Quantum electromechanics with dielectric oscillators

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CIT: M. Kalaee, P. Dieterle, O. Painter

Quantum Interfaces with Nano-Opto-Electro-Mechanical Devices: Applications and Fundamental Physics. Erice, Italy, August 2, 2016

Physics @ IST

- Experiment: Fink, Hof, Katsaros, Krogstrupp
- Theory: Lemeshko, Seiringer, Serbyn

- ~ 1-2 new physics groups till 2026
- Brandnew 300 m² nano-fabrication facility
- US-type graduate school
- International
- Start-up mentality
- In the Vienna Woods

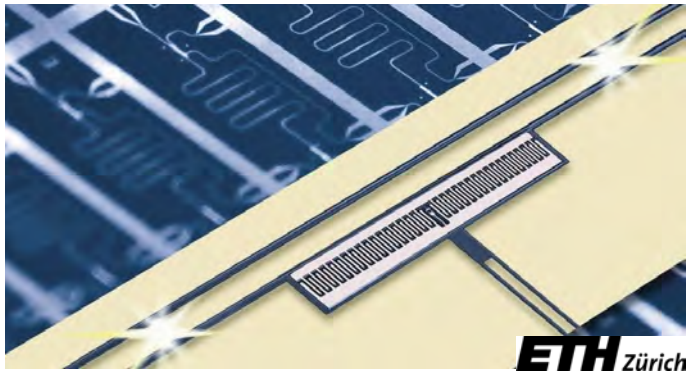
Quantum Integrated Devices Lab

Superconducting Circuits, Circuit QED

- Very strong light-matter coupling
- Quantum optics with microwave photons and qubits
- Small scale quantum computing
- Quantum simulation

R. J. Schoelkopf and S. M. Girvin, Nature 451 (2008)

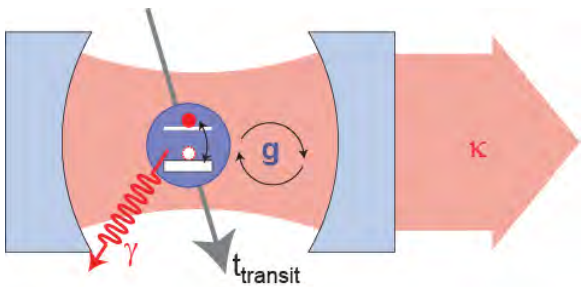
A. Wallraff, et. al, Nature 431 (2004)



Quantum Nonlinearity

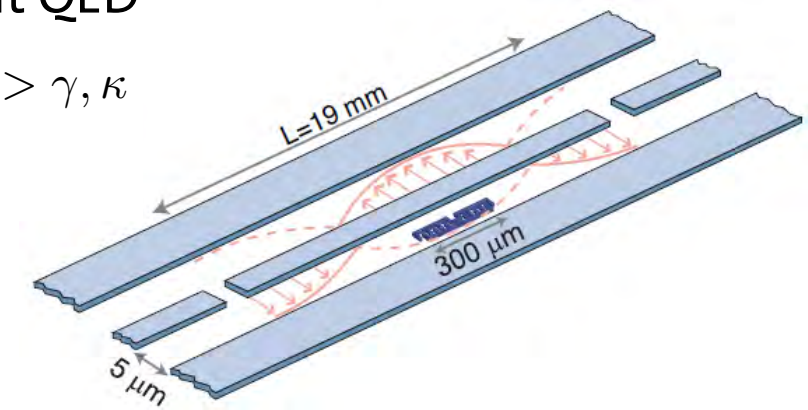
Cavity QED

$$g = E_0 d/\hbar \qquad E_0 \sim (\hbar\omega/V)^{1/2}$$



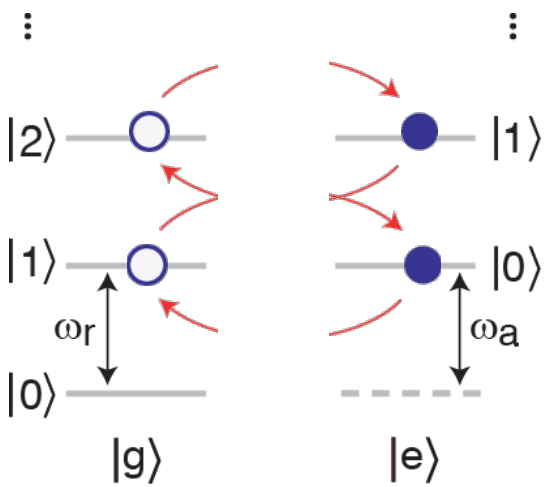
Circuit QED

$$g >> \gamma, \kappa$$



Coherent matter-light interaction

$$H = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\omega_a}{2}\sigma^z + \hbar g(a^\dagger\sigma^- + a\sigma^+)$$



D. Walls & G. Milburn, Quantum Optics (1994)

Sqrt(n) spectroscopy

J. M. Fink, *et al.* Nature **454** (2008)
I. Schuster, *et al.* Nat. Phys. **4** (2008)

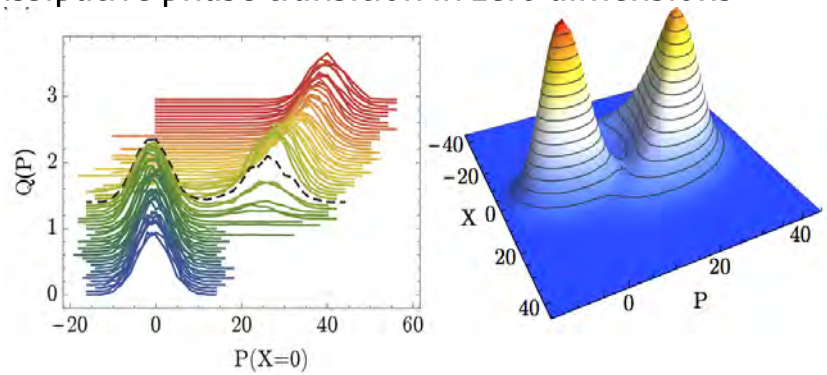
State of the art

$$\frac{g^2}{\kappa\gamma} \sim 10^6$$

- 100 photon Schrödinger cat states (Yale)
- Quantum teleportation (ETH)
- Cavity based algorithms (UCSB, IBM)
- Microwave quantum optics (ETH, TUM, JILA)

Quantum Nonlinearity

Dissipative phase transition in zero dimensions

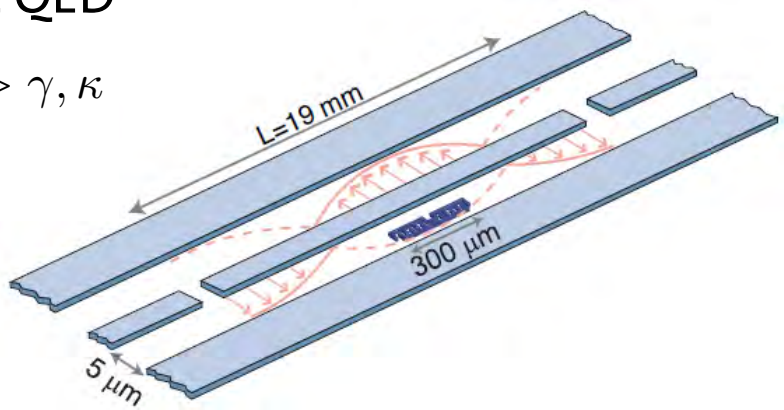


J. M. Fink et al., arxiv: 1607.04892

For 1D see: Fitzpatrick et al., arxiv:1607.06895

Circuit QED

$$g >> \gamma, \kappa$$



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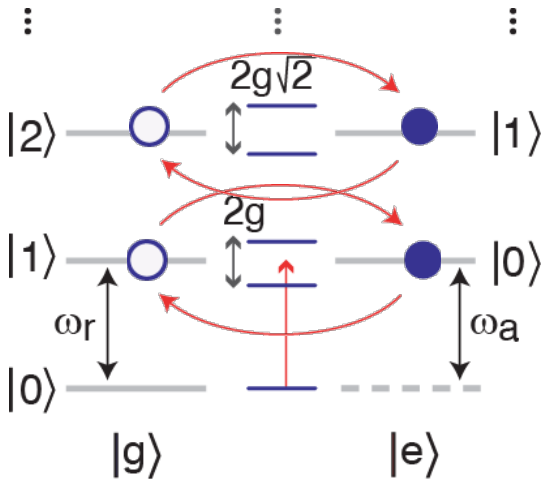

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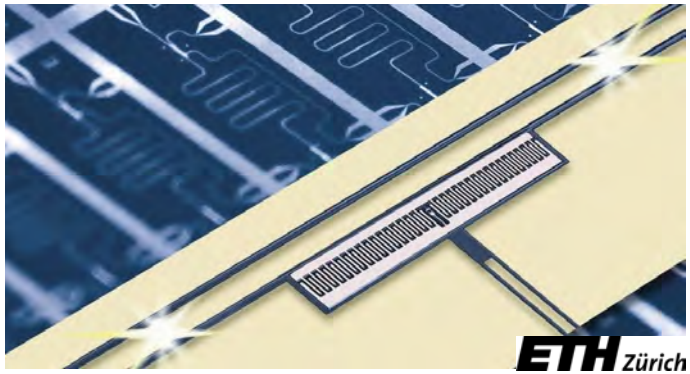
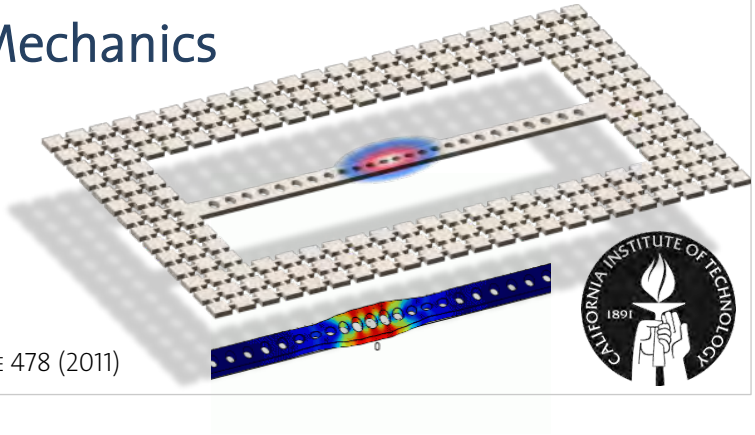


Quantum Photonics, Cavity Opto- and Electro-Mechanics

- Photonic crystals with strong field confinement
- Ground state cooling of mechanical systems
- Efficient acousto-optic modulation
- Communication and sensing

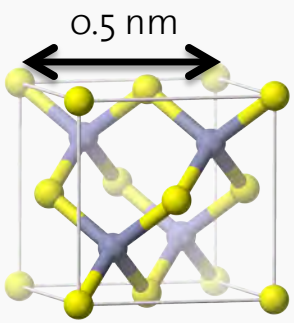
M. Aspelmeyer, et. al, Rev. Mod. Phys. 86 (2014)

J. Chan, et. al, Nature 478 (2011)



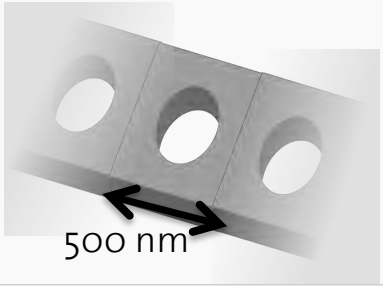
Optomechanical Crystals

Periodic Atomic Structure



→Bandgaps for electron waves

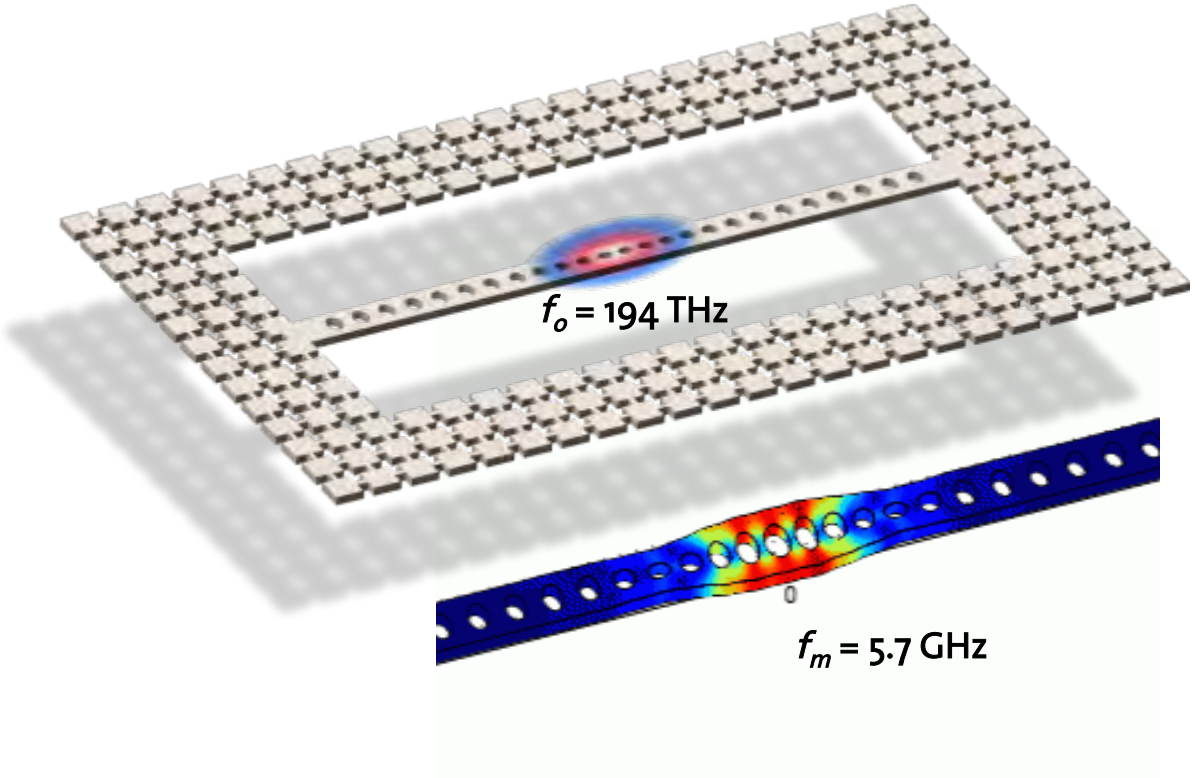
Periodically Placed Holes



→ Bandgaps for sound and light waves

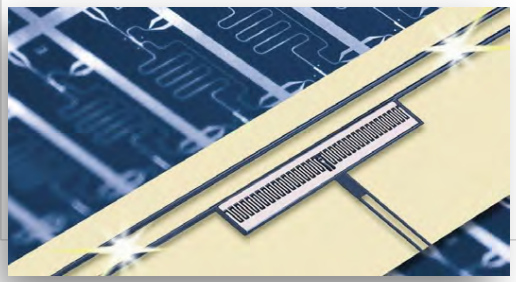
Coupling Strength

g_0 = 1,100 kHz
(experiment, 90% photo-elastic)

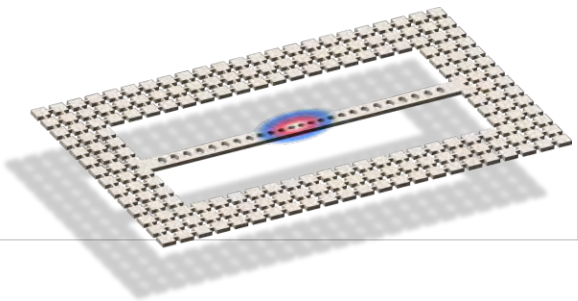


- Independent routing of acoustic and optical waves
- Strong co-localization of modes
- Large radiation pressure effect (g)
- Phononic shield for high mechanical Q
- Telecom wavelengths
- <n> << 1 at 10 mK

J. Chan, *et. al*, Nature **478** (2011)



Circuit QED + OMCs



µw Circuits + Optomechanics:
‘Quantum Microwave Photonics‘

Microwaves
- Good qubits
- Very large g

→ Processing

Optics
- Low loss
- Noise resilient

→ Communication

AO transducer
- State synthesis and distribution
- Interface for circuits and atoms
- ‘Quantum Internet’

µw Circuits + Acoustic Cavities:
‘Microwave Phonon Circuits‘

GHz acoustics
- No active cooling
- Acoustic waveguides & circuits
- Phonon interference, entanglement

Why microwaves?
- Expect less heating
- Circuit QED toolbox
- High detection efficiencies

Challenges

- Materials
- Size mismatch → small g_{em}
- Heating

QuantumIDs.com

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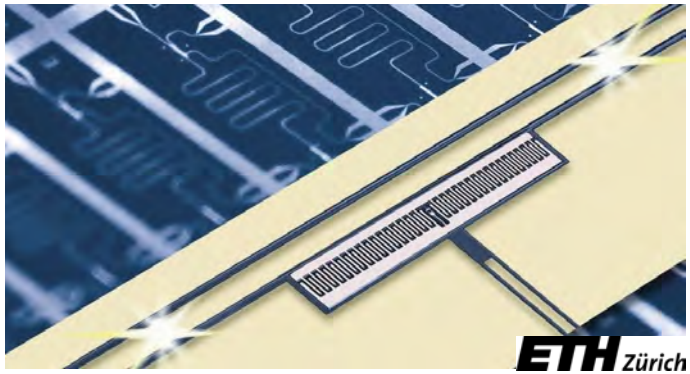

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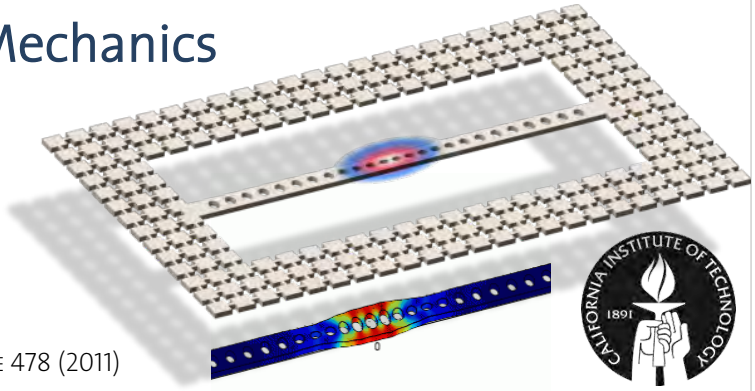
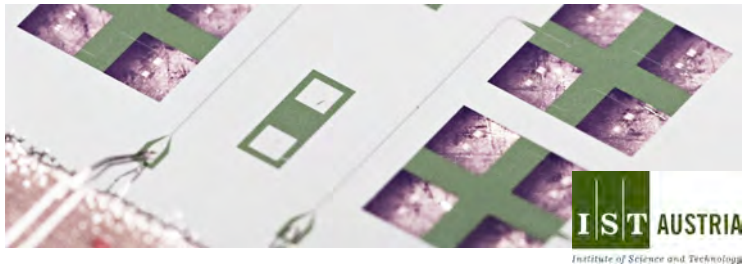


Research Goals

- Superconducting qubits + fiber optic networks
- On-chip control of individual phonons + photons
- Investigate hardware-protected compact qubits



Qubits + Fiber Optics

Quantum Communication

- Distribute non-classical microwave photon states
- Entangle superconducting qubit networks
  - quantum dial up modem
- Built small special purpose quantum computers for secure communication
  - quantum repeater nodes with entanglement purification and distillation

Quantum Enabled Sensing

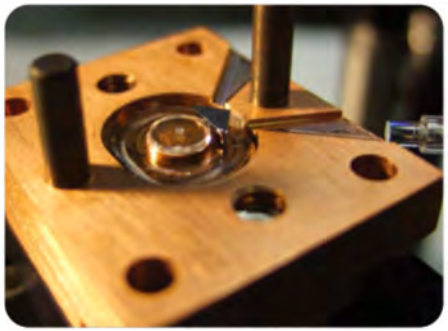
- Ghost imaging
- Quantum Illumination

Fundamental

- Large scale entanglement: mechanical or electronic
- Control the dynamics of individual quanta

How?

- Piezo-electric — Bochmann, J. *et al.*, Nat. Phys. 9, 2013
- Spin-based — Hisatomi, R. *et al.*, Phys. Rev. B 93, 2016
- Electro-optic — Tsang, M. Phys. Rev. A 81, 2010
- Mechanical — Andrews, R. W. *et al.*, Nat. Phys. 10, 2014
- ...

