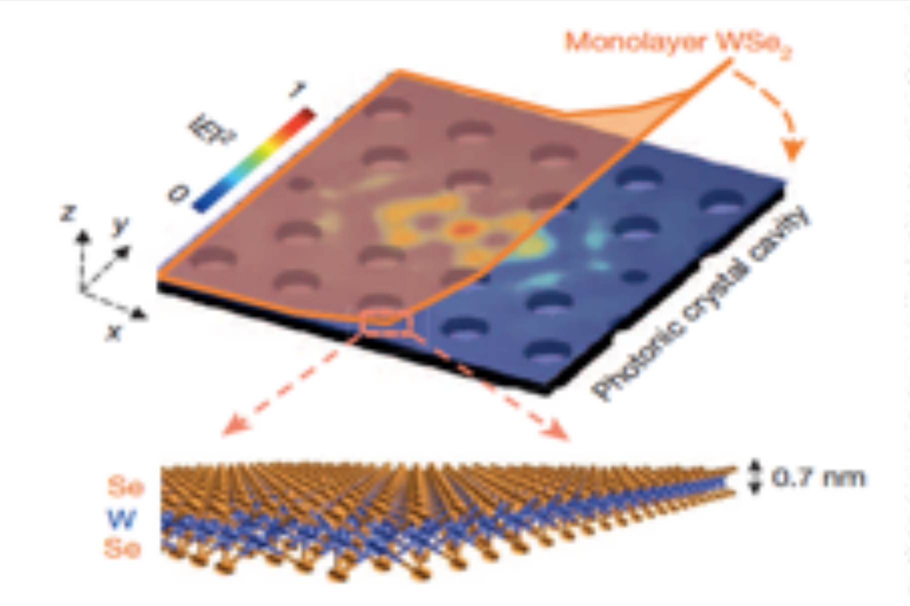
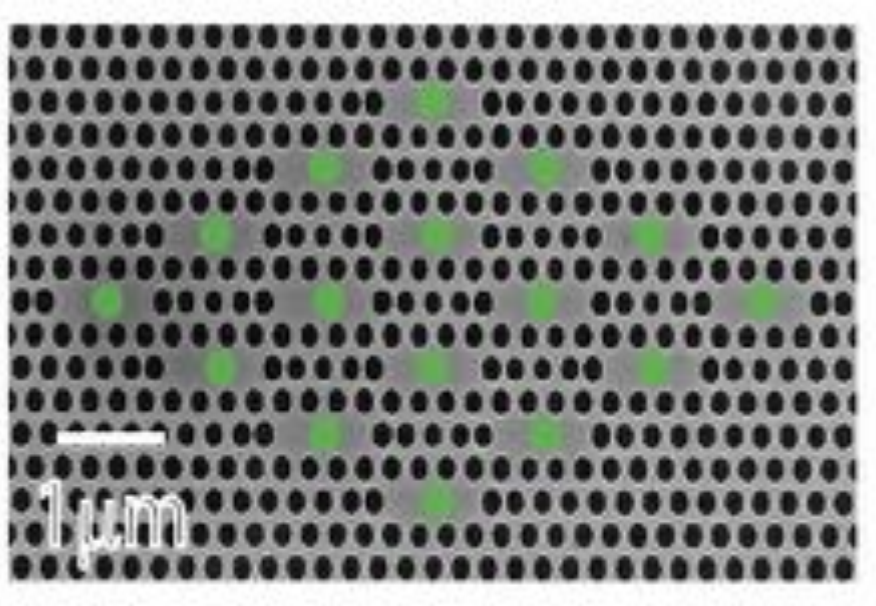
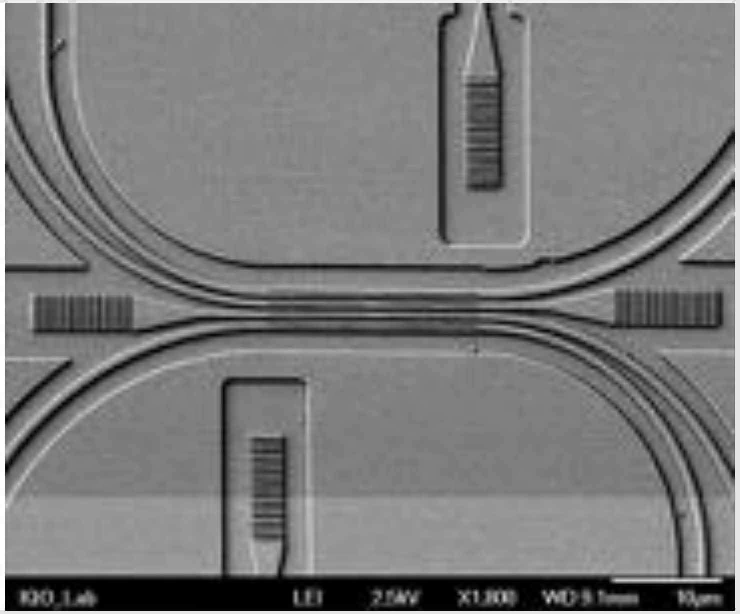
Towards single photon nonlinear nanophotonics with broad emitters







Arka Majumdar

Assistant Professor, Electrical and Computer Engineering and Physics

University of Washington, Seattle

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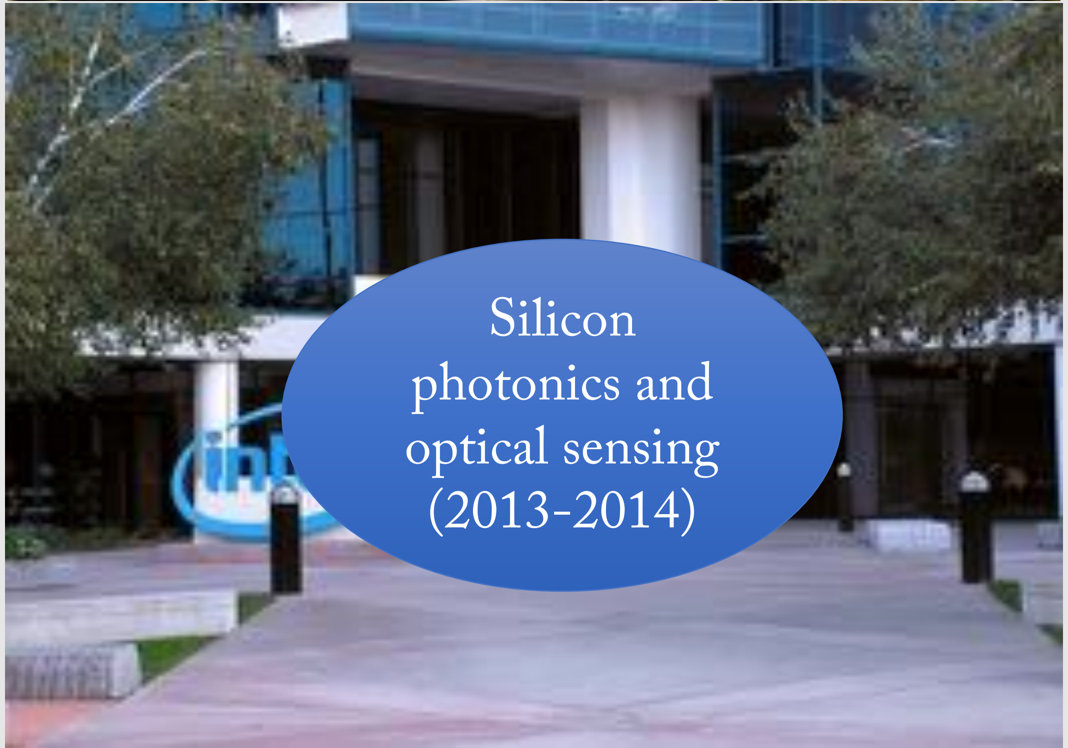
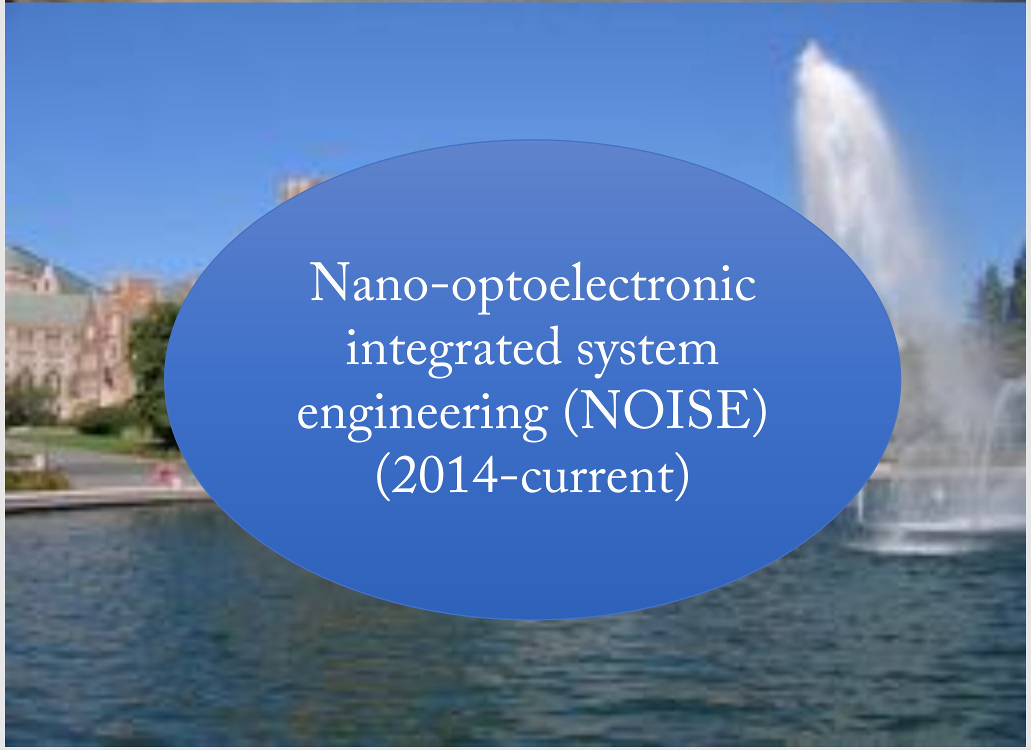
Undergraduate from India

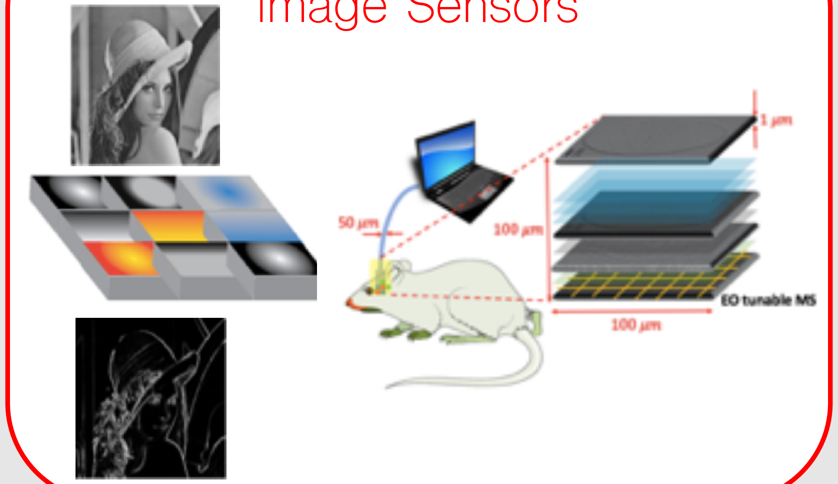
Worked on Radio-frequency integrated circuits to make better cell-phone.
Did not know any quantum mechanics or solid-state physics.
Have very little exposure to electromagnetics (Transmission Line).


Nonlinear and quantum optics (2007-2012)

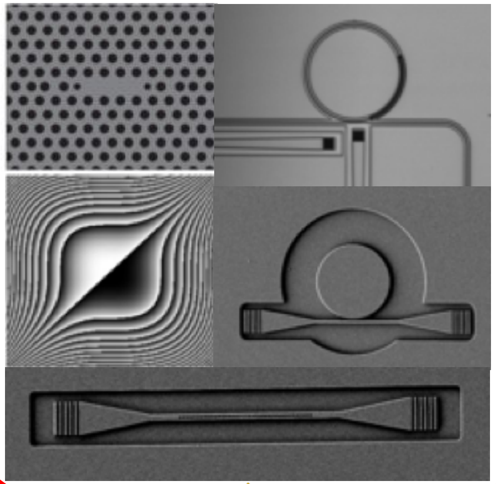
New materials: Monolayer material (2012-2013)

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)

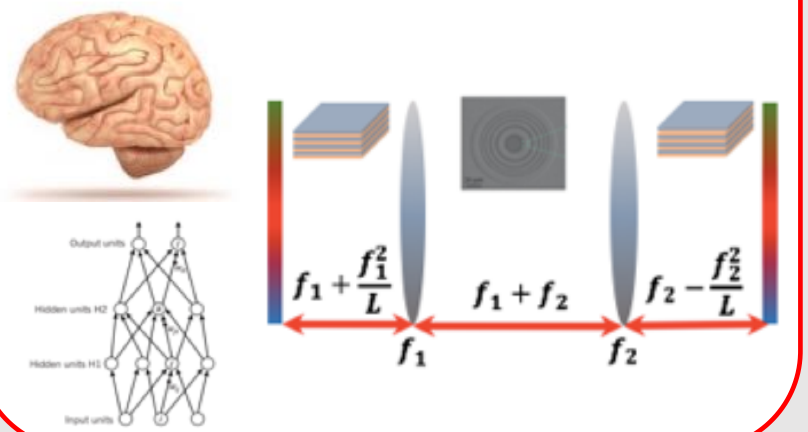
Nanophotonic Computational Image Sensors



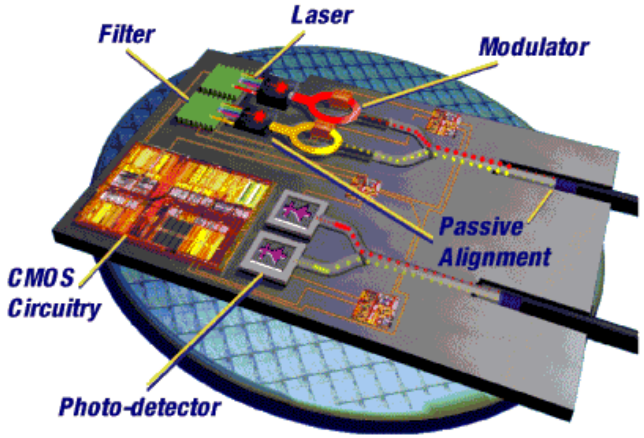
Light



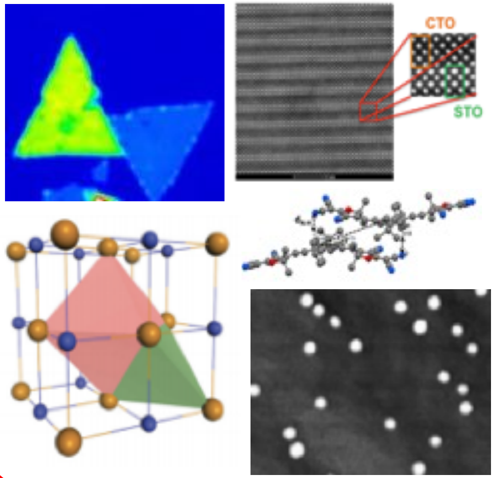
Nonlinear Image Processing and Monolithic Optical Neuron



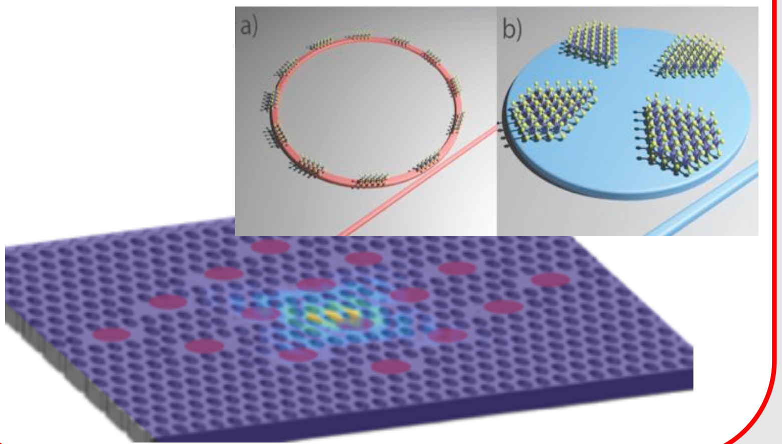
Hybrid Integrated Photonics



Matter



Quantum many-body simulation with photons



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

Team and Funding

My team at UW:
Arka Majumdar
Albert Ryou
Shreyas Shah
Alan Zhan
Shane Colburn
Jiajiu Zheng
Yueyang Chen
Elyas Bayati
David Rosser
James Whitehead
Abhi Saxena
Roger Fang
Maksym Zhelyeznyakov
Luocheng Huang
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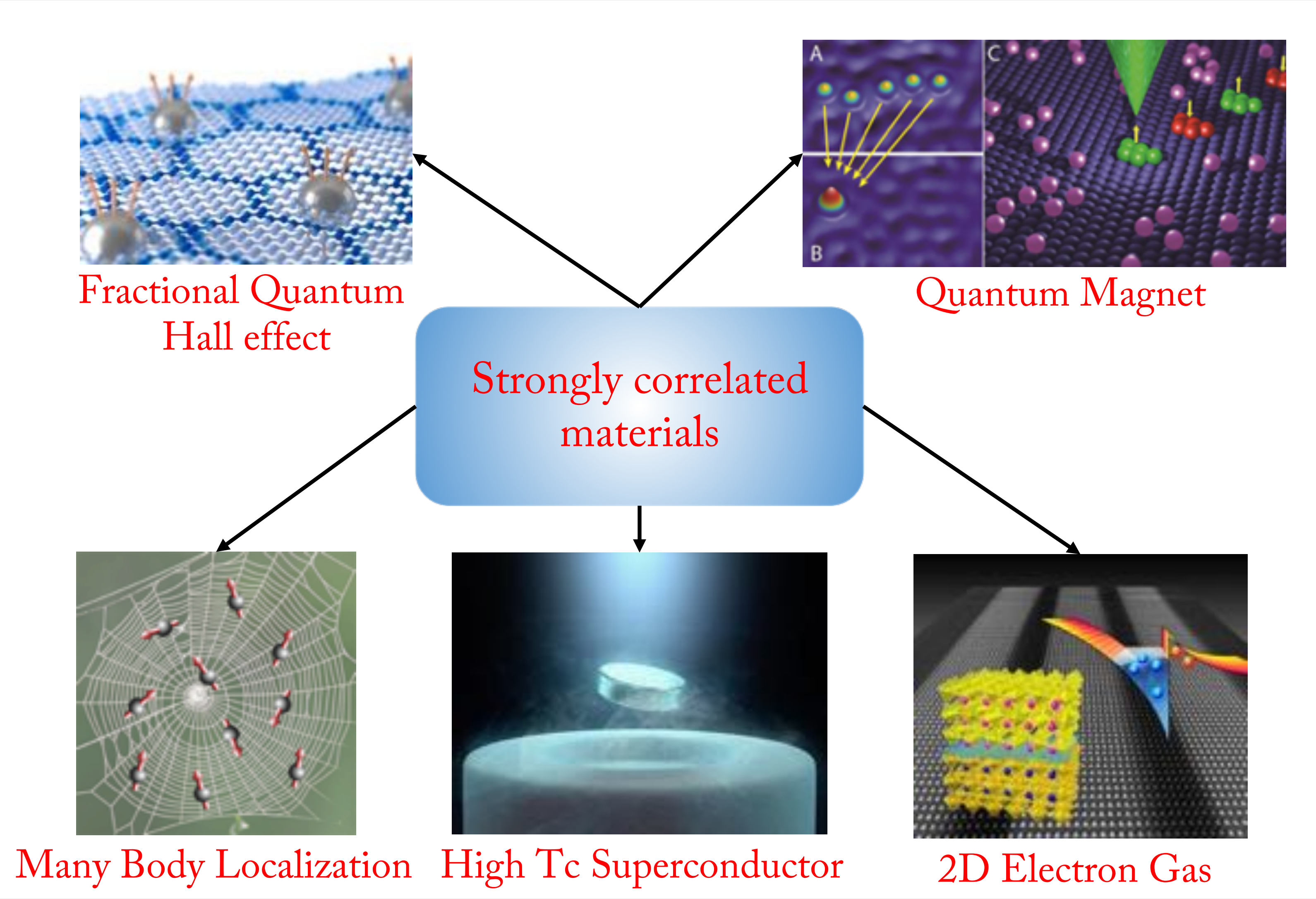
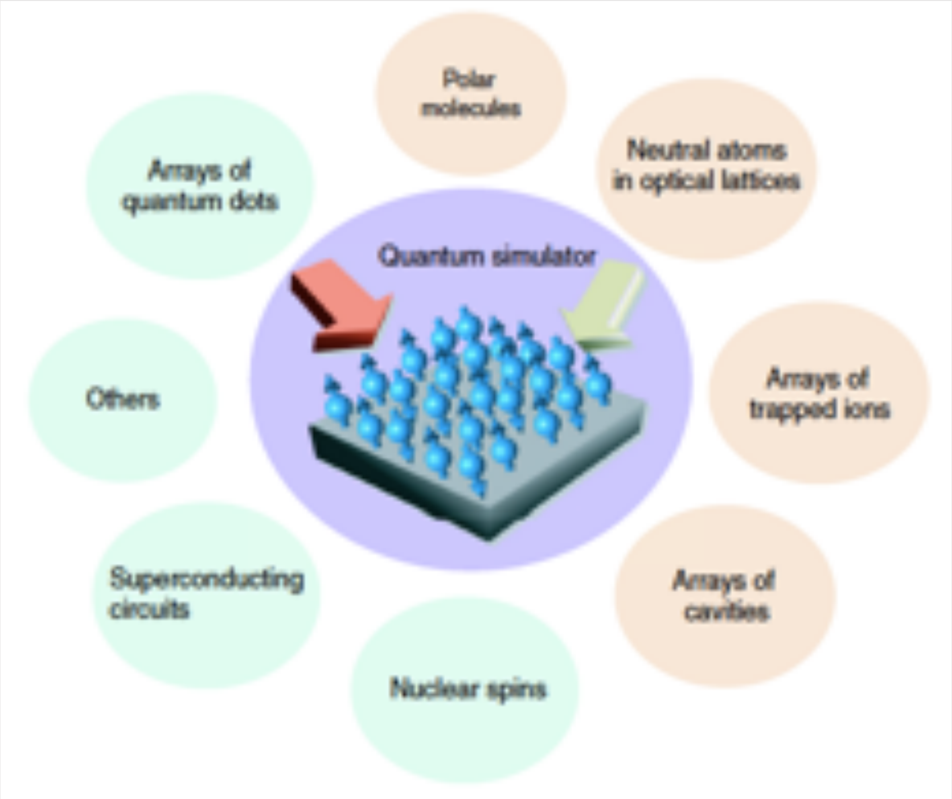
Christopher Dodson (in Apple)
Chang-hua Liu (in Tsing-Hua)

Collaborators:
Jason Meyers (NRL)
Jesse Frantz (NRL)
Joshua Hendrickson (AFRL)
Ricky Gibson (AFRL)
Eric Pop (Stanford)
Jayakanth Ravichandran (USC)
Xiaodong Xu (UW)
Kai-Mei Fu (UW)
Eli Shlizerman (UW)
Larry Dalton (UW)
Brandi Cossairt (UW)
Karl Bohringer (UW)
Felix Heide (Princeton)
Peipeng Xu (Ningbo University)
Jian-Hua Jiang (Soochow University)
Qihua Xiong (NTU)
Volker Sorger (GWU)
Xuedan Ma (ANL)

