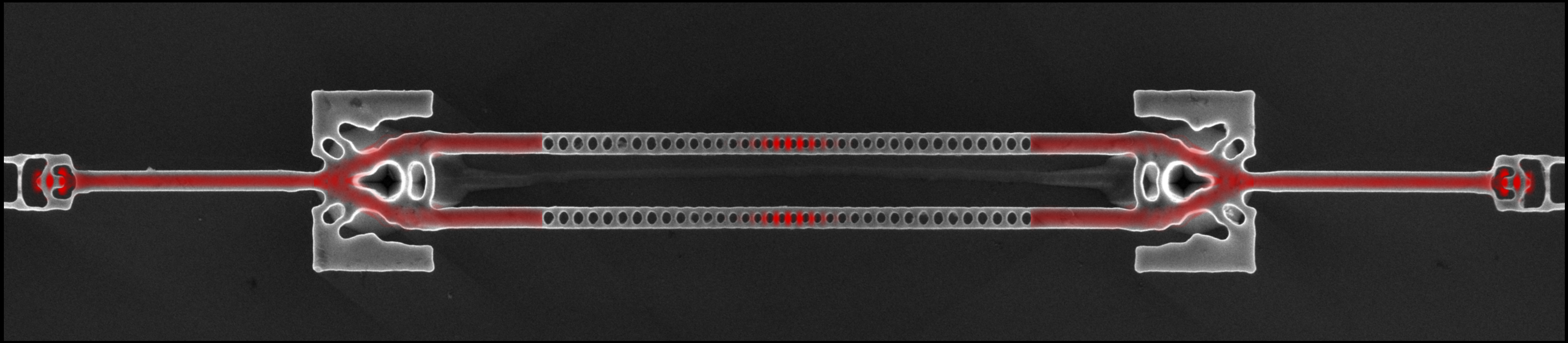
Connecting and scaling semiconductor quantum photonic systems



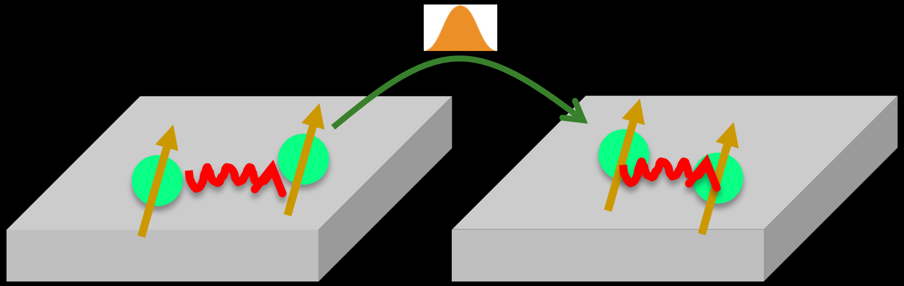
Jelena Vuckovic

Stanford University

Photonics for Quantum 2, June 2020

Quantum technologies

Quantum repeaters and networks

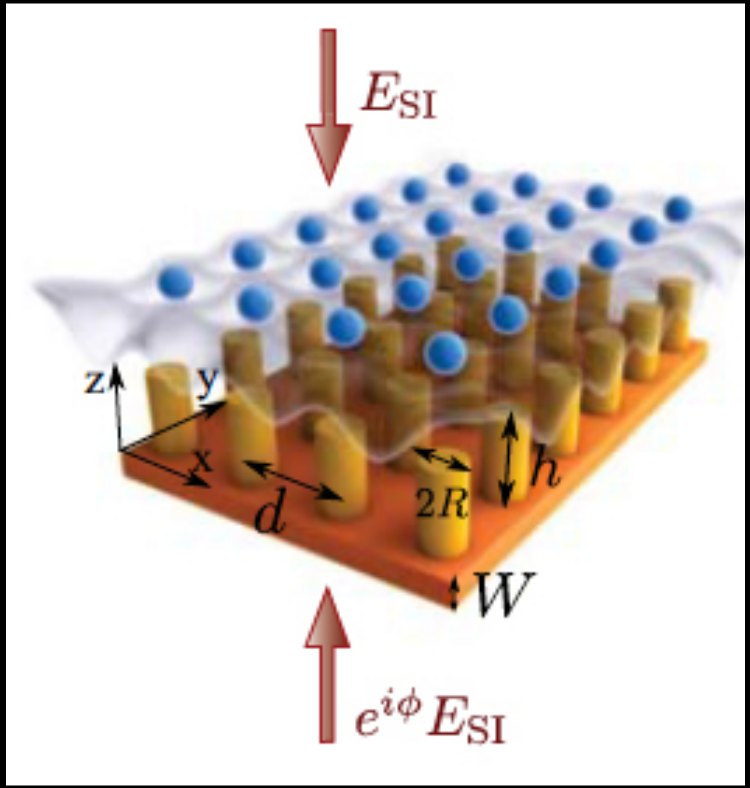


What do we need?

1) Homogeneous, long lived qubits with (optical) interfaces

2) Efficient optical interconnects

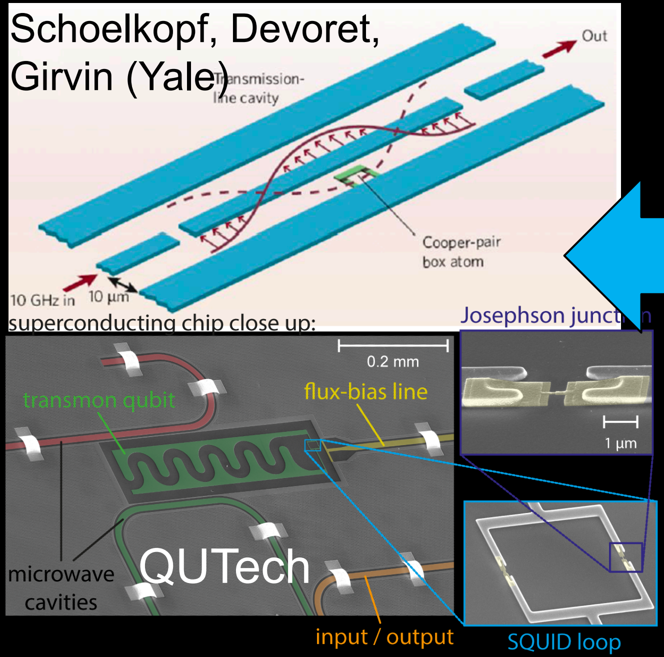
Quantum simulators & computers



Gonzales-Tudela et al., *Nature Photonics* 9, 320-325 (2015).
Douglas et al., *Nature Photonics* 9, 326-331 (2015).

Optically interfaced semiconductor spin qubits

Superconducting qubit in a microwave cavity



Schoelkopf, Devoret, Girvin (Yale)

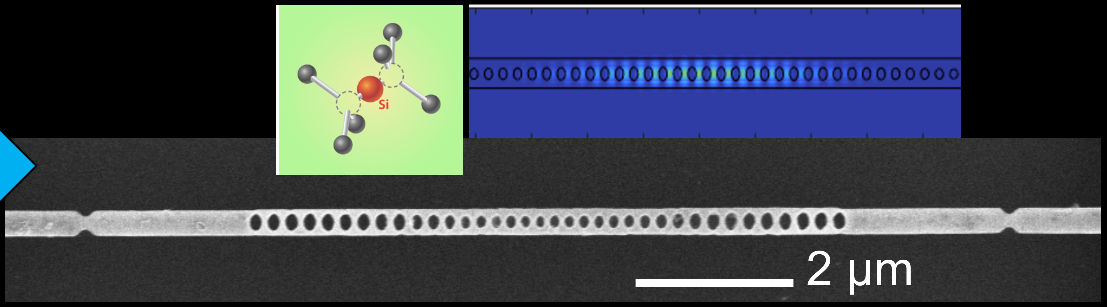
superconducting chip close up:

QUTech

- Large, traditional microfab => easy to make them all the same
- Superconductors
- Microwave frequencies
- No direct optical interface

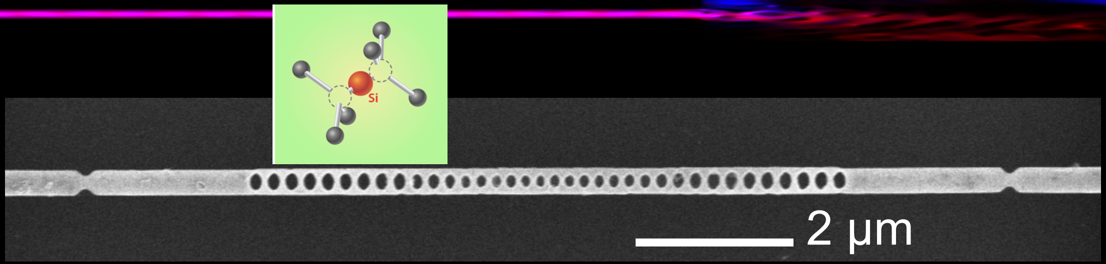
(Artificial) atom in an optical cavity

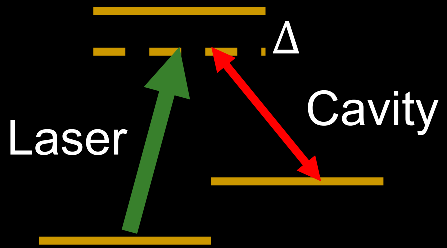
Color centers in diamond and silicon carbide

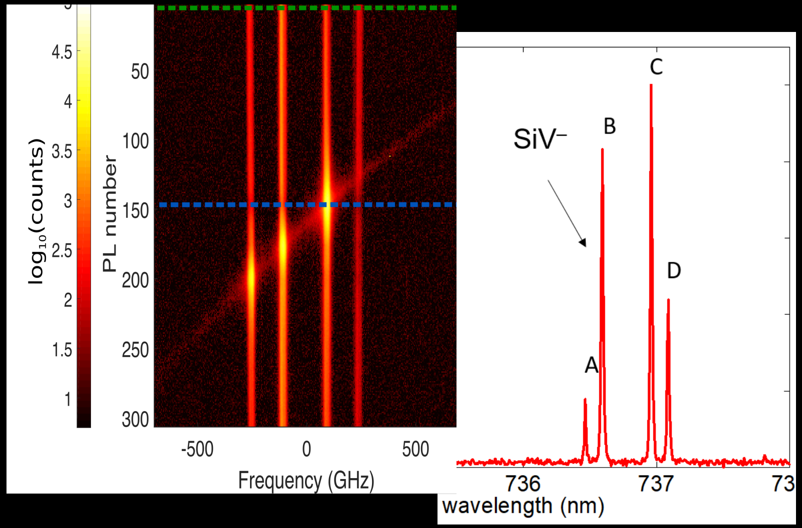


- Smaller by >1000x => nanofabrication + ion implantation/CVD (more challenging to make them all the same)
- Semiconductors
- Possibility of operation at higher temperatures (~2-10K)
- Excellent photon interface
- Number of 2-qubit gate operations per electron spin qubit coherence time > superconducting qubits

SiV color centers in diamond







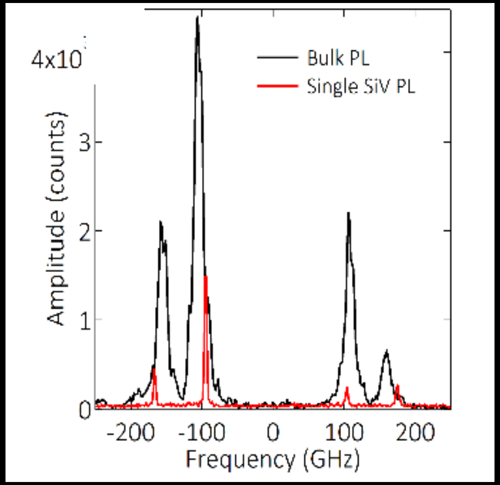
Excellent photonic interface for SiV

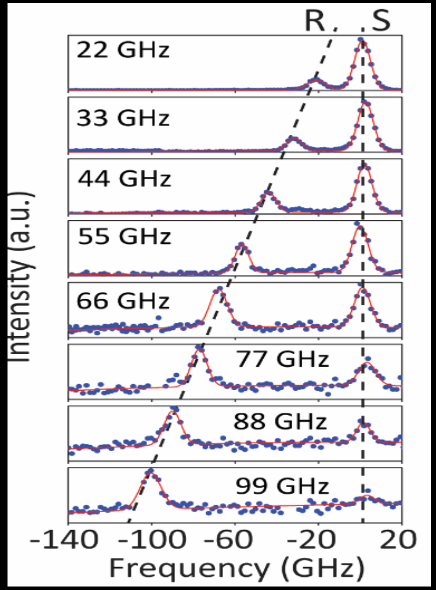
Nano Lett., *18* (2), pp 1360–1365 (2018)

2 qubit interaction (Harvard)

Science 362, 662-665 (2018)

Only 30GHz spectral broadening for SiVs on chip





Can couple SiVs on chip detuned by 100GHz by Raman scattering

Phys. Rev. Letters 121, 083601 (2018)

Collaborators: @ Stanford: Melosh, Safavi-Naeini. @ Harvard: Loncar

New inversion symmetric diamond color centers

6
C
Carbon
12.011

14
Si
Silicon
28.085

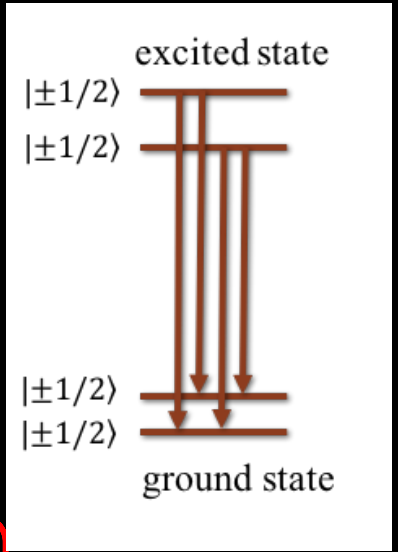
32
Ge
Germanium
72.630

50
Sn
Tin
118.71

82
Pb
Lead
207.2

114
Fl
Flerovium
(289)

	Ground state splitting	Debye–Waller factor	Quantum efficiency
SiV$^-$	50 GHz [1]	78% [6]	30% [8], 14% *[5]
GeV$^-$	152 GHz [2]	61% [7]	90% *[5]
SnV$^-$	850 GHz [3]	41% [3]	80% [3], 91% *[5]
PbV$^-$	2 THz [4] 4.4 THz *[5]	20% *[5]	unknown

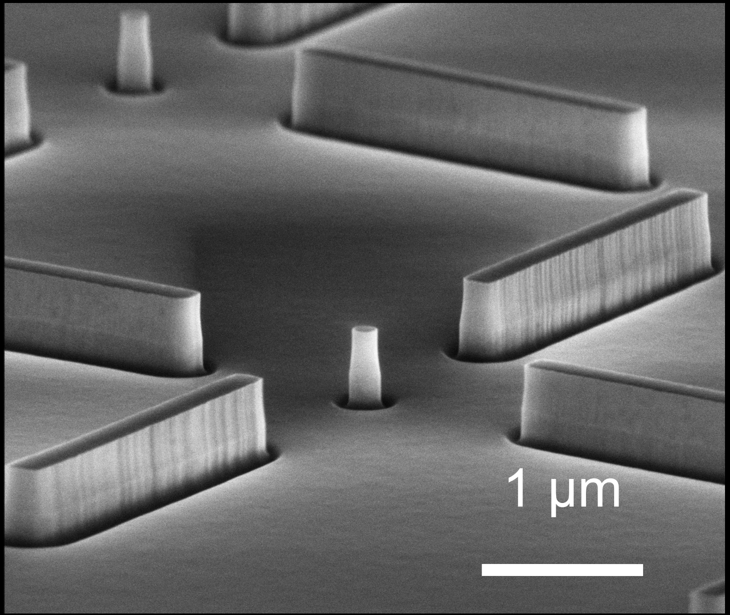


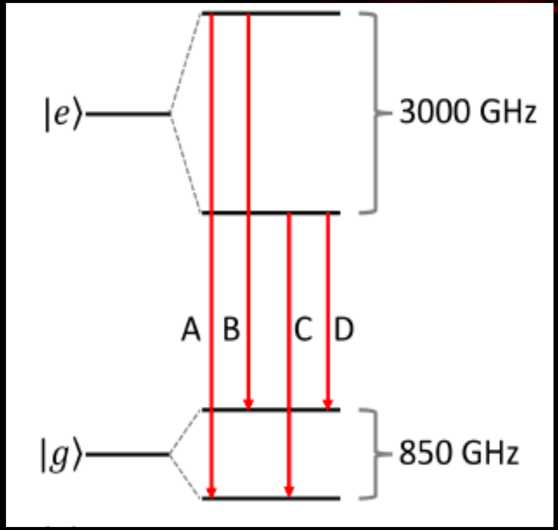
* Based on *ab initio* calculations

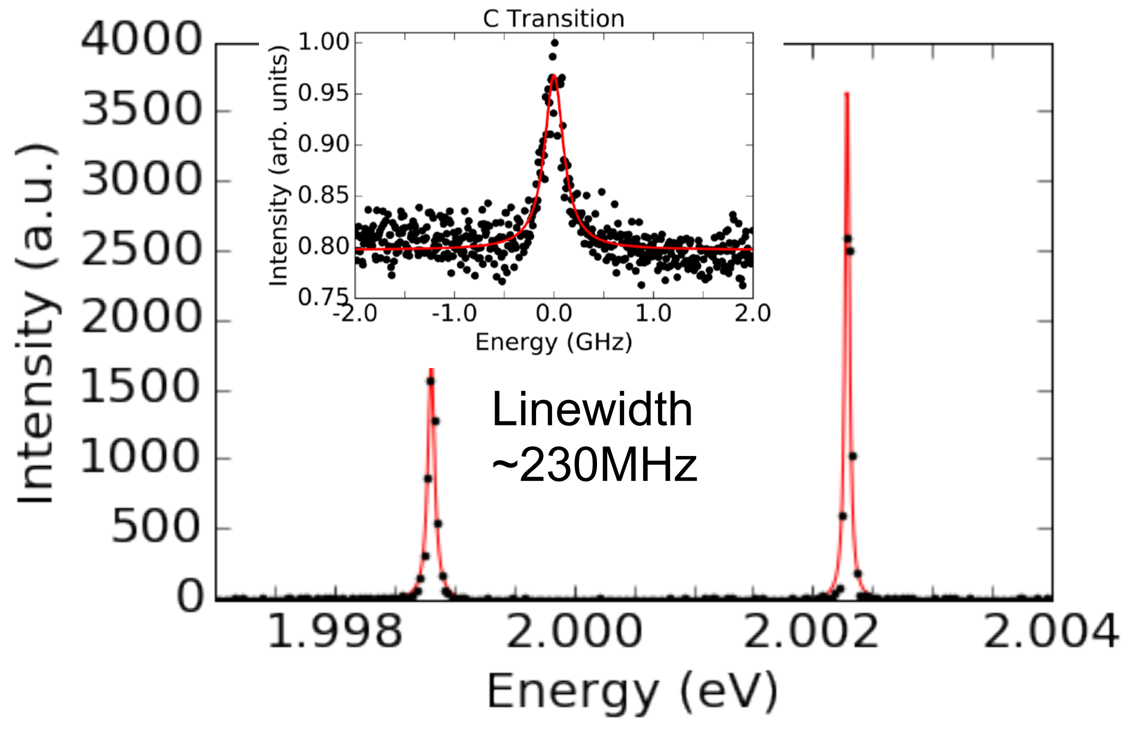
[1] Hepp et al., *Phys. Rev. Lett.* 112, 036405 (2014)
[2] Bhaskar et al., Phys. Rev. Lett. 118, 223603 (2017)
[3] Iwasaki et al., Phys. Rev. Lett. 119, 253601 (2017)
[4] Trusheim et al., arXiv:1805.12202
[5] Thiering and Gali, Phys. Rev. X 8, 021063 (2018)
[6] Neu et al., *New J. Phys.* 13, 025012 (2011)
[7] Palyanov et al., *Sci. Rep.* 5, 14789 (2015)
[8] Becker and Becher, Phys. Status Solidi A 214, 1700586 (2017)