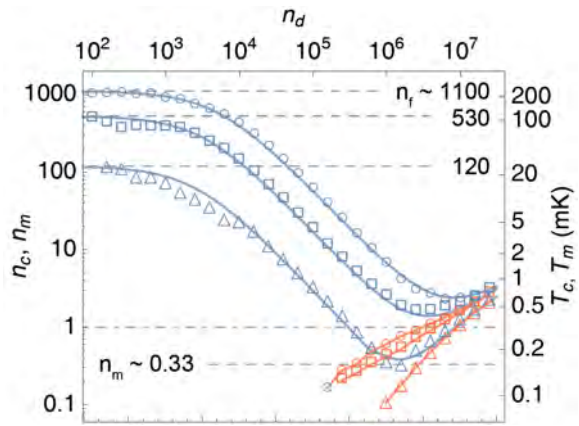


Rueda, A. *et al.*, Optica 3, 2016

$Q_o \sim 10^8$
BW ~ 1 MHz
0.1 % efficiency

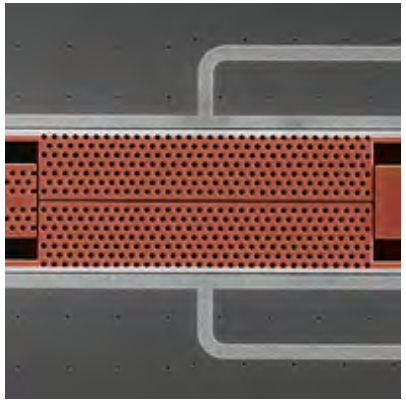
Outline

I: Motional Ground State Cooling of a Si3N4 Nanobeam



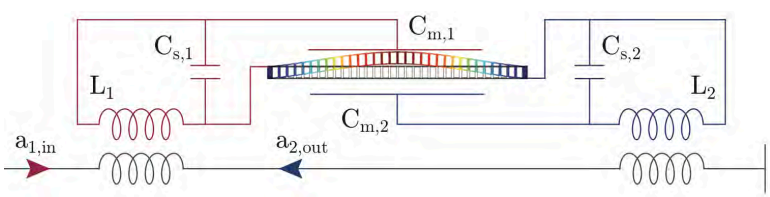
J. M. Fink *et al.*, Nat. Commun. (in print)

III: Cavity Electromechanics on Silicon-on-Insulator



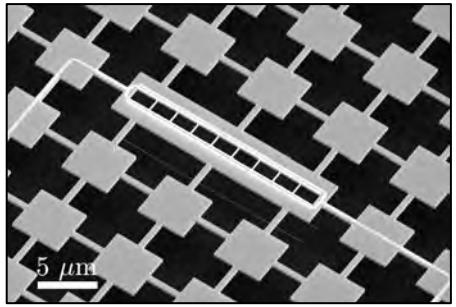
P. B. Dieterle, M. Kalaee, *et al.*, Phys. Rev. Applied 6, 2016

II: All-Microwave Frequency-Conversion

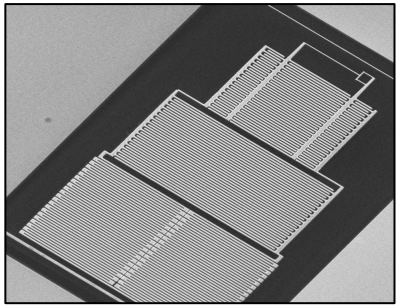


J. M. Fink, M. Kalaee, *et al.* in preparation

IV: Outlook



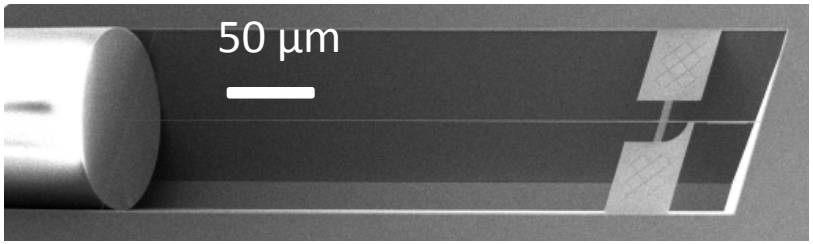
High ω_m



Qubits on SOI

Silicon Nitride

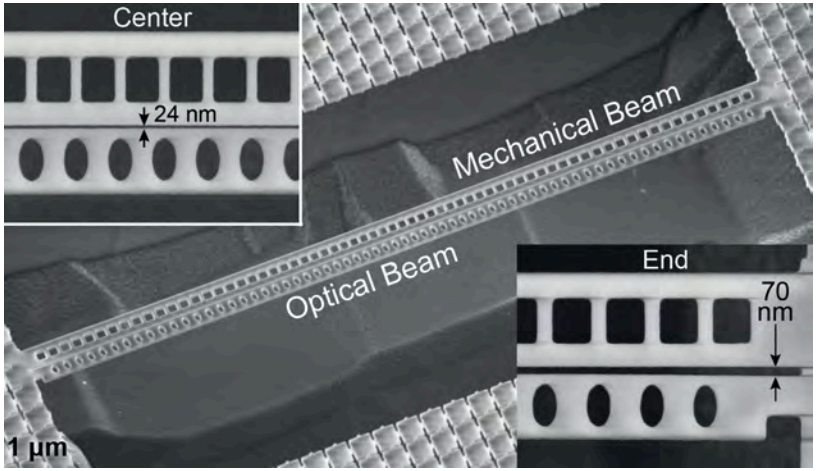
- Very low optical, mechanical and microwave losses
- Excellent fiber to chip coupling efficiency:



J. D. Cohen *et al.*, Opt. Express 21 (2013)

- Slot mode coupled optomechanical crystals:
- Electromechanics has been done but g_o is typically very small, n_m<1 not accessible

P.A. Truitt, et al. Nano Lett. 7 (2007)
X. Zhou, et al. Nat. Phys. 9 (2013)

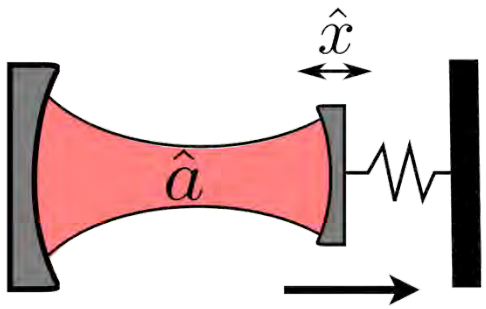


K. E. Grutter, et al., Optica 2 (2015)

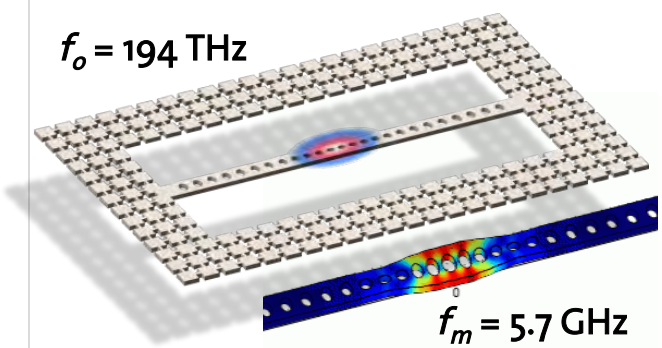
→ How to couple effectively to a small (acoustic) nanobeam?

Making the "smallest" high Q resonators

Optomechanical Coupling



$$\hat{F} = \frac{\hbar\omega_R}{L}\hat{a}^\dagger\hat{a}$$



g_o = 2π 1.1 MHz

J. Chan, *et. al*, Nature **478** (2011)

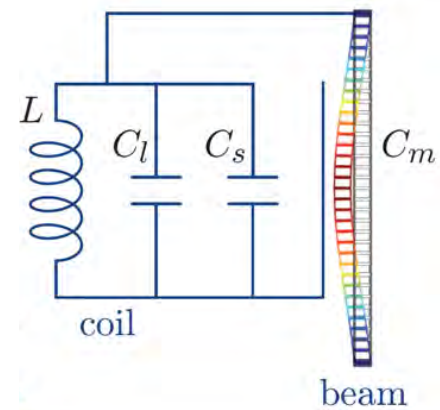
Electromechanical Coupling

$$g_0 = g_{\mathrm{em}} x_{\mathrm{zpf}}$$

$$g_{\mathrm{em}} = \frac{d\omega_{LC}}{dx} = \frac{d\omega_{LC}}{dC_m}\frac{dC_m}{dx}$$

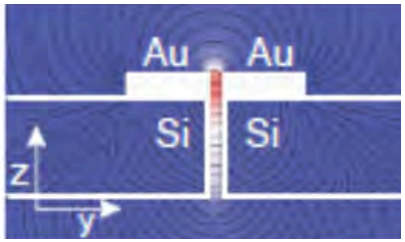
Circuit Geometry

$$\sim \eta \frac{\omega_{\mathrm{LC}}}{2x_0}$$



Geometry

→ small gaps, fringing fields



Circuit

C_s, C_l << C_m ~ 1 fF

maximize impedance

$$Z_0 = \sqrt{L/C_l}$$

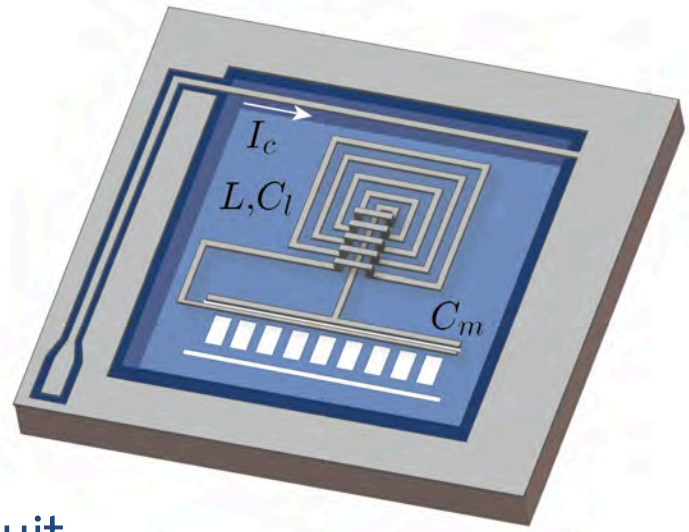
→ remove dielectric

→ miniaturize coils

A. Pitanti, J. M. Fink, et al., Opt. Expr. 23 (2015)

Silicon Nitride Chip Design

Schematic



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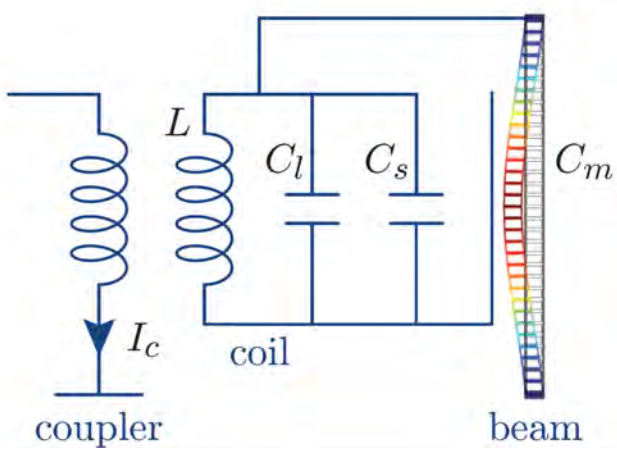
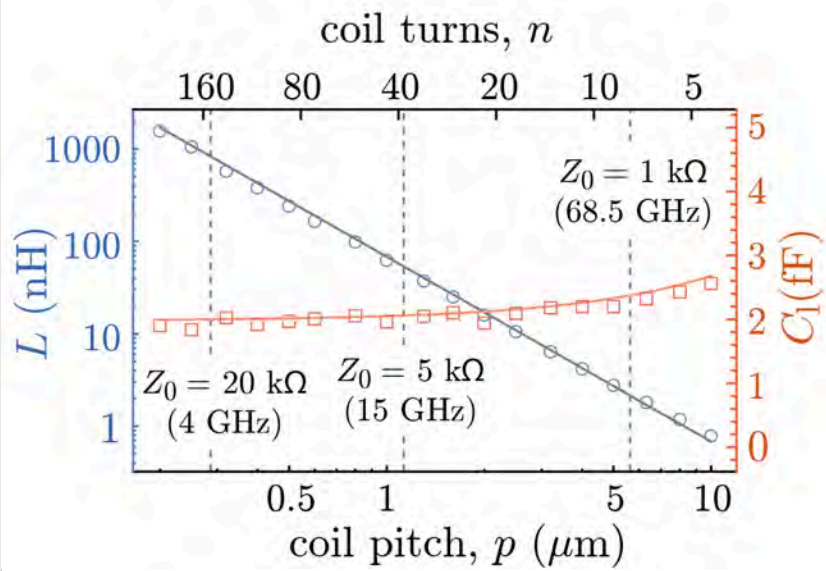


High Z_0 Inductors (const. area)



At constant frequency

$L \propto n$	$L \propto p^{-1/2}$
$C \propto 1/n$	$C \propto p^{1/2}$
$Z_0 \propto n$	$Z_0 \propto p^{-1/2}$

→ Great for coupling any small dipole moment object!

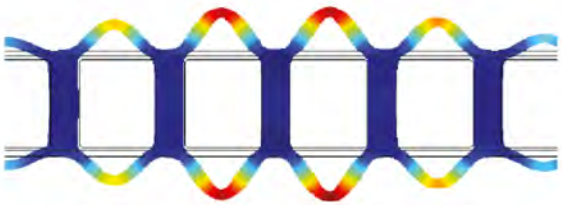
→ Localizes charge *(geometric superinductor)* $R_q = \hbar/(2e)^2$

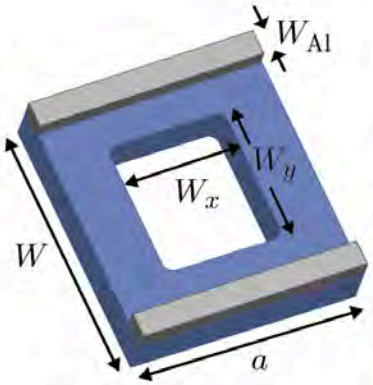
J. M. Fink *et al.*, Nat. Commun. (in print)

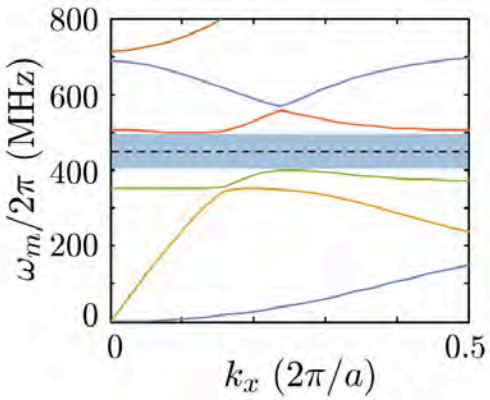
Silicon Nitride Chip Design

Mechanics: 4.5 MHz

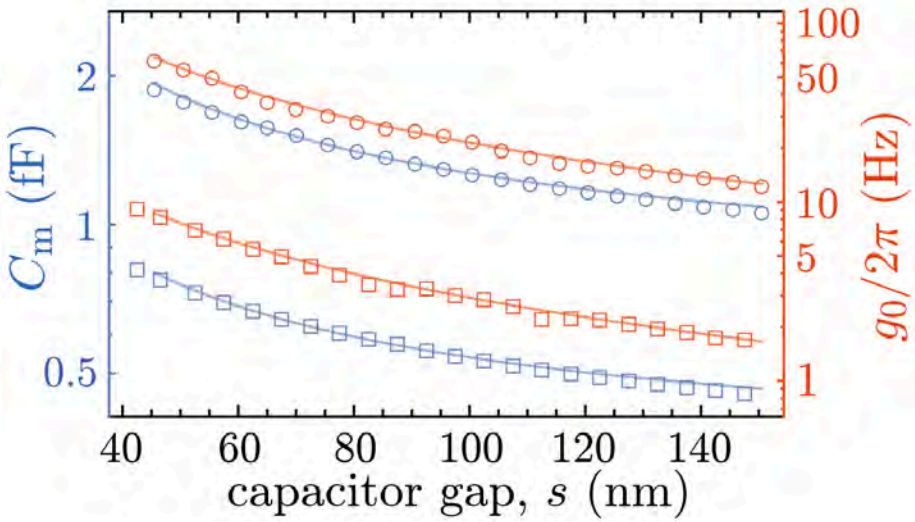
Mechanics: 460 MHz





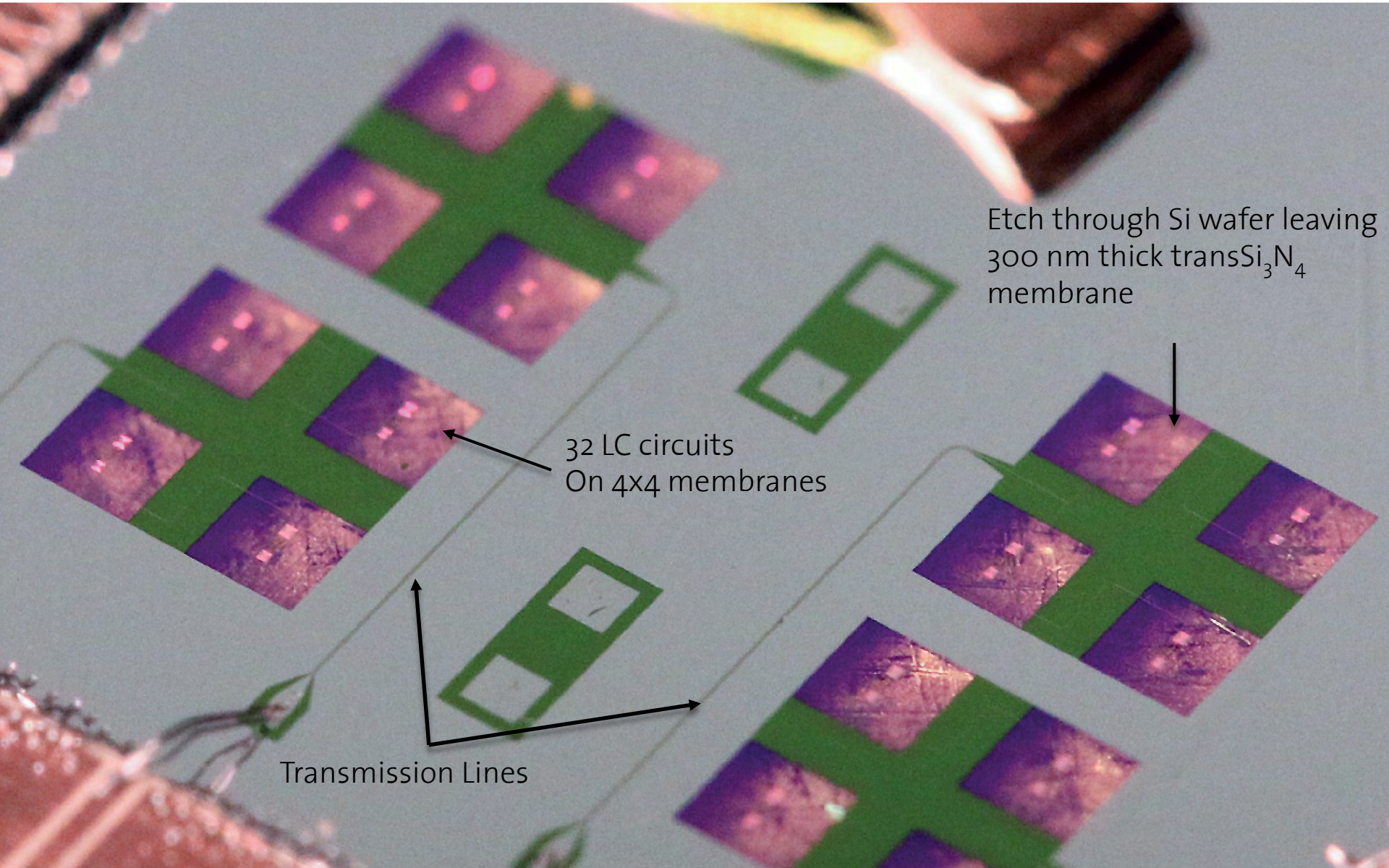


Numerical Simulations of g_0



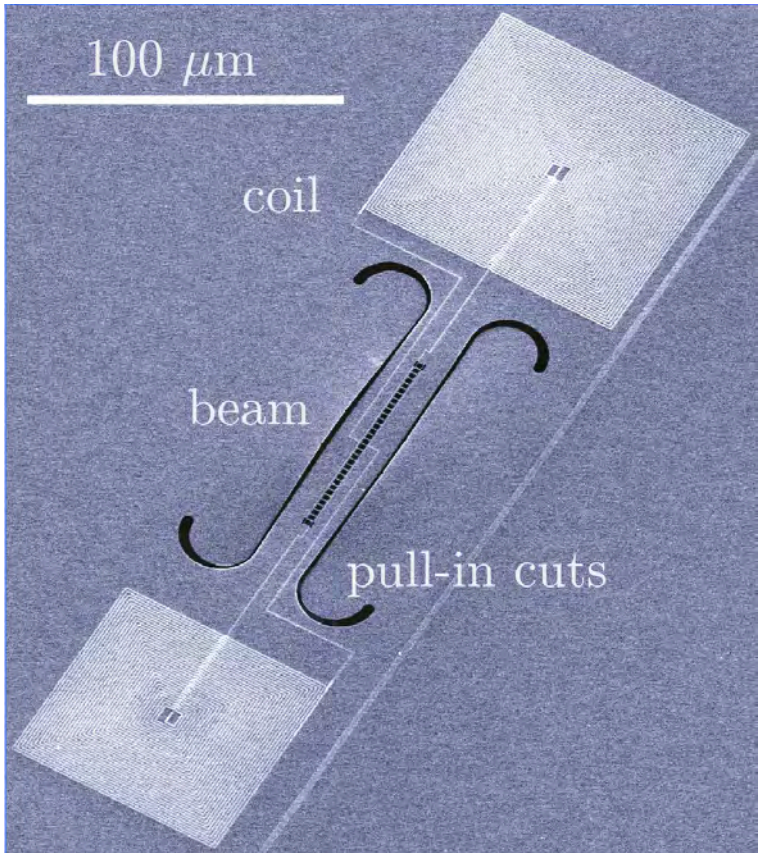
J. M. Fink *et al.*, Nat. Commun. (in print)

