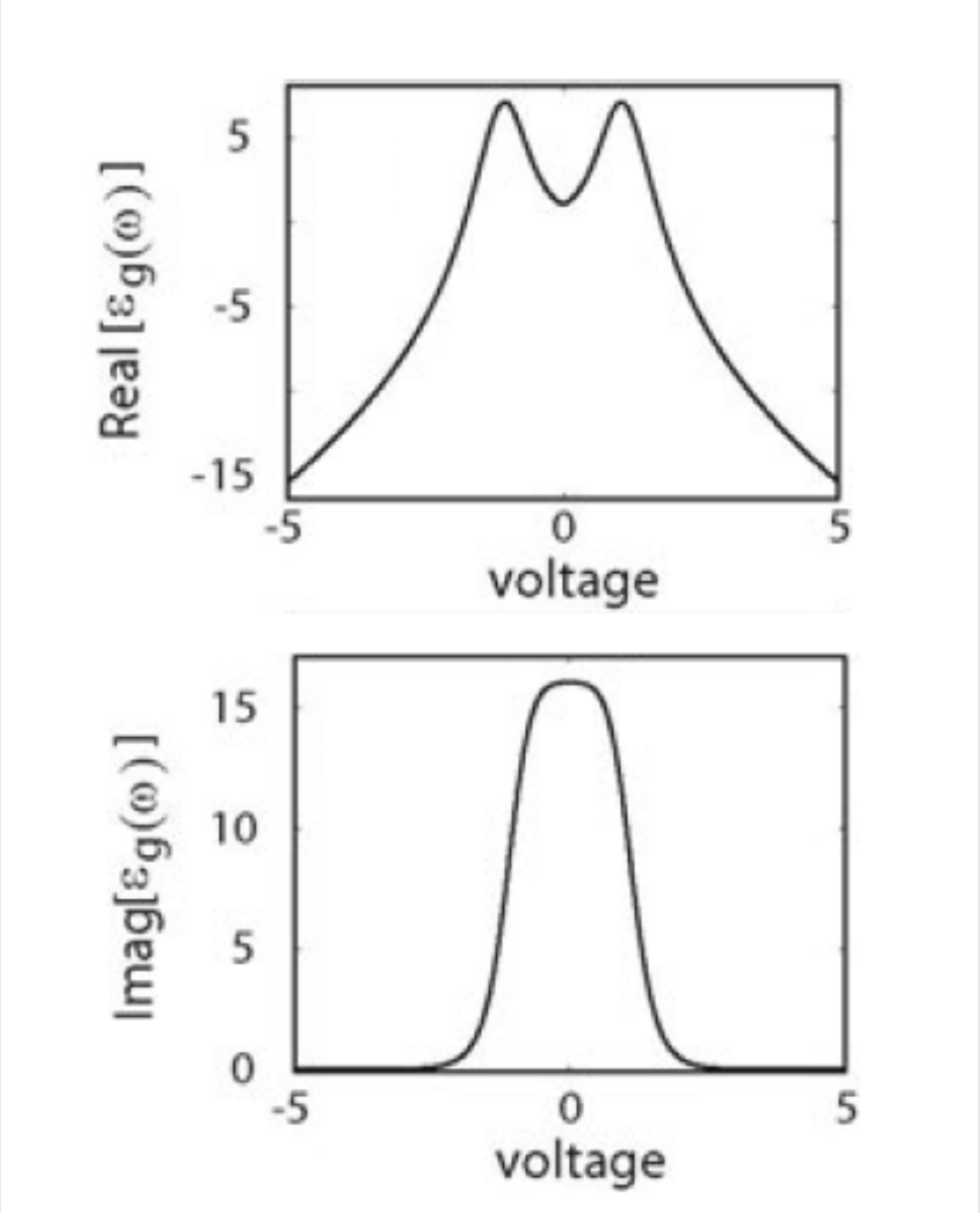


Properties of graphene:

- High carrier mobility.
- Large broadband absorption.
- Ease of electrical control.