SnV color centers: elevated temperatures (~2K) + much higher efficiency than SiV

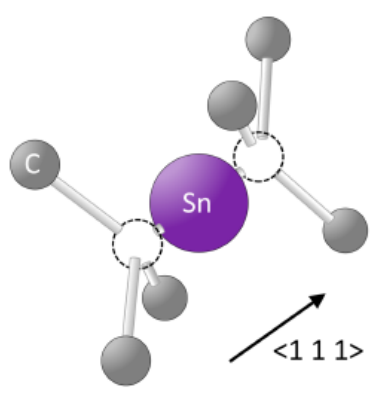
Characterization of single SnV's

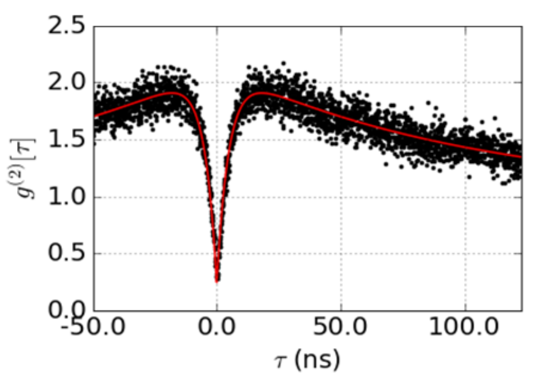


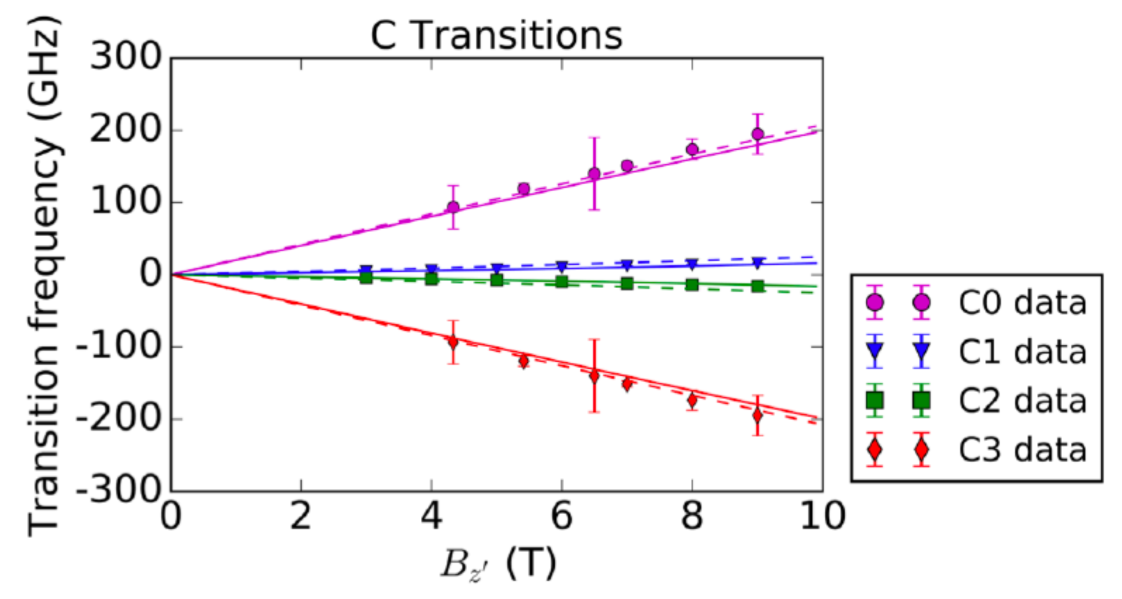




Linewidth ~230MHz



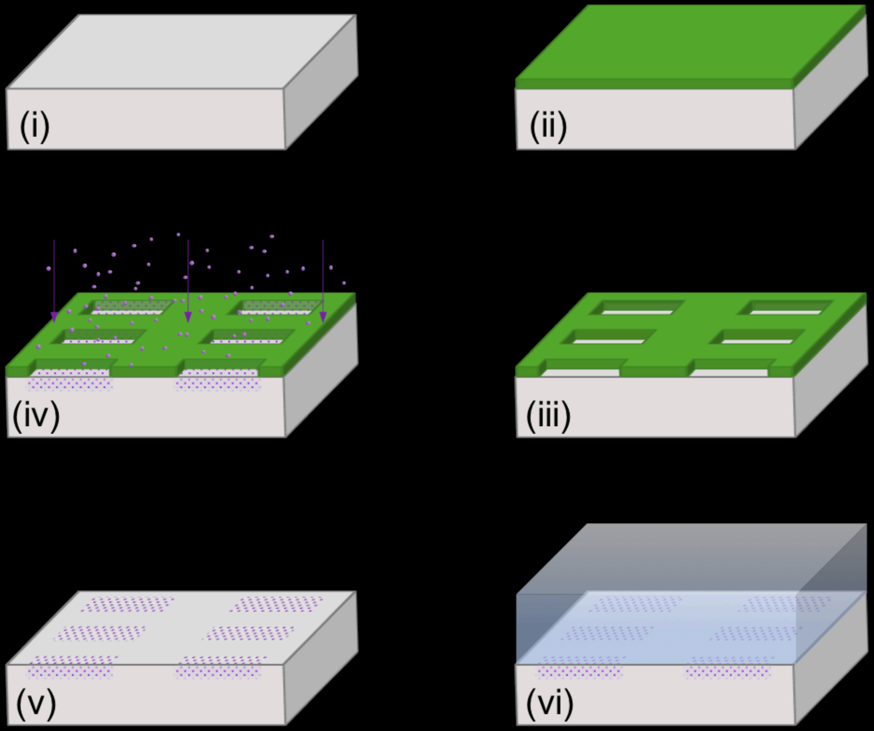


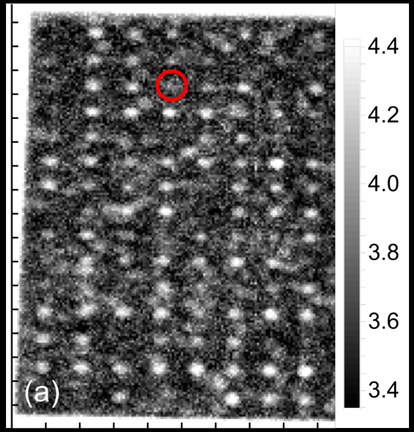


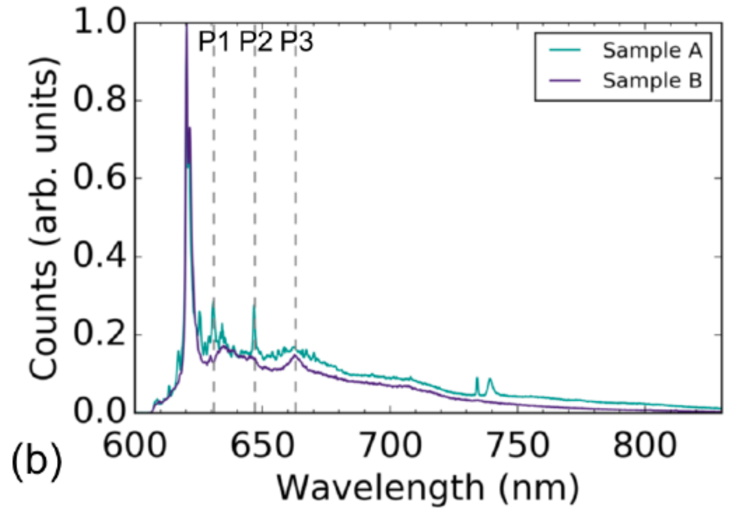
A. Rugar, et al., *Phys. Rev. B* 99, 205417 (2019)

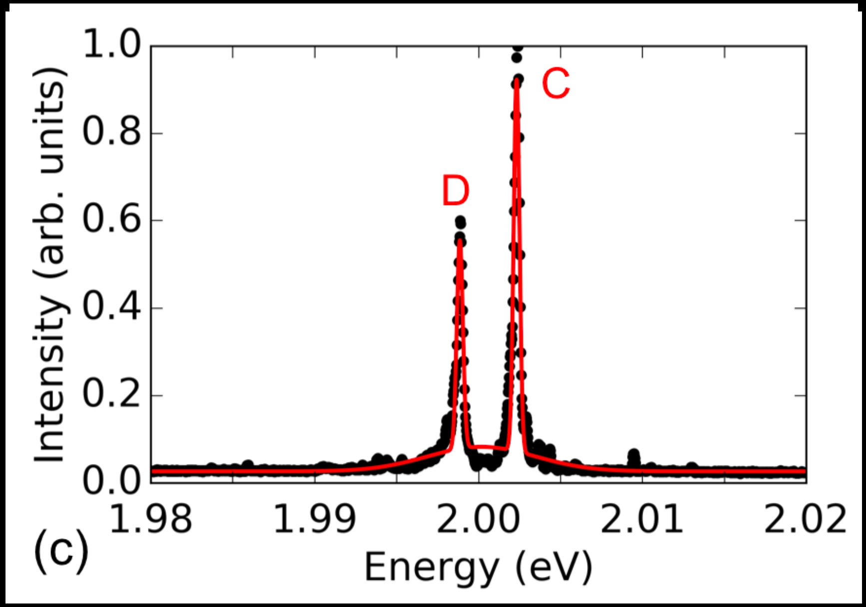
Similar work: Trusheim et al., *PRL* **124**, 023602 (2020

SnV in Diamond via Shallow Ion Implantation and Subsequent Diamond Overgrowth





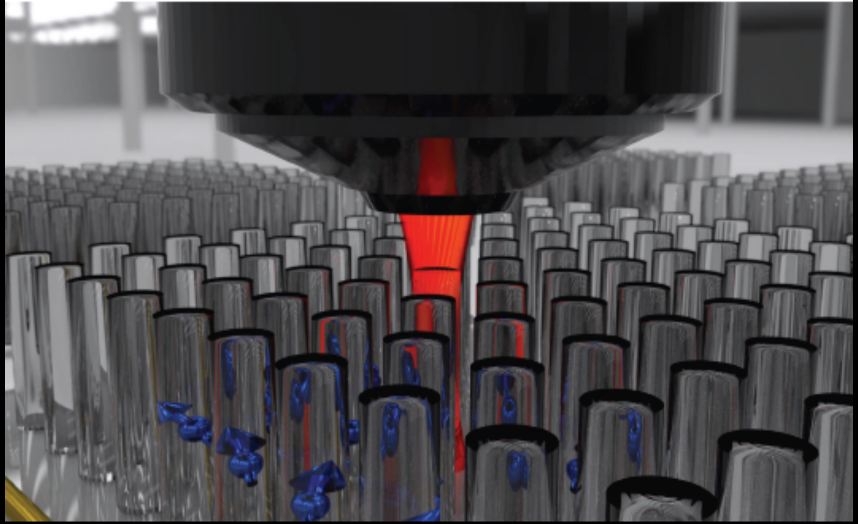




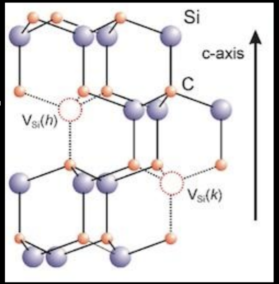
Sample A: 370keV implantation
Sample B: 1keV implantation

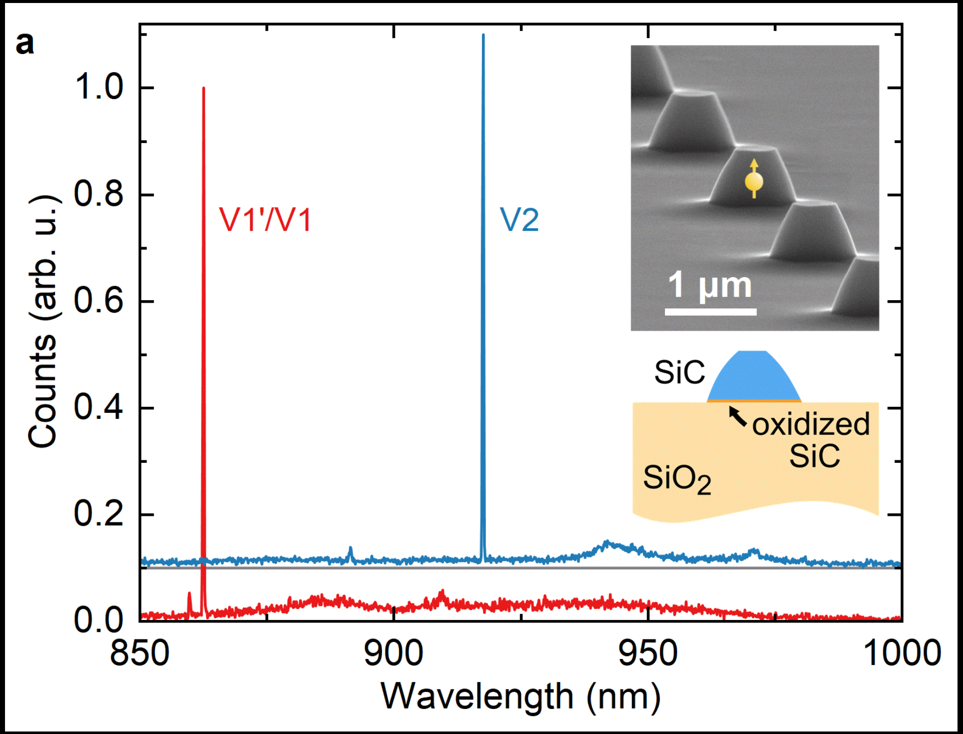
A. Rugar et al, *Nano Letters* **20**, pp. 1614-1619 (2020)

V_{Si} in 4H-SiC

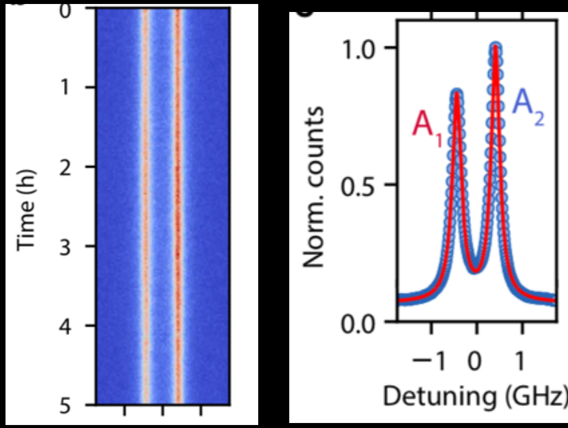


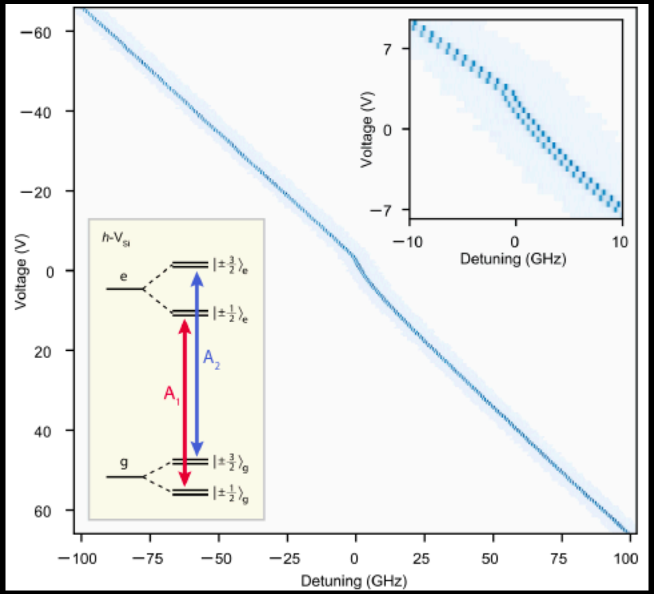
- collaboration with J. Wrachtrup (Stuttgart) & S. Economou (VTech)
- e-spin coherence time ~20ms
- Indistinguishable photons generated
- 65 MHz transitions (lifetime limit 35 MHz)





- Very stable transitions
- DC Stark tuning to compensate full inhomogenous broadening

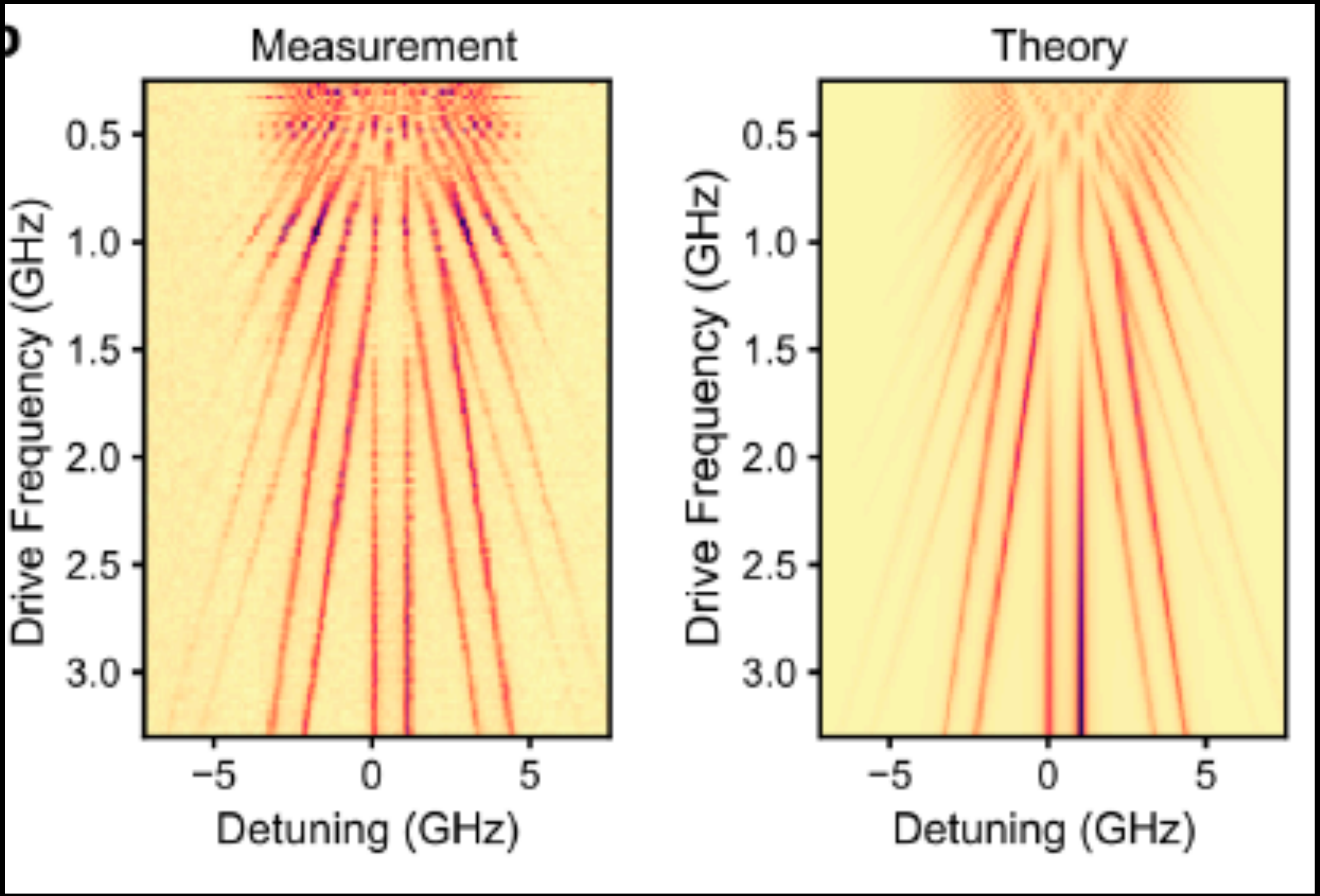




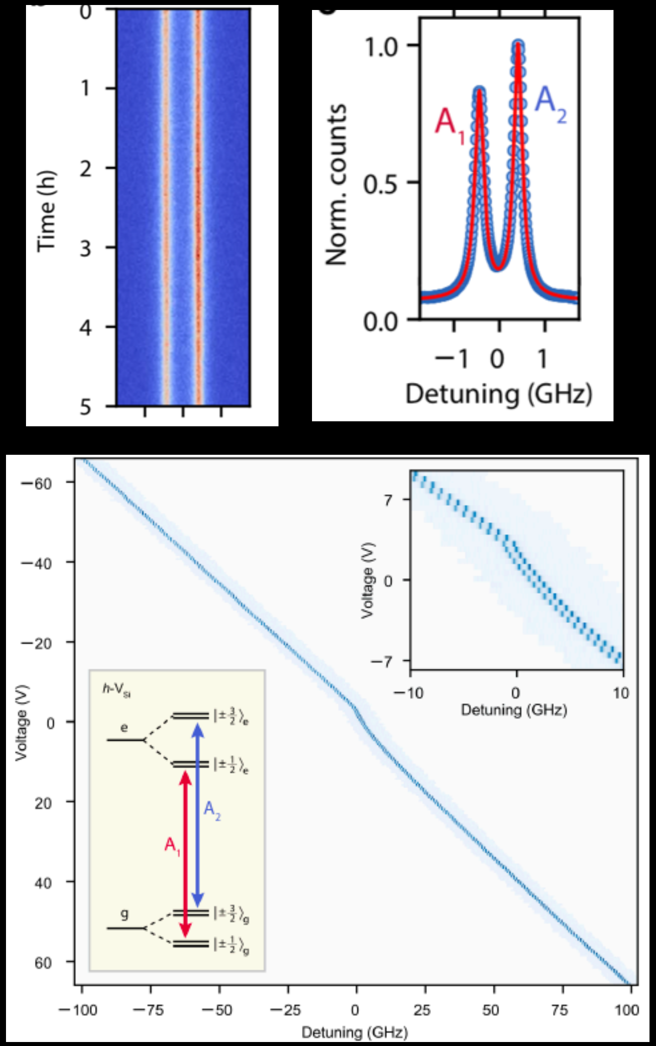
[arXiv:2003.12591]

Nano Letters **17**, 3, 1782-1786 (2017)
Physical Review Applied, **9**, 034022 (2018)
Nature Photonics vol.**14**, pp. 330–334 (2020)

Floquet eigenstates

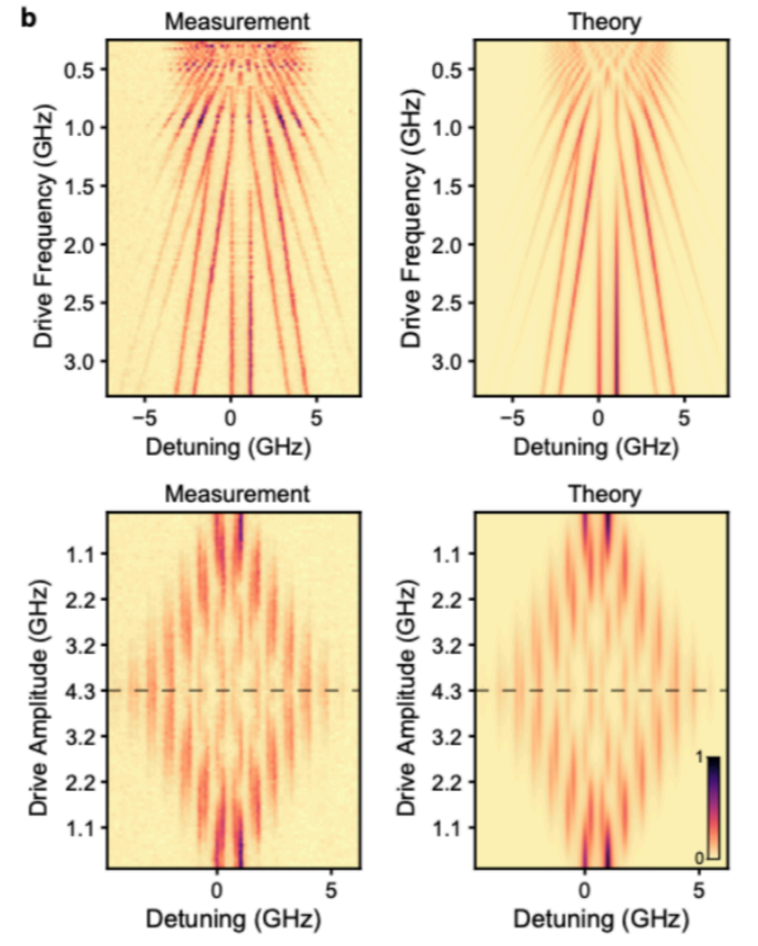


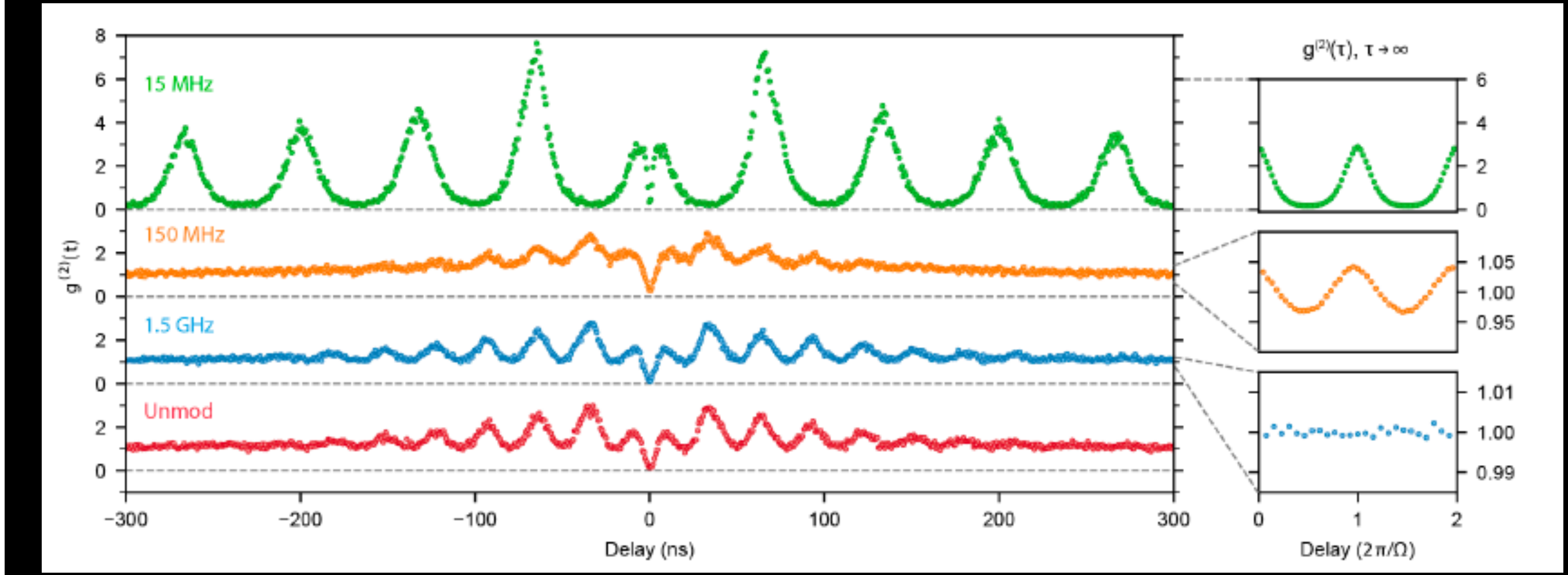
D. Lukin, A. White, M. Guidry, R. Trivedi et al *[arXiv:2003.12591]*



