Campinas, Brazil
17th-29th July 2016
São Paulo School of Advanced Science on Nanophotonics and
XV Jorge Andre Swieca School on Nonlinear and Quantum Optics

Tutorial

Chipscale Cavity Optomechanics and Cavity Opto-Electro-Mechanics

Part 1

Hong Tang
Department of Electrical Engineering
Yale University

2016-07-25

Introduction: Hong Tang

Yale

- Ph.D. 2002 in Condensed Matter Physics: Spintronics
- Started at Yale: 2006
- Yale research
  - Chipscale optomechanics

    + superconducting circuits (cavity electro-optomechanics)

    = microwave to optical frequency conversion

    Applications: acoustic inertial sensors

  - Integrated quantum/nonlinear photonic circuits
    - Superconducting single photon detector
    - Nonlinear optics of AlN
    - Visible light optical circuits based on GaN

  - Optomagnonics

- My other job titles
  - Director of graduate studies for 9 years (in charge of graduate admissions)
  - Undergraduate exchange program coordinator: established exchange programs with Univ. Sci. Tech of China, Tsinghua Univ.

- Website: http://www.eng.yale.edu/tanglab

Plan for the next five days

Yale

Chipscale Cavity
Optomechanics and Electro-Optomechanics, part 1
Monday, 12:00PM NP

Chipscale Cavity
Optomechanics and Electro-Optomechanics, part 2
Tuesday, 8:30AM NP

Hybrid Silicon Photonic Circuits
for Chip-Scale Nonlinear and Quantum Optics, part 1
Wednesday, 9:30AM NP

Hybrid Silicon Photonic Circuits
for Chip-Scale Nonlinear and Quantum Optics, part 2
Friday, 9:30AM NP

Contents

Yale

- Introduction: MEMS, NEMS, optomechanics
- Chipscale optomechanics and design guidelines
- Case studies
  - Silicon (electro-)optomechanics
  - Si_3N_4 (electro-)optomechanics
  - AlN (electro-)optomechanics
- Summary

Introduction: from MEMS/NEMS to optomechanics

Nano-electro-mechanical system

- Nano version of MEMS

- High sensitivity
  - Excellent mass, displacement, force, energy sensors
  - Quantum limit force and displacement detection

- Interesting physics

Mechanical resonator

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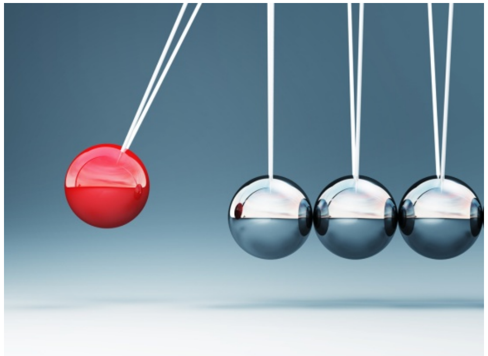
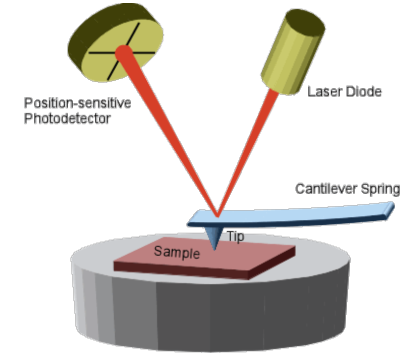
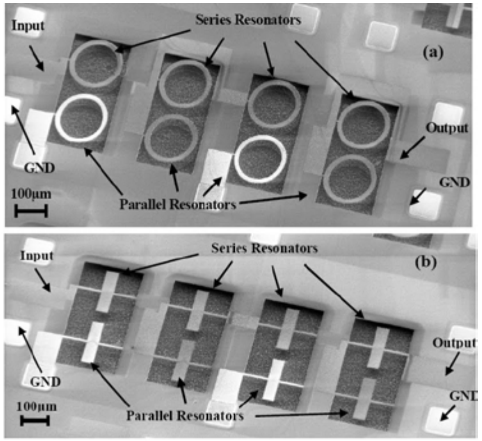


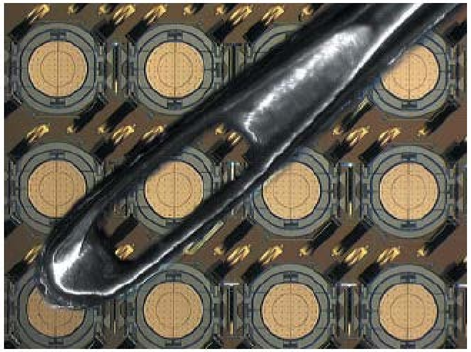
$$\frac{d^2x}{dt^2} + 2\gamma\frac{dx}{dt} + \Omega^2 x = F/m$$