Si3N4 Through Chip Membrane Devices

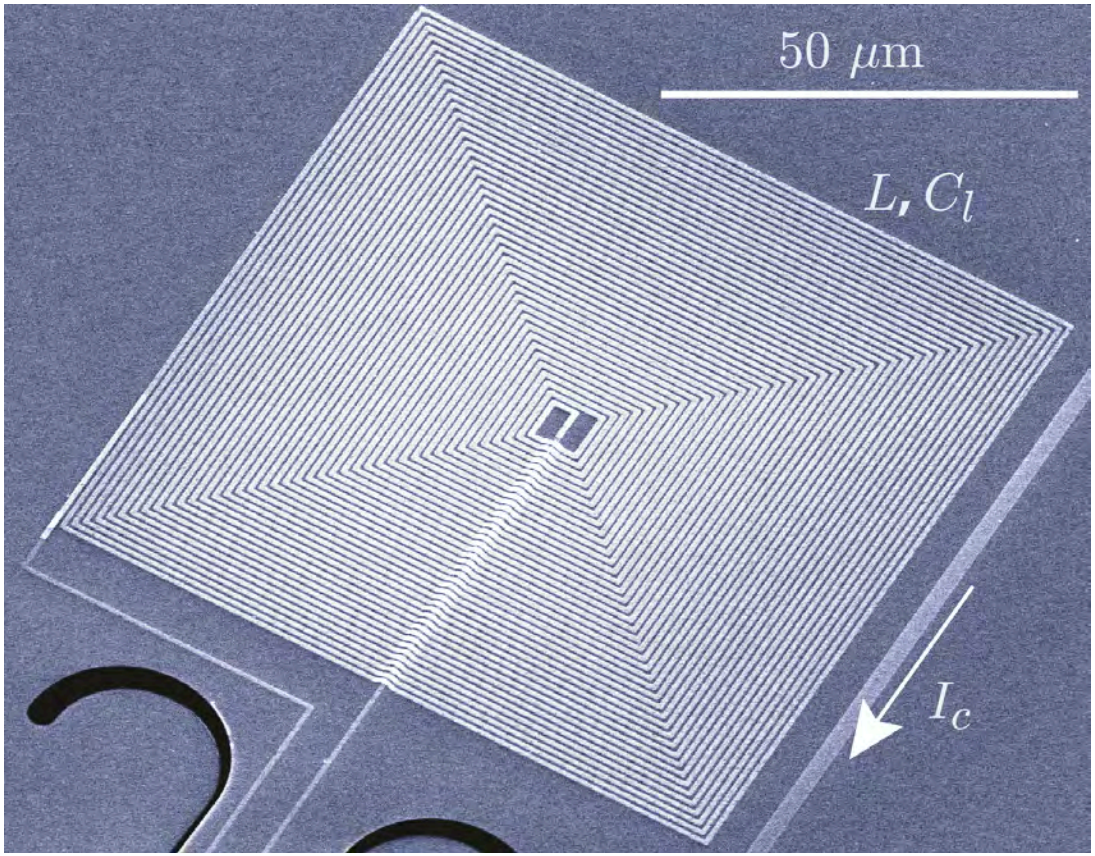


On-membrane circuit

Double cavity device



Top coil



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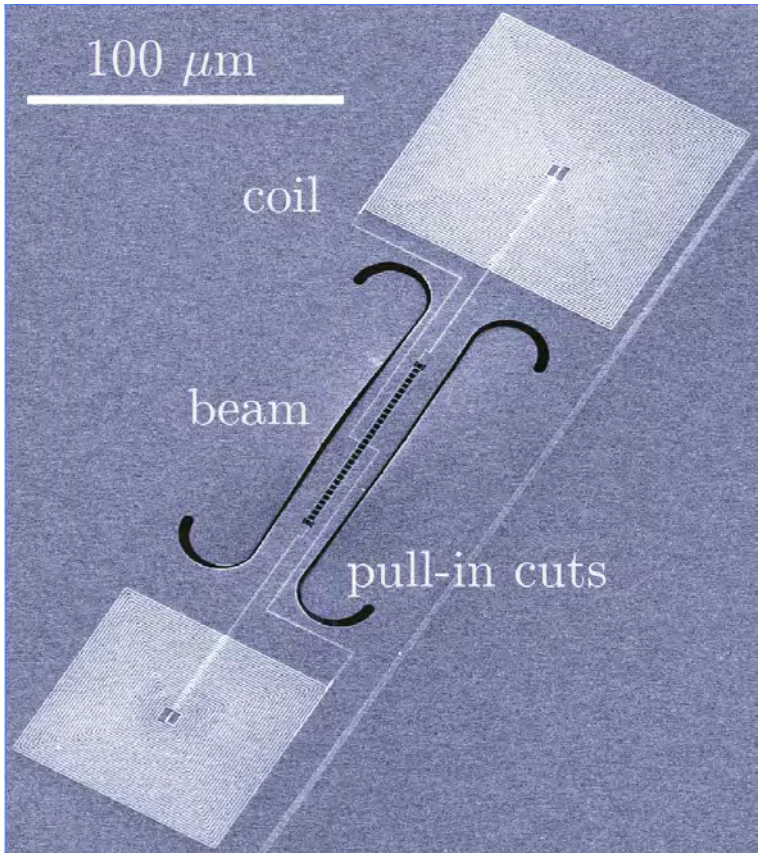
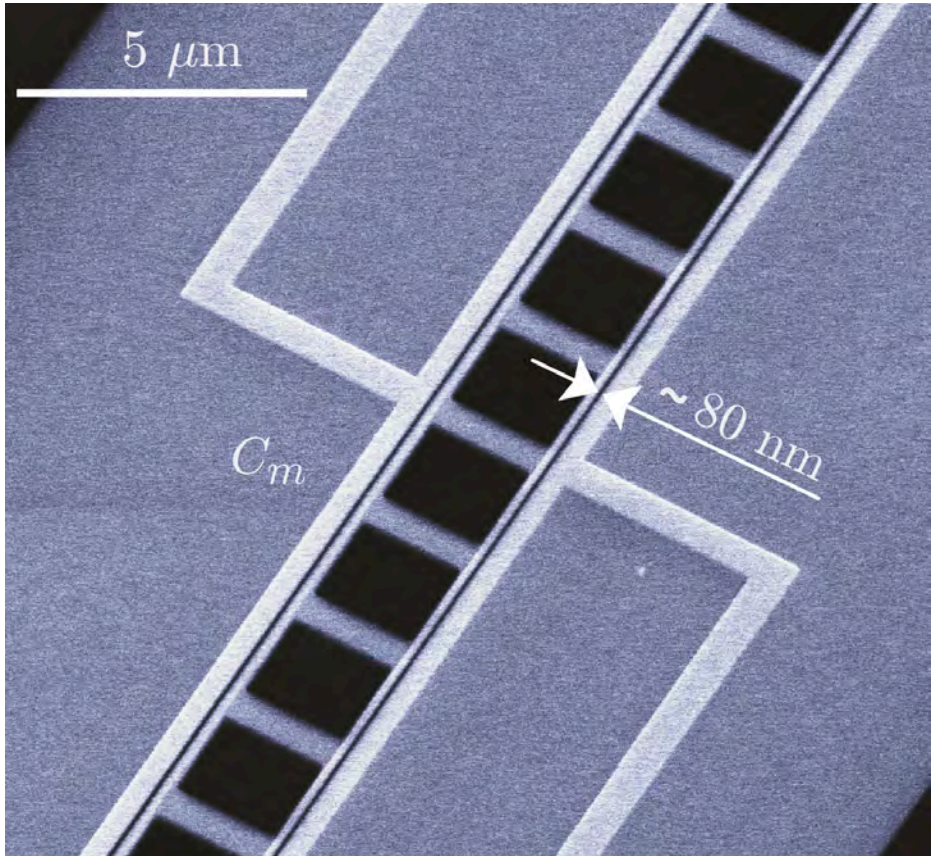


Nanobeam



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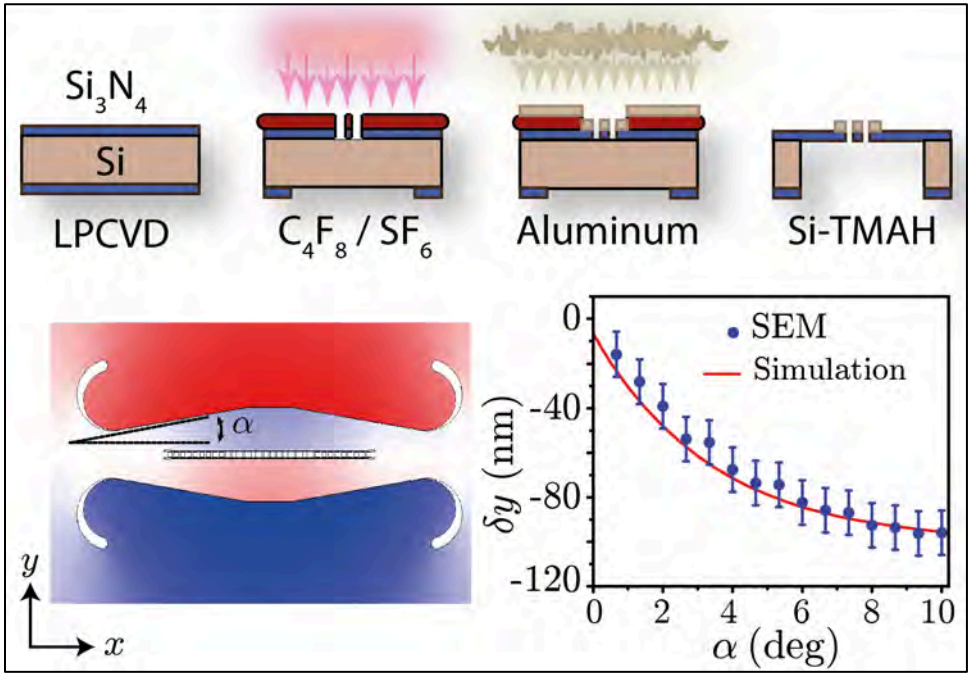
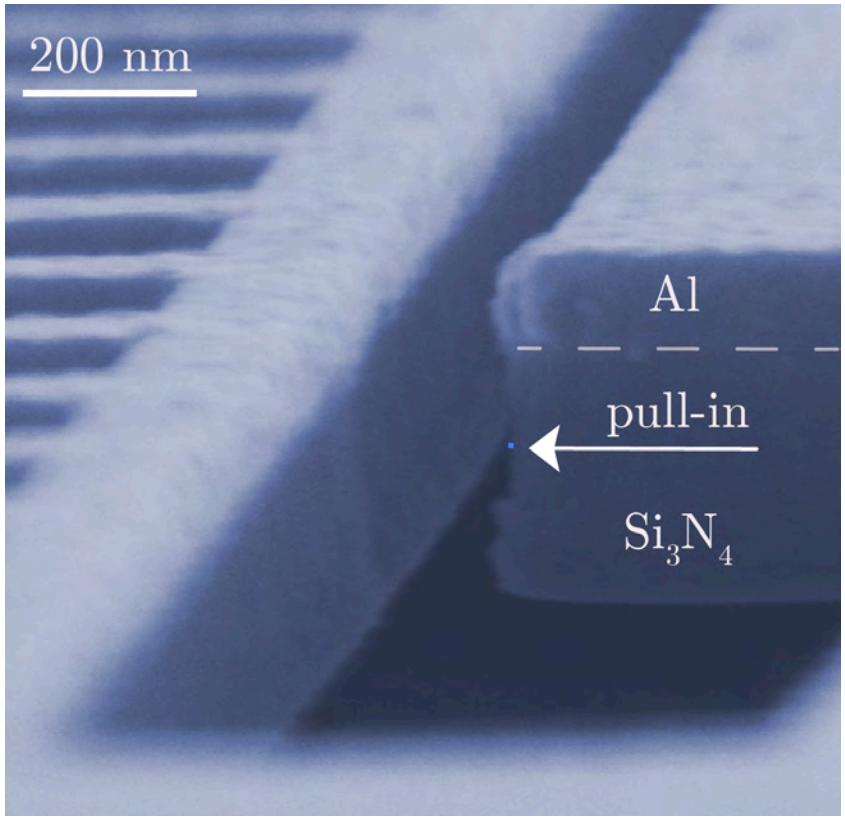
Fabrication

Key fab steps

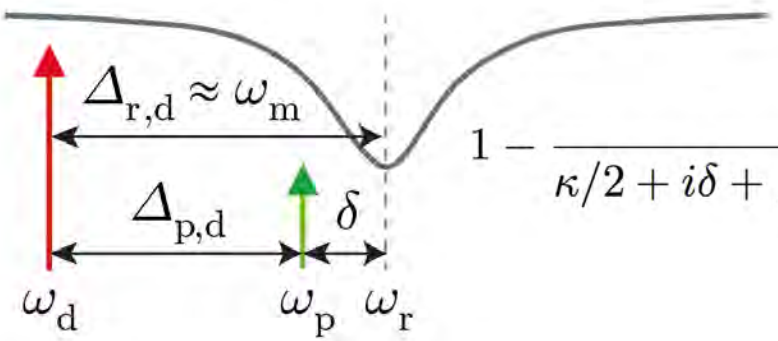


Gap view

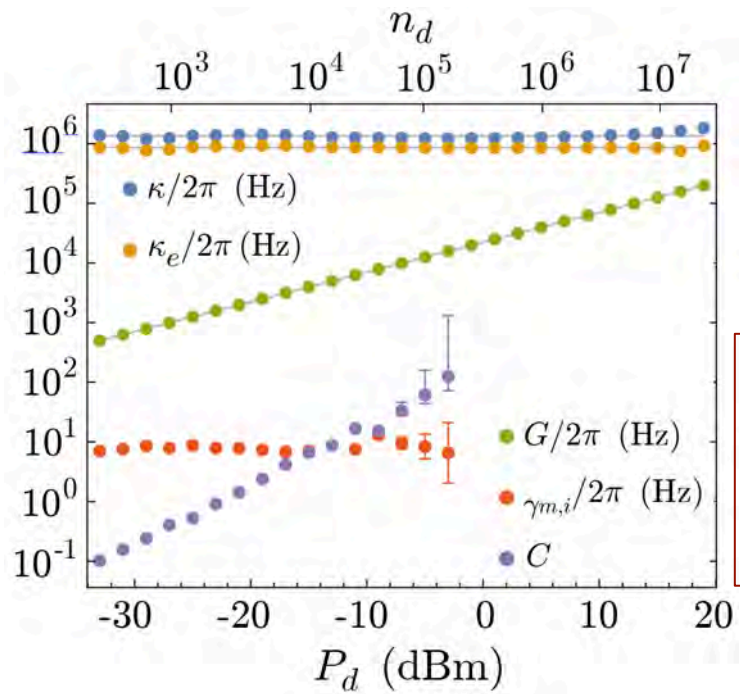


J. M. Fink *et al.*, Nat. Commun. (in print)

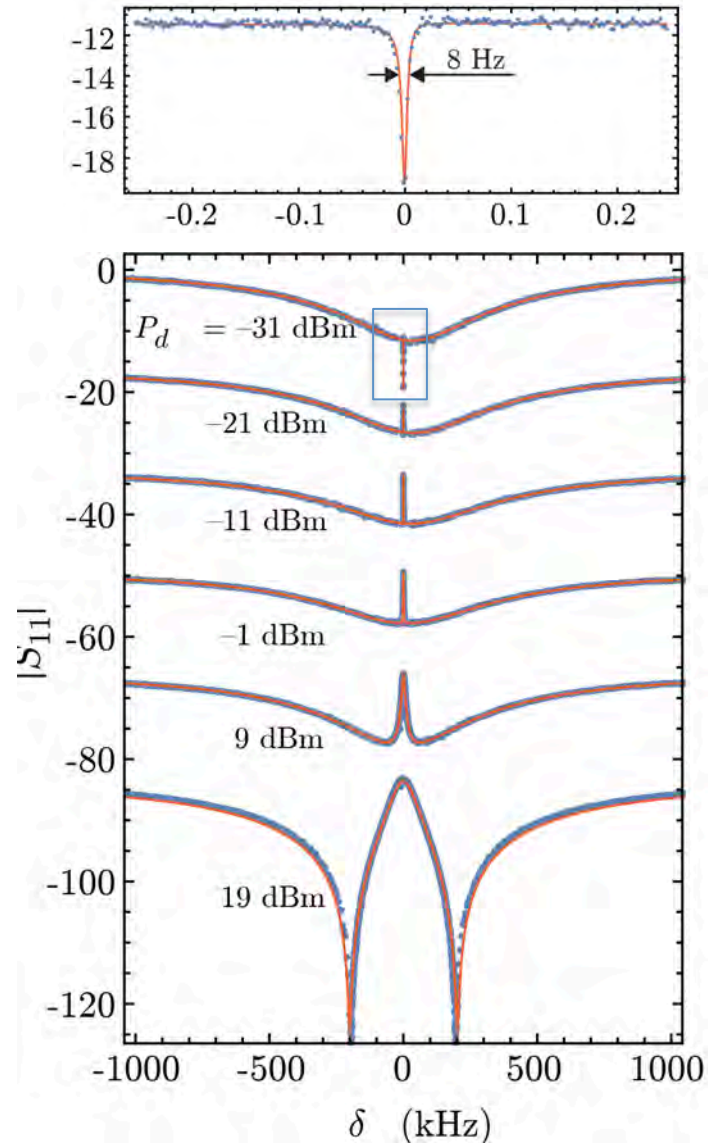
Coherent Response: EIT



$$1 - \frac{\kappa_e}{\kappa/2 + i\delta + \frac{2G^2}{\gamma_{m,i} + i2(\delta - (\omega_m - \Delta_{r,d}))}}$$



→ $n_d > 10^7$
→ $Q_m \sim 5\times10^5$
→ $G/\pi \sim 400$ kHz
→ $C_{max} \sim 10^4$



