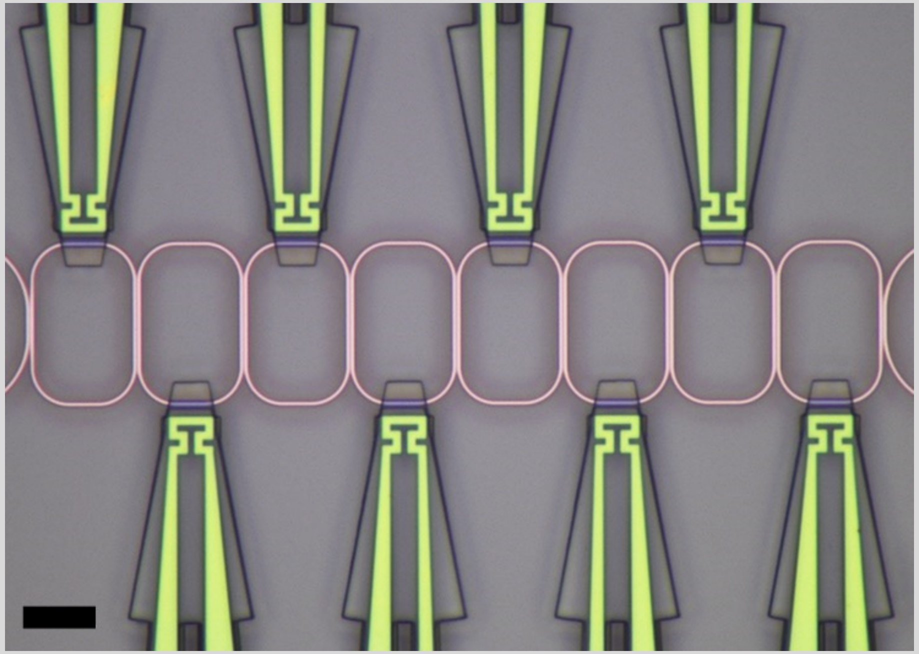
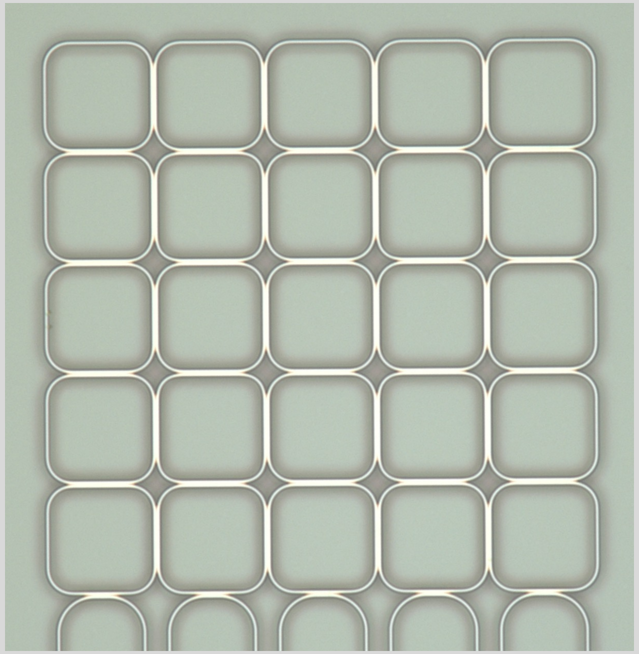
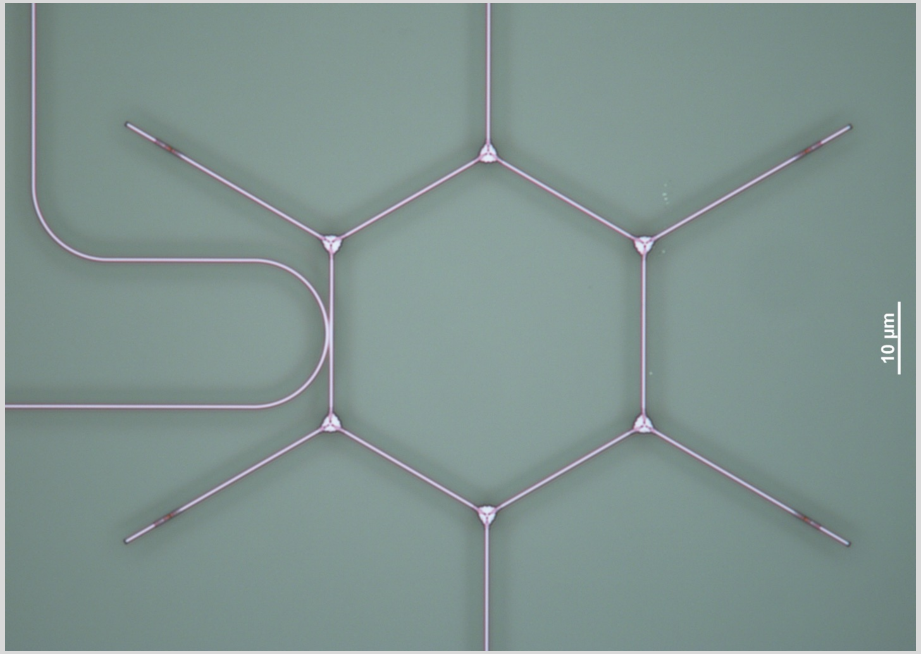
Hamiltonian engineering using coupled cavity arrays







Arnab Manna, Abhi Saxena, Rahul Trivedi, Arka Majumdar

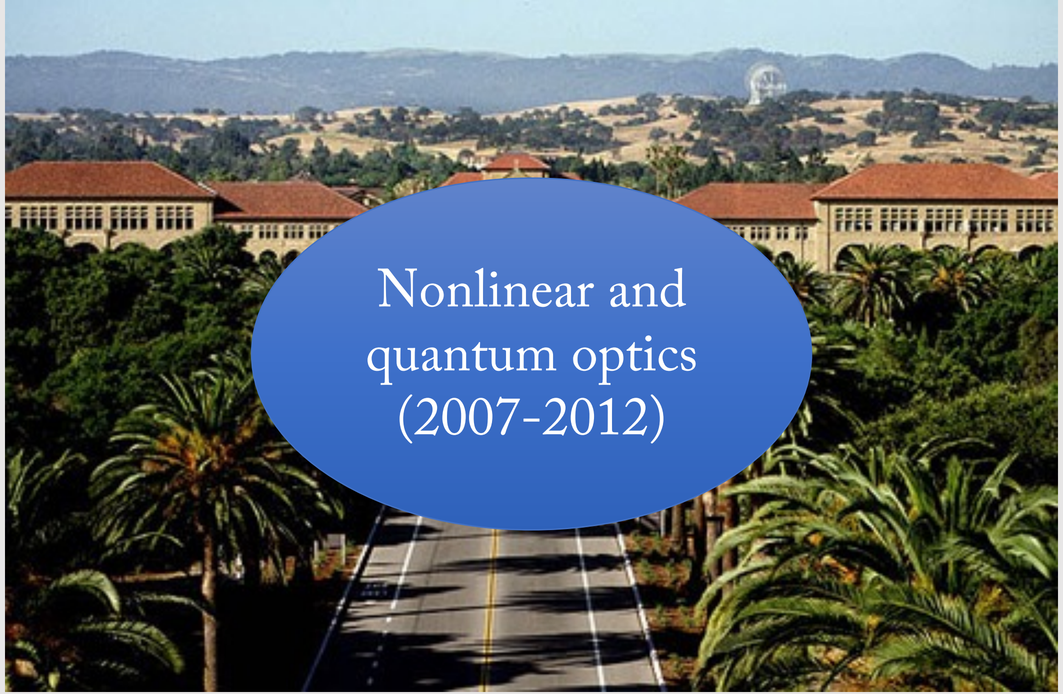
Electrical and Computer Engineering and Physics Department

University of Washington, Seattle

https://labs.ece.washington.edu; Email: arka@uw.edu

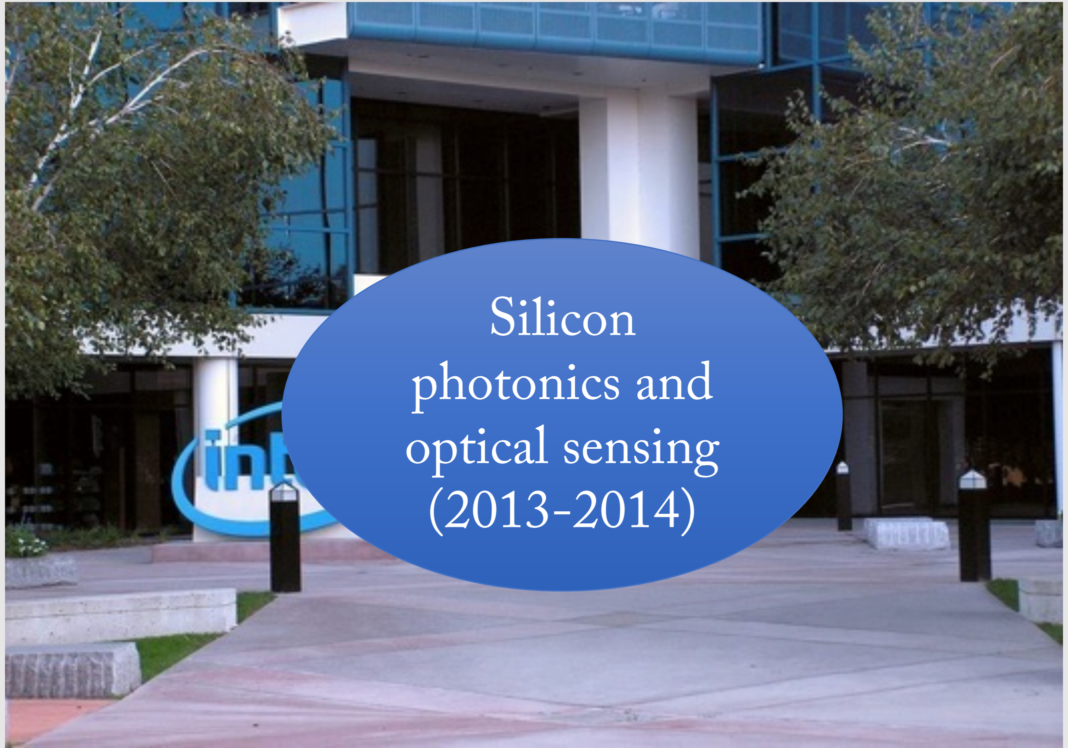
Undergraduate from India

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).

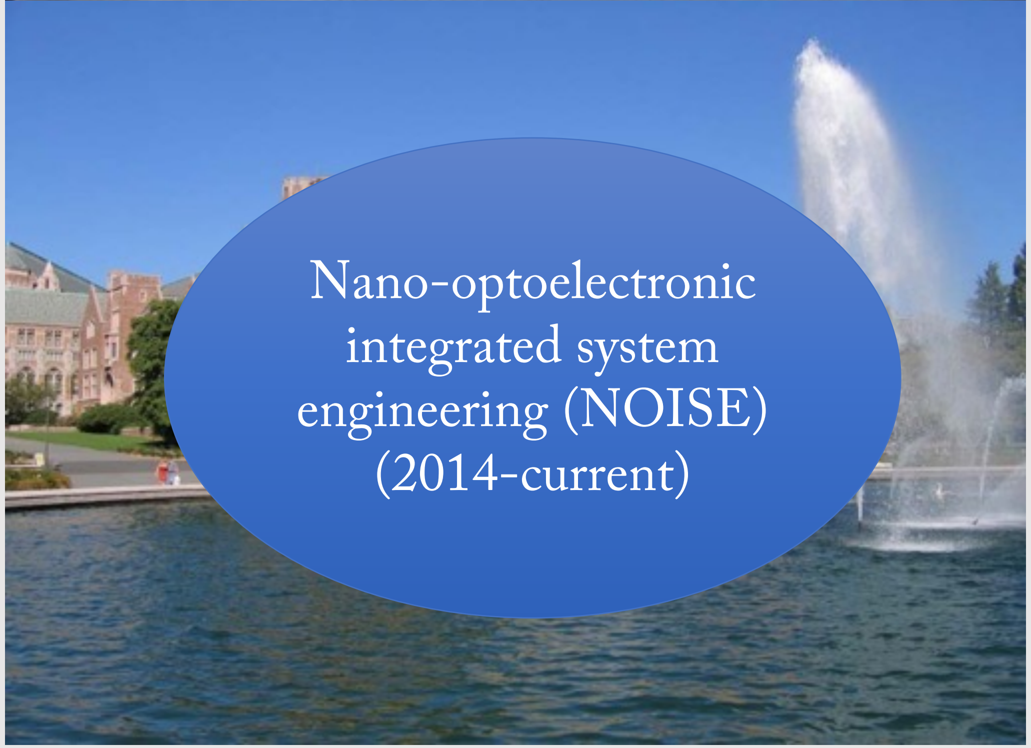


Nonlinear and quantum optics (2007-2012)

New materials: Monolayer material (2012-2013)



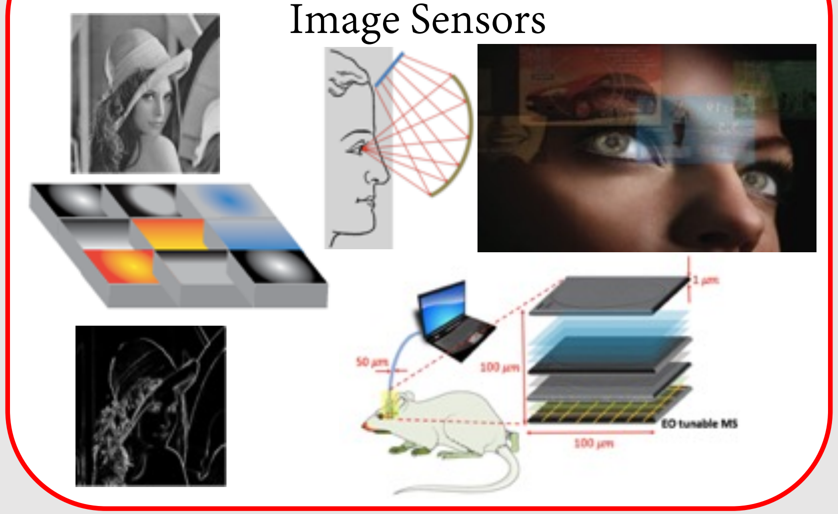
Silicon photonics and optical sensing (2013-2014)



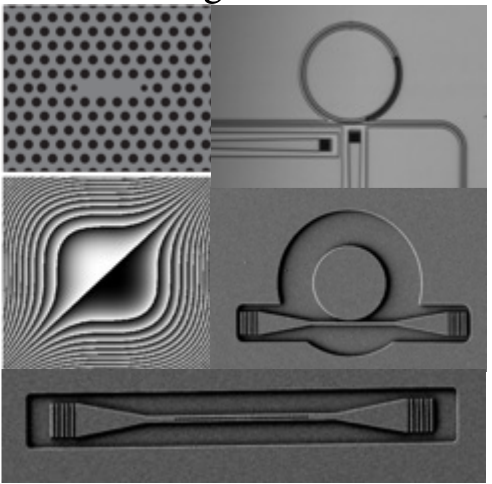
Nano-optoelectronic integrated system engineering (NOISE) (2014-current)

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

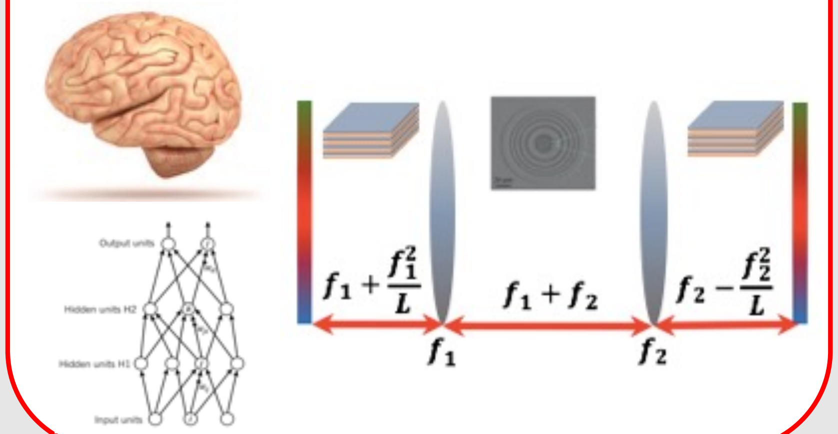
Nanophotonic Computational Image Sensors



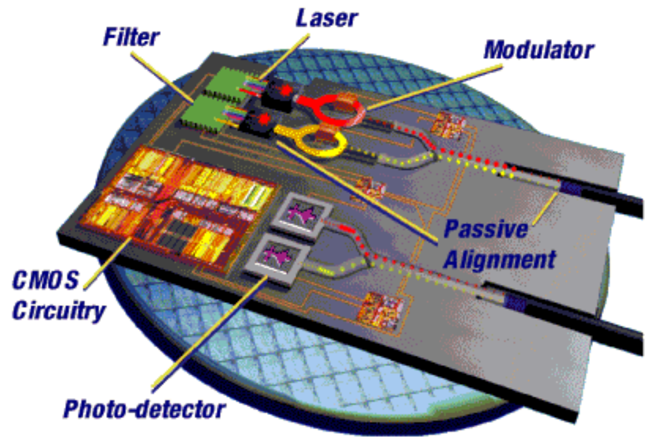
Light



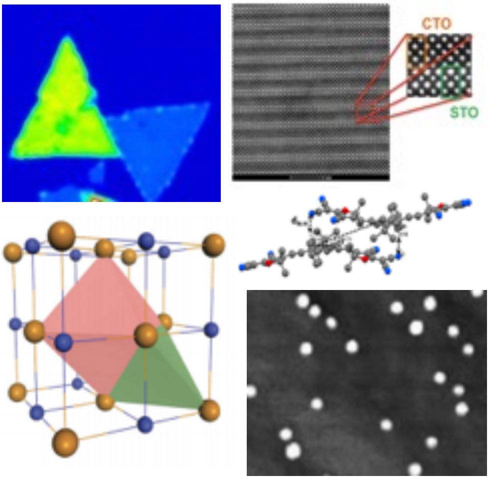
Nonlinear Image Processing and Monolithic Optical Neuron



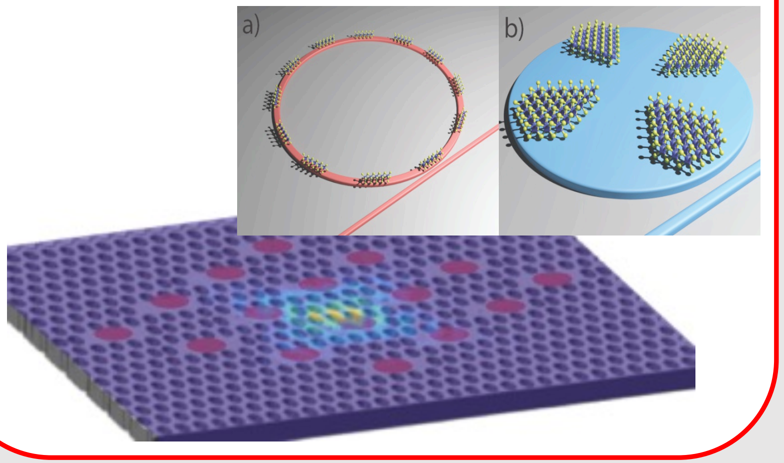
Hybrid Integrated Photonics



Matter

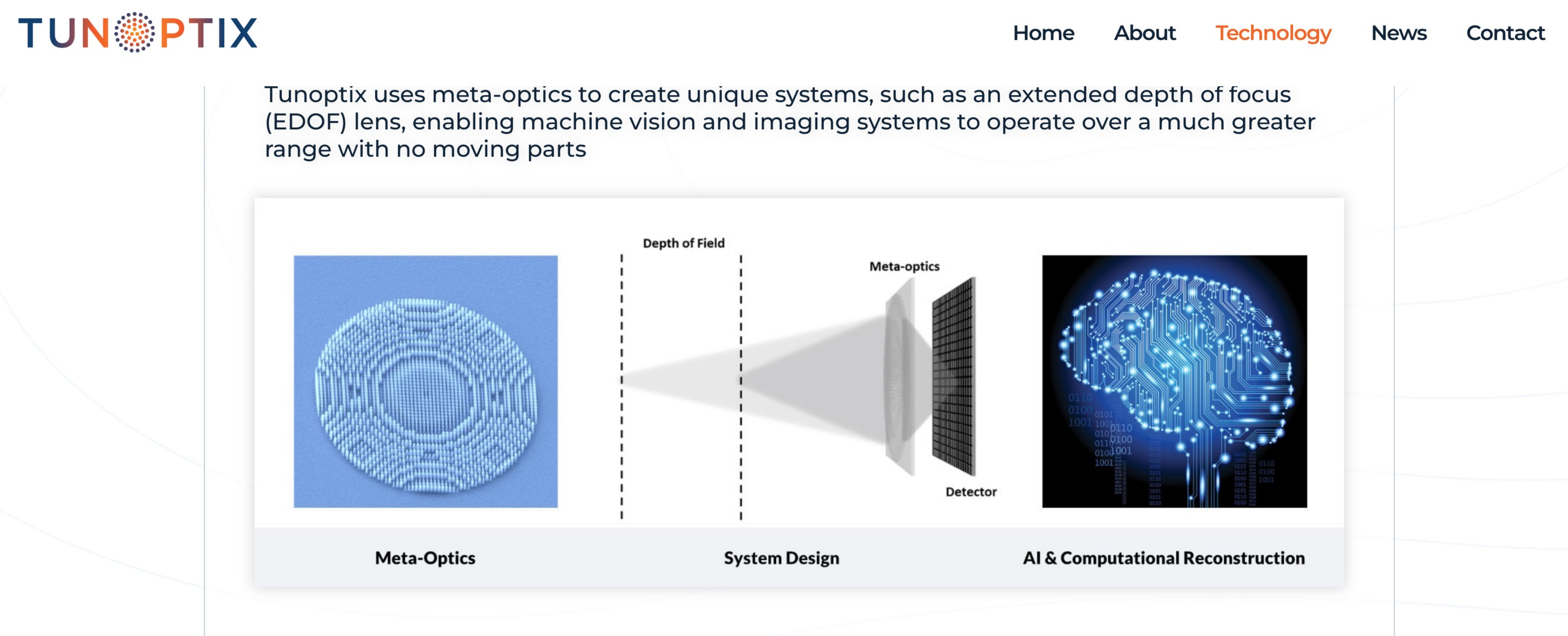


Quantum many-body simulation with photons



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

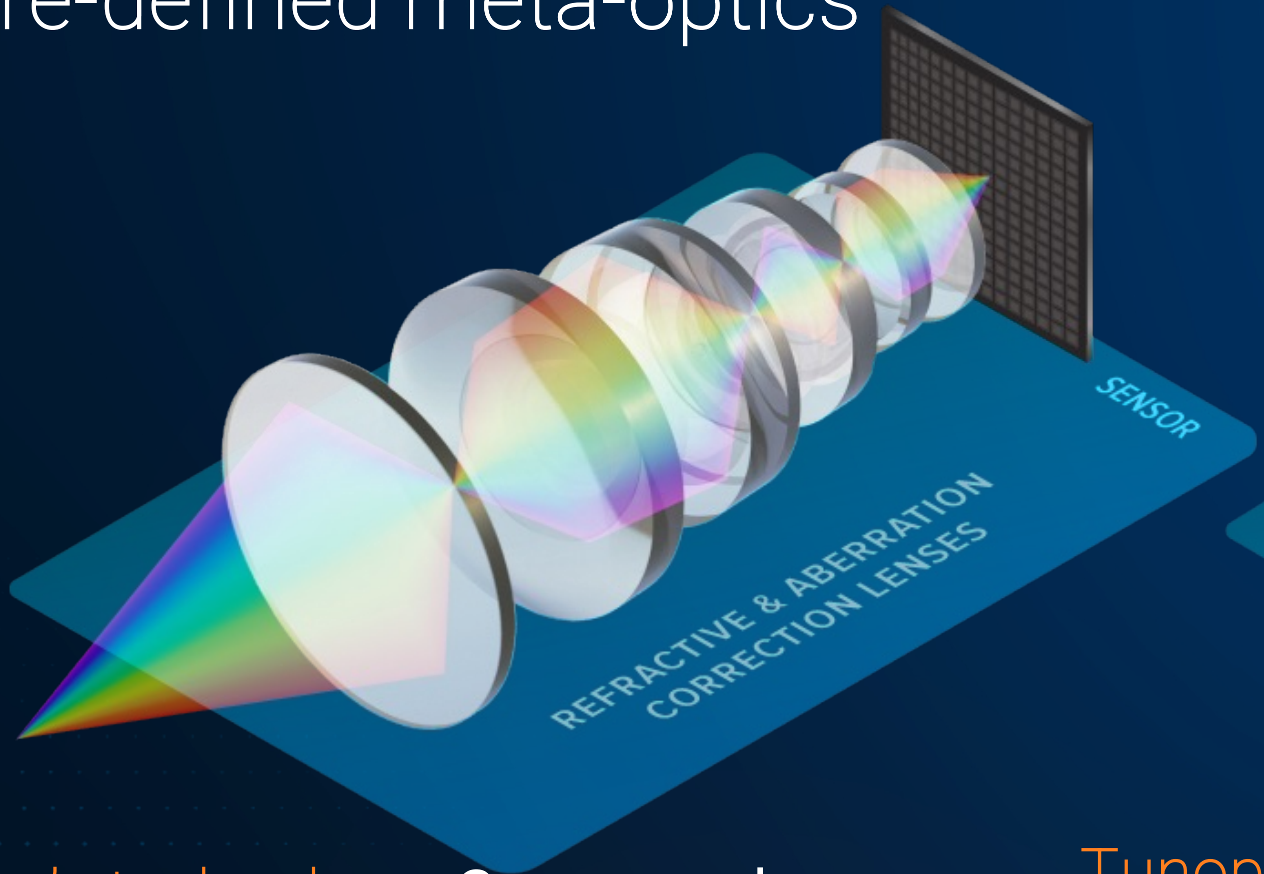
Startup: Tunoptix

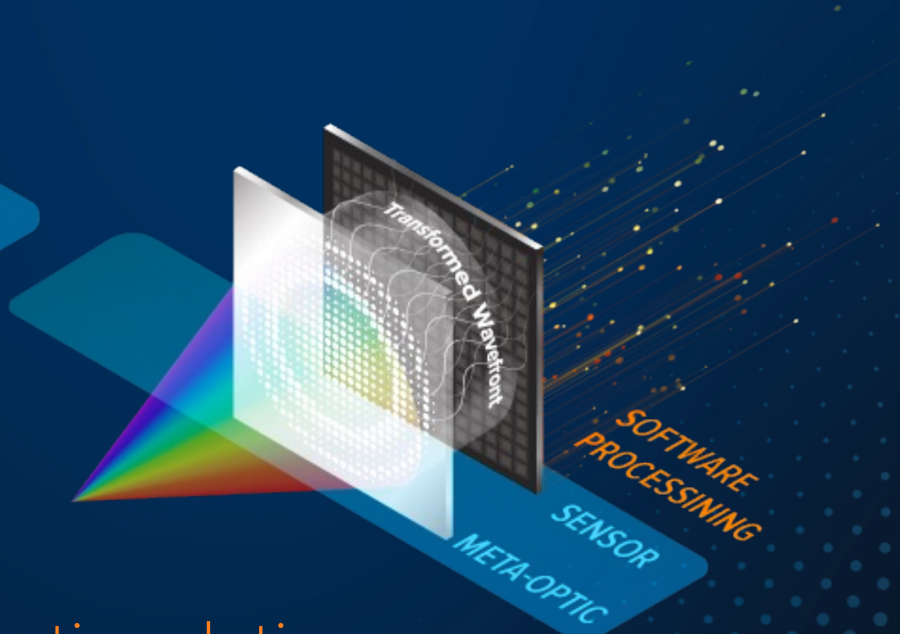


Tunoptix uses meta-optics to create unique systems, such as an extended depth of focus (EDOF) lens, enabling machine vision and imaging systems to operate over a much greater range with no moving parts

https://www.tunoptix.com/

Software-defined meta-optics





Today’s technology: **Compound Lenses**

- Assemblies of multiple, cascaded optics
- Compound systems often require additional optics for mitigating geometric aberrations,
- Bulky, costly, thermally sensitive

https://www.tunoptix.com/

Tunoptix solution:
Computational Meta-optics

- Tunoptix replaces bulky optics with a thin film
- Computer-designed nano-scatterers apply transformations on broadband light. Algorithms reconstruct complex scenes
- Requires only a single, flat meta-optic

Our team and funding

Christmas, 2020:
Current Group + Alumni

Air Force Office of Scientific Research
United States Air Force
NSF
DARPA
Army Research Office
Office of Naval Research
ONR
Science & Technology

intel
a
facebook
SAMSUNG
Reality Labs
TUNOPTIX
FUTUREWEI
Technologies

Students interned at: *Apple, Google-X, Meta, Samsung, Microsoft, Intel, Aerospace Corporation, Seagate, HP, Osram.*

Graduated students/ postdocs are working at: *Maple Photonics, Analog Photonics, Ansys, Tunoptix, Apple, Rockley Photonics, Atom Computing, ASML, Micron, Aerospace Corporation; Faculty members at : NTSU and Brown University*

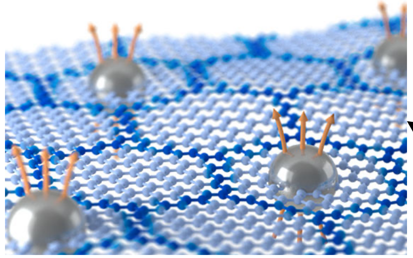
Advice for graduate school/ future career

- Reach out to professors in your institute
- Read papers, talk to graduate students; show initiative, interest
- Ideally choose a project and go with it. You do not (and cannot) plan the rest of your life perfectly at any point of time. Do something as long as you are learning something new (technical, non-technical)!! Your actions will most certainly impact your future career, but the future is not completely in your control.
- Talk to people outside your disciplines. Ask them what are the (scientific) problems that are keeping them awake at night. Understand pain points of others.
- Minimize “silly” mistakes!!
- Success in research requires hard work, grit, creativity. Domain level expertise is important, but other soft-skills are more important, and they are transferrable.
- Your lived experiences (both scientific and non-scientific) make you unique. Think how can you “connect the dots (courtesy: Jobs)”.