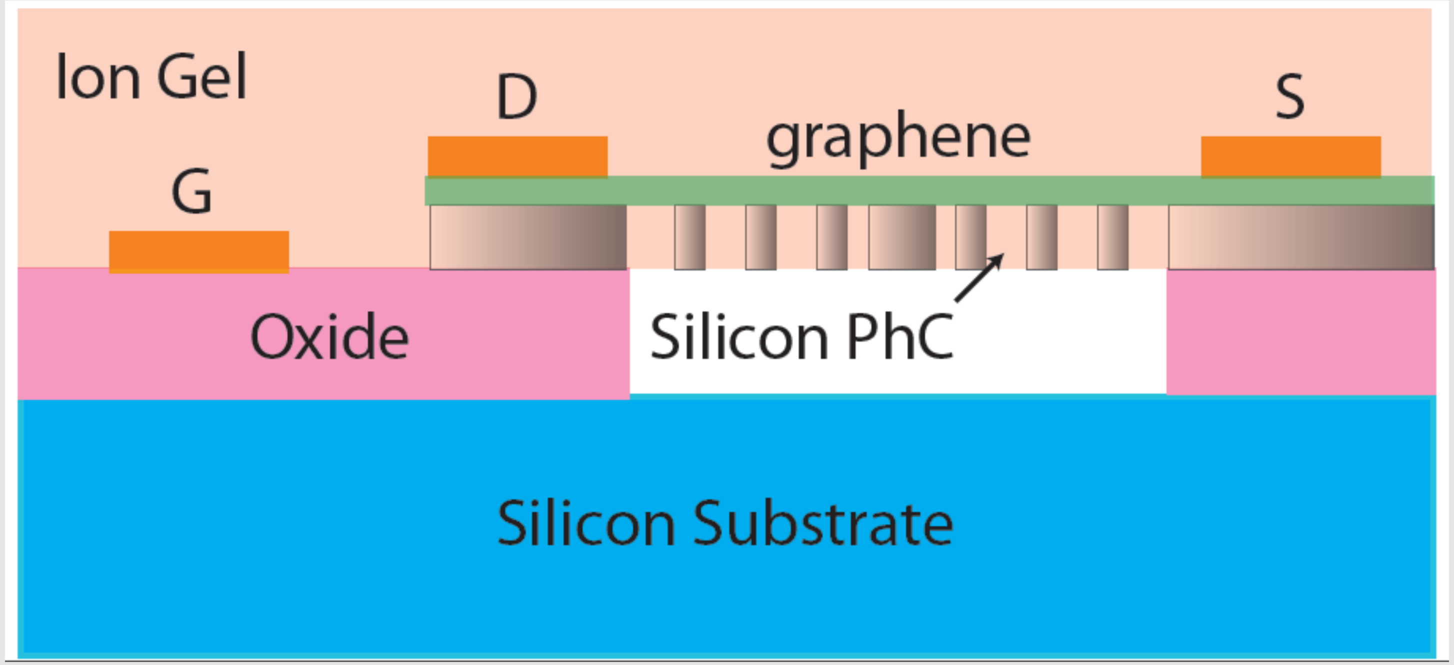
Large fractional change in refractive index