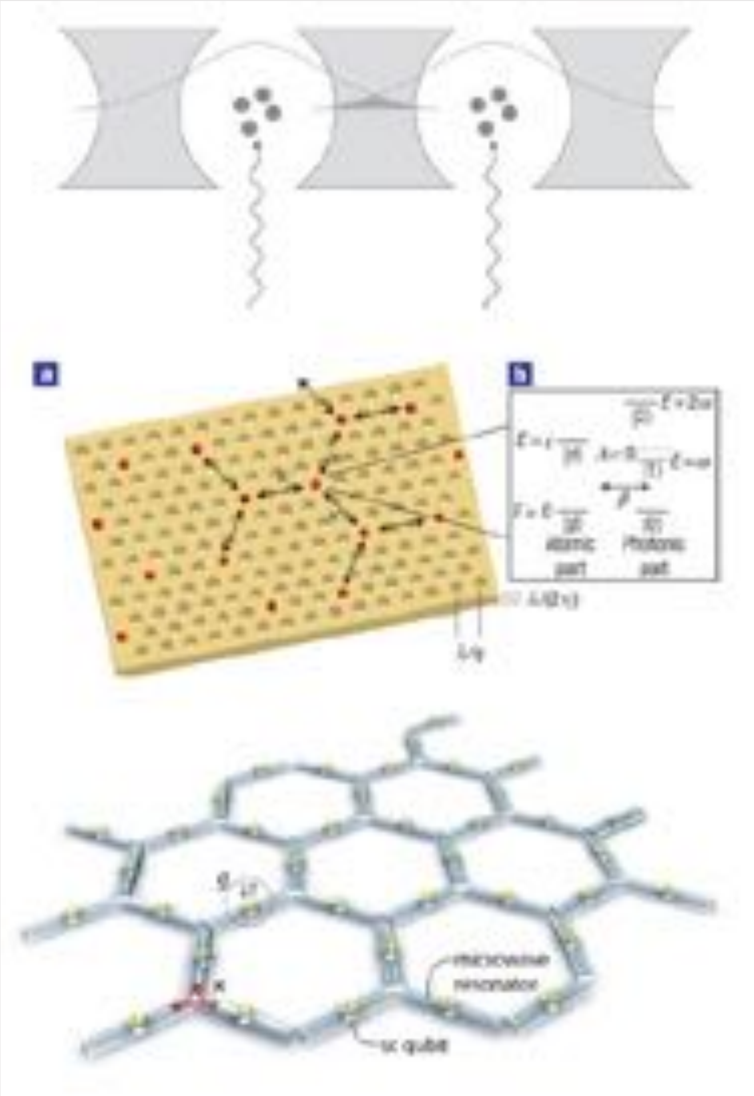
Non-equilibrium quantum many-body simulation



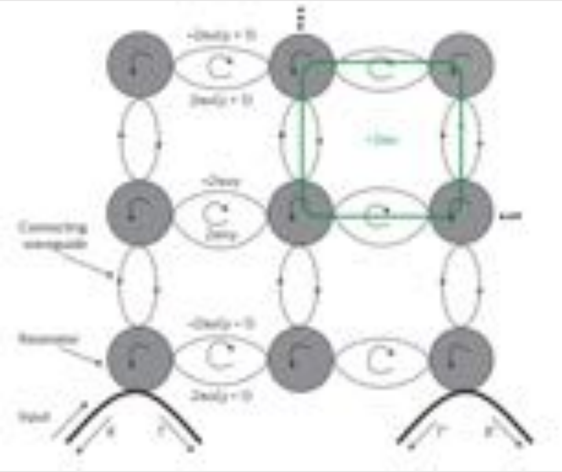


Quantum Simulation, Rev. Mod. Physics, Vol. 86, January-March 2014

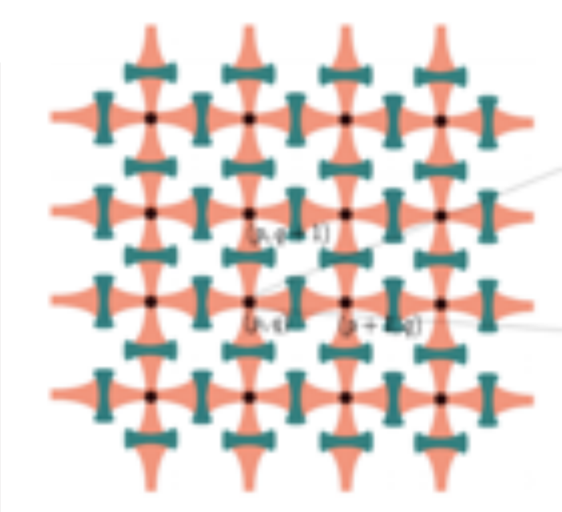
Quantum simulation with correlated light



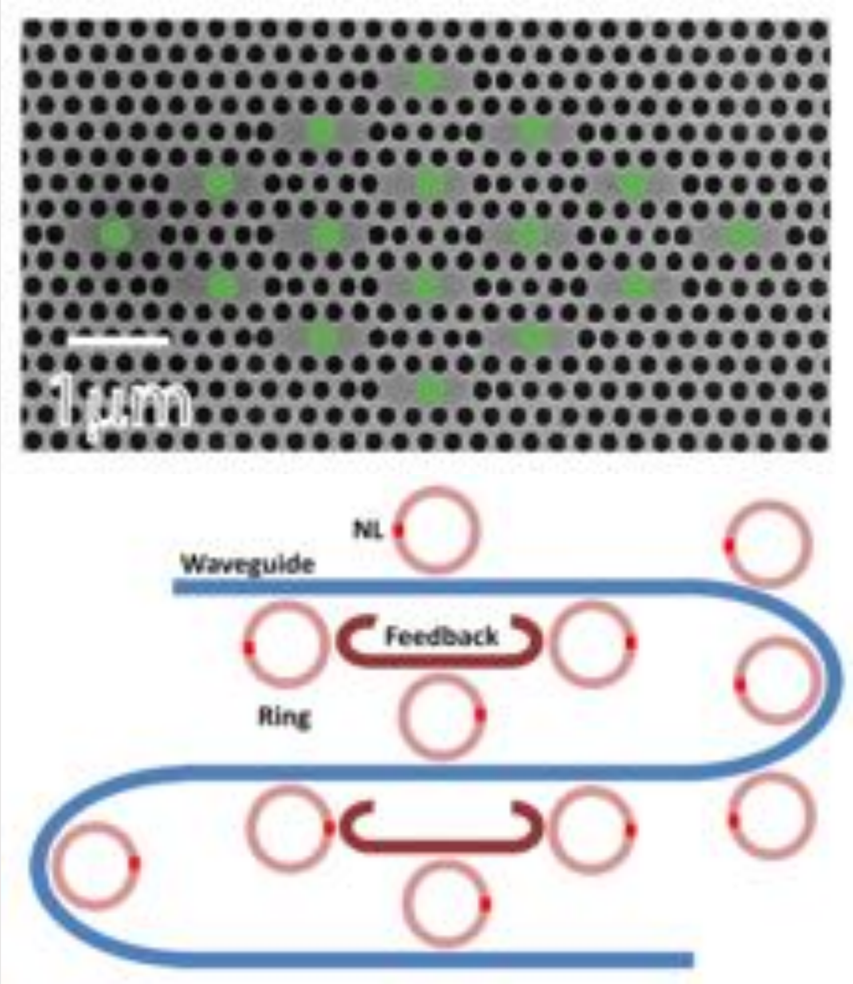
Quantum fluids of light, Rev. Mod. Phys. 85, 299 (2013)



Nature Physics 7, 907–912 (2011)



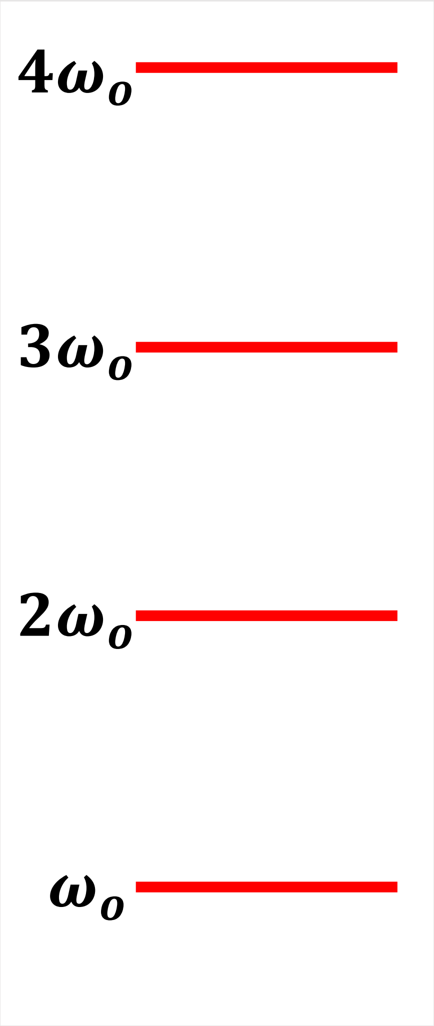
Report of Progress in Physics, 80, 016401 (2016)



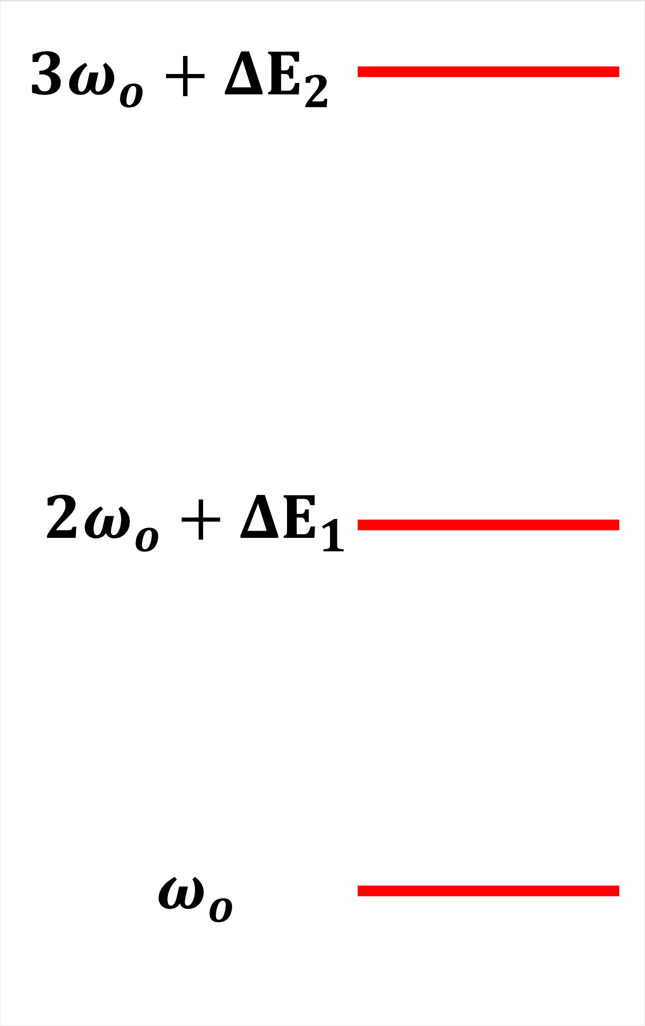
- Driven-dissipative nature provide a platform to study non-equilibrium quantum systems.
- Easy to measure multi-photon correlations.

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

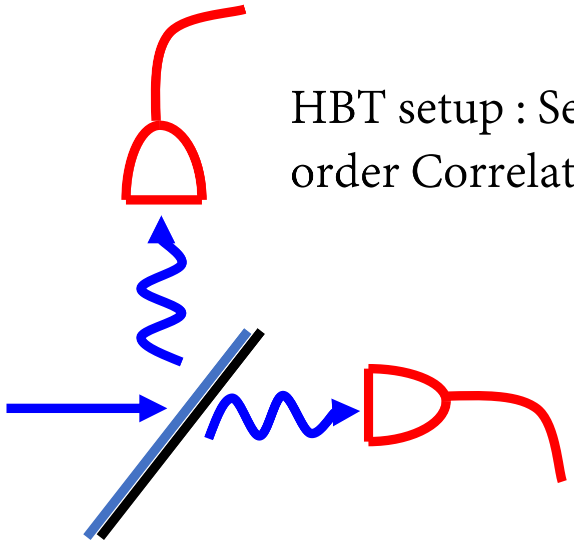
Anharmonicity and signature of single photon nonlinearity



Linear cavity



Non-linear cavity



HBT setup : Second order Correlation

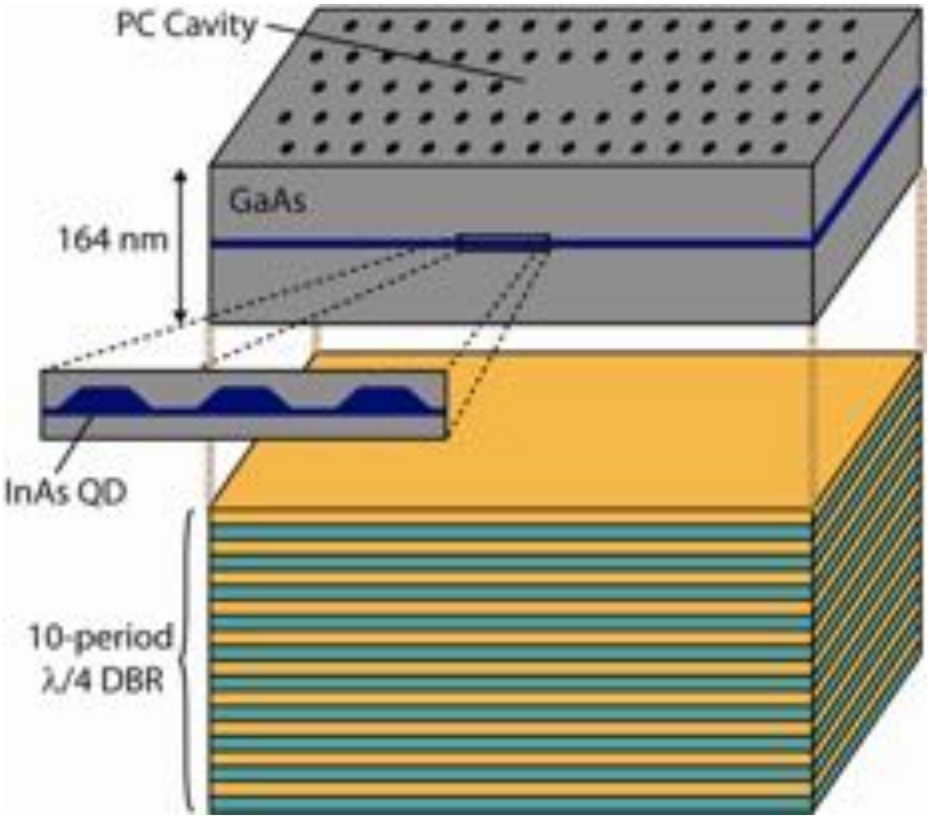
$$g^{(2)}(\tau) = \frac{\langle a^{\dagger}(0)a^{\dagger}(\tau)a(\tau)a(0)\rangle}{\langle a^{\dagger}(0)a(0)\rangle^{2}}$$

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

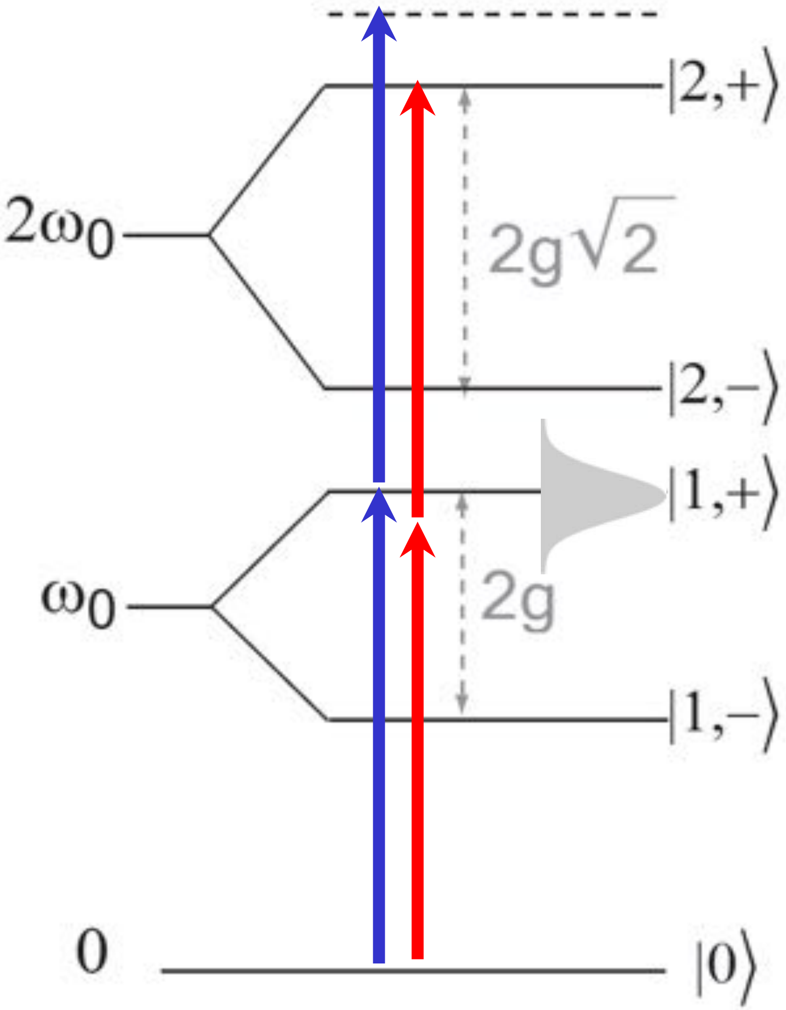
$g^{(2)}(0) = 1$: Poissonian

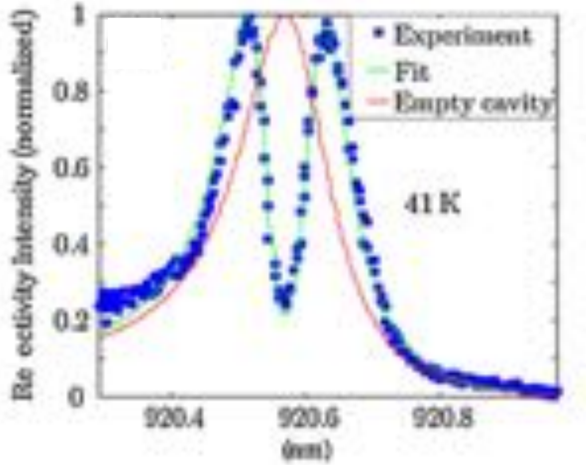
$g^{(2)}(0) > 1$: Super-Poissonian

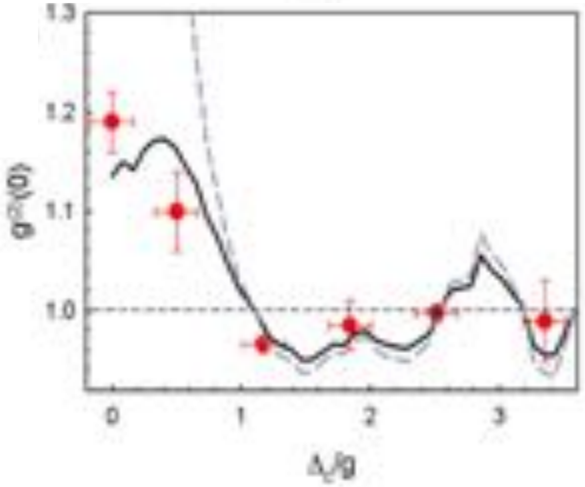
Single photon nonlinearity: self-assembled quantum dots in nano-cavity



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



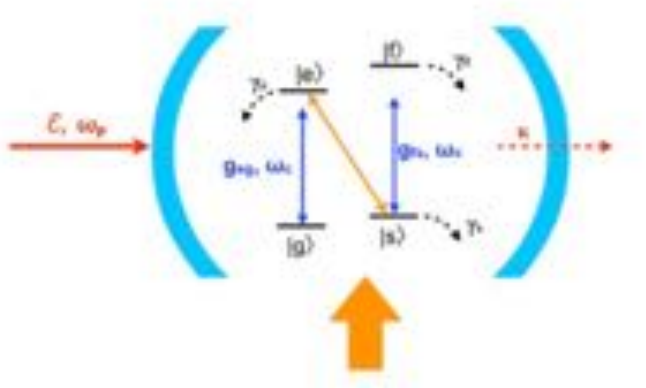




- Strongly coupled quantum dot-cavity system: Jaynes-Cummings Nonlinearity
- Spectral and spatial matching remains problem
- The largest number of coupled cavities with dots is only two

Improving single photon nonlinearity exploiting interference

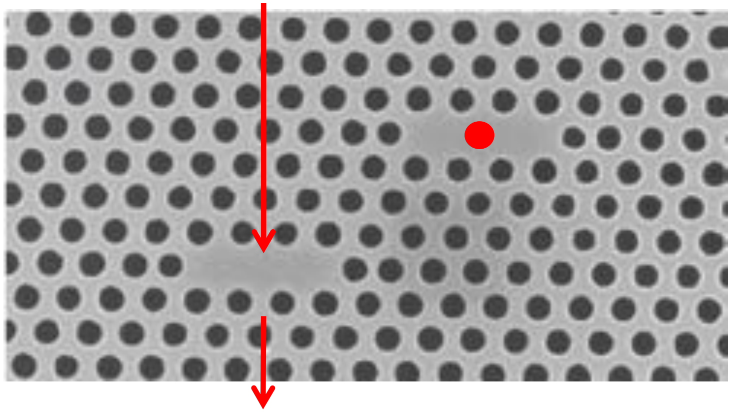
Single cavity mode with multilevel emitter



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

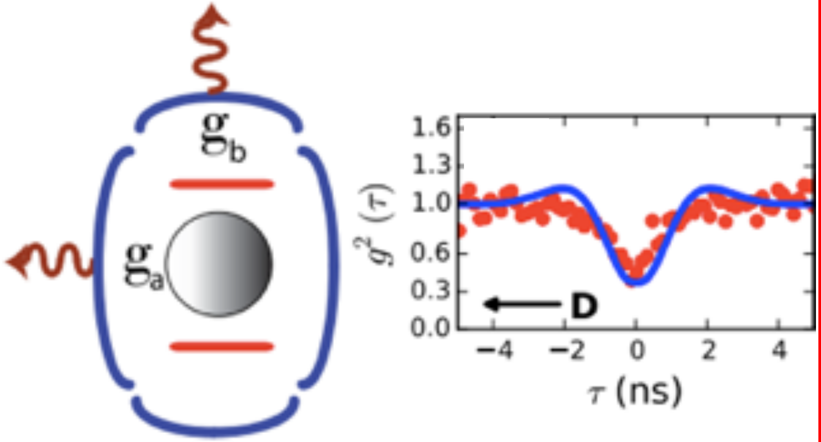
coherent state



Sub-poissonian

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

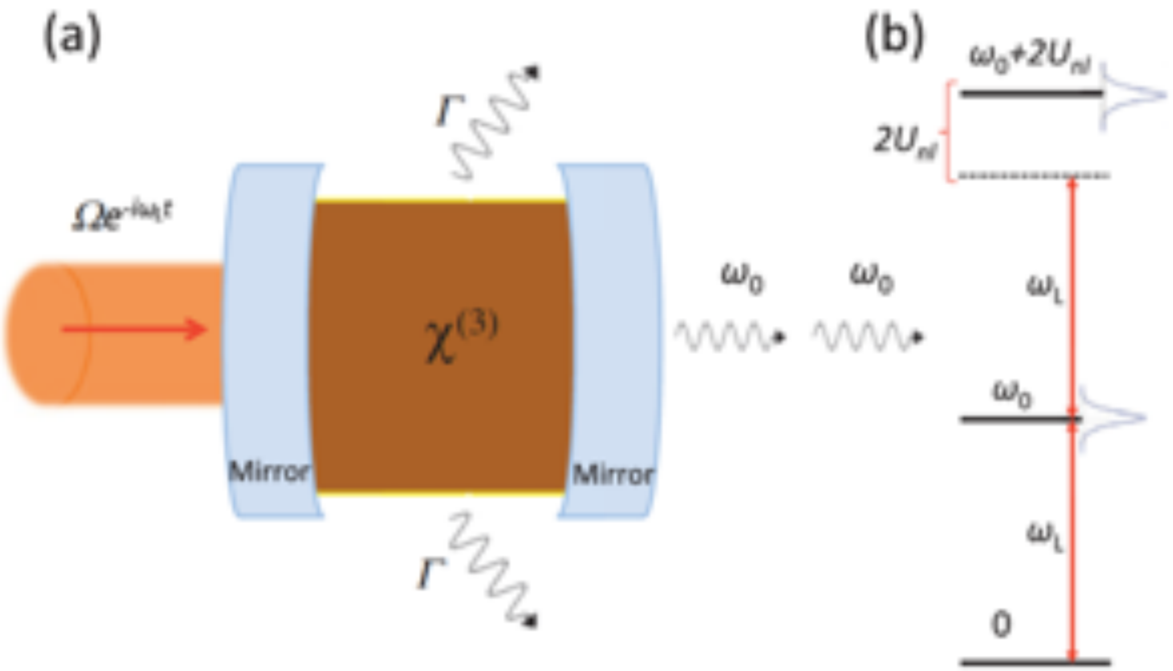
2-level emitter coupled to multimode cavity



Majumdar et.al., Phys Rev. Letters, 108, 183601 (2012).
Experiment: arXiv:1803.10992, 2018