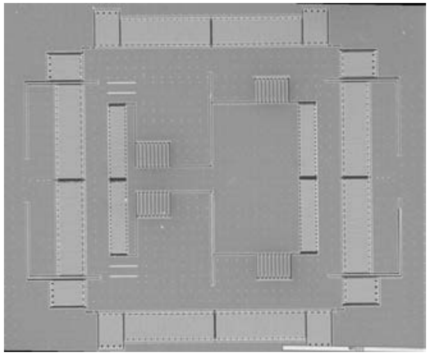
Atomic force microscopy



Microwave filters



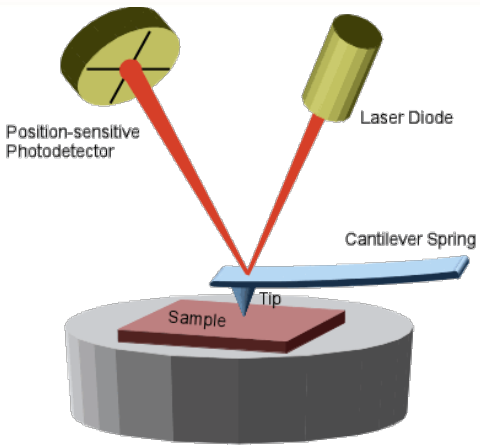
Optical switch

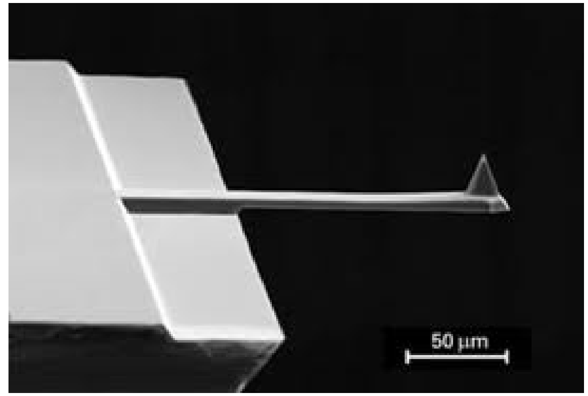


Accelerometer

Oscillators

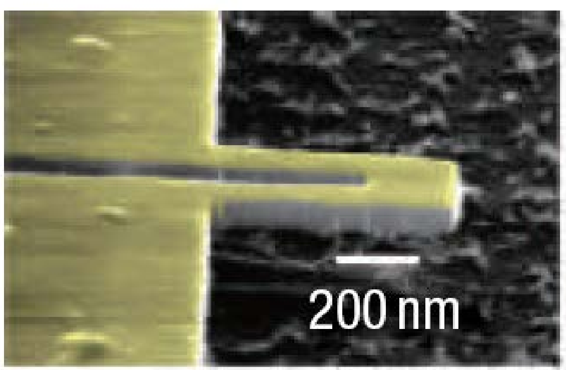
Nanomechanics



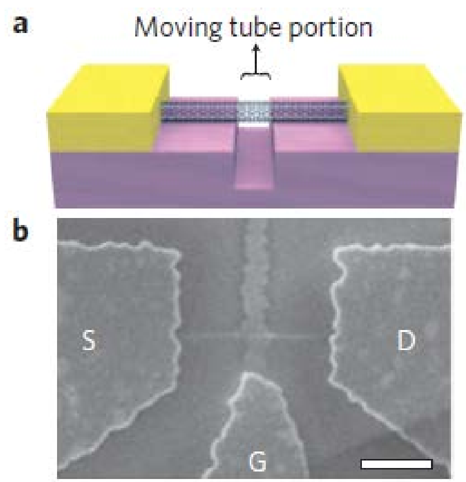


~10^{-11} N force sensitivity

~10^{-10} m resolution



10^{-18} g mass sensitivity in air
M. Li, *et al.*, Nat. Nanotech. 2, 144 (2007)



$1.7\text{x}10^{-24}$ g mass sensitivity (~1 proton)
J. Chaste, et al, Nat. Nanotechnol. **7**, 301 (2012).

10^{-18} N force sensitivity
H. J. Mamin, *et al.*, App Phys Lett 79, 3358 (2001)

10^{-19} m displacement sensitivity
O. Arcizet, *et al.*, Phys Rev Lett 97, 133601 (2006)

Displacement imprecision below standard quantum limit
J. D. Teufel, et al, Nat. Nanotechnol. **4**, 820 (2009).

What is cavity optomechanics?