VSi in SiC

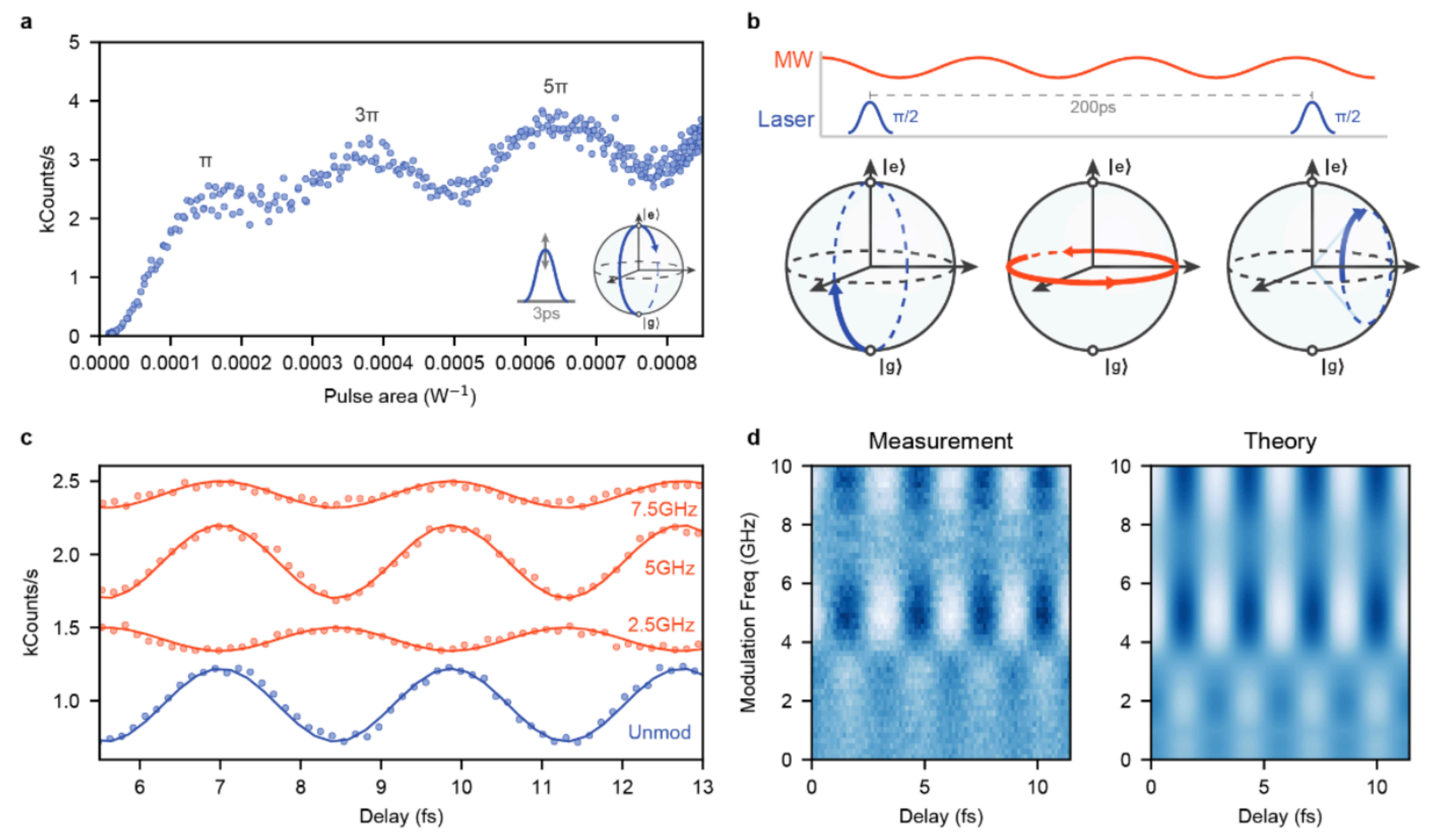
Photon statistics



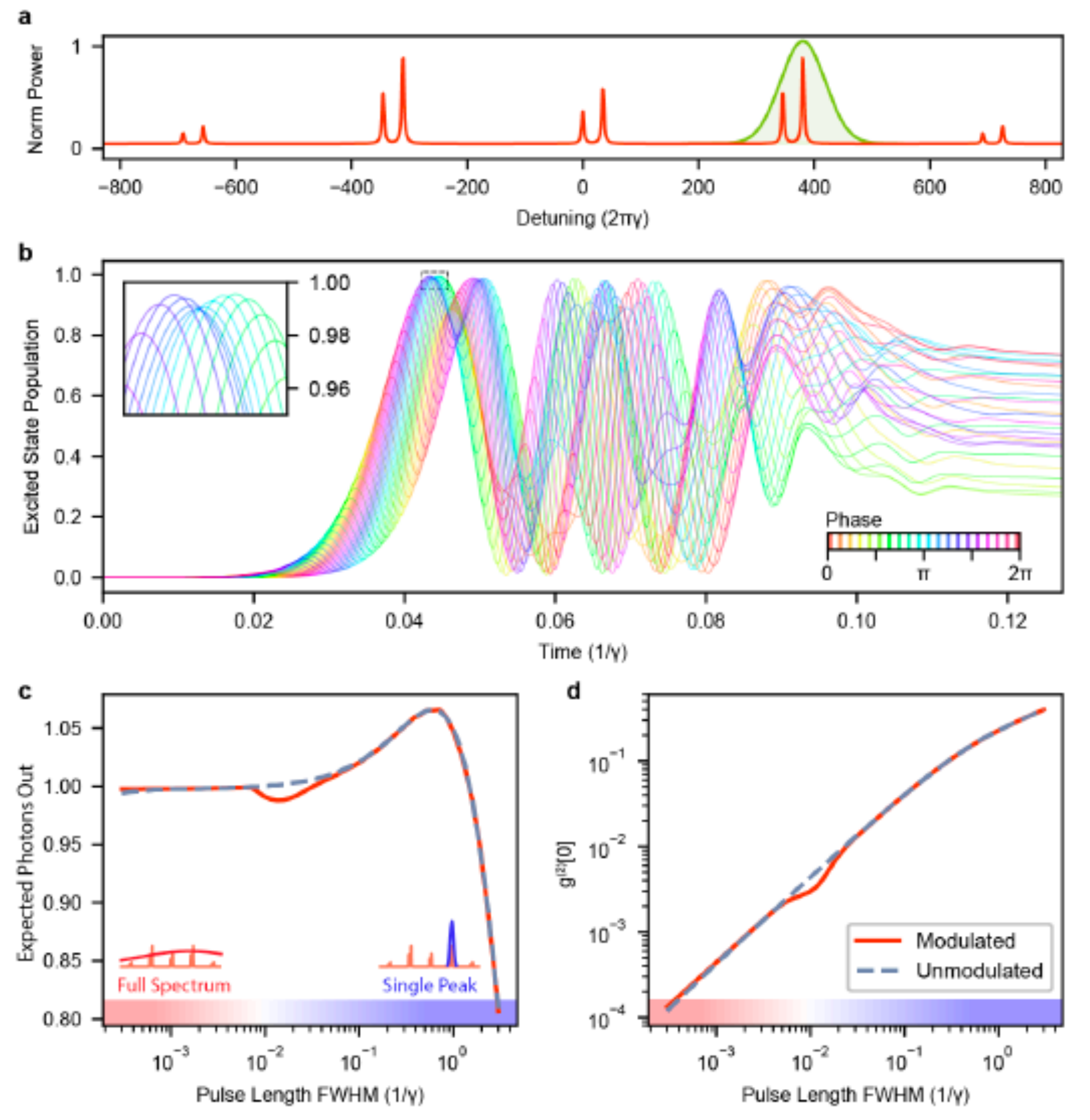


D. Lukin, A. White, M. Guidry, R. Trivedi et al *[arXiv:2003.12591]*

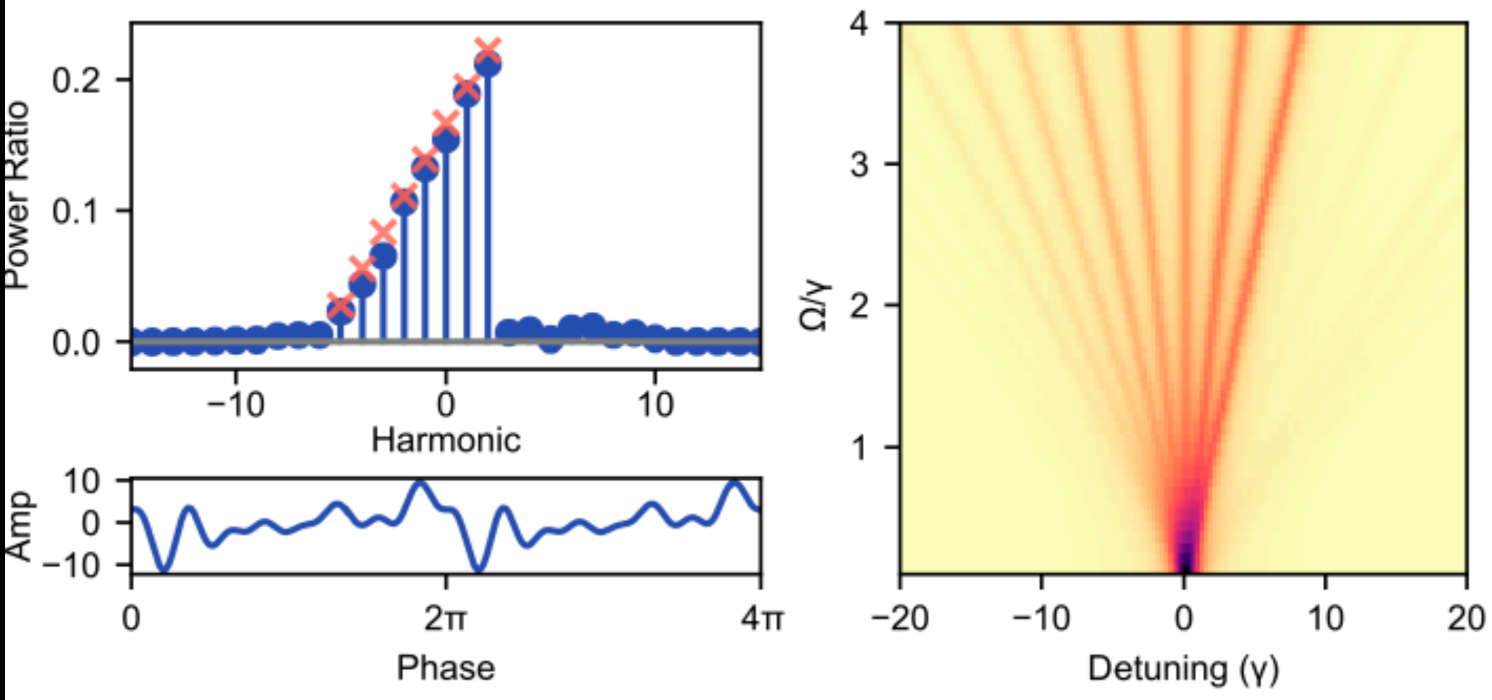
Pulsed optical coherent control of a modulated single emitter



Shaped single photon emission by pulsed modulation



Spectrally reconfigurable quantum emitters enabled by optimized fast modulation



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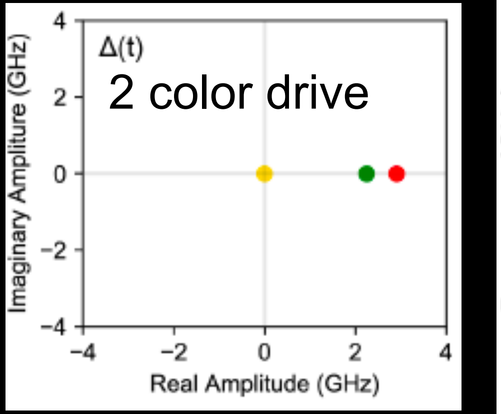
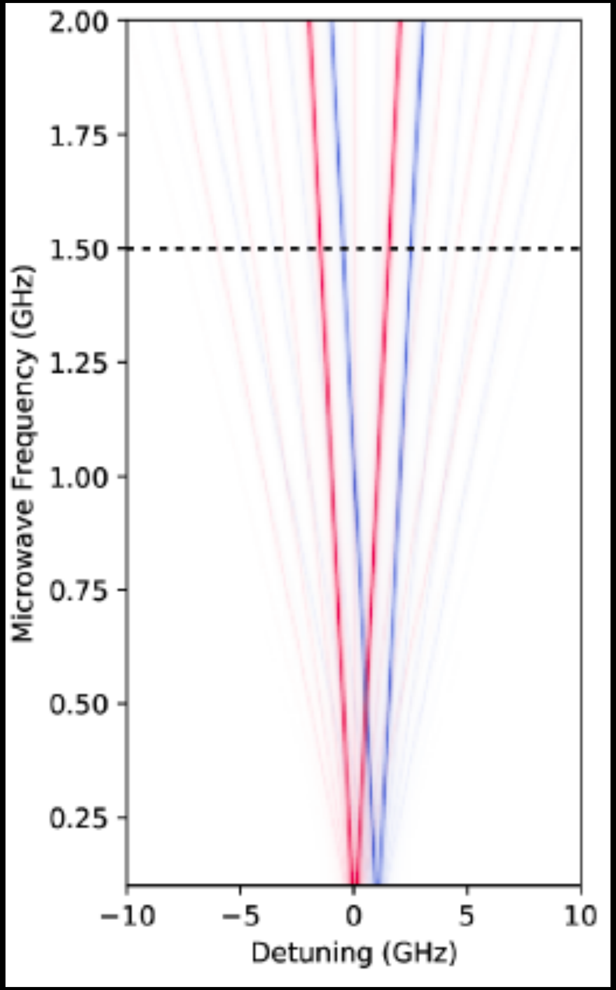
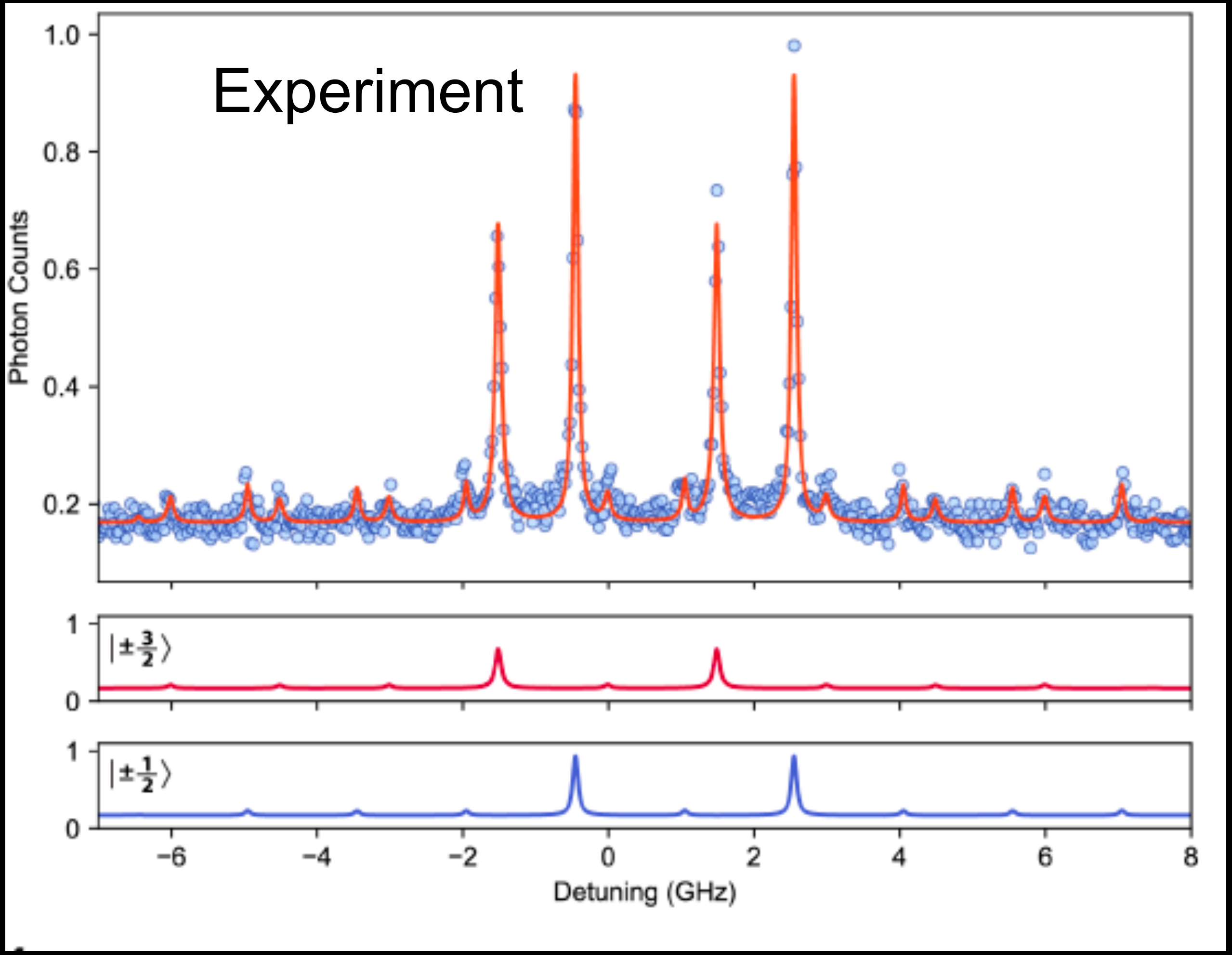