Bulk optical nonlinearity in cavity

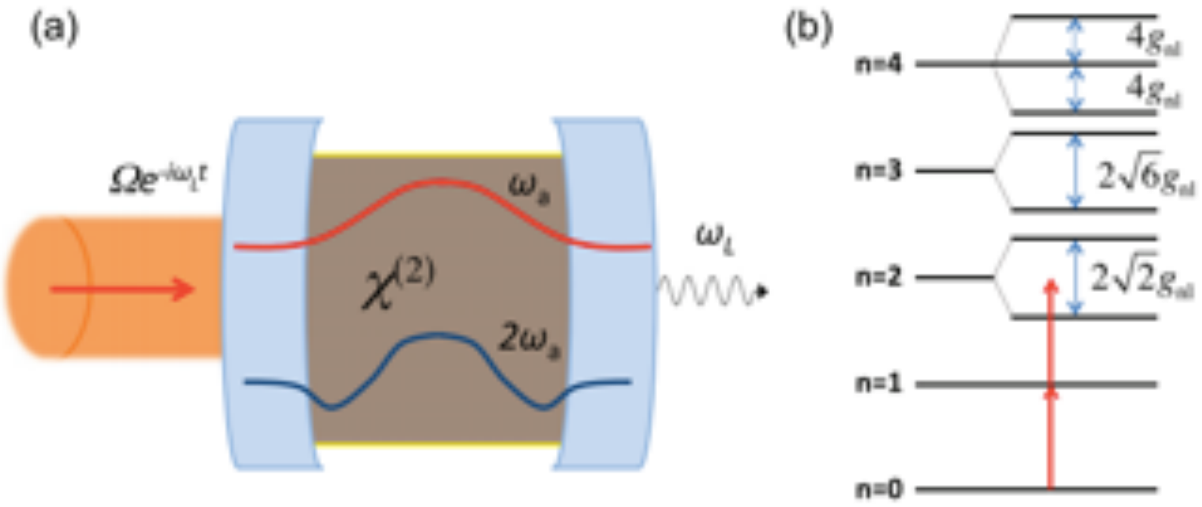
Kerr-nonlinearity



Quality factor needed: $\sim 10^7$

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

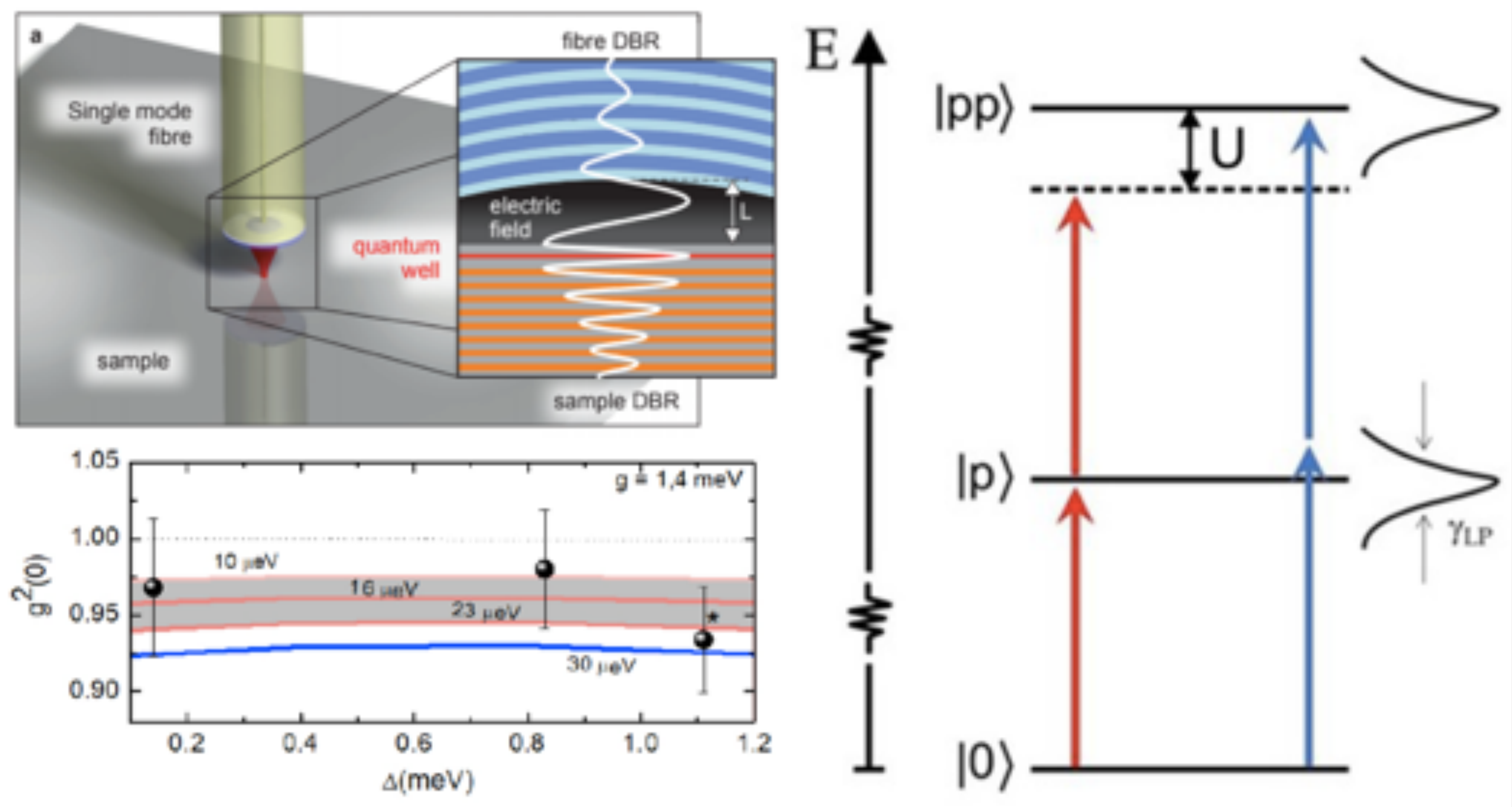
Second-order ($\chi^{(2)}$)nonlinearity



Quality factor needed: $\sim 10^6$

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

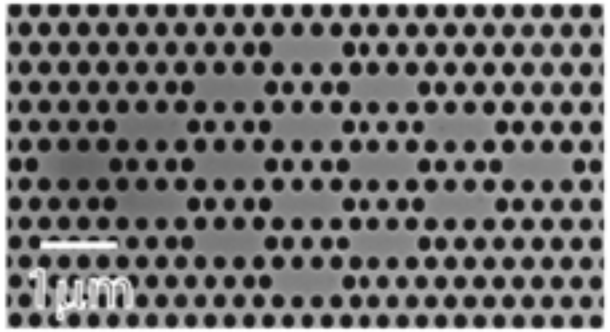
Quantum nonlinearity in polaritonic boxes: confine photon



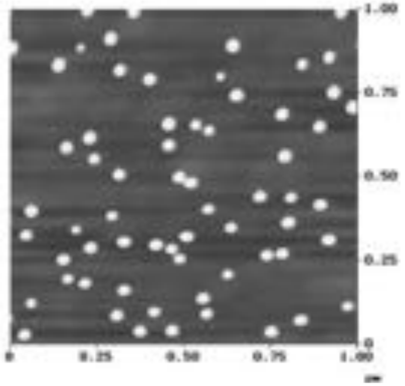
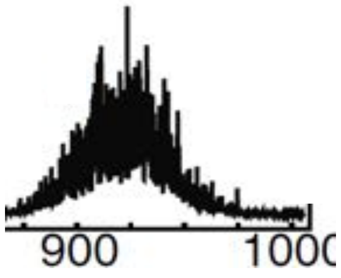
Phys. Rev. Applied 3, 014008, 2015; Nature Materials, volume 18, pages 219–222 (2019); Nature Materials, volume 18, pages 213–218 (2019)

Challenges

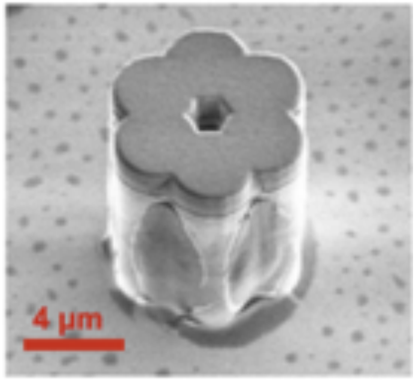
Large number of optical resonators required.
All resonators should have same resonance and high quality factor.
Integrated photonics provide an attractive solution.
Tunability of each cavity is required.



Each resonator should have a nonlinearity.
If excitonic nonlinearity, they should have same resonance.
Spectral matching with narrow emitters are difficult.
Tuning of single emitters, including QD is limited.
Deterministic positioning is difficult.

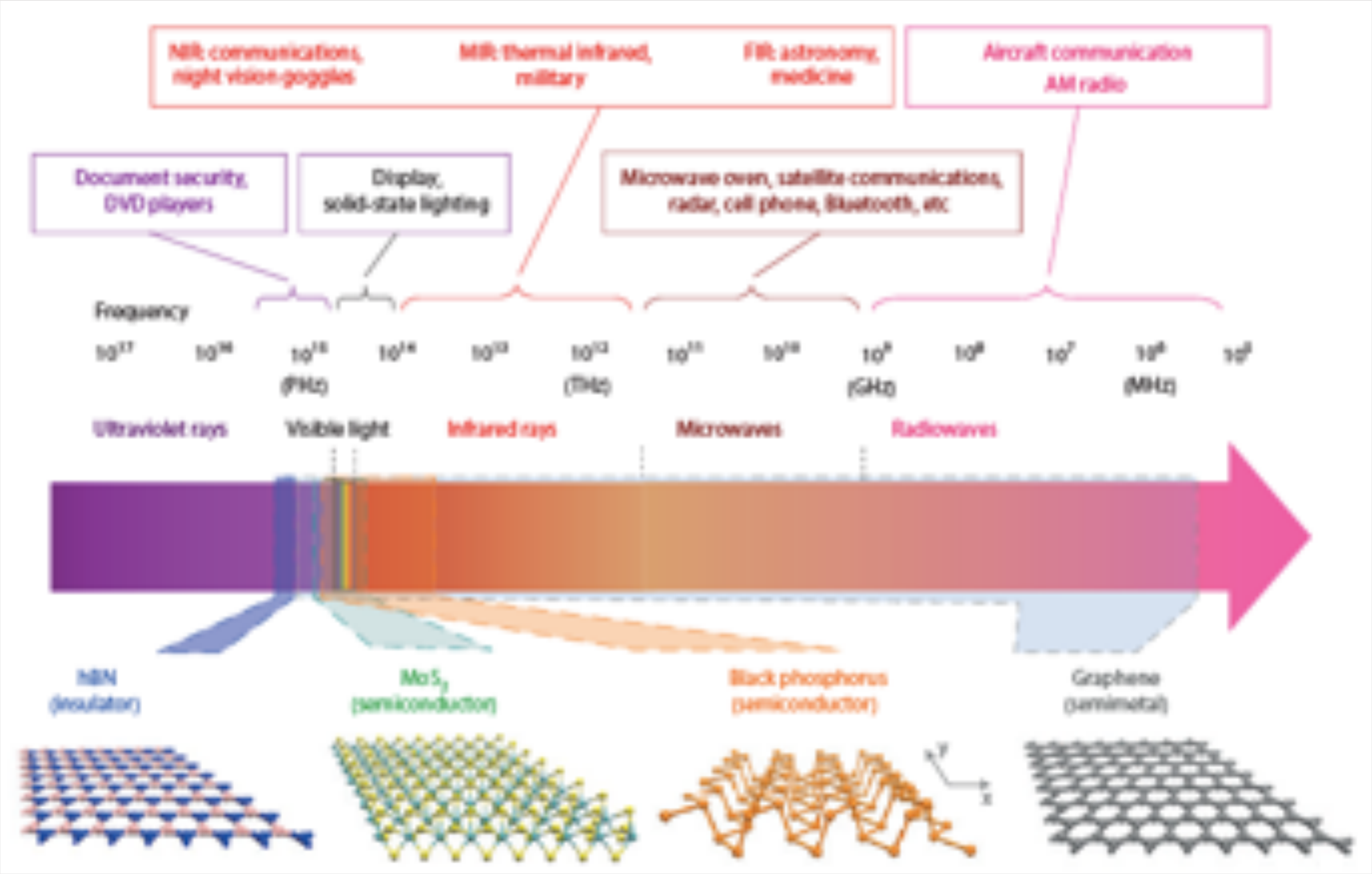



Confine the electronic and photonic wave-function to enhance the optical nonlinearity.
Etched surface near emitters degrade the materials.

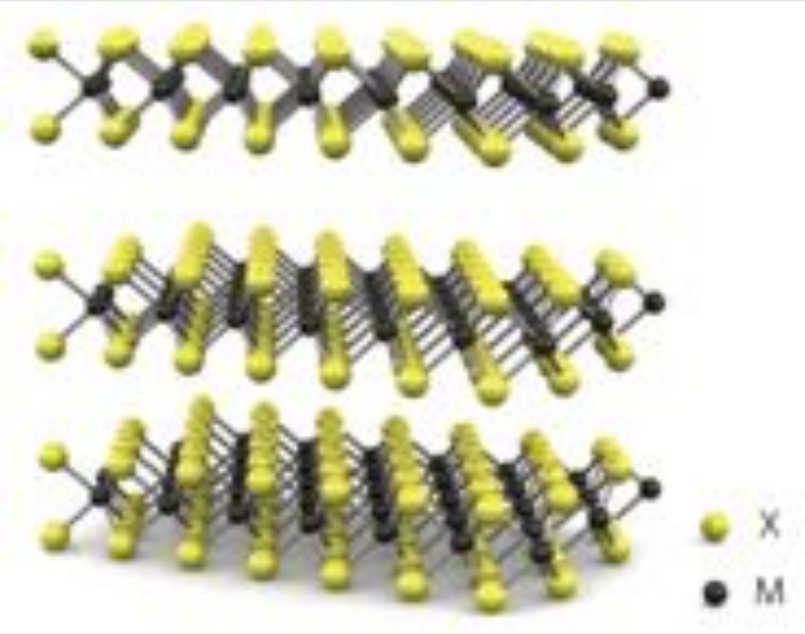


Explore broad emitters (good cavity regime) and focus on deterministic coupling: 2D materials and solution processed QD.

2D Materials: new opportunities in exciton-polaritons



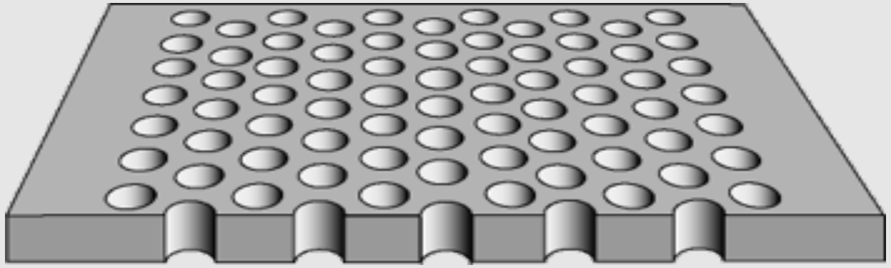
Nature Photonics 8, 899–907 (2014)