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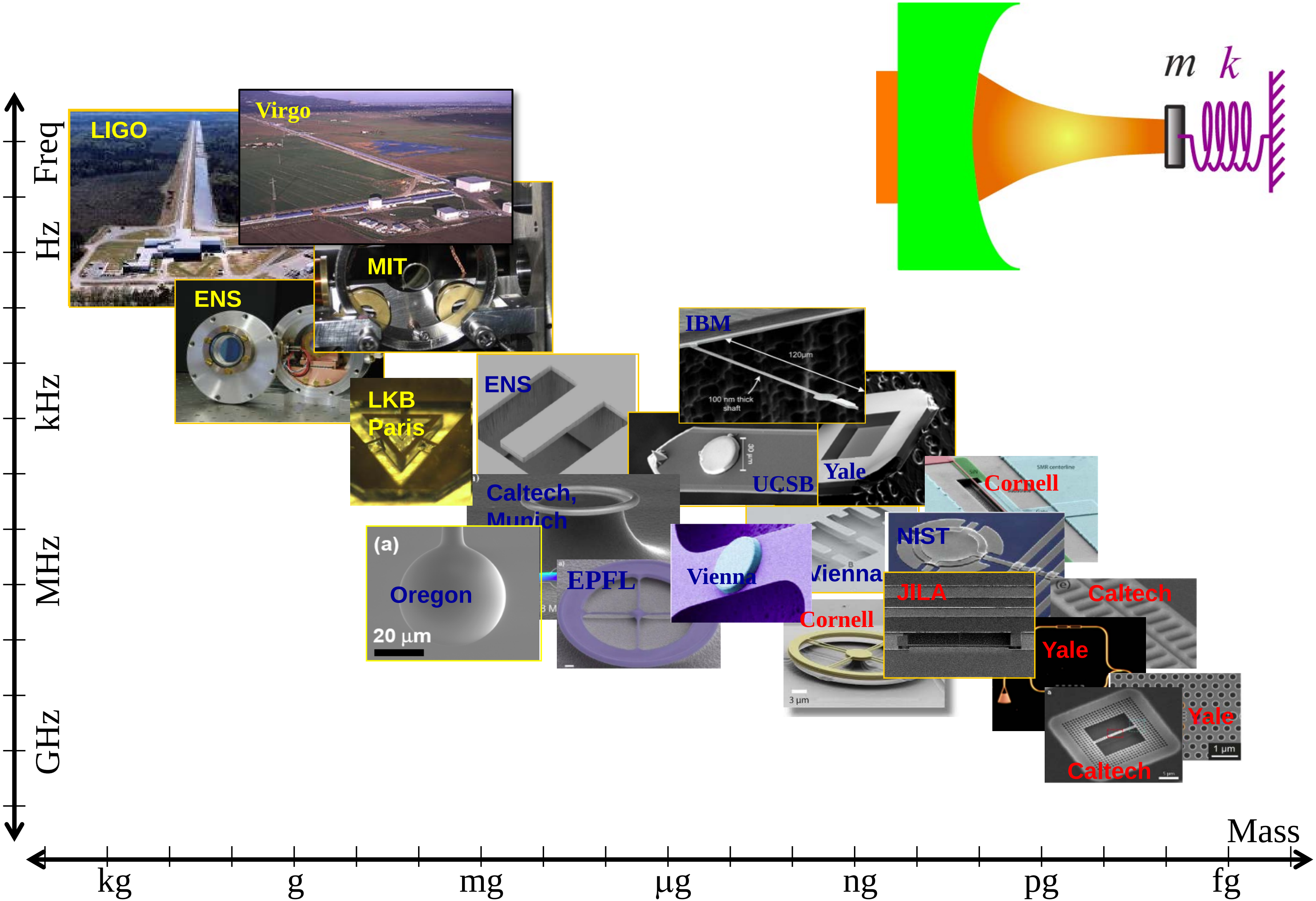

Opto-electromechanics

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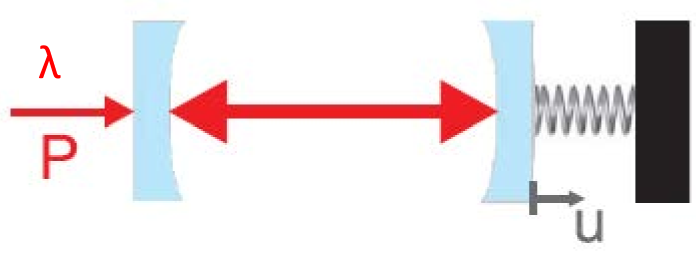
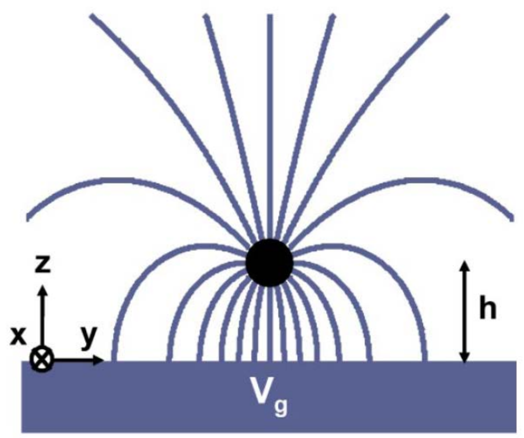
Optomechanics

- Very good sensitivity
  - Quantum-limited lasers
  - Shot noise limited detectors
- Photons interact only very weakly with the resonator
  - Momentum: $h/\lambda = 4.3\ 10^{-28}$ kg m/s
- Need cavity or small mode volume to enhance forces of photons



Nanoelectromechanics

- Sensitivity "low" without mesoscopic devices
- Strong electrostatic forces
  - inversely proportional to the gap → make small



Phys Rev A. **86** 053826 (2012)

Phys. Stat. Sol. B **244** 4253 (2007)

Chipscale optomechanics and design rules

Integrated electro-optomechanical circuits

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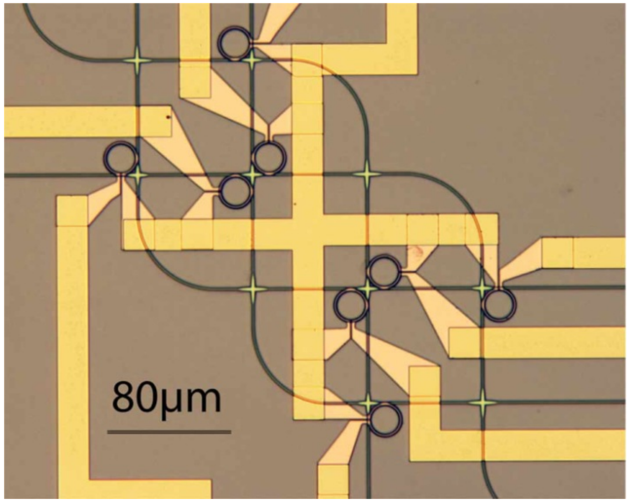
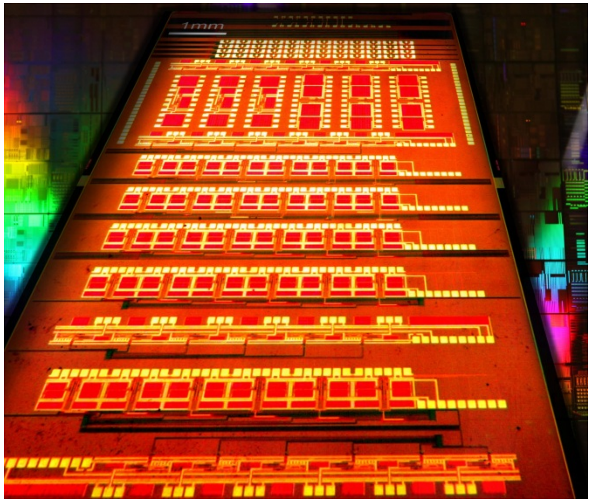
- Benefit NEMS by high sensitive readout
- Benefit Nanophotonics by high optical non-linearity, which implies tunability
- Combine the two in an integrated circuit