theory





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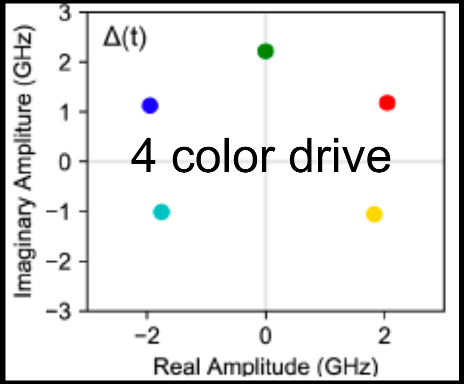
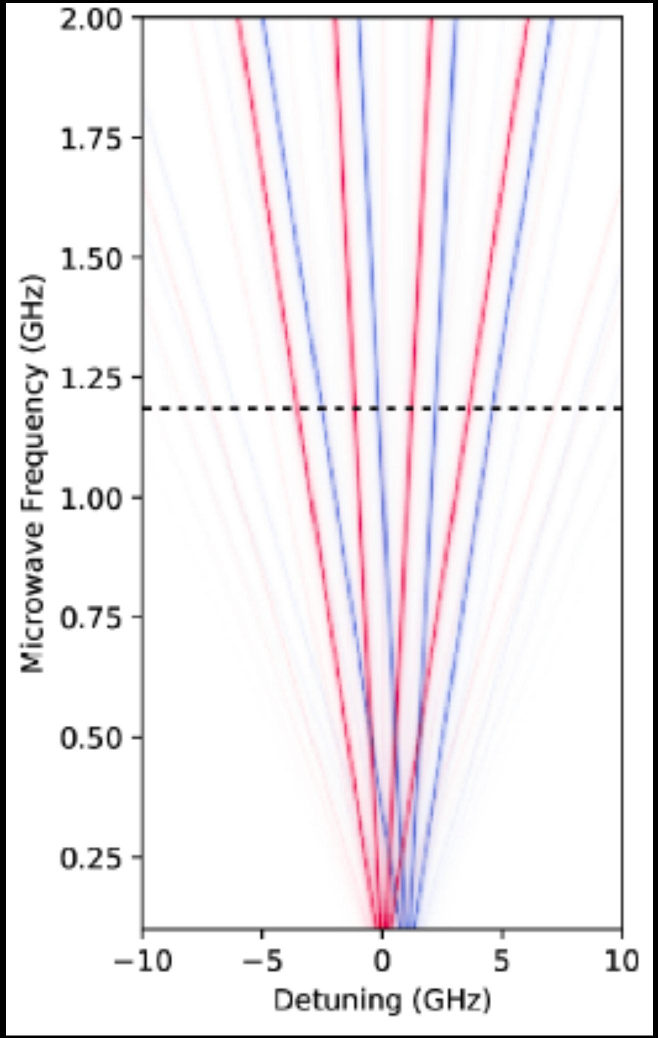
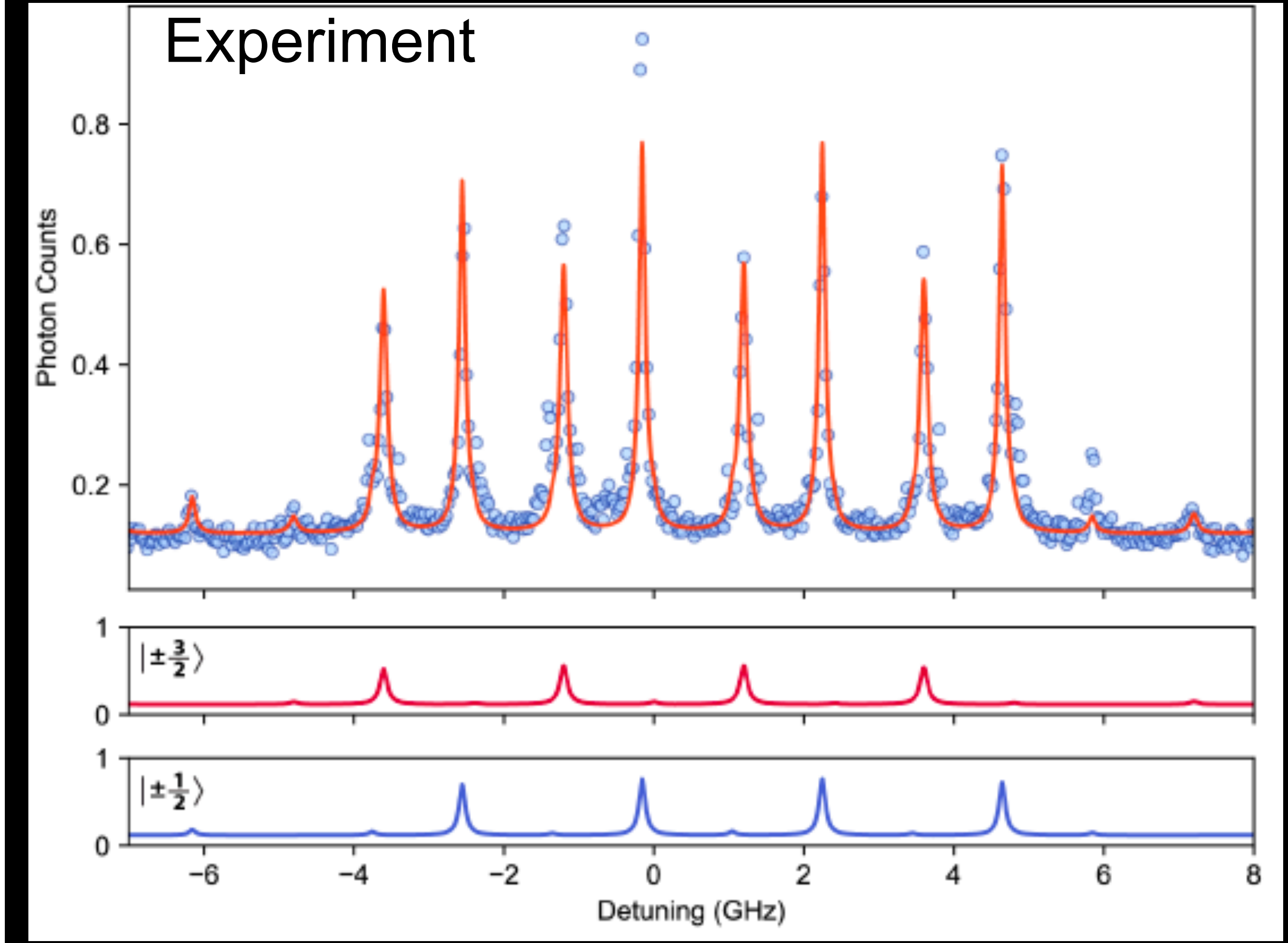


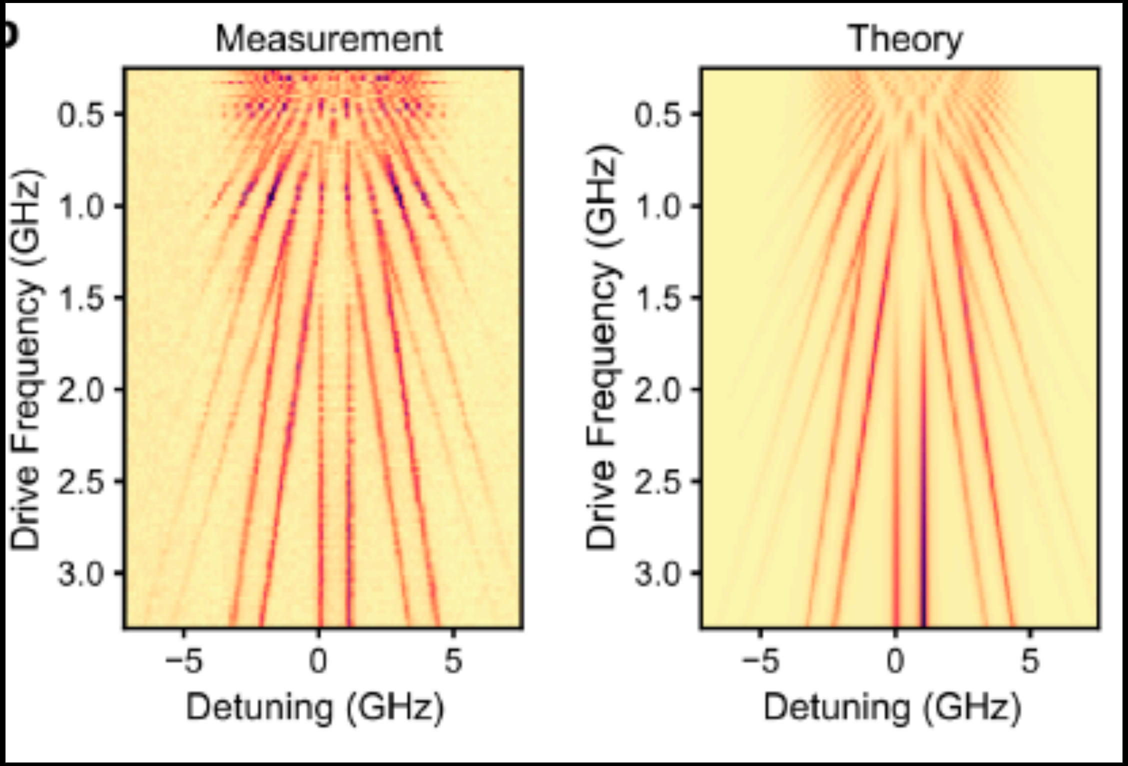
theory





D. Lukin, A. White, M. Guidry, R. Trivedi et al *[arXiv:2003.12591]*

Floquet engineering for removing emitter inhomogeneity



Spectral reconfiguring of VSi in SiC
D. Lukin, A. White, M. Guidry, R. Trivedi et al
[arXiv:2003.12591]

Controllably pulsing a Hamiltonian with inhomogeneously broadened spins.

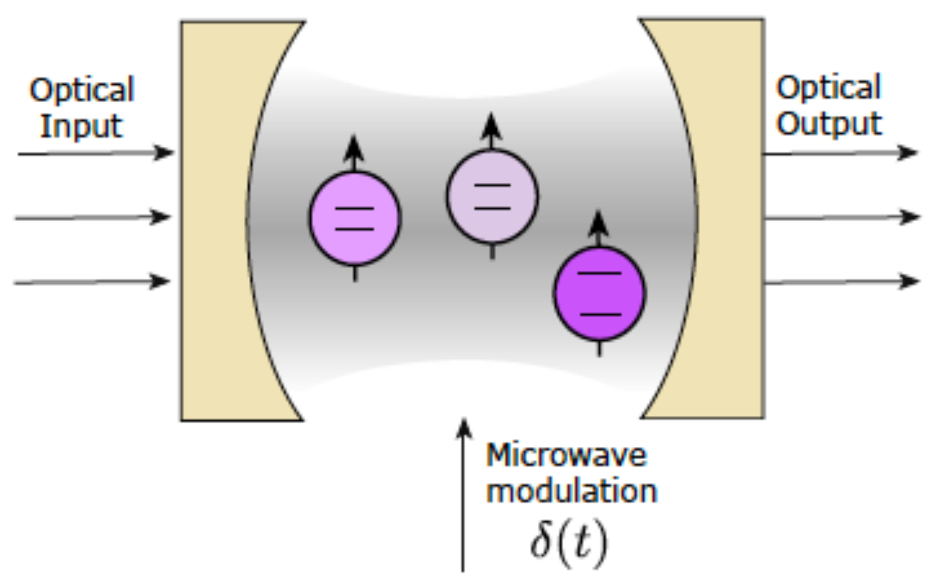
$$H = \sum_i \frac{\omega_i}{2}\sigma_z^i + \sum_i J\left[\alpha(t)\sigma_+^i\sigma_-^{i+1} + \text{h.c.}\right]$$

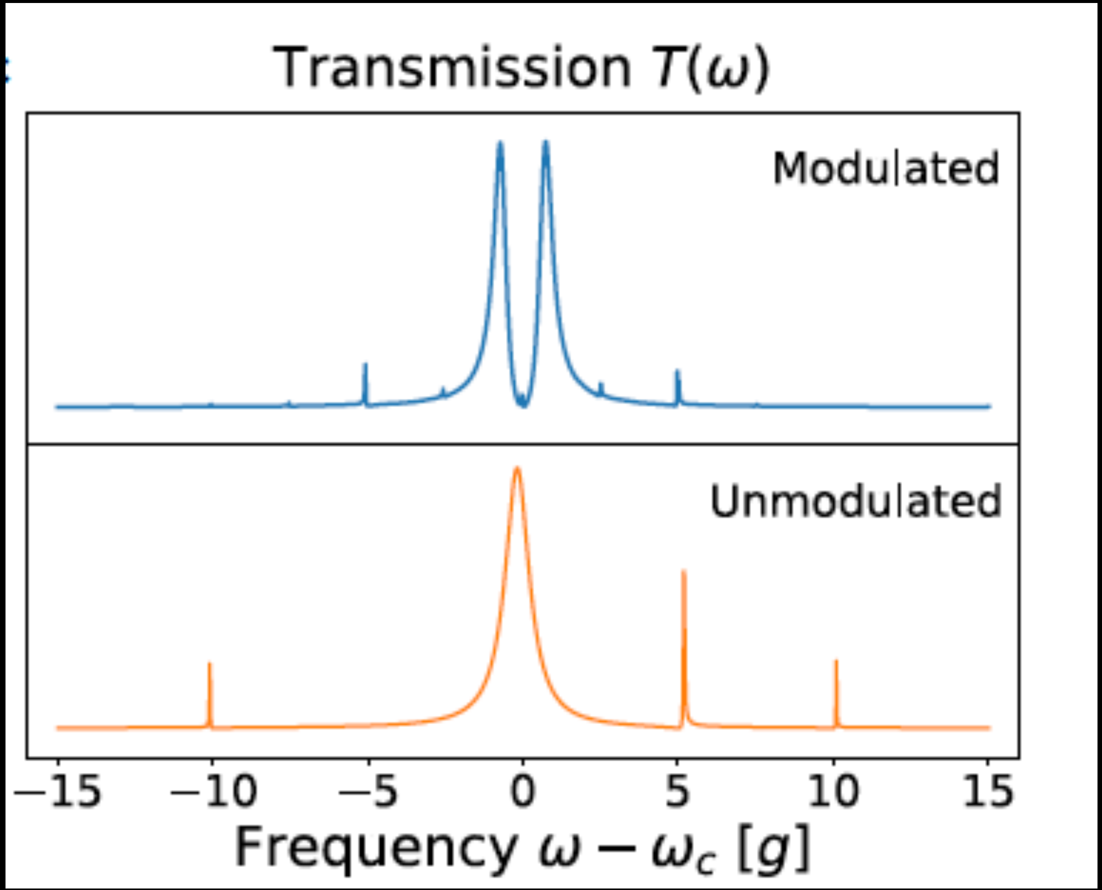
Time-independent Hamiltonian with identical spin resonances.

$$H_0 = \sum_i \frac{\omega_0}{2}\sigma_z^i + \sum_i J\left[\sigma_+^i\sigma_-^{i+1} + \text{h.c.}\right]$$

R. Trivedi, S. Sun, in collaboration with
I. Cirac, D. Malz (MPQ)

Inhomogeneous broadening compensation by dynamic modulation

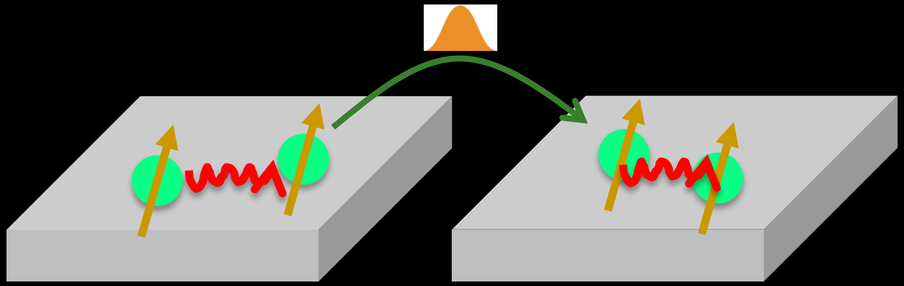




Inhomogenously broadened emitters under optimized pulsed modulation exhibit signature of collective coupling to cavity mode.

Quantum technologies

Quantum repeaters and networks



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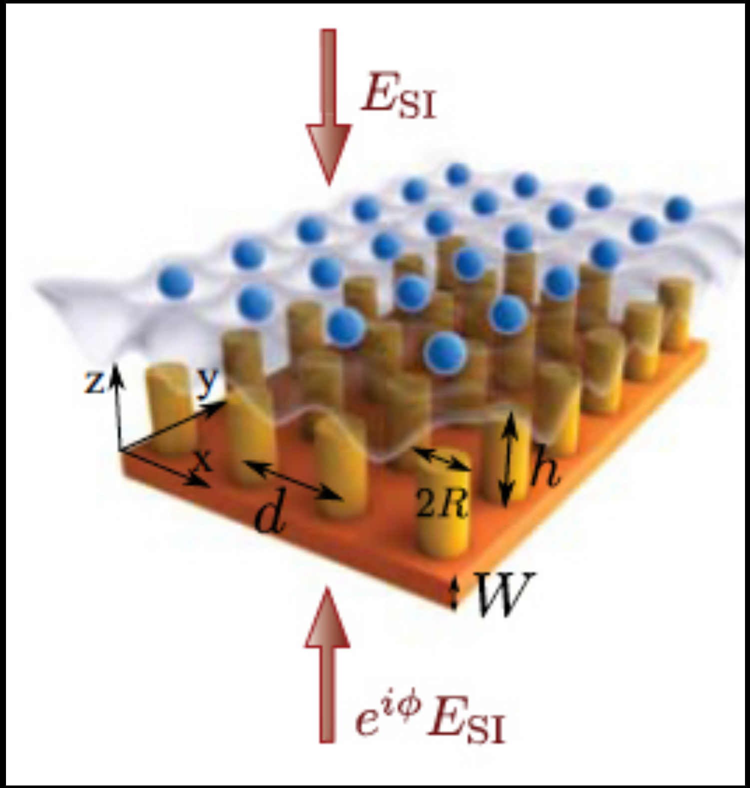
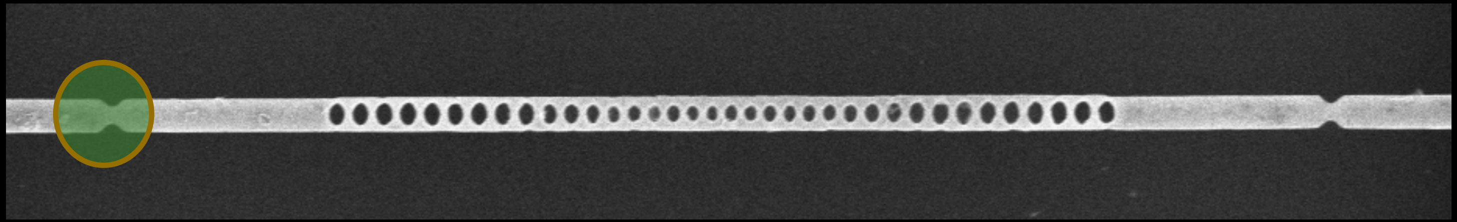
Quantum simulators & computers



Gonzales-Tudela et al., *Nature Photonics* 9, 320-325 (2015).
Douglas et al., *Nature Photonics* 9, 326-331 (2015).

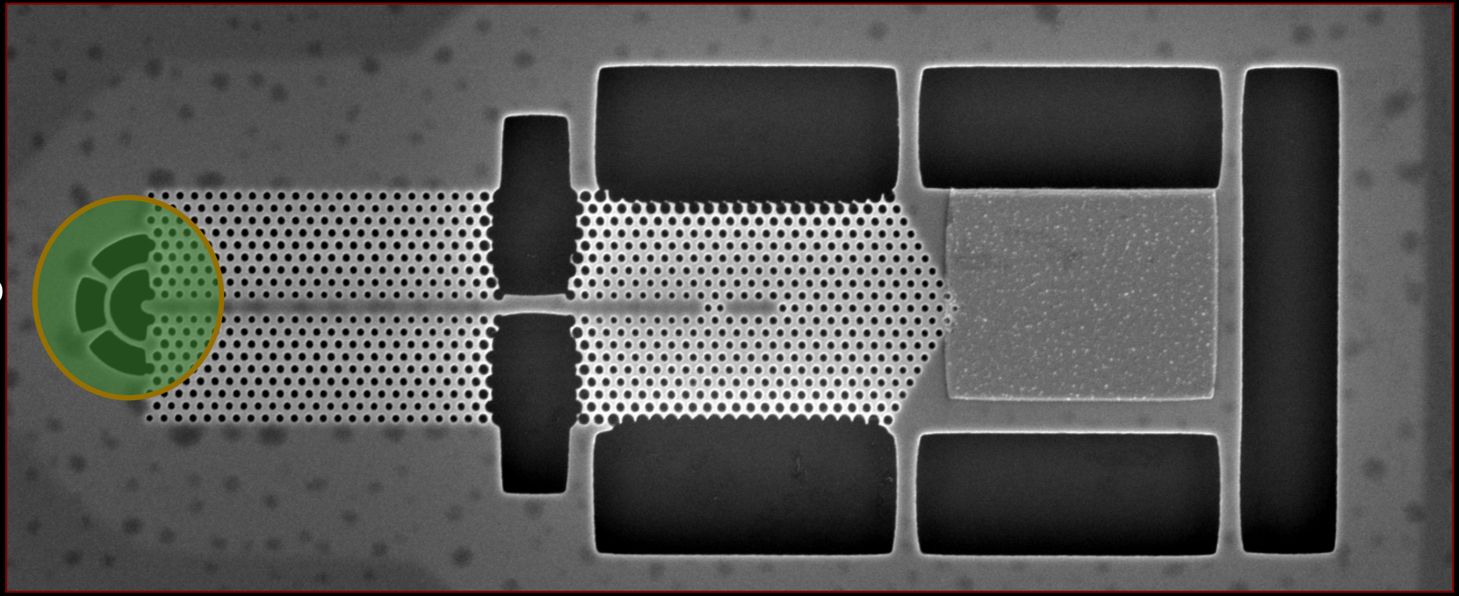
Efficient quantum optical interconnects necessary for system-level integration

1%



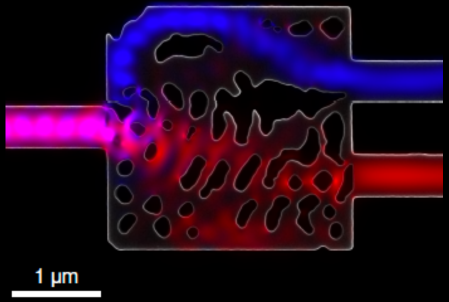
Zhang*, Sun* et al., *Nano Lett.* 18, 1360–1365 (2018)

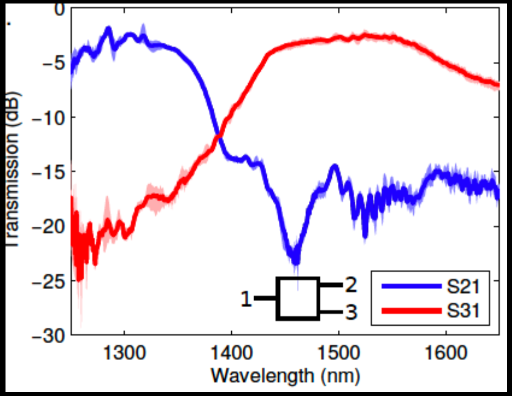
~5%



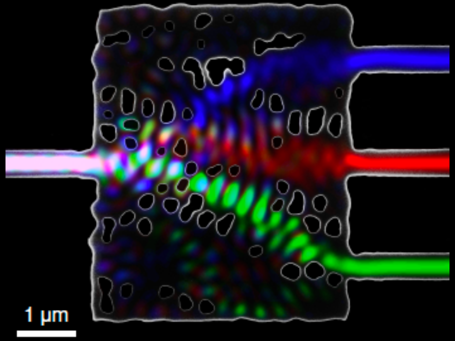
Faraon et al., *Optics Express* 16, 12154 (2008)

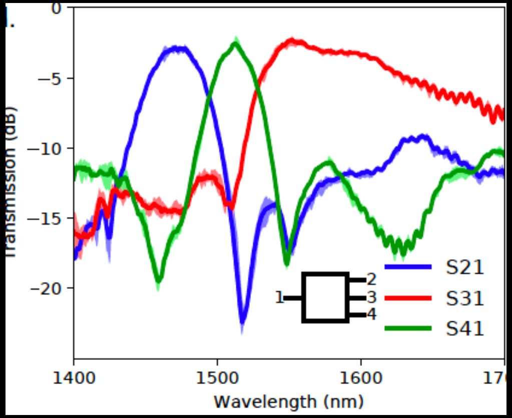
Photonics can be efficient, robust, and insensitive to errors