J. M. Fink *et al.*, Nat. Commun. (in print)

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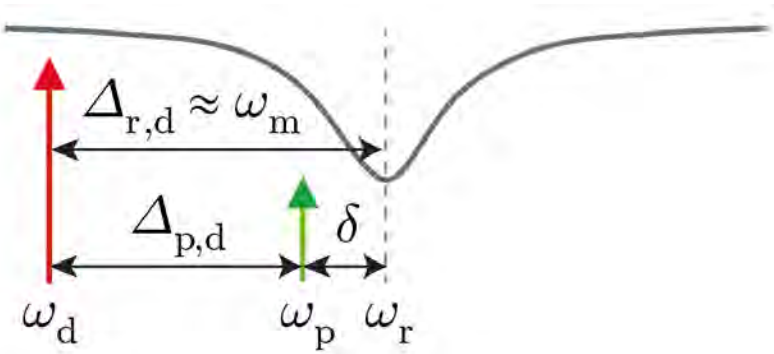
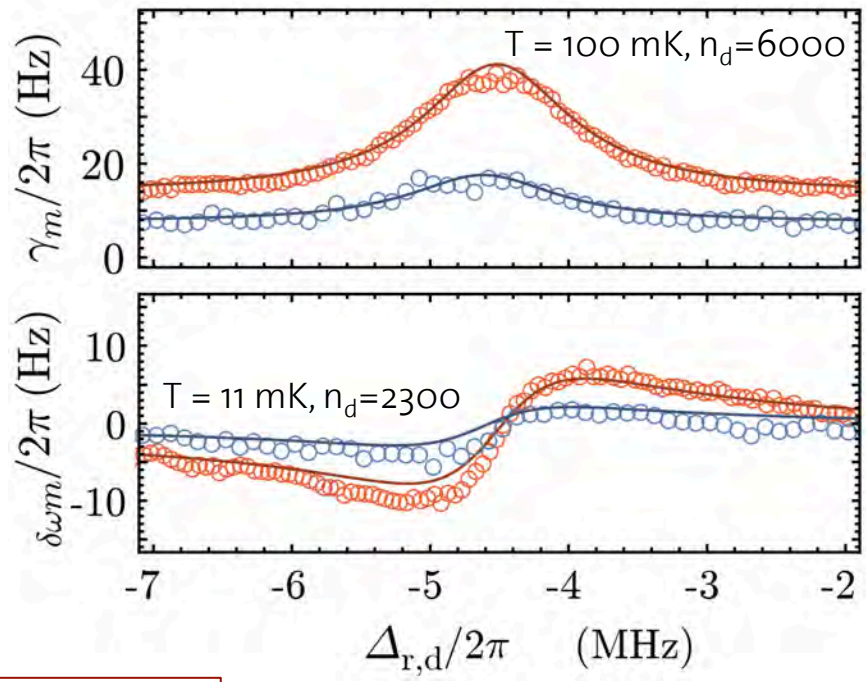
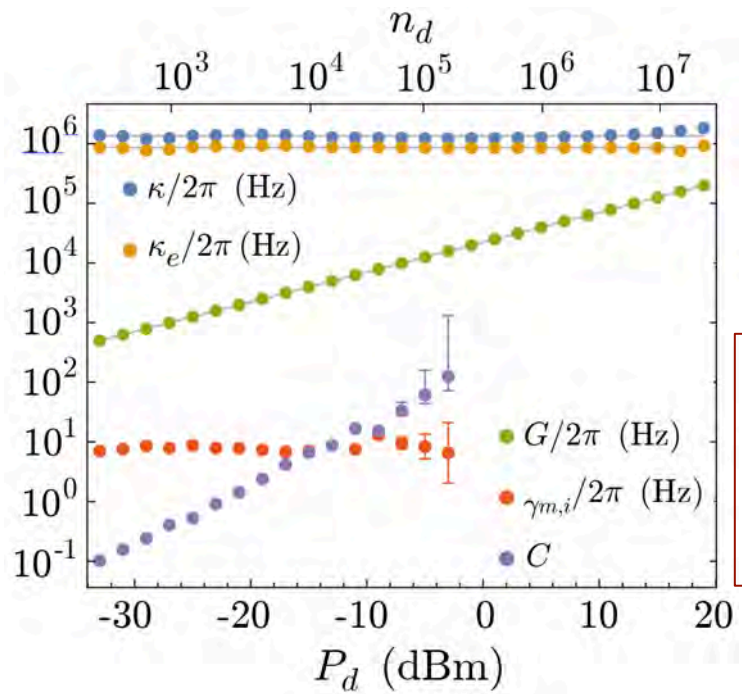


"Optical" damping and spring shift





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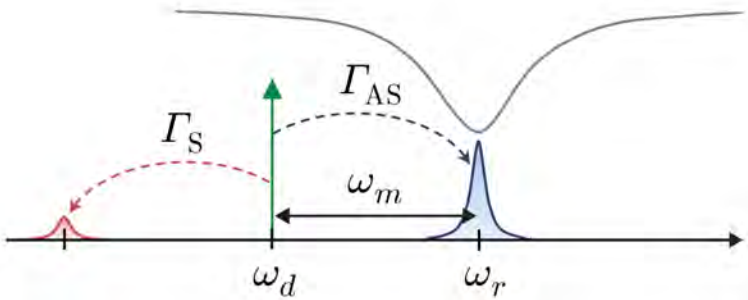
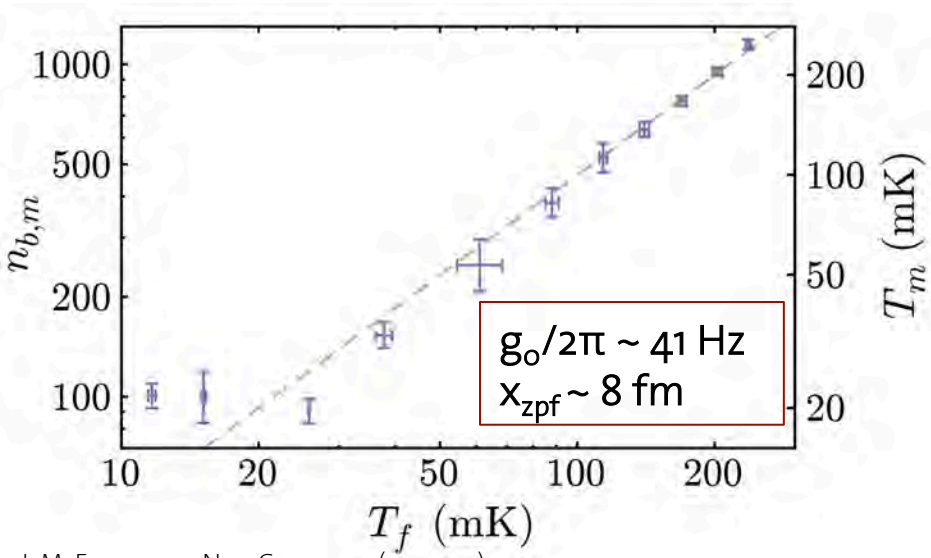
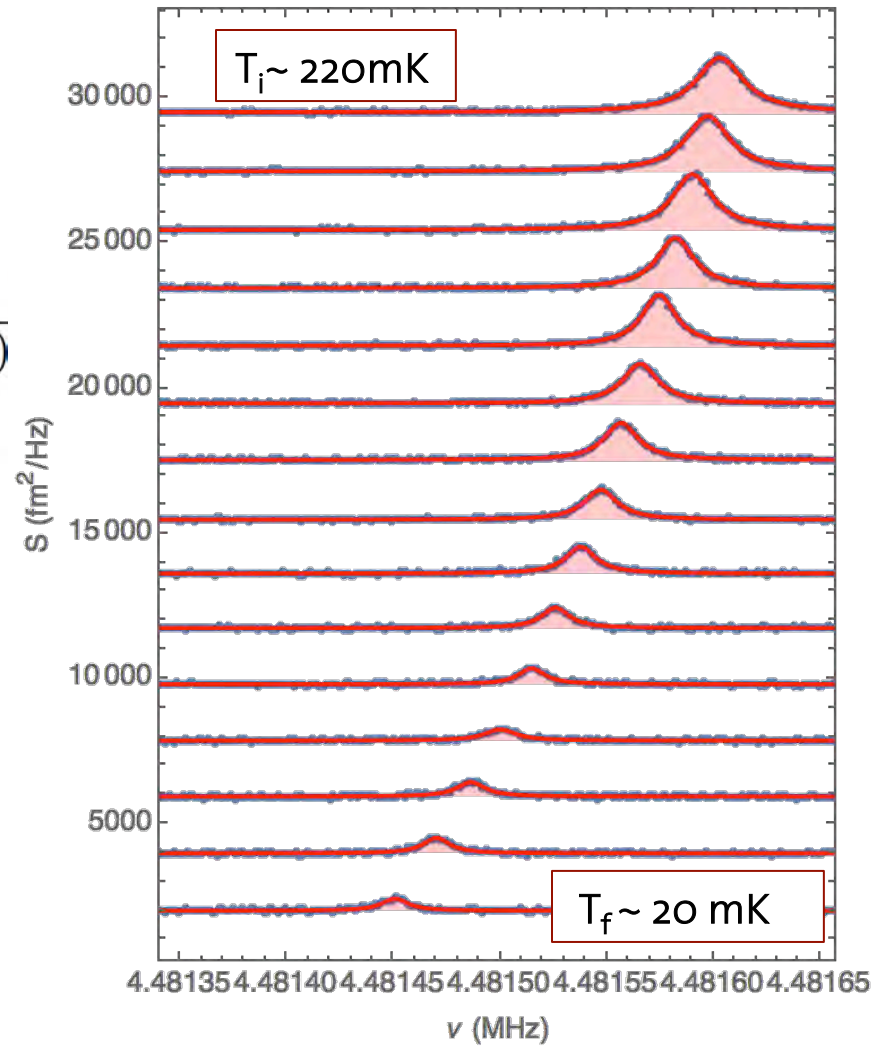
Thermometry Calibration (C<<1)



$$\frac{S(\omega)}{P_{\text{ref}}} \approx \mathcal{O} + \frac{16 g_0^2 \kappa_e^2}{\left((\kappa - 2\kappa_e)^2 + 4\omega_m^2\right)\left(\kappa^2 + 4(\omega_m - \omega)^2\right)} \times \frac{4 n_{b,m} \gamma_{m,i}}{\gamma_{m,i}^2 + 4(\omega - \omega_m)^2}.$$





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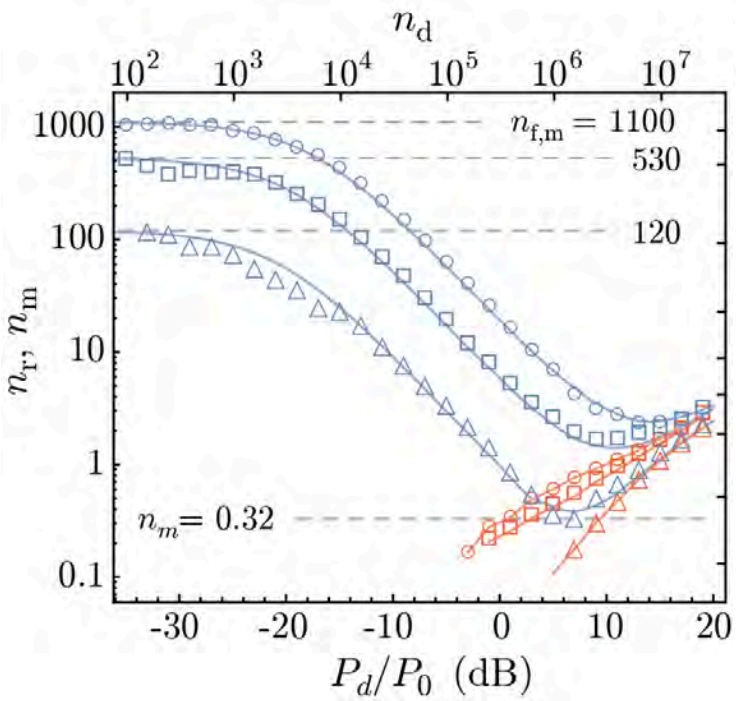
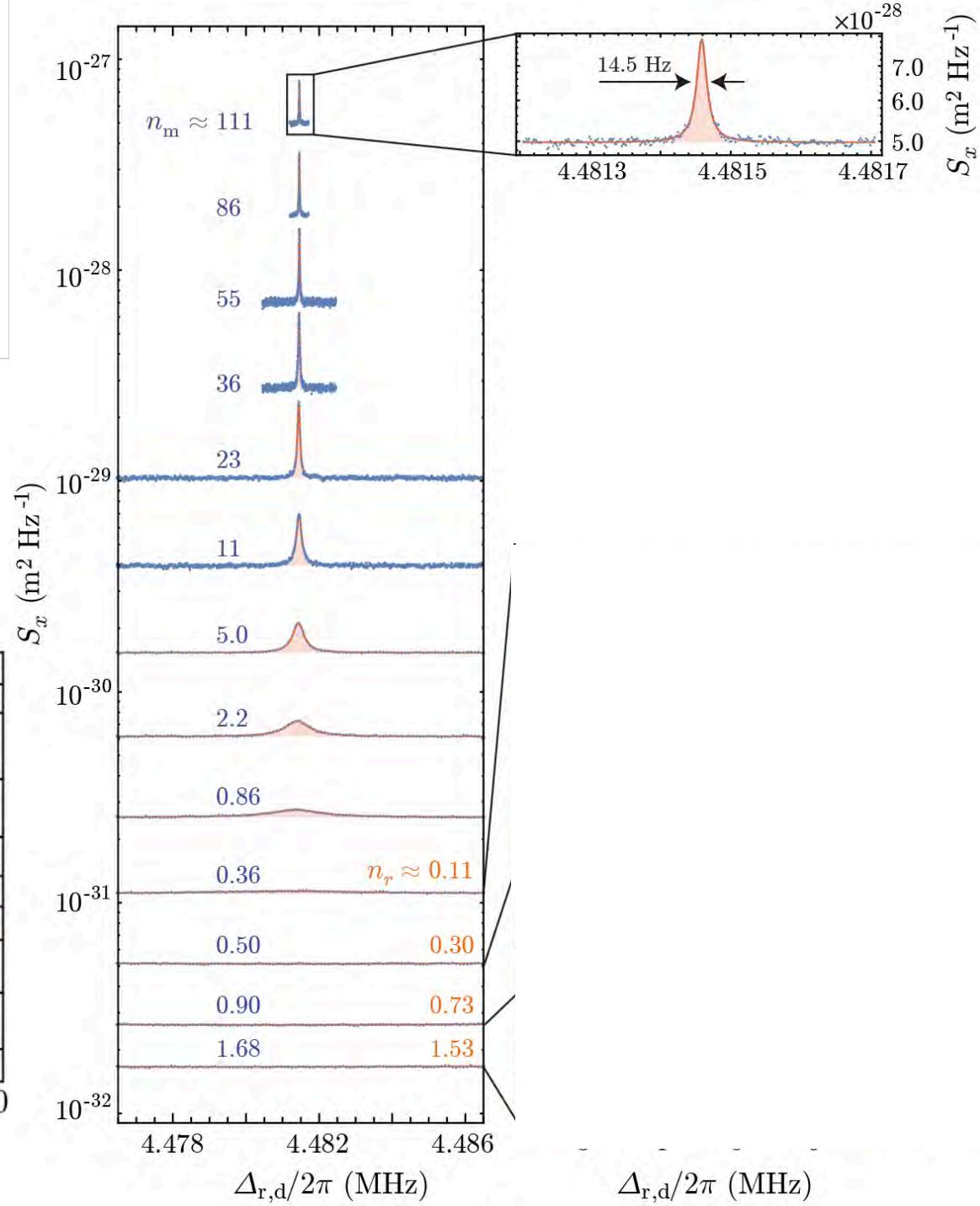
Motional Ground State Cooling





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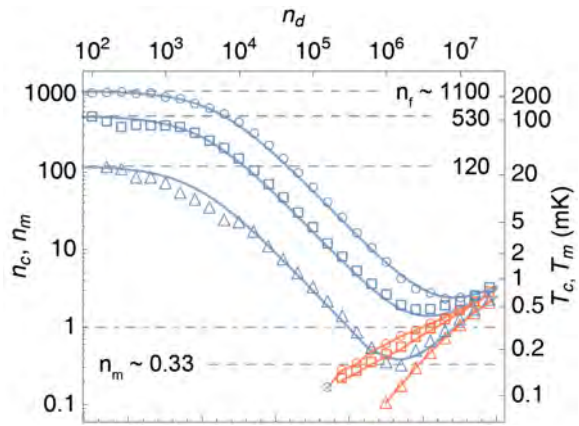

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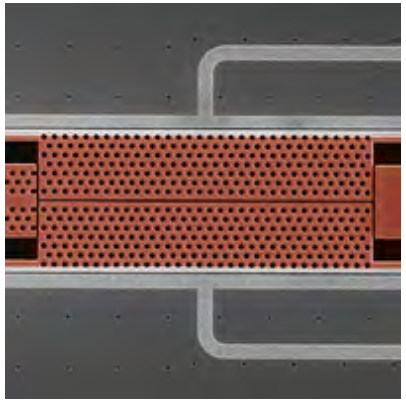

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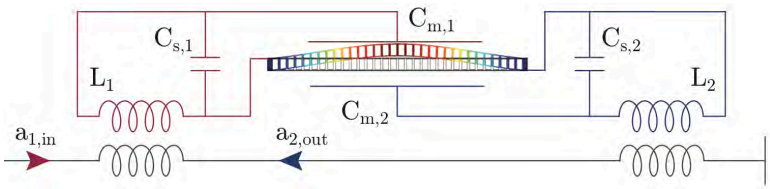
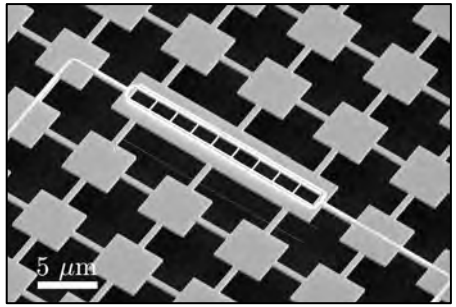
II: All-Microwave Frequency-Conversion