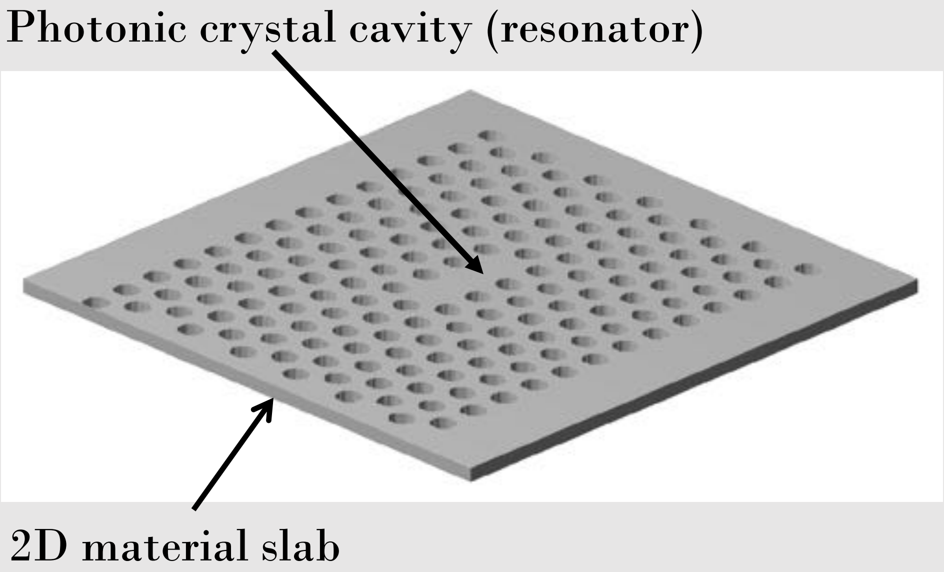


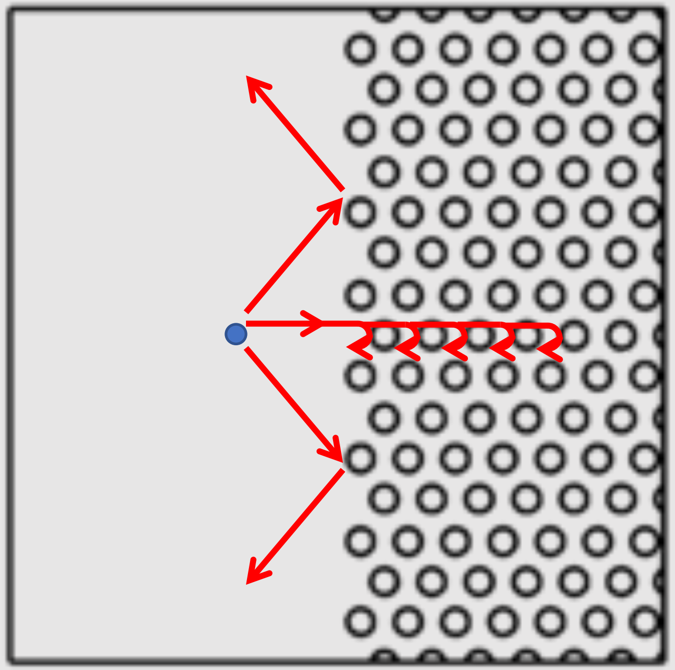
Nature nanotechnology, 7, 699, 2012

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

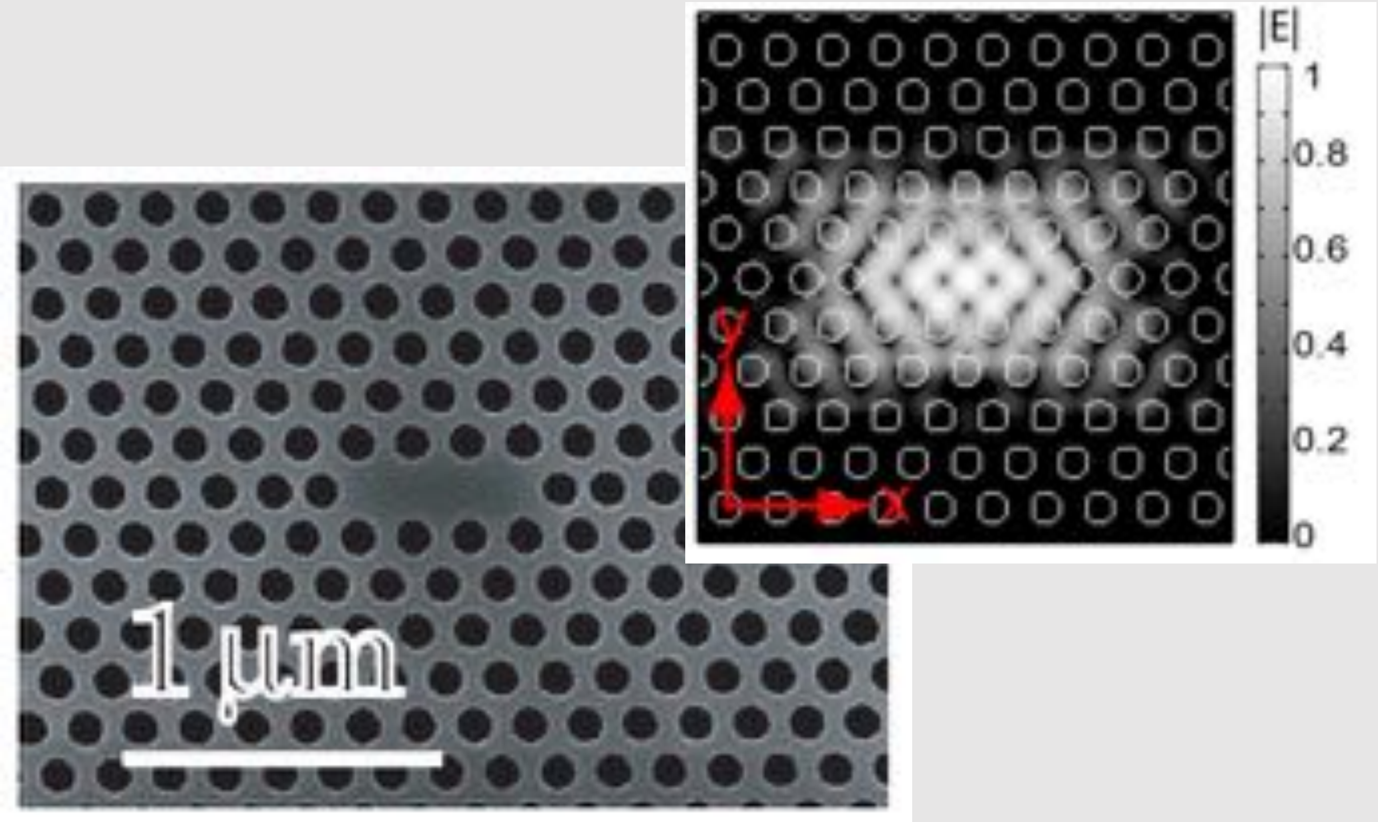
Photonic Crystal Resonator

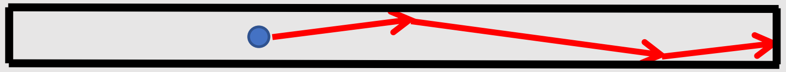






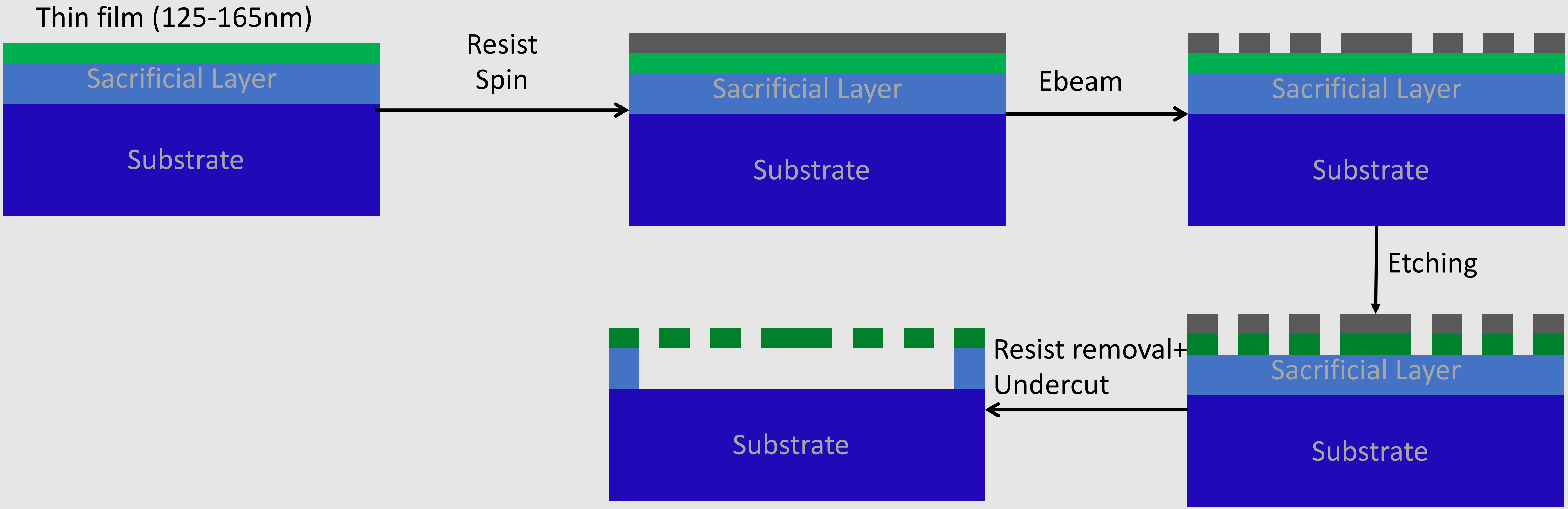
Distributed Bragg Reflection



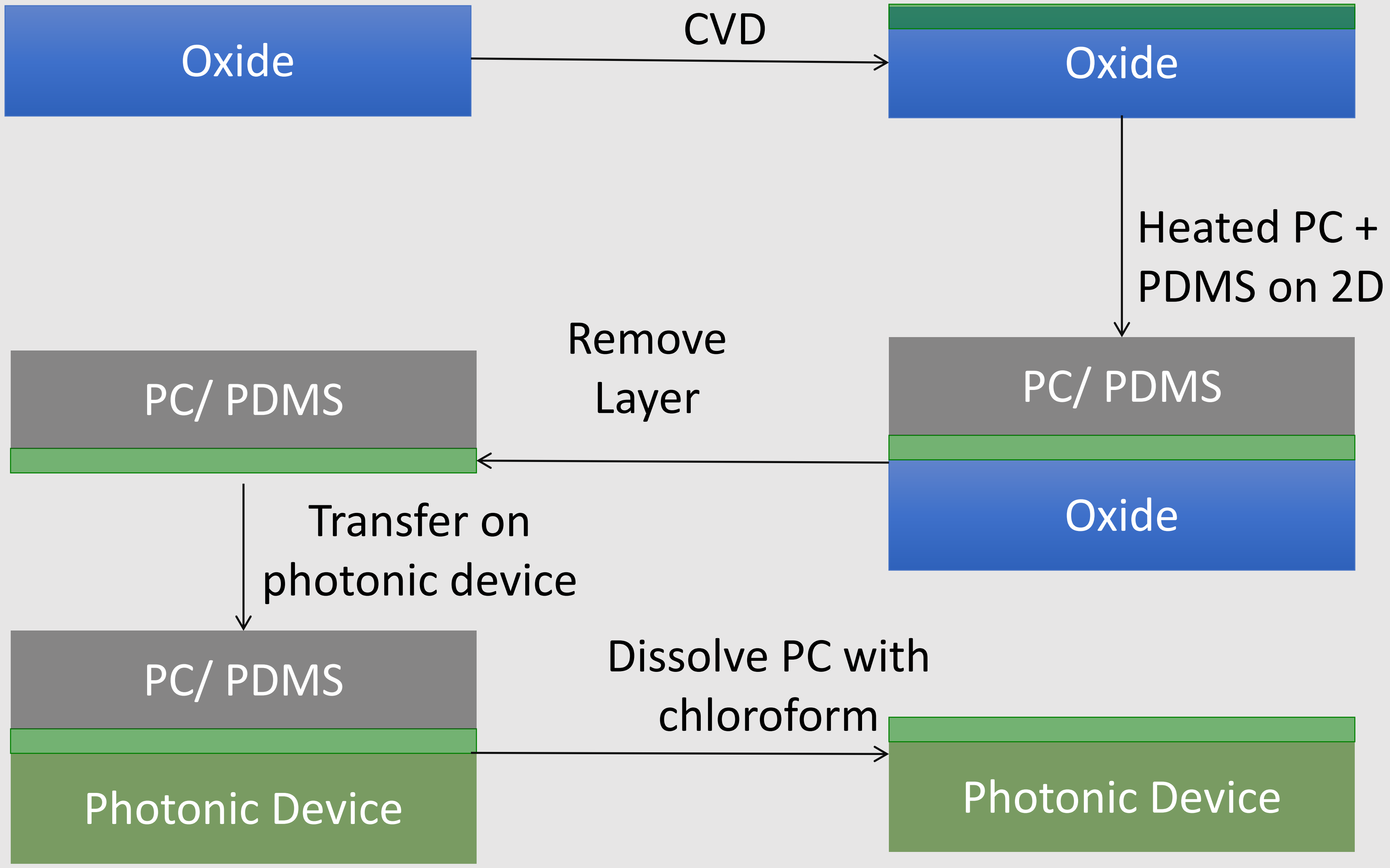


Total Internal Reflection

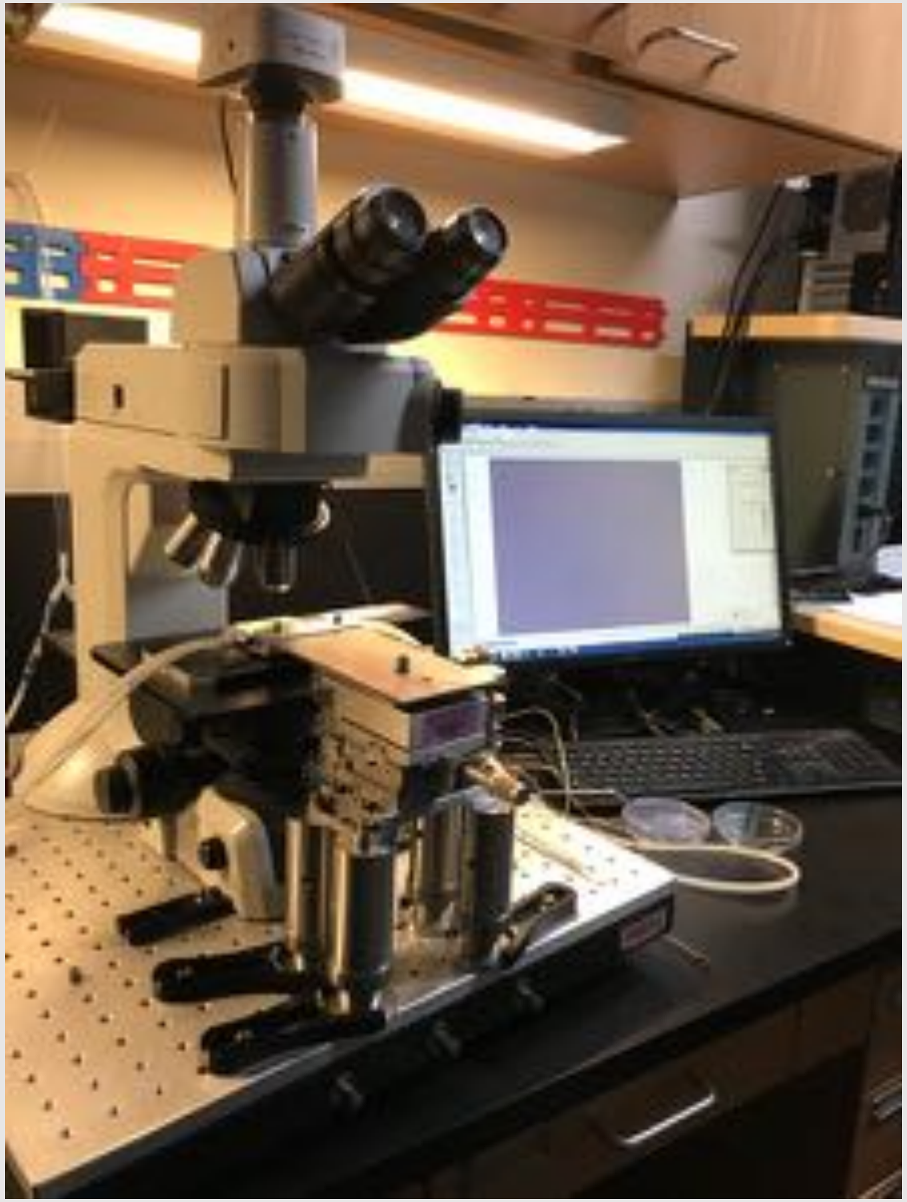
Cavity fabrication

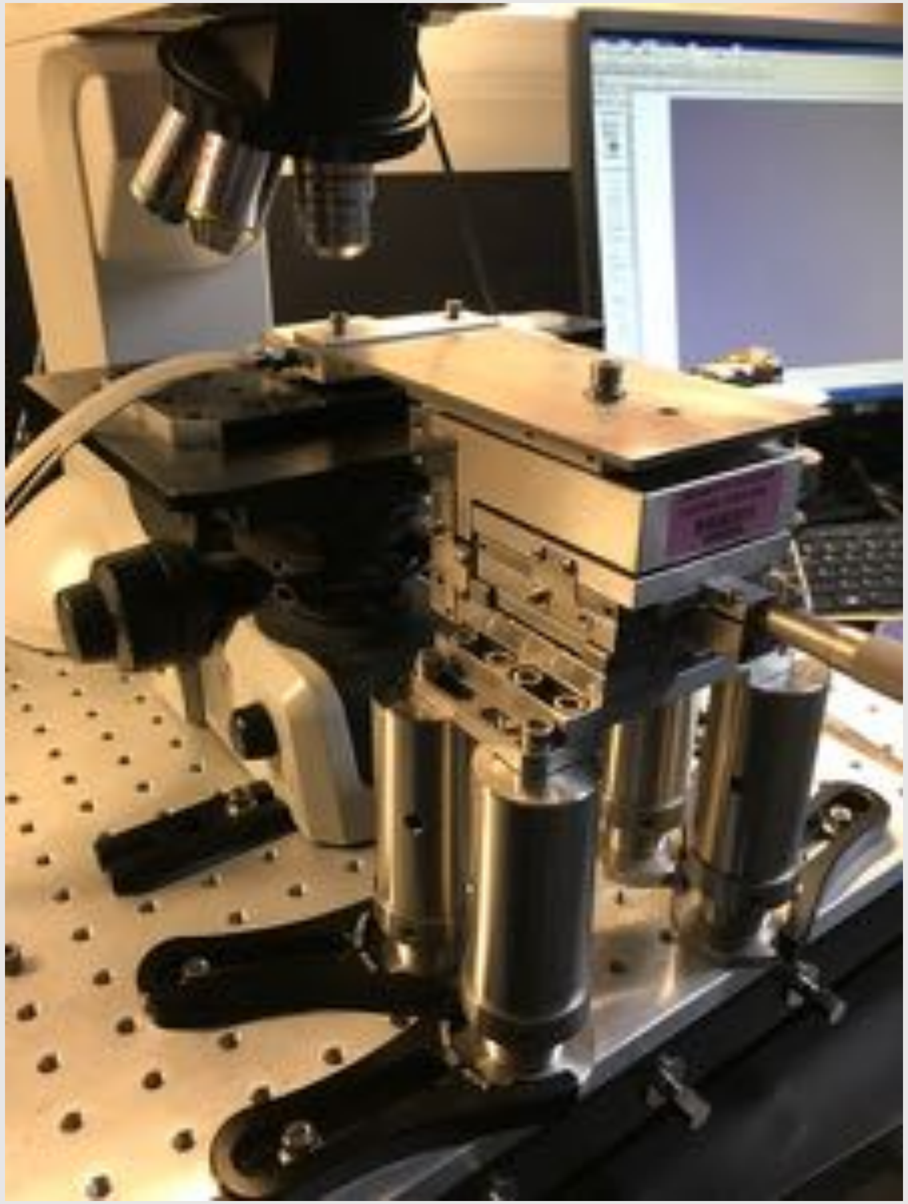


2D material transfer



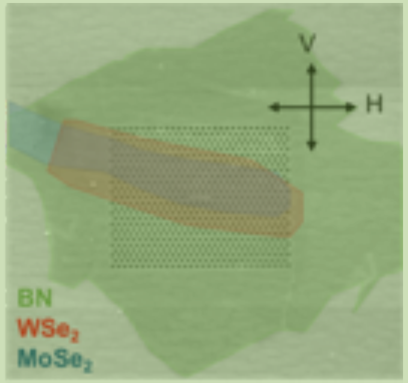
Transfer Stage





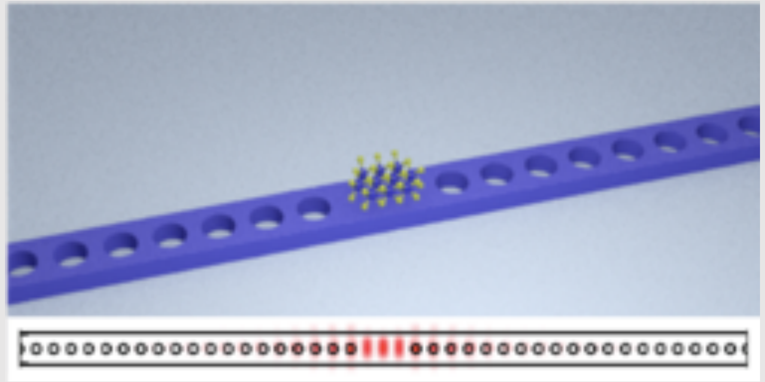
2D material integrated cavity platform

Rivera et. al., in preparation.
Rosser et. al., in preparation.



Single photon nonlinear optics with 2D material

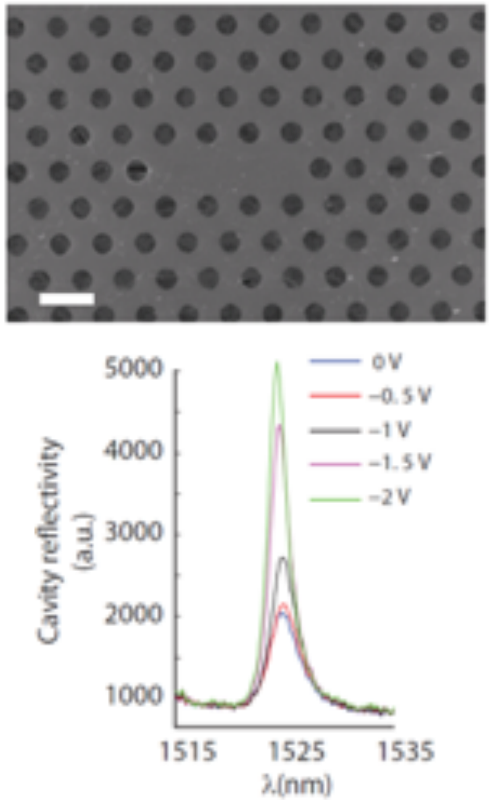
Ryou et. al., Phys Rev. B, 2018
Wang et. al., Journal of Physics: Condensed Matter, 2017



Solution Processed QD in cavities

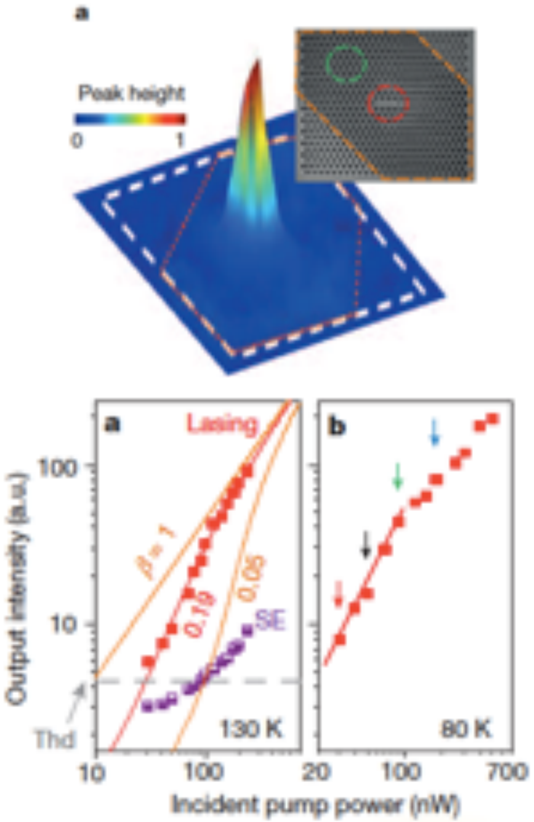
Chen et. al., Nano Letter, 2018
Chen et. al., Optics Letter, 2019

2D material integrated photonics devices



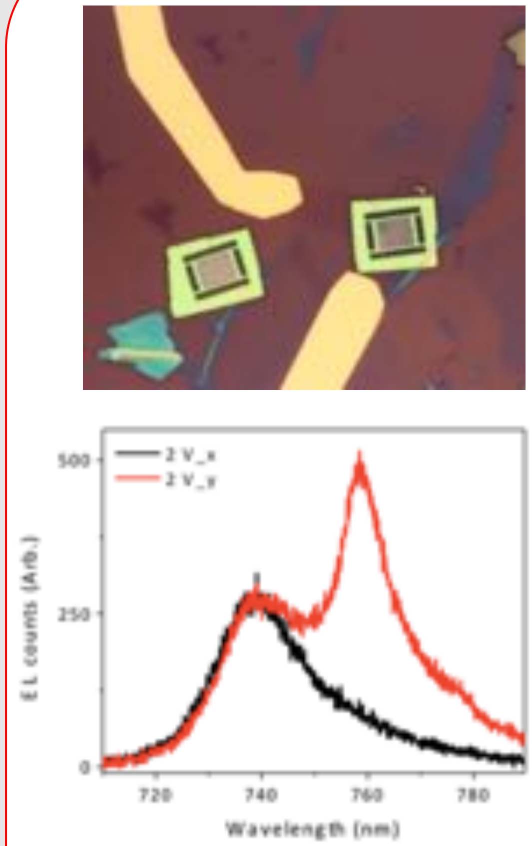
Graphene-silicon modulator, detector and self-electro optic switch

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



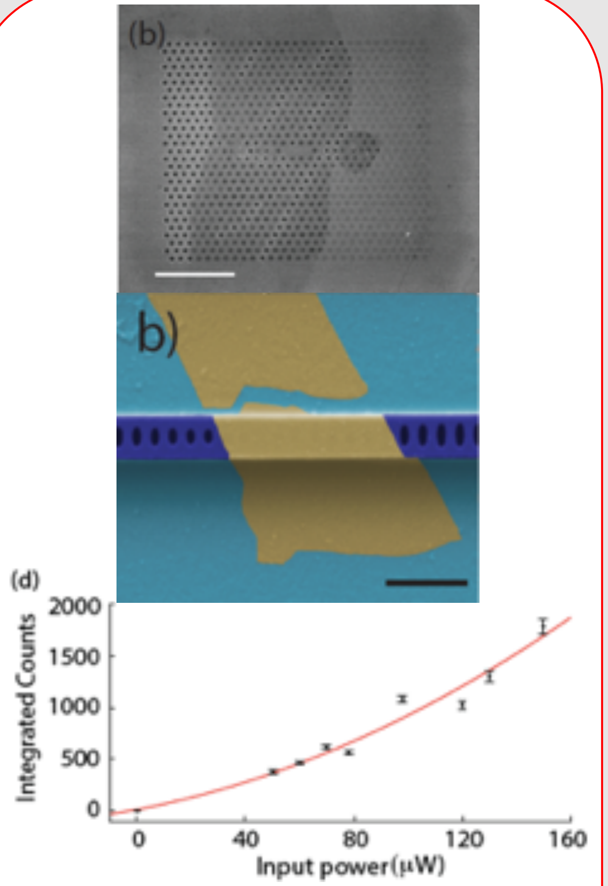
TMDC-cavity optically pumped laser

Majumdar & Xu, Nature, 520, 69-72, (2015).



Cavity enhanced electroluminescence

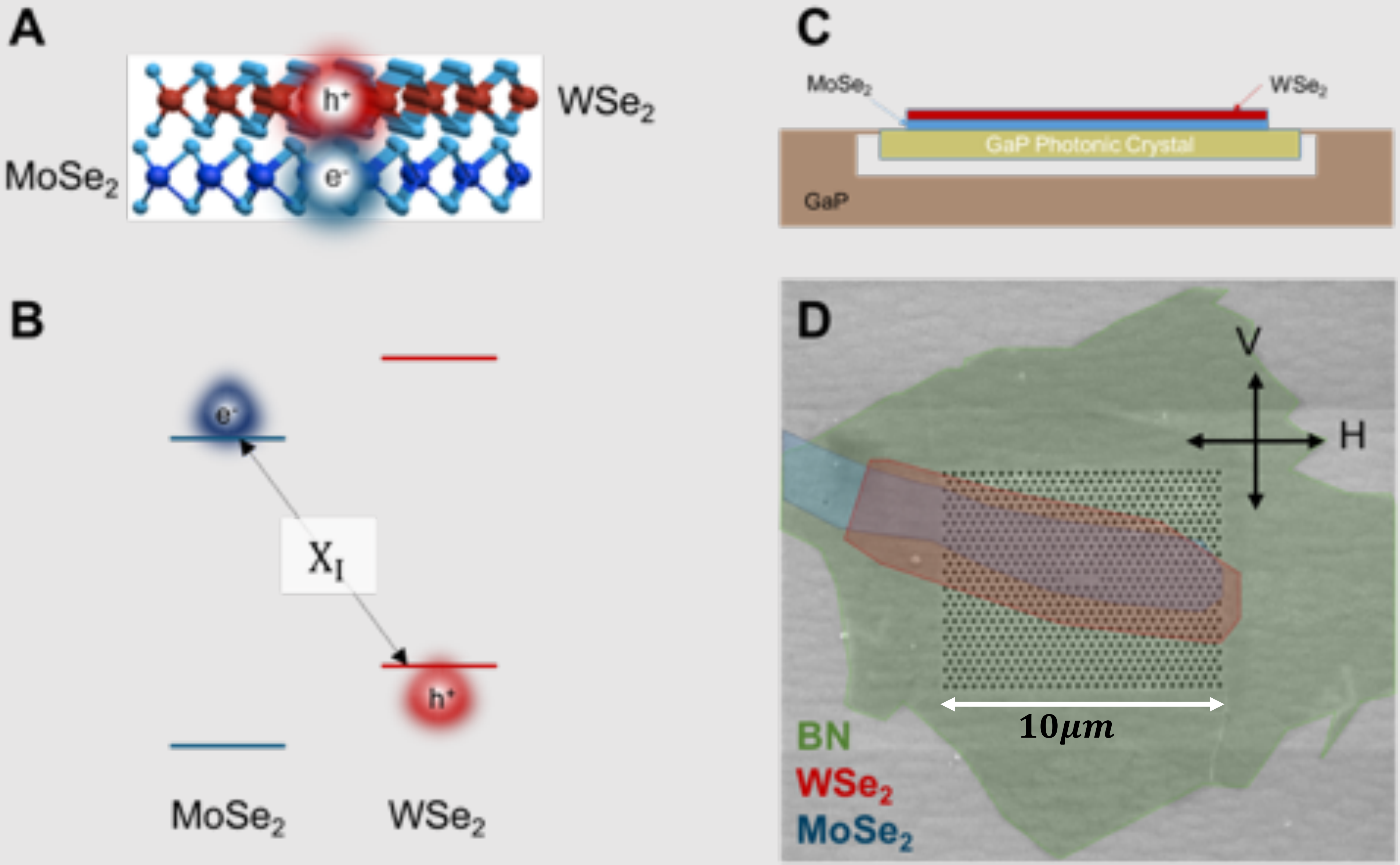
Majumdar & Xu, Nano Letters, 2016



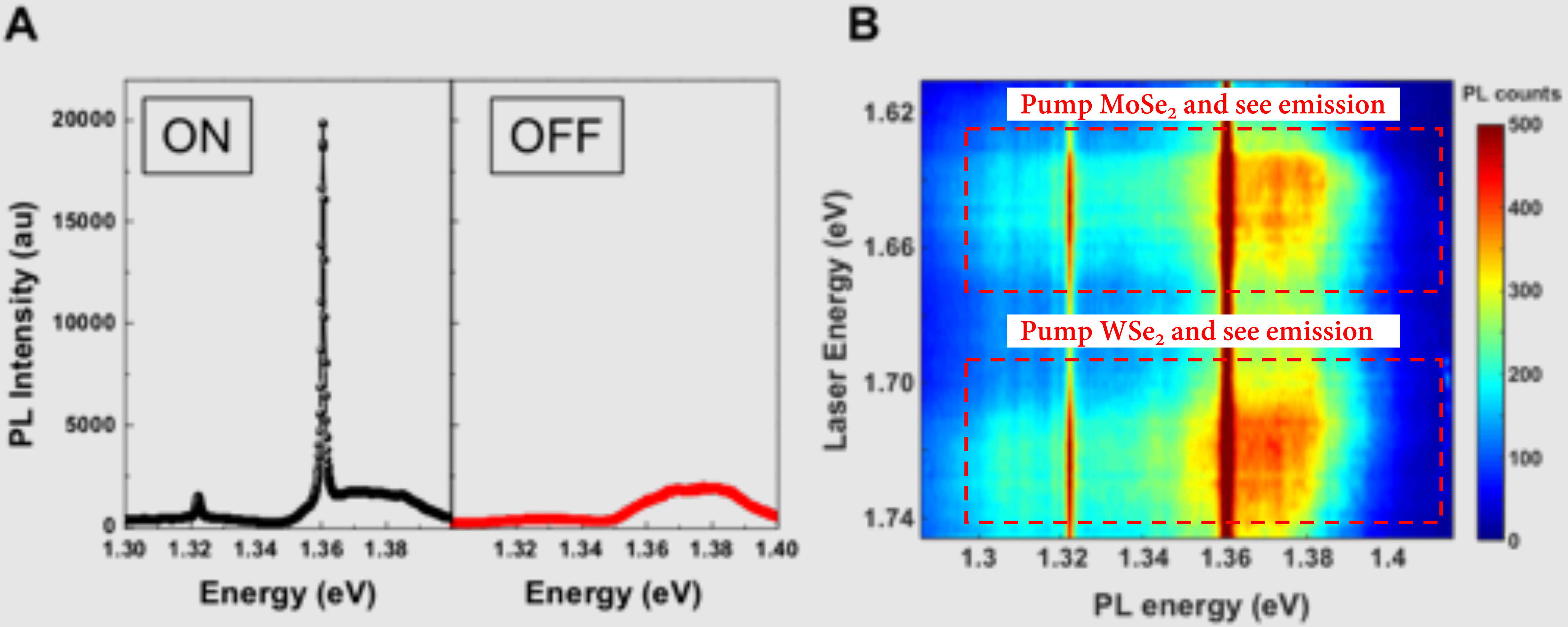
Cavity enhanced second harmonic generation