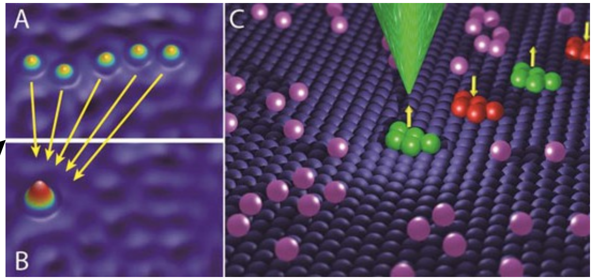
Talks on our research

- Silicon Photonics for Optical Computing (2014): https://www.youtube.com/watch?v=r1w_7RaL2iw
- Dielectric Metasurface (2019): https://www.youtube.com/watch?v=PD4uaX_MYlk
- Metaphotonic Computational Image Sensor (2020): https://www.youtube.com/watch?v=GJIviD_Af78
- Hybrid Integrated Photonics (2020): https://www.youtube.com/watch?v=32sAme0MYg4
- Design and Optimization of Dielectric Metasurfaces (by Alan Zhan, MSR, 2016): https://www.youtube.com/watch?v=il-PpAT5l5Q

Quantum many-body simulation

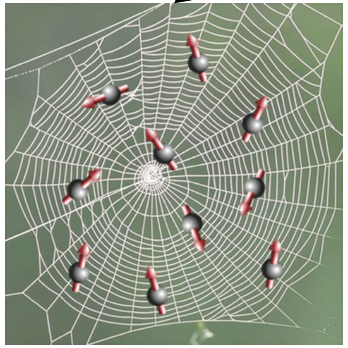


Fractional Quantum Hall effect

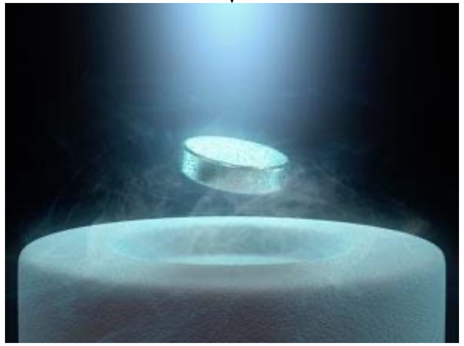


Quantum Magnet

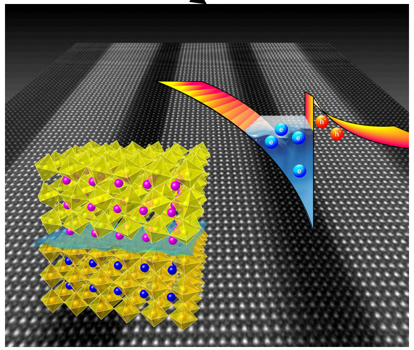
Strongly correlated materials



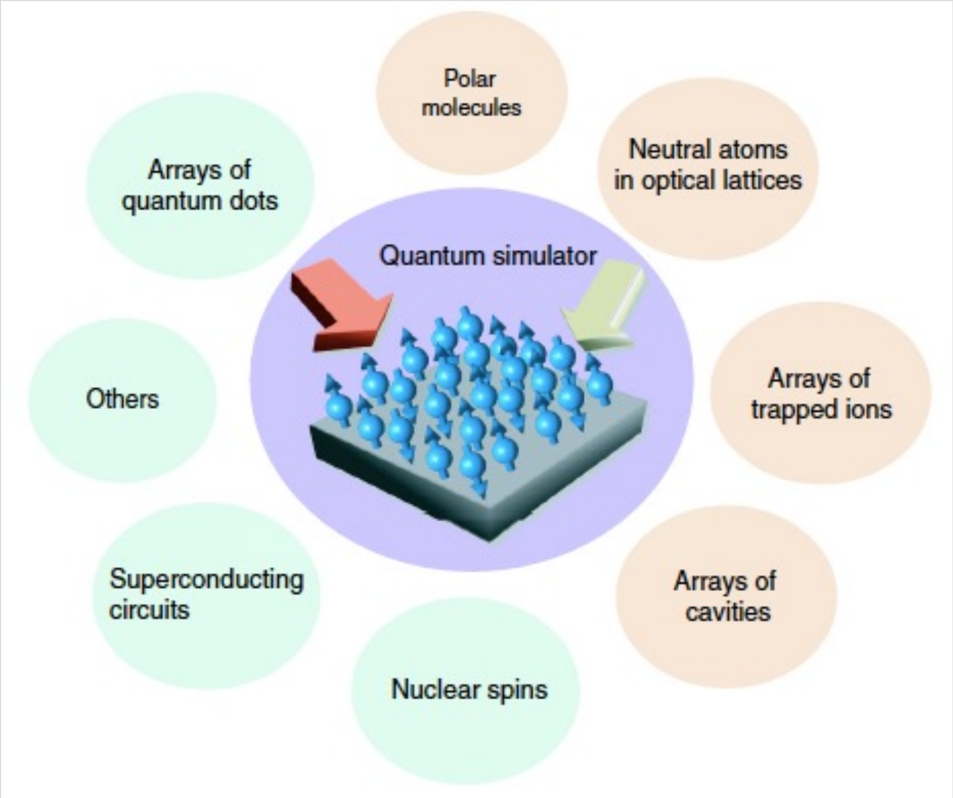
Many Body Localization



High Tc Superconductor

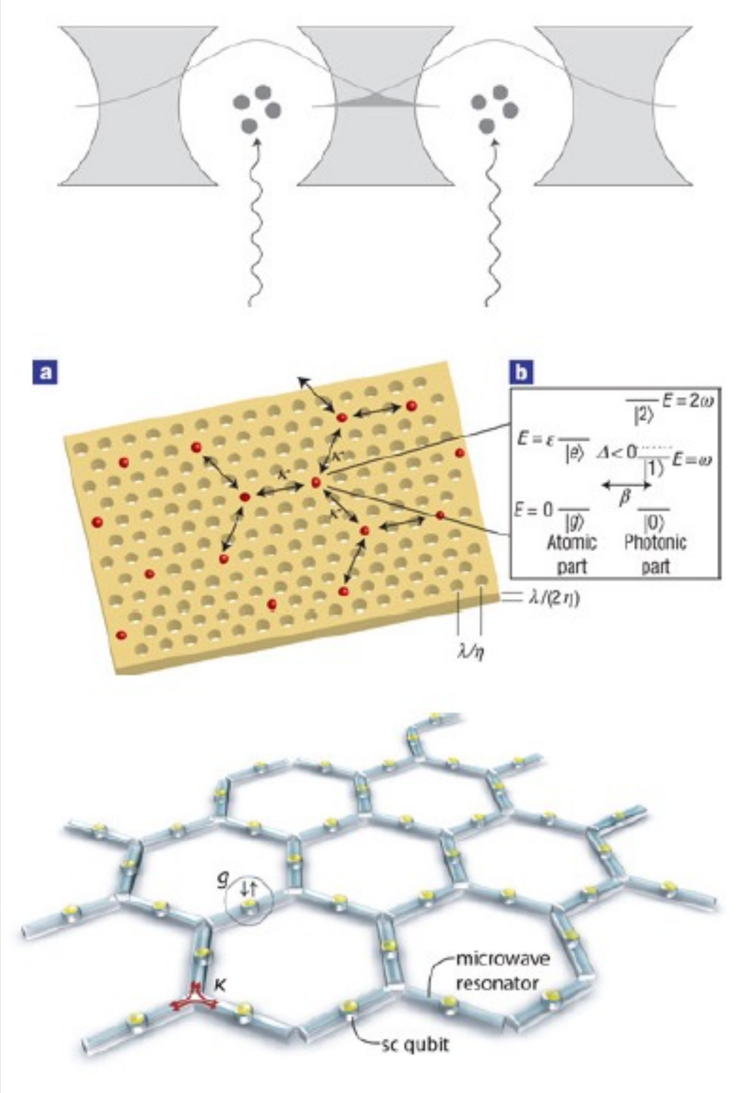


2D Electron Gas

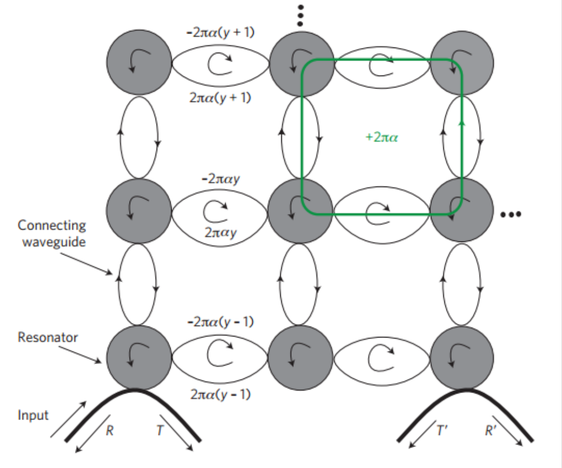


Quantum Simulation, Rev. Mod. Physics, Vol. 86, January–March 2014

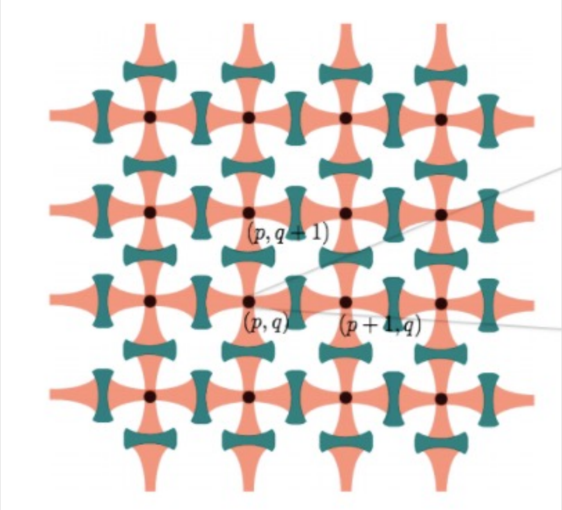
Non-equilibrium quantum simulation with correlated light



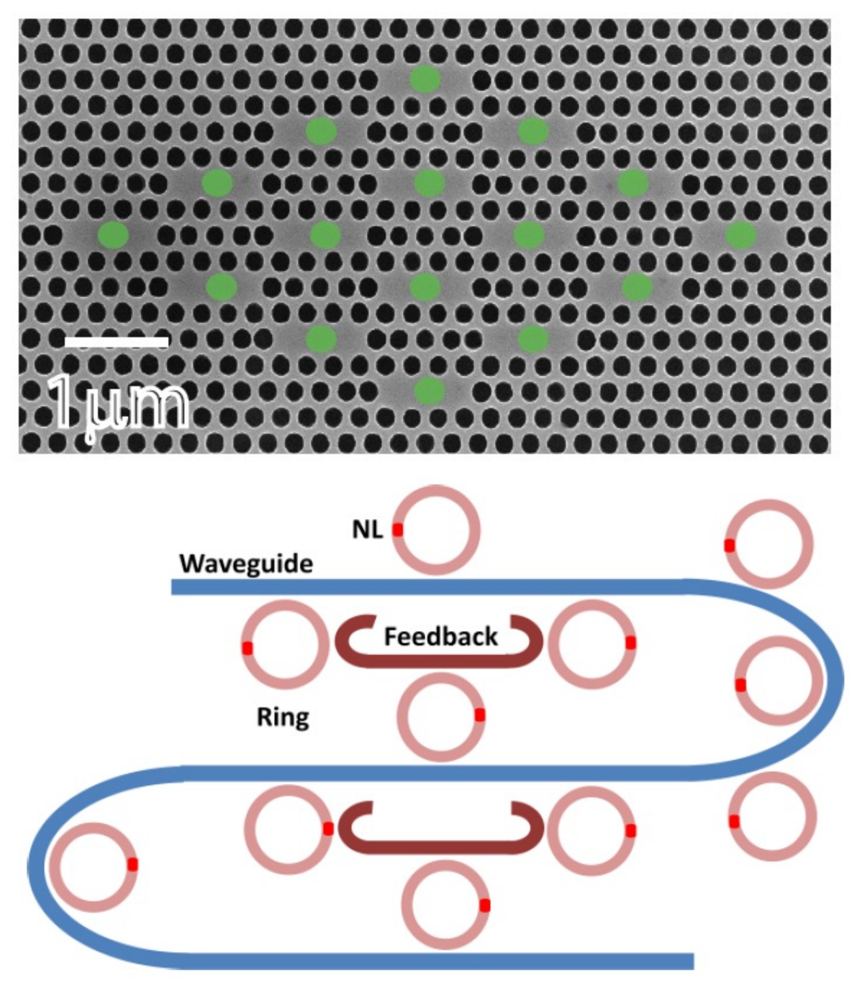
Quantum fluids of light, Rev. Mod. Phys. 85, 299 (2013)



Nature Physics 7, 907–912 (2011)

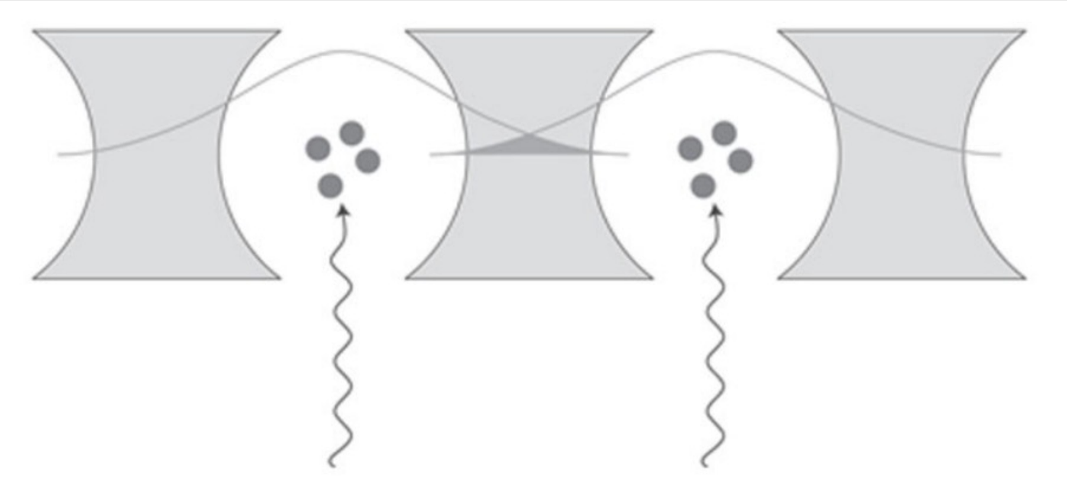


Report of Progress in Physics, 80, 016401 (2016)



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

Hamiltonian of the system



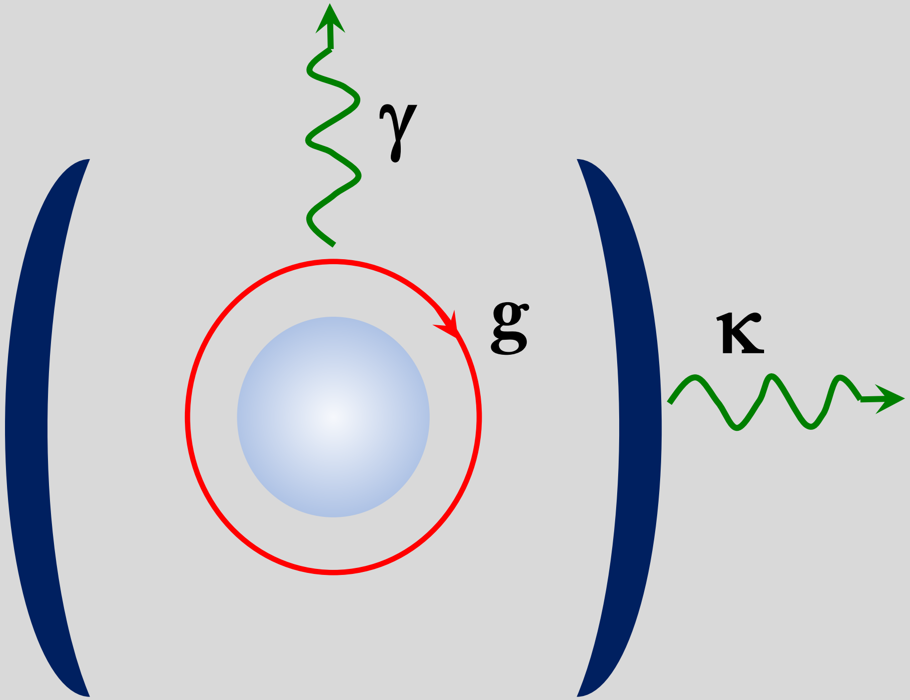
Nearest-Neighbor coupling:

$$H = \sum_i \Delta_{\mathrm{i}}\, a_i^\dagger a_i + \sum_i t_i\left(a_i^\dagger a_{i+1} + a_{i+1}^\dagger a_i\right) + \sum_i U_i a_i^\dagger a_i^\dagger a_i a_i$$

Arbitrary coupling:

$$H = \sum_i \Delta_{\mathrm{i}}\, a_i^\dagger a_i + \sum_{i,j} t_{ij}\left(a_i^\dagger a_j + a_j^\dagger a_i\right) + \sum_i U_i a_i^\dagger a_i^\dagger a_i a_i$$

Cavity quantum electrodynamics (cQED): narrow and broad emitters



$g \propto {}^{\mu}/_{\sqrt{V_m}}$: light-matter interaction

$\kappa \sim 1/Q$: cavity decay rate

γ: exciton decay rate

$g > \kappa, \gamma$: Strong Coupling: Polariton is formed

$g < \kappa, \gamma$: Weak Coupling

Bad cavity regime: Narrow emitter
$(\boldsymbol{\kappa} > \boldsymbol{\gamma})$

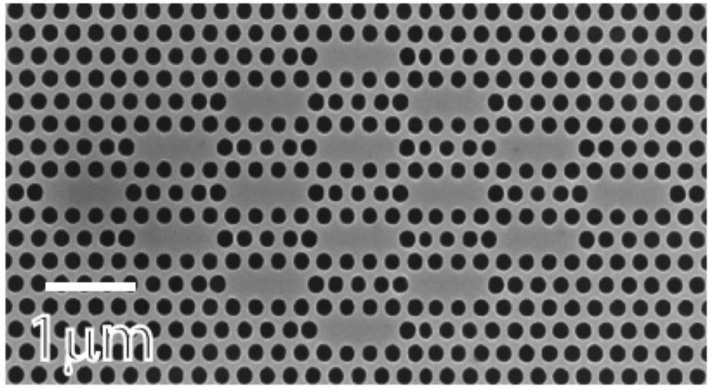
- Cavity is broader than emitter
- Atom, semiconductor quantum dots, defects (NV, SiV centers etc.)
- Need to tune each emitter for quantum simulation.

Good cavity regime: Broad emitter
$(\boldsymbol{\gamma} > \boldsymbol{\kappa})$

- Emitter is broader than cavity
- Quantum well, solution processed quantum dots, 2D material excitons
- Emitters are always overlapping in each node.

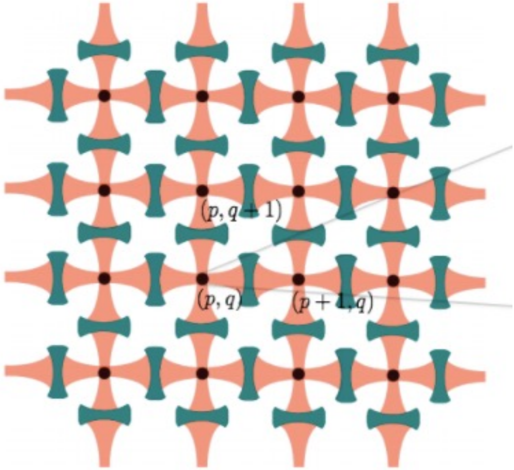
Challenges to photonic quantum simulation

Scalability



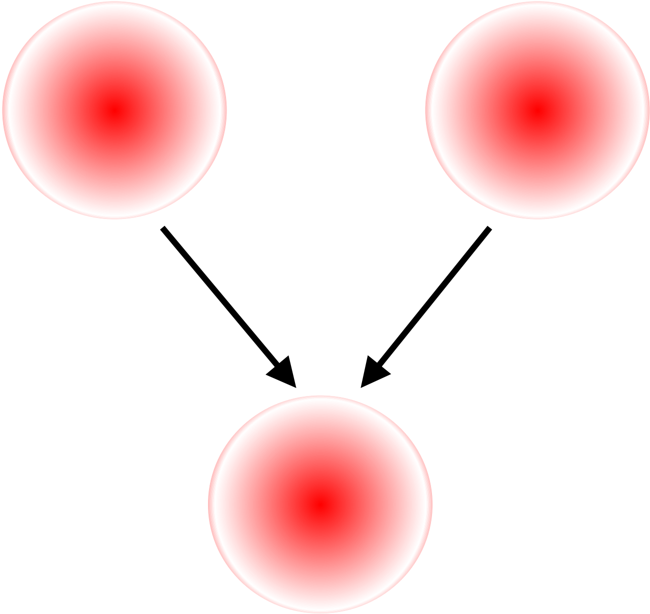
- Large number of optical resonators required.
- All resonators should have same resonance and high quality factor.

Programmability



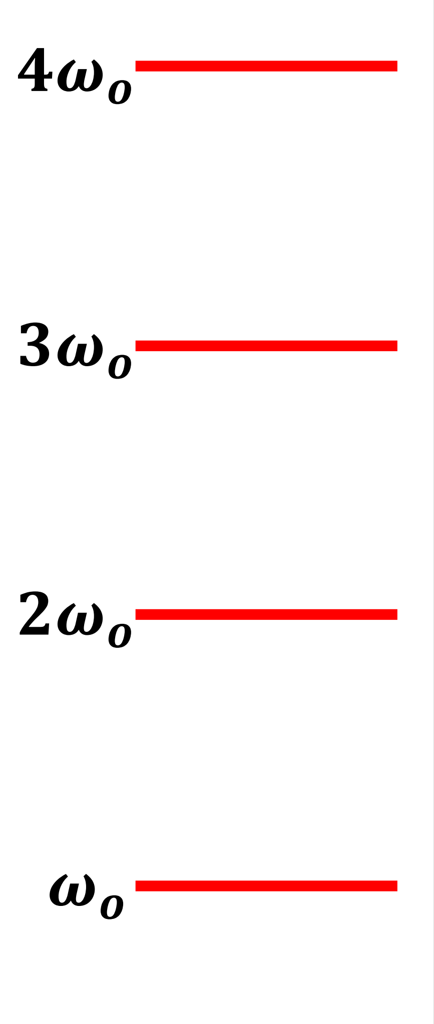
- Need independent tuning of each resonator and quantum emitter to circumvent the inhomogeneity.
- Need tuning of the coupling strength.

Single Photon NLO

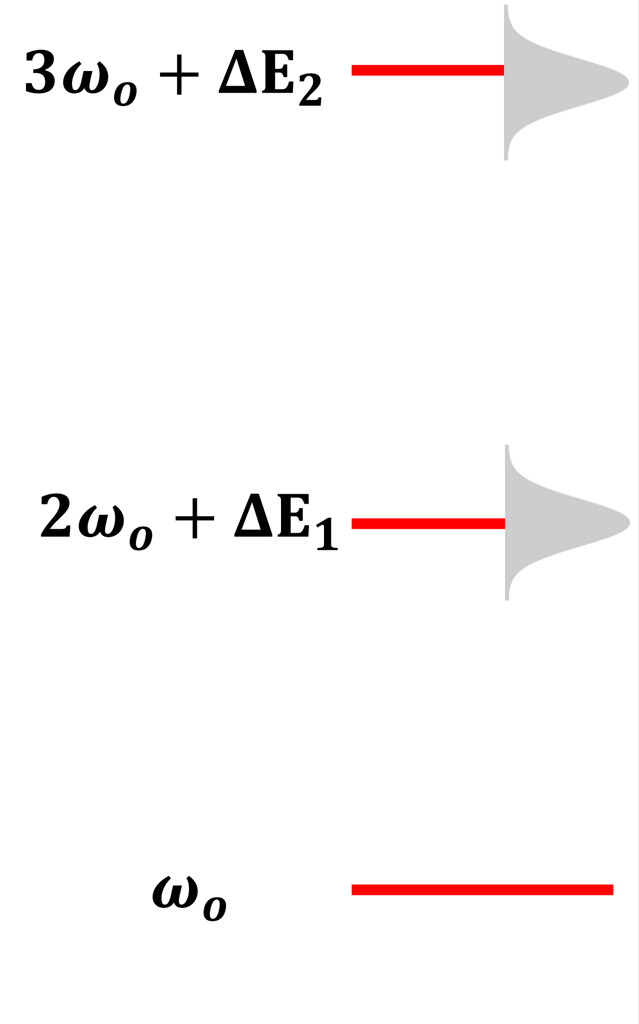


- Strong photon-photon repulsion at single photon level to mimic correlation between electrons.

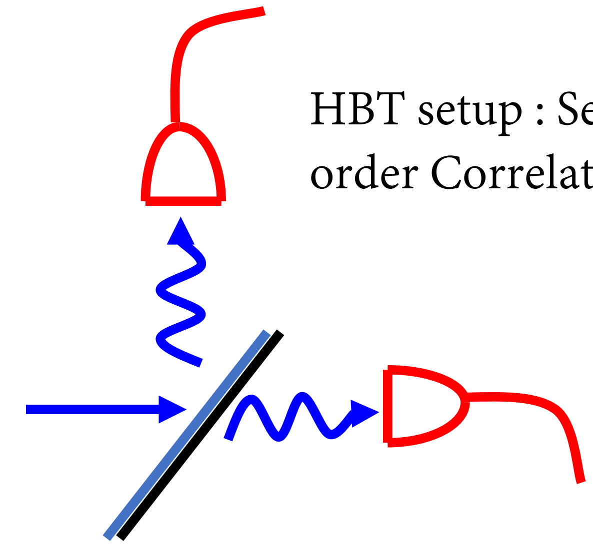
Anharmonicity and signature of single photon nonlinearity



Linear cavity



Non-linear cavity



HBT setup : Second order Correlation

$$g^{(2)}(\tau) = \frac{\langle a^\dagger(0)a^\dagger(\tau)a(\tau)a(0)\rangle}{\langle a^\dagger(0)a(0)\rangle^2}$$

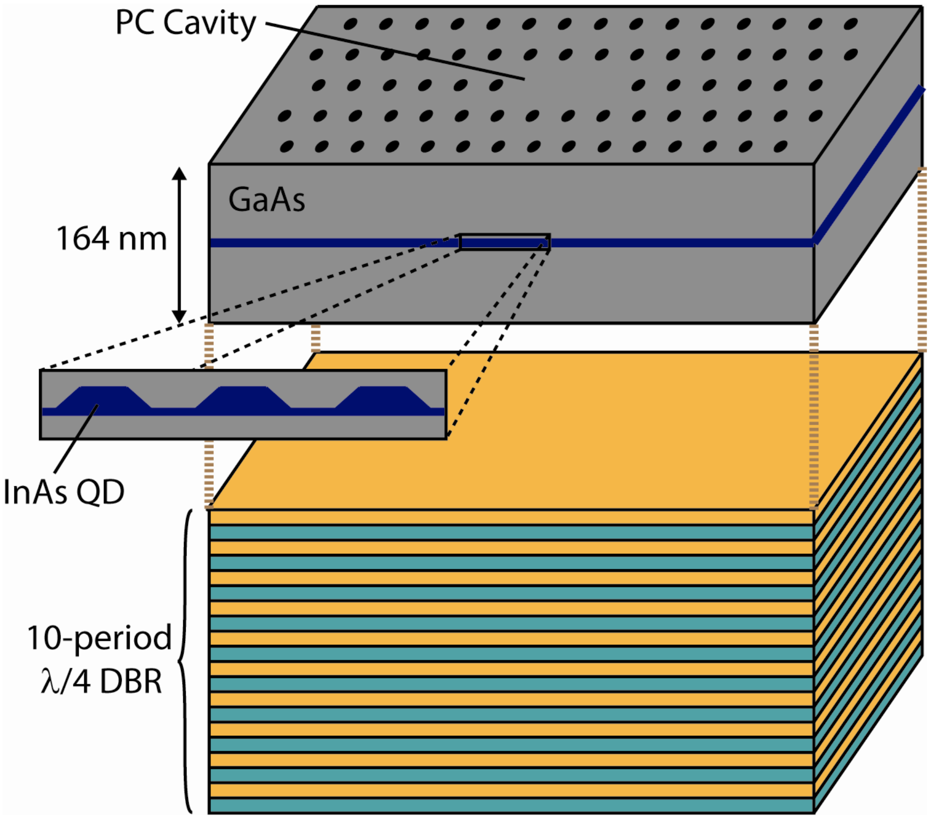
$g^{(2)}(0) < 1$: Sub-Poissonian

$g^{(2)}(0) = 1$: Poissonian

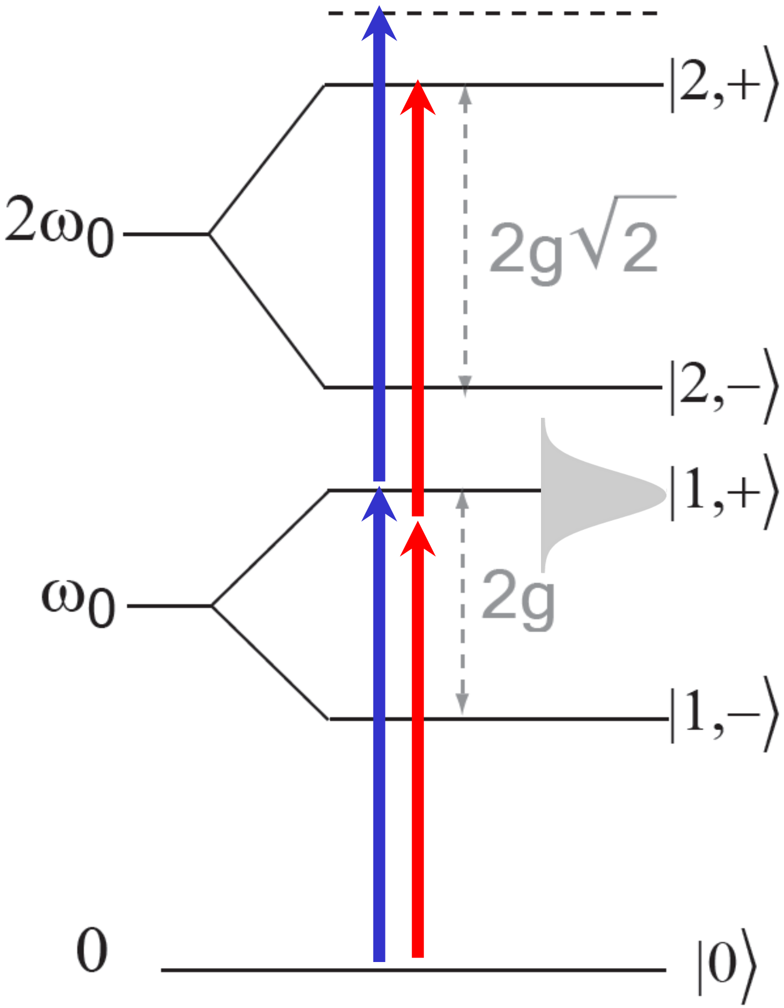
$g^{(2)}(0) > 1$: Super-Poissonian

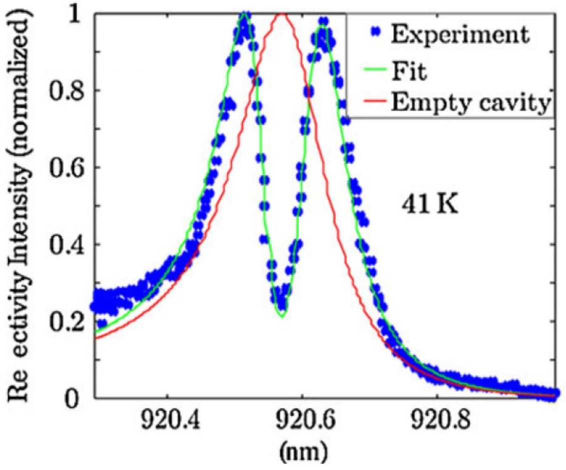
$g^{(2)}(0) = 0$: Hardcore Boson

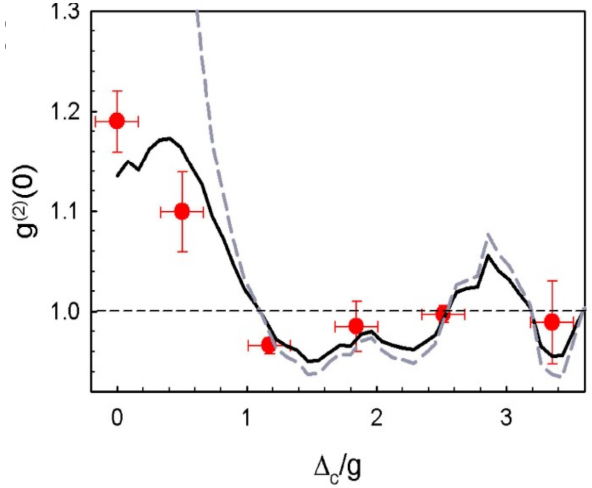
Single photon nonlinearity: narrow self-assembled quantum dots in cavity



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



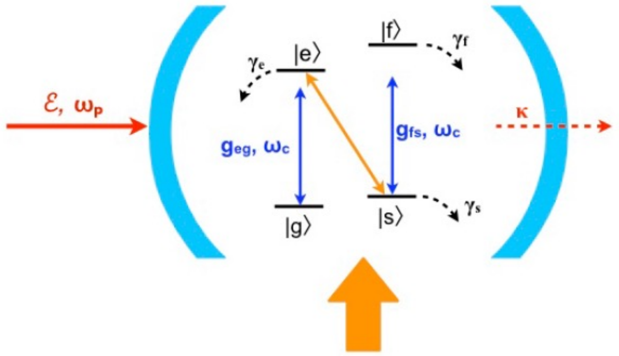




- Strongly coupled quantum dot-cavity system: Jaynes-Cummings Nonlinearity
- Spectral and spatial matching remain unsolved
- The largest number of coupled cavities with dots is only two