A. Piggott et al, *Nature Photonics* (2015)



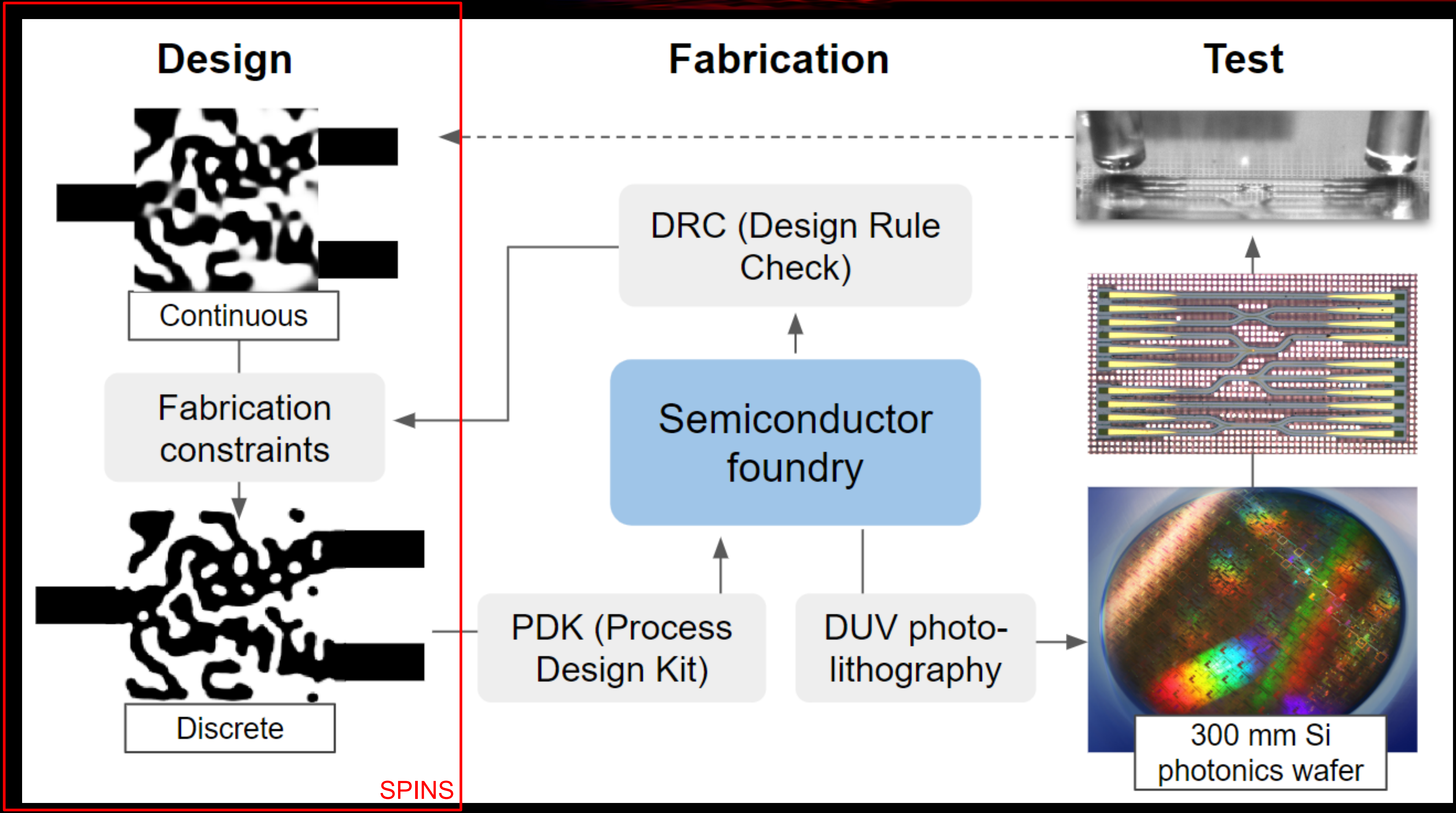


L. Su et al, *ACS Photonics*, 5 (2), pp 301–305 (2018)

Logan Su et al, *Appl. Phys. Rev.* 7, 011407 (2020)

Stanford **P**hotonics **IN**verse design **S**oftware (**SPINS**)
Vuckovic Group - Stanford OTL Docket Number: S18-012
SPINS–B (open source, 3D) on Github
http://github.com/stanfordnqp/spins-b

Foundry fabricated inverse designed photonics



Design

Continuous

Fabrication constraints

Discrete

SPINS

Fabrication

DRC (Design Rule Check)

Semiconductor foundry

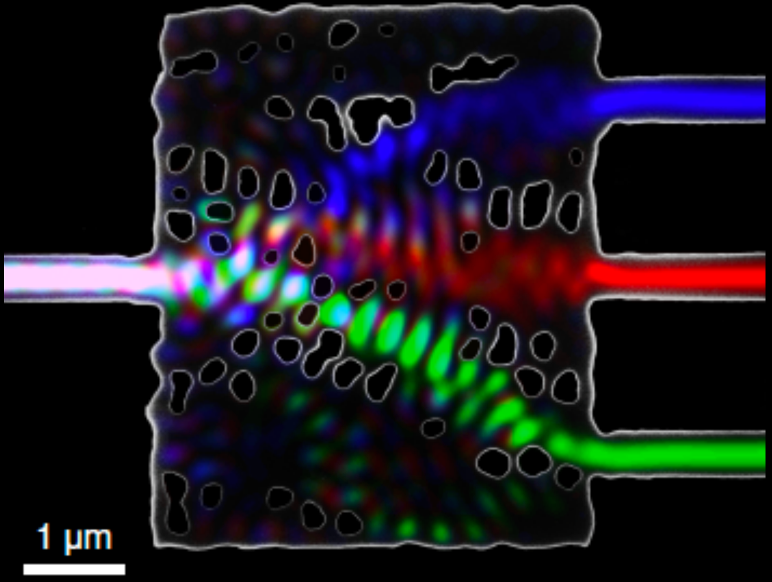
PDK (Process Design Kit)

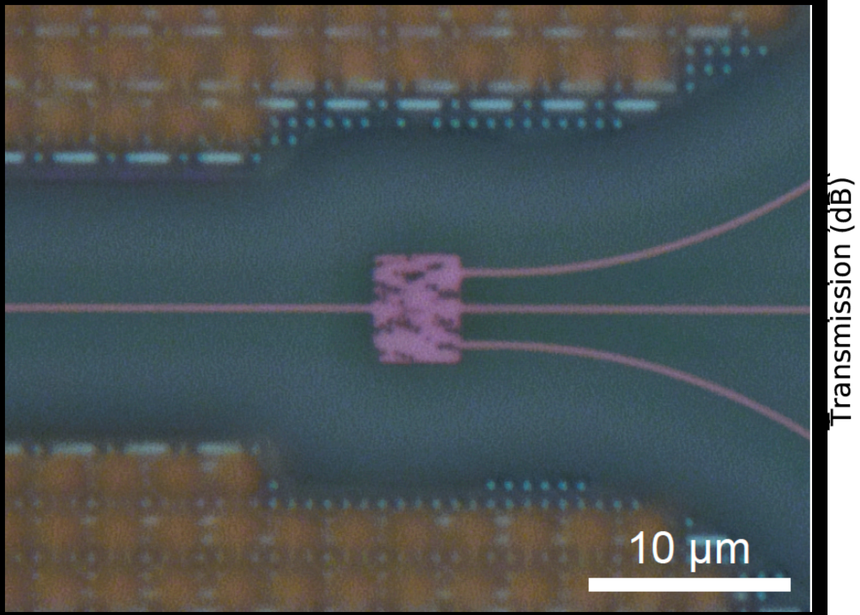
DUV photo-lithography

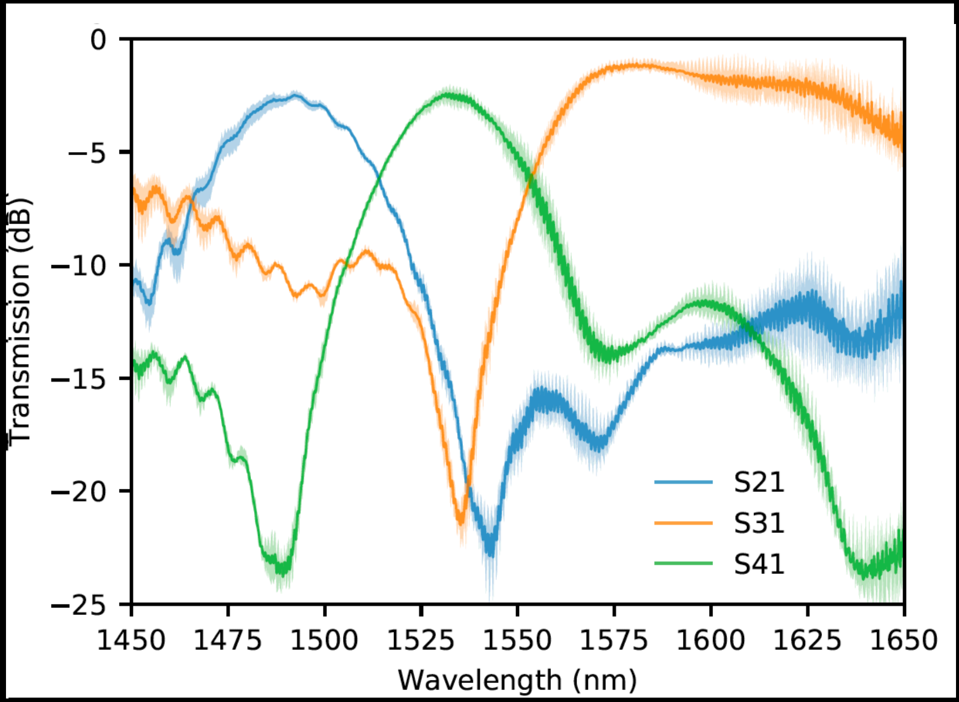
Test

300 mm Si photonics wafer

Foundry fabricated inverse designed photonics



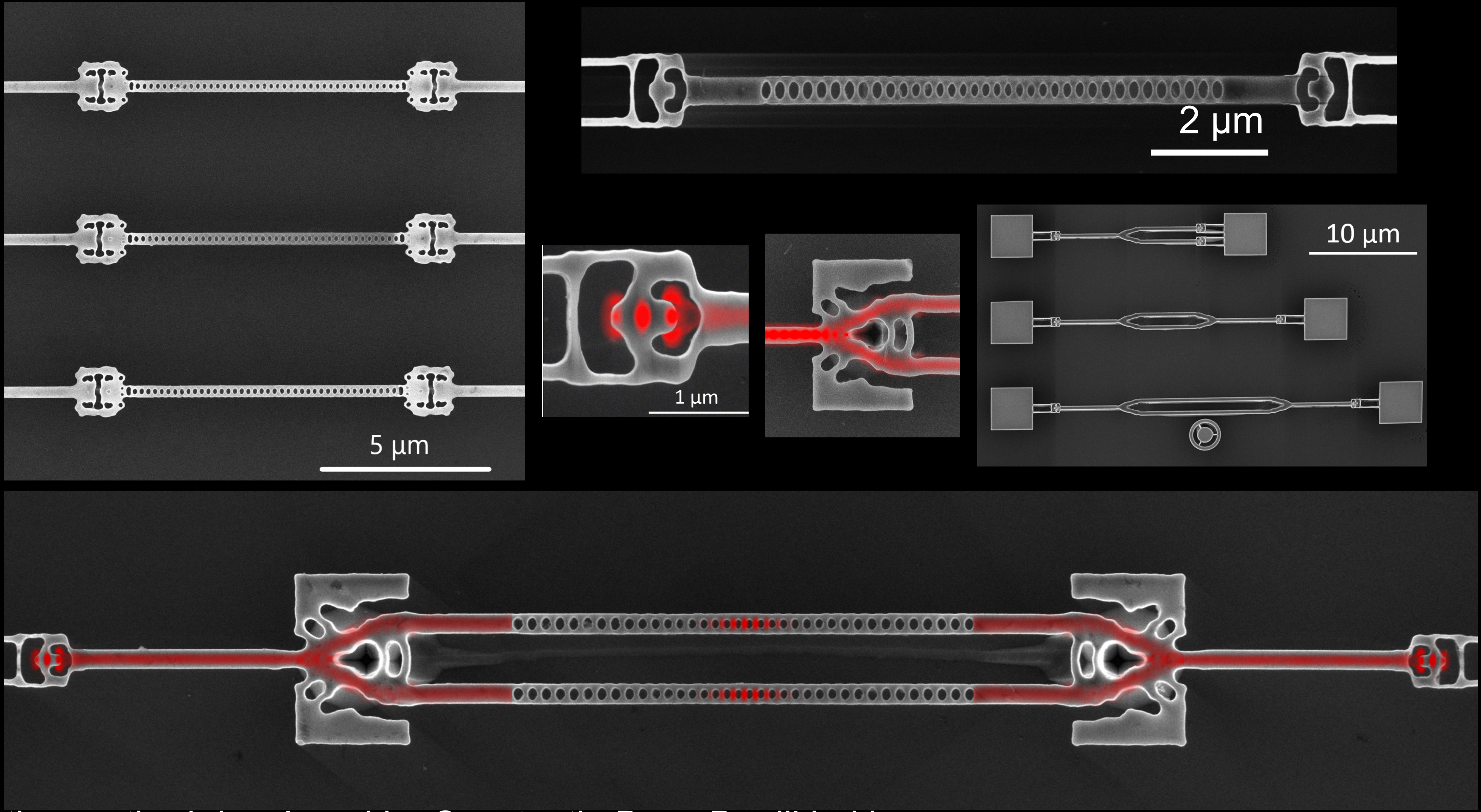




L. Su et al, *ACS Photonics*, 5 (2), pp 301–305 (2018)

Collaboration with John Bowers, UCSB
Piggott, E. Ma, L. Su et al, *ACS Photonics*
https://doi.org/10.1021/acsphotonics.9b01540 (2020)

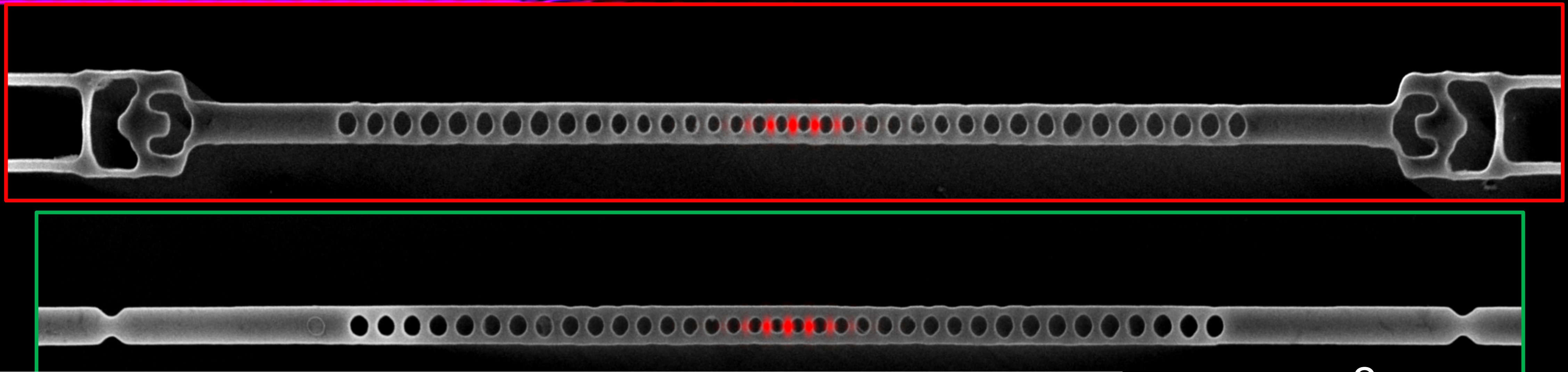
Optimized diamond quantum photonics

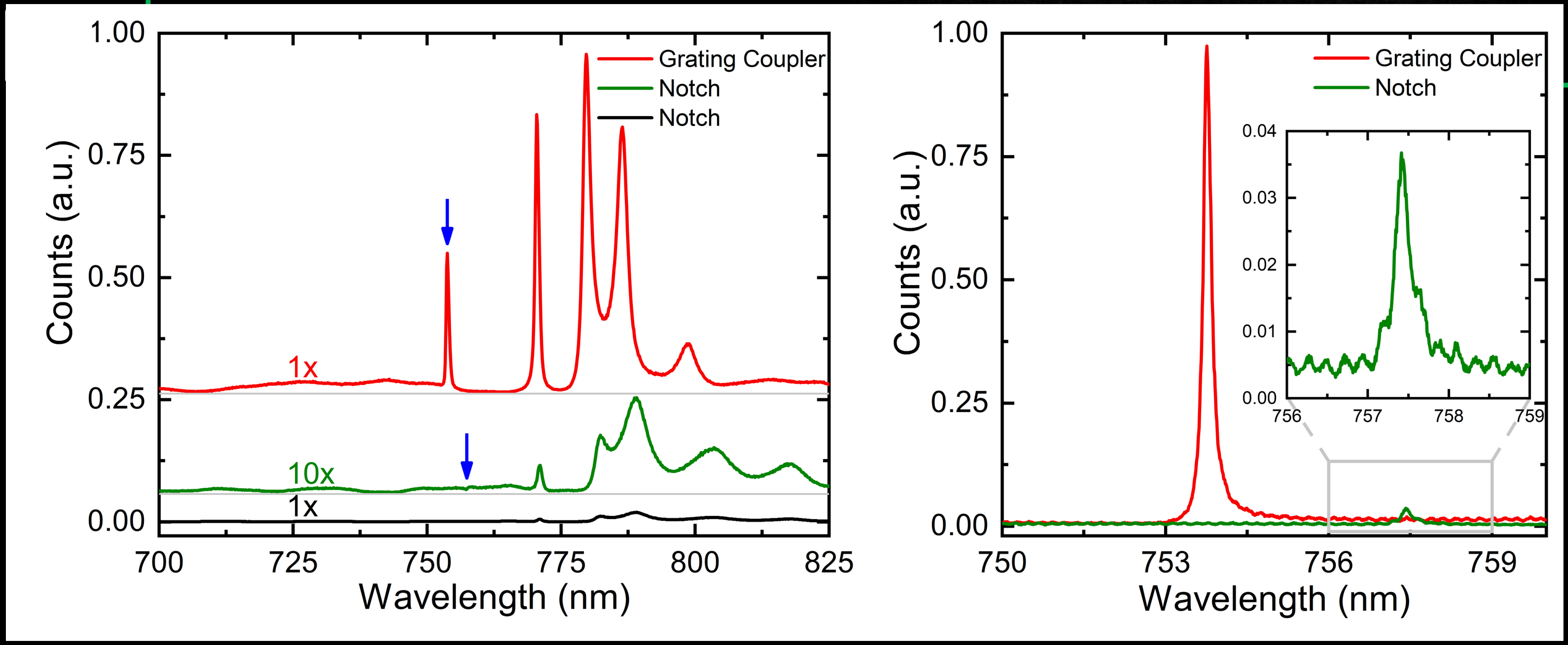


Fabrication method developed by Constantin Dory, Daniil Lukin (inspired by work from Paul Barclay, Calgary; Dirk Englund, MIT)

C. Dory, et al., *Nature Comm.* 10, 3309 (2019)

Optimized coupler-cavity integration



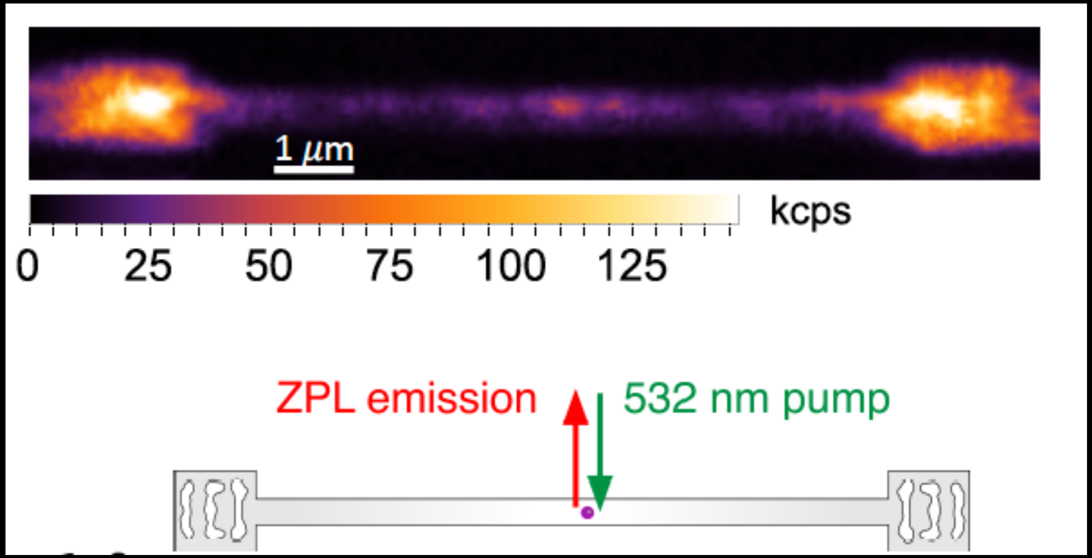


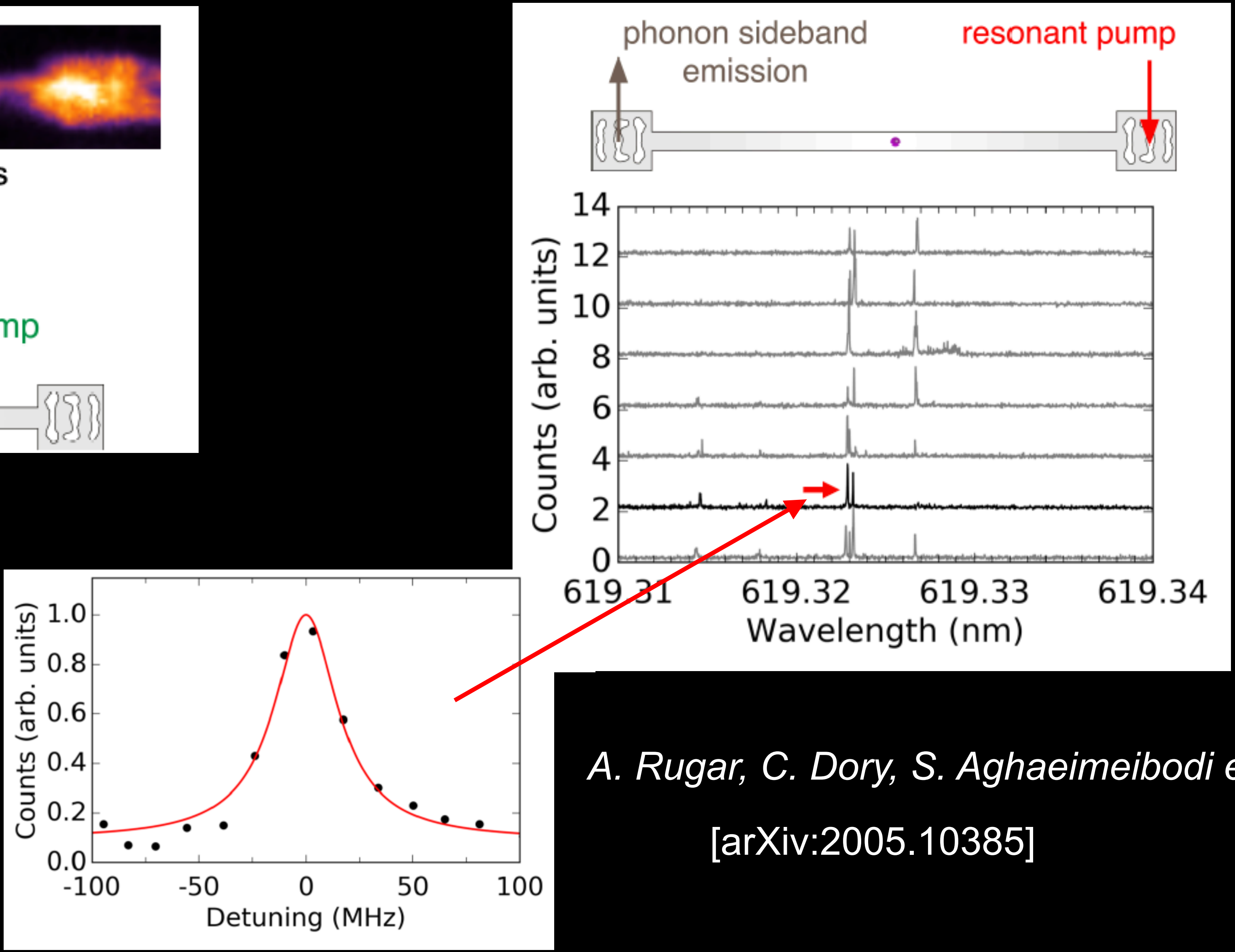
$Q \sim 10\text{-}15 \cdot 10^3$

- ~500-fold enhancement in counts, reduction in experimental time!
- Easier to scale to multiple nodes