Majumdar & Xu, ACS Photonics, 2016; 2D materials (2016)

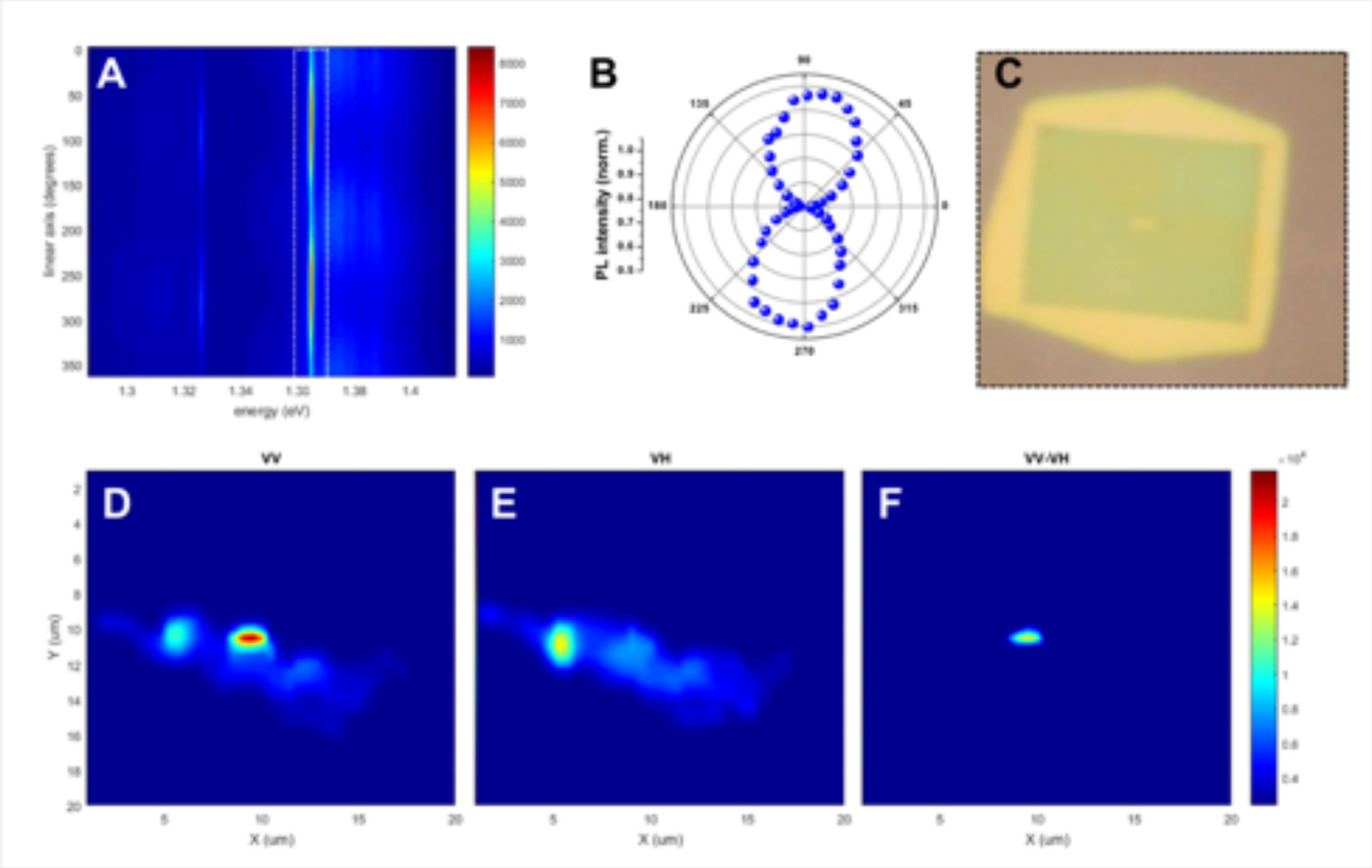
Inter-layer excitons coupled to photonic crystal cavity



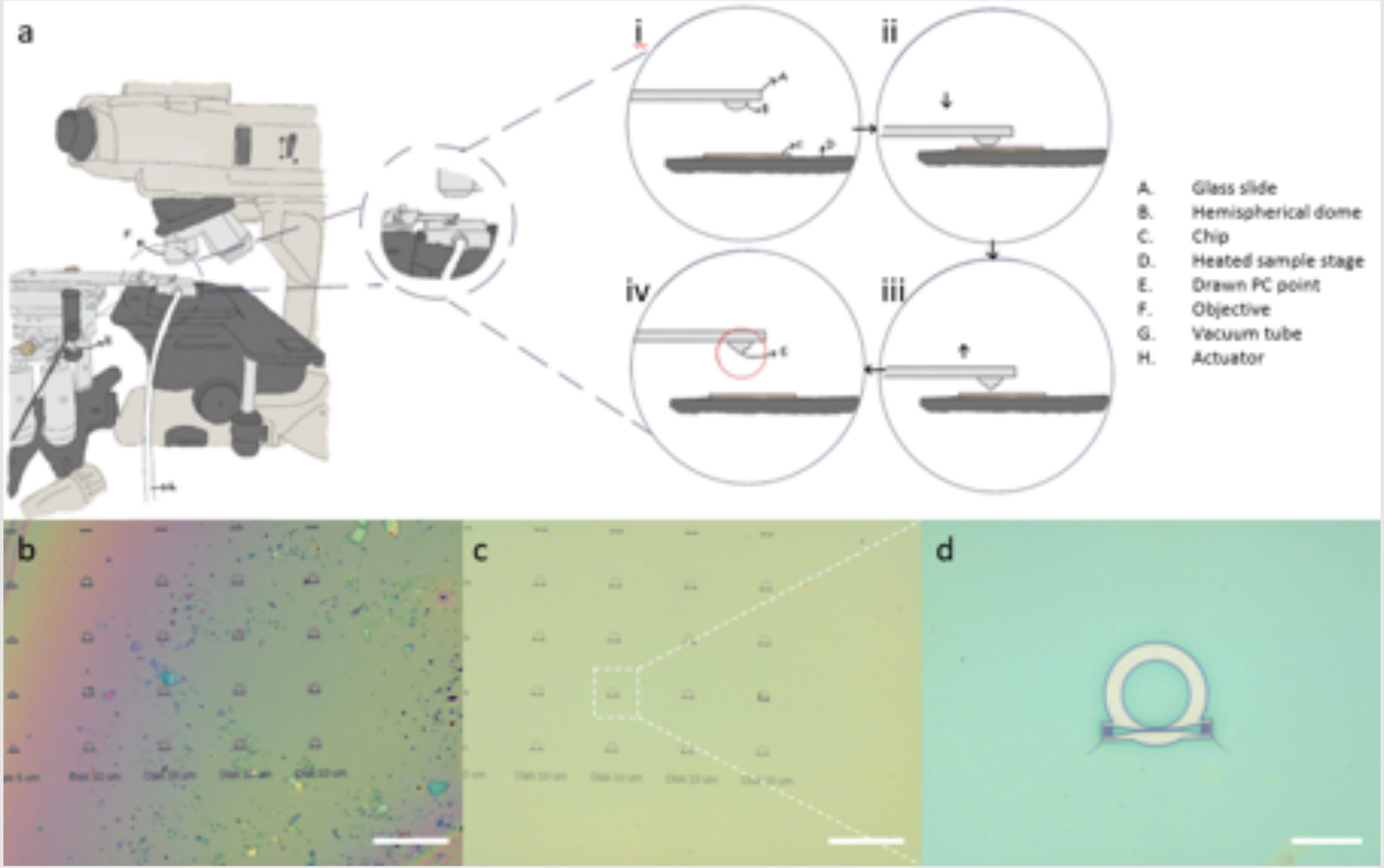
Cavity coupling is observed



Polarization resolved study



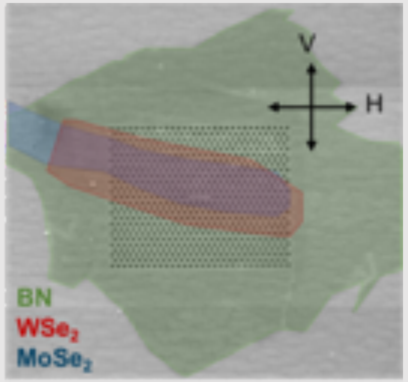
Local transfer of 2D materials



Clean local transfer on nanophotonic structures

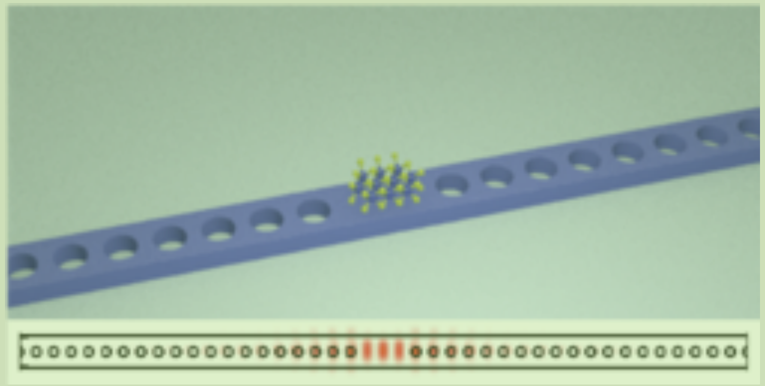
2D material integrated cavity platform

Rivera et. al., in preparation.
Rosser et. al., in preparation.



Single photon nonlinear optics with 2D material

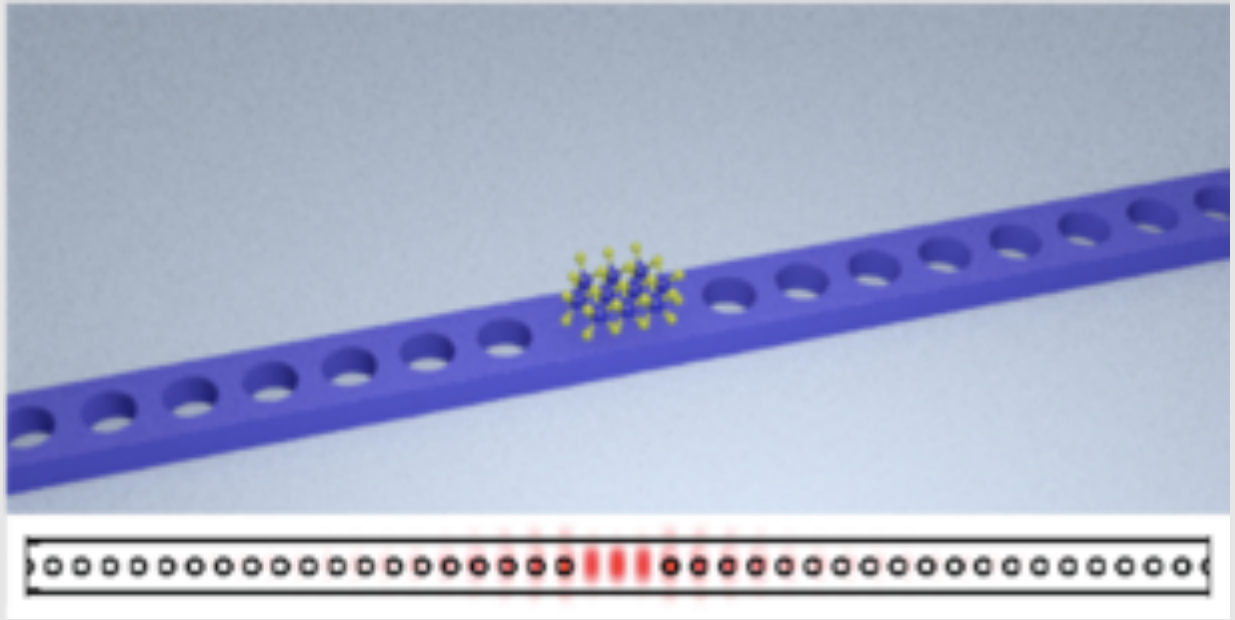
Ryou et. al., Phys Rev. B, 2018
Wang et. al., Journal of Physics: Condensed Matter, 2017



Solution Processed QD in cavities

Chen et. al., Nano Letter, 2018
Chen et. al., Optics Letter, 2019

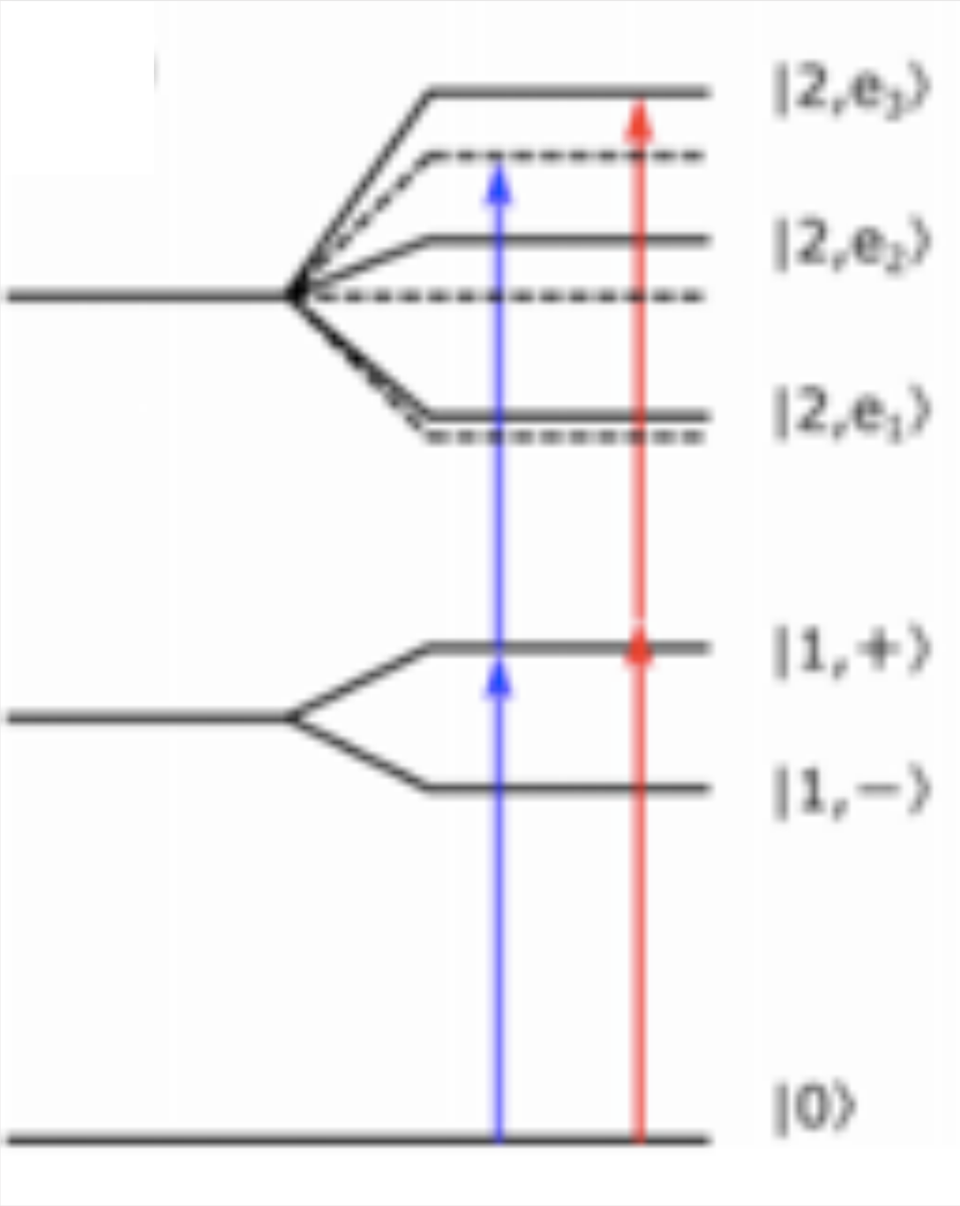
Single photon nonlinear optics



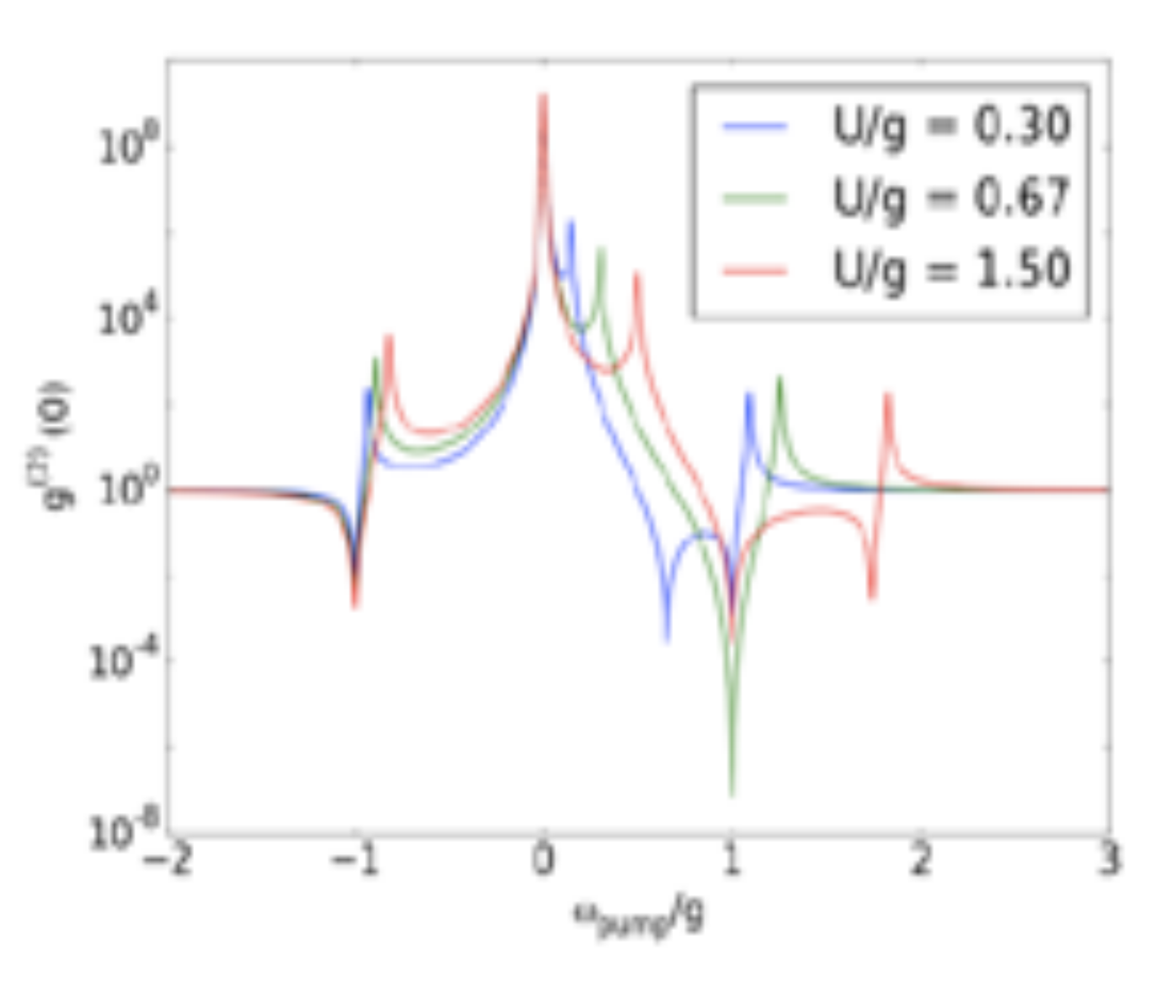
$$\mathcal{H} = \Delta_c a^\dagger a + \Delta_x b^\dagger b + g(a^\dagger b + a b^\dagger) + U_x b^\dagger b^\dagger b b$$

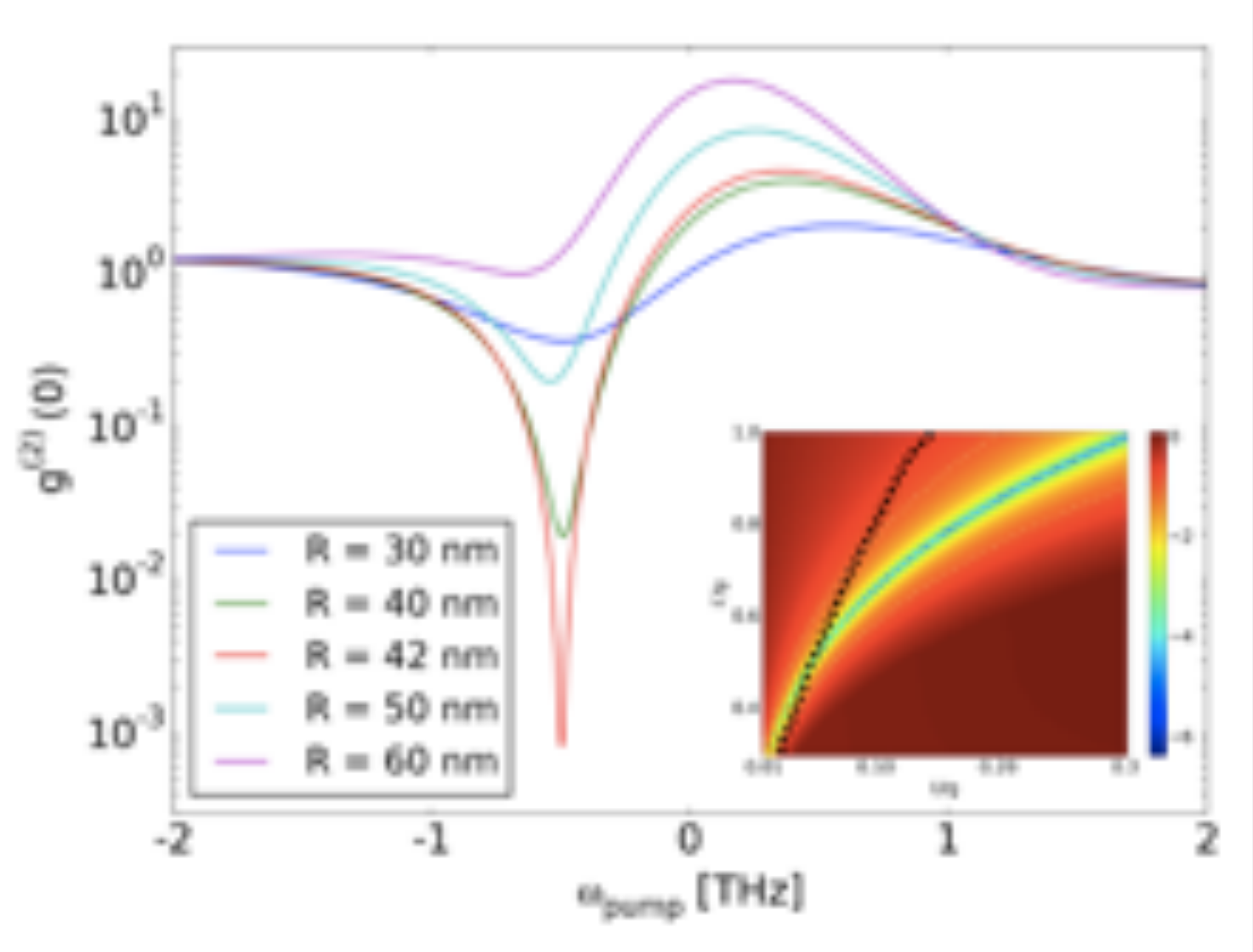
$$\hbar g \approx \frac{d_{cv}|\phi(0)|\sqrt{\hbar\omega_c}}{\sqrt{(2\epsilon_0 L_c)}}\sqrt{\frac{S_x}{S_{mode}}} \quad \hbar U_x = \frac{6E_b a_B^2}{S_x}$$