Improving photon antibunching exploiting interference

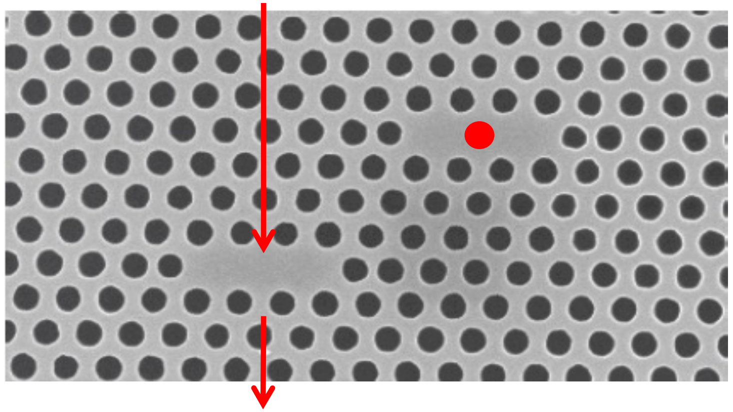
Single cavity mode with multilevel emitter



Bajcsy, Majumdar et. al., New Journal of Physics 15, 025014 (2013)
Immamoglu et. al., Phys. Rev. Lett. 79, 1467–1470 (1997)

2-level emitter, with photonic molecules: unconventional photon blockade

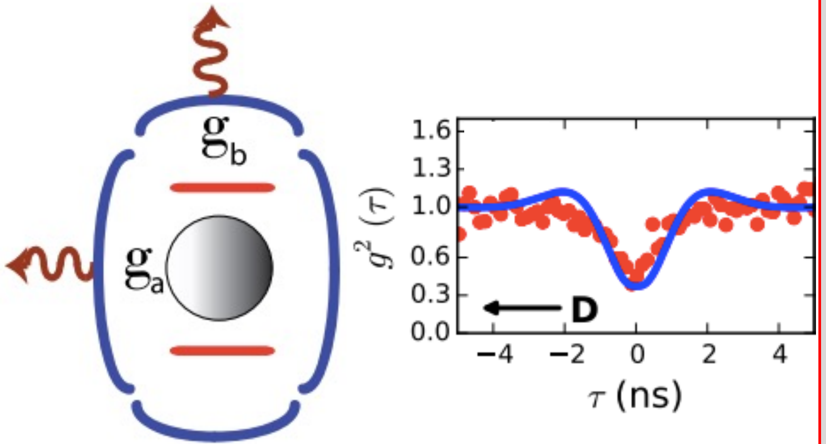
coherent state



Sub-Poissonian

Majumdar et. al., PRB, 86, 045315, (2012).
Liew and Savona, PRL104, 183601,(2010)
Bamba et al, PRA 83, 021802 (2011)

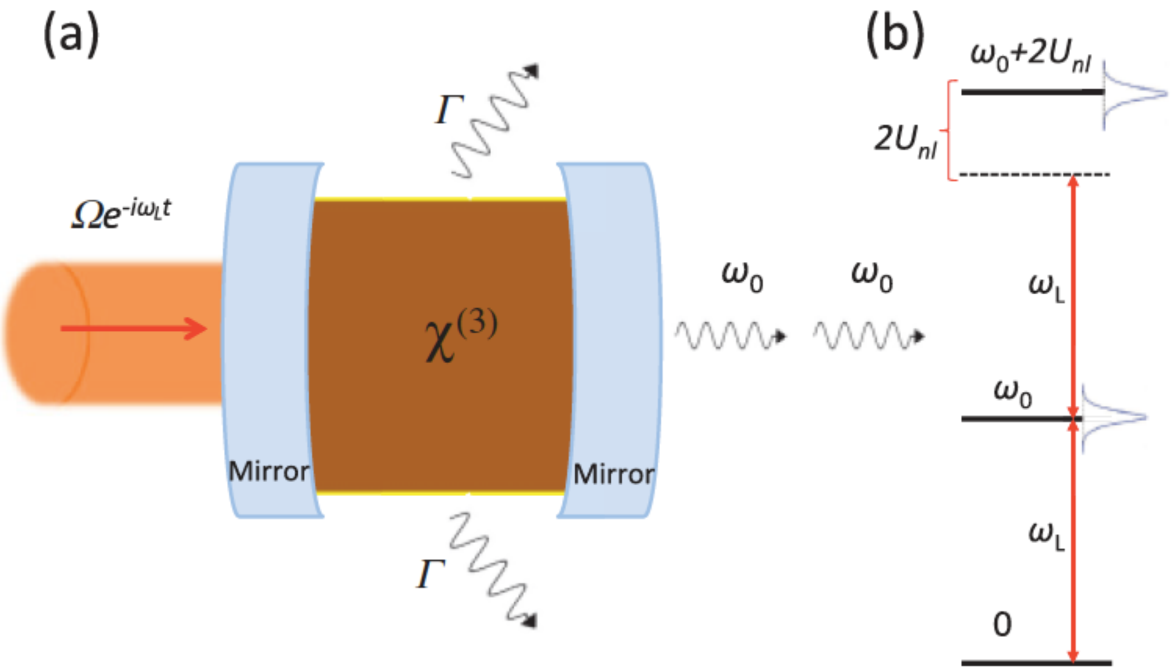
2-level emitter coupled to multimode cavity



Majumdar et.al., Phys Rev. Letters, 108, 183601 (2012).
Experiment: Phys. Rev. Lett. 121, 043601, 2018

Bulk optical nonlinearity in cavity

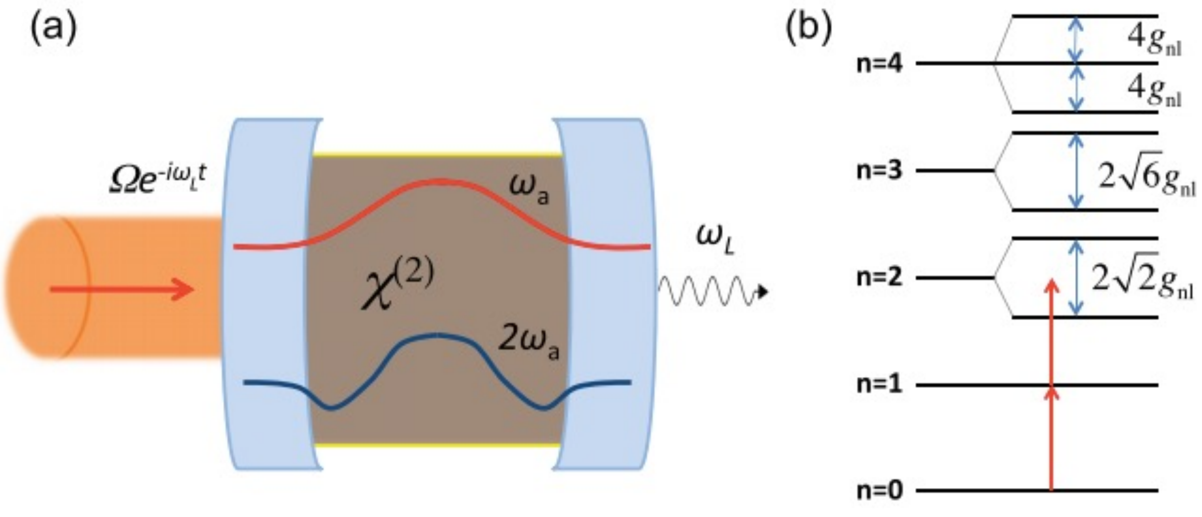
Kerr-nonlinearity



Quality factor needed: $\sim 10^7$

Ferretti and Gerace, PRB, 85, 033303 (2012)

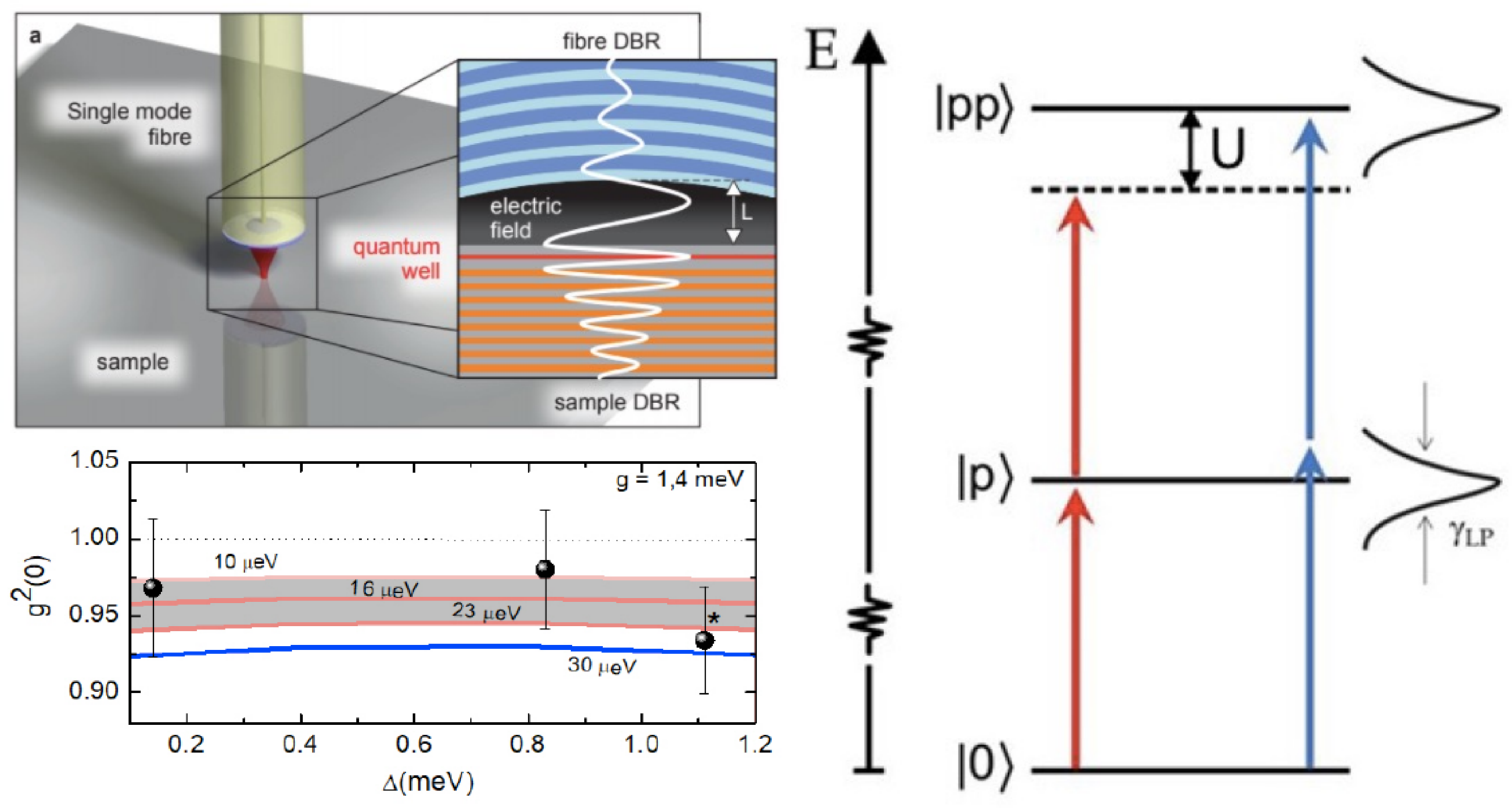
Second-order ($\chi^{(2)}$)nonlinearity



Quality factor needed: $\sim 10^6$

Majumdar and Gerace, PRB, 87, 235319 (2013)

Quantum nonlinearity in polaritonic boxes: confine photon



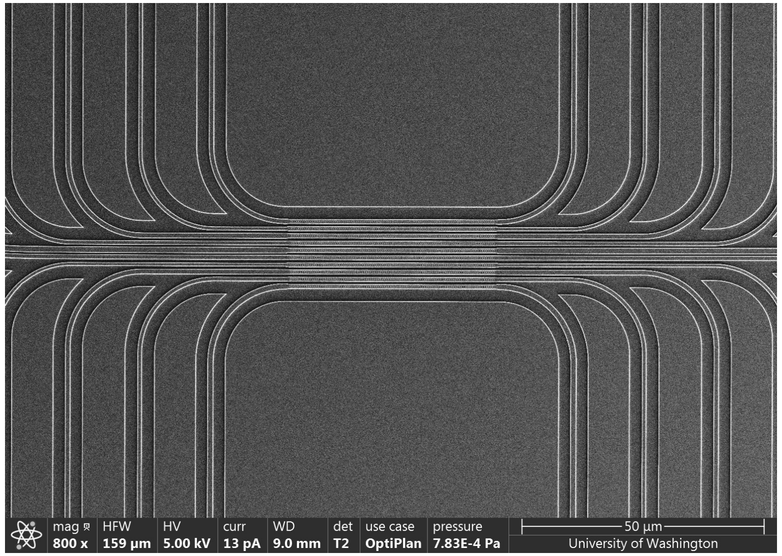
Phys. Rev. Applied 3, 014008, 2015; Nature Materials, volume 18, pages 219–222 (2019); Nature Materials, volume 18, pages 213–218 (2019)

Our strategy for quantum simulation with correlated photons

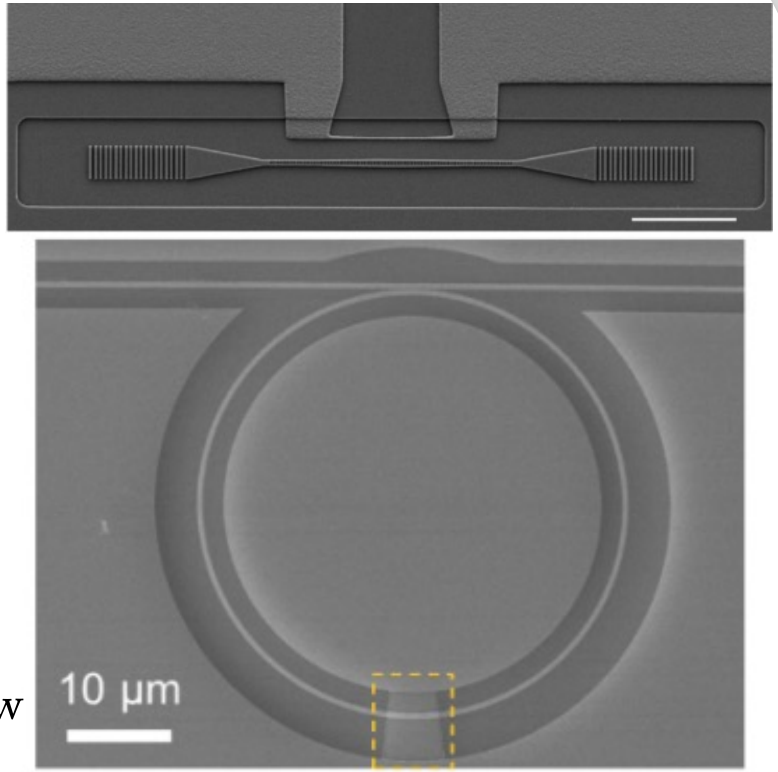
Scalability

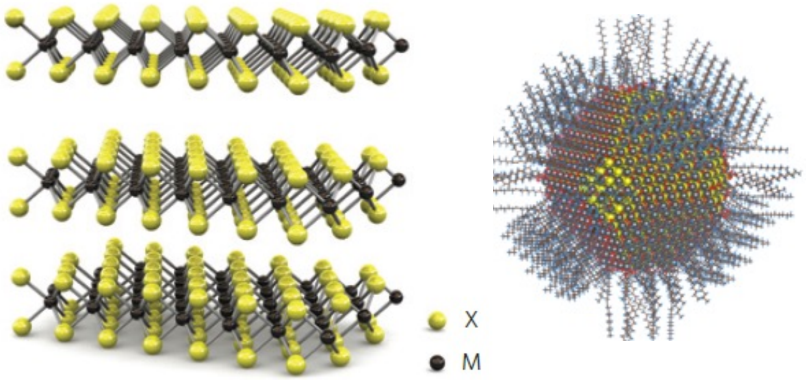
Tunability

Single Photon NLO



- Use integrated silicon/ silicon nitride photonic resonators.
- Develop local tuning mechanisms (new material and device engineering).

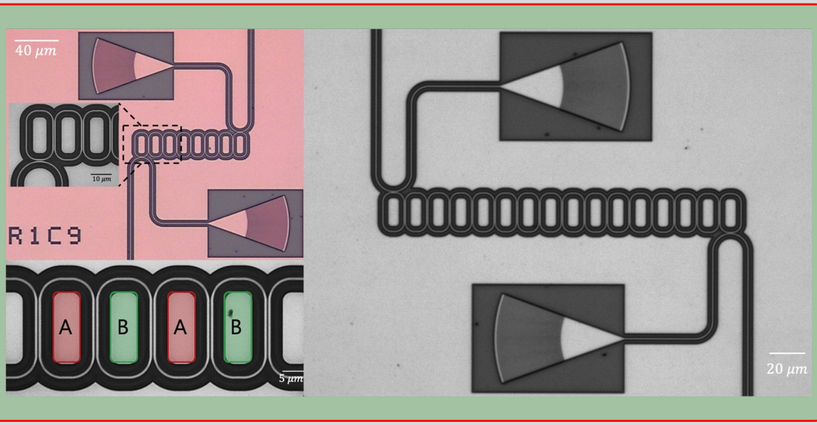




- Use broad emitters (2D material and solution processed quantum materials) to avoid the need for spectral tuning
- Confine the electronic and photonic wave-function to enhance the optical nonlinearity.

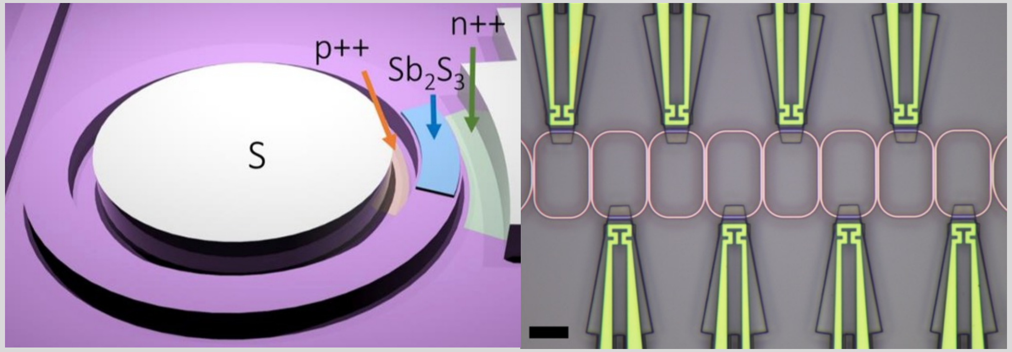
Scalability: Coupled cavity array in integrated photonics

Saxena et al., ACS Photonics, 2022



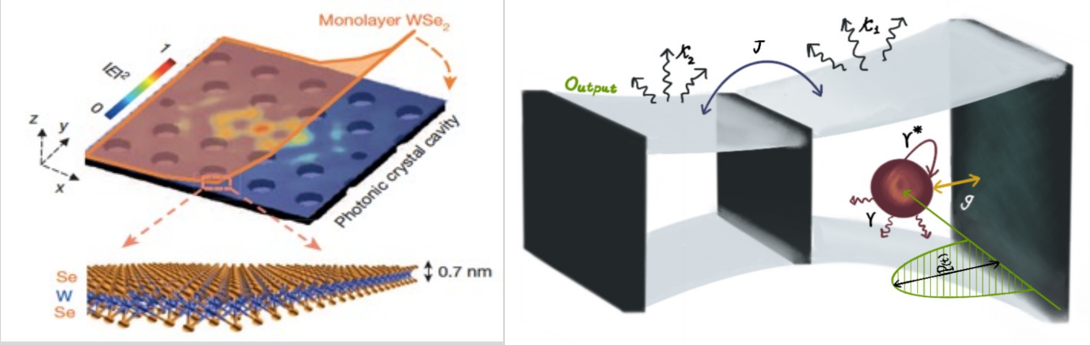
Programmability: Site-controlled tuning of CCA

Saxena et al., Nature Communications, 2023
Chen et al., Nature Communications, 2023

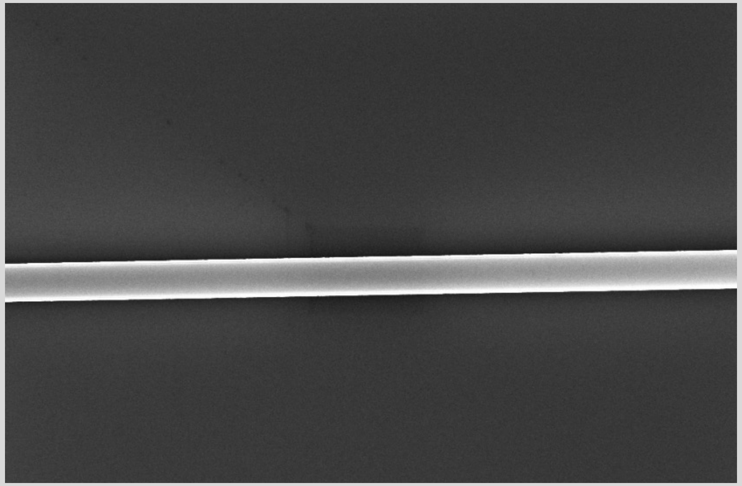


Nonlinearity: Quantum materials in cavity

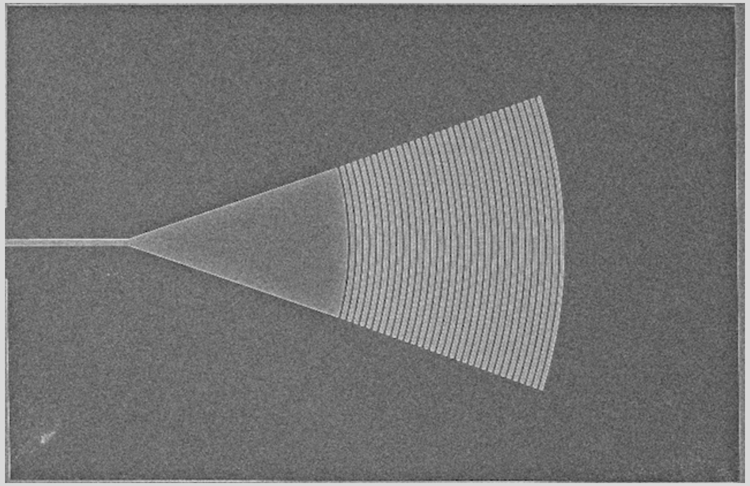
Fryett et. al., ACS Photonics, 2018
Chen et. al., Nano Letter, 2018
Chen et. al., Optics Letter, 2019
Saxena et. al., ACS Photonics, 2019



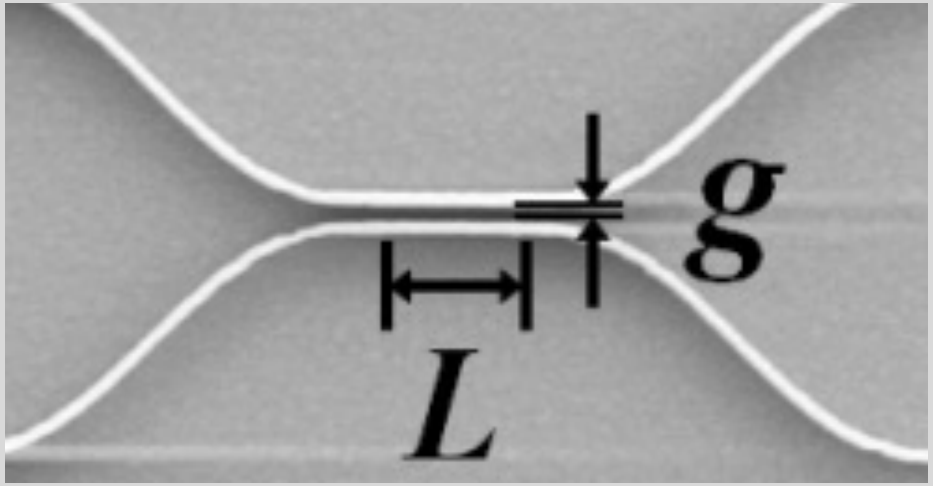
Integrated photonics: bringing optics from table to on-chip



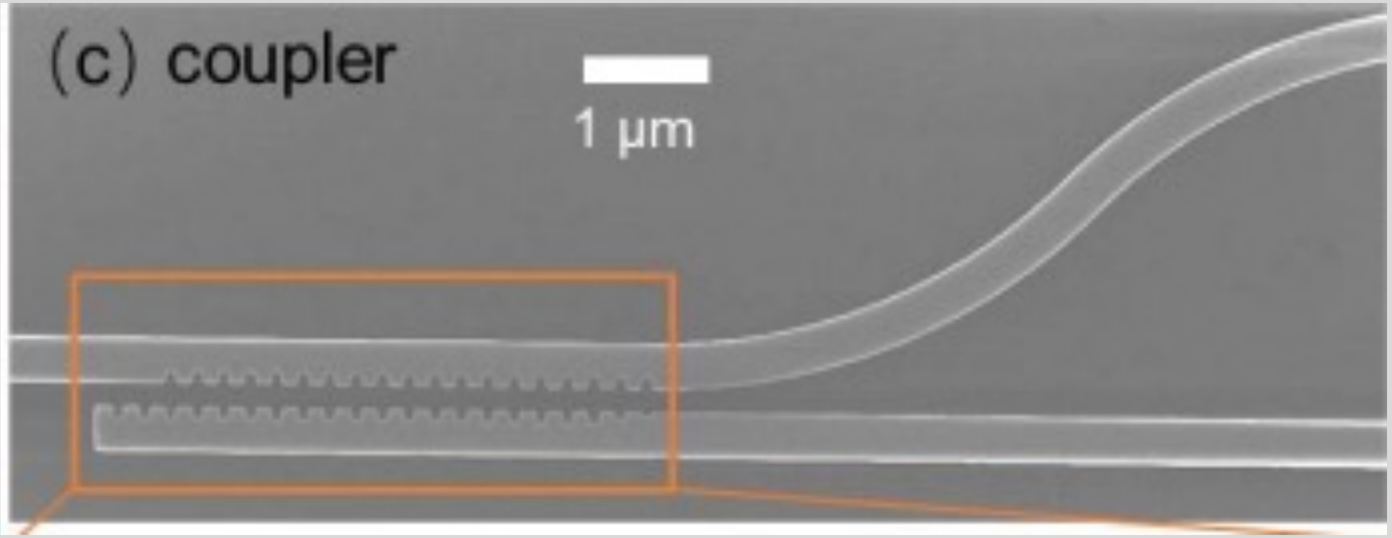
Waveguide (Fiber)



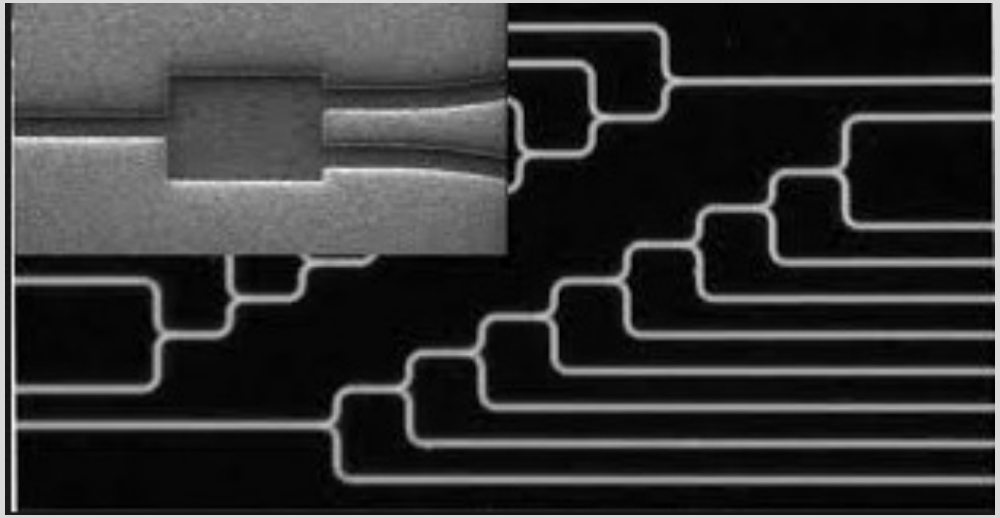
Grating (Mirror)



Directional Coupler (Beam Splitter)