C. Dory, et al., *Nature Comm.* 10, 3309 (2019)

SnV coupling to diamond photonics





- Combined SIIG and diamond fab
- ~30 MHz linewidth of SnV- in diamond photonic structures, on par with best bulk PLE measurements

A. Rugar, C. Dory, S. Aghaeimeibodi et al

[arXiv:2005.10385]

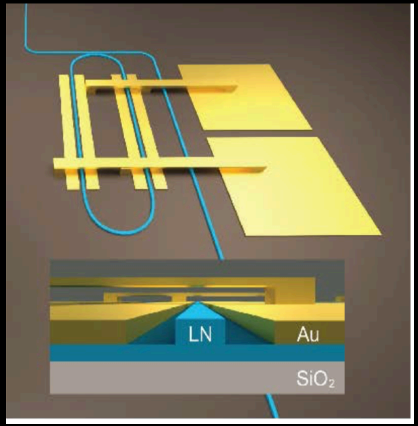
Silicon Carbide - ideal photonics material

- **Strong optical nonlinearity**
- **Piezoelectric**
- **Excellent thermal conductivity**
- **Large bandgap**

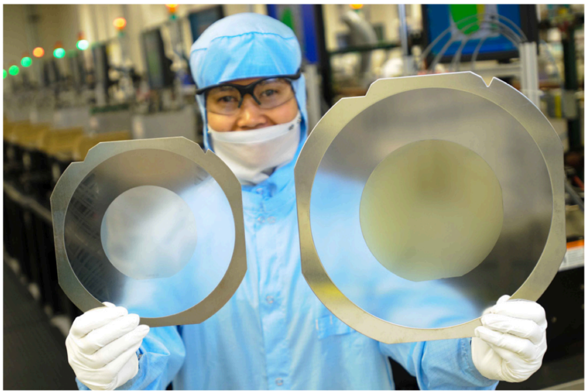
- **Silicon compatible**
- **Available on wafer scale**
- **Host high quality quantum emitters – color centers => quantum technologies**

1960's: Silicon (Si) wafers commercialized.
2000's: Silicon-on-Insulator (SOI) commercialized.
→ **Silicon photonics enters golden age.**

1990's: Lithium Niobate ($LiNbO_3$) wafers commercialized.
2010's: $LiNbO_3$-on-Insulator is commercialized.
→ **$LiNbO_3$ photonics**



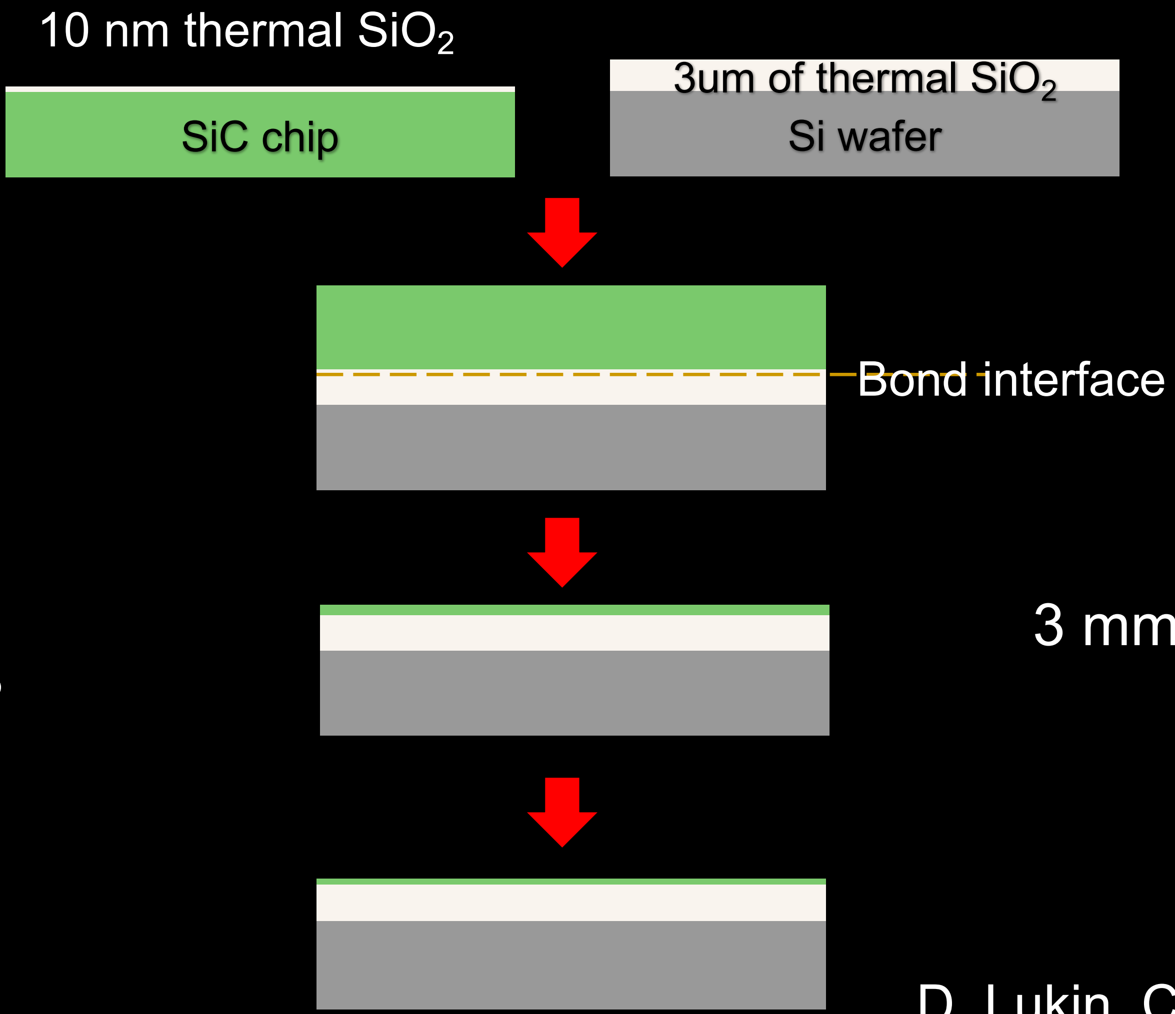
C. Wang, Opt. Express 26, 2018



100 mm and 150 mm 4H-SiC wafers (CREE)

1990's: SiC wafers commercialized…
2019: SiC-on-insulator?

SiCOI (SiC on Insulator)

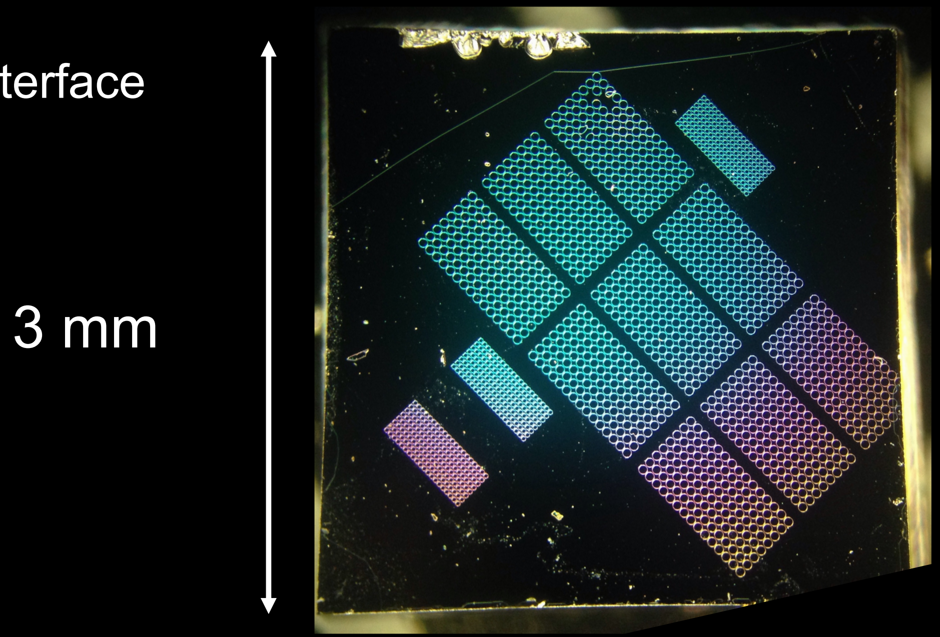


Preparation of the stack

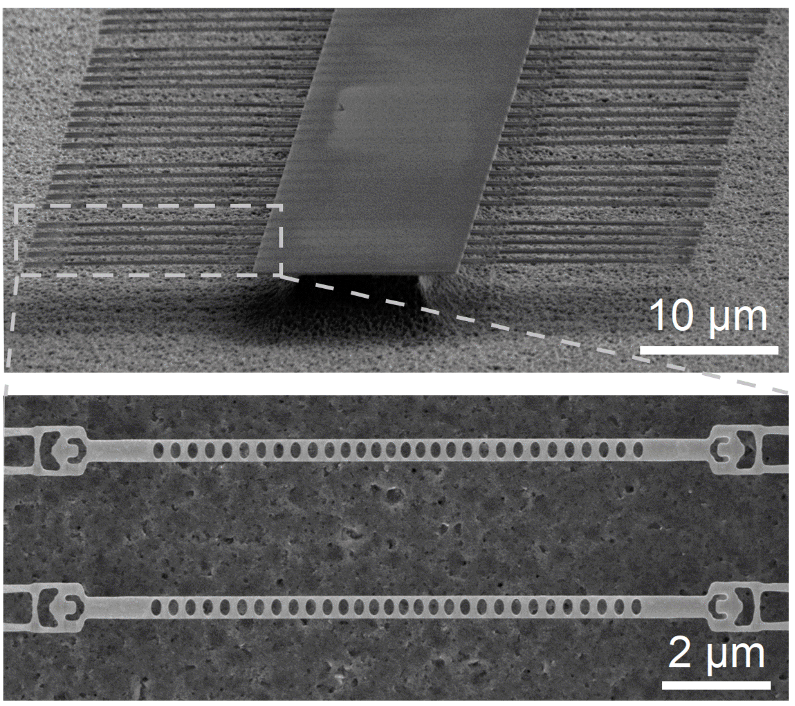
Fusion bonding (900 °C)

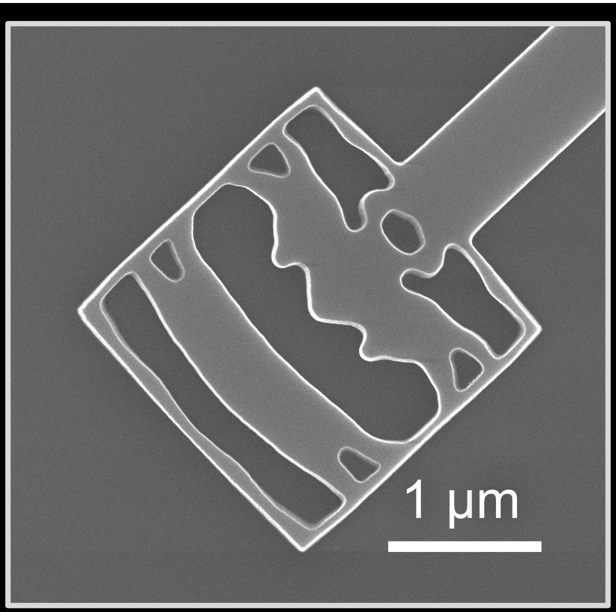
Grinding and CMP

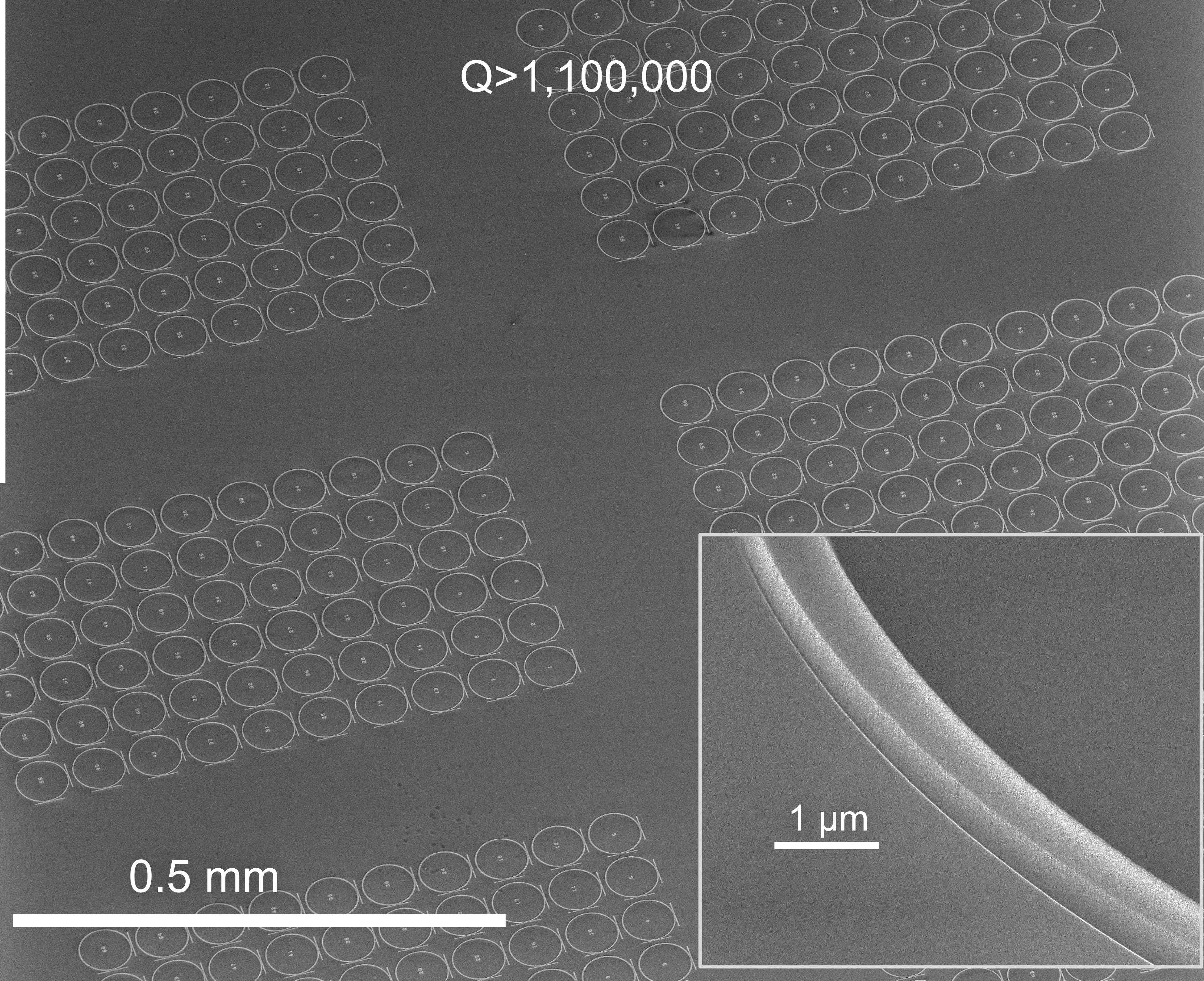
RIE thinning



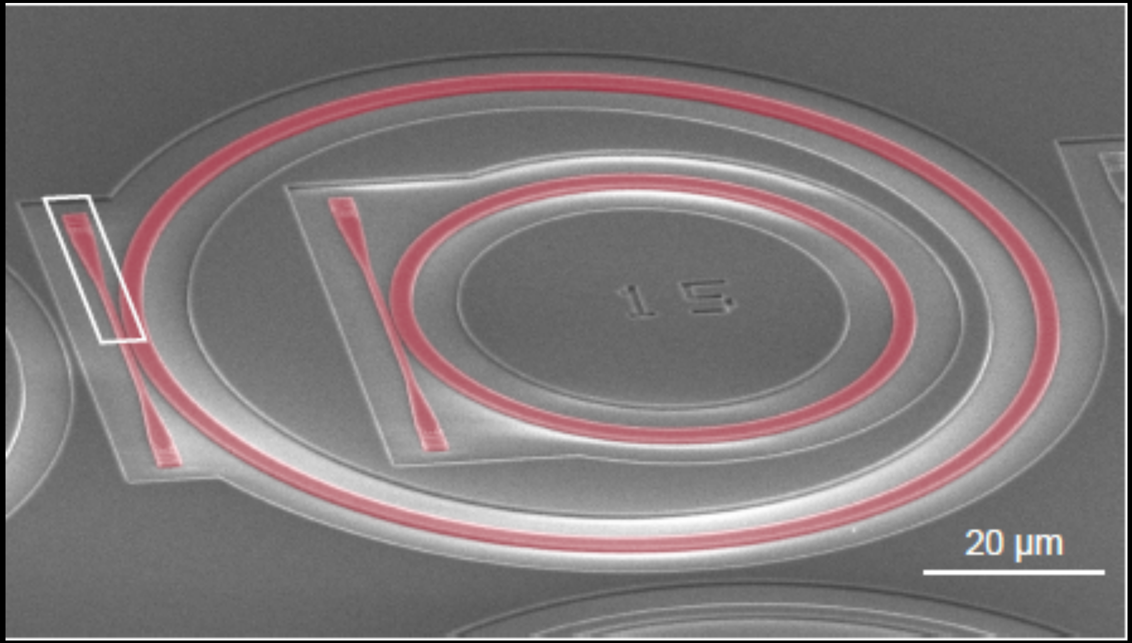
D. Lukin, C. Dory, M. Guidry et al,
Nature Photonics vol.**14**, pp. 330–334 (2020)