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



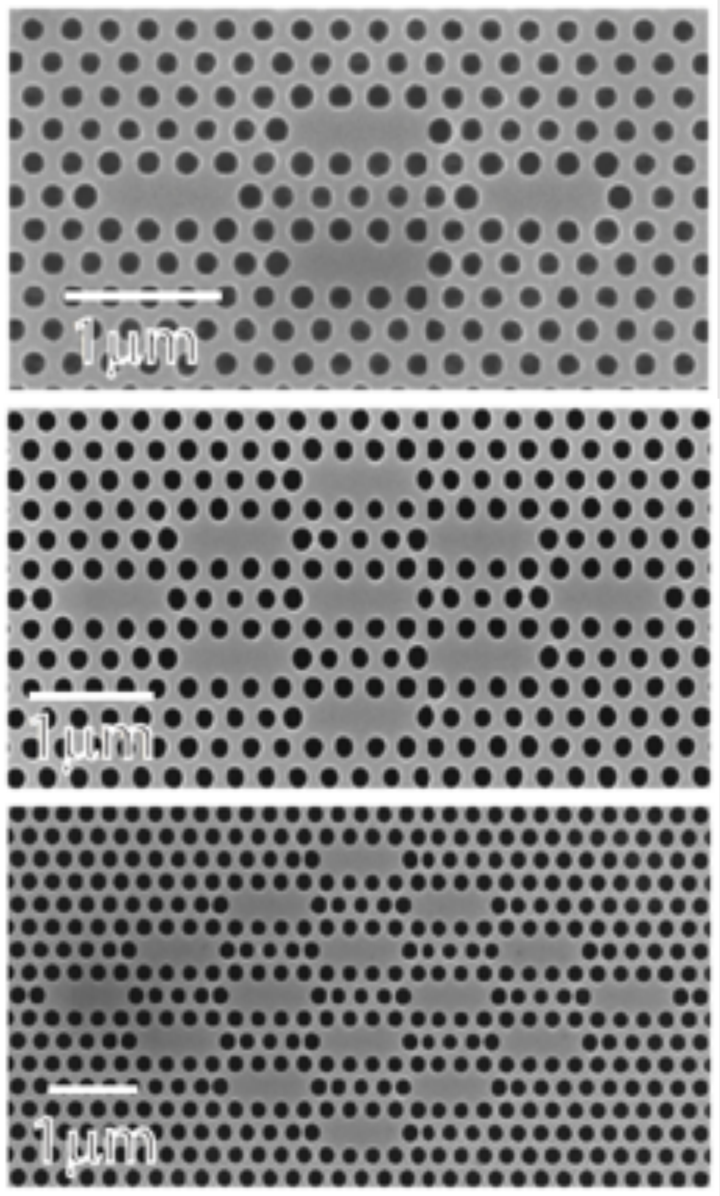
Photon correlation calculation



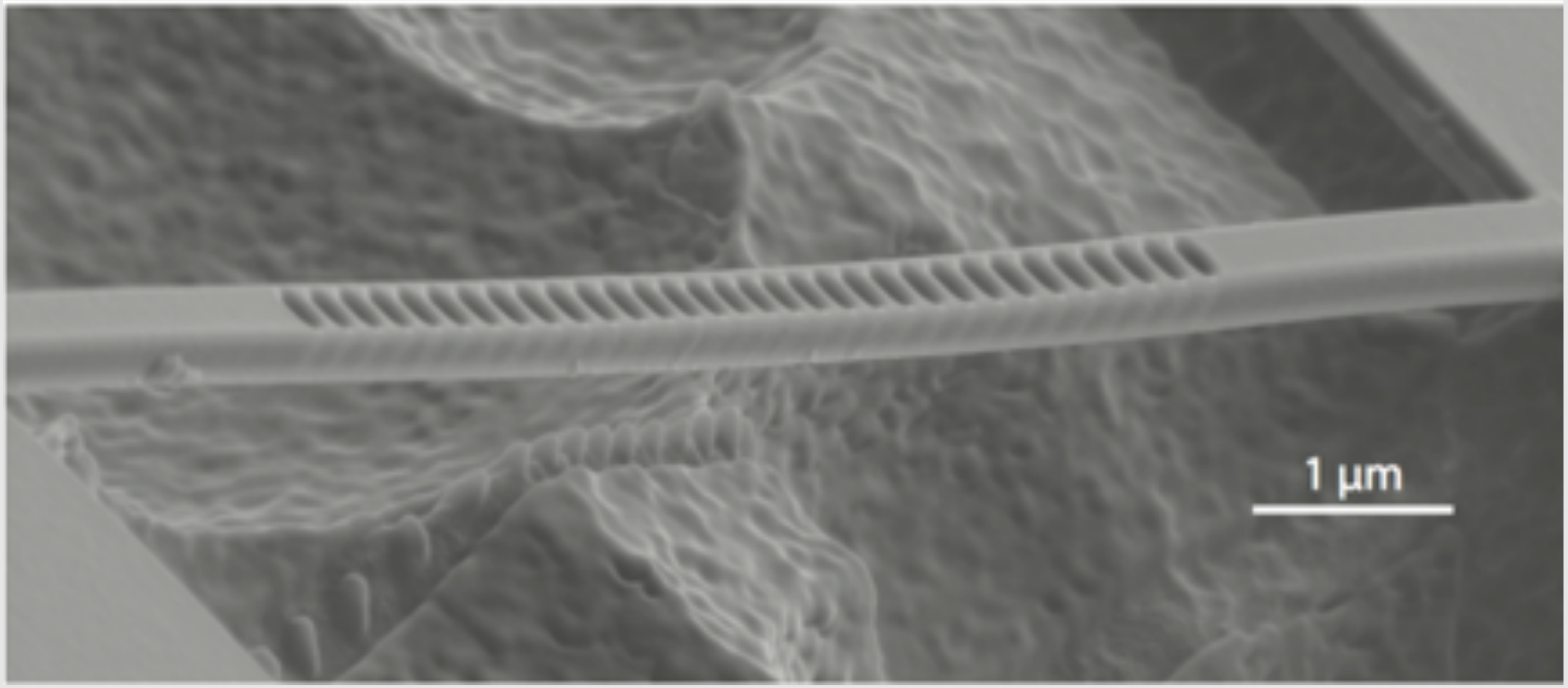


Dipole decay rate: $\gamma \sim \sqrt{S_x}$

Cavity array: how many cavities are possible?



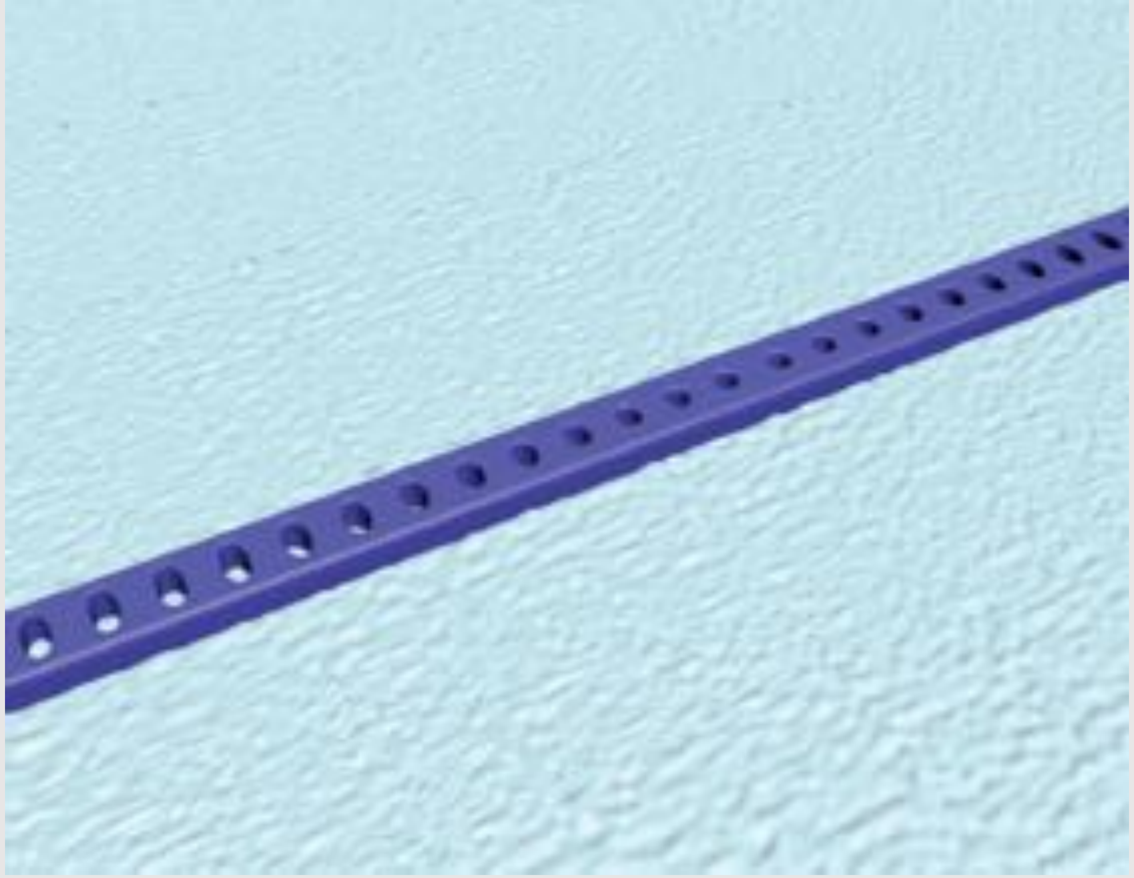
Majumdar et.al., PRB, 86, 195312 (2012)



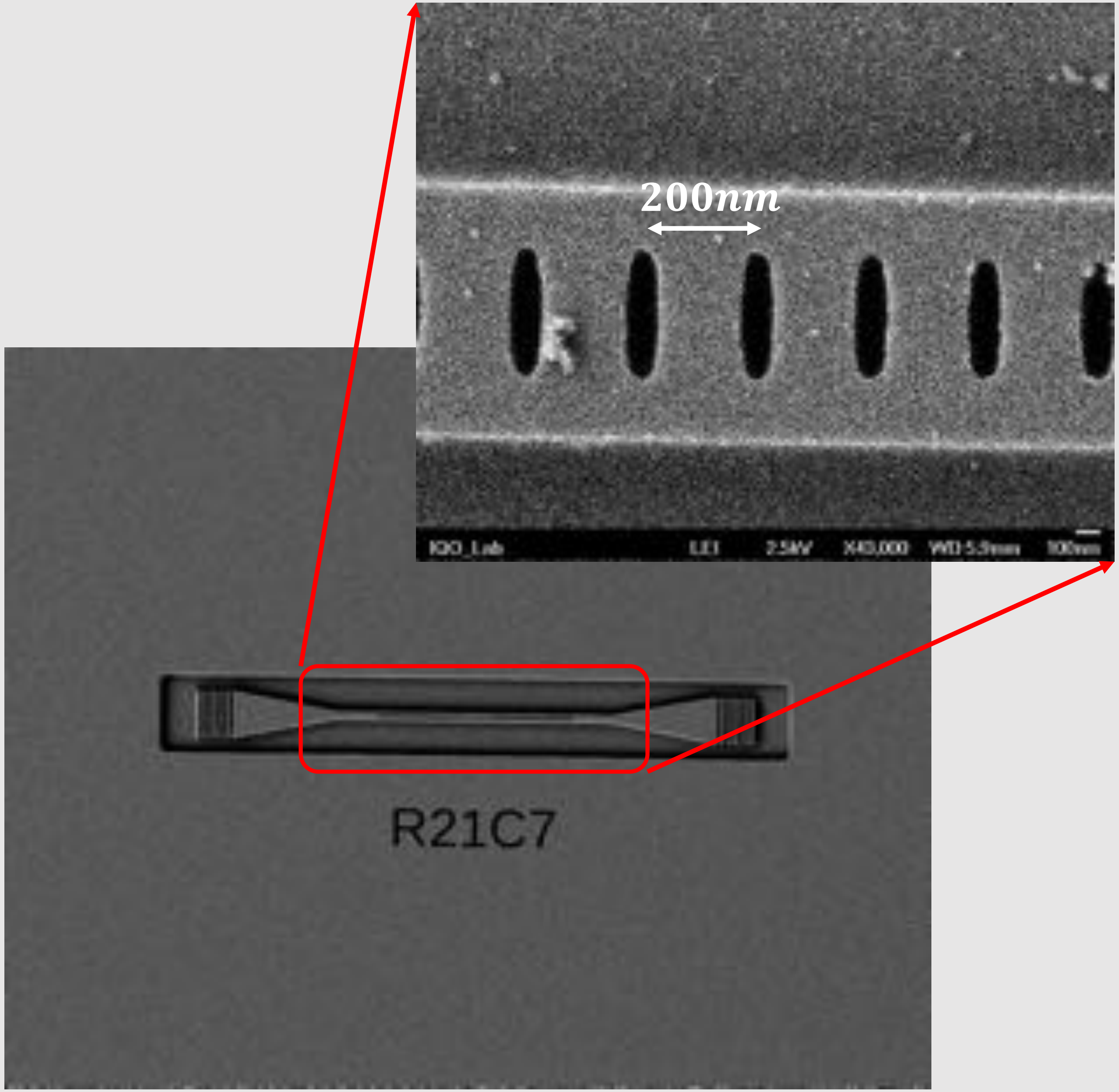
Deotare et. al., ACS Nano, vol. 8, no. 11, pp. 11080–11085, Sep. 2014

Suspended cavity array is difficult to scale beyond ~20.

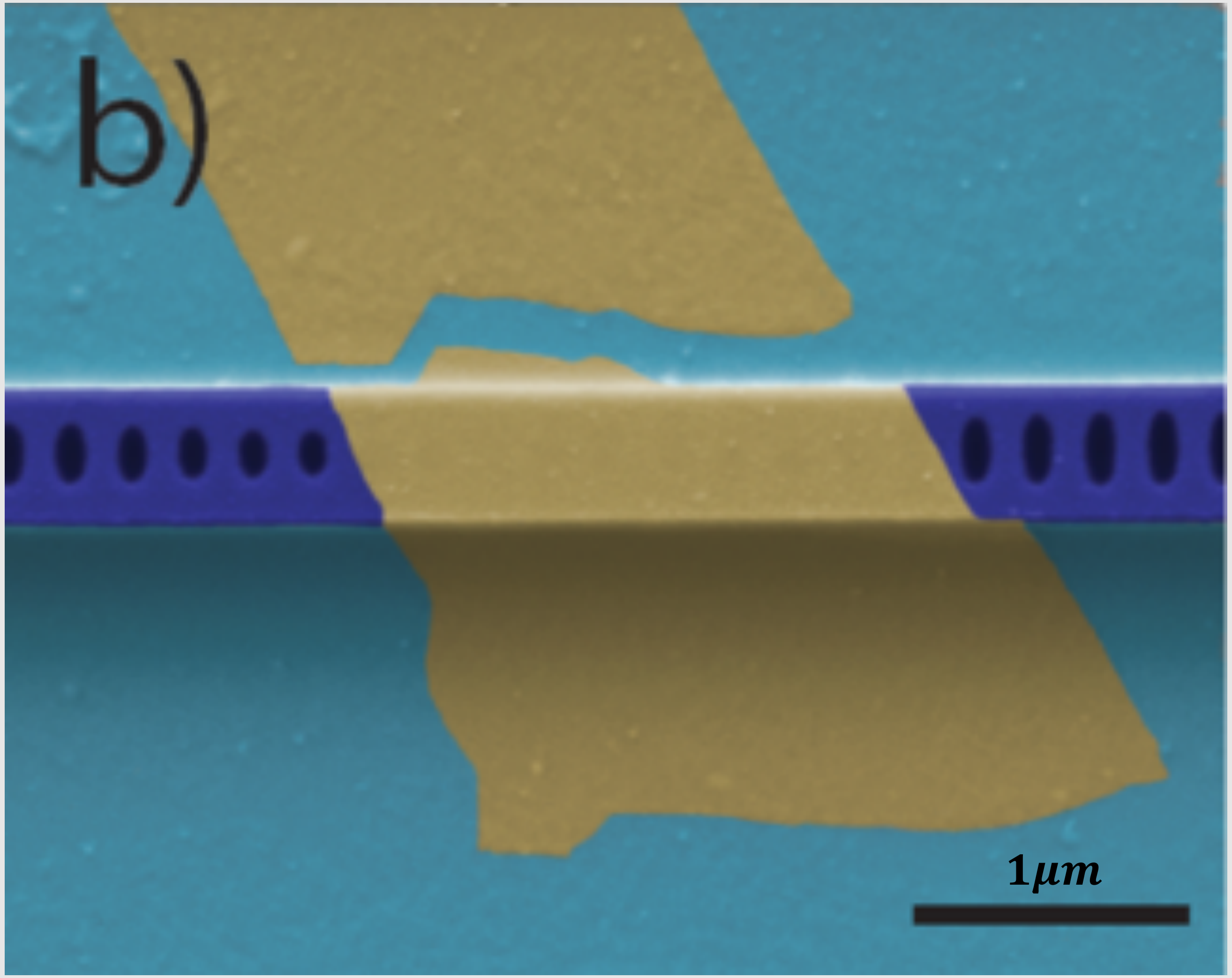
Mechanically stable encapsulated silicon nitride nanobeam