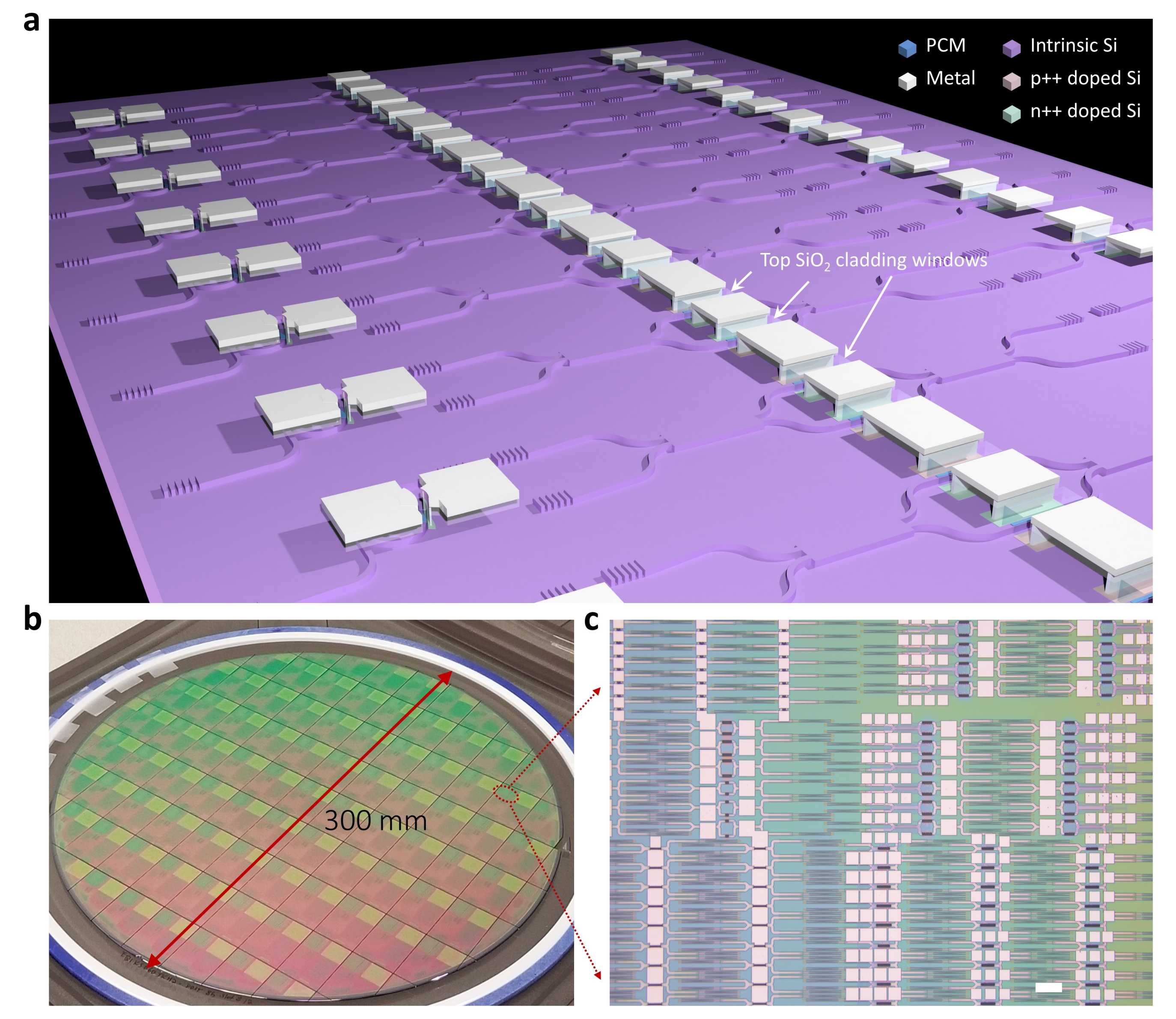


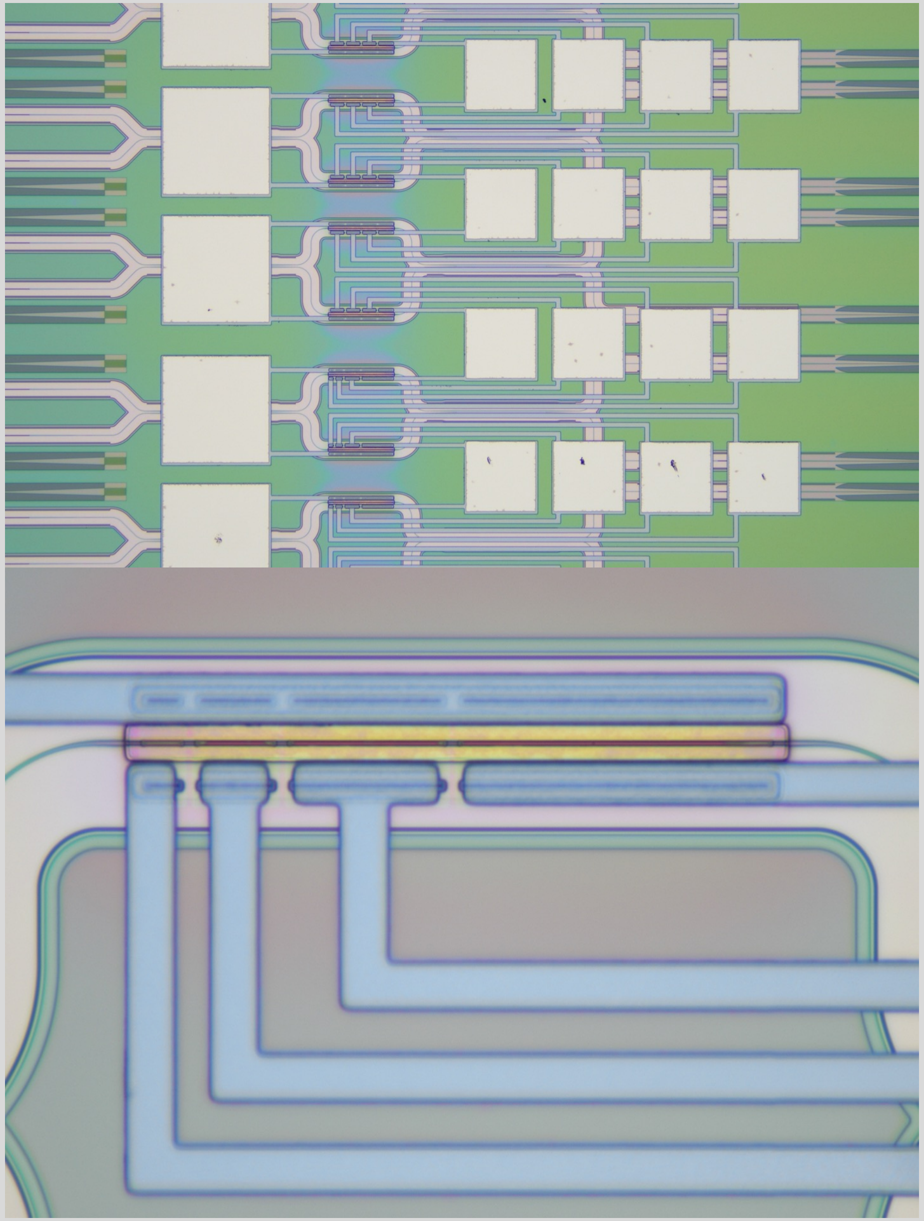
Polarizing Directional Coupler (Polarizing Beam Splitter)



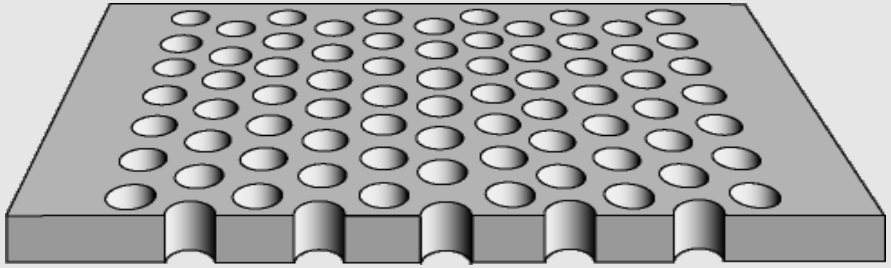
Multi mode interference tree (Array of beam splitters)

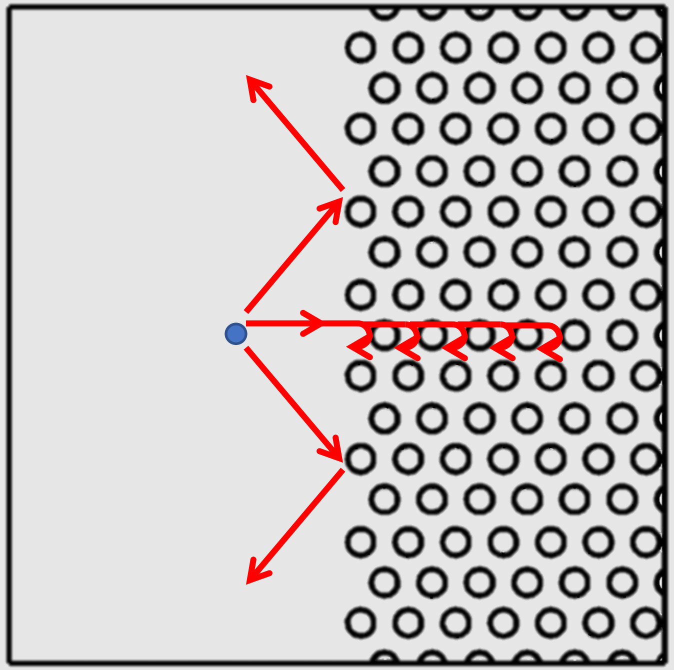
High volume manufacturing in collaboration with Intel



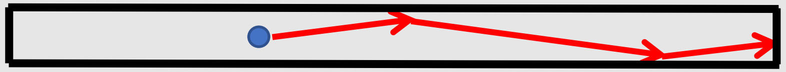


Photonic Crystal Resonator

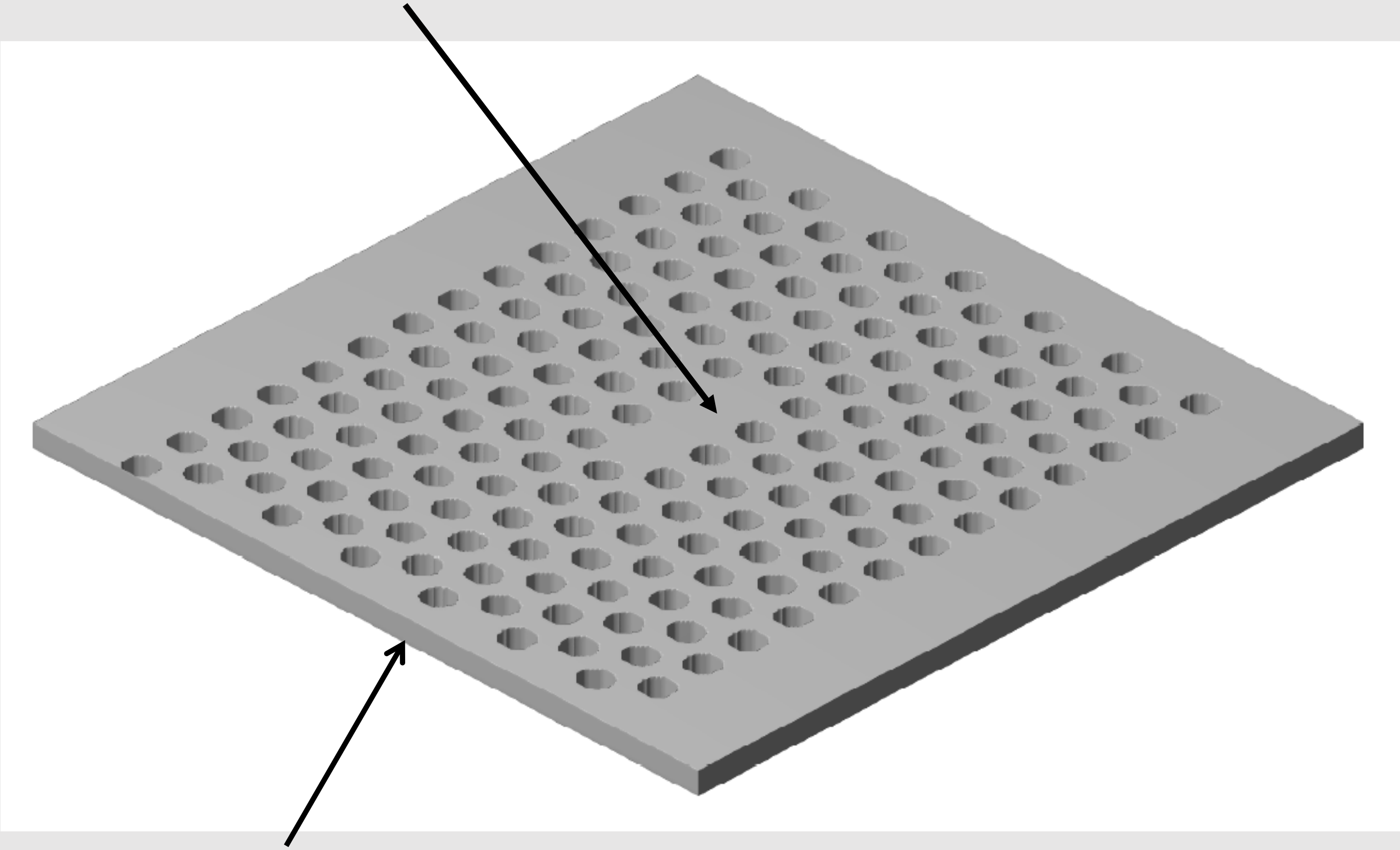




Distributed Bragg Reflection



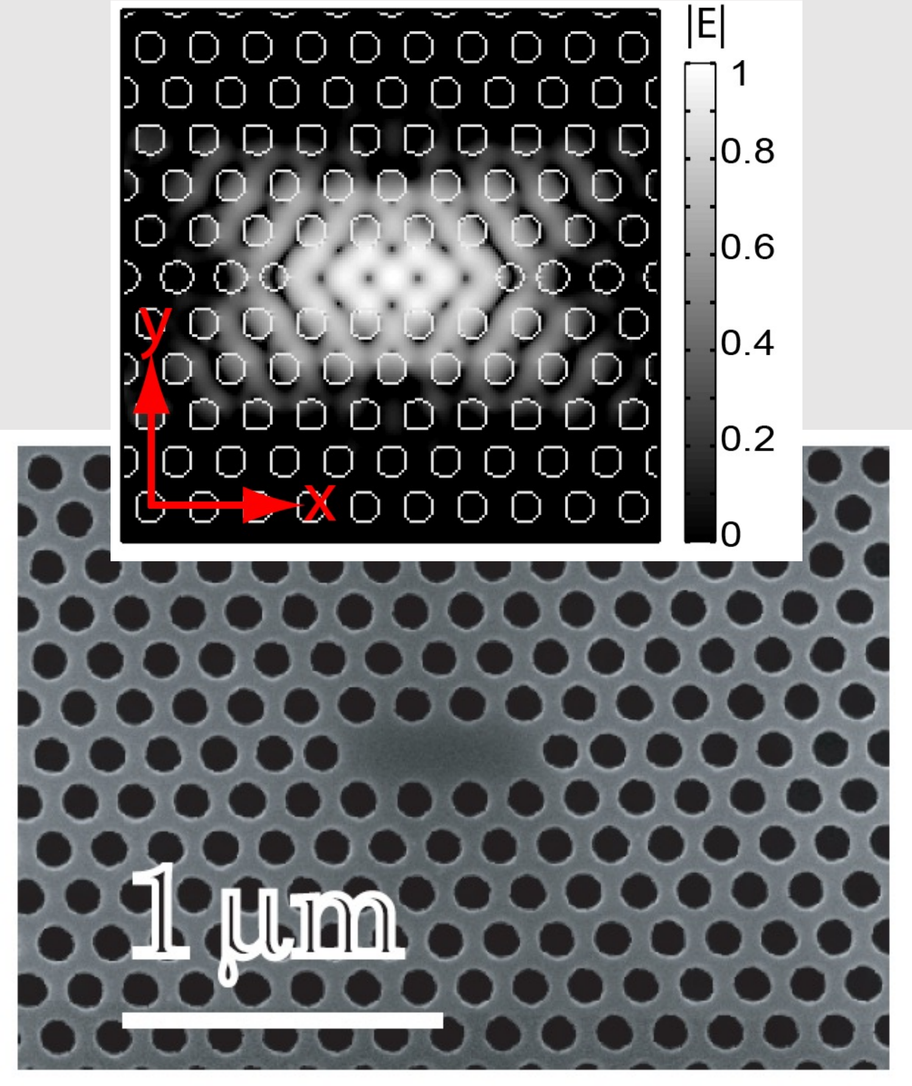
Total Internal Reflection

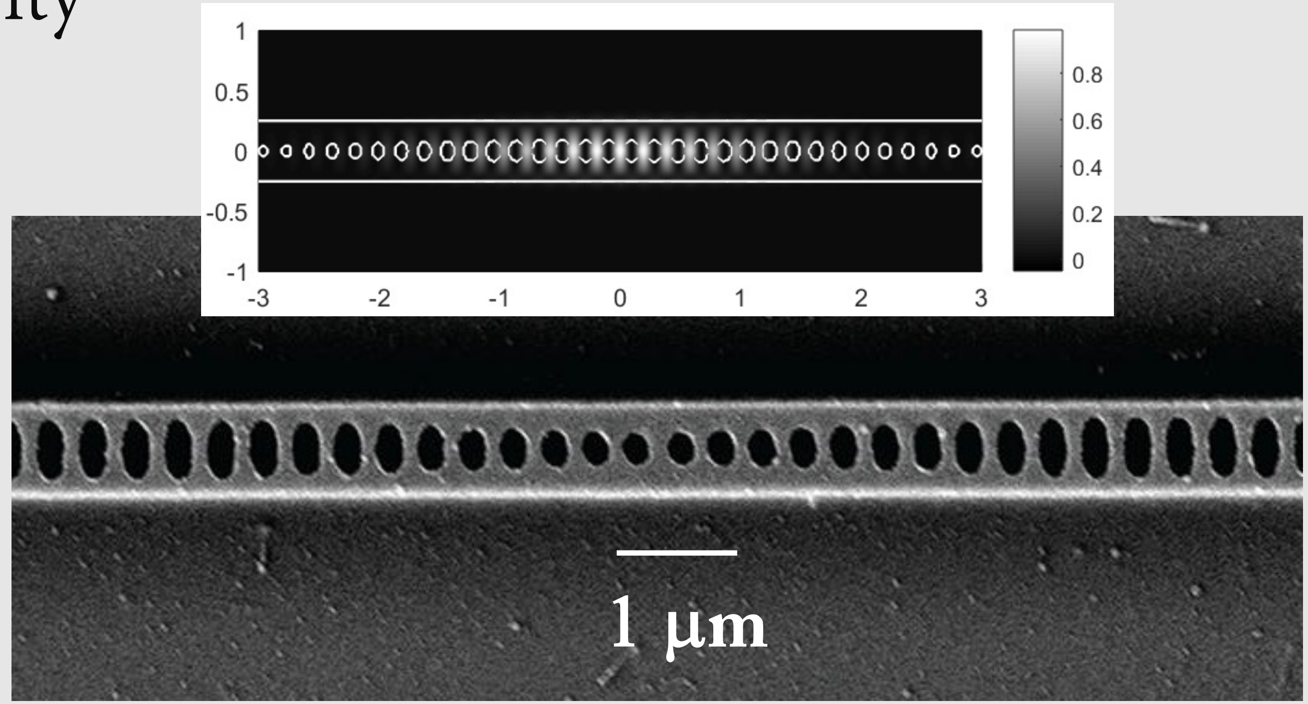


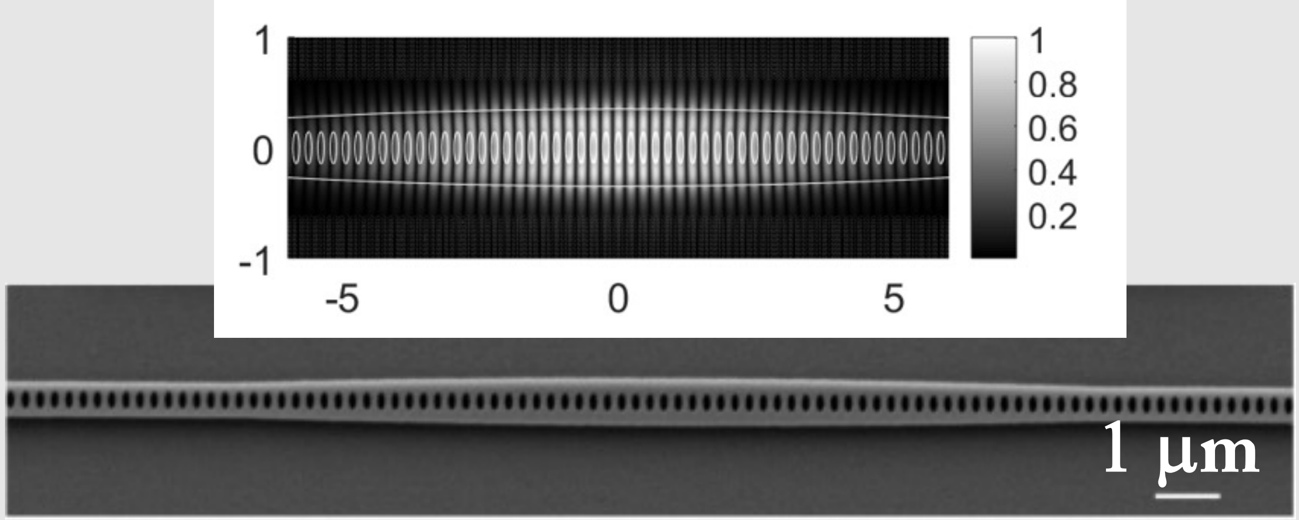
Photonic crystal cavity (resonator)

material slab

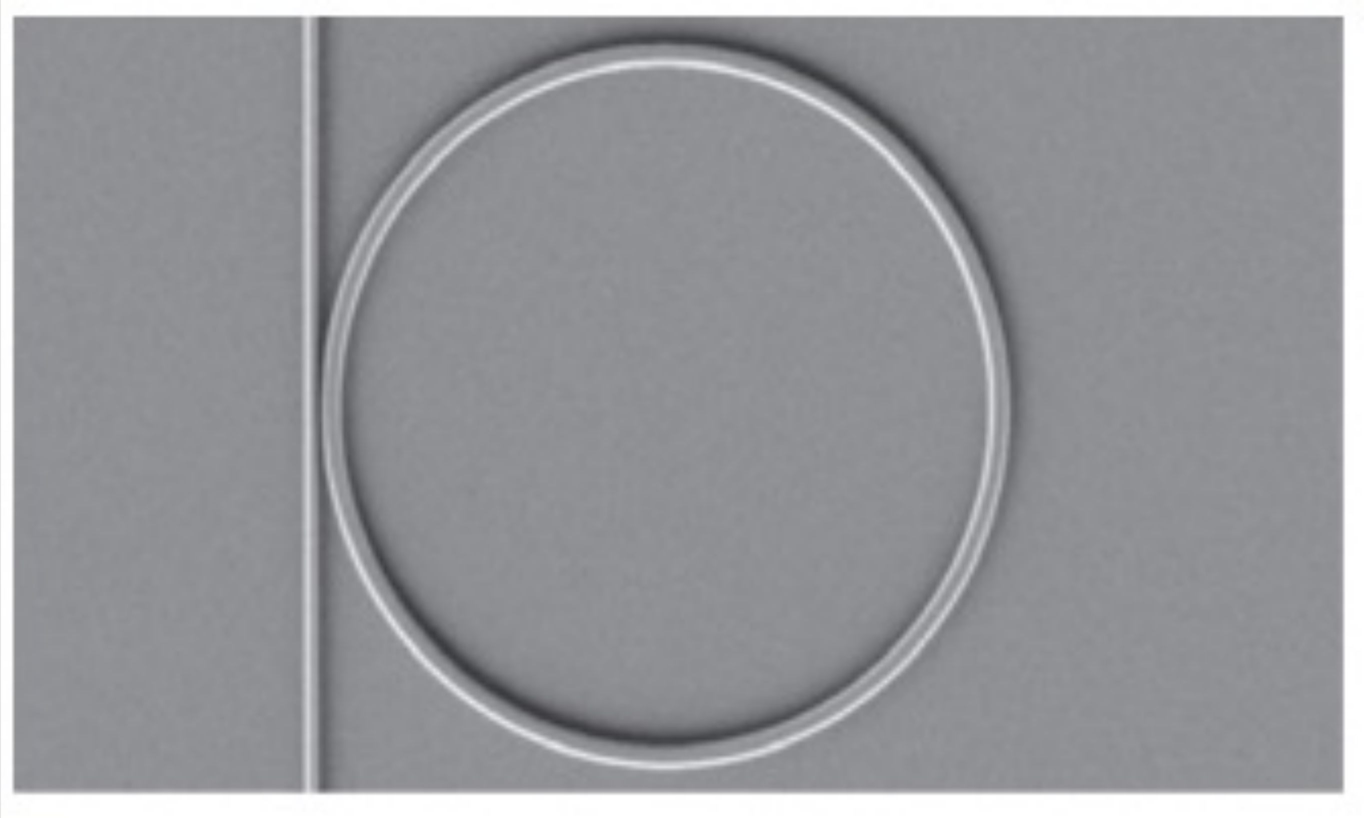
Strongly Confined Light in the cavity



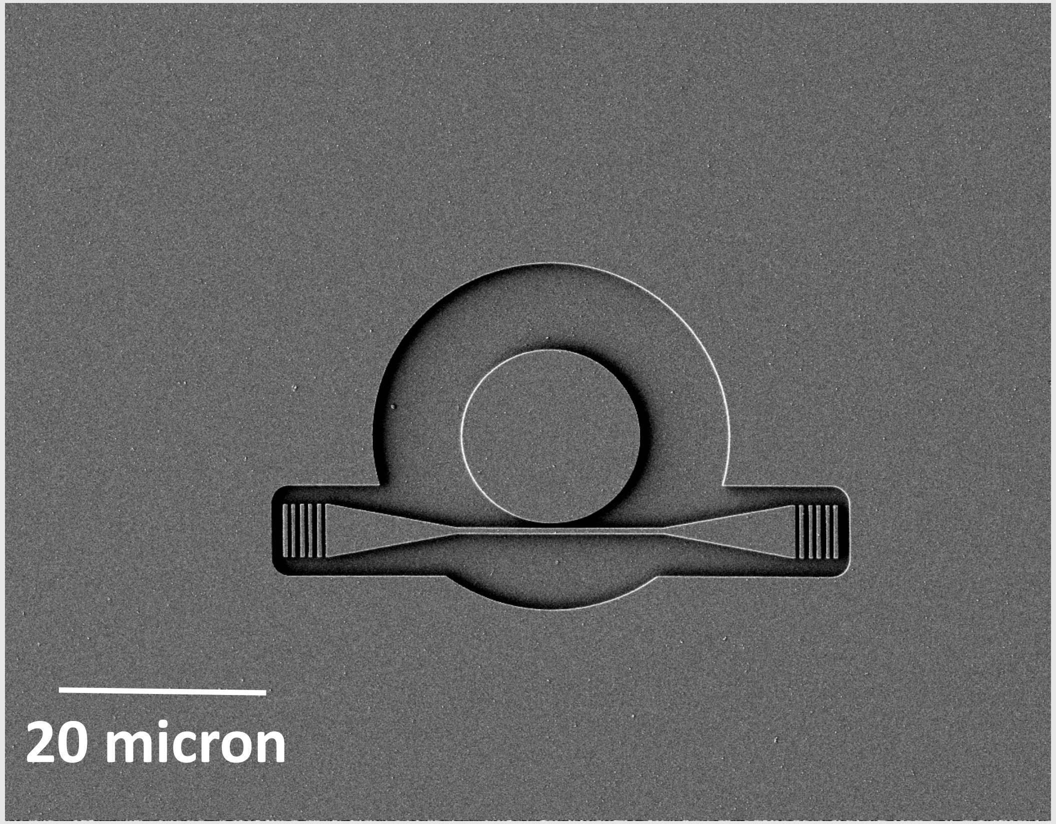




Whispering Gallery Mode Resonator

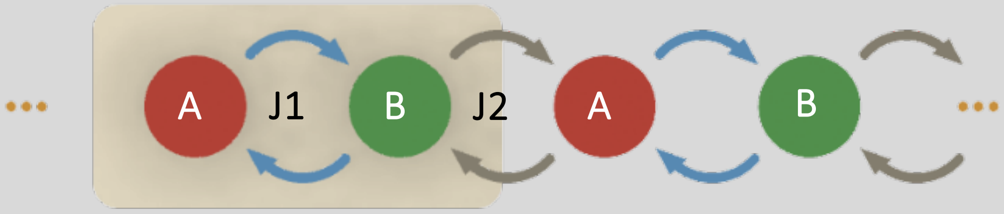


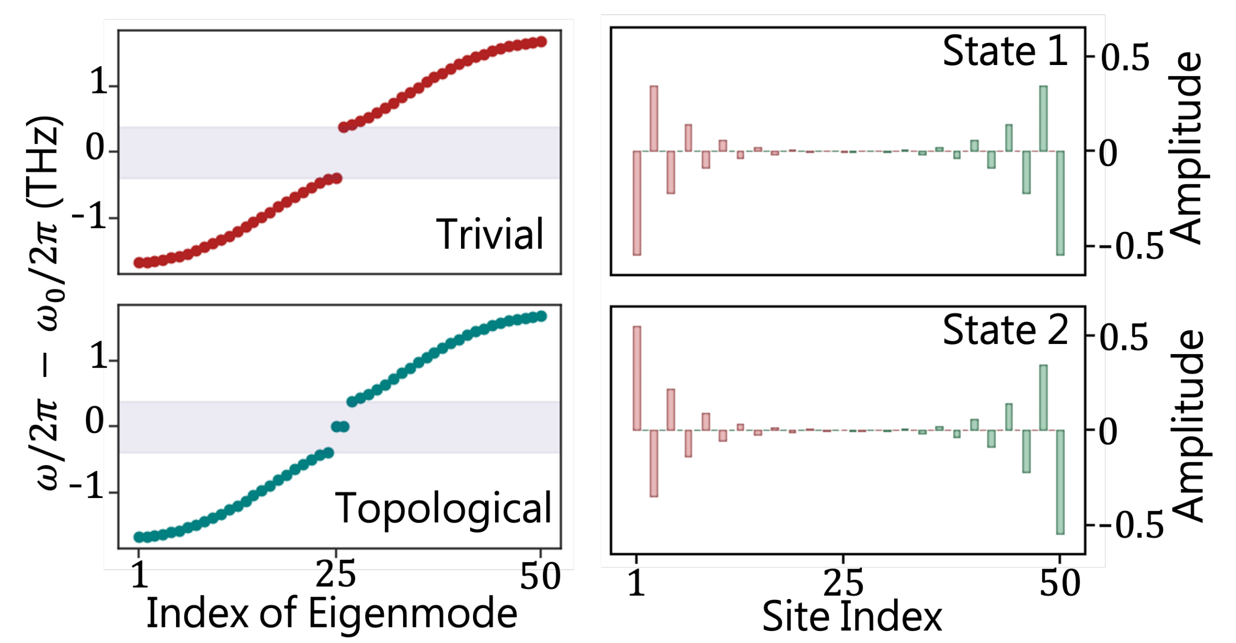
Microring



Microdisk

Su-Schrieffer-Heeger (SSH) model



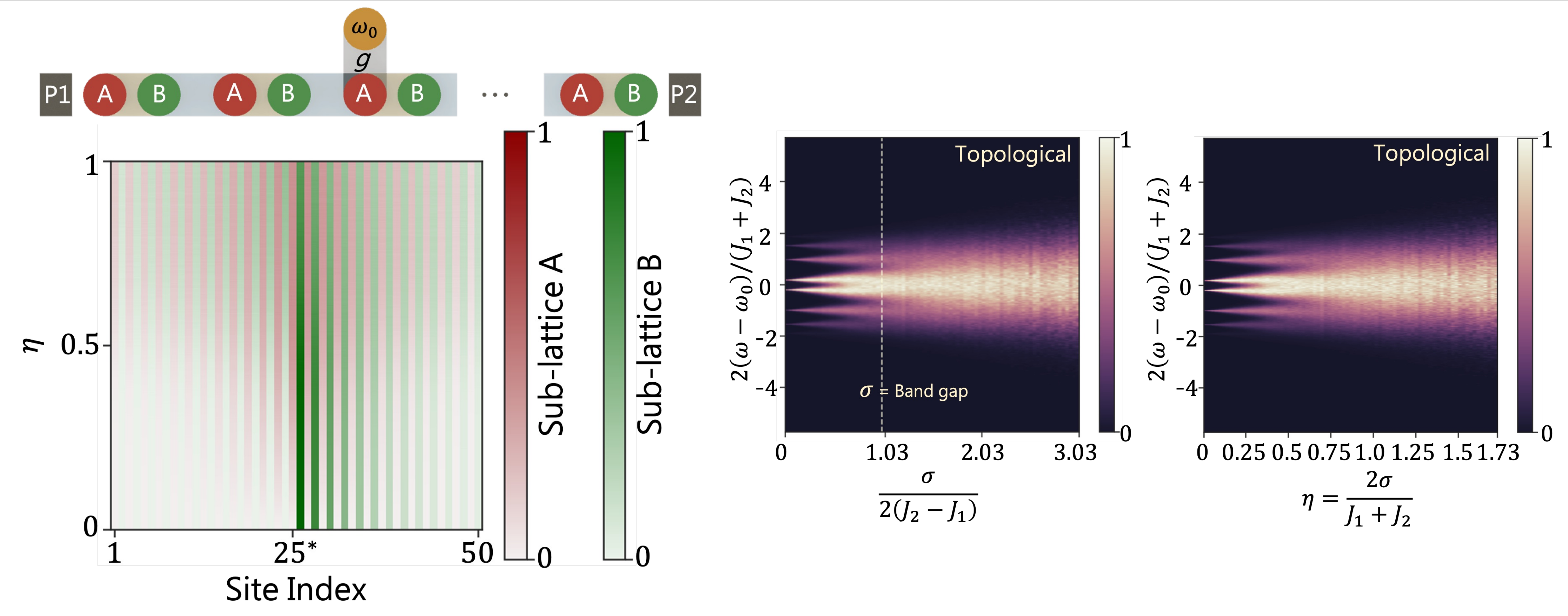


- Hamiltonian H_B is given by: $H_B = \sum_i \omega_0\left(a_i^\dagger a_i + b_i^\dagger b_i\right) + J_1\left(b_i^\dagger a_i + a_i^\dagger b_i\right) + J_2\left(b_i^\dagger a_{i+1} + a_{i+1}^\dagger b_i\right)$

a) This bath supports topologically non-trivial phases depending on whether:
   i. $J_1 < J_2$ which is termed as the topological phase or
   ii. $J_1 > J_2$ which is termed as the trivial phase.

b) The band gap size is $2|J_1 - J_2|$.