Lipson group, Opt. Express 16, 15915 (2008)



Vlasov @ IBM(2010)

Electrical Circuit + Optical Circuit = Optoelectronic Circuit

+ Mechanical Resonator

= (Electro-)optomechanical circuits

Yale's silicon optomechanical circuitry

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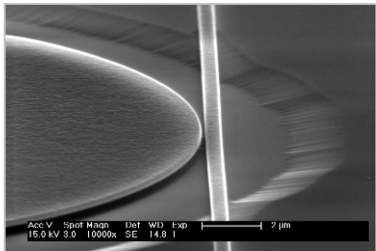

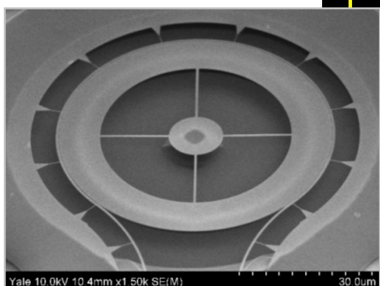

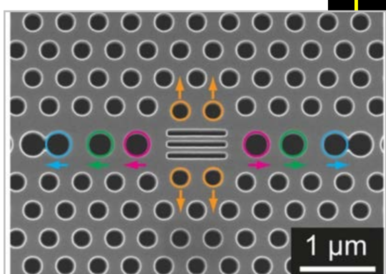

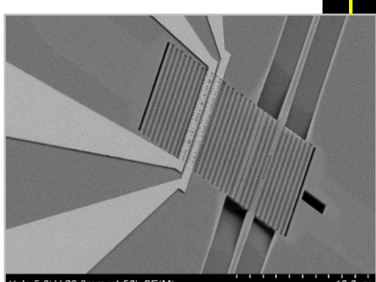

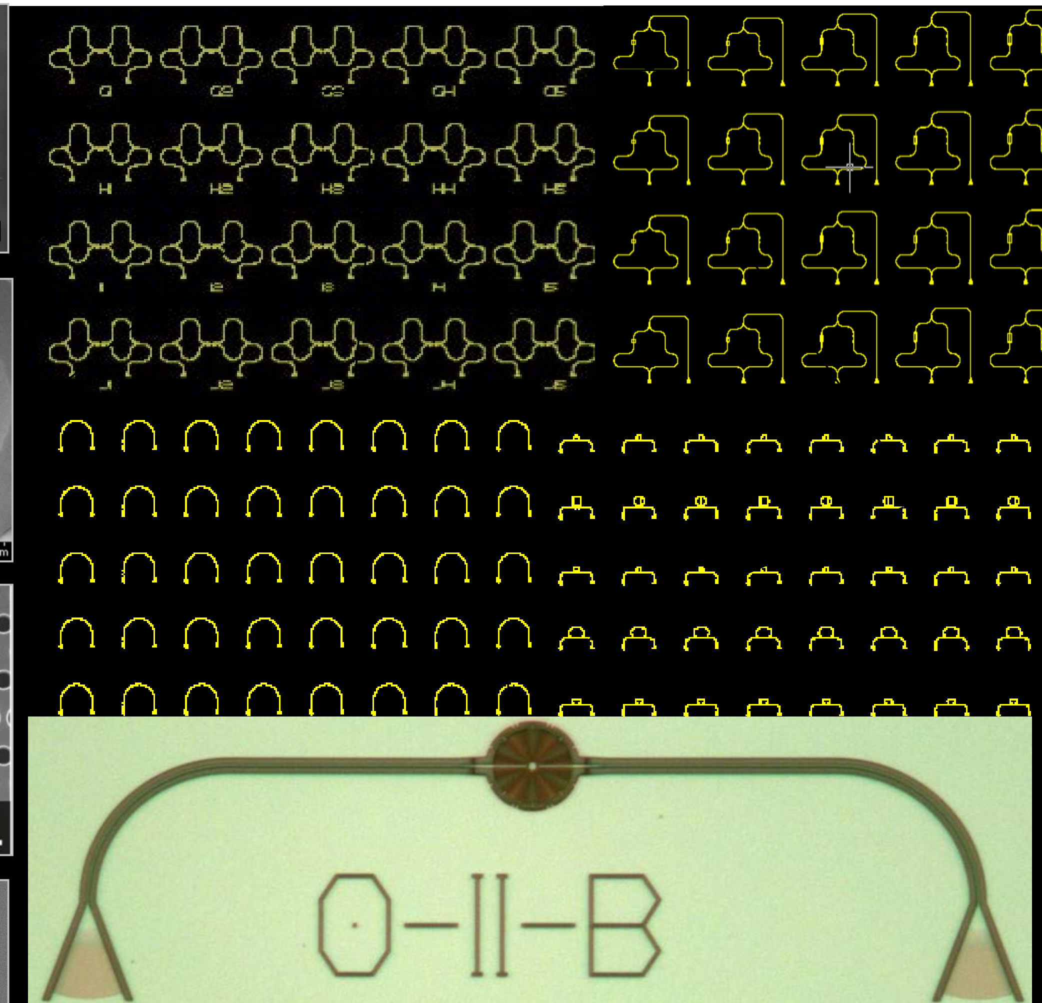

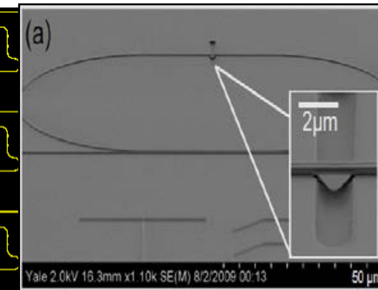

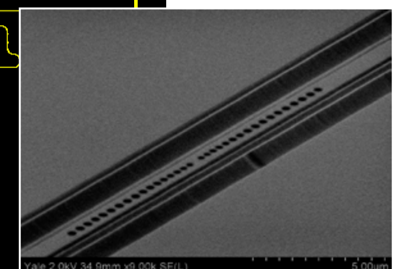

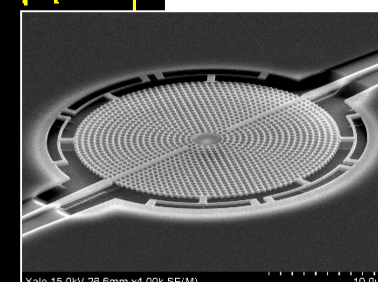

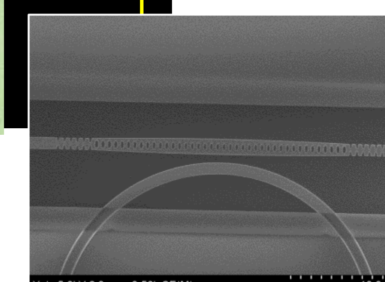

cadence

Funded by DARPA/MTO ORCHID

Advances in optomechanics bring in

- Very high frequency resonator (beyond 10GHz)