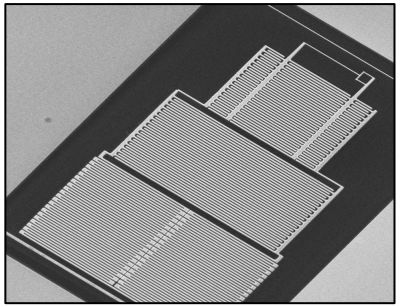


J. M. Fink, M. Kalaee, *et al.* in preparation

IV: Outlook

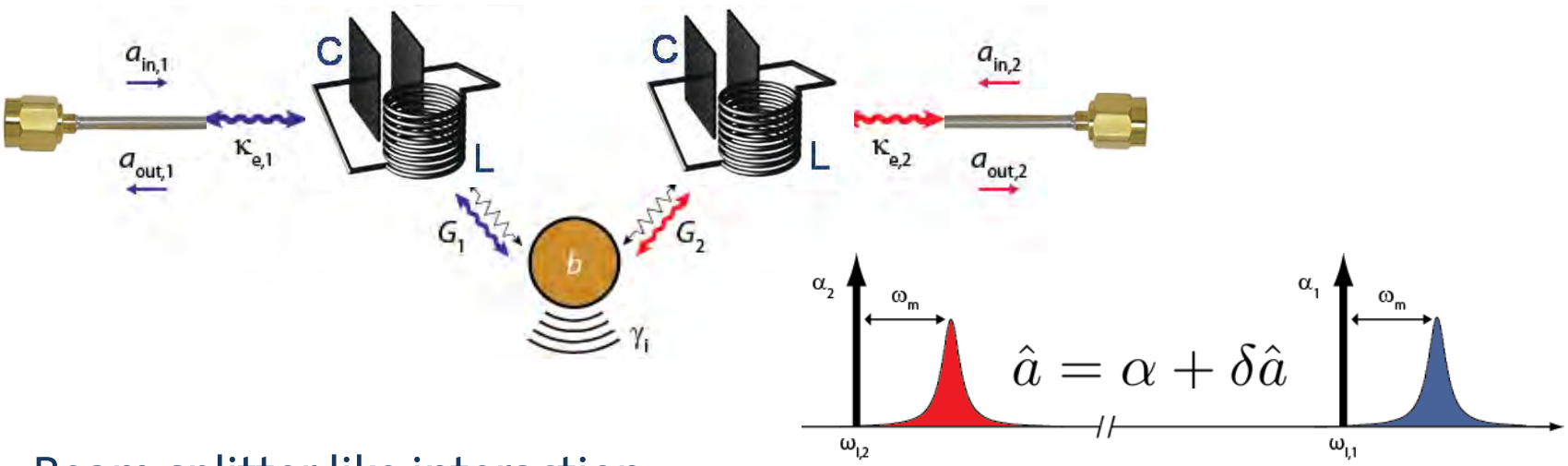


High ω_m



Qubits on SOI

II: All-Microwave Wavelength Conversion



Beam splitter like interaction

$$\hat{H}_{\rm int} = \hbar G_1(\hat{a}_1^\dagger \hat{b} + \hat{a}_1 \hat{b}^\dagger) + \hbar G_2(\hat{a}_2^\dagger \hat{b} + \hat{a}_2 \hat{b}^\dagger)$$

$$G_k = g_k \sqrt{n_{{\rm c},k}}$$

Conversion efficiency

$$\eta_{\rm max,int} = \frac{4C_1C_2}{(1+C_1+C_2)^2}$$

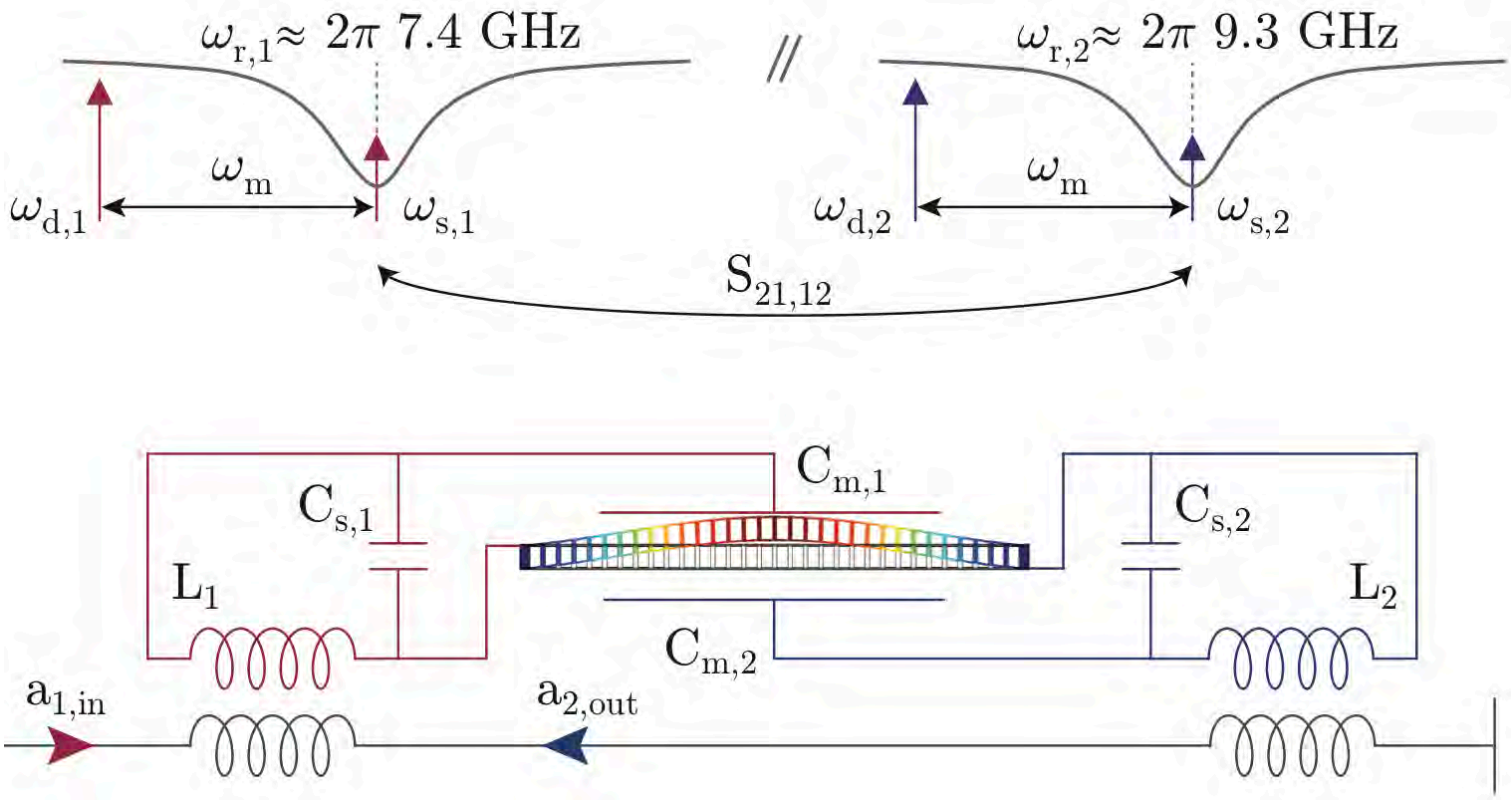
$$C_k = \gamma_{{\rm OM},k}/\gamma_{\rm i} \qquad \gamma_{{\rm OM},k} = 4G_k^2/\kappa_k$$

Beat losses: $C_1 \; C_2 \gg 1$

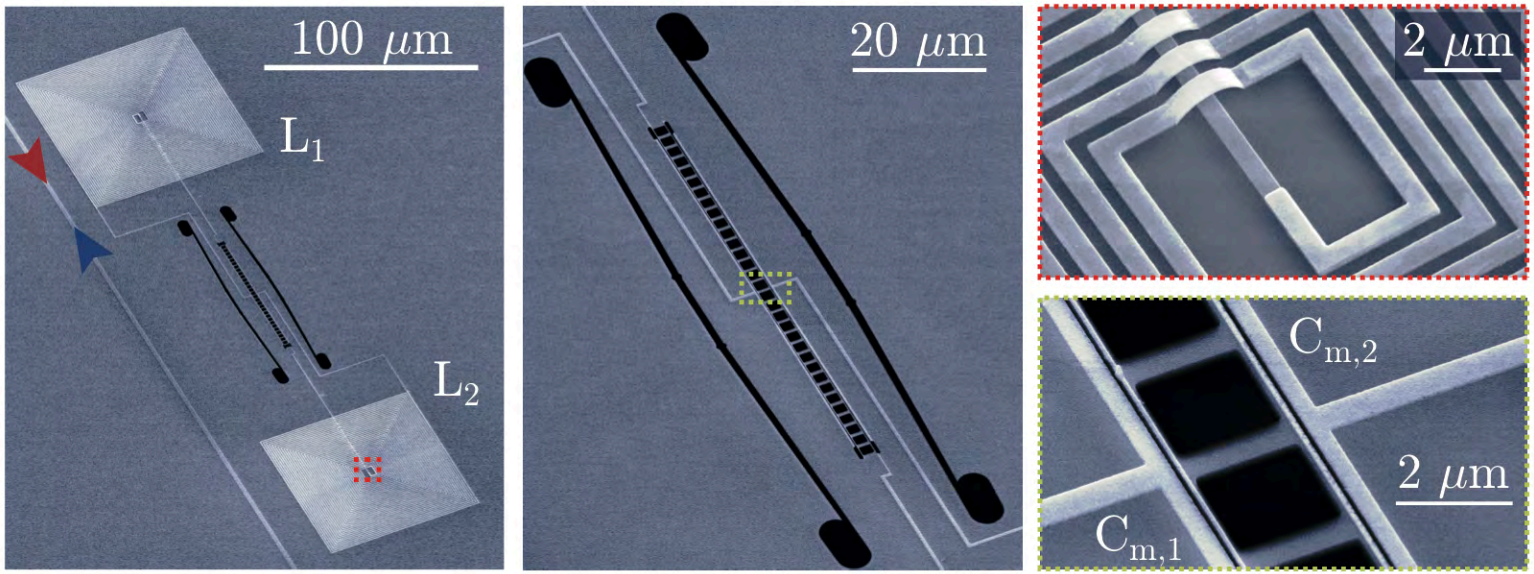
Impedance matching: $C_1 = C_2$

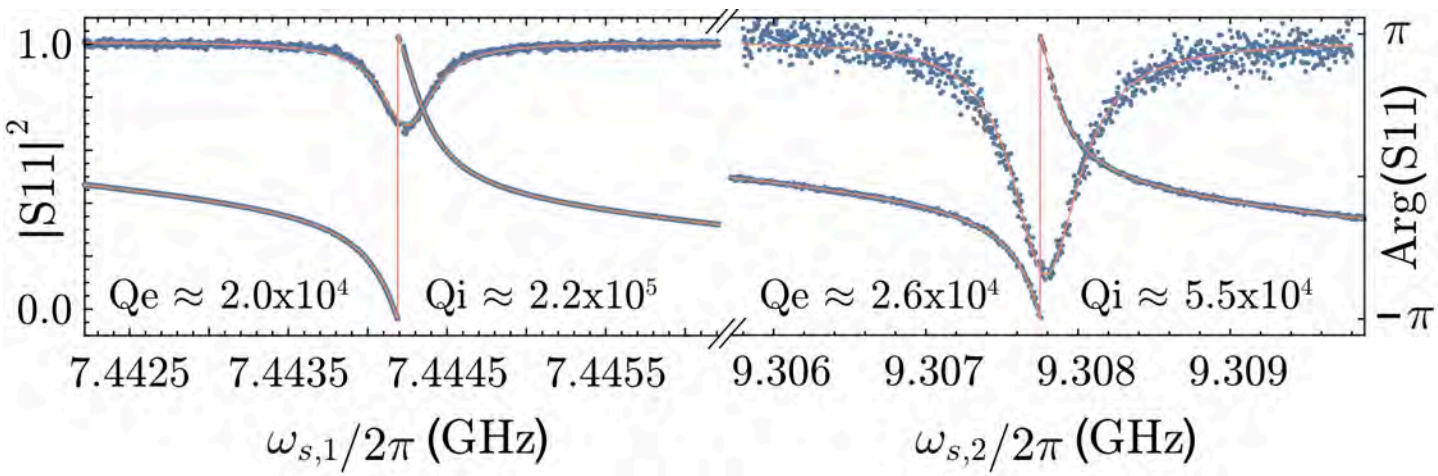
Safavi-Naeini, A. H. *et al.*, NJP **13**, 013017 (2011)
Wang, Y. and Clerk, A., PRL **108**, (2012)
Vitali, D. *et al.*, PRL **109**, (2012)
Hill, J. T. *et al.*, Nat. Commun. **3**, (2012)

Scheme / Circuit

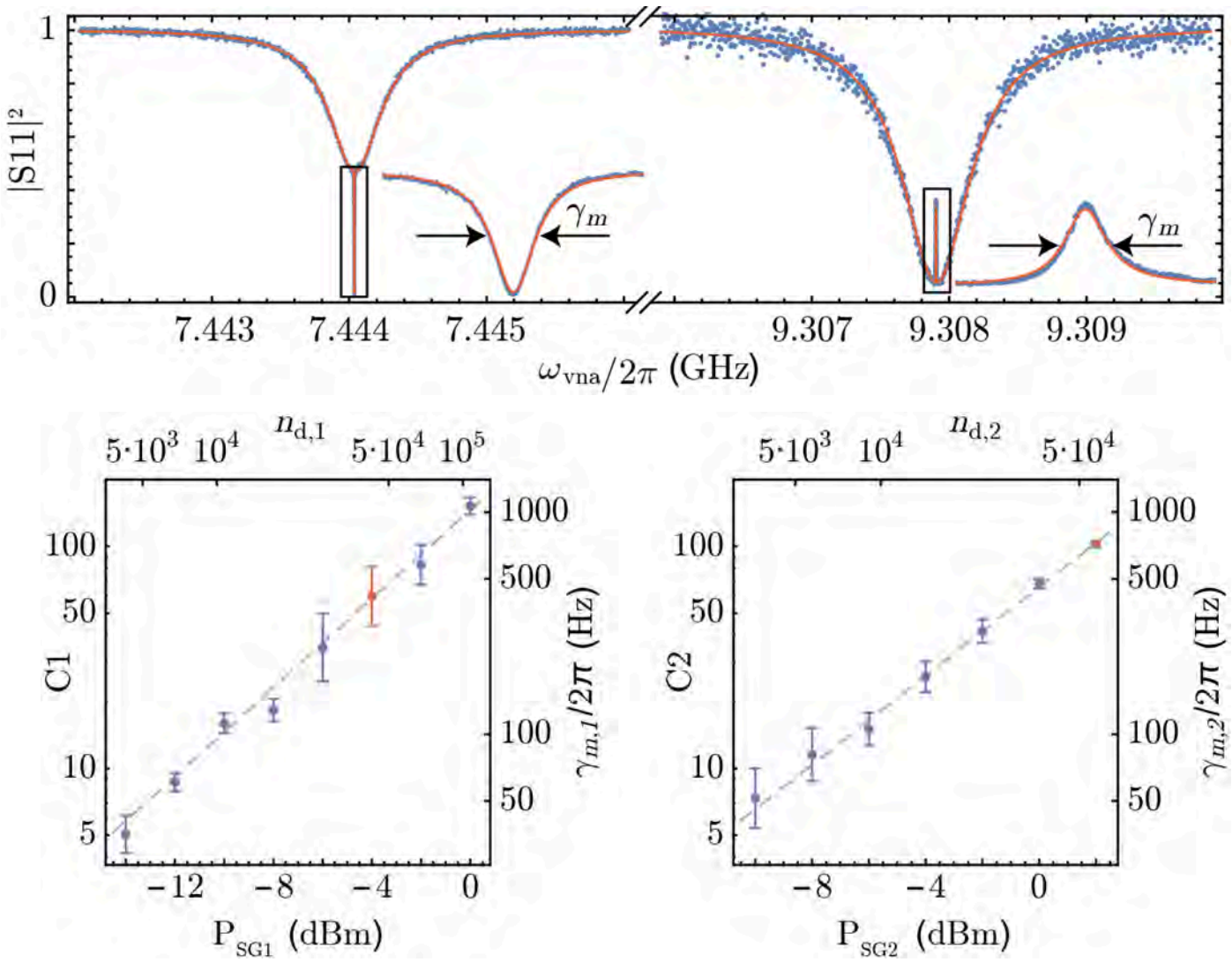


Sample / Qs


100 μm
L1
L2
20 μm
2 μm
Cm,2
2 μm
Cm,1


1.0
0.0
|S11|²
Qe ≈ 2.0x10⁴
Qi ≈ 2.2x10⁵
Qe ≈ 2.6x10⁴
Qi ≈ 5.5x10⁴
π
−π
Arg(S11)
7.4425
7.4435
7.4445
7.4455
9.306
9.307
9.308
9.309
ωs,1/2π (GHz)
ωs,2/2π (GHz)

Double EIT / Cooperativity

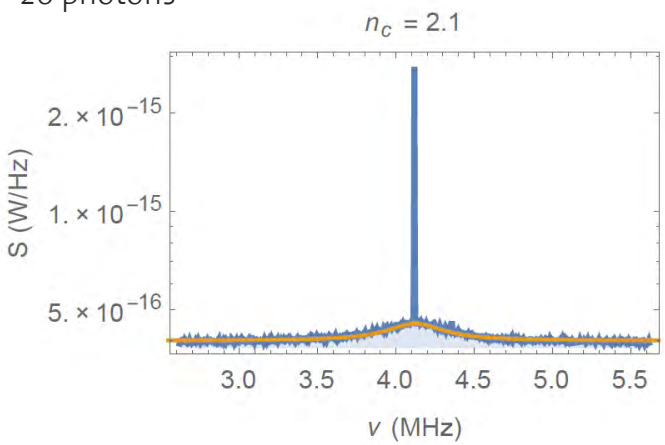


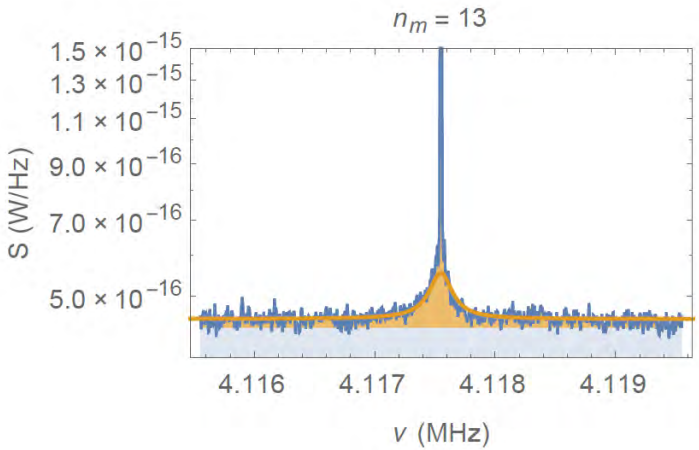
→ γ/2pi: 7 / 8 Hz
→ go/2pi: 33 / 44 Hz

Noise properties

Conversion:

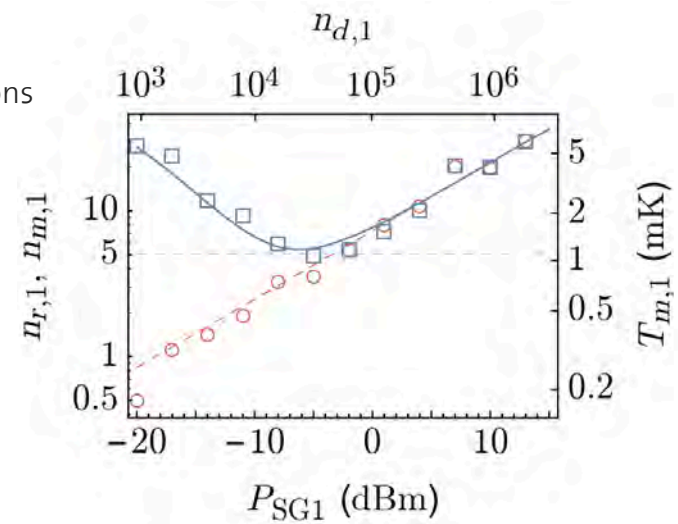
P_{signal} = - 60 dBm ~ 26 photons

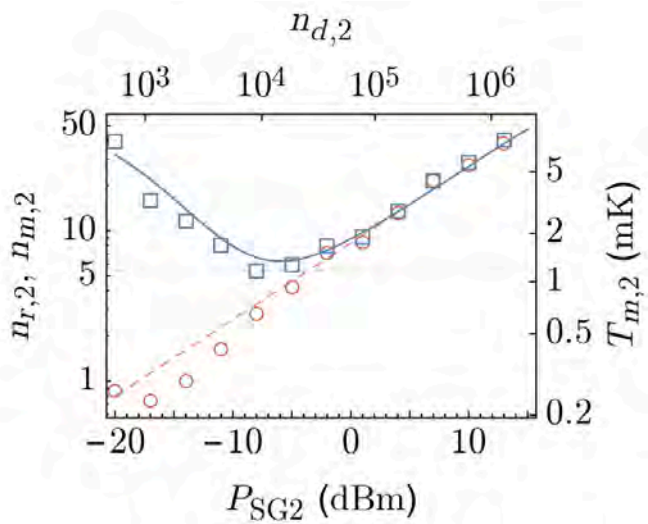




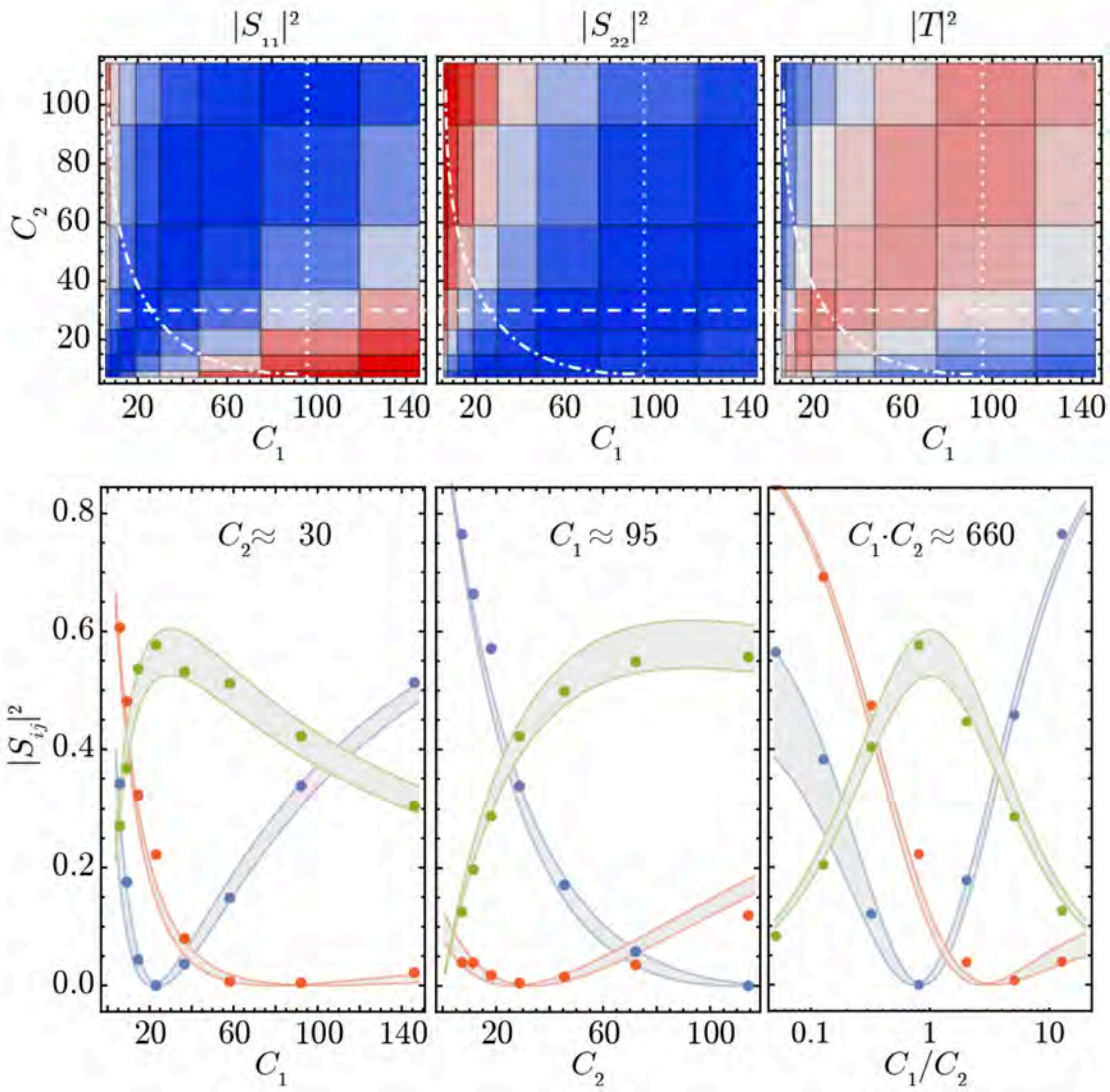
Noise:

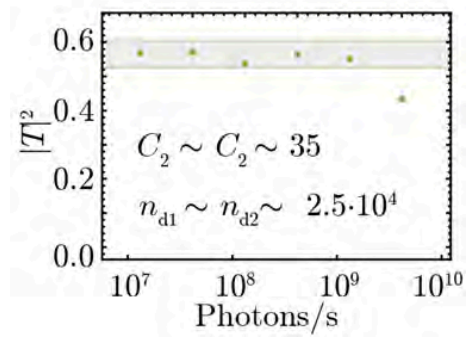
Added noise: ~ 5 phonons

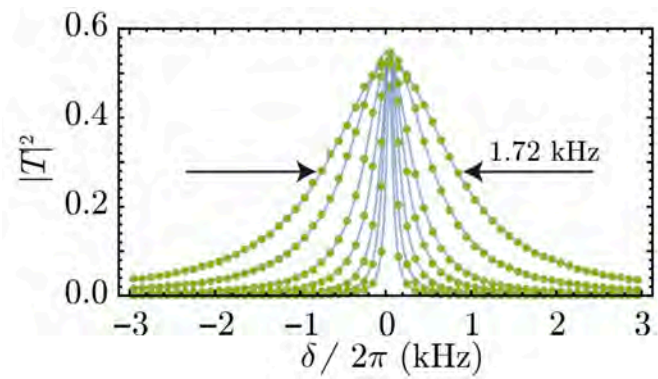




Conversion Efficiency







$$|T| = \eta_1 \eta_2 \frac{4C_1C_2}{(1+C_1+C_2)^2}$$

$$|R_1| = \left(\frac{(1+C_1+C_2) - 2\eta_1(1+C_2)}{1+C_1+C_2} \right)^2$$

$$|R_2| = \left(\frac{(1+C_1+C_2) - 2\eta_2(1+C_1)}{1+C_1+C_2} \right)^2$$

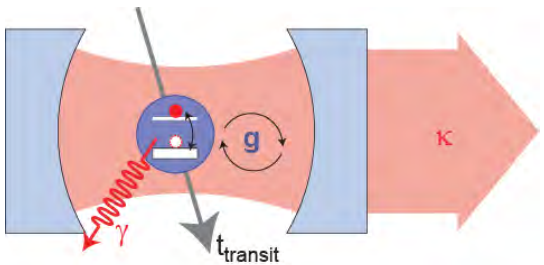
J. M. Fink, M. Kalaee, et al. in preparation

similar recent work from NIST and Aalto

Coherent coupling to microscopic TLS

Cavity QED physics

$$g = E_0 d/\hbar \qquad E_0 \sim (\hbar\omega/V)^{1/2}$$



D. Walls & G. Milburn, Quantum Optics (1994)

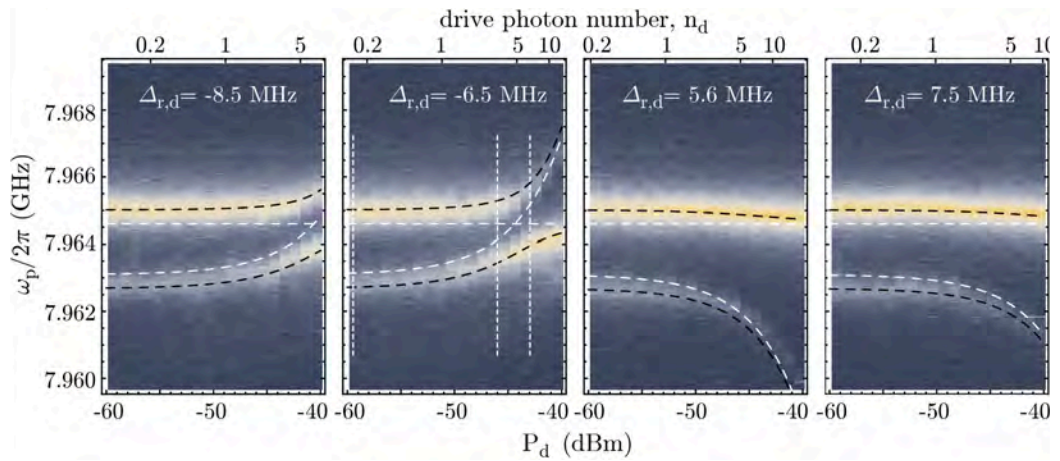
Facilitated by high impedance and extreme electric field confinement

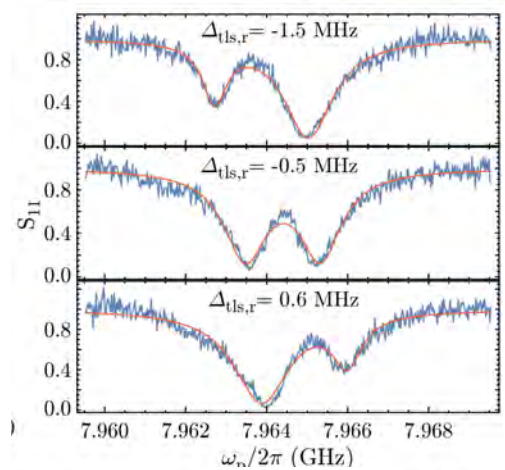
→ ~ 340 V/m for single photon in the gap

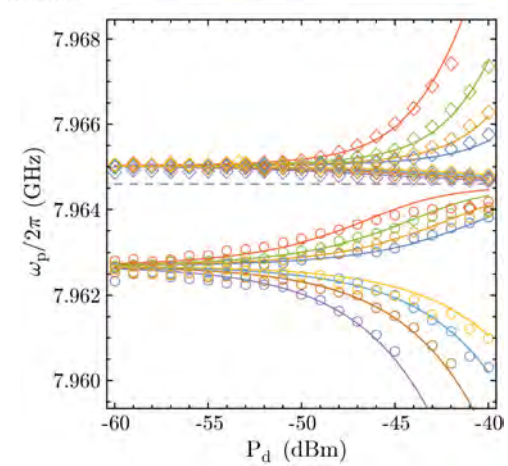
→ |d|>0.7 Debye

→ provides accurate ac-Stark photon number calibration

Vacuum Rabi splitting, ac Stark tuning







$$\tilde{\omega}_{\rm tls} \approx \omega_{\rm tls} + \frac{\Omega_R^2}{2\Delta_{\rm tls,d}} \qquad \Omega_R = 2g_{0,\rm tls}\sqrt{n_d}$$

J. M. Fink *et al.*, Nat. Commun. (in print)

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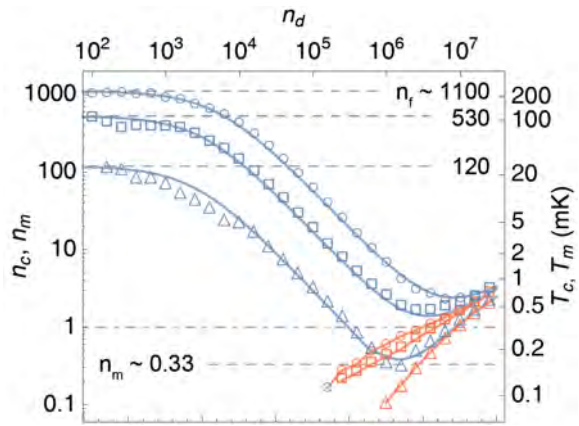

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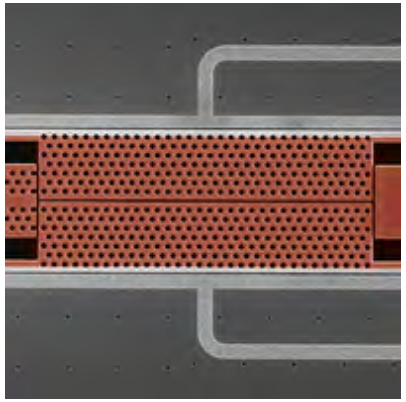

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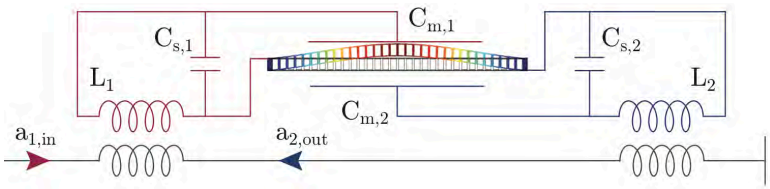

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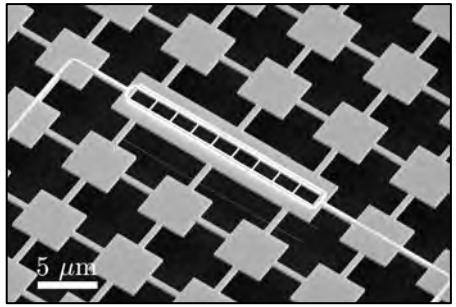
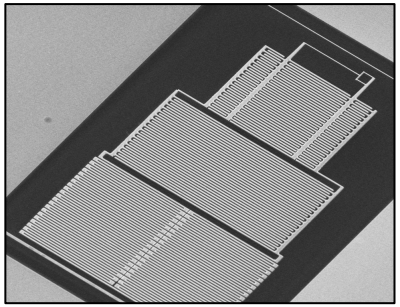


High ω_m



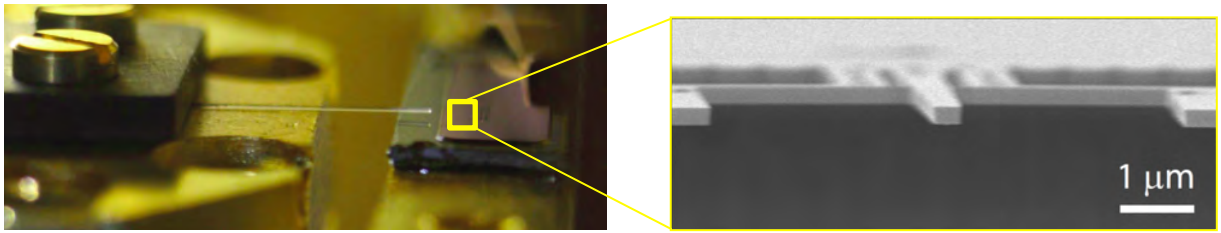
Qubits on SOI

Silicon on Insulator (SOI)

- Very low optical and mechanical losses
  → crystalline – fewer TLS expected

- Large stress-optic constant
  → less optical pump photons necessary

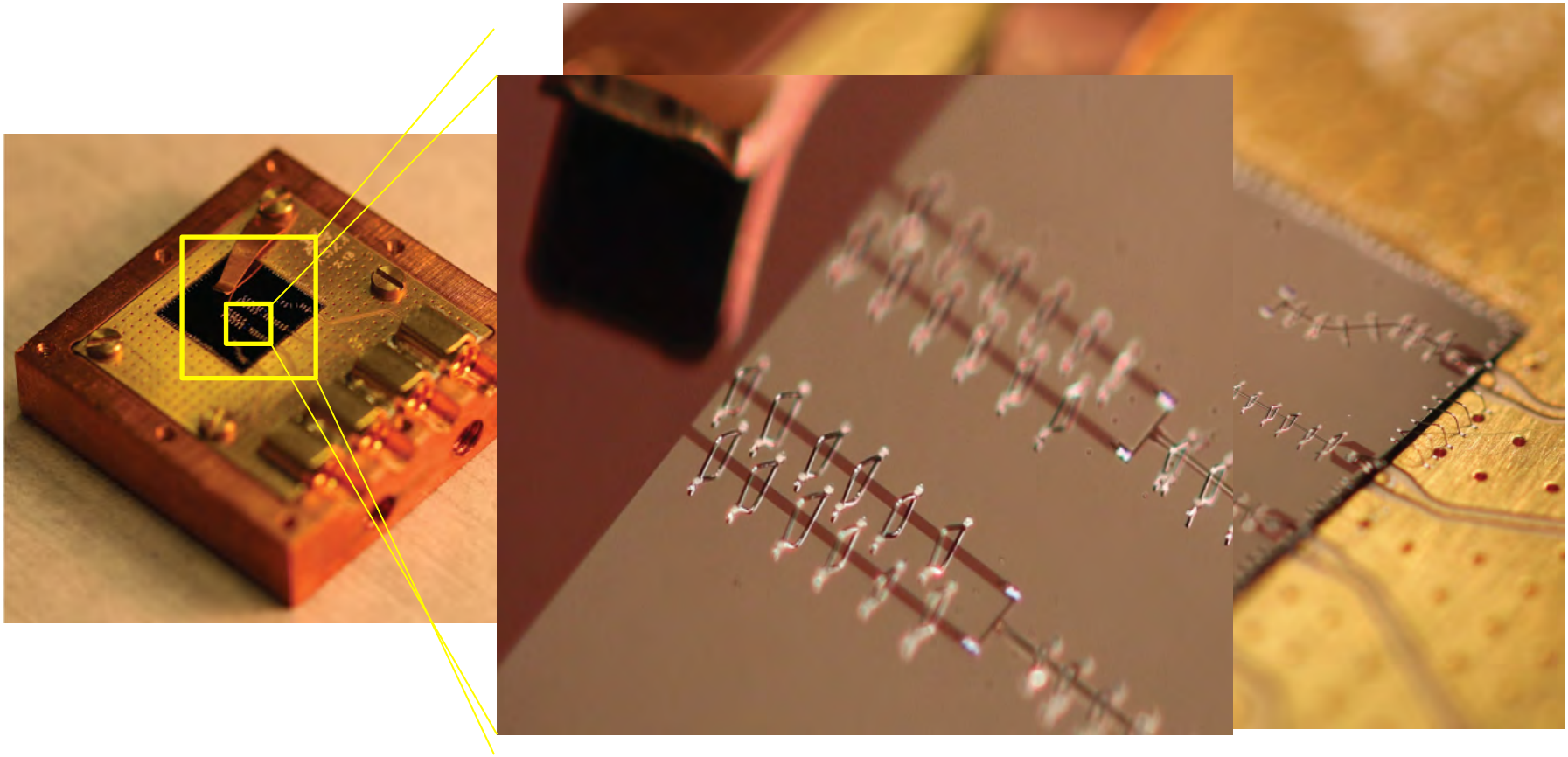
- Excellent fiber to chip coupling technology



- Reliable fabrication!

→ How does the microwave part perform?
→ Can we integrate it all?