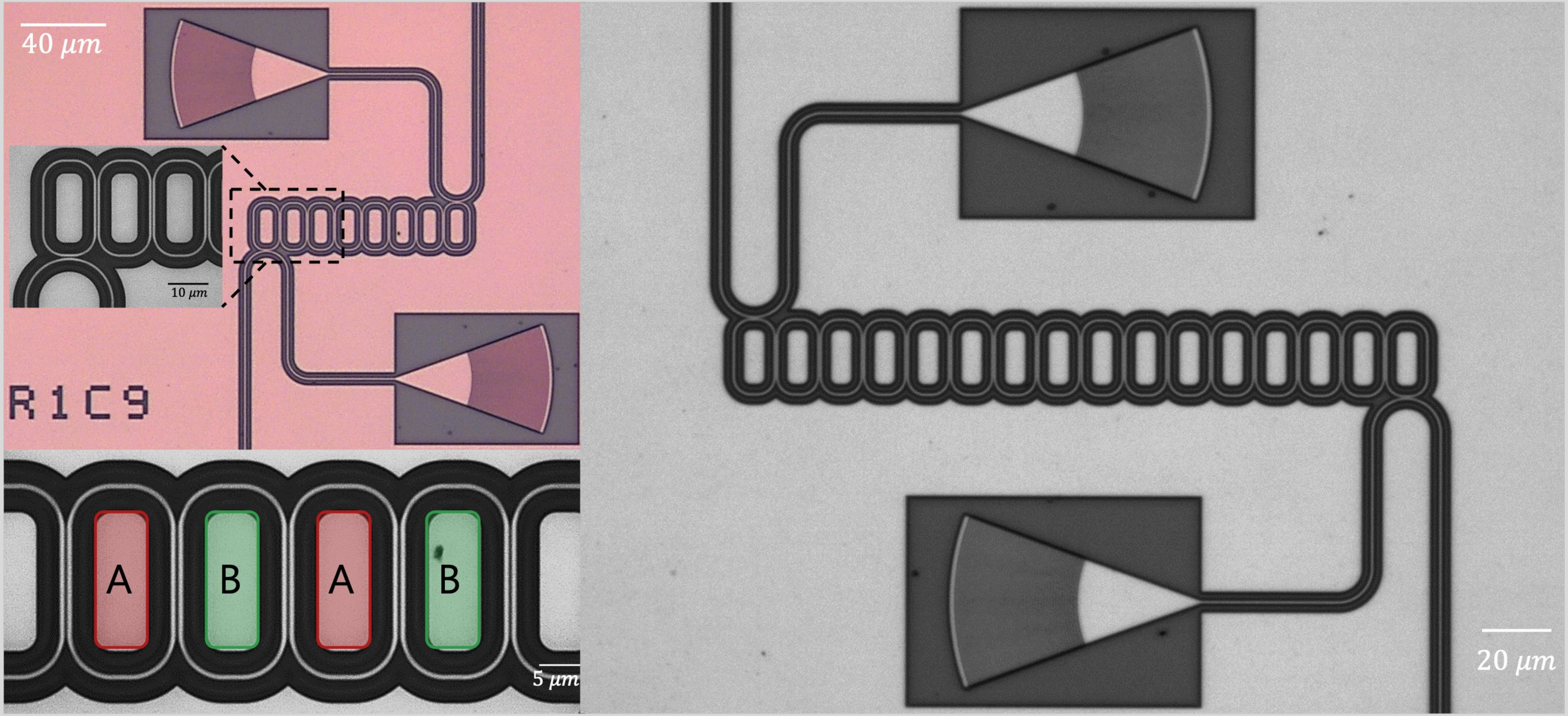
Disorder Study



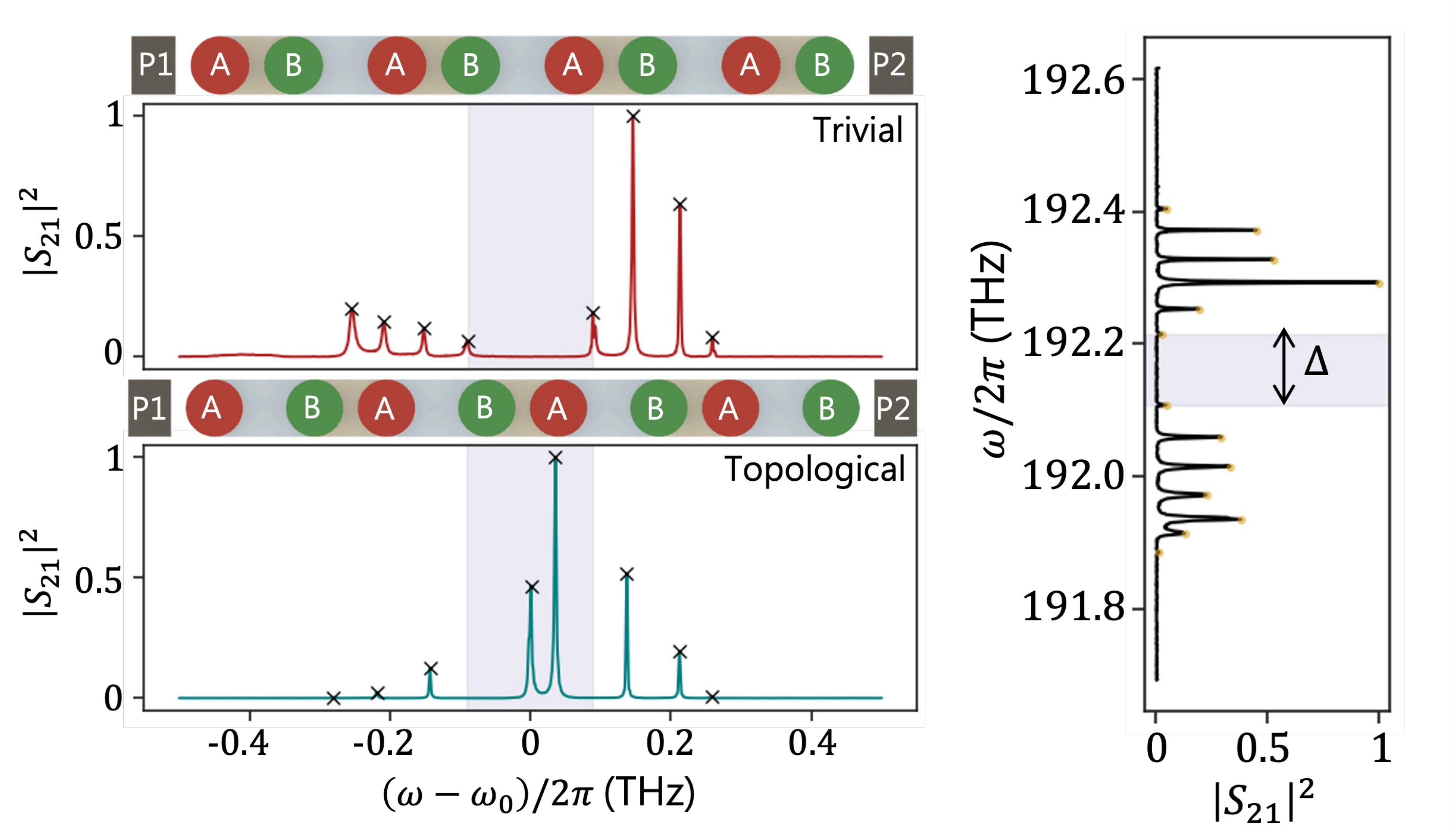
$$\left\{\eta = \frac{2\sigma}{(J_1 + J_2)}\right\}$$

Disorders are much more problematic to find all the super-modes, than probing the bandgap or edge-states!!

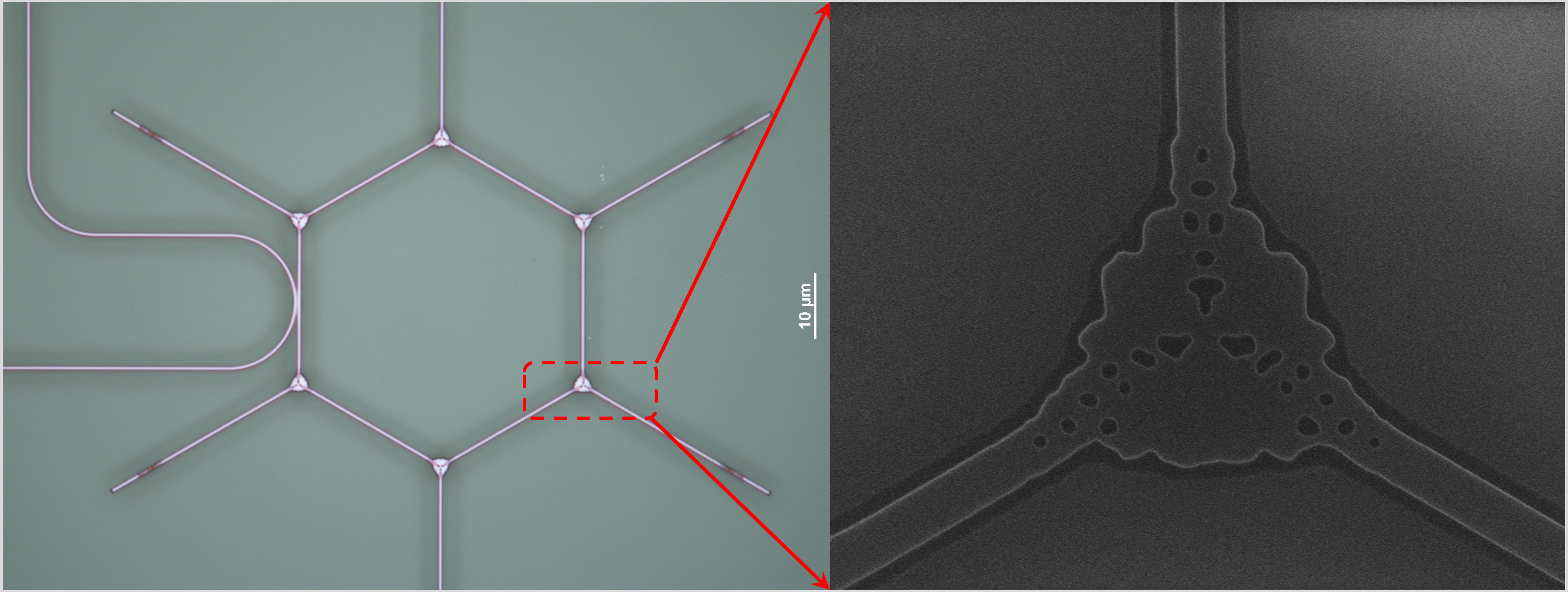
Fabricated CCA



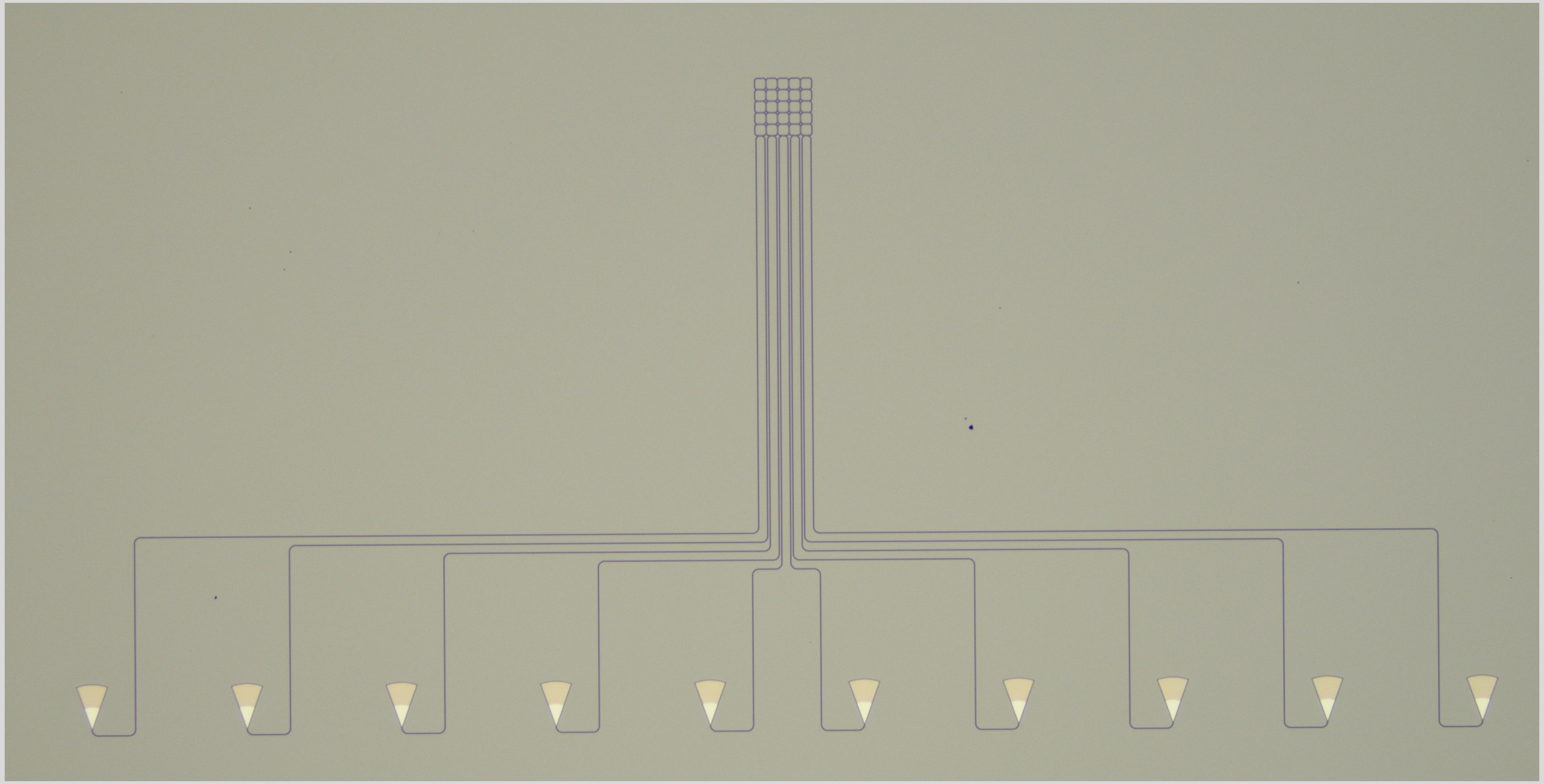
Topological bath characterization

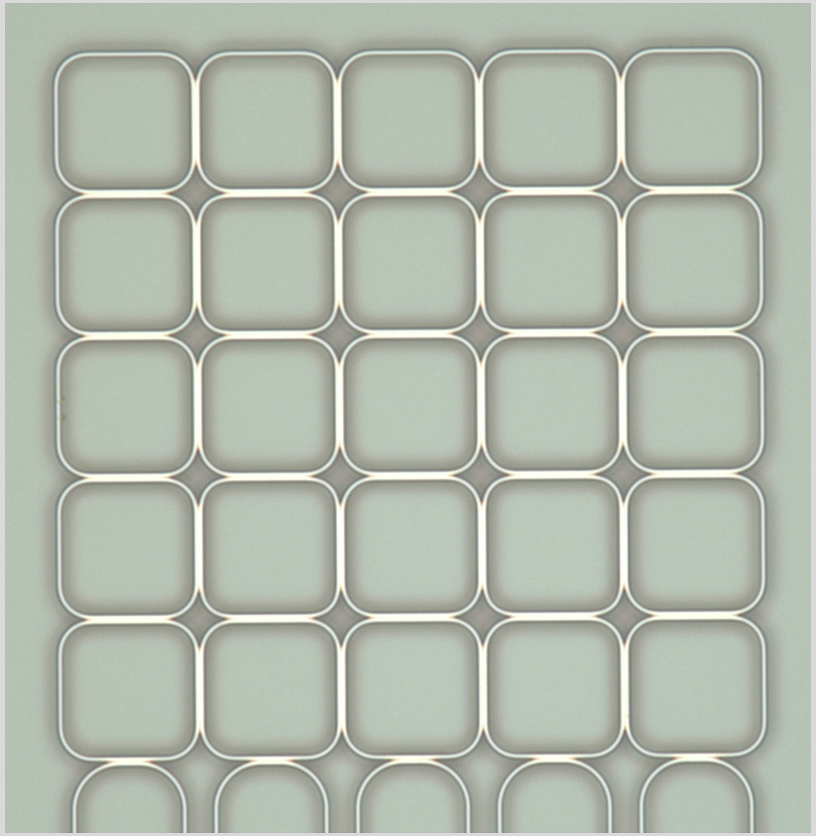


More complex coupling



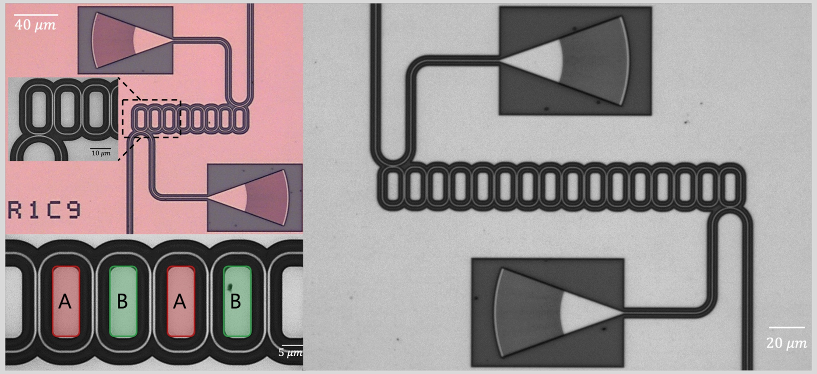
Complex hopping rates between sites





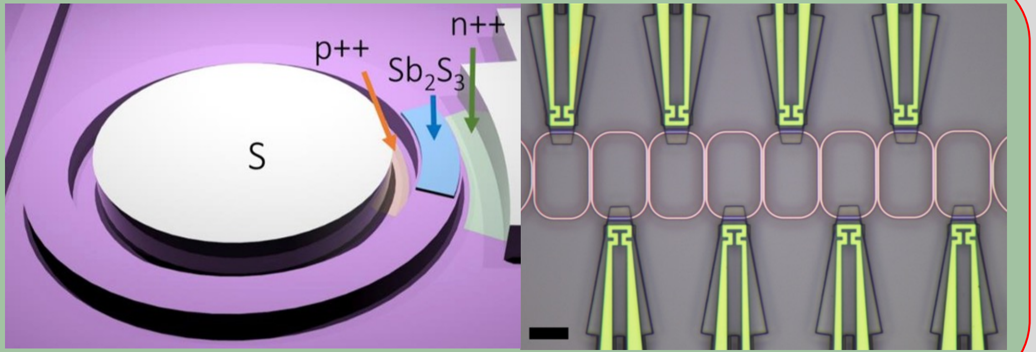
Scalability: Coupled cavity array in integrated photonics

Saxena et al., ACS Photonics, 2022



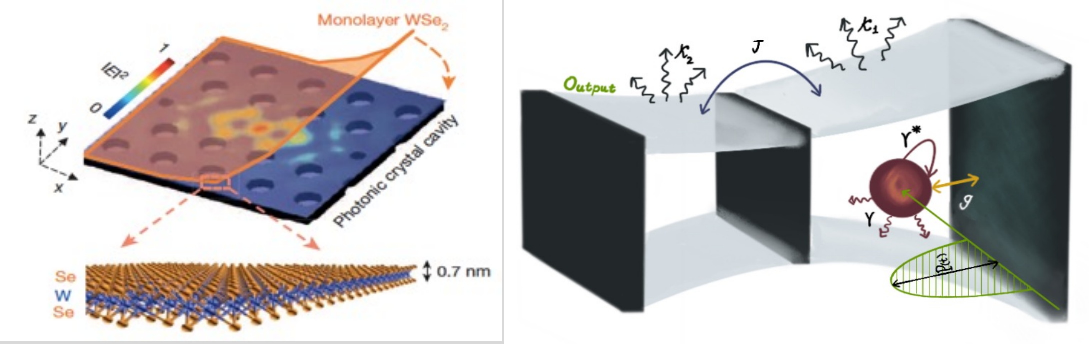
Programmability: Site-controlled tuning of CCA

Saxena et al., Nature Communications, 2023
Chen et al., Nature Communications, 2023

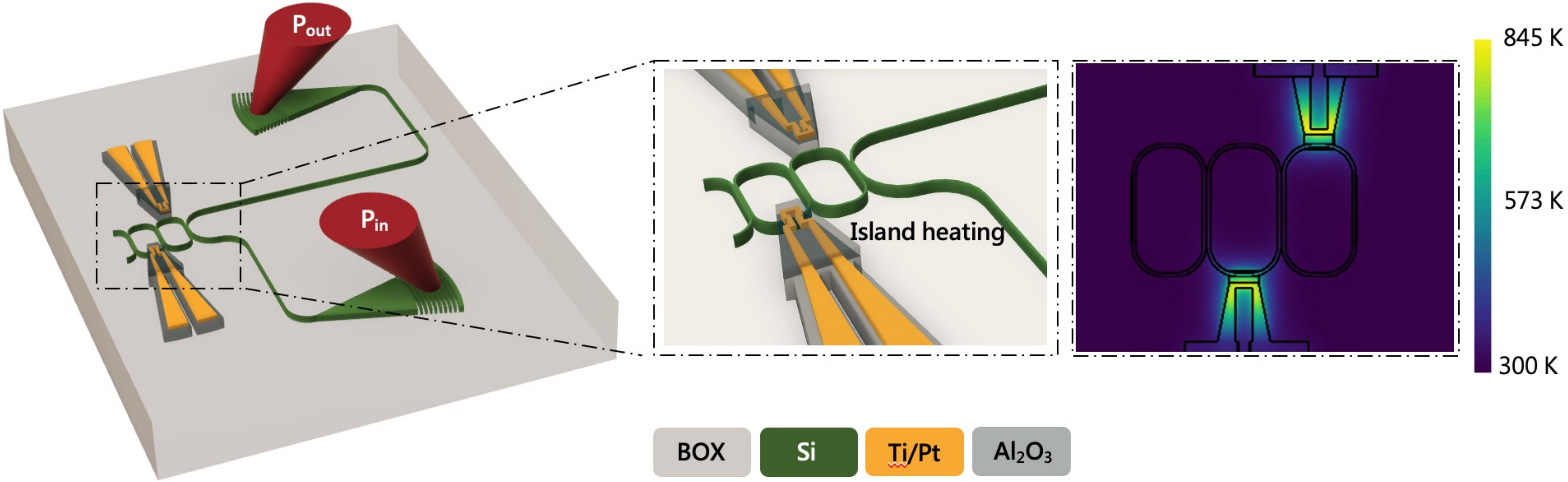


Nonlinearity: Quantum materials in cavity

Fryett et. al., ACS Photonics, 2018
Chen et. al., Nano Letter, 2018
Chen et. al., Optics Letter, 2019
Saxena et. al., ACS Photonics, 2019

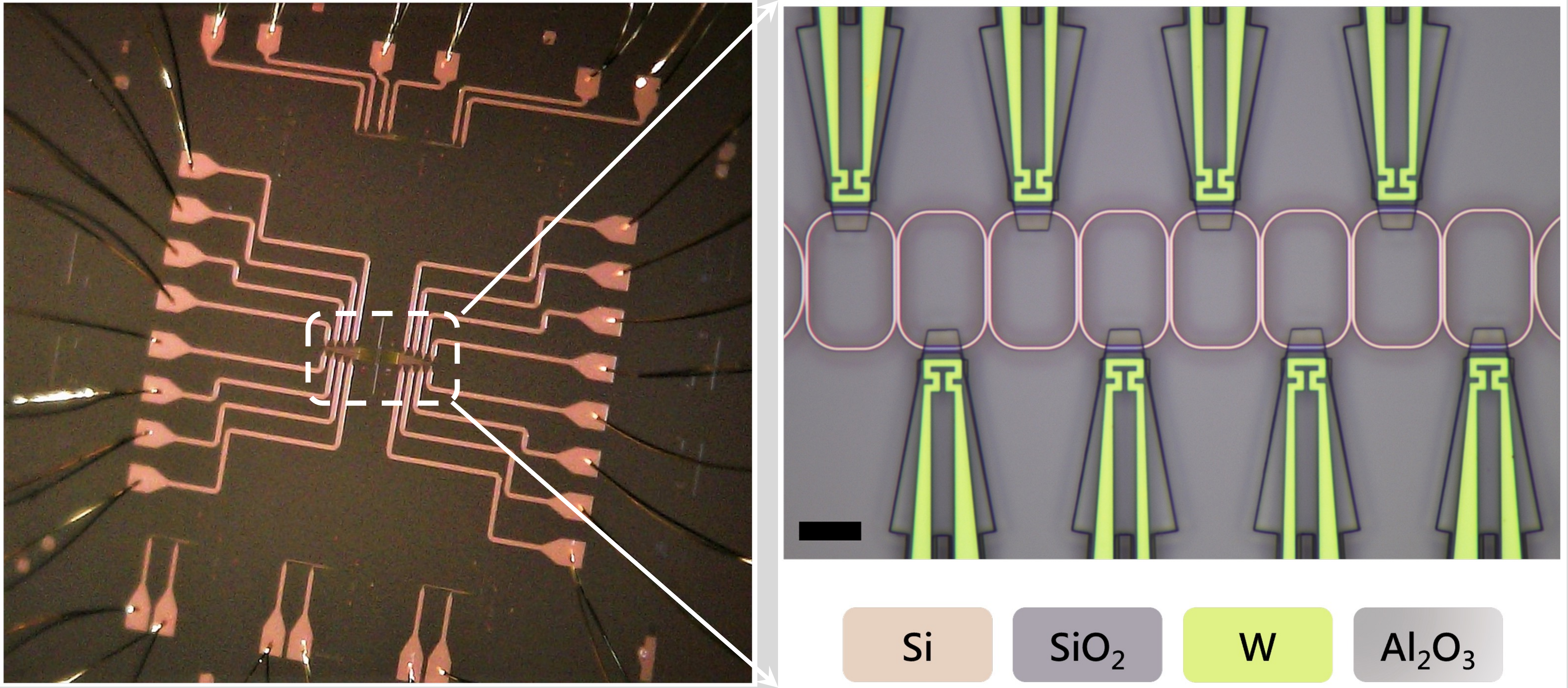


Local tuning of the cavities in the CCA

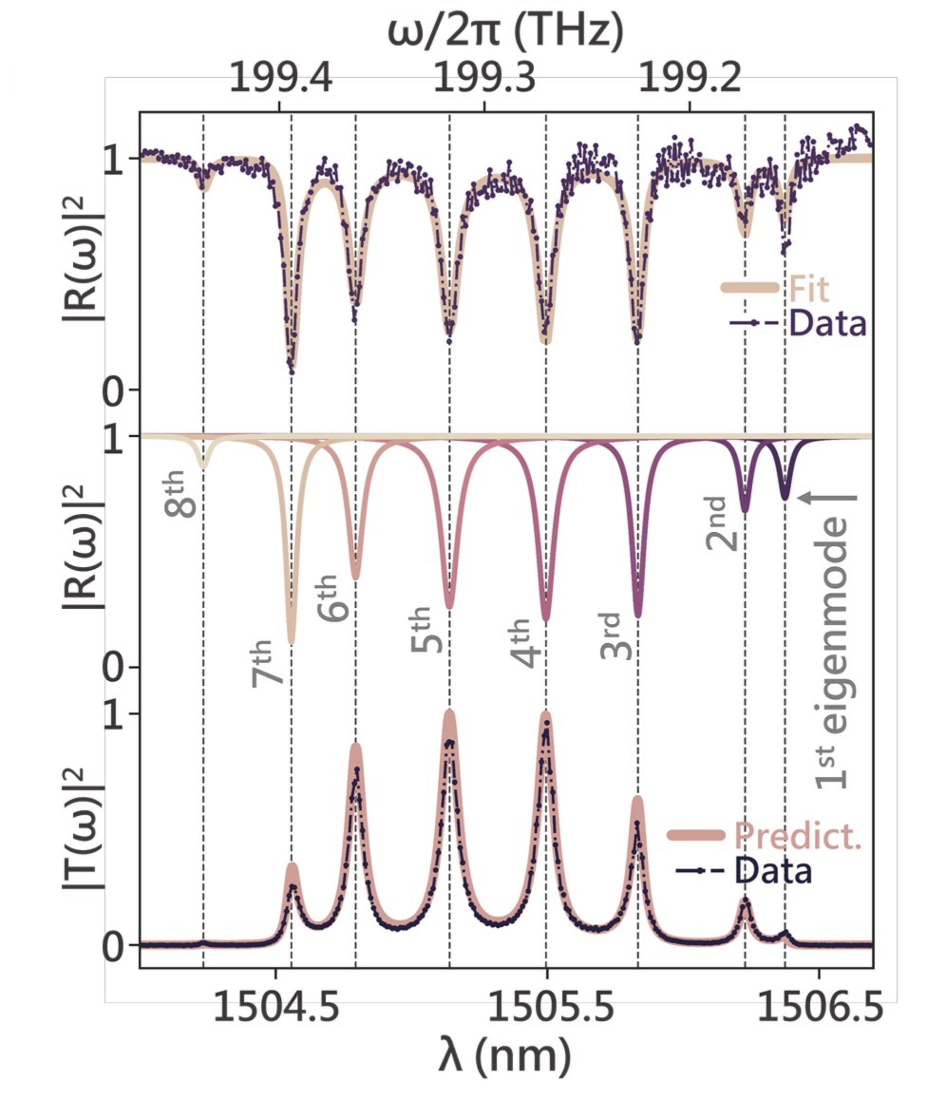


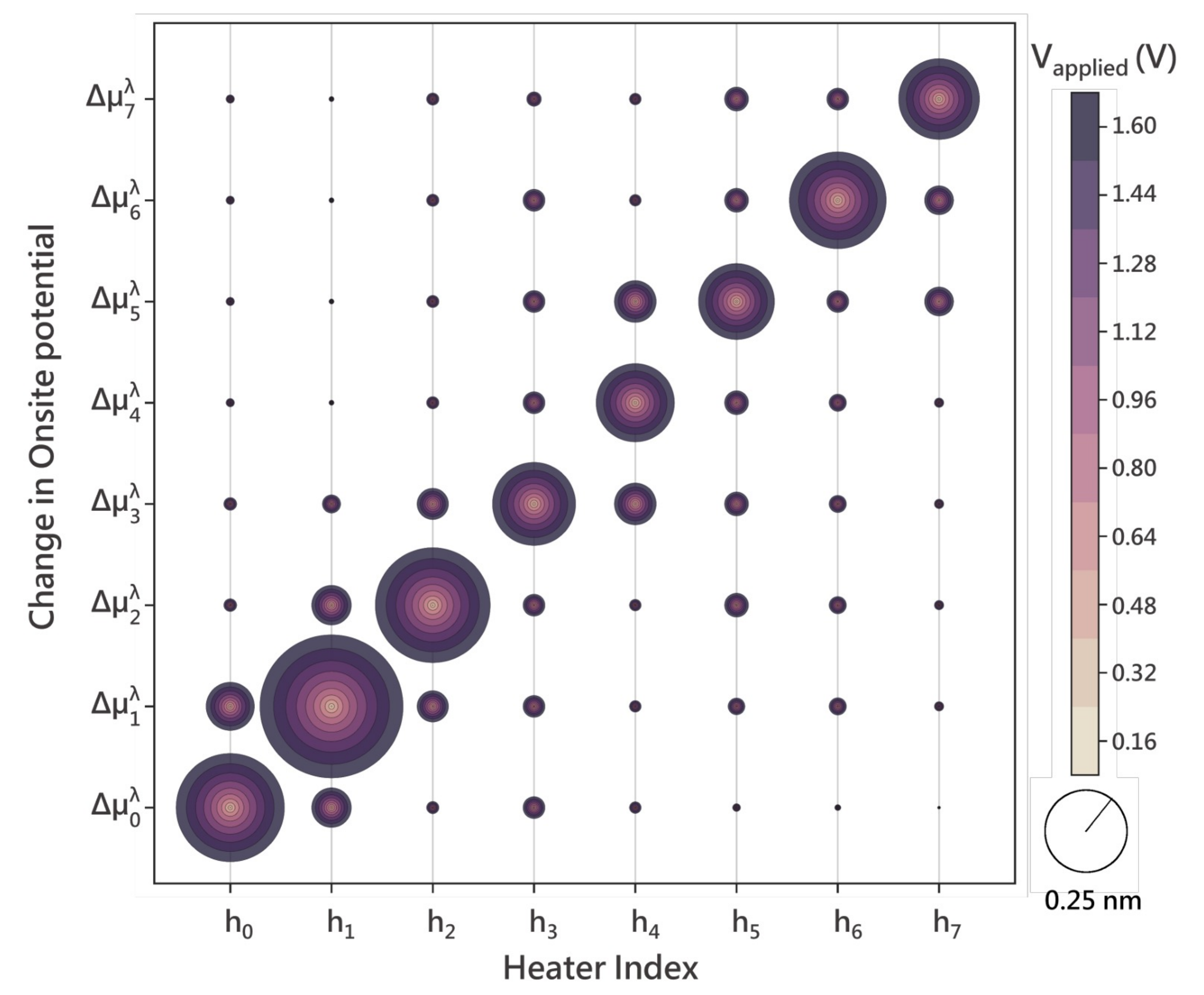
New heater architecture to reduce the cross-talk.