- Integrated transduction of mechanical resonators far smaller than wavelength of light
- Ultrasensitive force sensors
- Circuit integration of nanomechanical resonators
- Quantum limited displacement detection
- Operation of devices in ambient and even fluidic environments

Design considerations

- Light to chip coupling
- Mechanics
  - Material
  - Quality factor (mechanical loss)
  - Resonant frequencies
  - Actuation (electrical or mechanical)
  - Readout
- Photonics
  - Material
  - Quality factor (optical loss)
  - Mode volume
  - Coupling strength (to mechanics)

Device Design – Fiber to Waveguide coupling

Fiber to Chip Coupling – facet coupling

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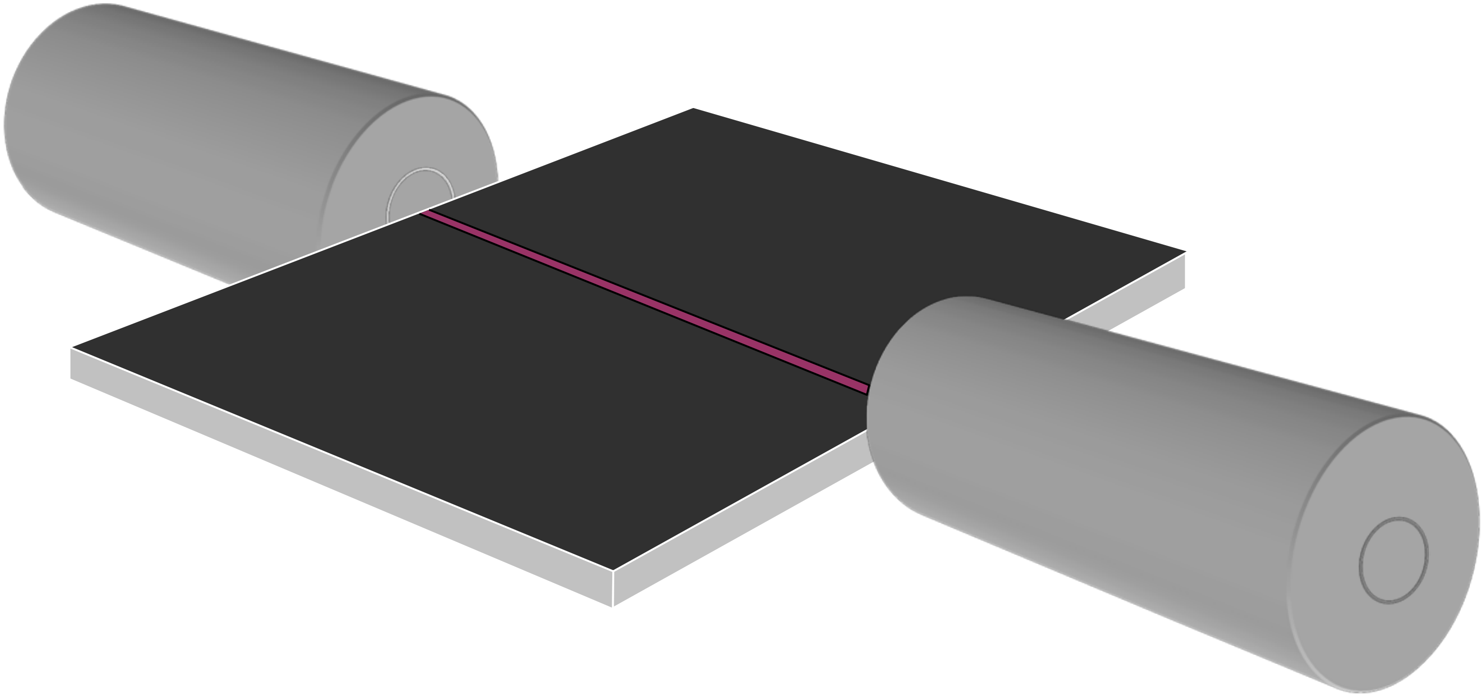