H-bar design: packaging



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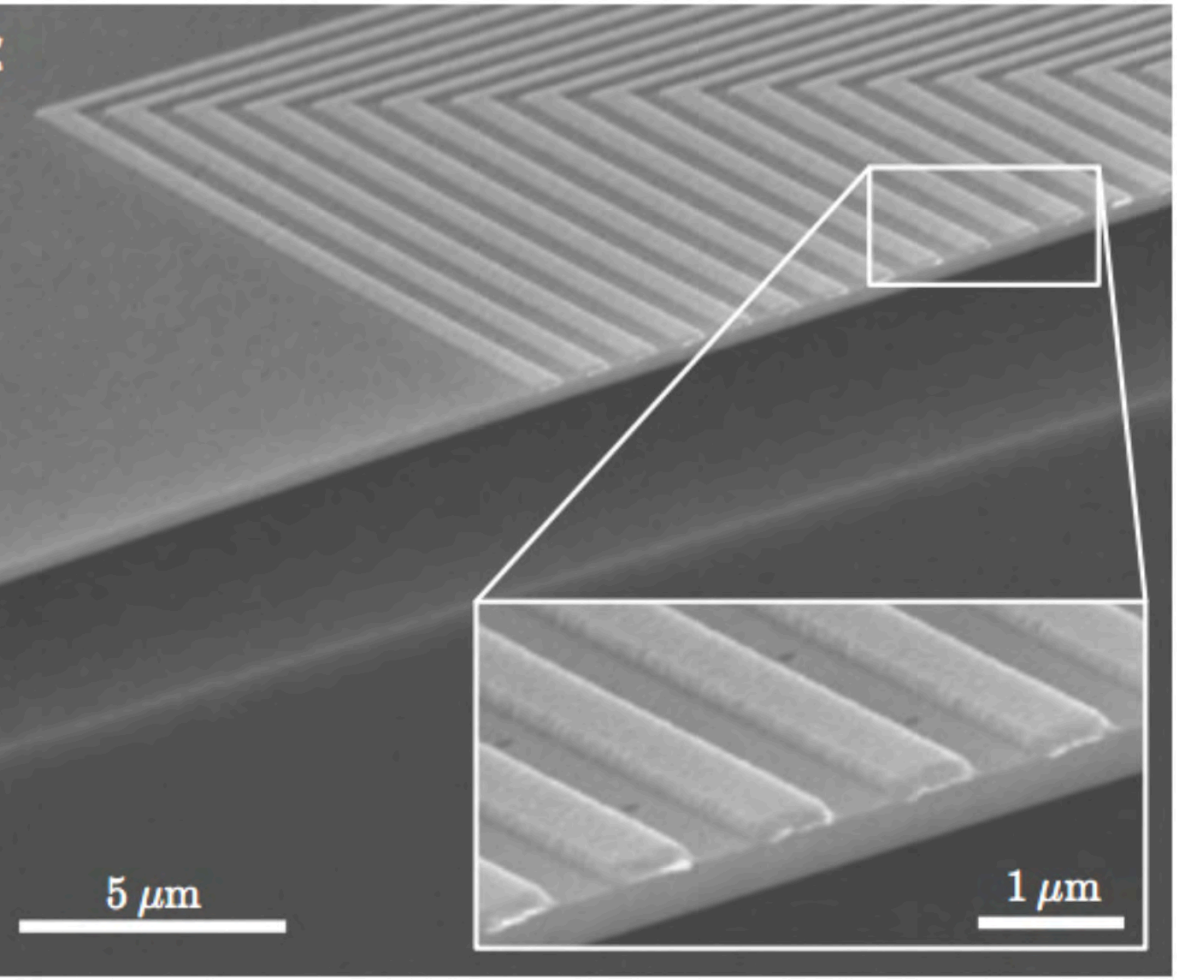
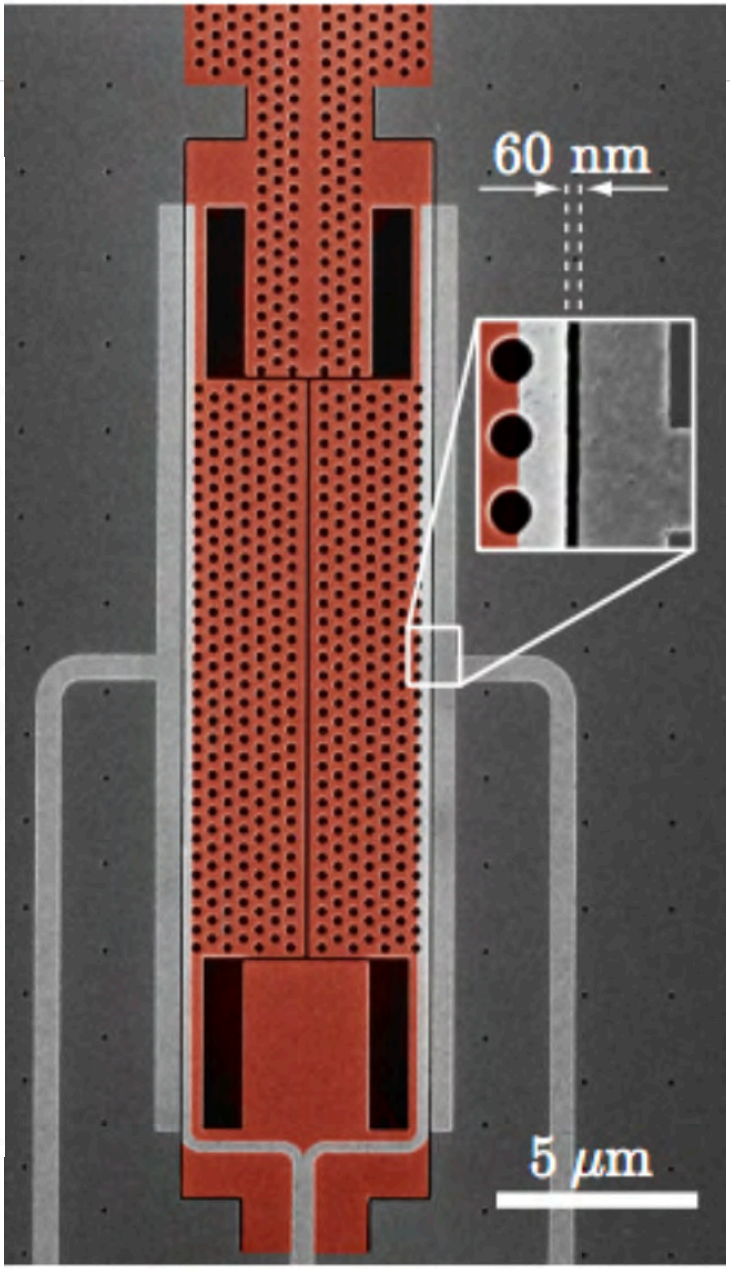
H-bar under the microscope





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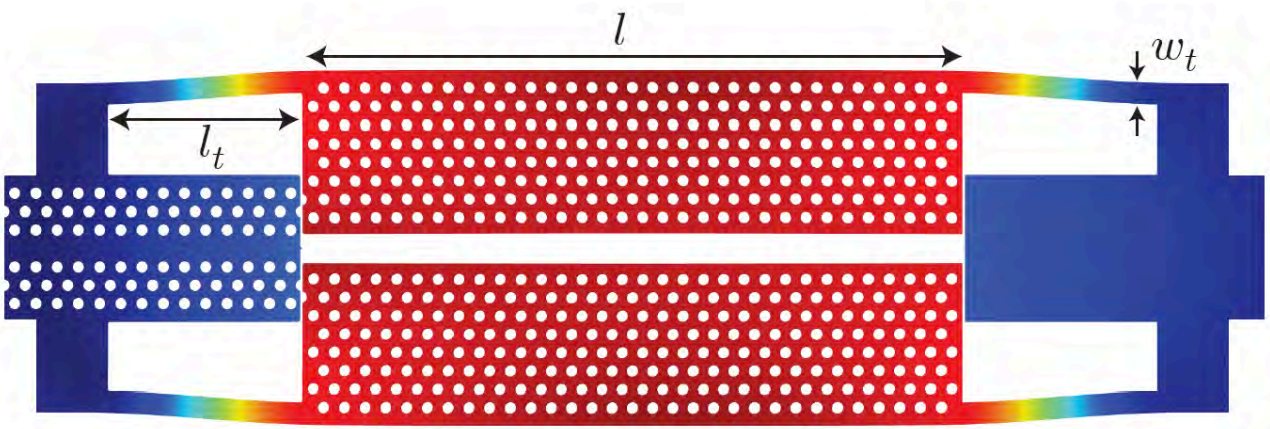
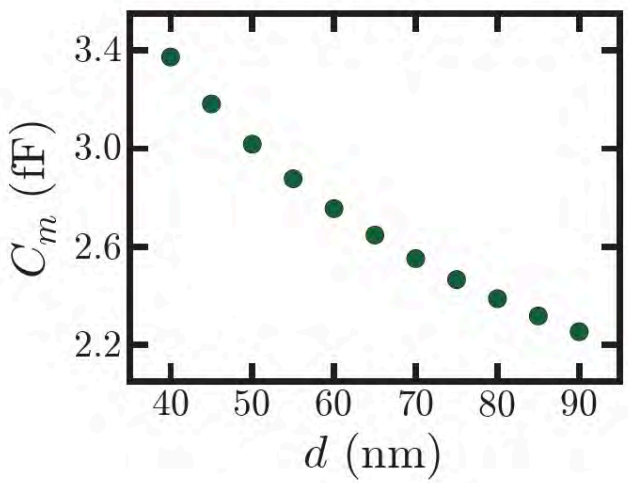
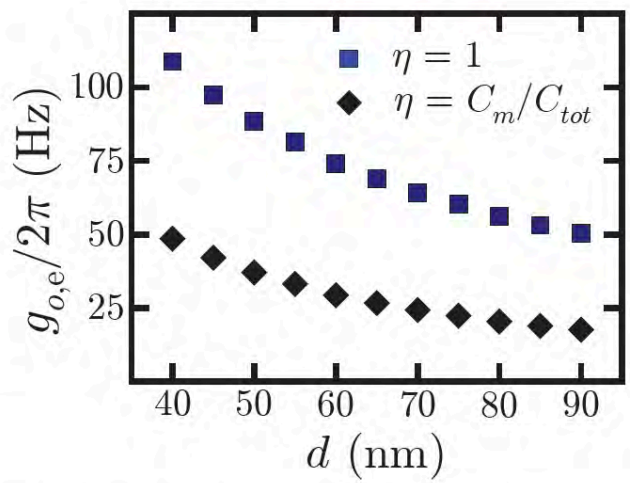
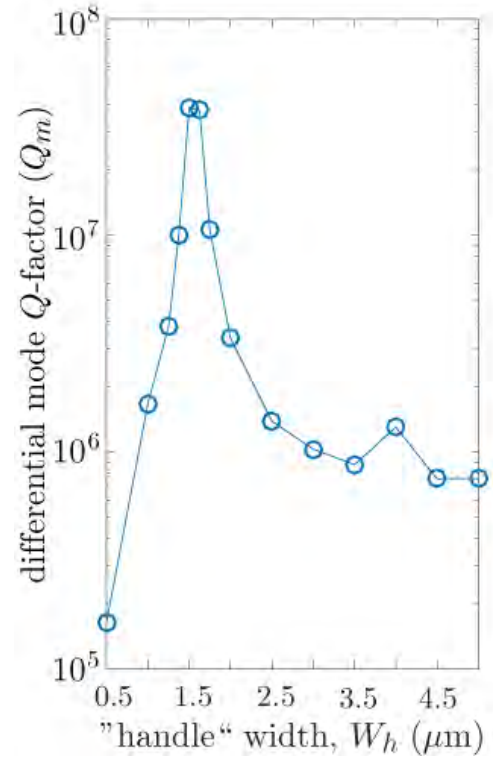
Mechanical design







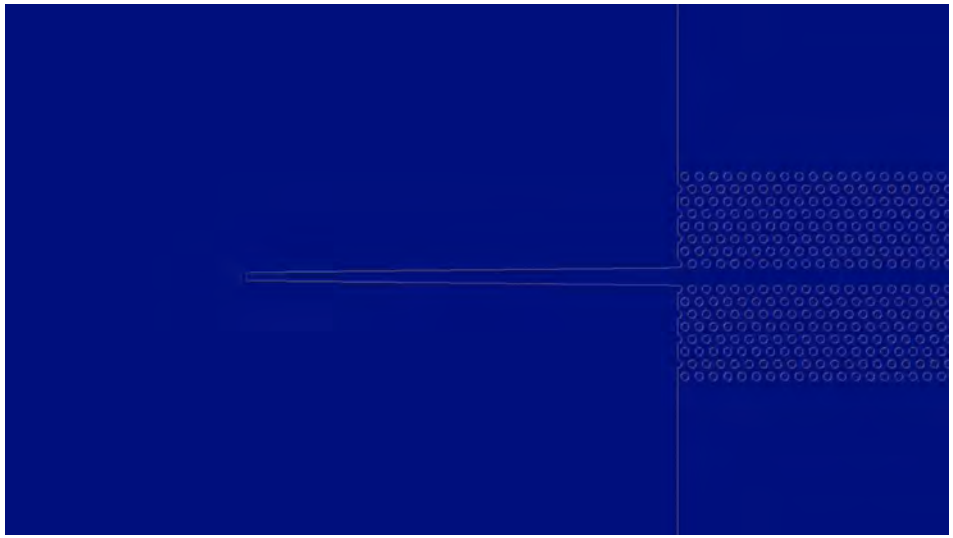


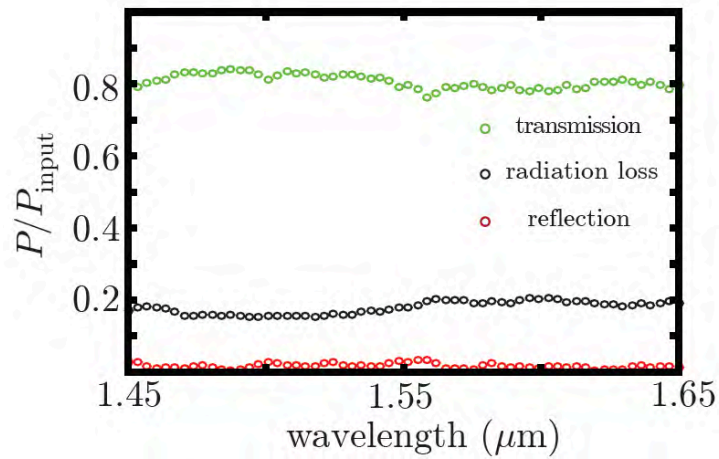
$\omega_r/2\pi = 8.88$ GHz $\quad \omega_m/2\pi = 9.76$ MHz $\quad x_{\mathrm{zpf}} = 4.5$ fm

$C_s = 4.18$ fF $\quad m_{\mathrm{eff}} = 42.9$ pg

P. B. Dieterle, M. Kalaee, *et al.*, Phys. Rev. Applied 6, 2016

Optical design

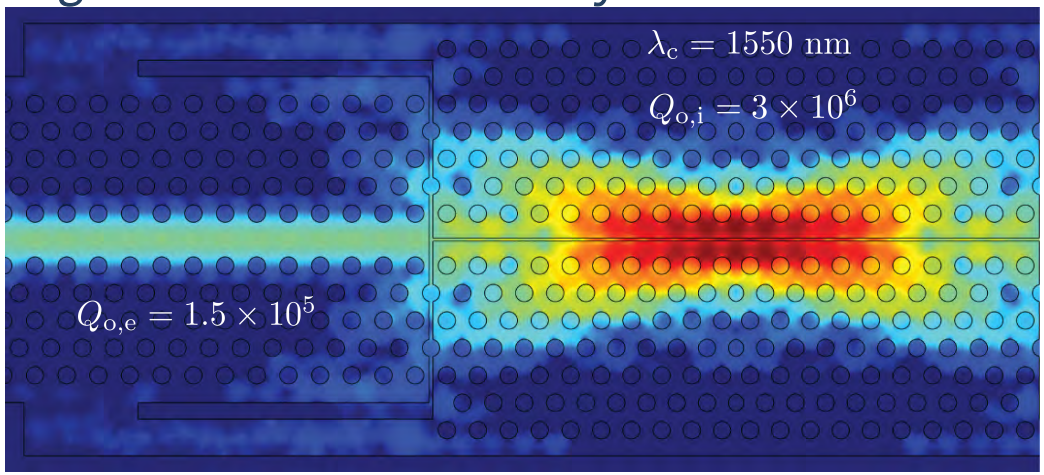




$\omega_o/2\pi = 195$ THz $\quad Q_l = 200{,}000$

$g_{o,o}/2\pi = 1.7$ MHz $\quad Q_{\text{parasitic}} = 840{,}000$

Log10 scale of radiative cavity field



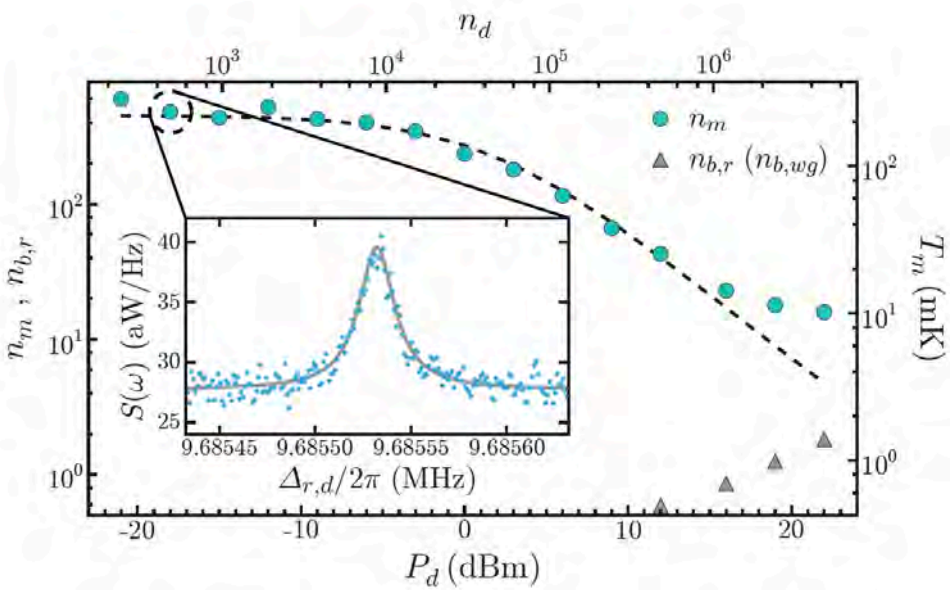
$\eta_{o,\text{coup.}} \equiv$ fiber-to-chip effic. $= 0.8.$

$\eta_{o,\text{cav}} \equiv$ WG-to-cav effic. $= \kappa_{o,e}/\kappa_{o,t} = 0.85.$

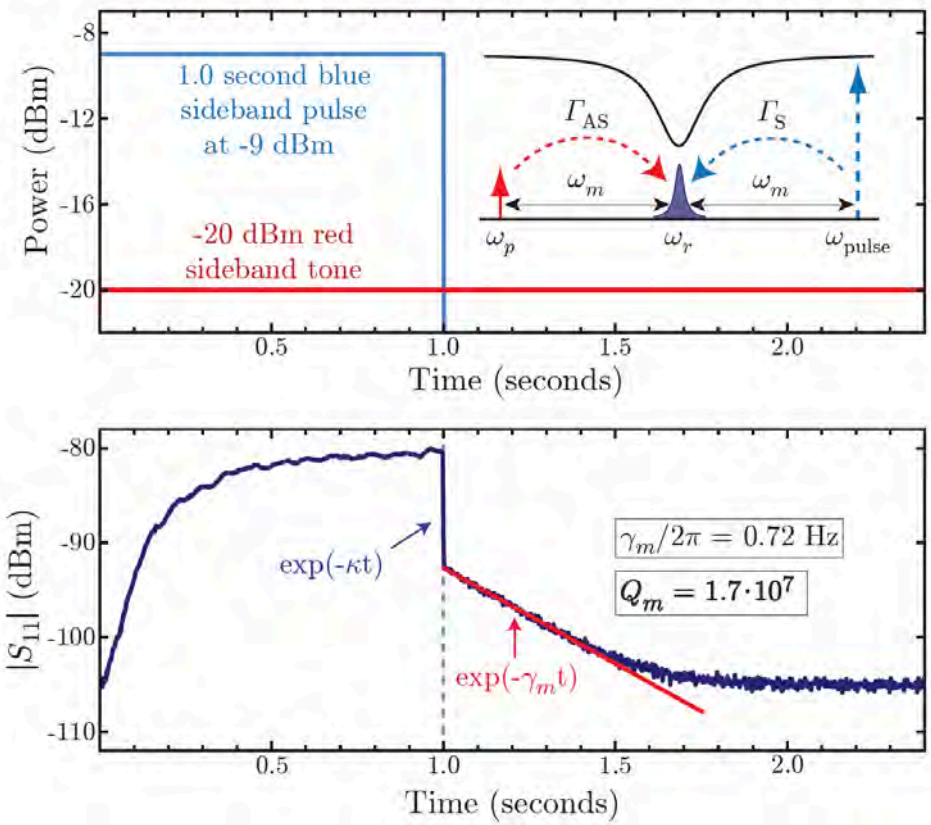
P. B. Dieterle, M. Kalaee, *et al.*, Phys. Rev. Applied 6, 2016

Noise Thermometry / Ring down

Sideband Cooling



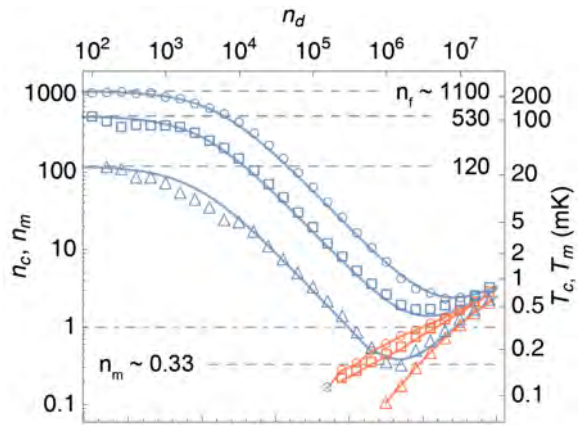
Mechanical Q



P. B. Dieterle, M. Kalaee, *et al.*, Phys. Rev. Applied 6, 2016

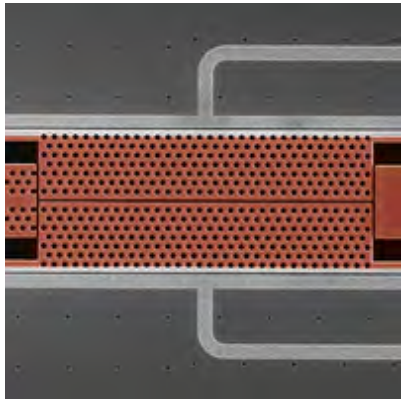
Outline

I: Motional Ground State Cooling of a Si3N4 Nanobeam



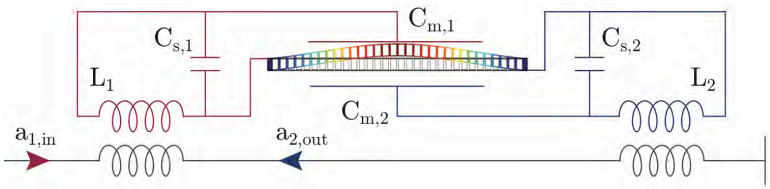
J. M. Fink *et al.*, Nat. Commun. (in print)