Fabricated CCA with local tuning

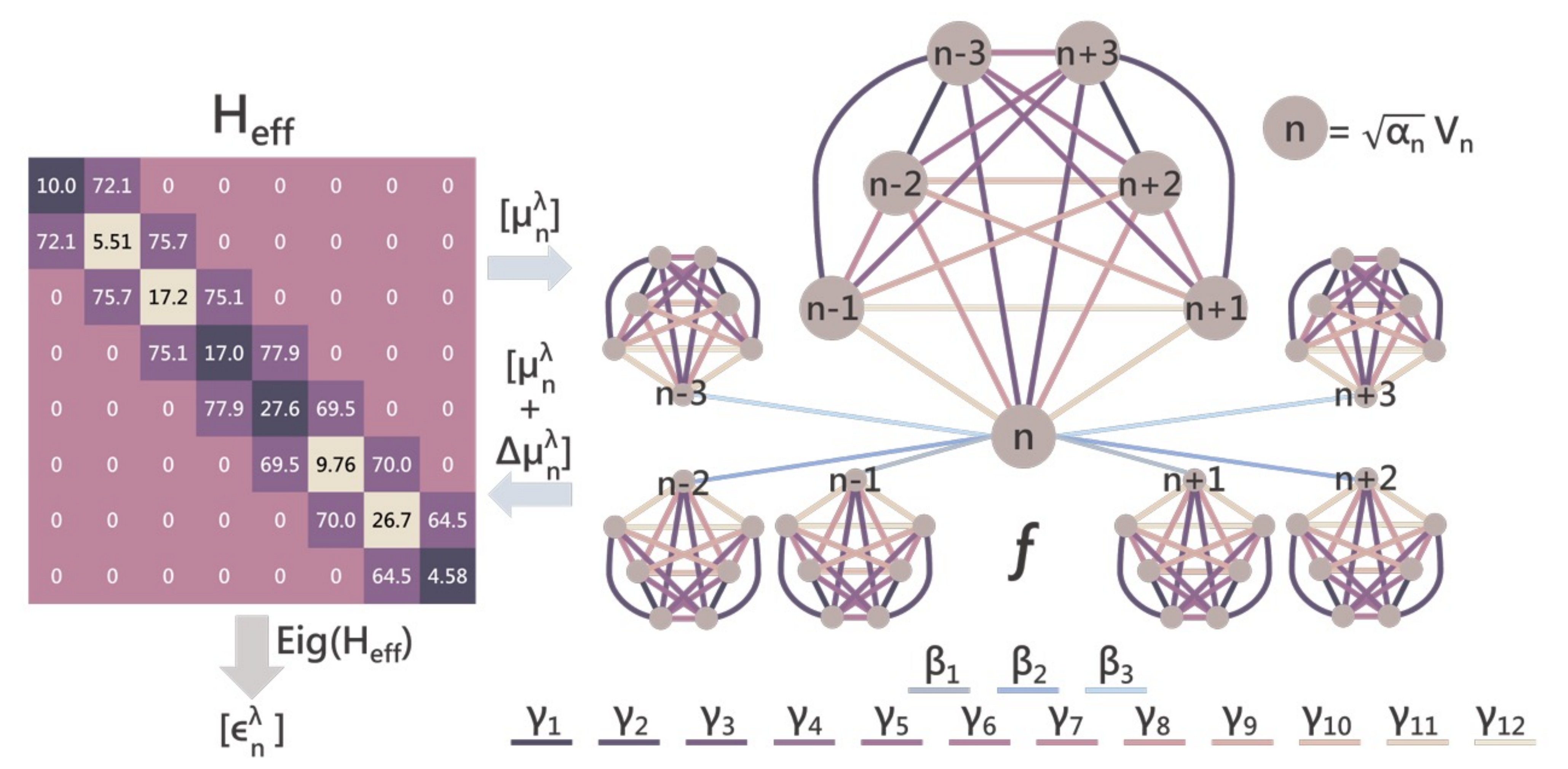


Characterization



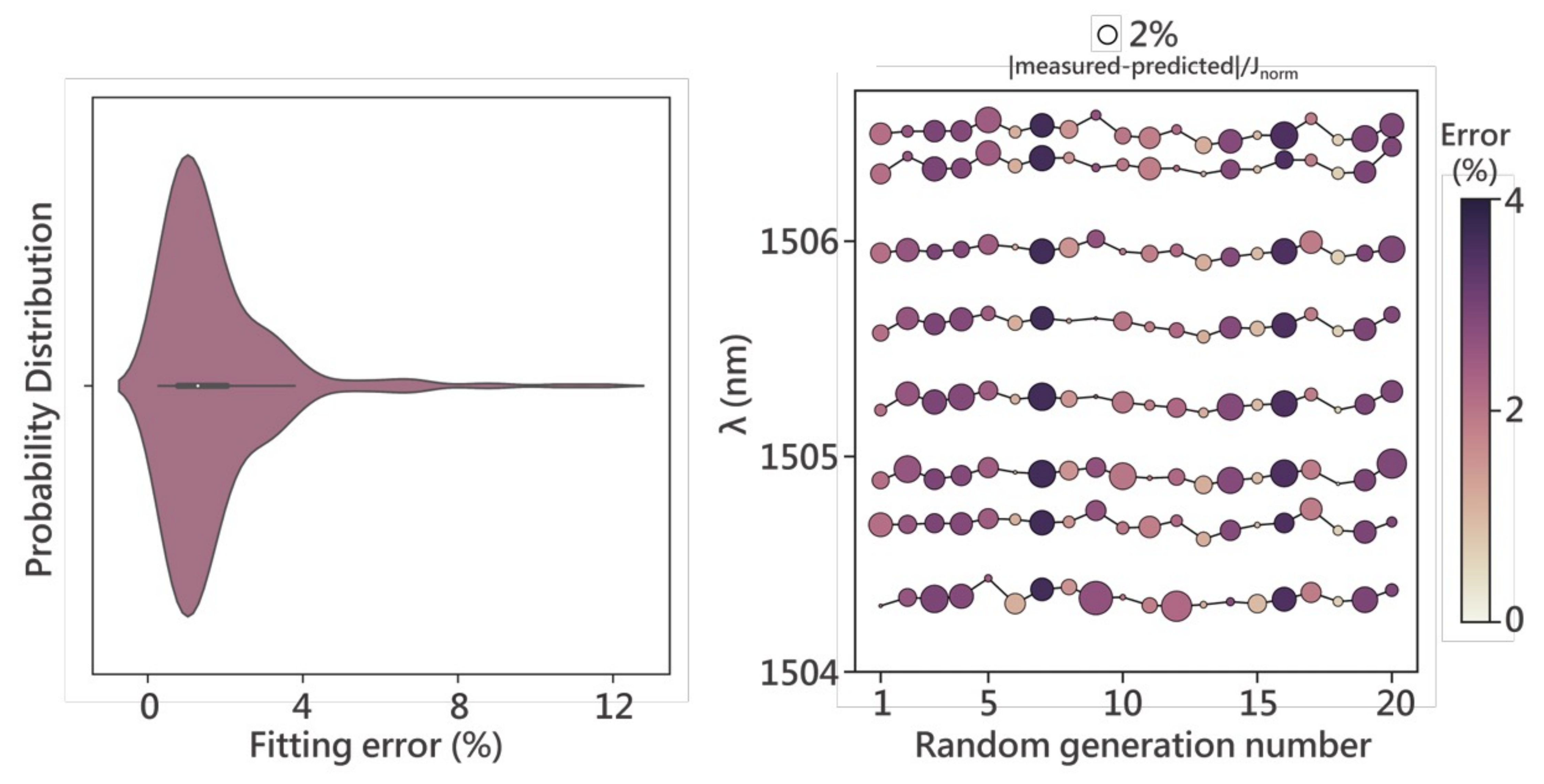


Hamiltonian Engineering and Tomography

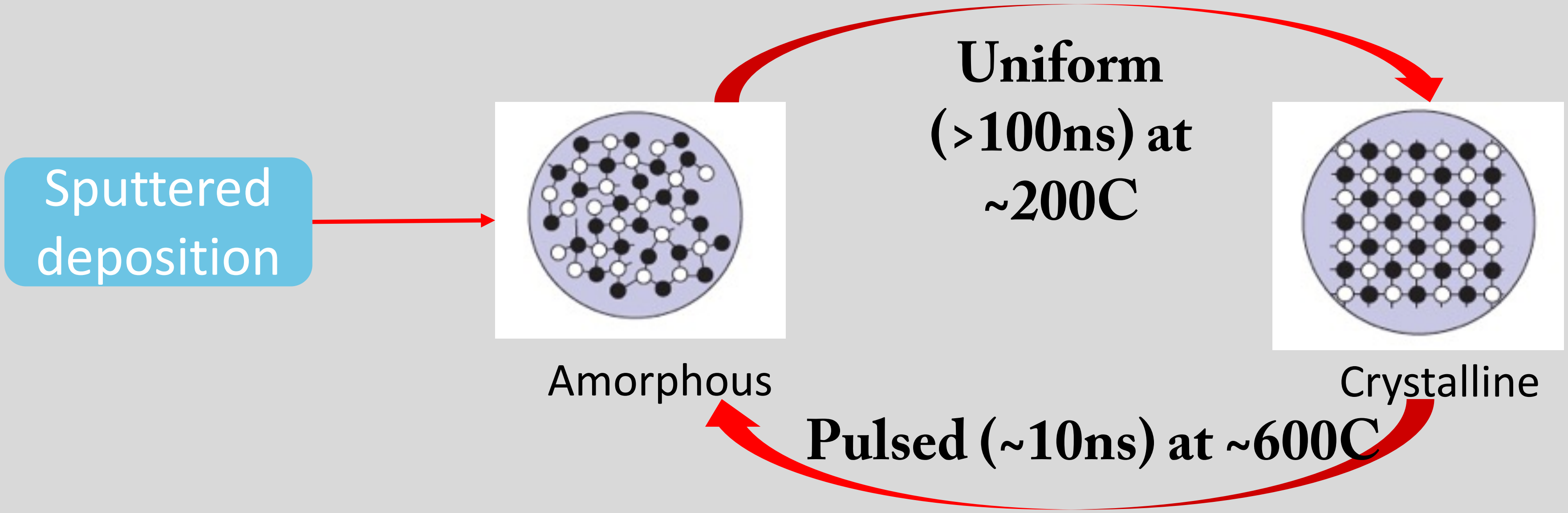


$$H_{eff} = \begin{bmatrix} 10.0 & 72.1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 72.1 & 5.51 & 75.7 & 0 & 0 & 0 & 0 & 0 \\ 0 & 75.7 & 17.2 & 75.1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 75.1 & 17.0 & 77.9 & 0 & 0 & 0 \\ 0 & 0 & 0 & 77.9 & 27.6 & 69.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 69.5 & 9.76 & 70.0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 70.0 & 26.7 & 64.5 \\ 0 & 0 & 0 & 0 & 0 & 0 & 64.5 & 4.58 \end{bmatrix}$$

Prediction Error



Non-volatile phase-change materials (PCMs)



Sputtered deposition

Amorphous

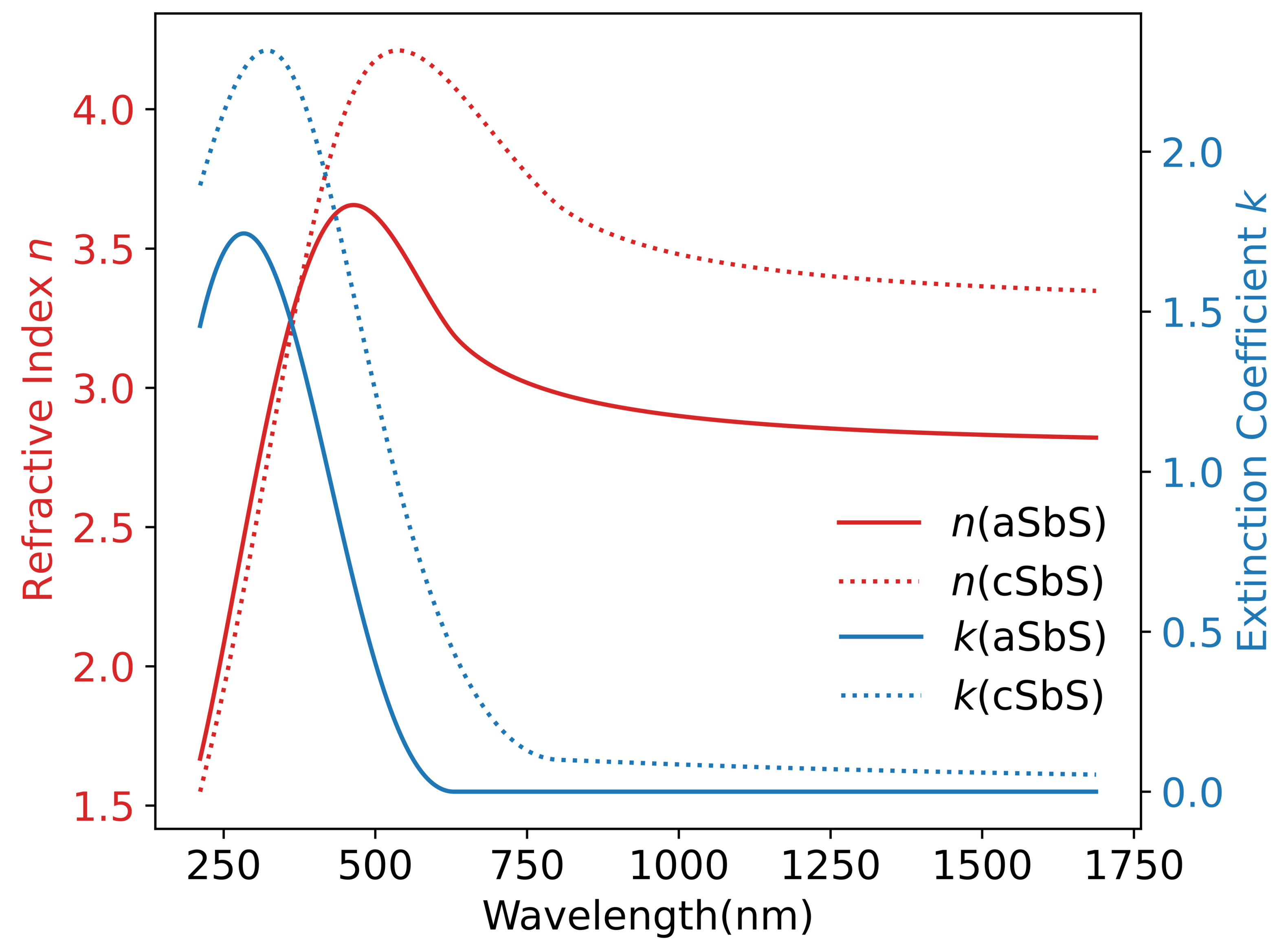
Uniform (>100ns) at ~200C

Crystalline

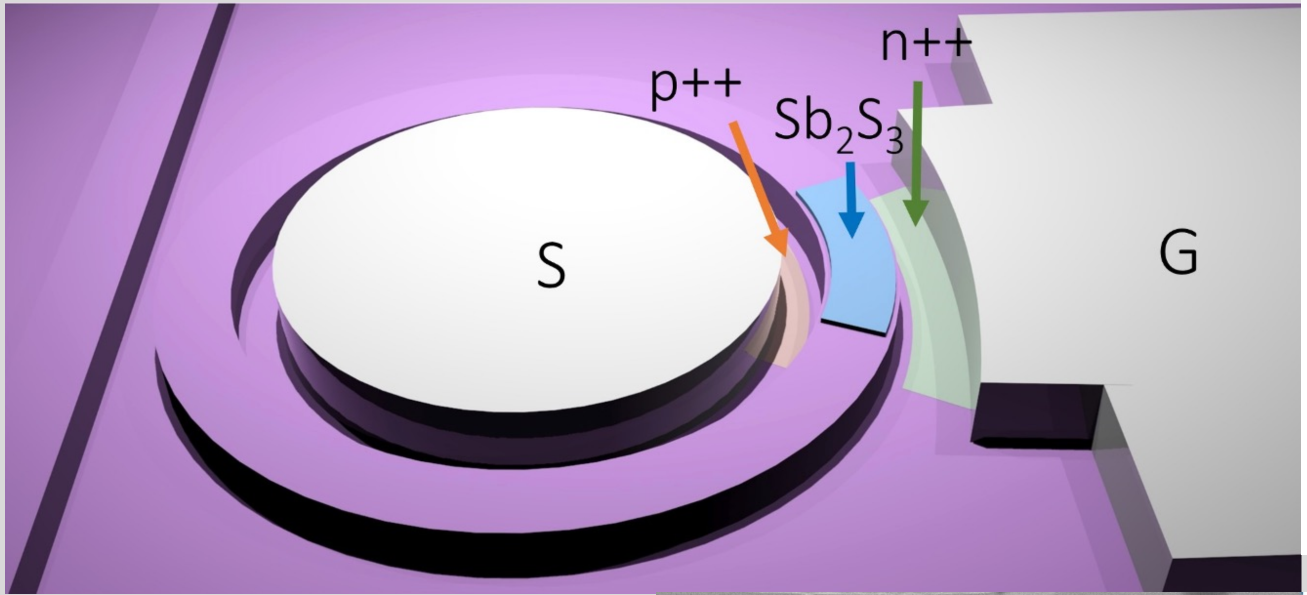
Pulsed (~10ns) at ~600C

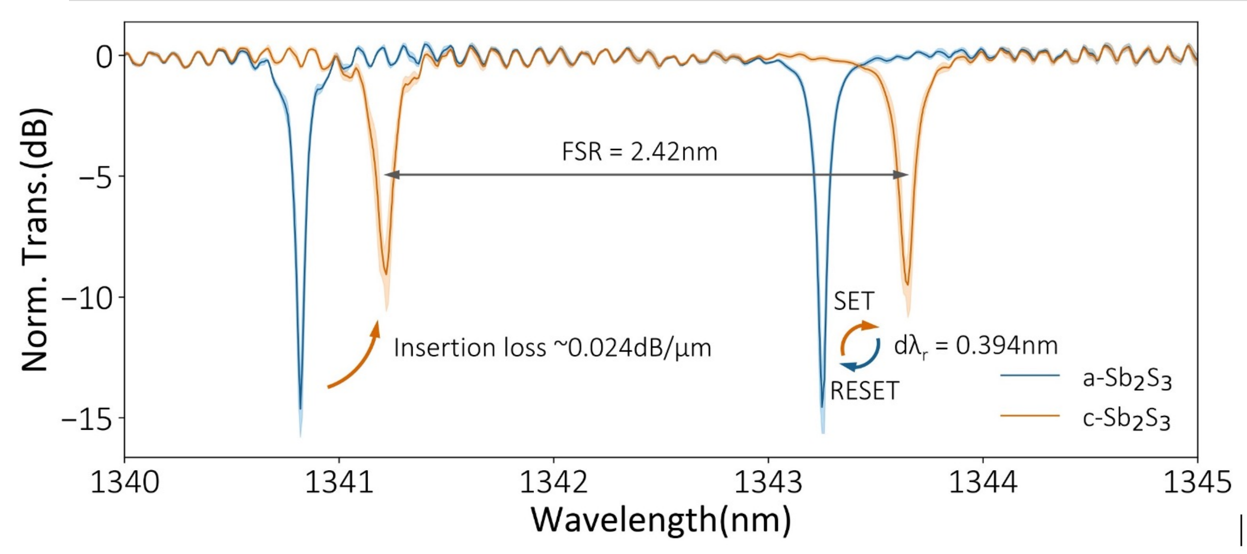
Zheng, J. et al. Opt. Mater. Express 8(6) (2018).

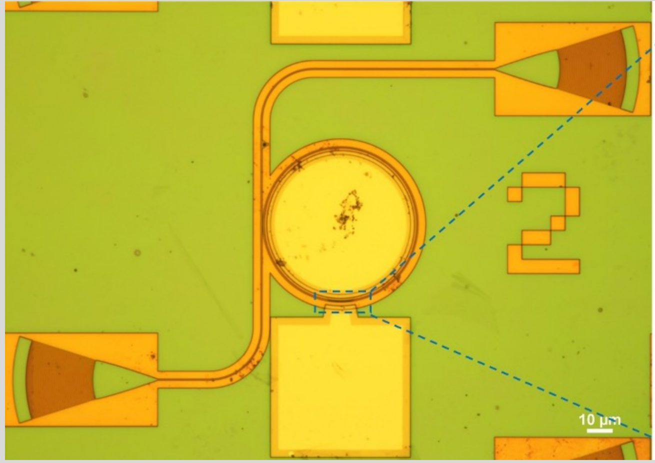
Wide bandgap PCM: SbS

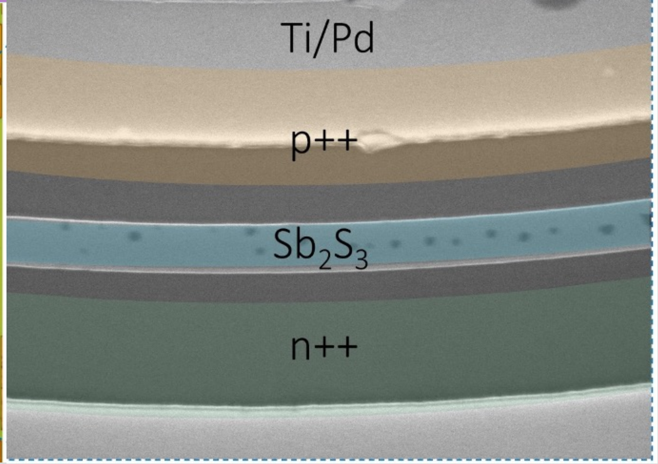


Nonvolatile microring switch integrated with Sb_2S_3





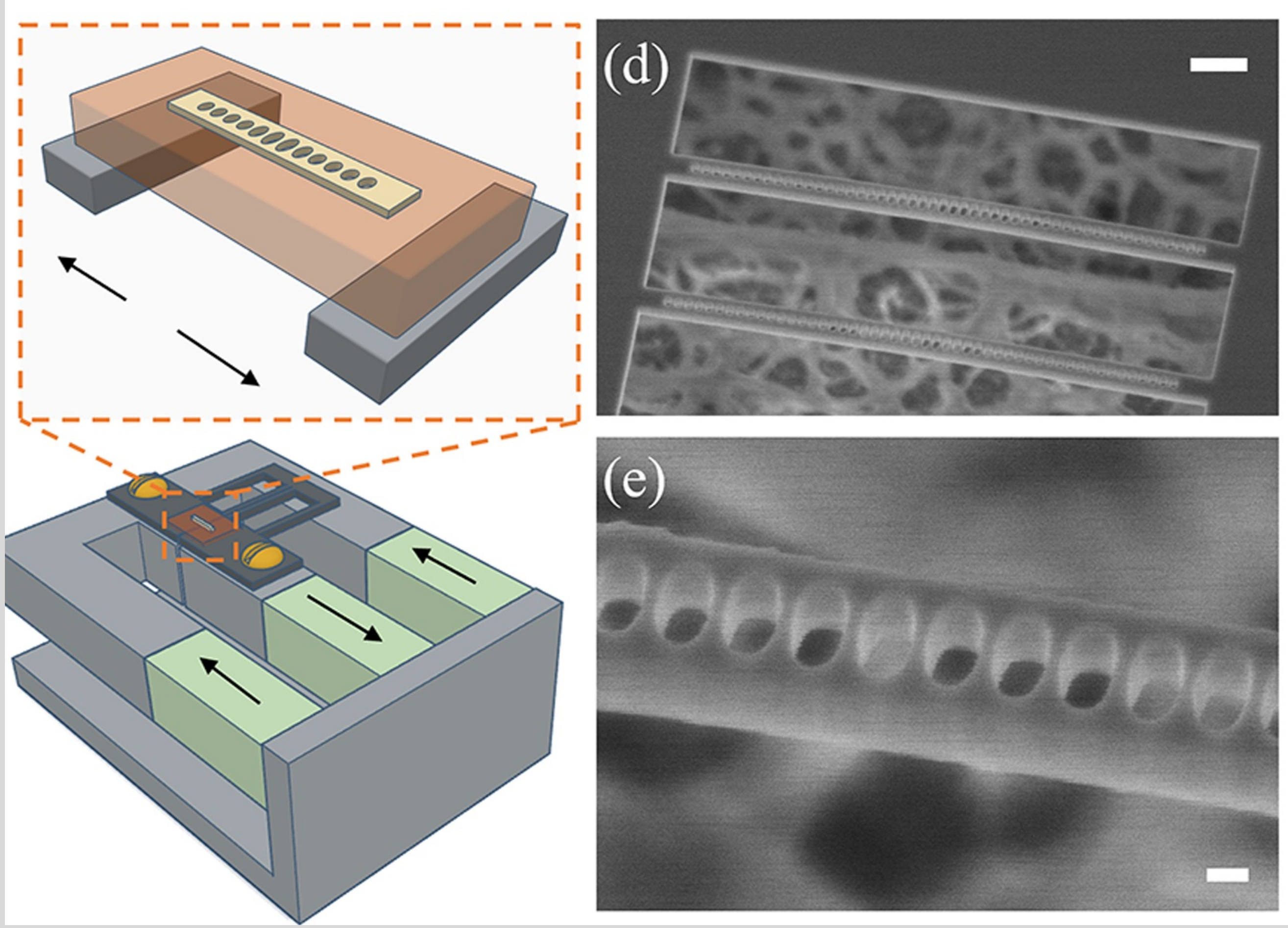


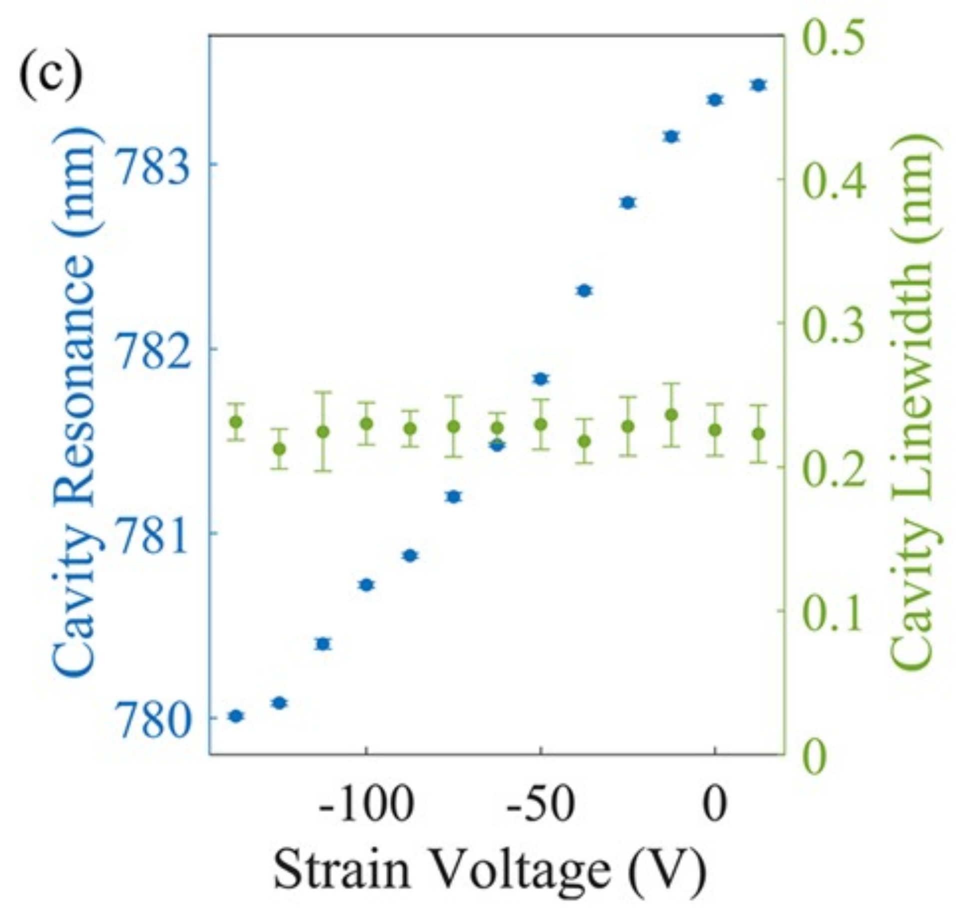


We see reversible tuning of the ring resonator.
SbS length: 10 μm
Low-loss operation in both crystalline and amorphous states.
Five cycles are shown here.
Pulse conditions: for amorphization: 100 or 500 ns, ~10 V;
for crystallization: ~2V, ~500 μs

Chen, R. et al. Nature Communications 2023

Strain Tuning of cavities



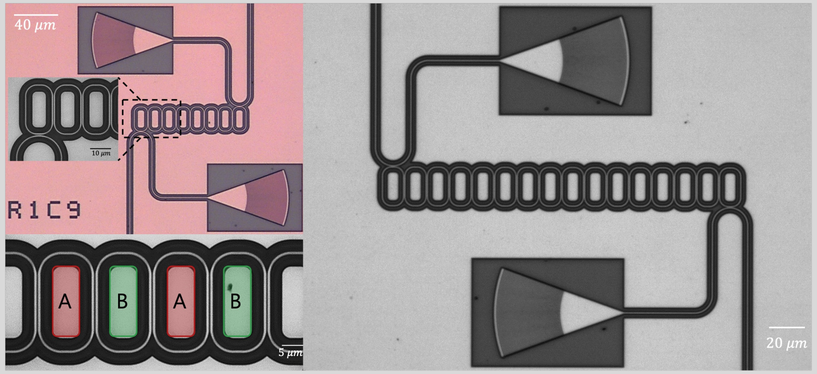


Large tuning without affecting the cavity linewidth in cryogenic environment

Manna et al. ACS Photonics, 2023

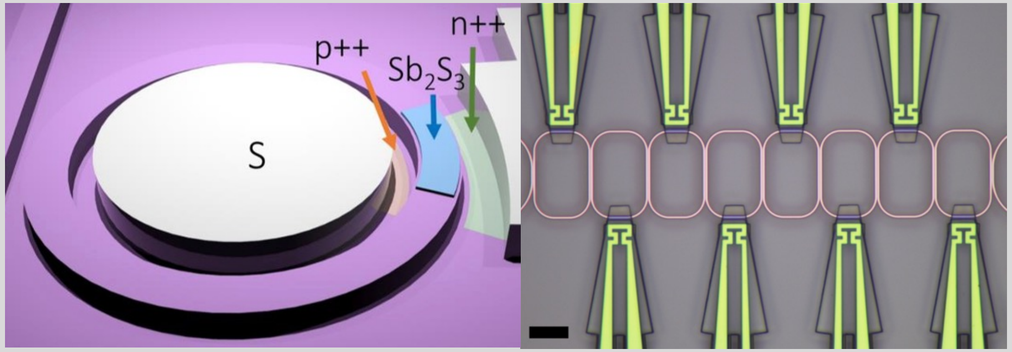
Scalability: Coupled cavity array in integrated photonics