Waveguide core: 400nmx110nm = $0.05\mu m^2$
Fiber core: $50 um^2$
Coupling efficiency: 0.000001

Facet coupling

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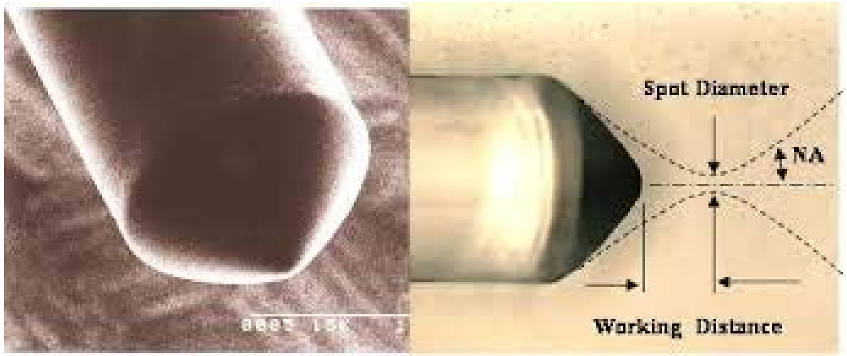
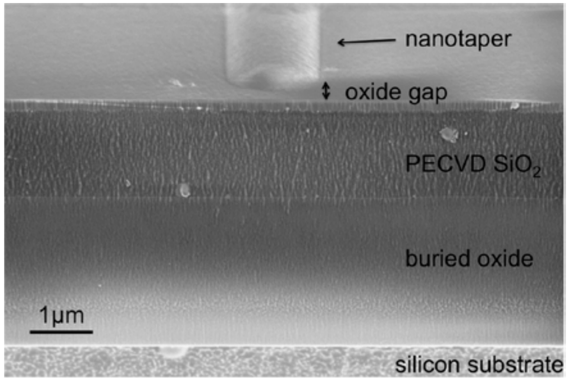
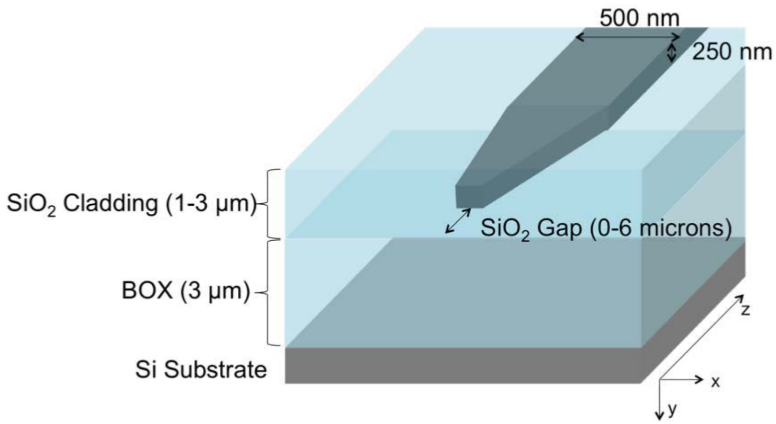
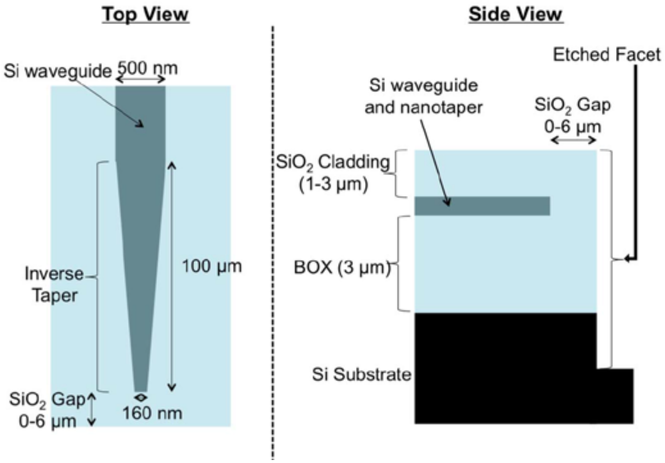
Lensed fiber + tapered waveguide



http://moritex.com/products/optocom/optical/optical_telecom_components/6-1-1-5.html







0.7dB/facet

Cardenas, J., Poitras, C. B., Luke, K., Luo, L. W., Morton, P. A., & Lipson, M. (2014). High coupling efficiency etched facet tapers in silicon waveguides. IEEE Photonics Technol. Lett, 26(23), 2380-2382.