III: Cavity Electromechanics on Silicon-on-Insulator



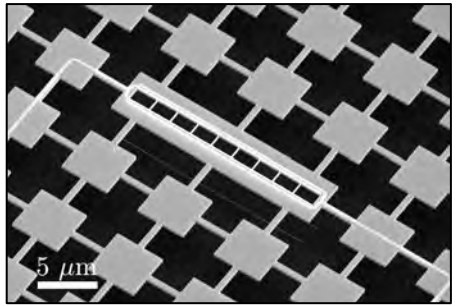
P. B. Dieterle, M. Kalaee, *et al.*, Phys. Rev. Applied 6, 2016

II: All-Microwave Frequency-Conversion

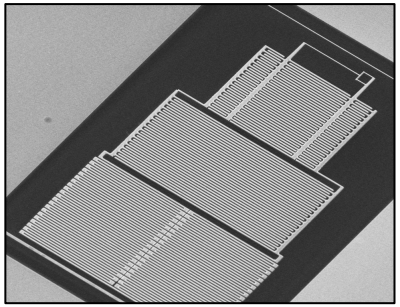


J. M. Fink, M. Kalaee, *et al.* in preparation

IV: Outlook



High ω_m



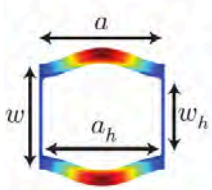
Qubits on SOI

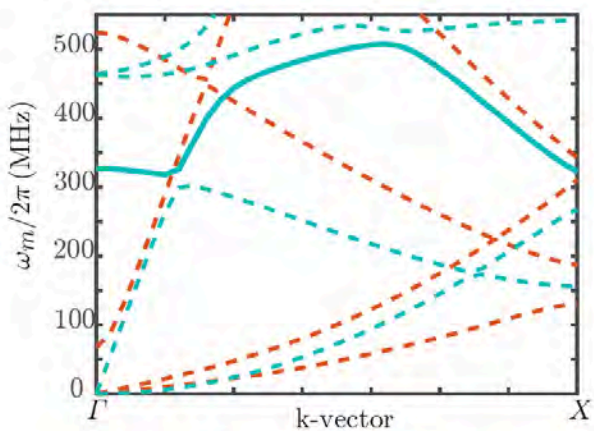
Outlook: I High frequency electro-mechanics

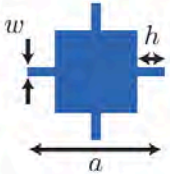
Advantages

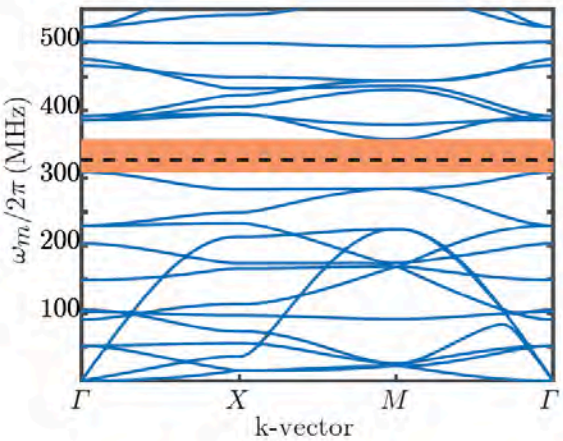
- Lower occupancy
- Can use phononic shields
- Sideband resolution (on optics side)

Mechanical Design I







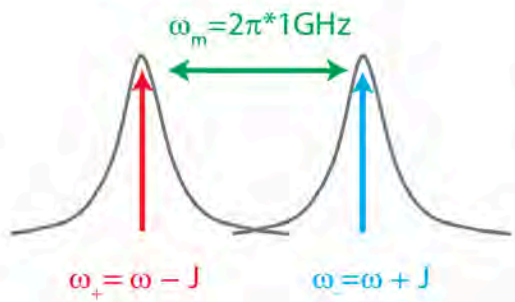


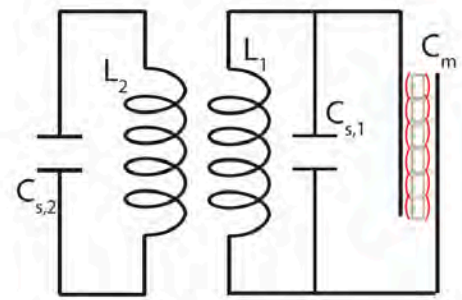
$\omega_m/2\pi = 331$ MHz $\quad x_{\mathrm{zpf}} = 4.31$ fm

$m_{\mathrm{eff}} = 1.37$ pg

Outlook I: Higher mechanical frequency

Double coil design



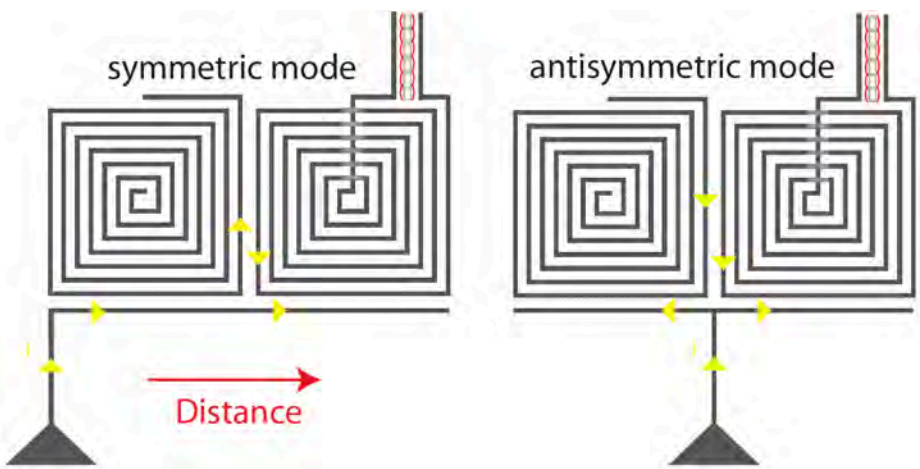


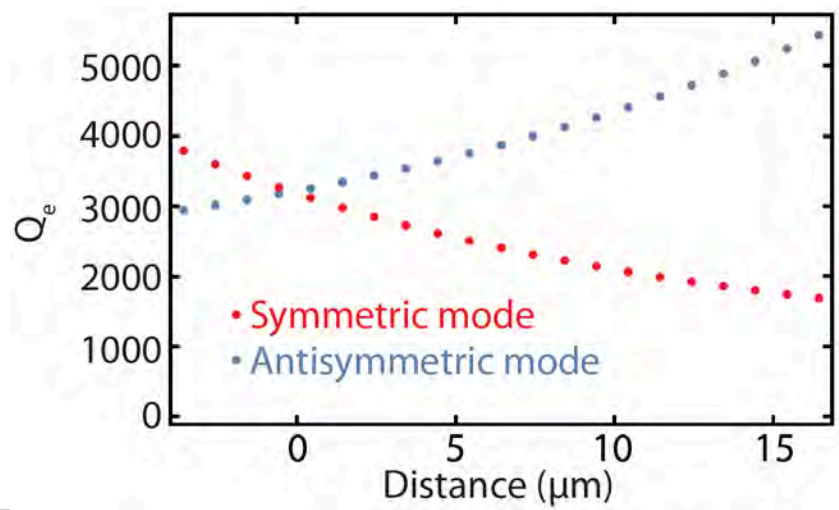
→ Lower input power

[1] . M. Dobrindt and T. J. Kippenberg, PRL **104**, 033901 (2010)
[2] G.Heinrich and F. Marquardt, EPL **93,** 18003 (2011)

$$H = \hbar\omega_1 a_1^+ a_1 + \hbar\omega_2 a_2^+ a_2 + \hbar J(a_1^+ a_2 + a_2^+ a_1) + \hbar\omega_m b^+ b + \hbar g_0 a_1^+ a_1 (b^+ + b)$$

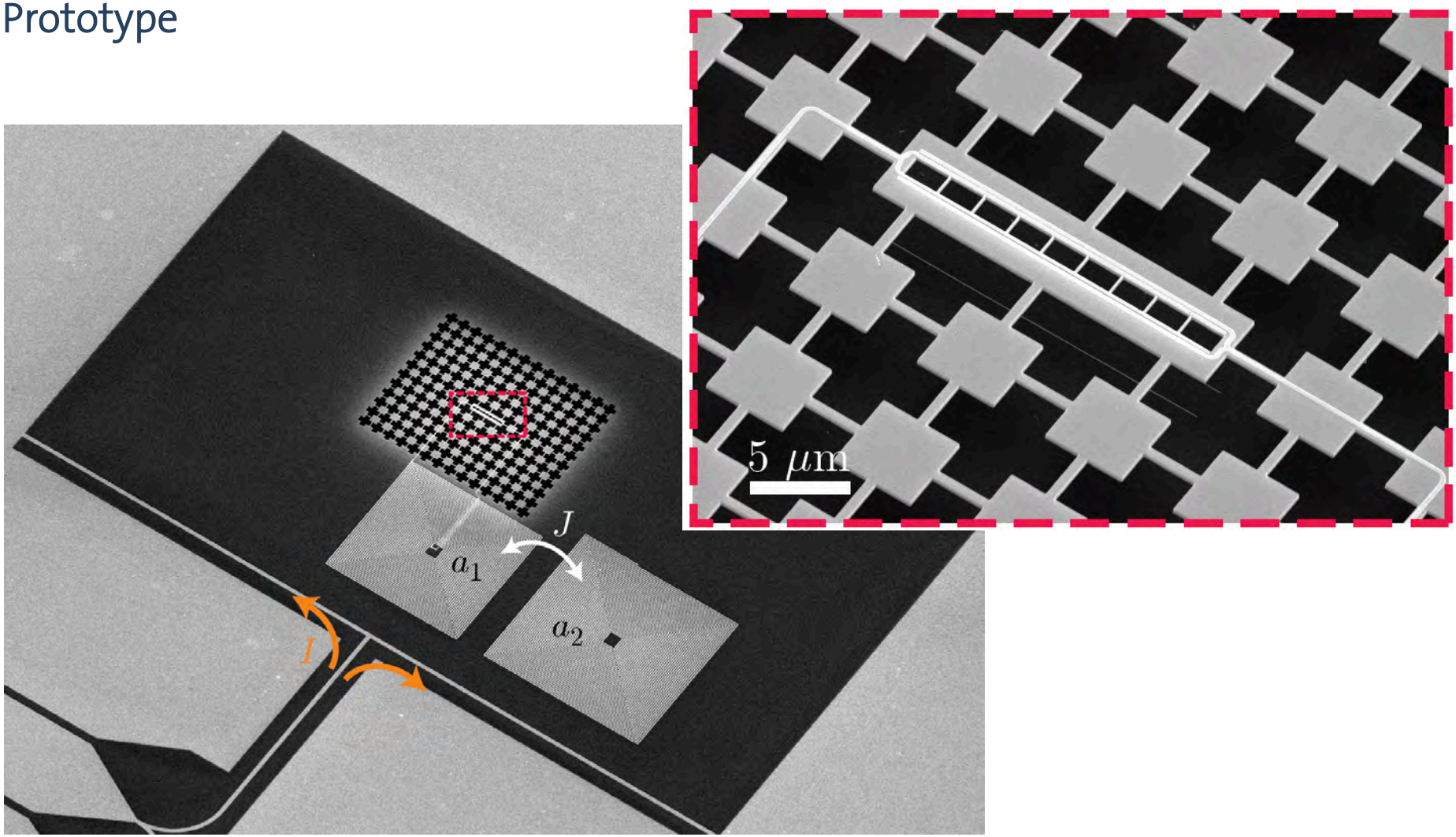
Supermode coupling





Outlook I: Higher mechancial frequency

Prototype



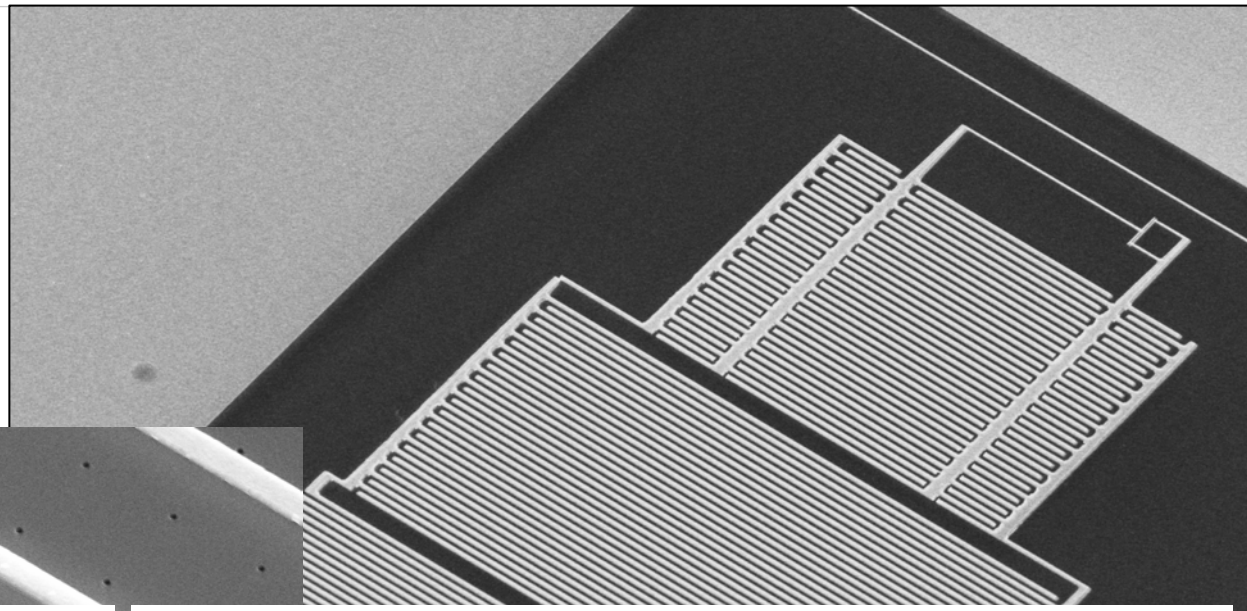
Outlook 2: Qubits on SOI

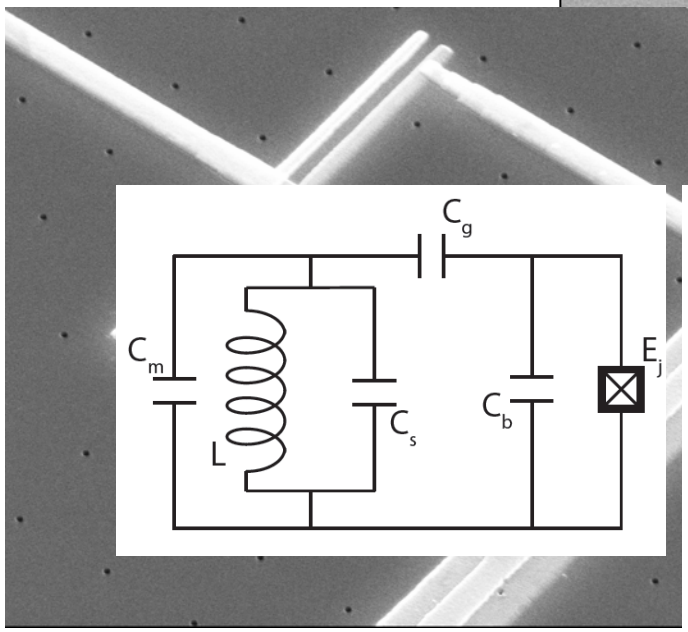
"Compact circuit QED"

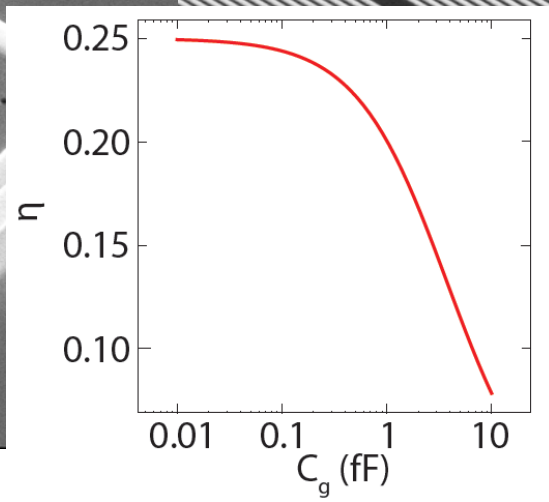
→ A non classical resource

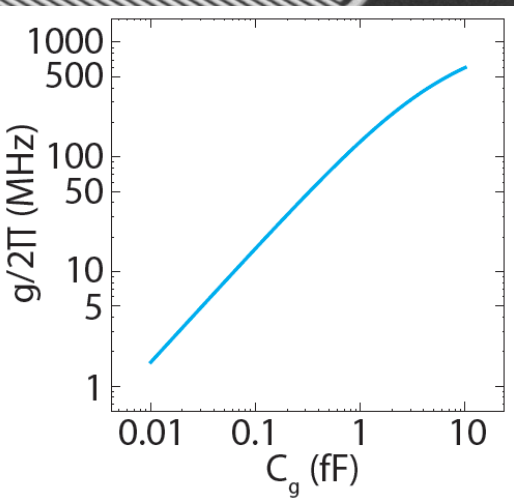
→ Interesting geometries

→ Small!



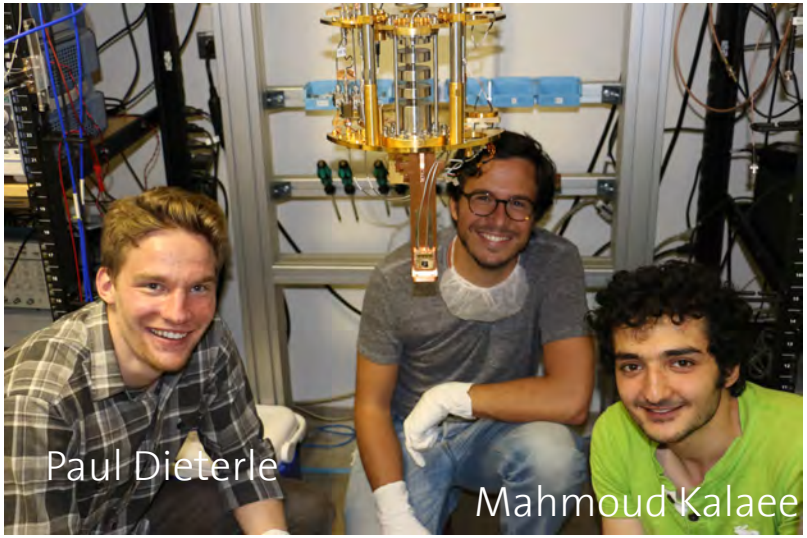






The Team

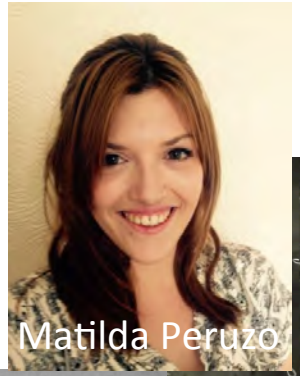
Quantum Photonics @ Caltech

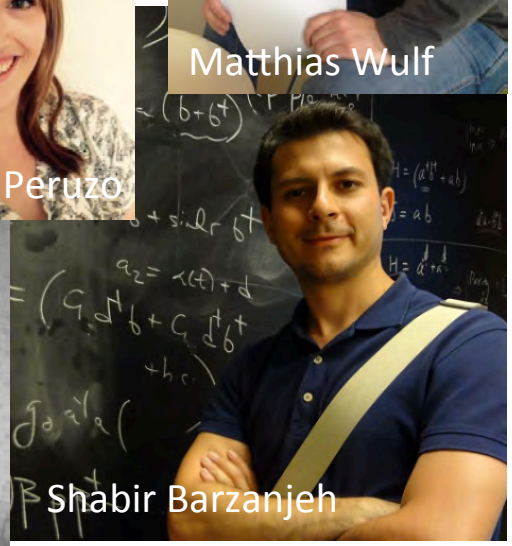


Alessandro Pitanti, Richard Norte
Greg MacCabe, Justin Cohen and Oskar Painter

Quantum Integrated Devices @ IST Austria

QuantumIDs.com





We are looking for PostDocs and PhD students!