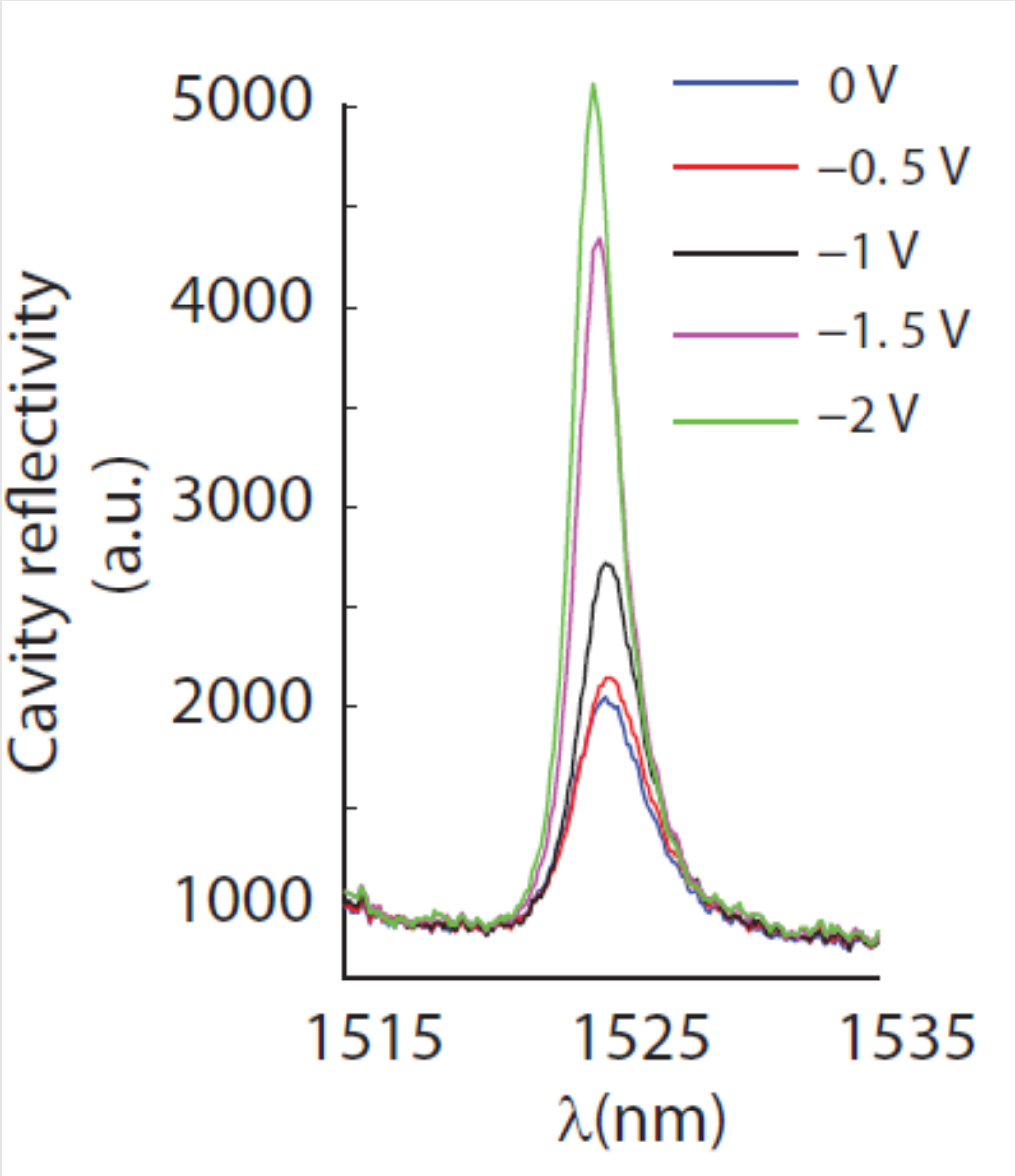
- Electro-optic modulation
- Optical beam steering
- Reflective display
- Solid-state spatial light modulator



Arka Majumdar et. al., IEEE Journal of Selected Topics in Quantum Electronics Vol. 20, 1 (2014)