Saxena et al., ACS Photonics, 2022



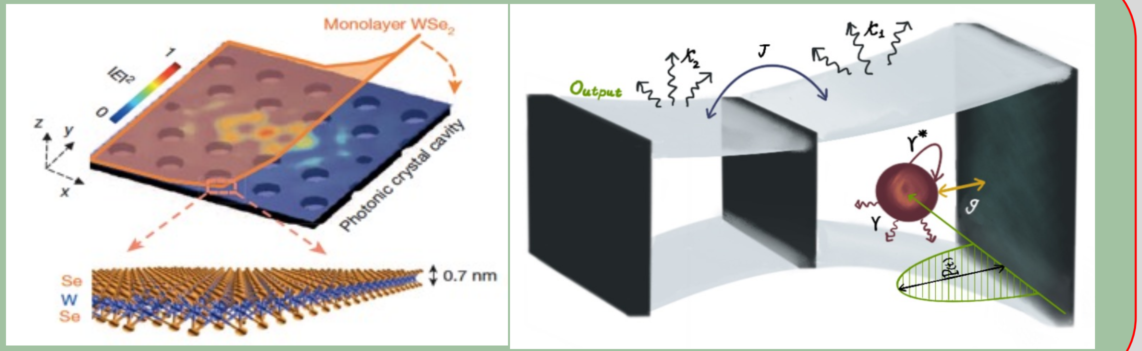
Programmability: Site-controlled tuning of CCA

Saxena et al., Nature Communications, 2023
Chen et al., Nature Communications, 2023

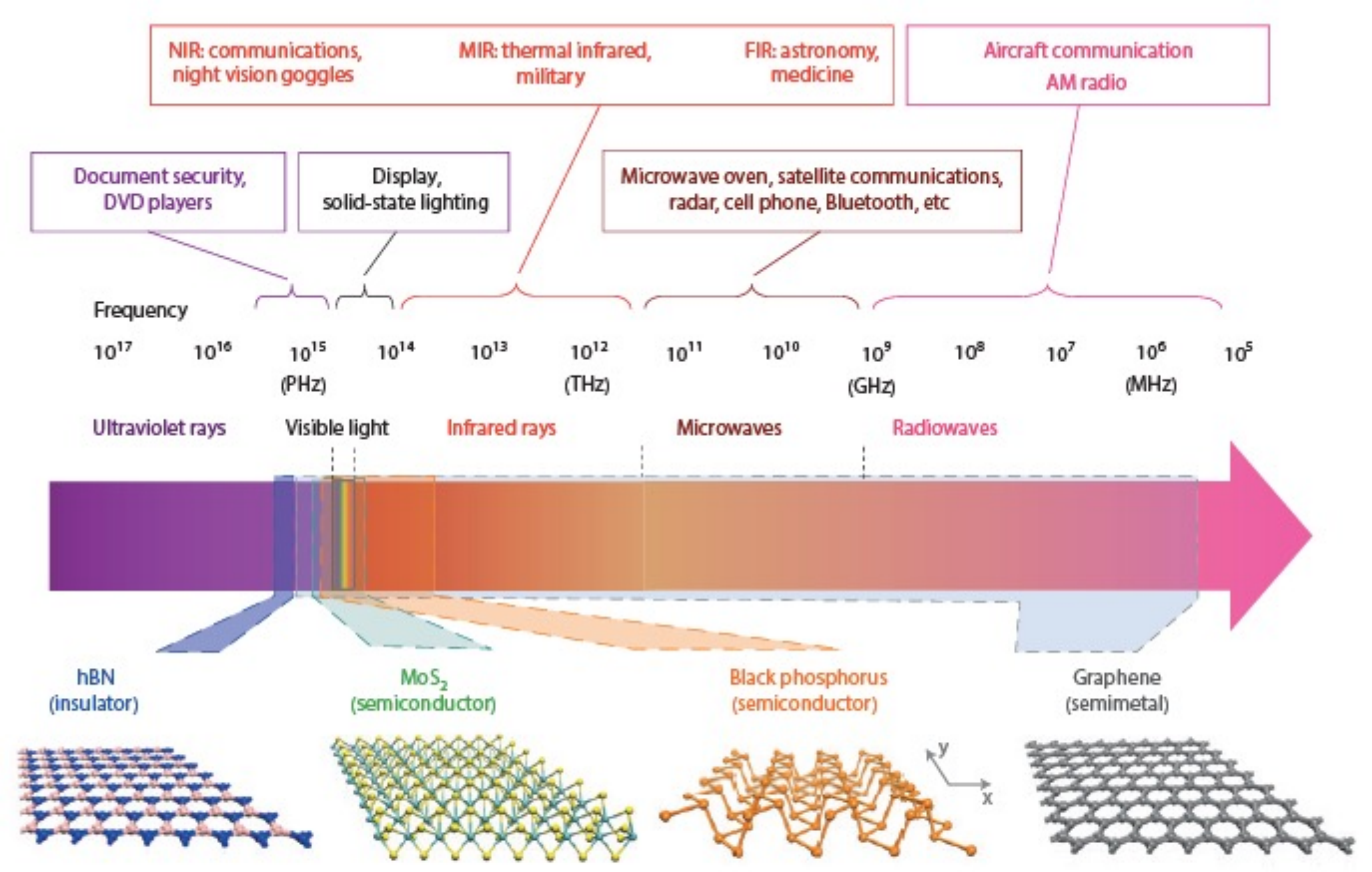


Nonlinearity: Quantum materials in cavity

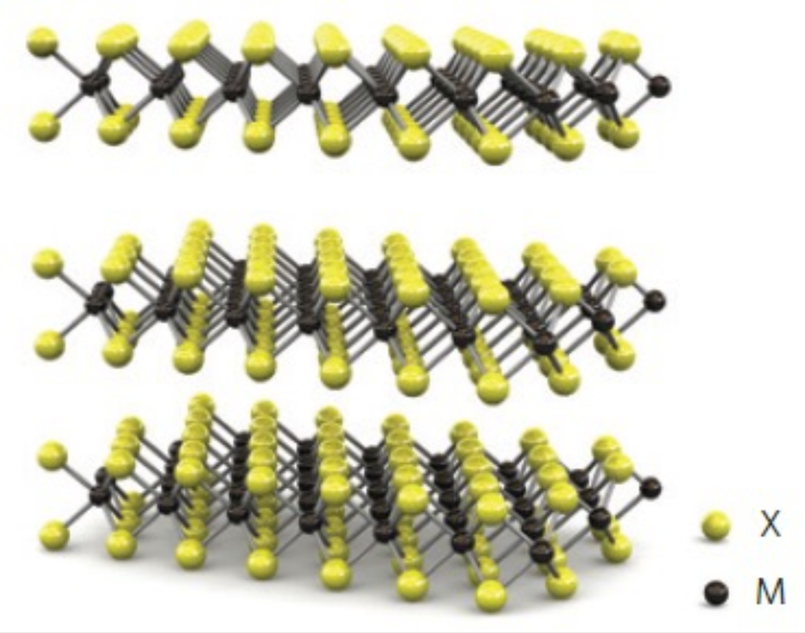
Fryett et. al., ACS Photonics, 2018
Chen et. al., Nano Letter, 2018
Chen et. al., Optics Letter, 2019
Saxena et. al., ACS Photonics, 2019



2D Materials: new opportunities in exciton-polaritons



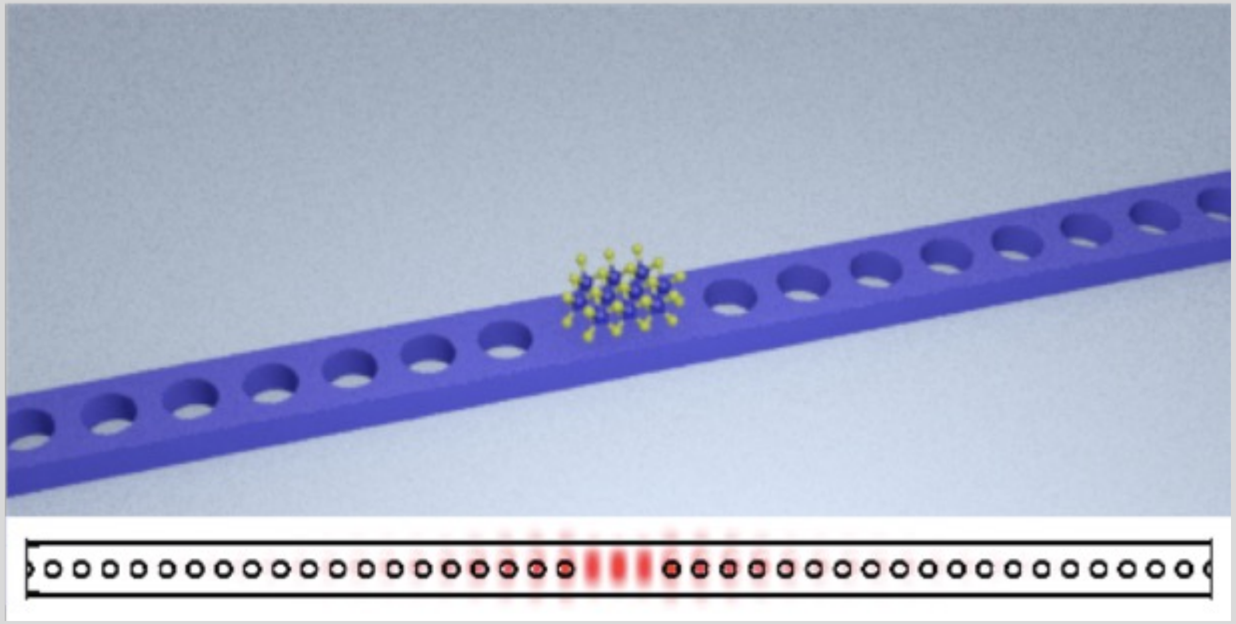
Nature Photonics 8, 899–907 (2014)



Nature nanotechnology, 7, 699, 2012

- Excitonic System: large exciton binding energy
- No explicit lattice matching is required and can be transferred on any material system.

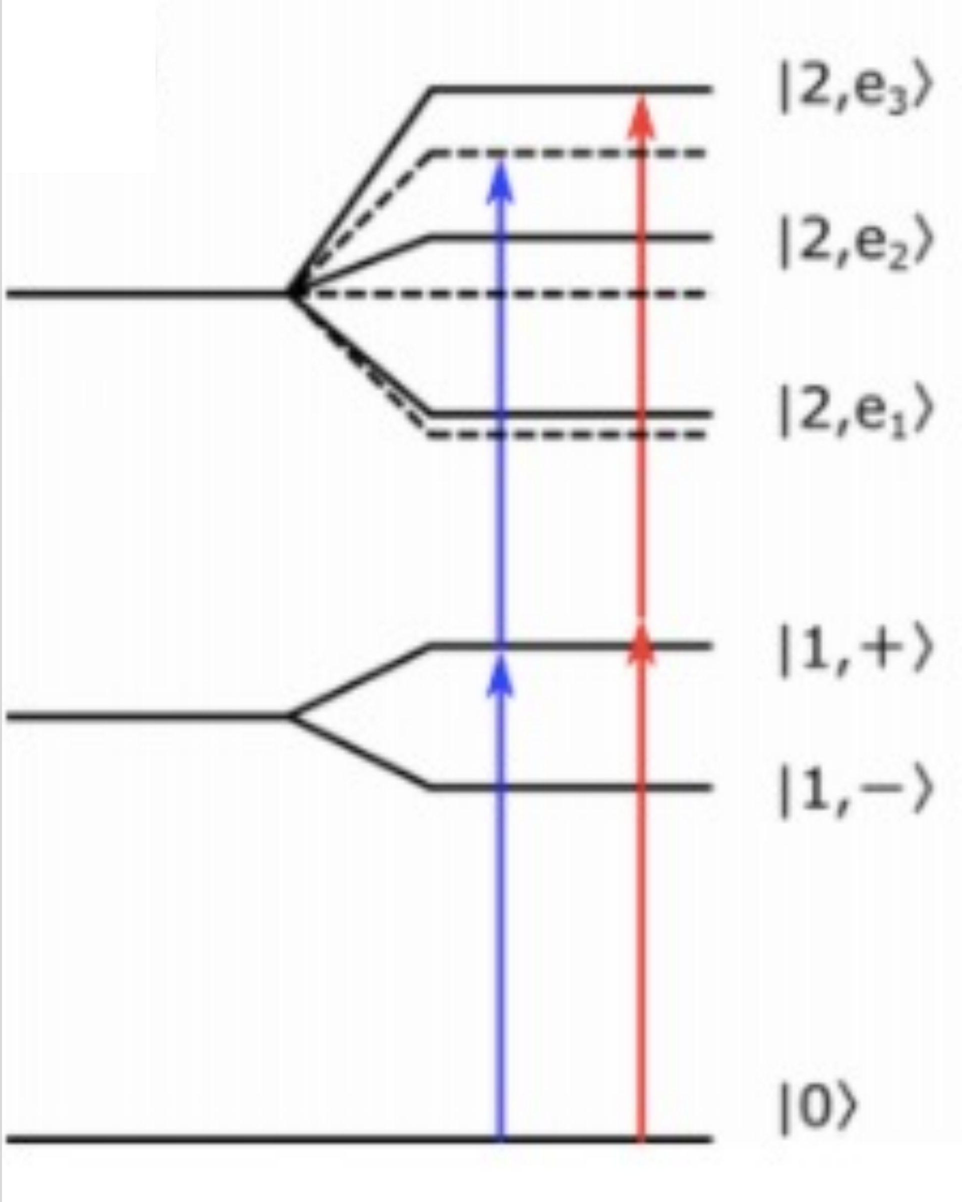
Single photon nonlinear optics



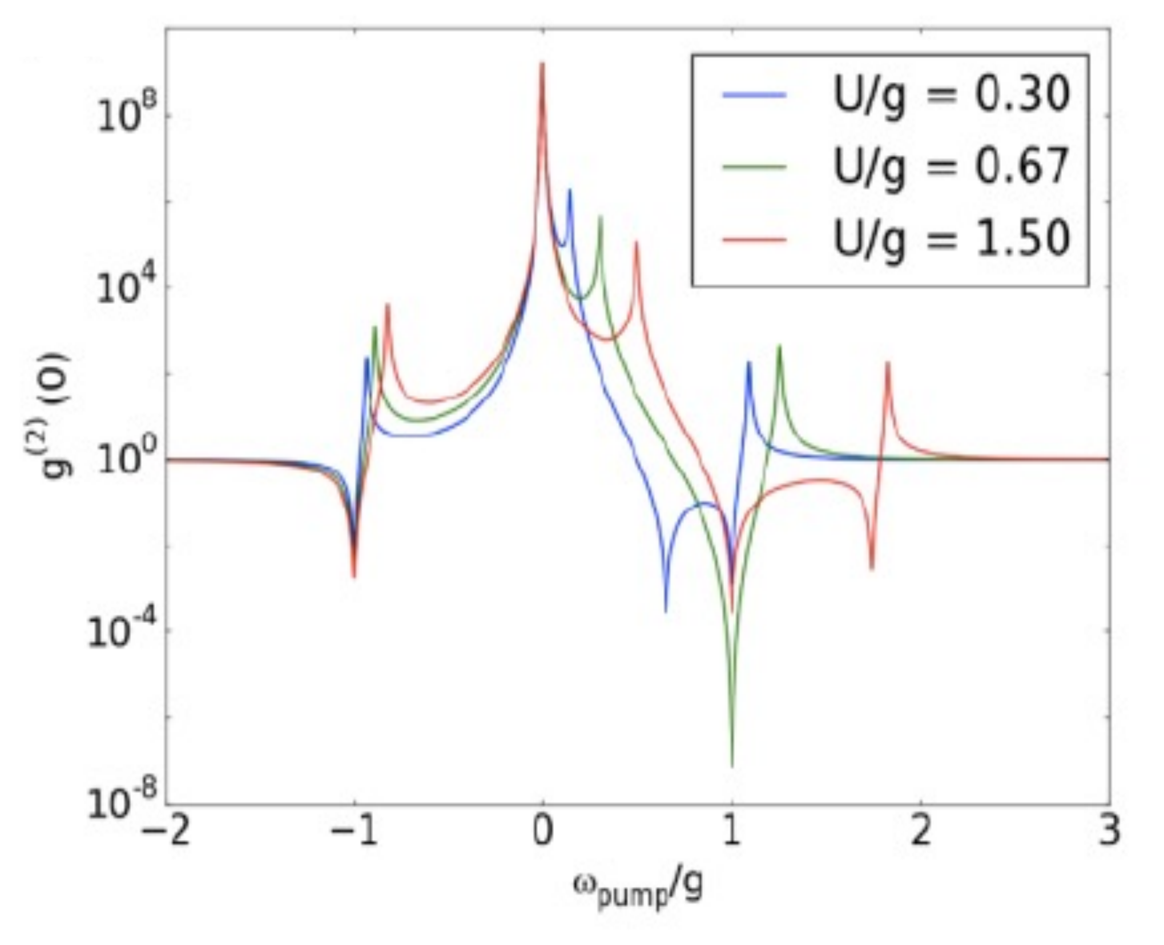
$$\mathcal{H} = \Delta_c a^\dagger a + \Delta_x b^\dagger b + g(a^\dagger b + a b^\dagger) + U_x b^\dagger b^\dagger b b$$

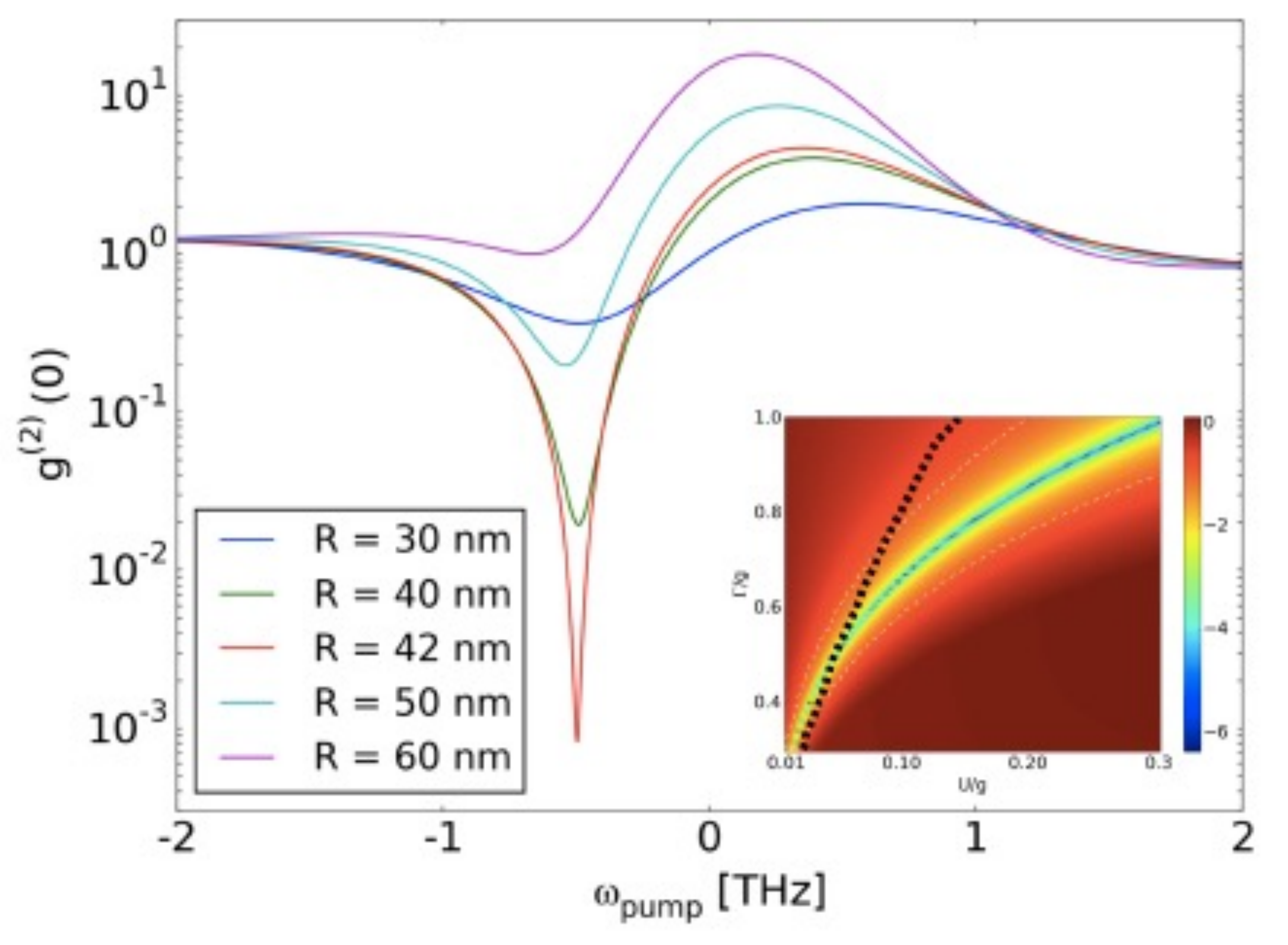
$$\hbar g \approx \frac{d_{cv}|\phi(0)|\sqrt{\hbar\omega_c}}{\sqrt{(2\epsilon_0 L_c)}}\sqrt{\frac{S_x}{S_{mode}}} \quad \hbar U_x = \frac{6E_b a_B^2}{S_x}$$

Ryou et. al., PRB, 2018
QD array from 2D materials: Nathaniel Stern group



Photon correlation calculation

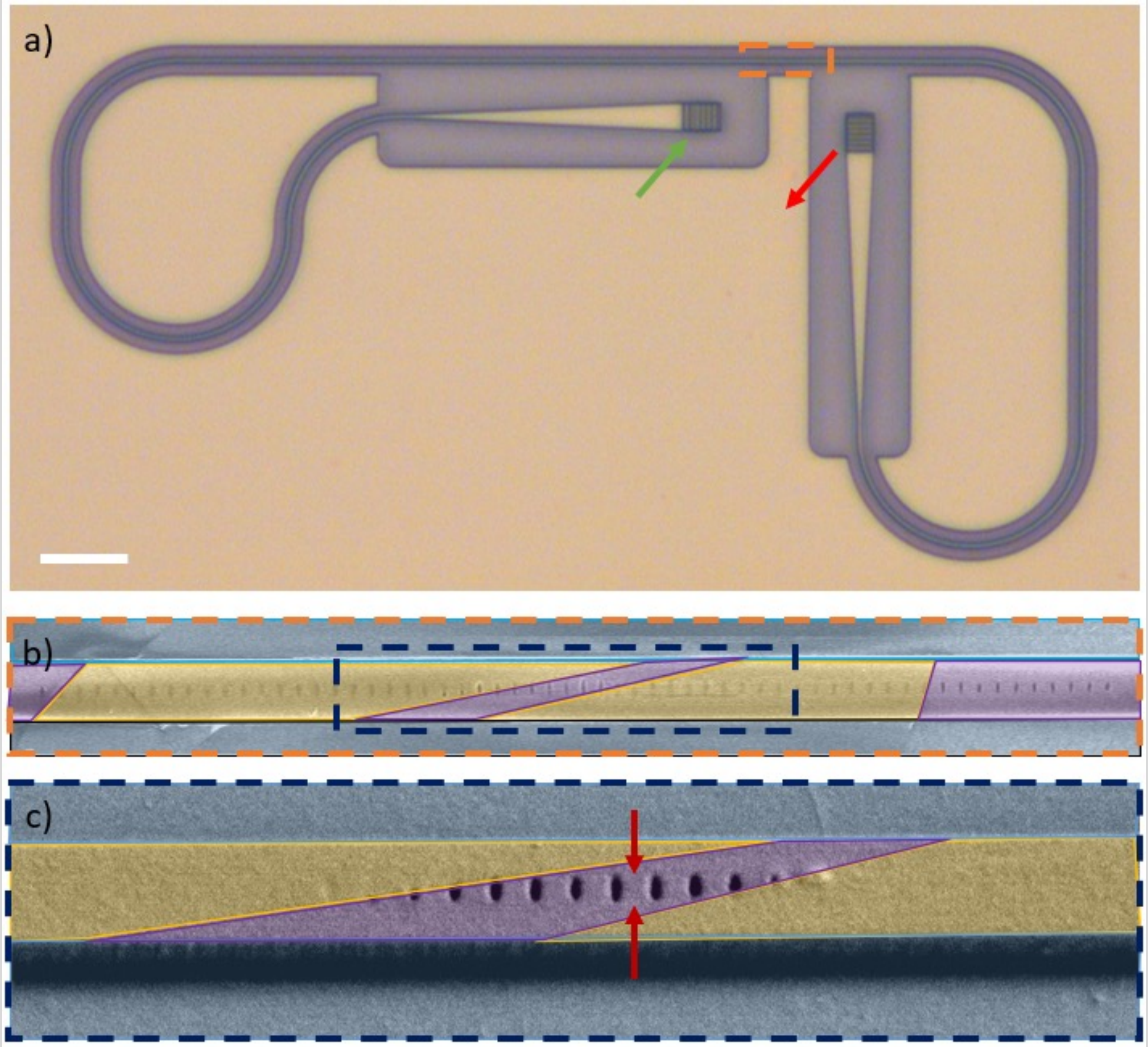




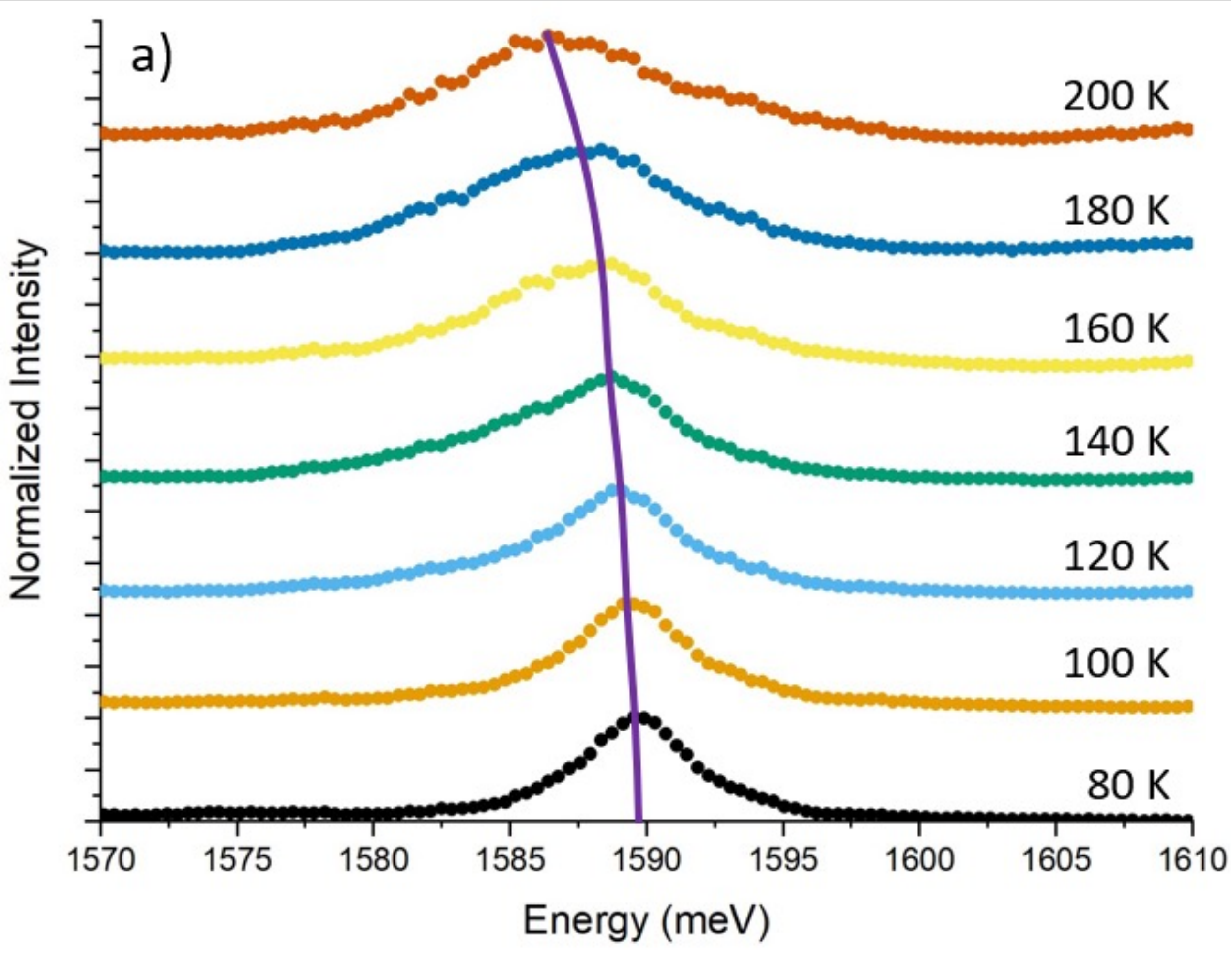
Dipole decay rate: $\gamma \sim \sqrt{S_x}$

Ryou et. al., PRB, 2018

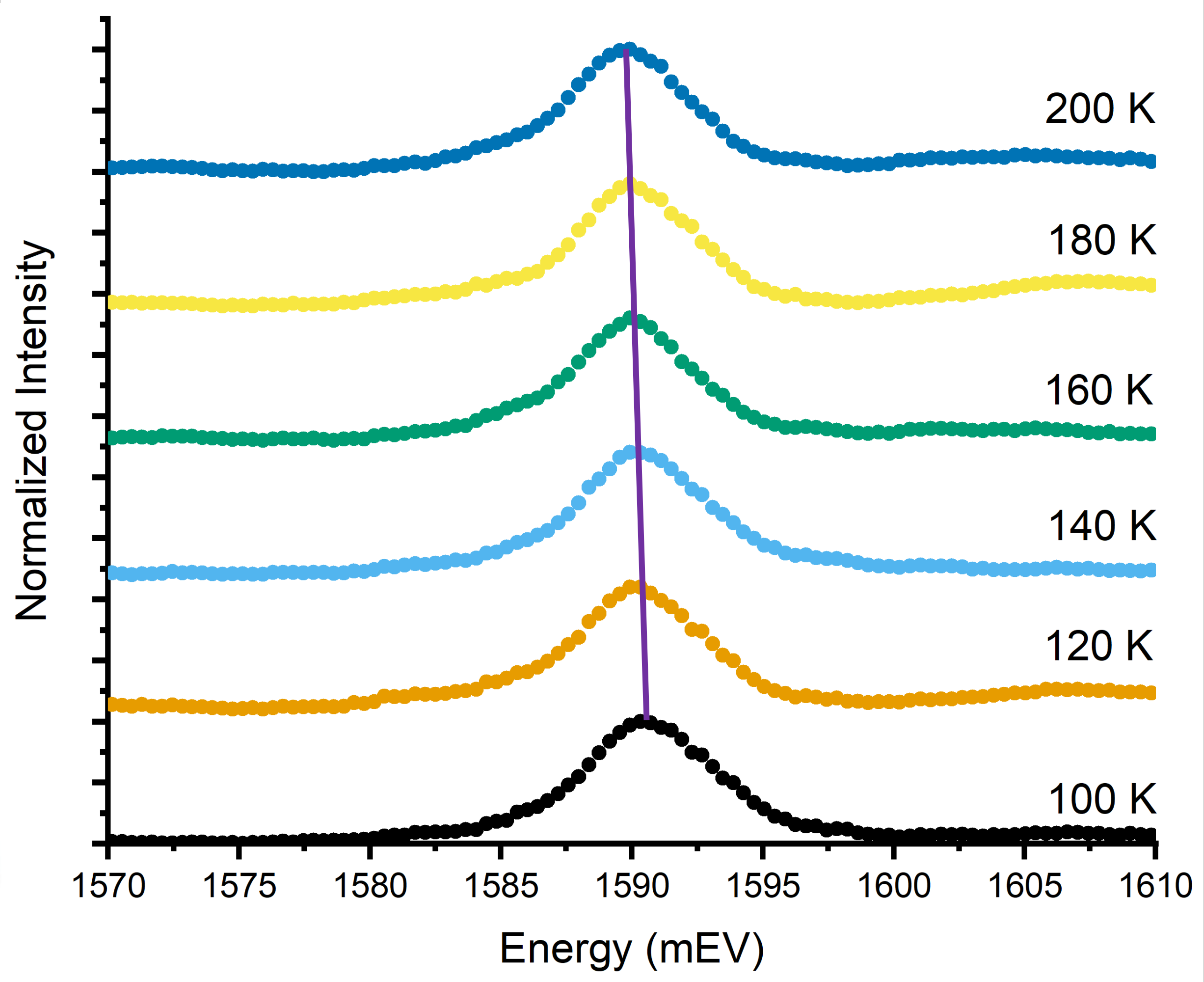
Nanobeam resonator integrated with $MoSe_2$