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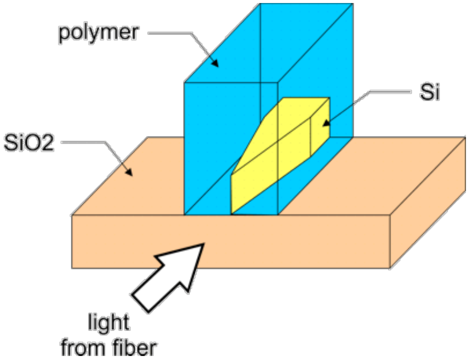
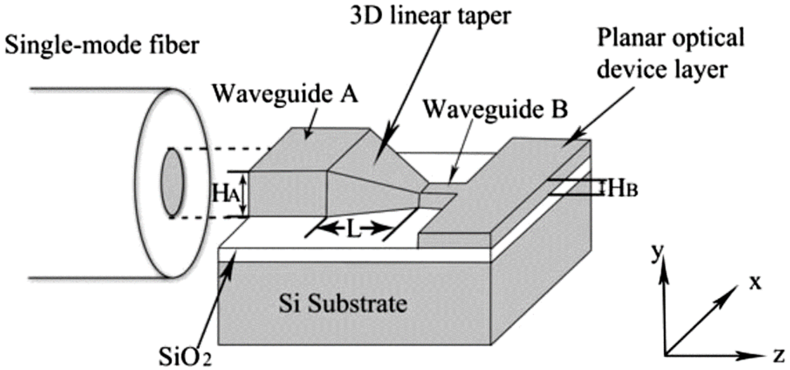
Other variations

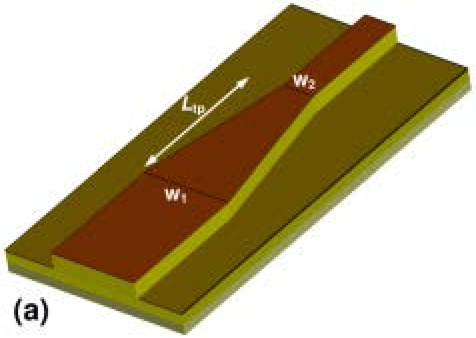
- Inverted taper with polymer coating
- Taper
- 3D taper



https://www.photond.com/products/fimmprop/fimmprop_applications_06.htm



Yang Z, Fang N, Wu A, et al; Fabrication and characterization of integrated three-dimensional linear taper on silicon-on-insulator. Opt. Eng. 48, 030503 (2009)



Dai, D., Tang, Y., & Bowers, J. E. (2012). Mode conversion in tapered submicron silicon ridge optical waveguides. Optics express, 20(12), 13425-13439

Grating coupler

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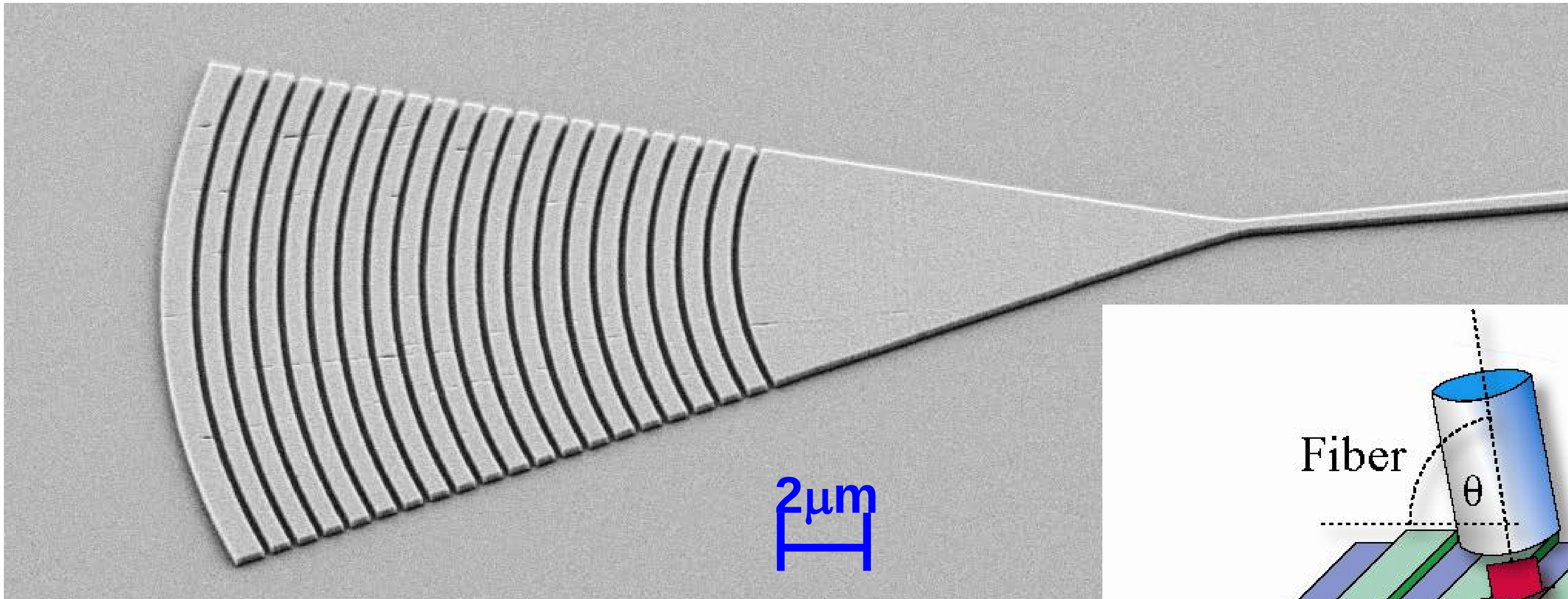
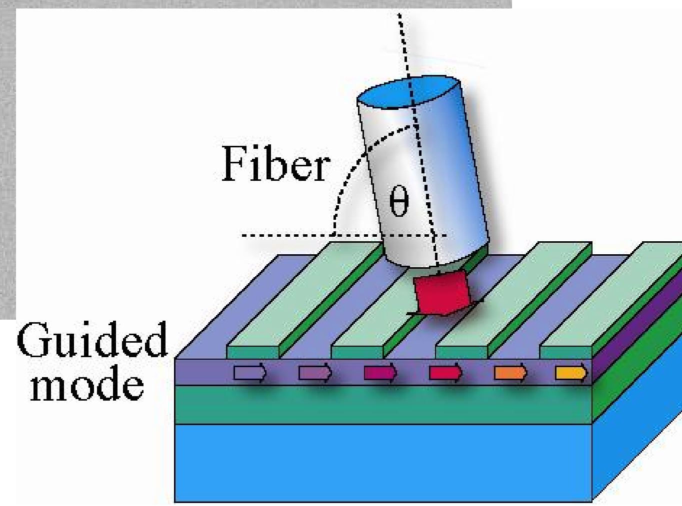
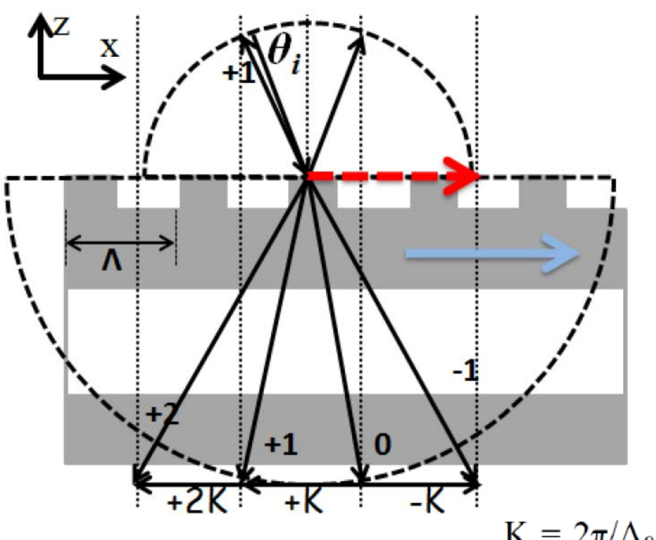