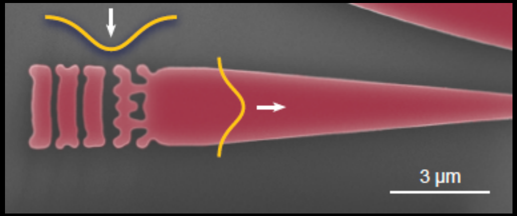

10 μm
2 μm

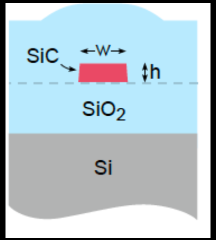

1 μm

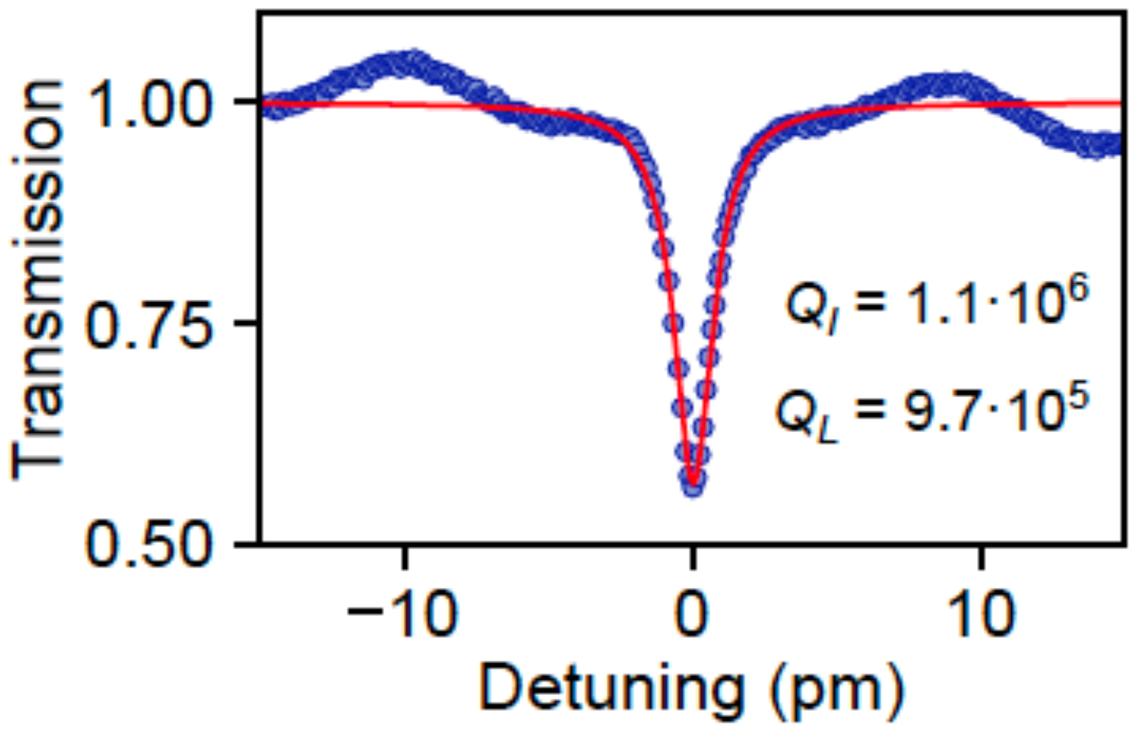

Q>1,100,000
0.5 mm
1 μm

SiCOI photonics





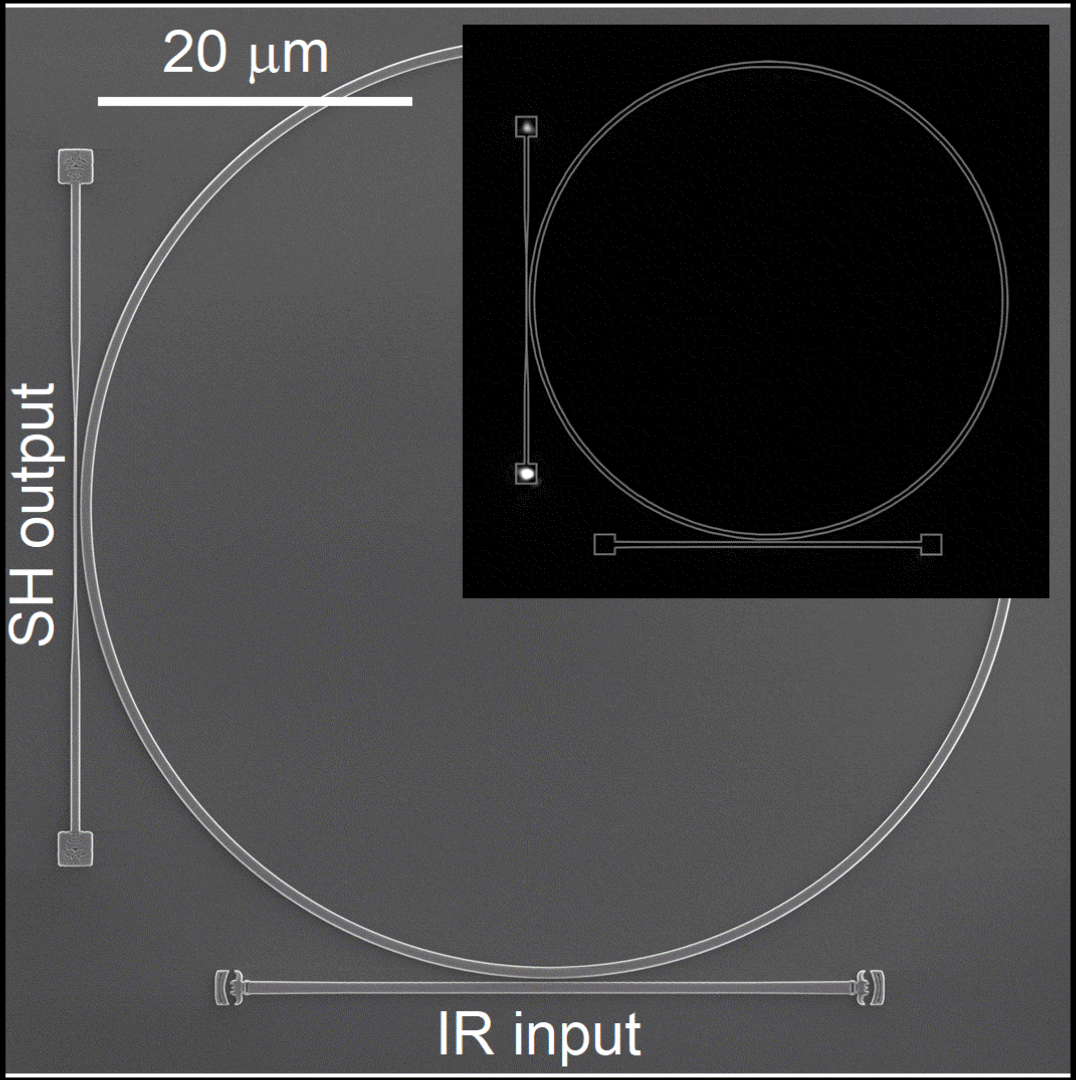


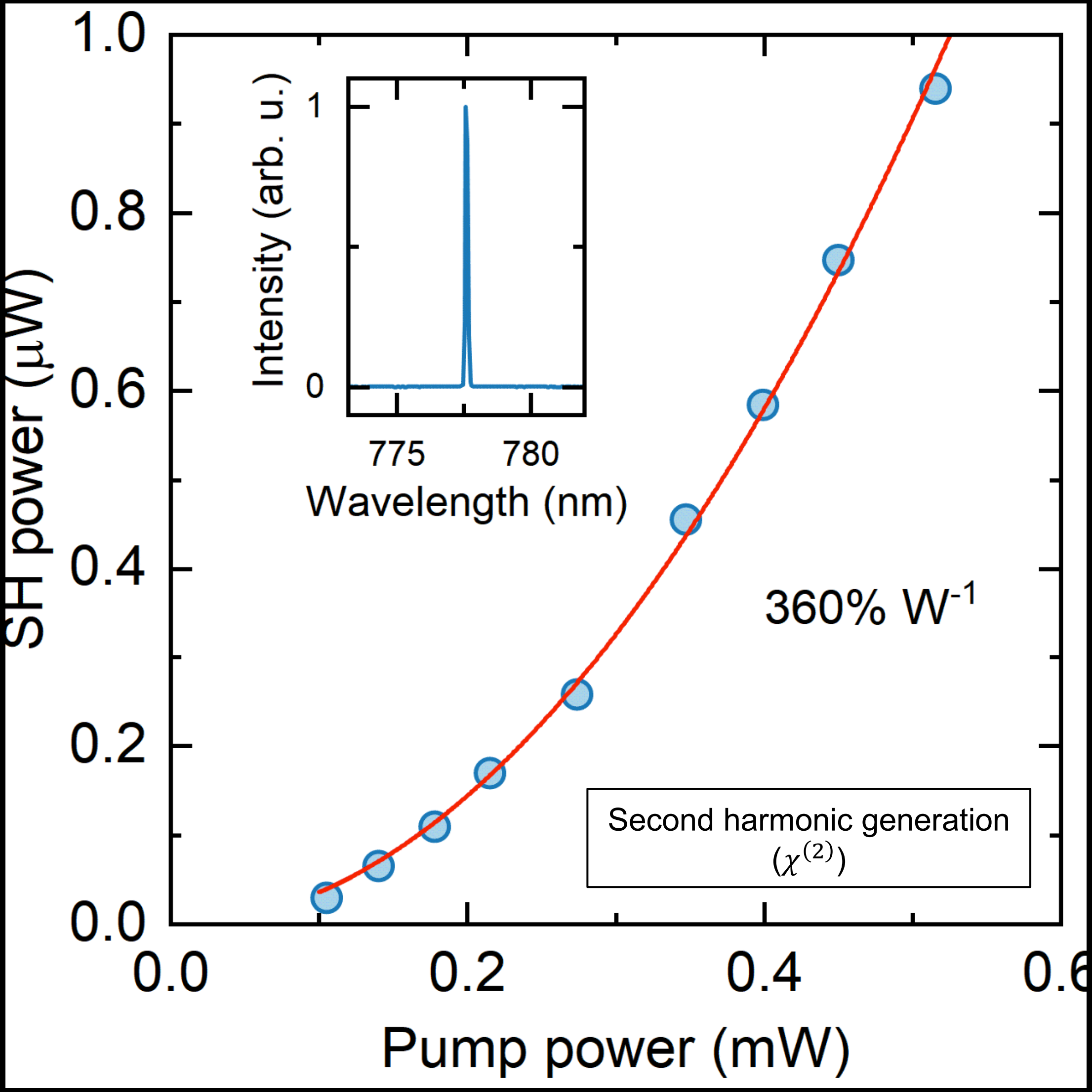


D. Lukin, C. Dory, M. Guidry et al,
Nature Photonics vol.**14**, pp. 330–334 (2020)

M. Guidry, K. Yang, D. Lukin et al [arXiv:2004.13958]

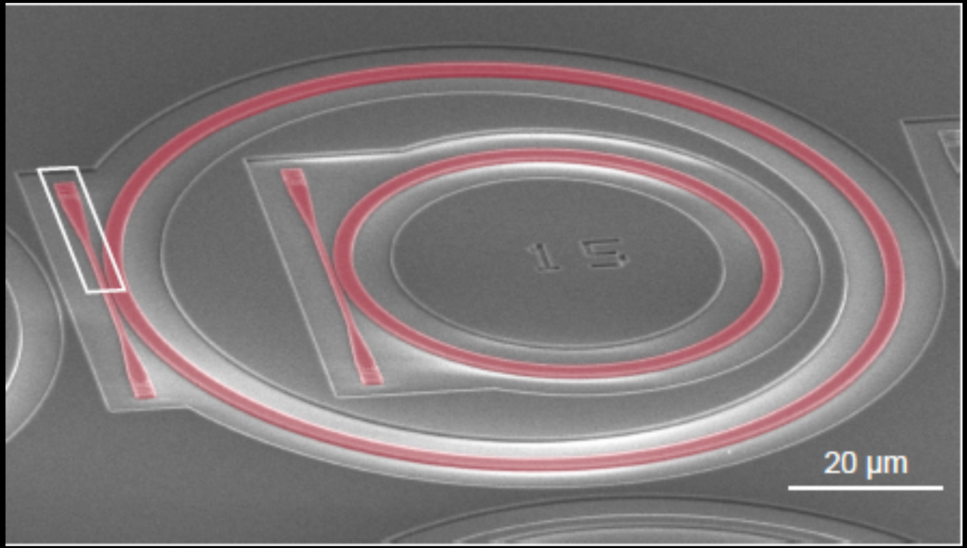
SiCOI nonlinear photonics

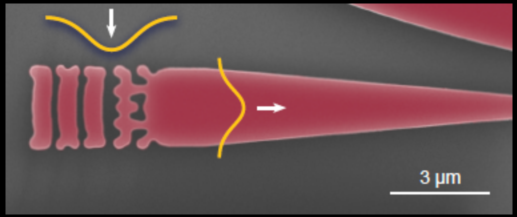


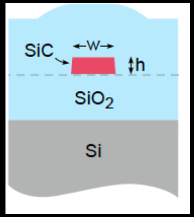


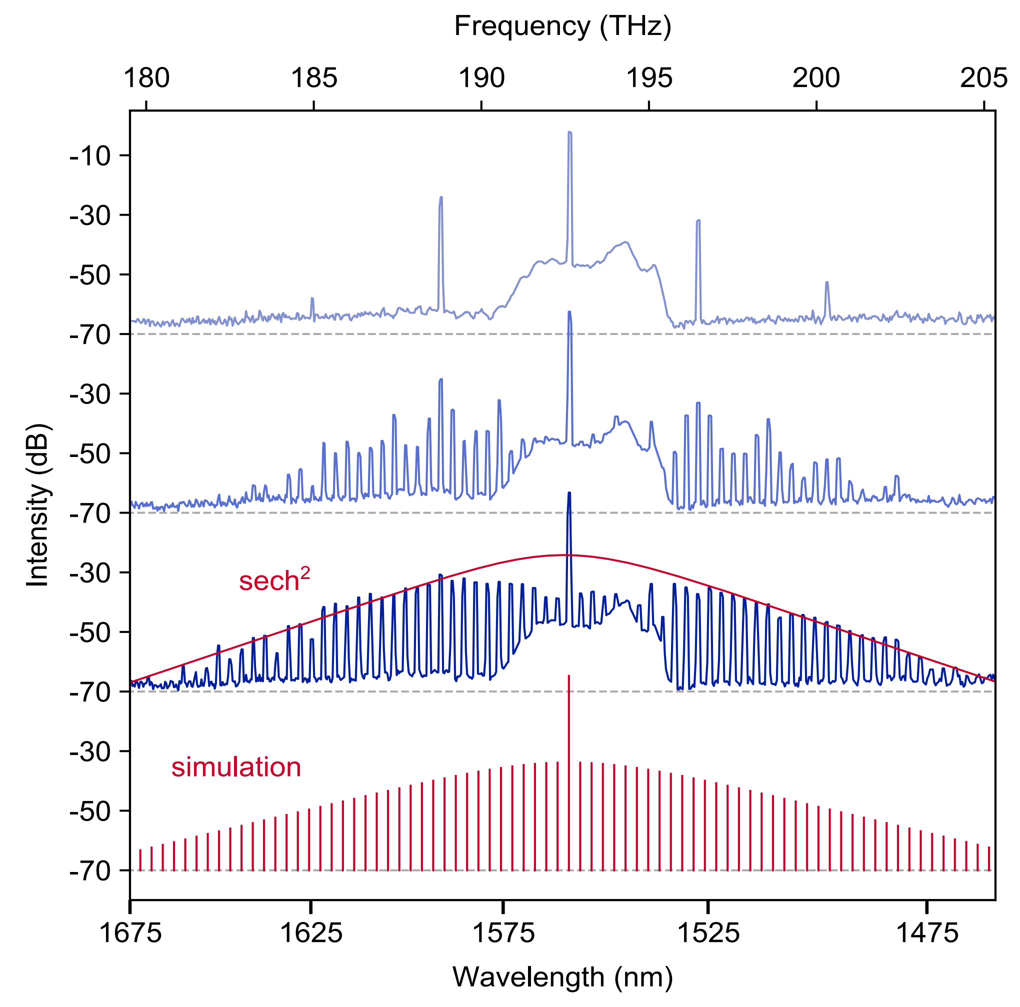
D. Lukin, C. Dory, M. Guidry et al,
Nature Photonics vol.**14**, pp. 330–334 (2020)

Nonlinear photonics: optical parametric oscillation (OPO)







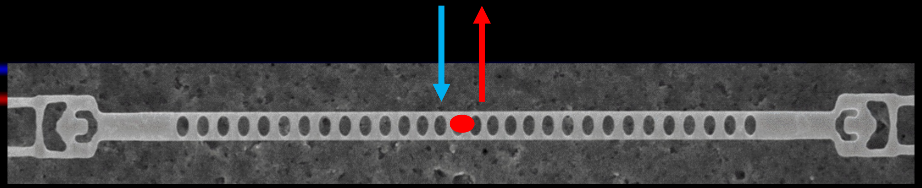


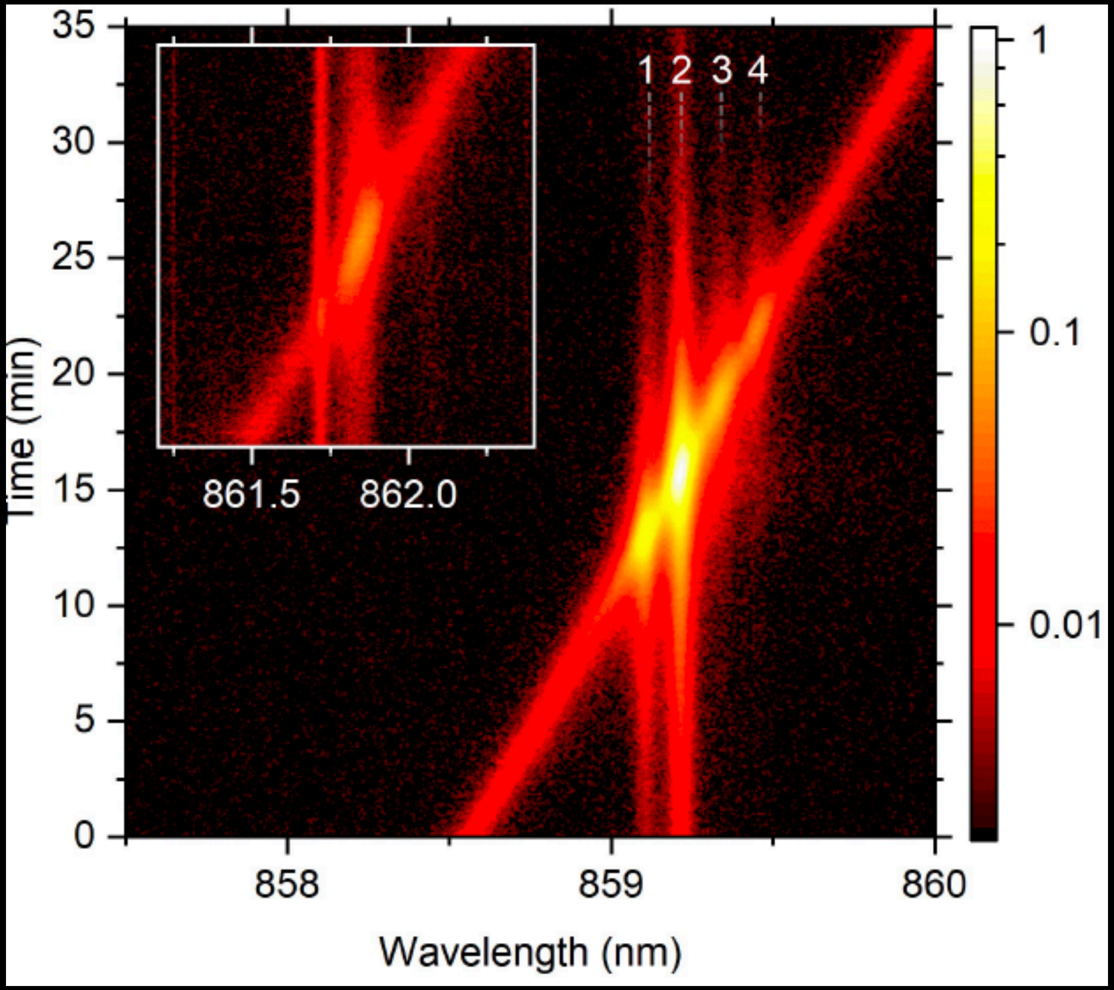
Four-wave-mixing
$(\chi^{(3)})$

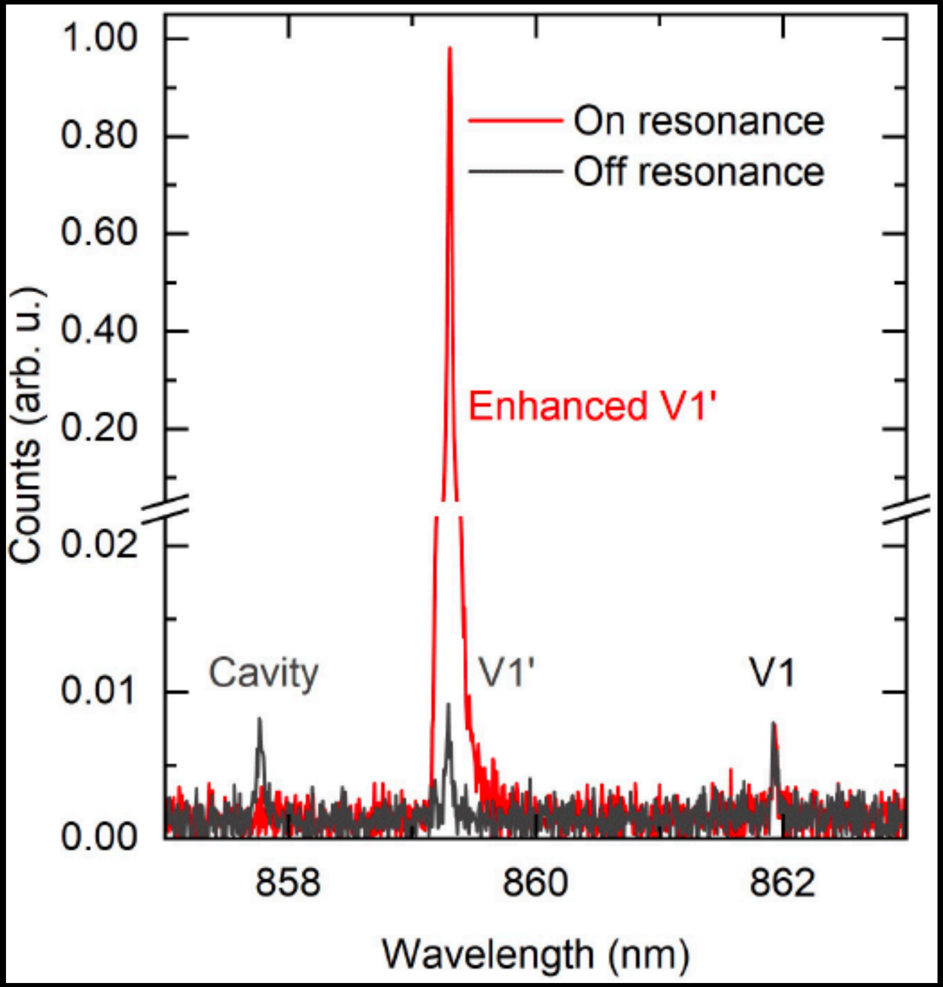
8mW threshold
for OPO

M. Guidry, K. Yang, D. Lukin et al [arXiv:2004.13958]

Quantum photonics: interaction with color centers

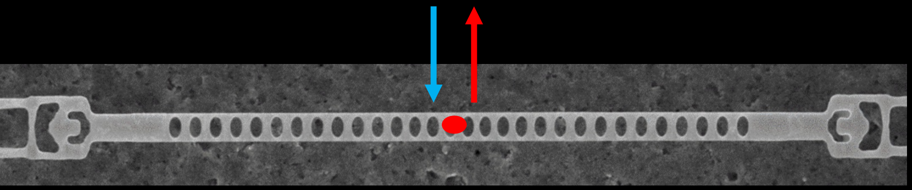






~100-fold enhancement on cavity resonance

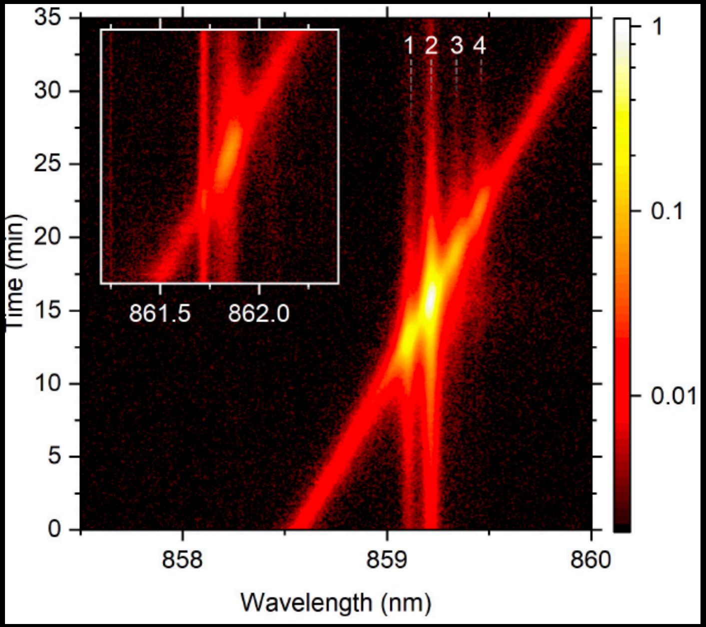
Purcell enhancement

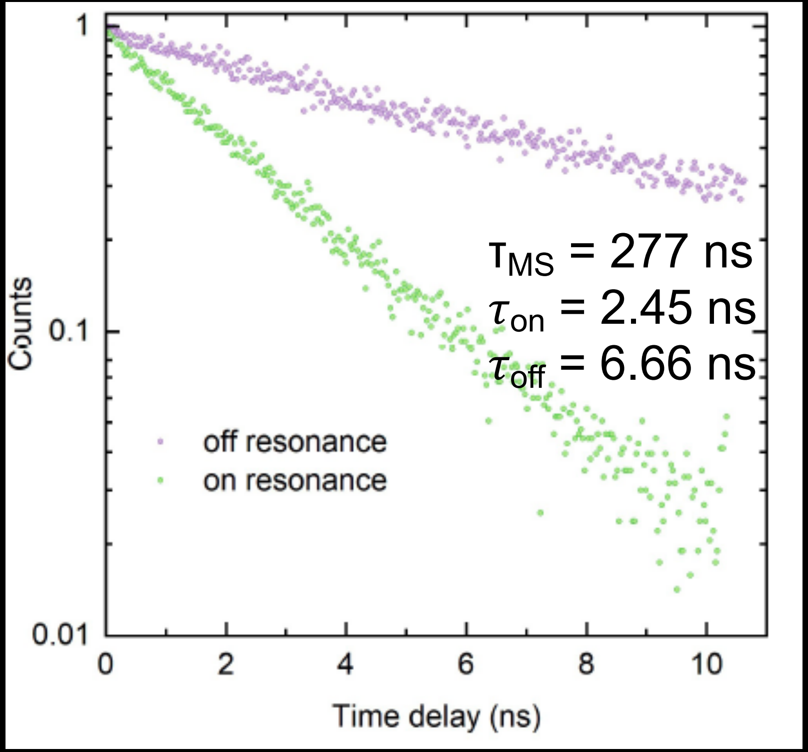


Purcell Enhancement Lower Bound: $F = \frac{\frac{\tau_{off}}{\tau_{on}} - 1}{\xi}$