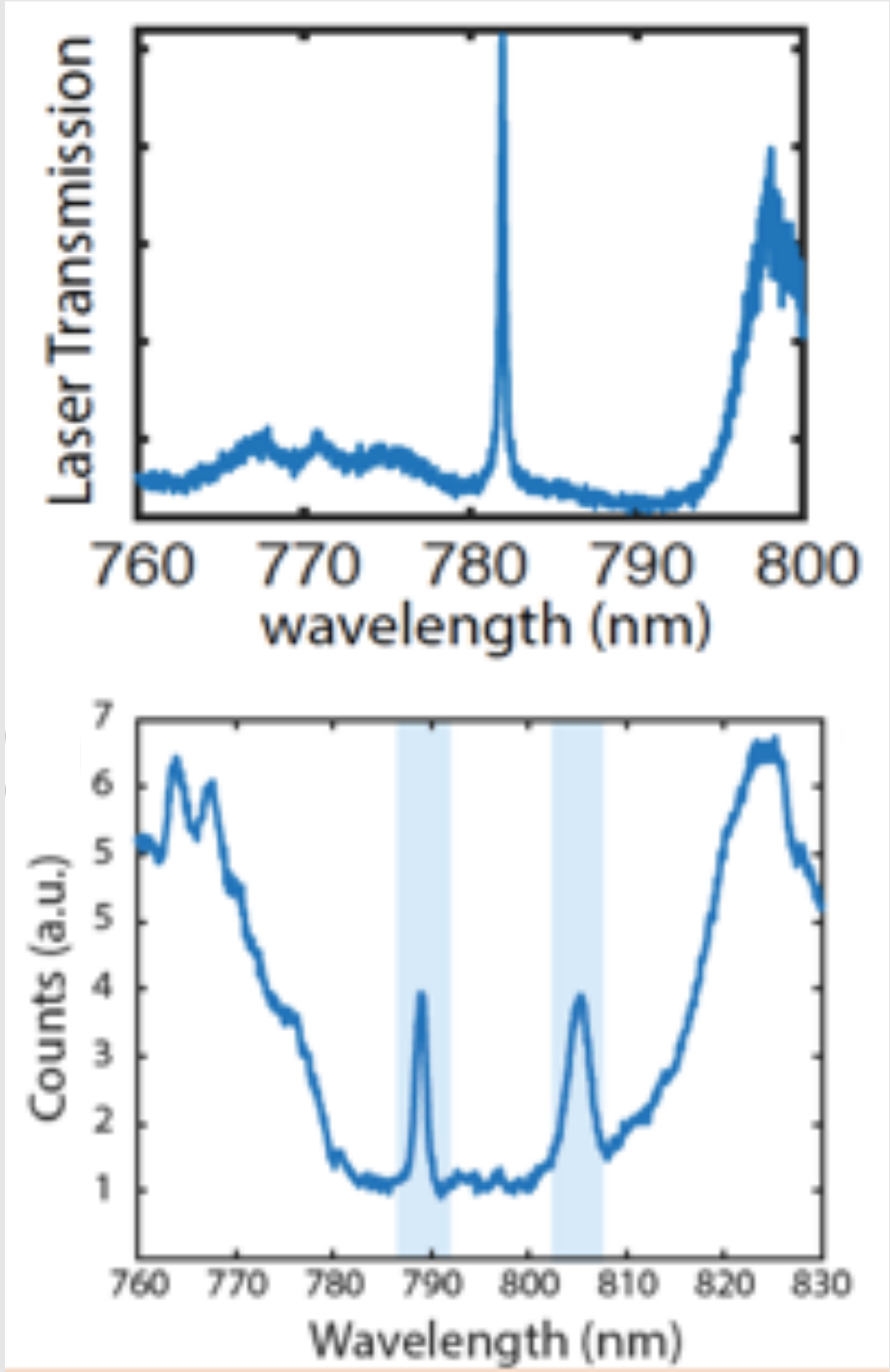


Fryett, Majumdar et. al., ACS Photonics, Article ASAP, 2018

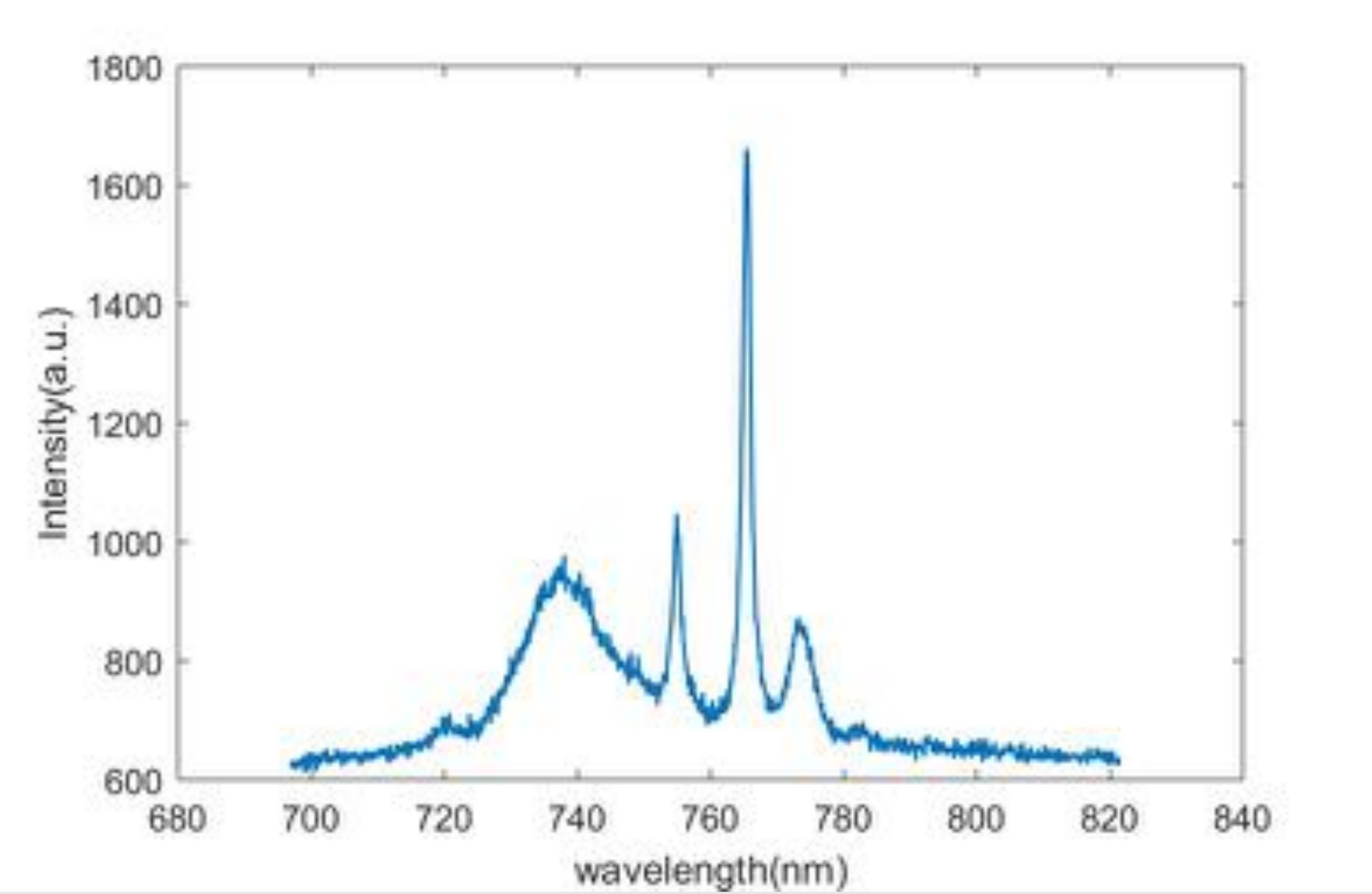


Monolayer integrated SiN nanobeam

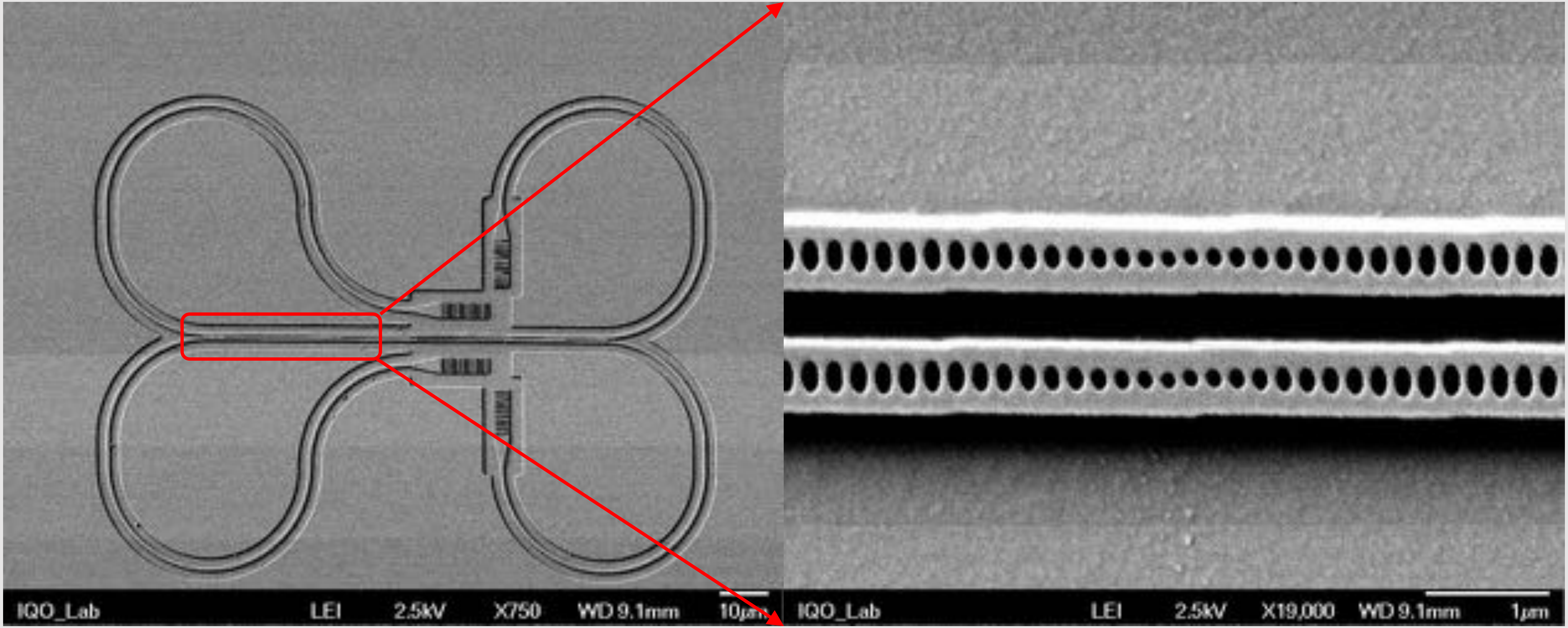




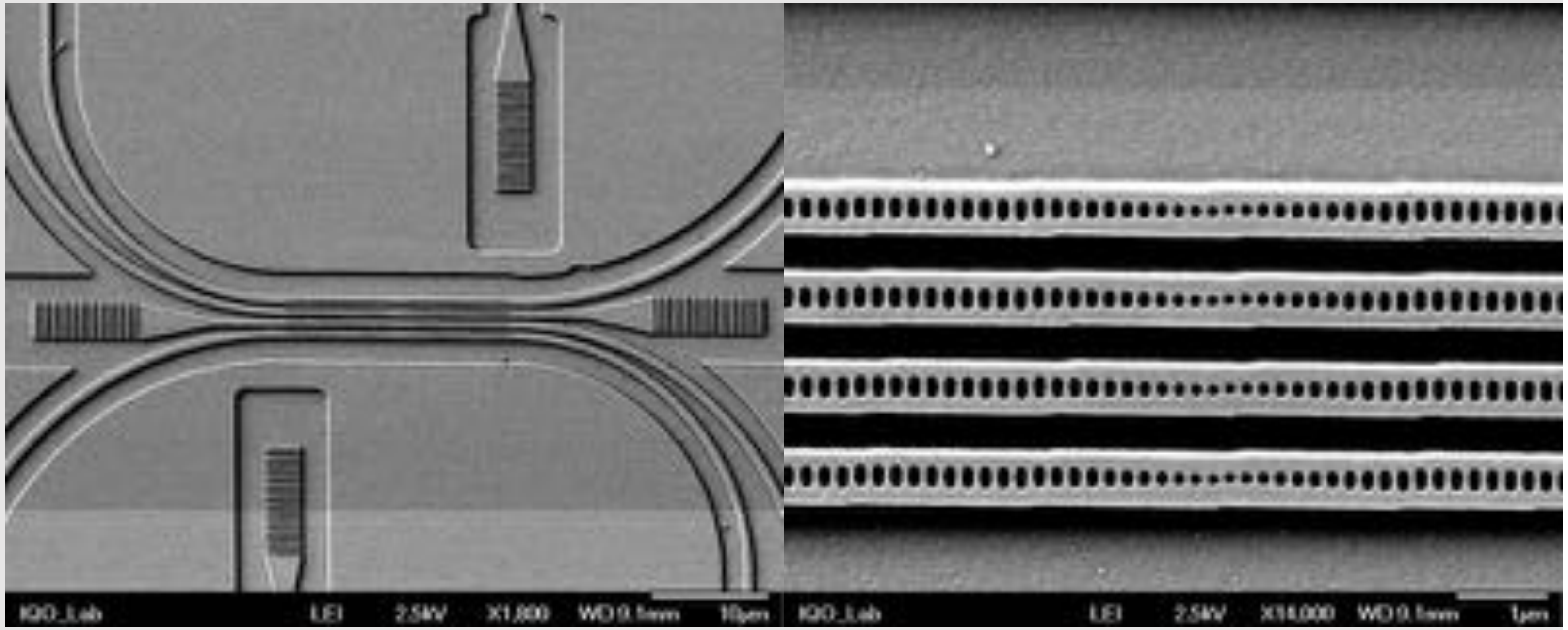
Cavity coupled photoluminescence

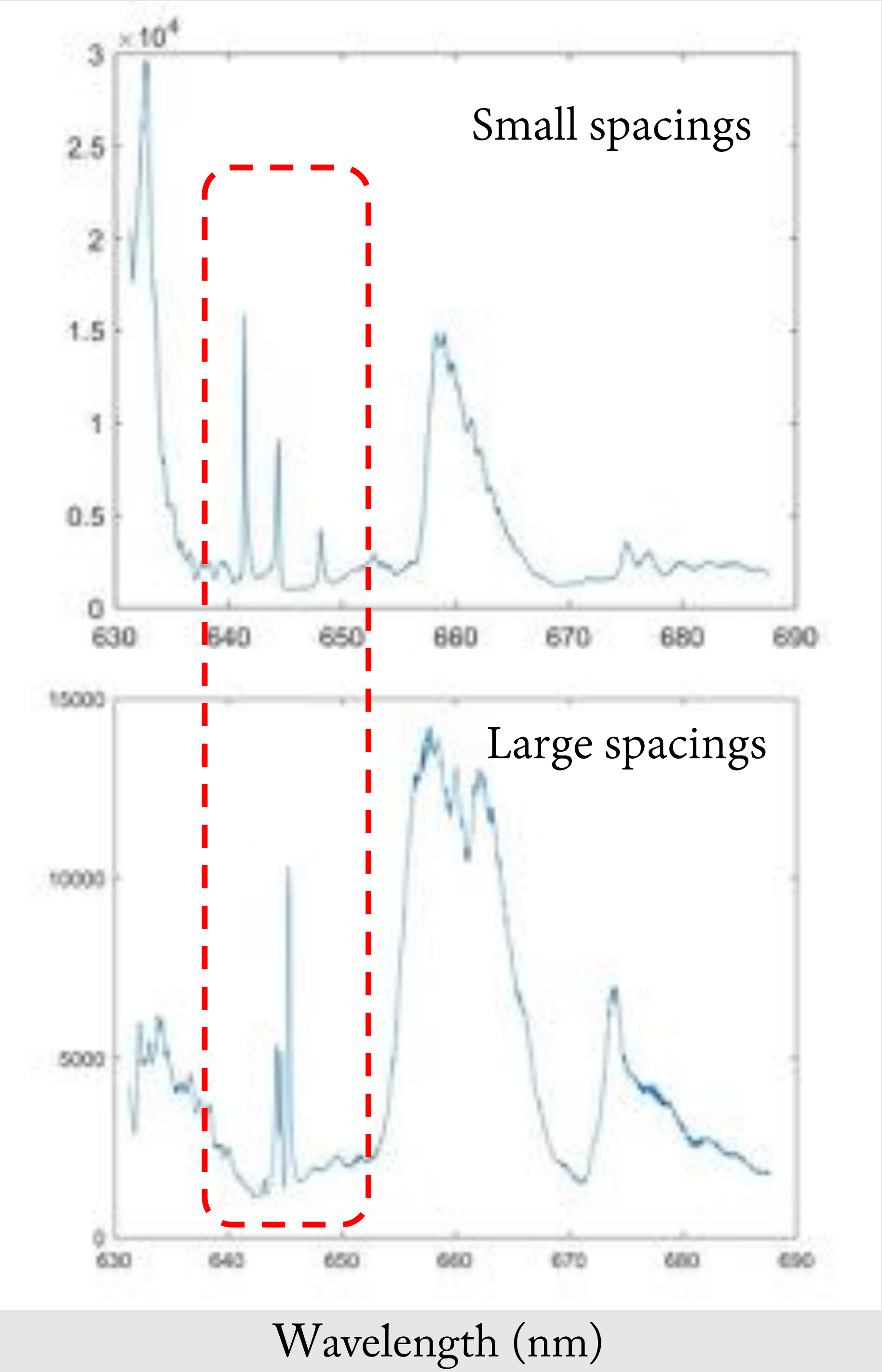


Coupled cavity array: photonic molecule



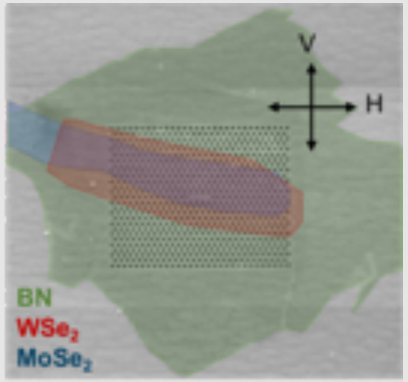
Coupled cavity array





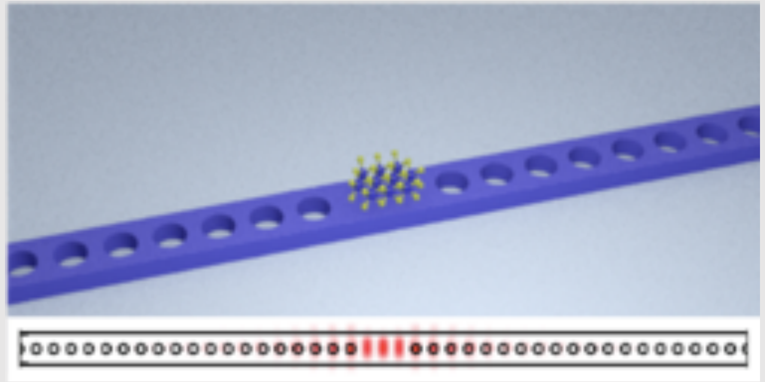
2D material integrated cavity platform

Rivera et. al., in preparation.
Rosser et. al., in preparation.



Single photon nonlinear optics with 2D material

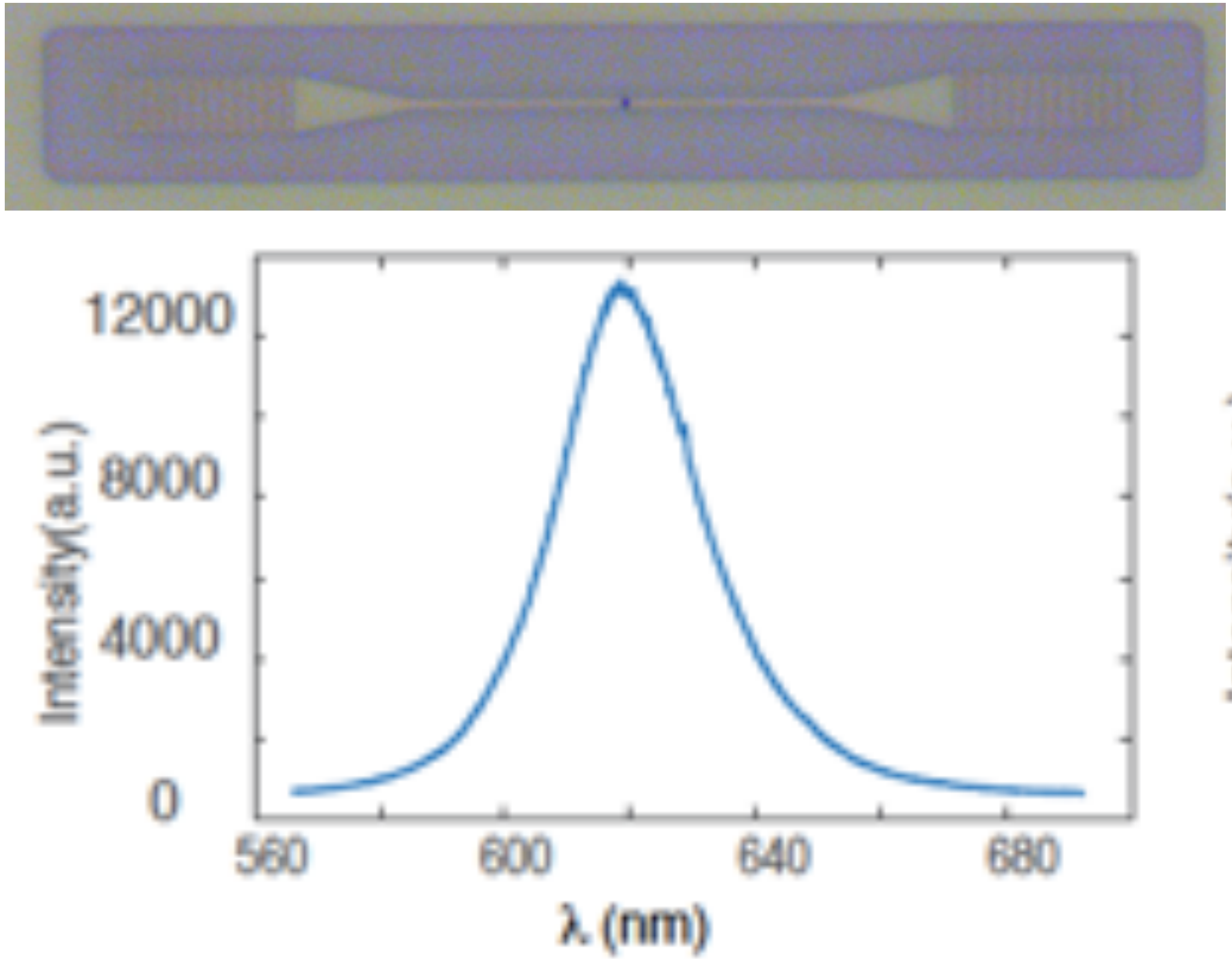
Ryou et. al., Phys Rev. B, 2018
Wang et. al., Journal of Physics: Condensed Matter, 2017

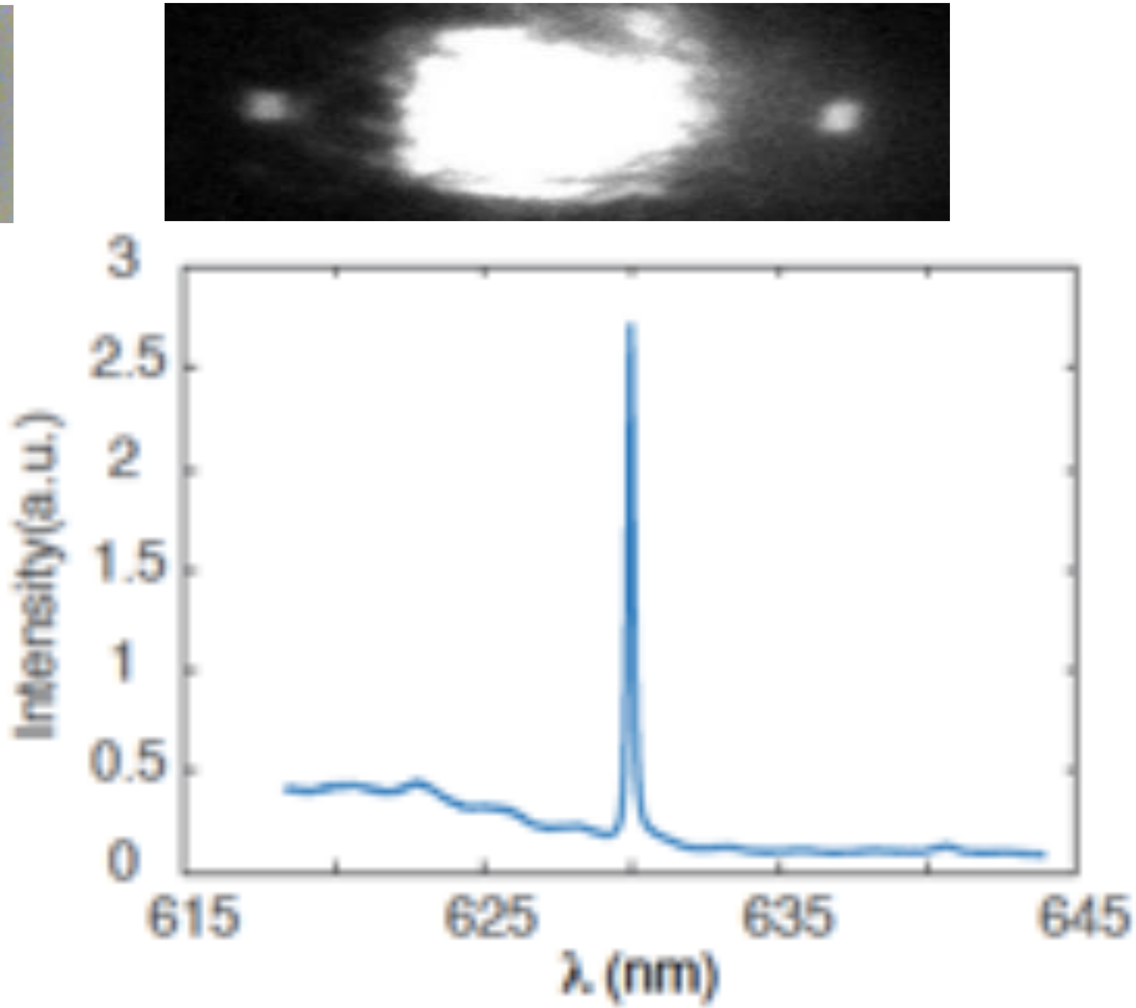


Solution Processed QD in cavities

Chen et. al., Nano Letter, 2018
Chen et. al., Optics Letter, 2019

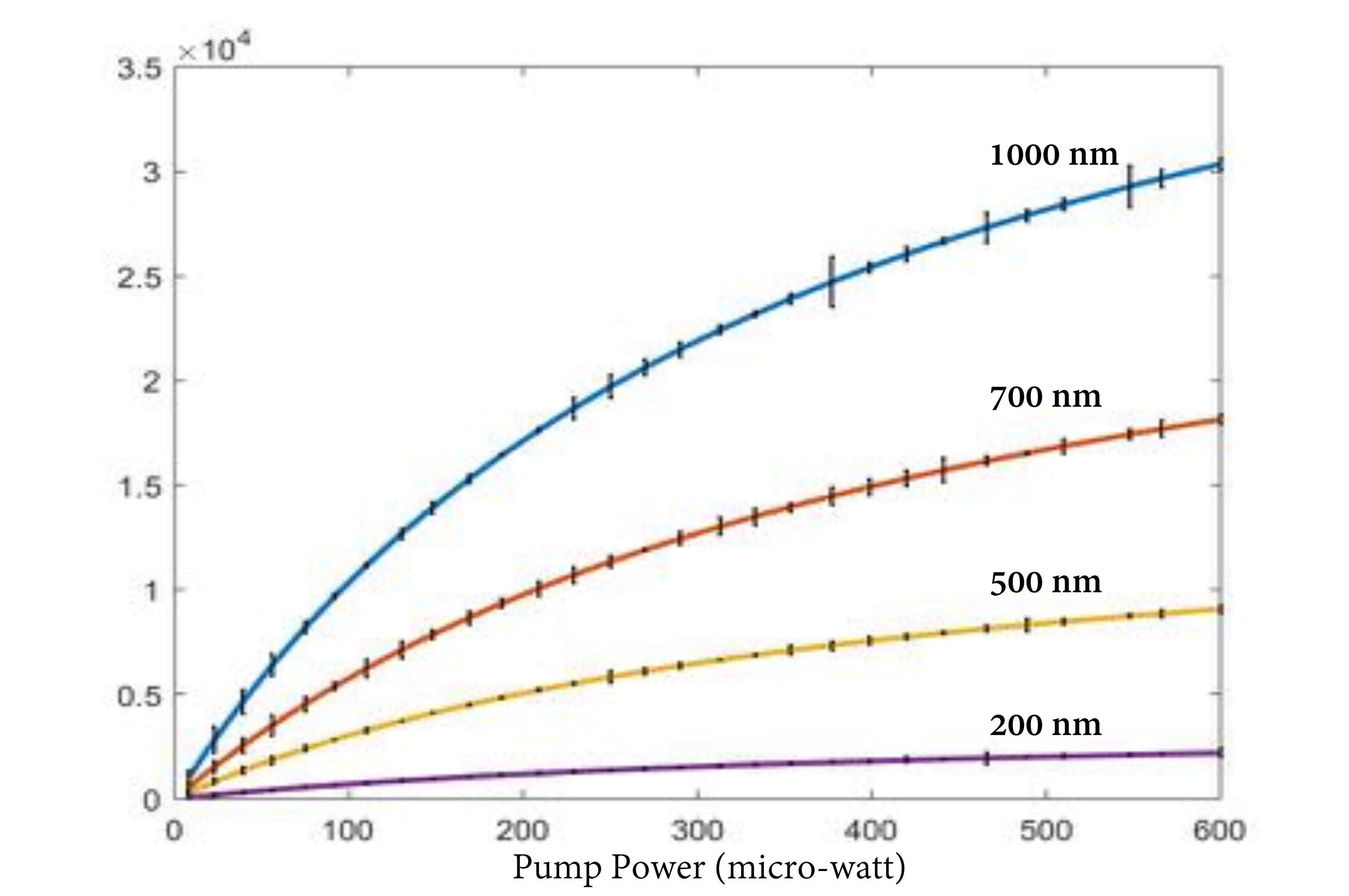
Solution Processed Quantum Dots coupled to cavities





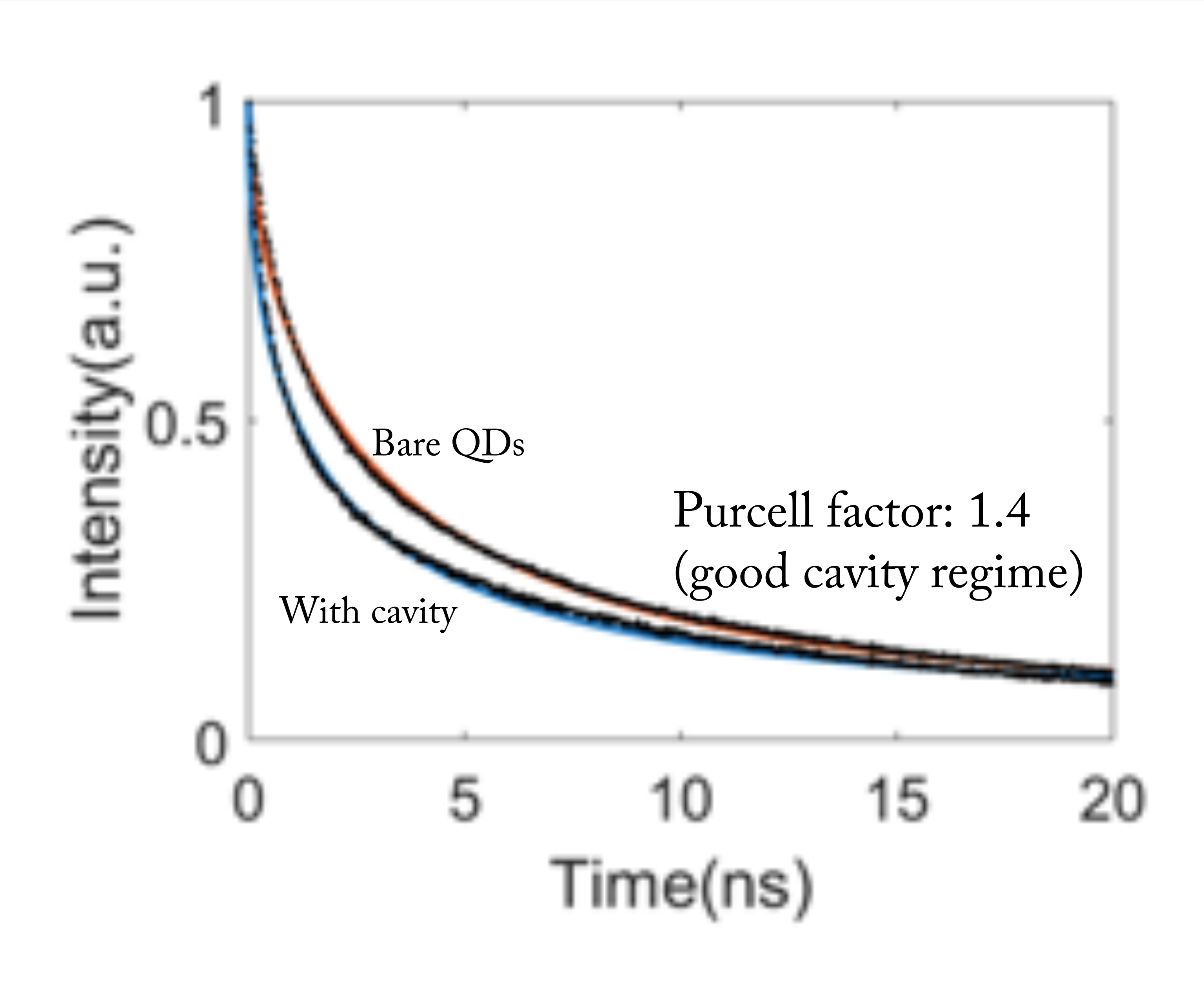
Deterministically place quantum dots in the cavity.