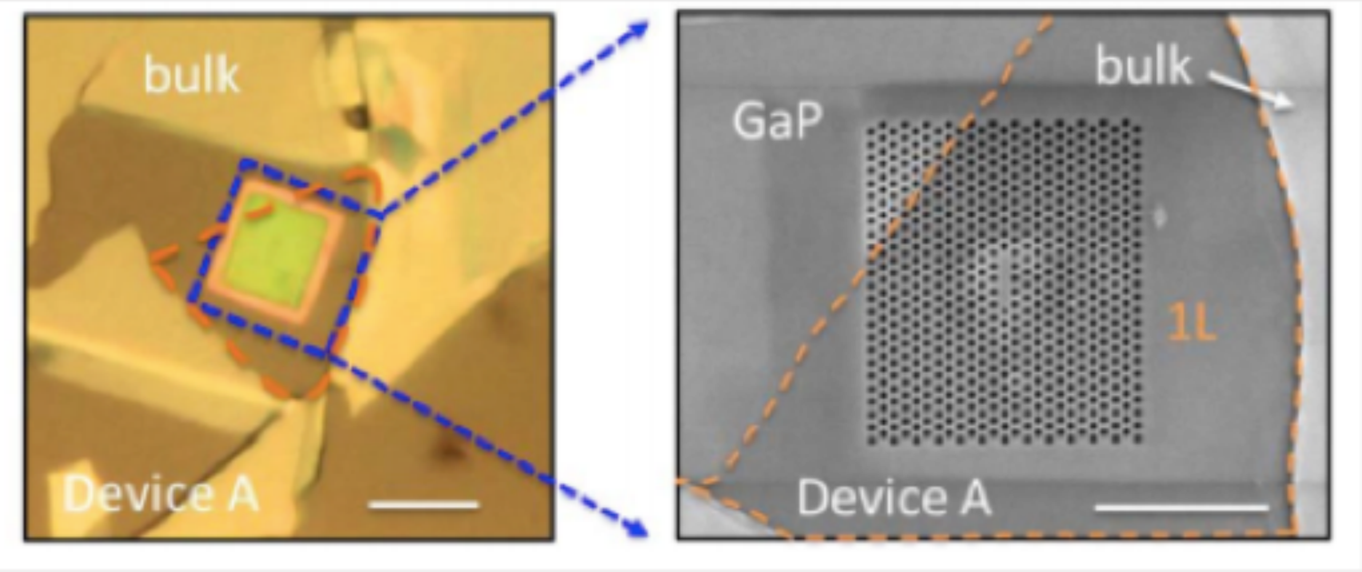
Electrical Control



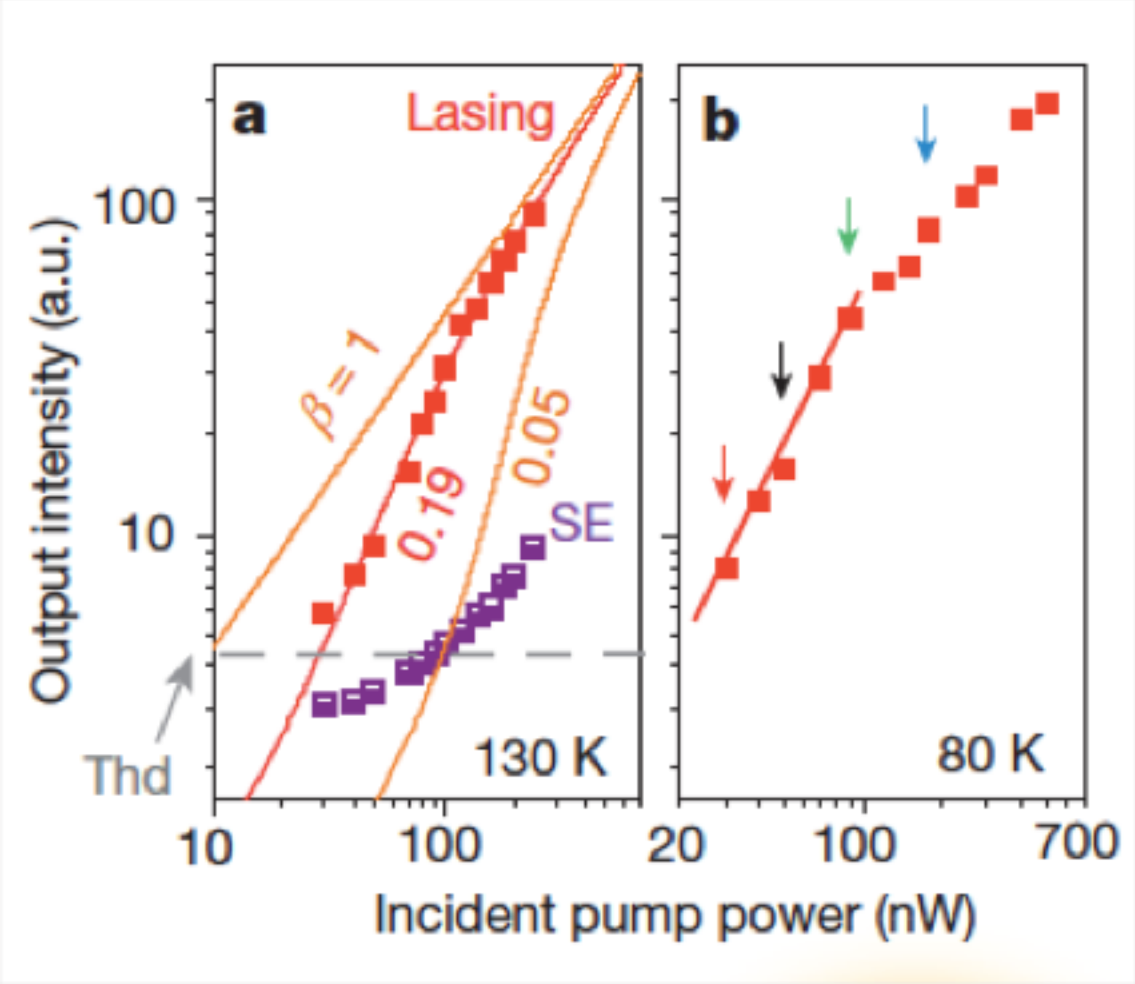


Arka Majumdar et. al., Nano Letters, 13 (2), 515-518, (2013)