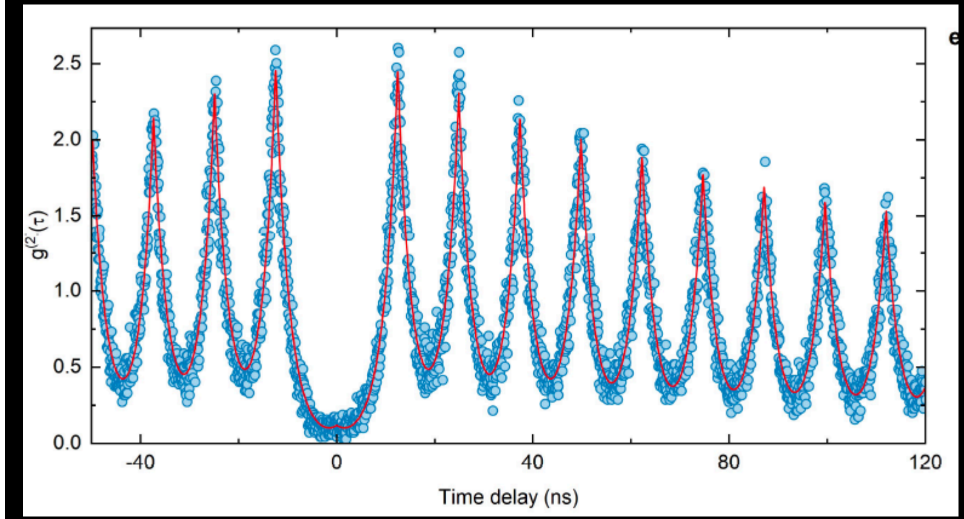
$\xi = 0.19$ Debye-Waller Factor (upper limit)

F>>9

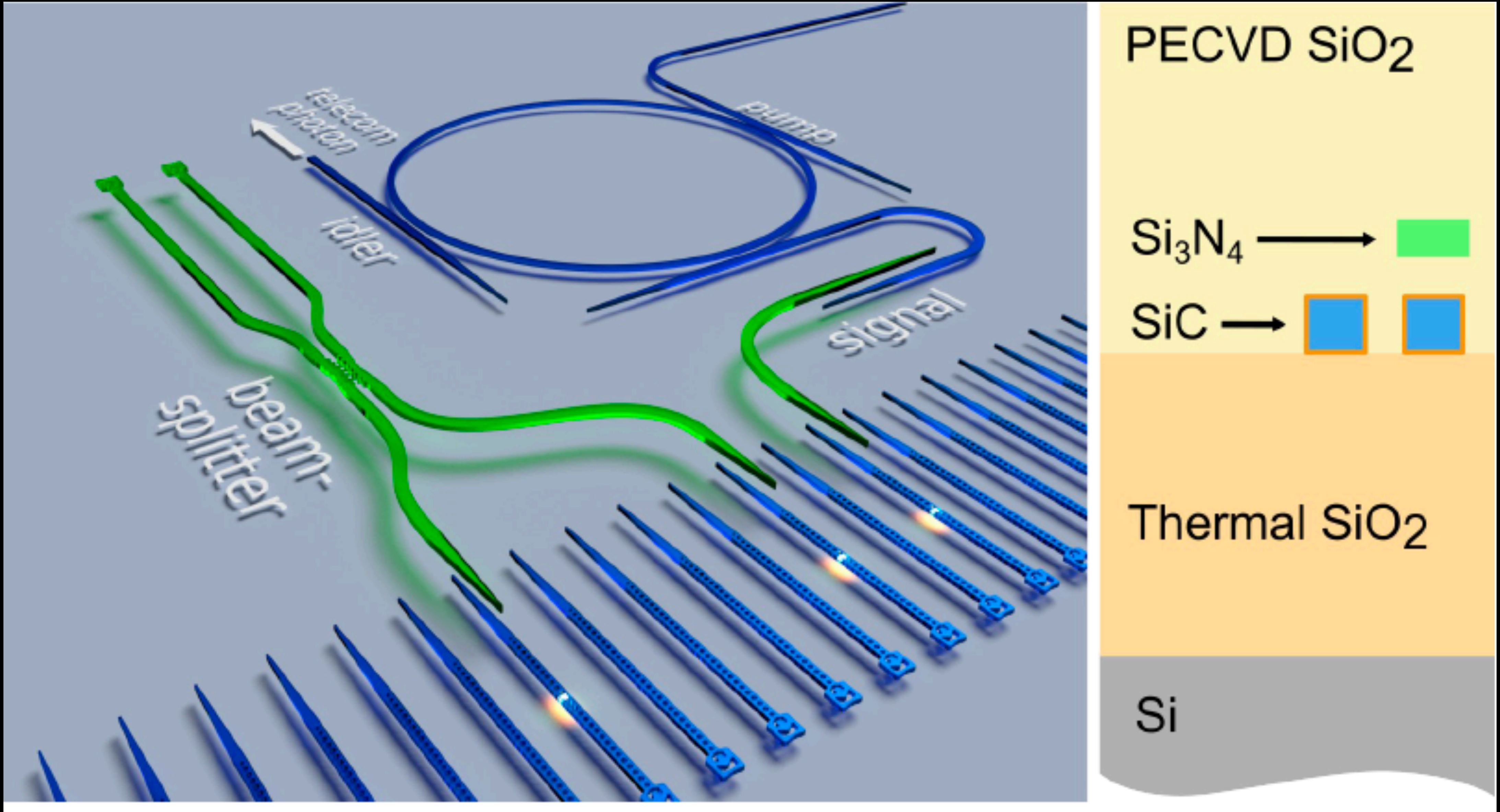




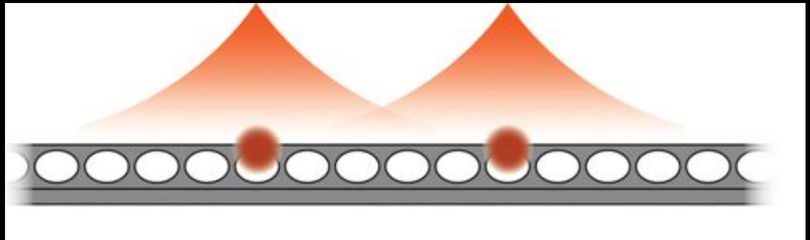
τ_{MS} = 277 ns
τ_{on} = 2.45 ns
τ_{off} = 6.66 ns



Outlook – SiCOI chip-scale quantum networks

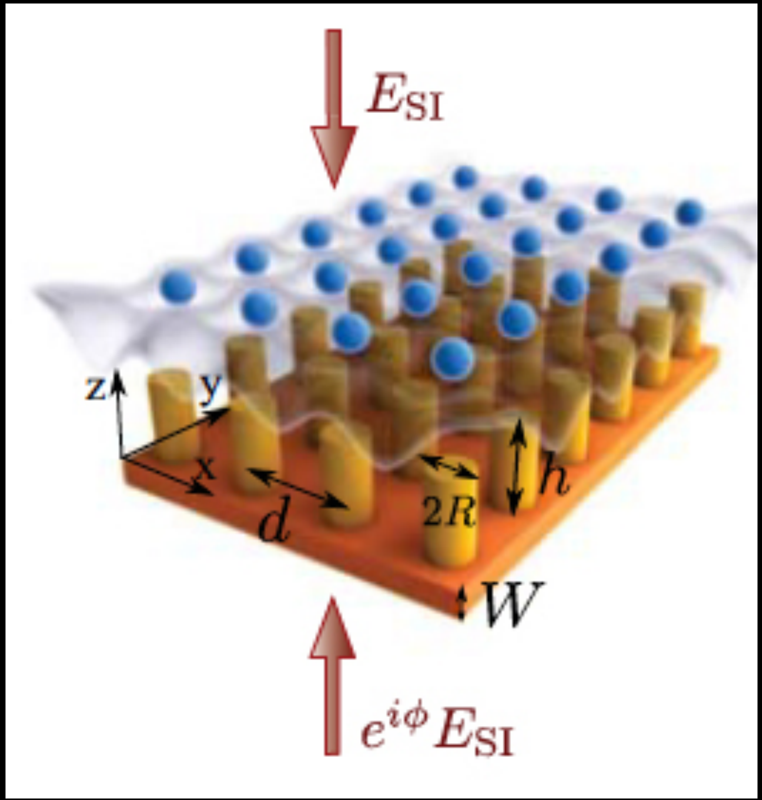


Outlook: solid-state quantum simulators



$$H_I \approx \frac{\hbar \bar{g}_c^2}{\bar{\Delta}_c} \sum_{j,l}^{N} \sigma_{eg}^{j} \sigma_{ge}^{l} \boxed{f(z_j, z_l)}$$

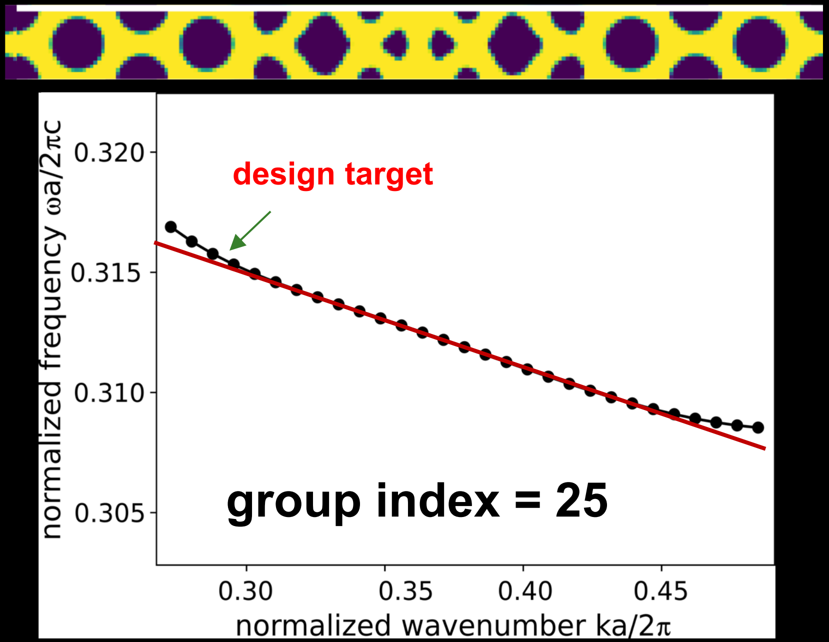
We can specify an interaction Hamiltonian by inverse engineering the photonic environment!



González-Tudela et al., *Nature Photonics* 9, 320–325 (2015).
Douglas et al., *Nature Photonics* 9, 326–331 (2015).

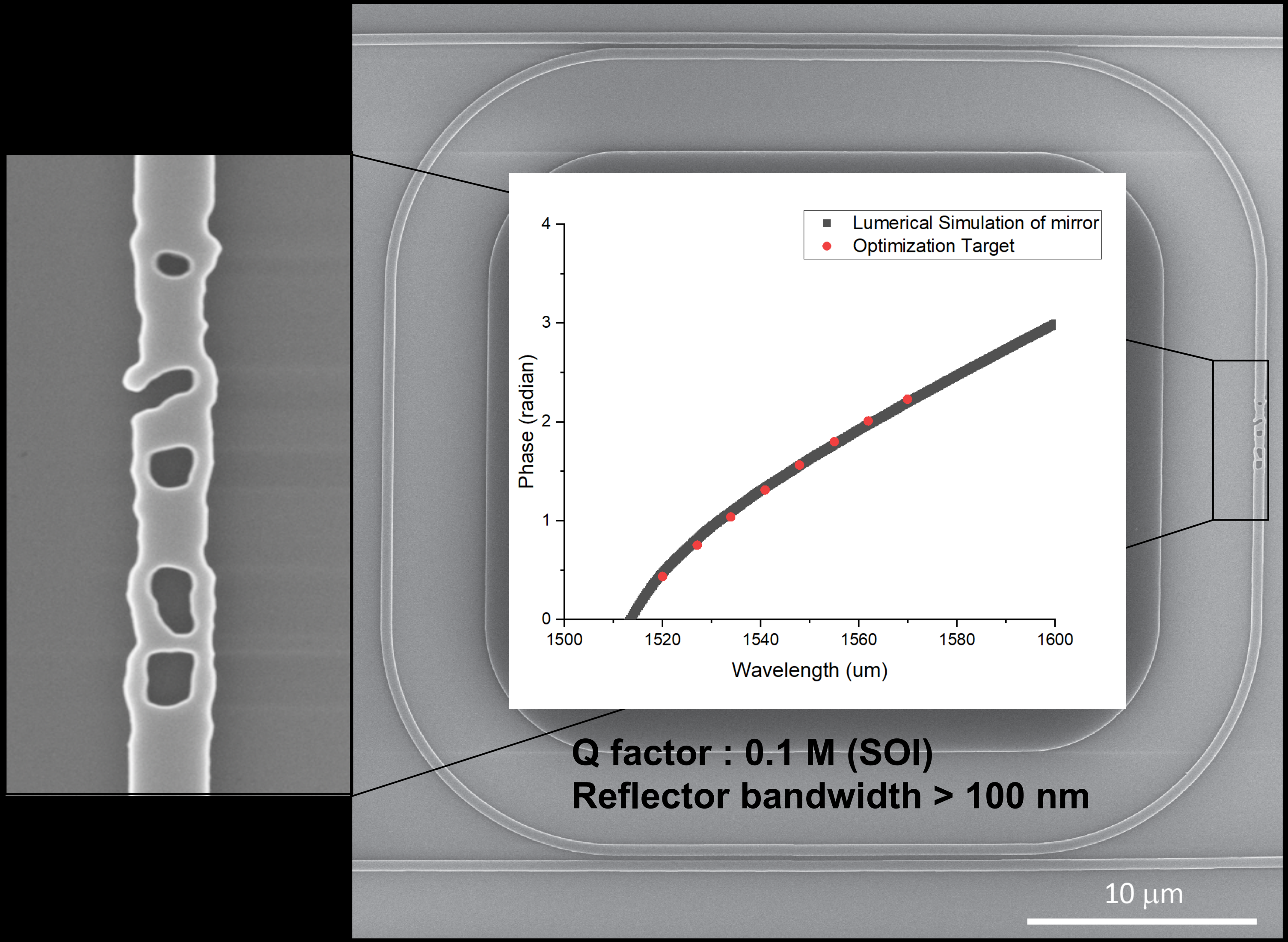
R. Trivedi, S. Sun, in collaboration with I. Cirac, D. Lanz (MPQ)

Inverse design for dispersion engineering



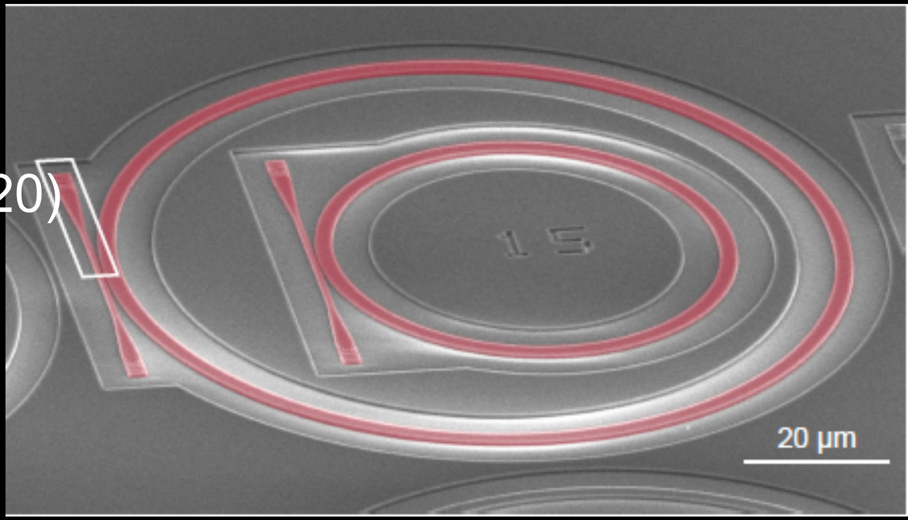
Dries Vercruysse et al, IEEE JSTQE (2019)

Microresonator dispersion



Q factor : 0.1 M (SOI)
Reflector bandwidth > 100 nm

G. Ahn, K. Yang et al, J. Vuckovic

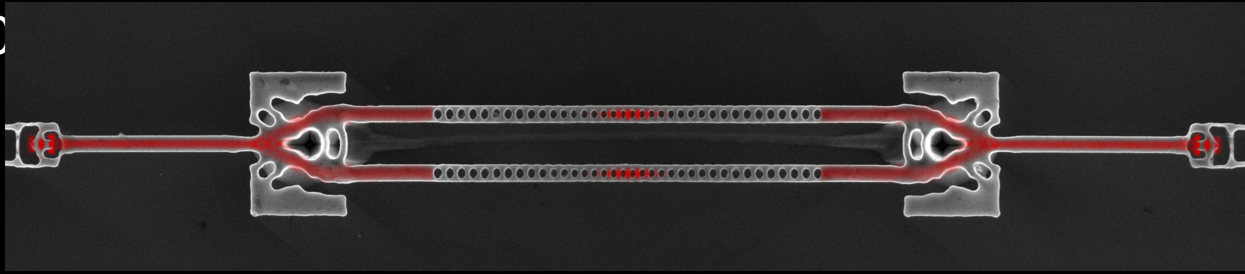


- **4H silicon Carbide Quantum and nonlinear Photonics**

D. Lukin, C. Dory, M. Guidry et al, *Nature Photonics* **14**, 330–334 (2020)
D. Lukin, A. White, M. Guidry, R. Trivedi et al *[arXiv:2003.12591]*
M. Guidry, K. Yang, D. Lukin et al [arXiv:2004.13958]

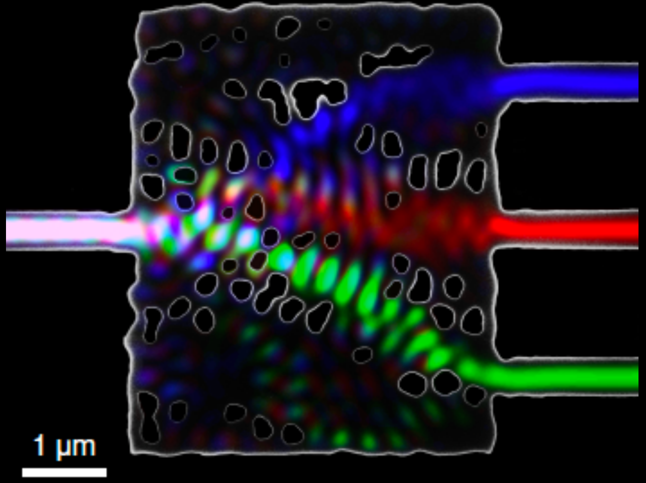
- **SiV and SnV in inverse designed diamond cavities**

Shuo Sun et al, *Phys. Rev. Letters* 121, 083601 (20
C. Dory, et al., *Nature Comm.* 10, 3309 (2019)
A. Rugar, et al., *Phys. Rev. B* 99, 205417 (2019),
Nano Letters **20**, 1614-1619 (2020)
[arXiv:2005.10385]



- **Photonics optimization critical for implementation of scalable and practical classical and quantum photonic systems**

Stanford **P**hotonics **IN**verse design **S**oftware (**SPINS**), OTL S18-012
SPINS–B (open source) on Github http://github.com/stanfordnqp/spins-b
Fully compatible with foundry fabrication



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DARPA

NSF

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J. Bowers @ UCSB