Saturable photoluminescence

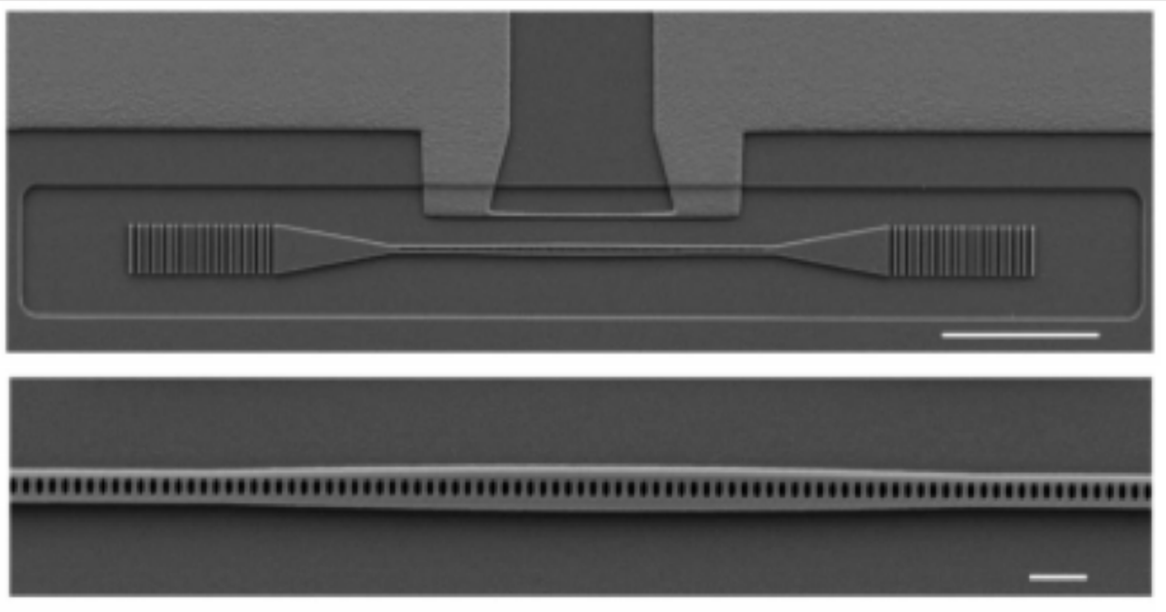


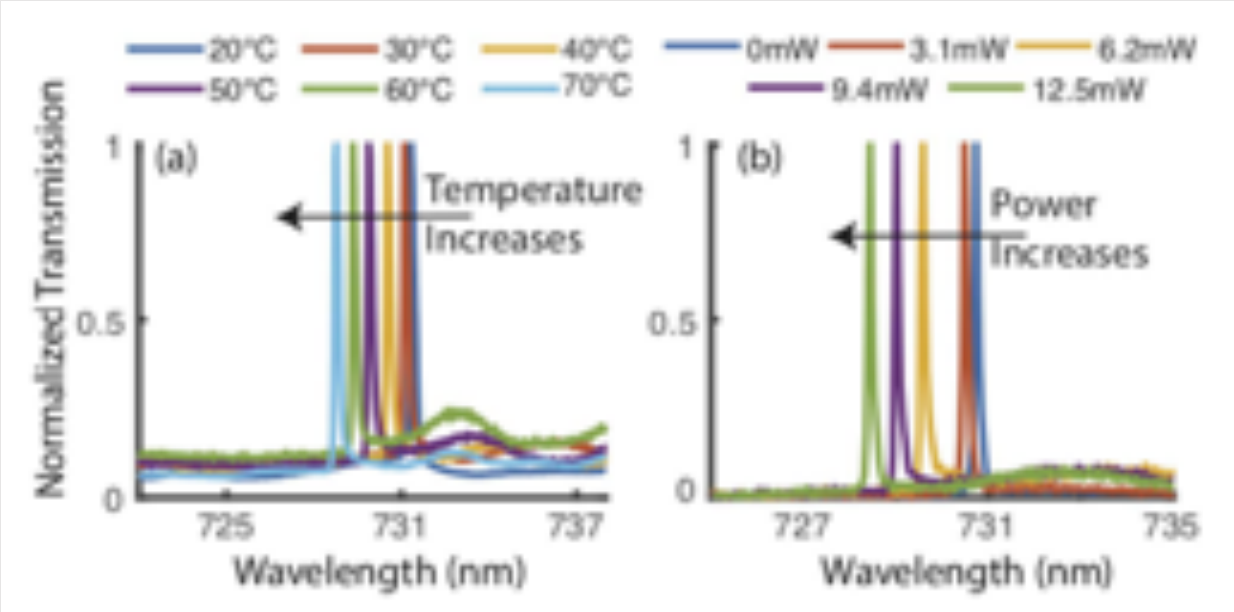
Size control of dot via chemistry and opening via lithography will enable coupling of single quantum dots to a cavity.

Purcell Enhancement



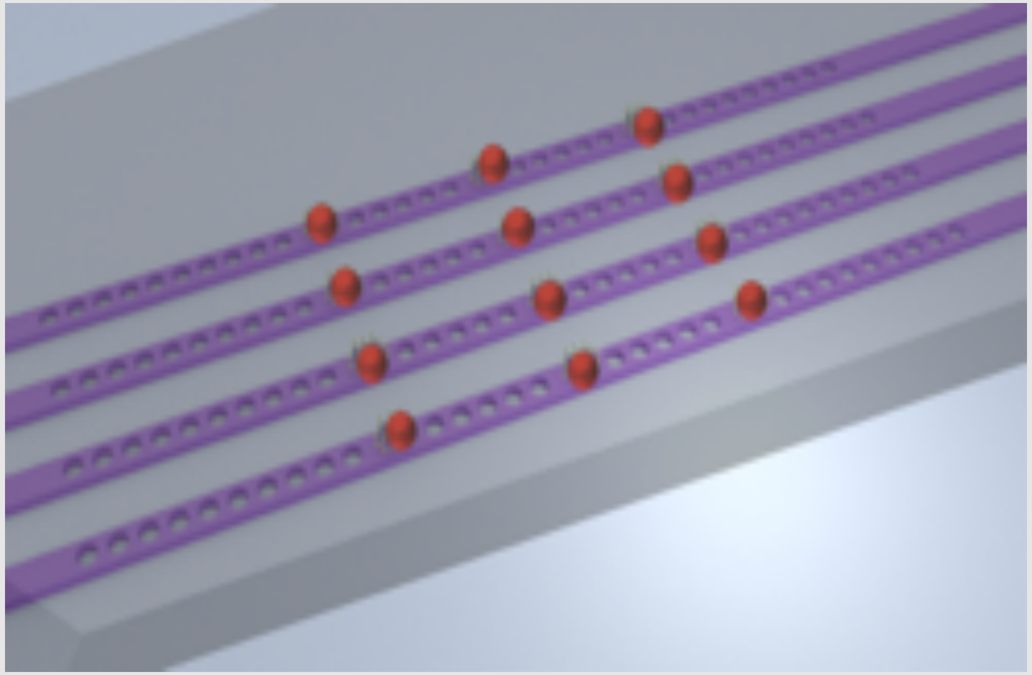
Thermo-optic tunability of SU-8 clad SiN resonator

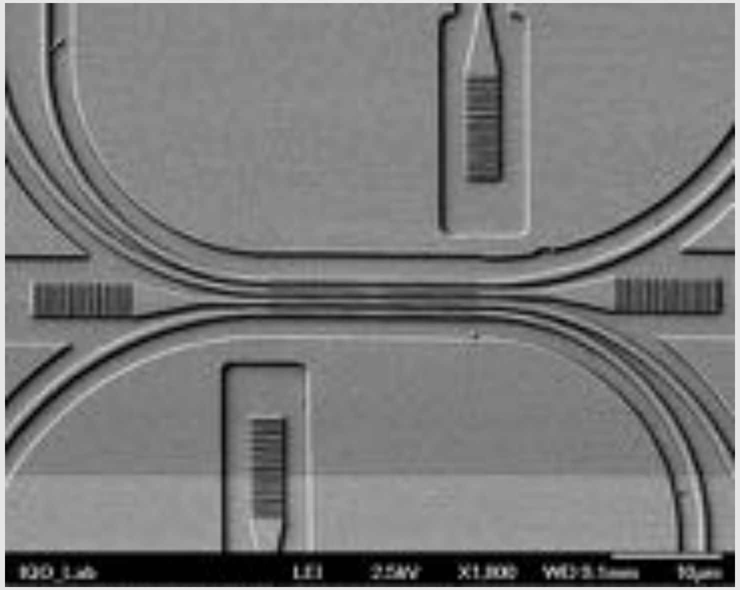




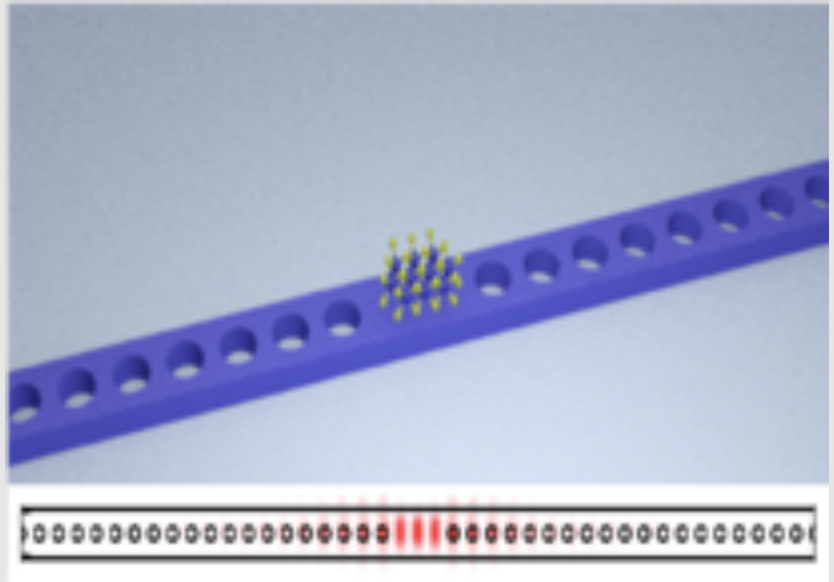
- Air-mode cavity covered with SU-8.
- SU-8 has negative thermo-optic effect: blue shift with heating.
- Large change is observed: enough to have all the cavities resonant.

Summary

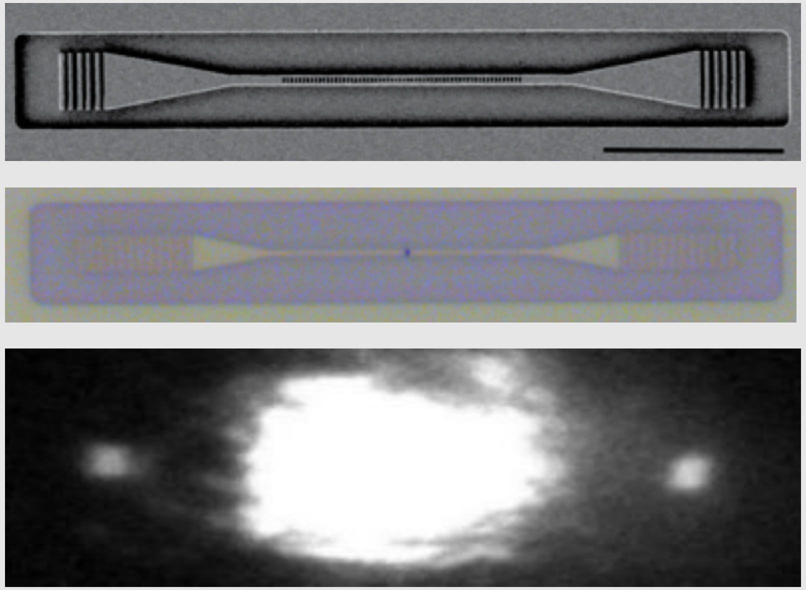




Coupled cavity array



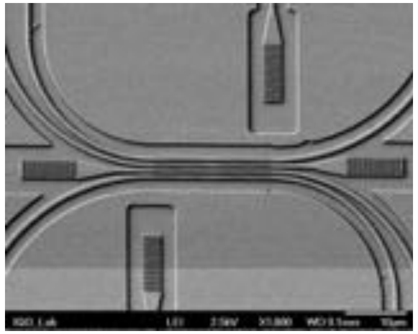
Patterned 2D material

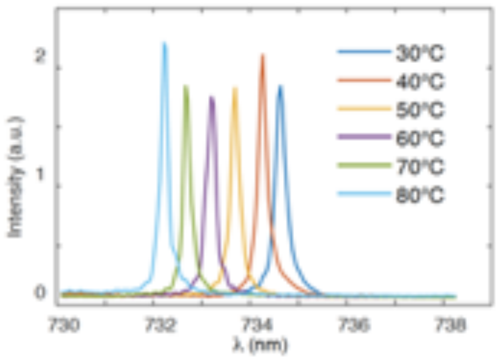


Deterministically positioned QD

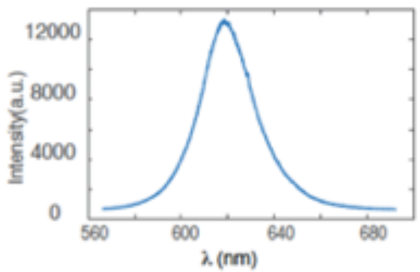
Challenges

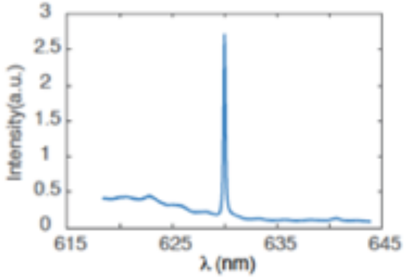
Large number of optical resonators required.
All resonators should have same resonance and high quality factor.
Integrated photonics provide an attractive solution.
Tunability of each cavity is required.



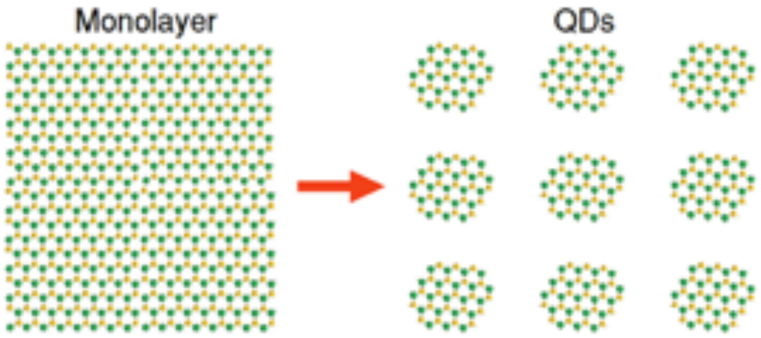


Each resonator should have a nonlinearity.
If excitonic nonlinearity, they should have same resonance.
Broad emitters do not need spectral matching.
Deterministic positioning is possible with 2D materials and solution processed QDs.

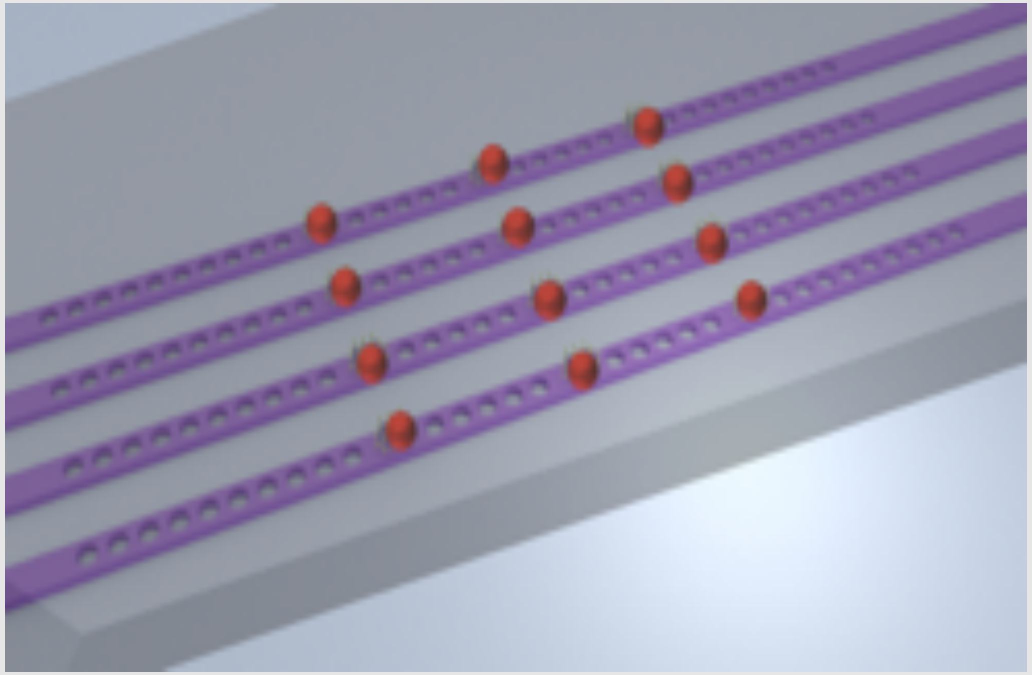


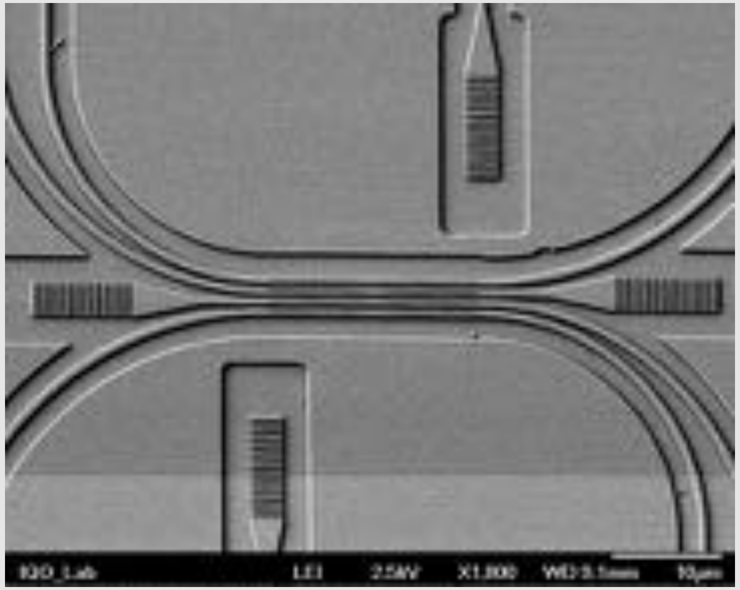


Confine the electronic and photonic wave-function to enhance the optical nonlinearity.
QD automatically confine wave-functions.
2D material excitons are more robust.
Small mode-volume enabled by photonic crystal cavity.

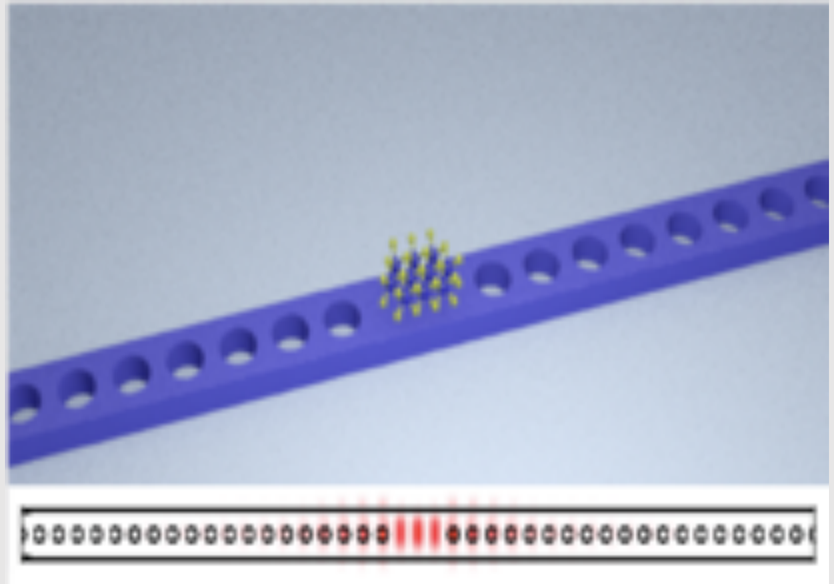


Summary

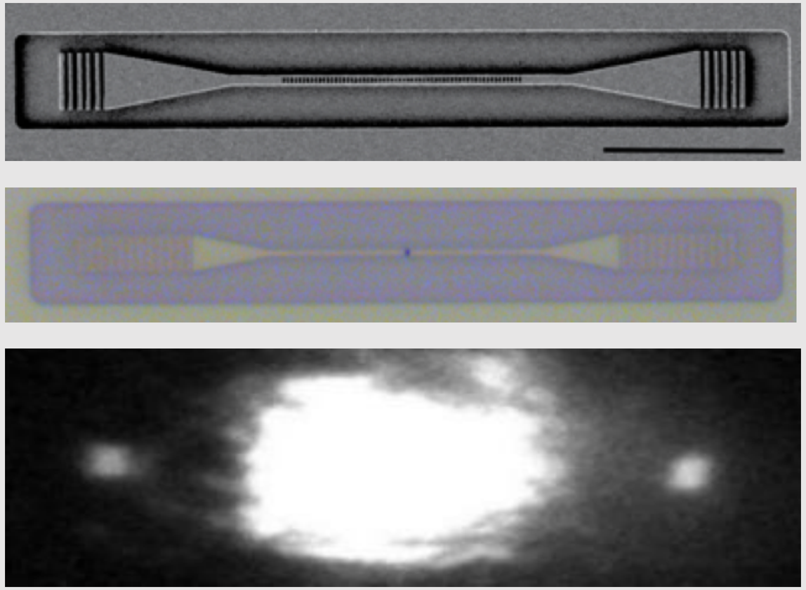




Coupled cavity array



Patterned 2D material



Deterministically positioned QD