WSe_2 coupled to gallium phosphide photonic crystal

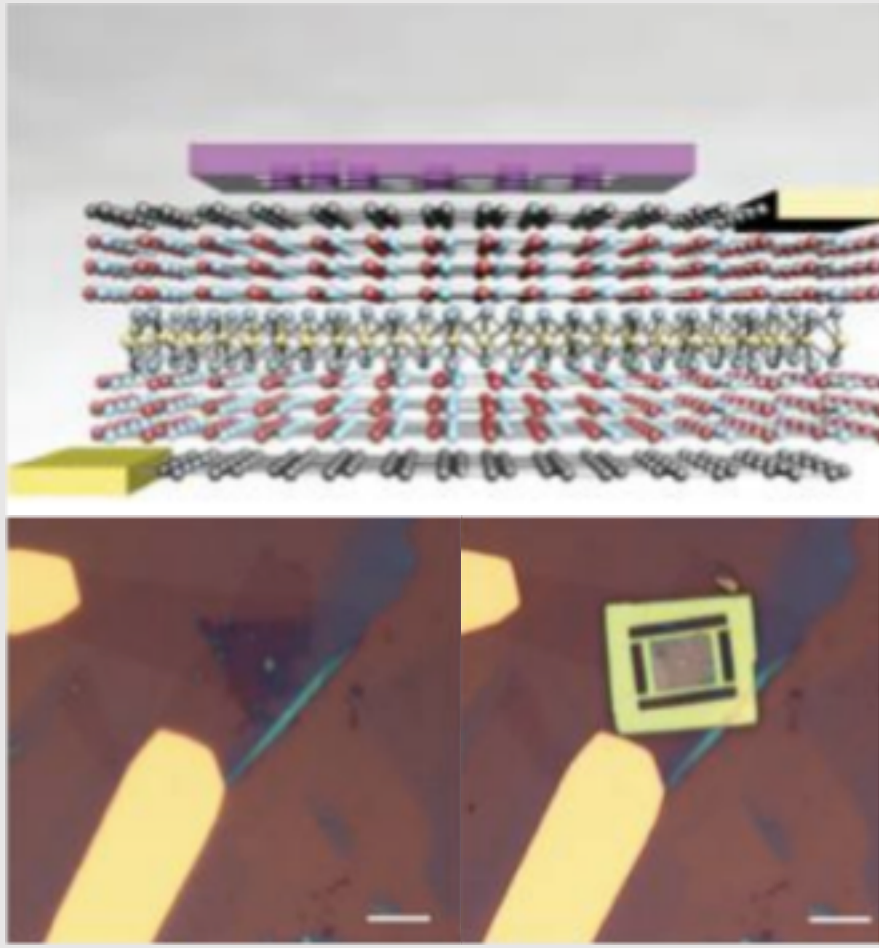


Majumdar & Xu, 2D Mater. 1 (2014) 011001

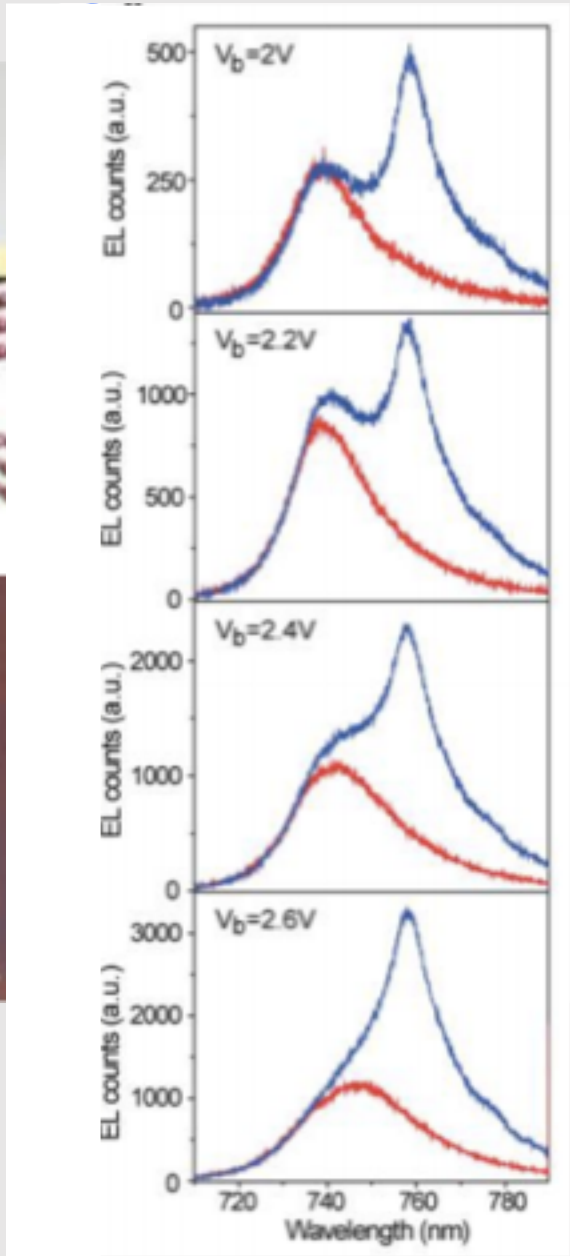


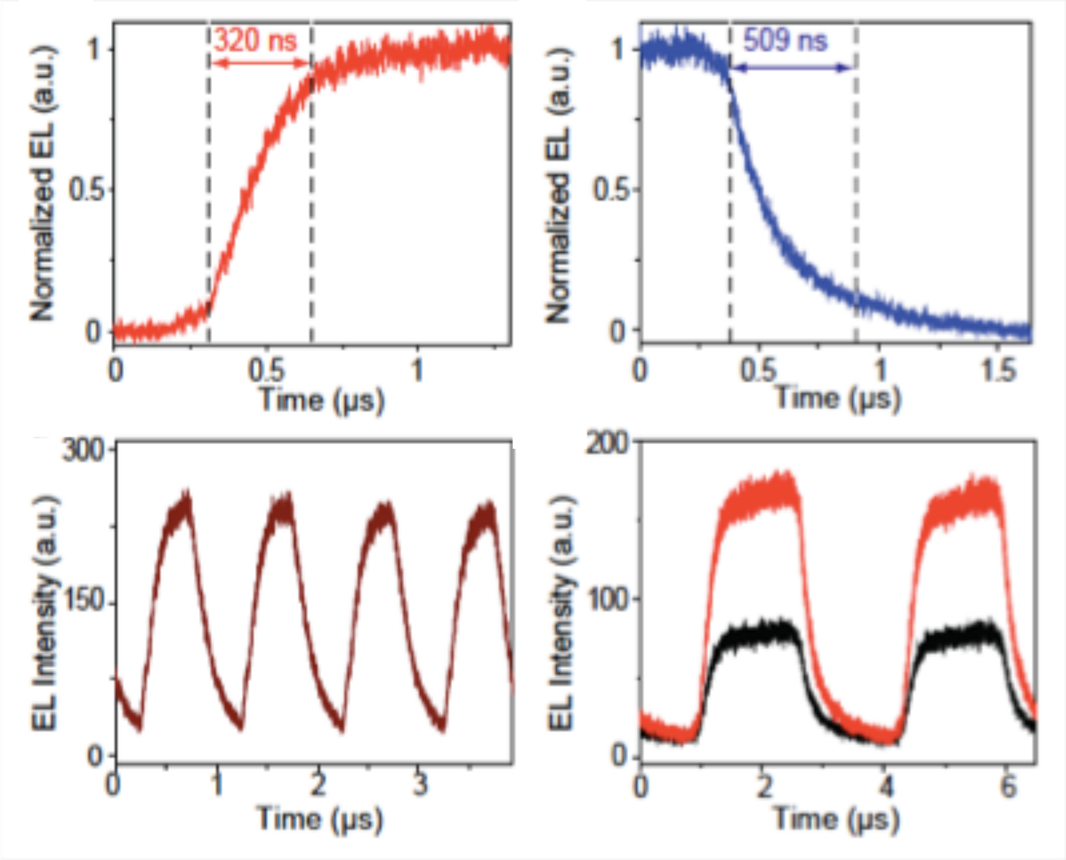
Majumdar and Xu, Nature, 520, 69-72, 2015
Also shown by: Xiang Zhang (UCB)
Y. Li, Nature Nanotechnology (2017)

Cavity enhanced electroluminescence at room temperature



Majumdar Lab, Nano Letters, 2016



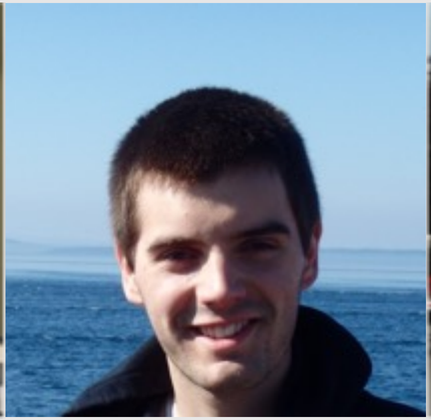


1MHz modulation speed

Team and Funding (Email: arka@uw.edu
Lab: http://labs.ee.washington.edu/amlab/)