Dispersive Coupling

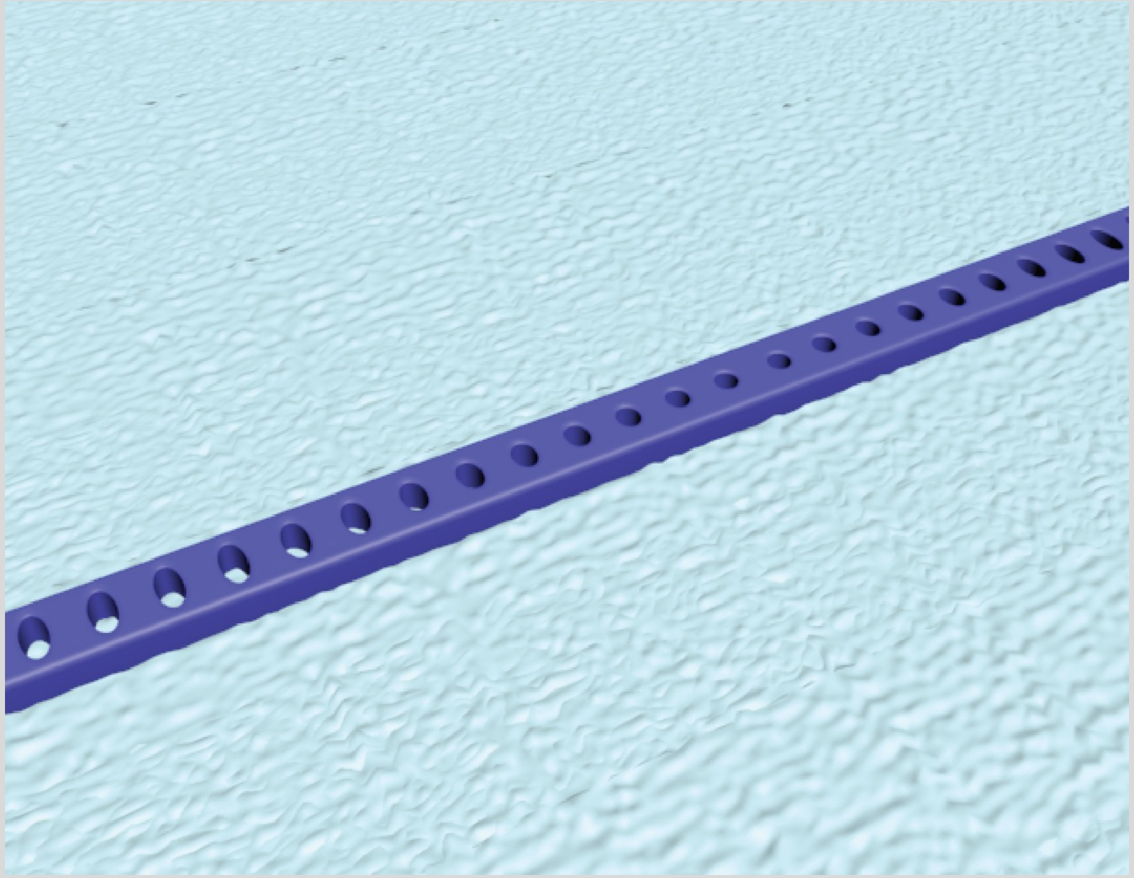


With Integrated Monolayer

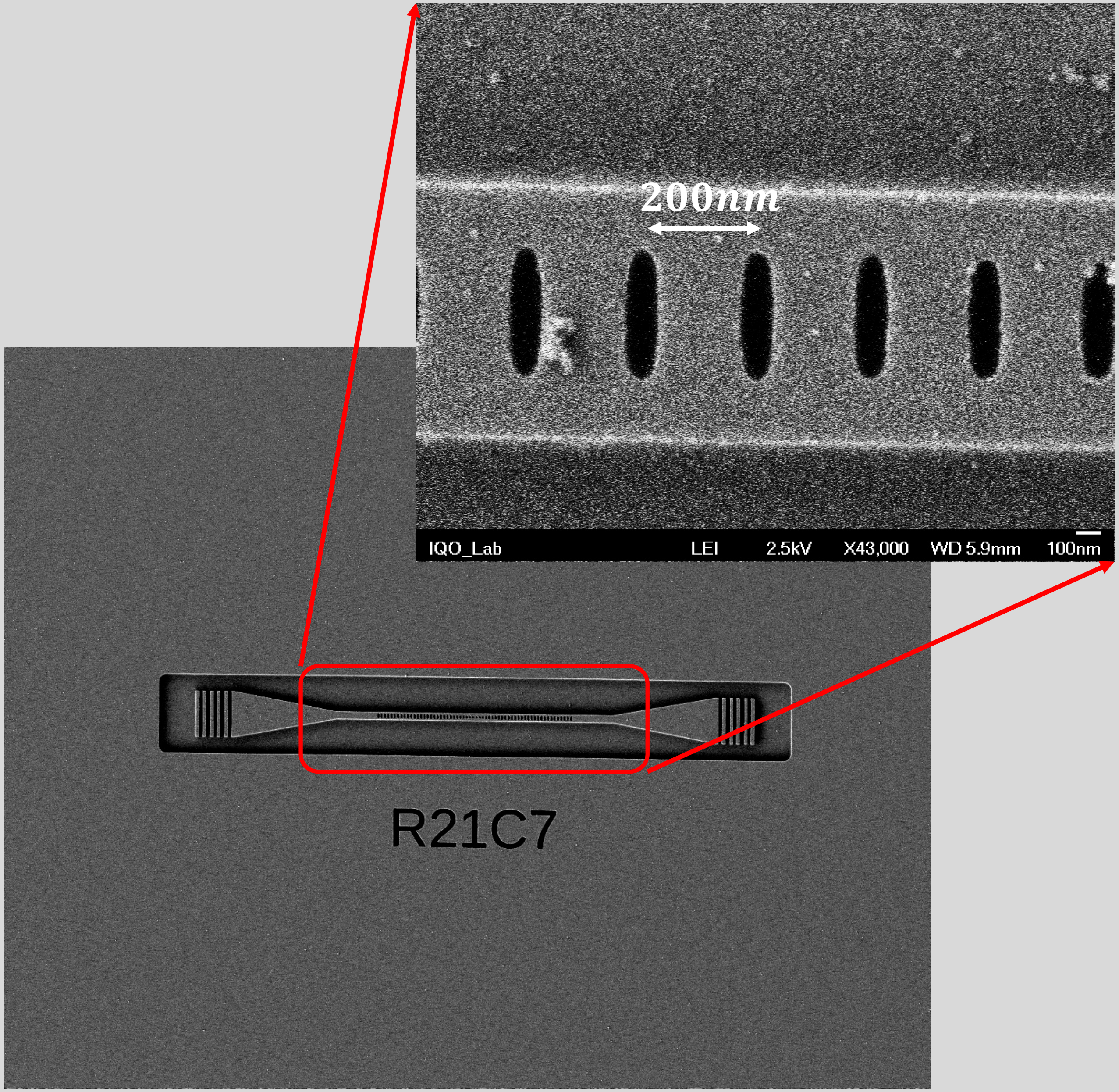


Without Integrated Monolayer

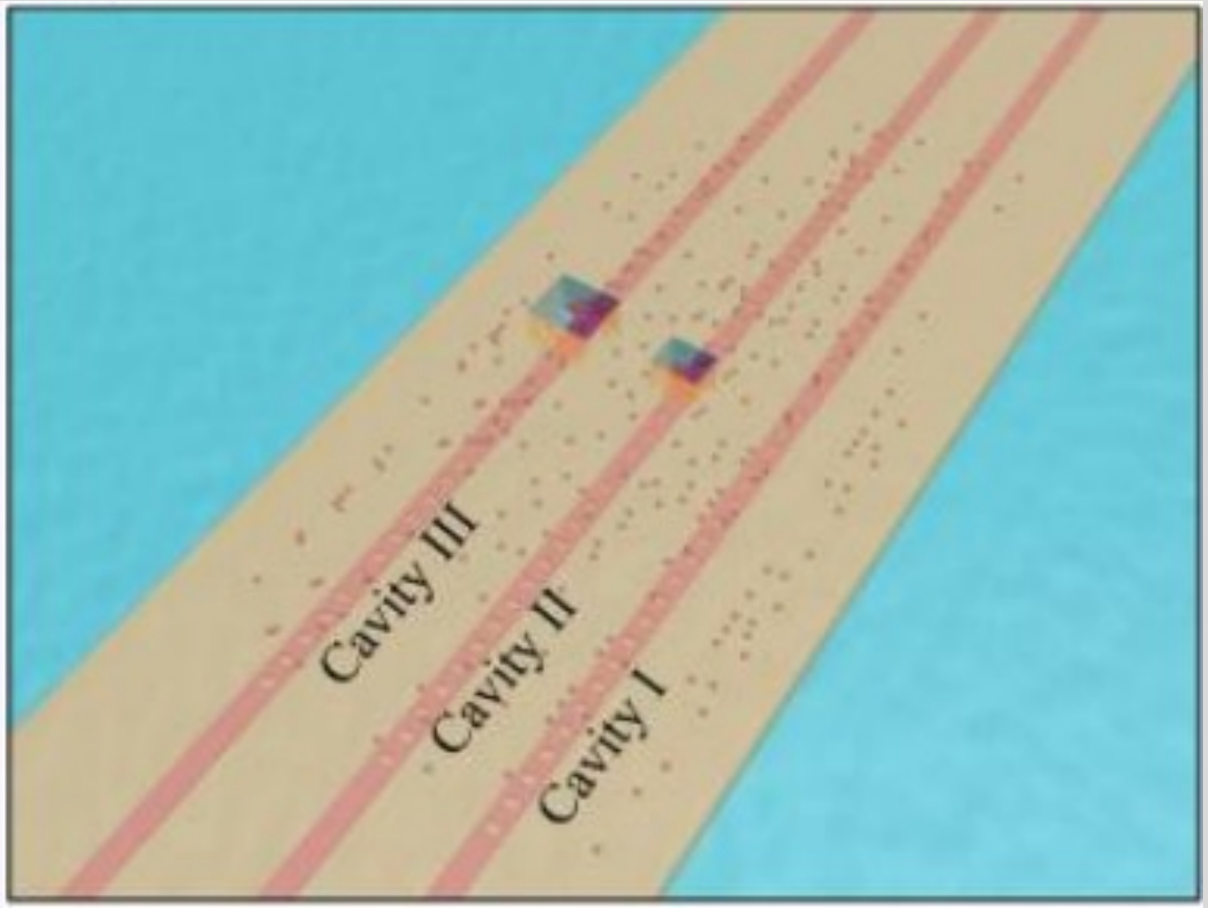
Mechanically stable encapsulated silicon nitride nanobeam

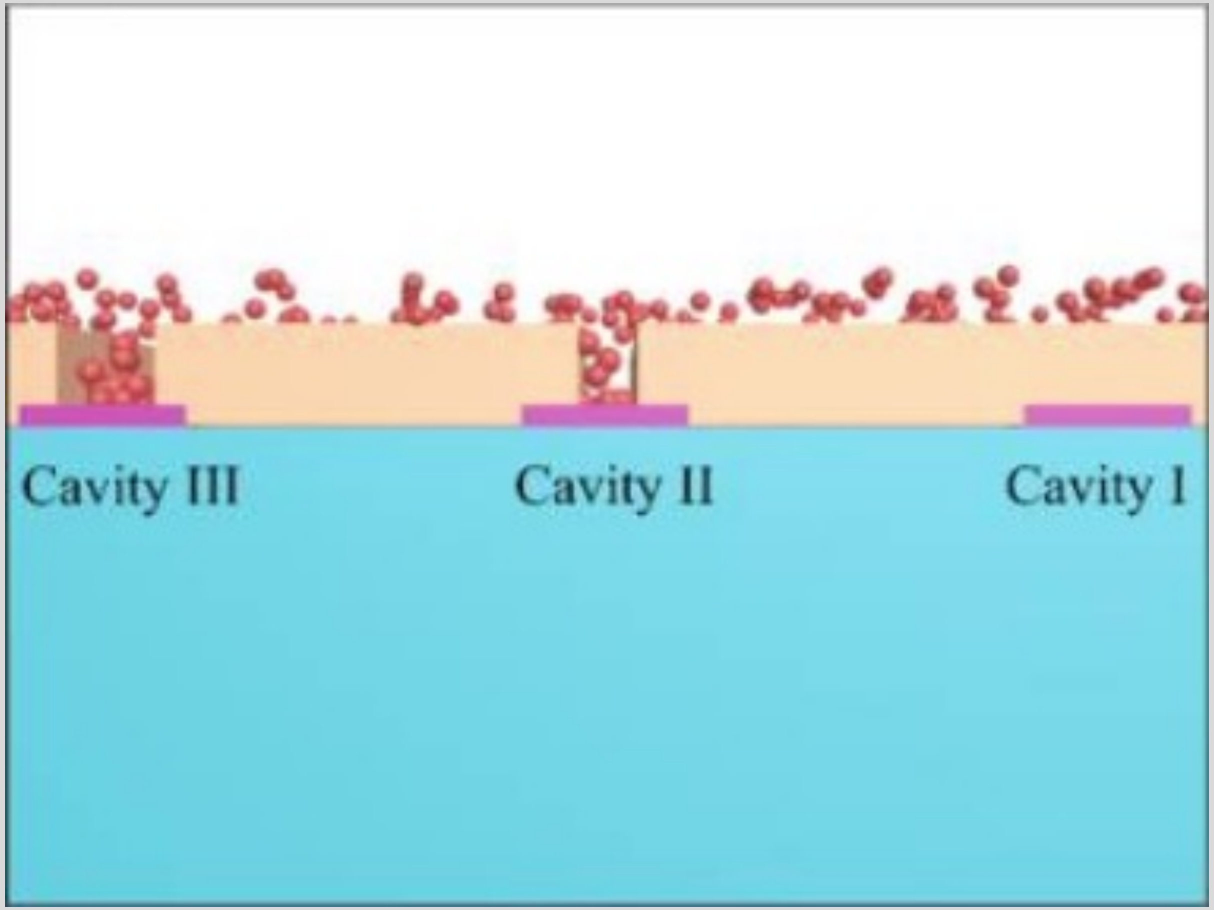


Fryett, Majumdar et. al., ACS Photonics, Article ASAP, 2018

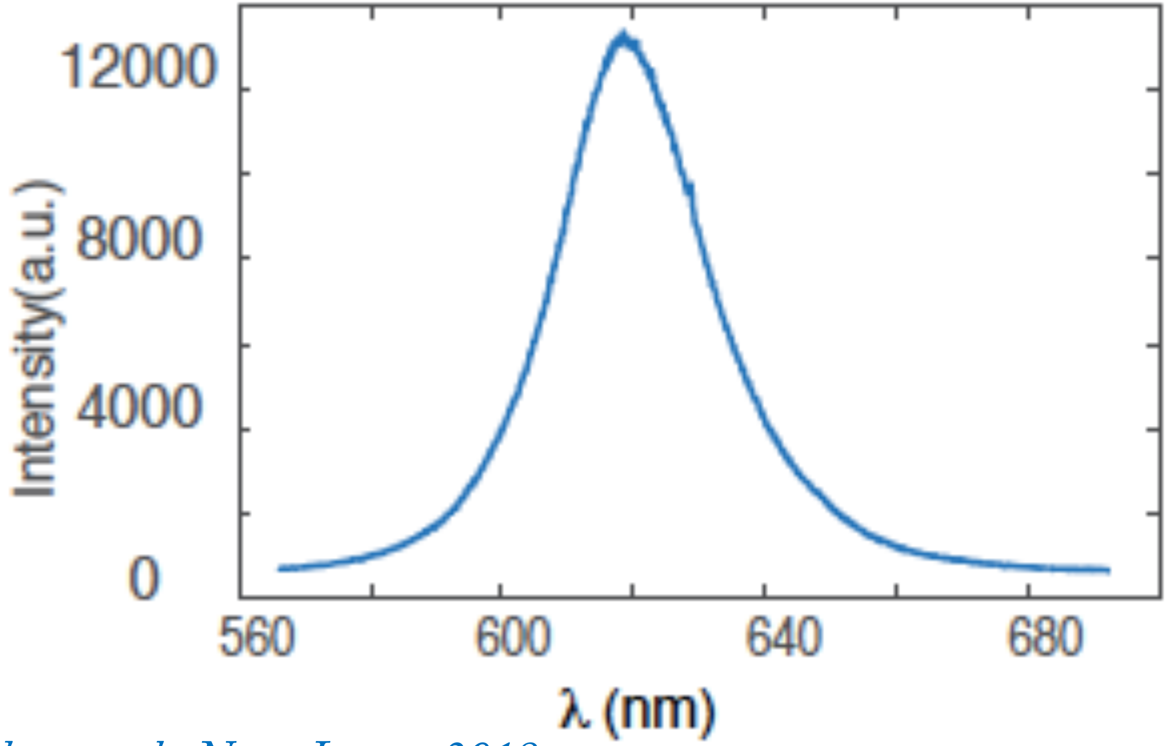


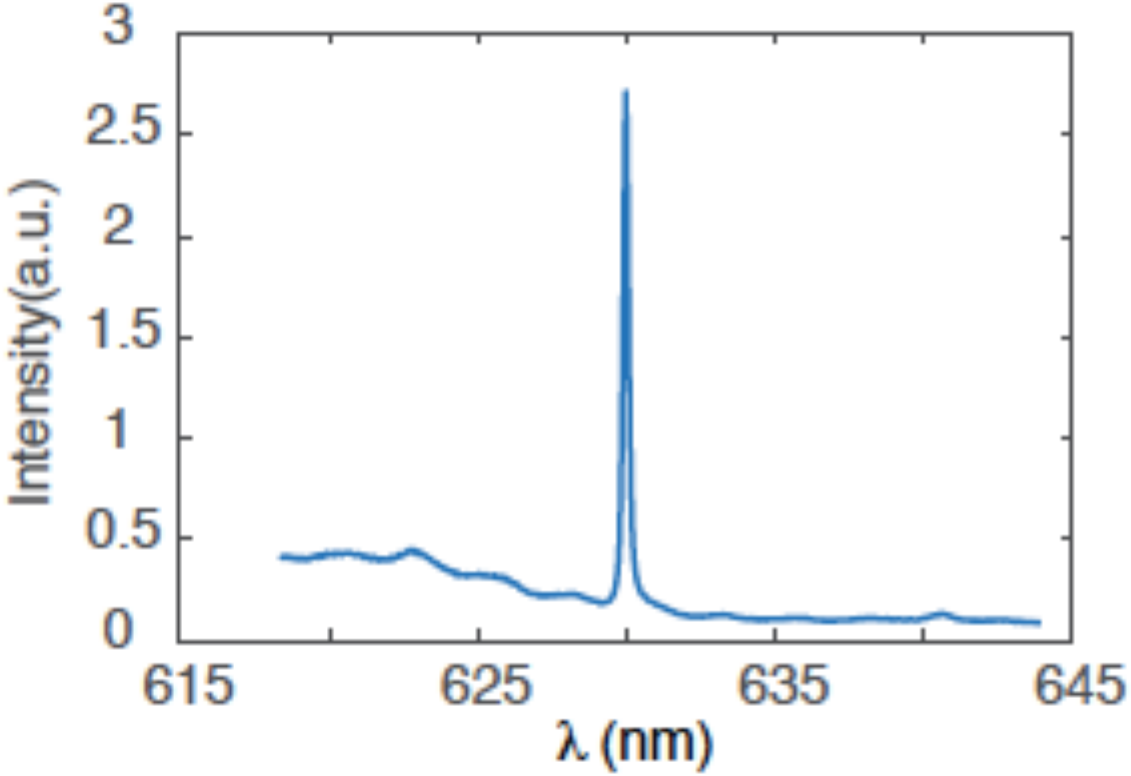
Deterministically position quantum dots





Solution Processed Quantum Dots coupled to cavities

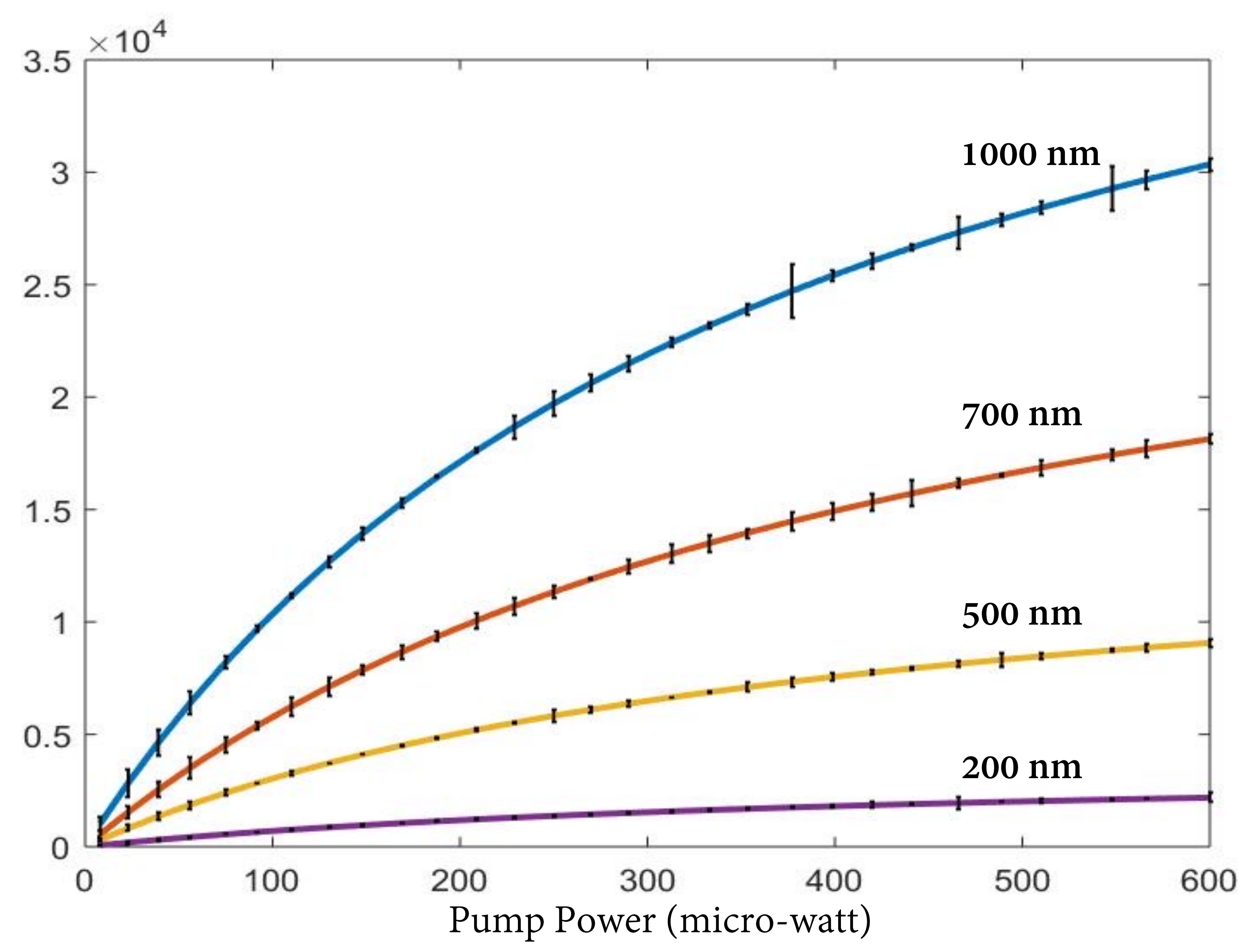




Chen et. al., Nano Letter, 2018

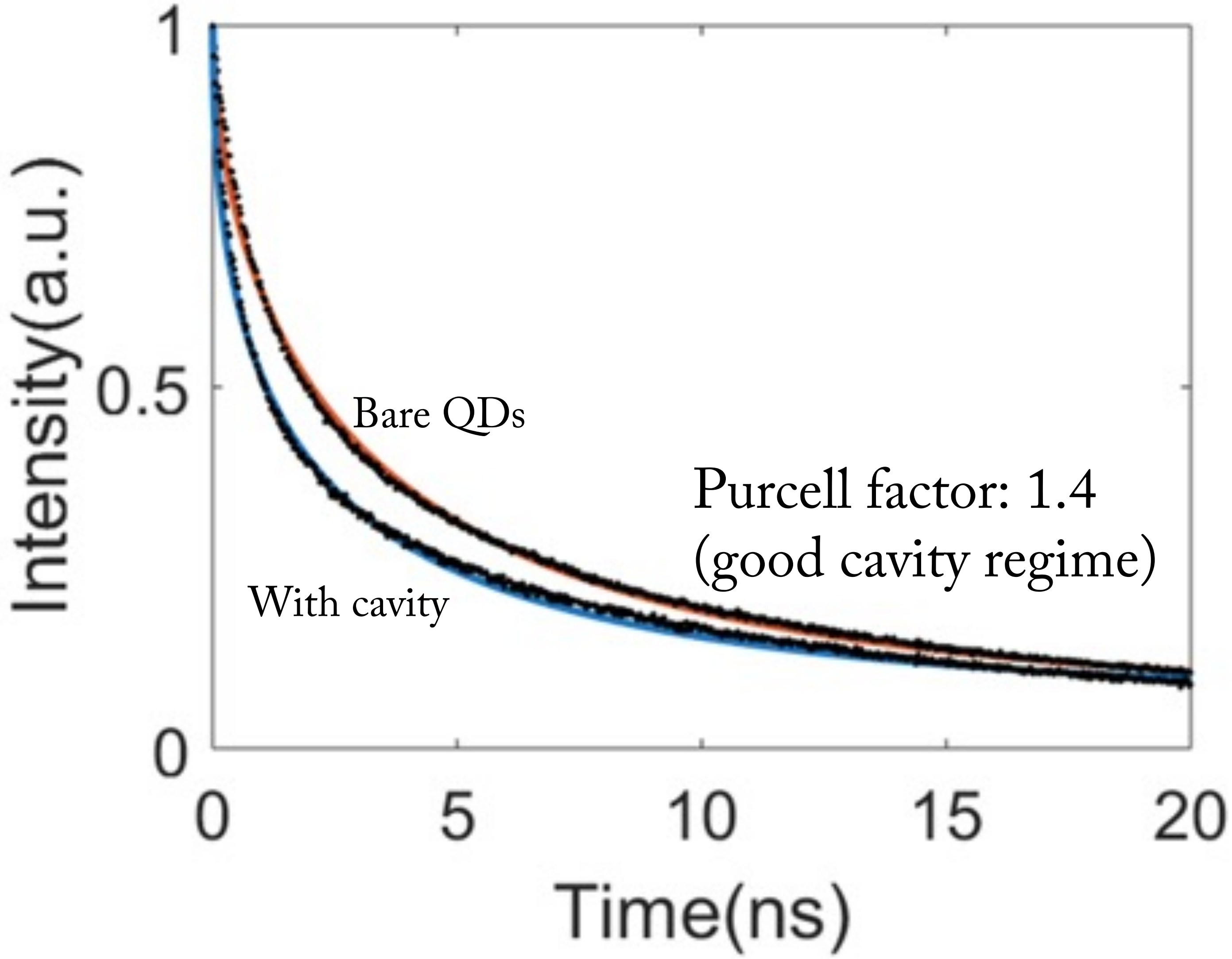
Deterministically place quantum dots in the cavity.

Saturable photoluminescence



Size control of dot via chemistry and opening via lithography will enable coupling of single quantum dots to a cavity.

Purcell Enhancement



Purcell factor: 1.4
(good cavity regime)

Chen et. al., Nano Letter, 2018

Narrow emitter (bad cavity regime):

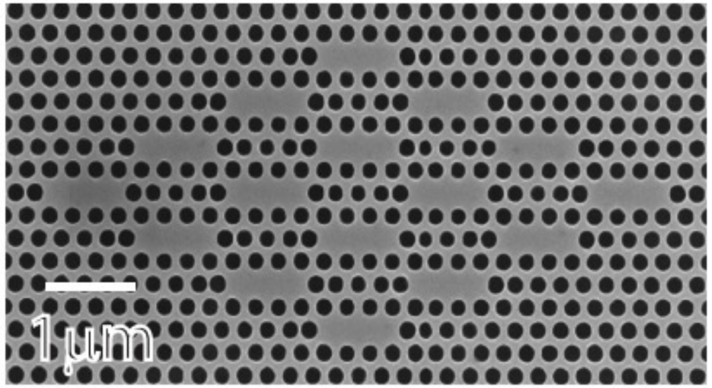
$$F_p = 1 + \frac{3\lambda^3}{4\pi^2 n^2} \frac{Q_{cavity}}{V_{cavity}}$$

Broad emitter (good cavity regime):

$$F_p = 1 + \frac{3\lambda^3}{4\pi^2 n^2} \frac{Q_{QD}}{V_{cavity}}$$

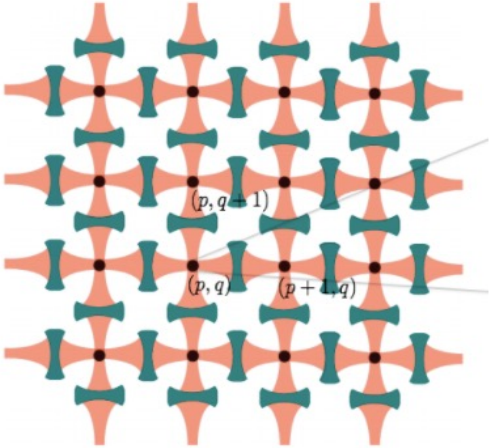
Towards photonic quantum simulation

Scalability



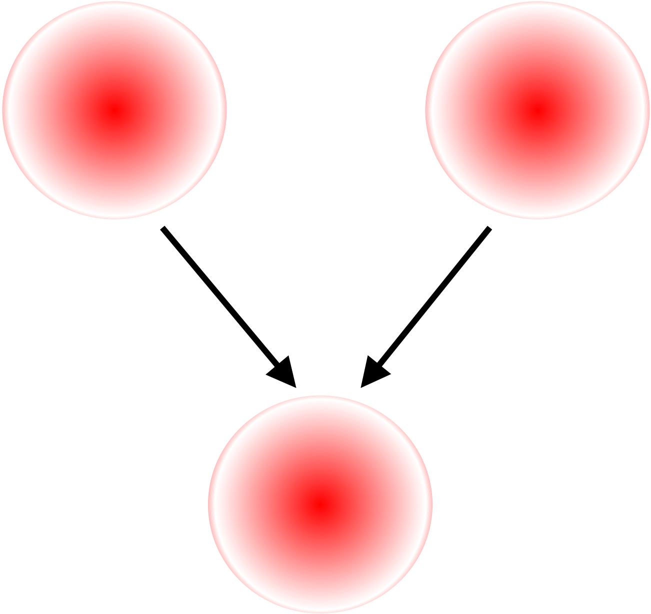
- Large number of optical resonators required.
- All resonators should have same resonance and high-quality factor.

Tunability



- Need independent tuning of each resonator to circumvent the inhomogeneity.
- Need tuning of the coupling strength.

Single Photon NLO



- Confine electron and photon wave-function to enhance the nonlinear interaction strength.