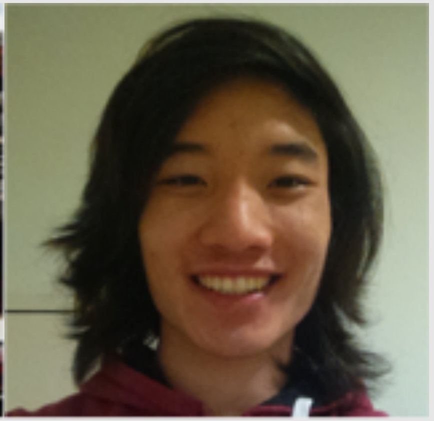
Arka

Taylor



Shane

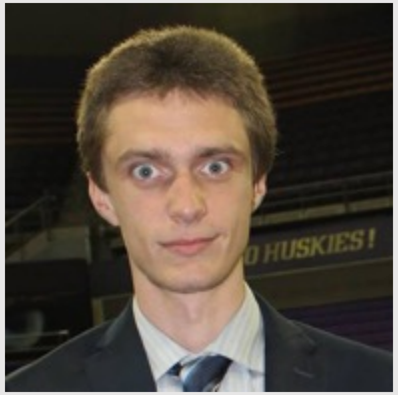
Jiajiu



Alan

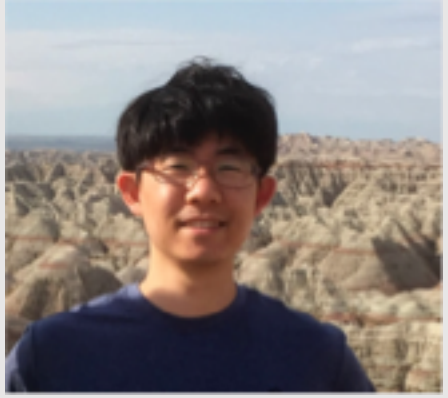
Elyas

David



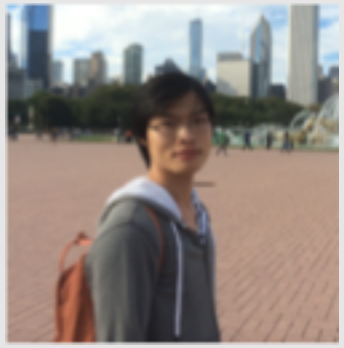
James

Yueyang



Albert

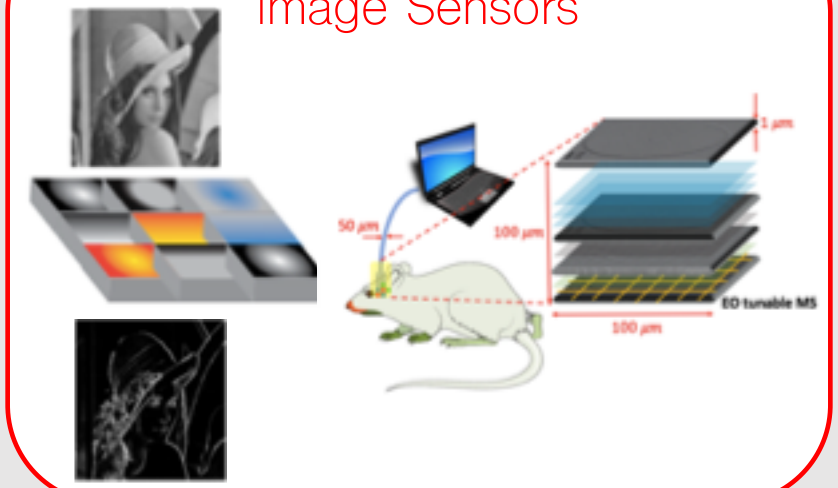
Chris
(Currently in Apple)



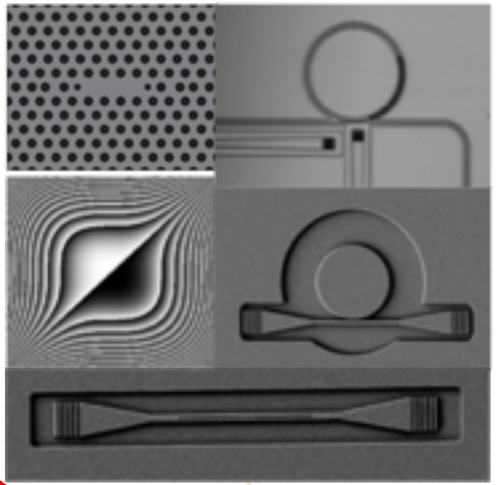
Chang-hua
(Currently in NTSU)

Nano-Optoelectronic Integrated System Engineering (NOISE) Lab
(Electrical Engineering + Physics)

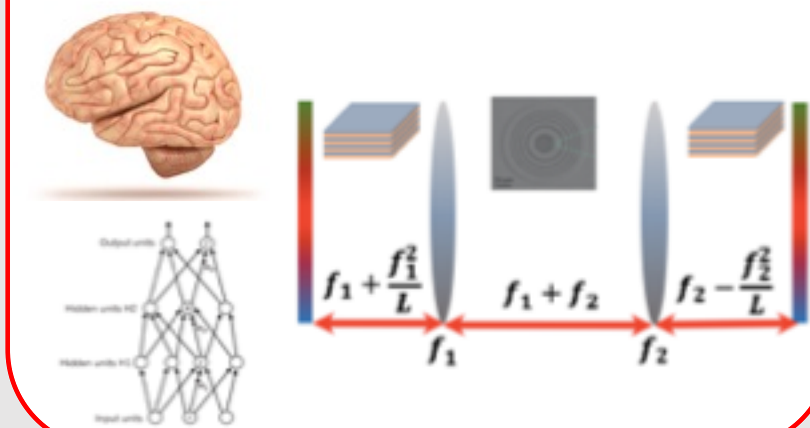
Nanophotonic Computational Image Sensors



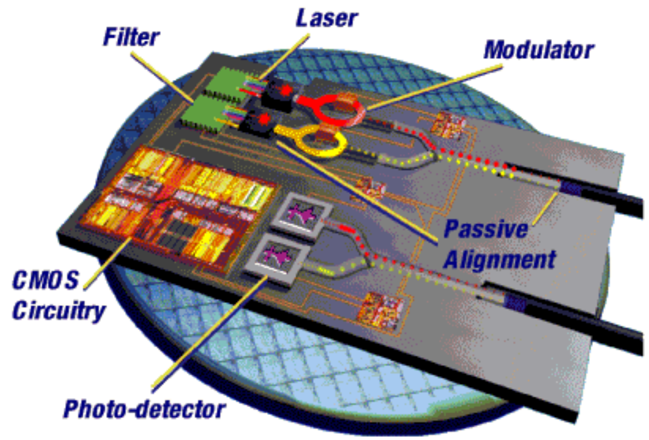
Light



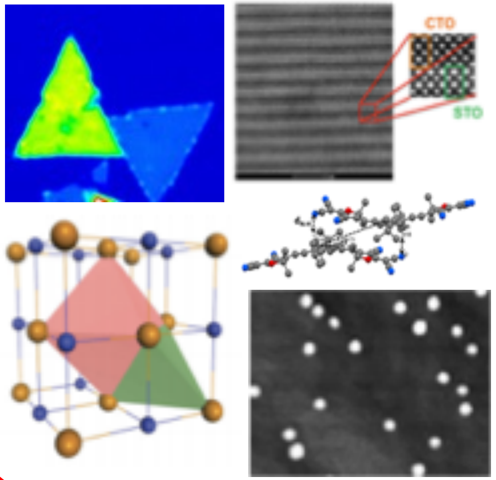
Nonlinear Image Processing and Monolithic Optical Neuron



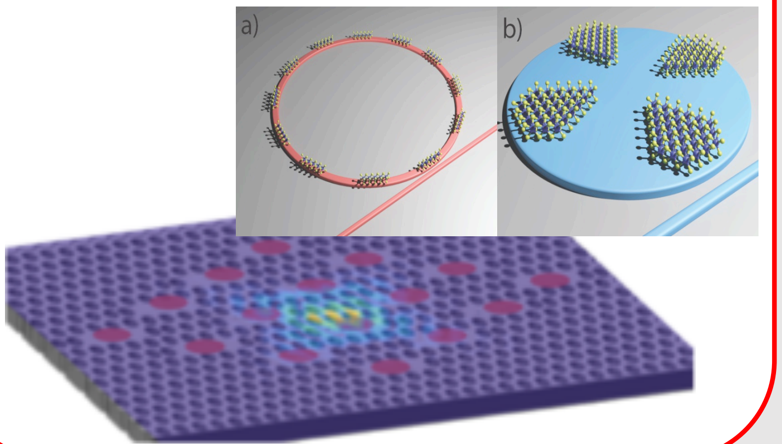
Hybrid Integrated Photonics



Matter



Quantum many-body simulation with photons



Sorger & Majumdar, Fundamental Scaling Laws in Nanophotonics, Scientific Reports 6, Article number: 37419, (2016).