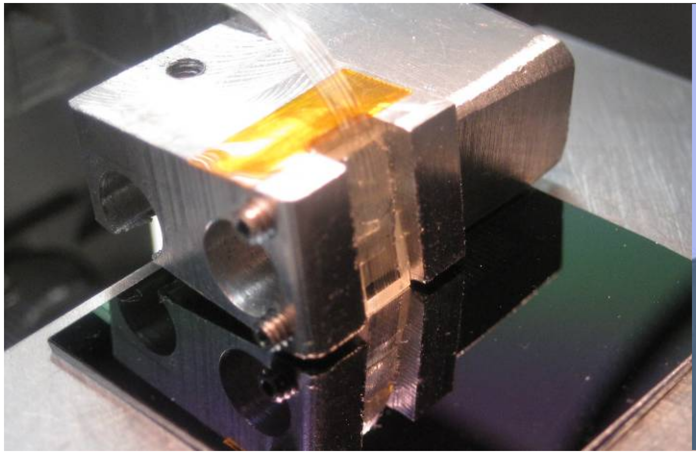


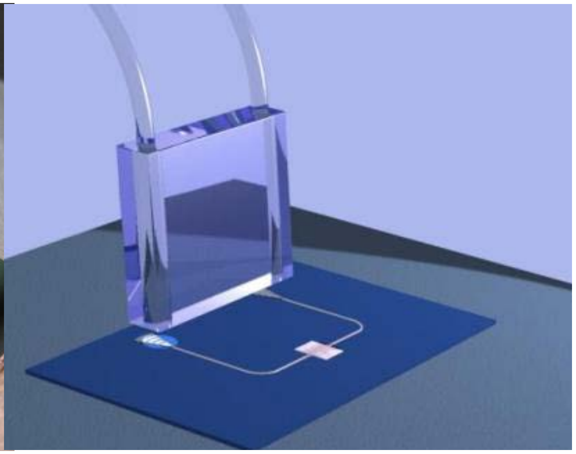


$$\Delta\beta = \beta_w - \beta_{-1}^{x} = \frac{2\pi}{\lambda} n_w - \left(\frac{2\pi}{\lambda} n_0 \sin\theta_i + \frac{2\pi}{\Lambda_0}\right)$$

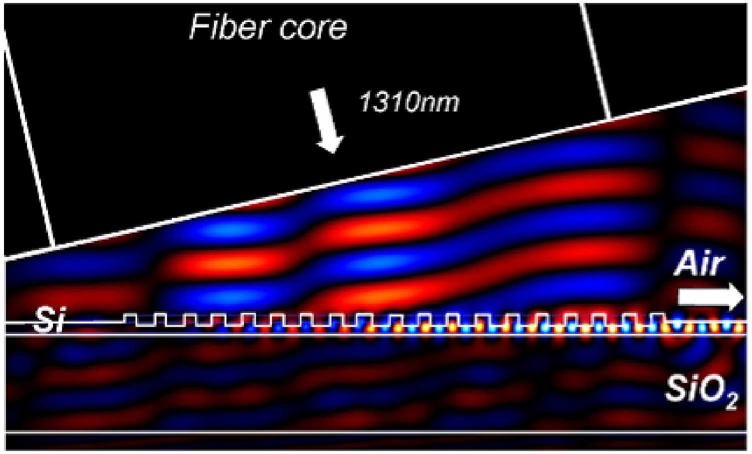
$$\frac{2\pi}{\lambda} n_0 \sin\theta_i + \frac{2\pi}{\Lambda_0} = \frac{2\pi}{\lambda} n_w$$

Fiber array



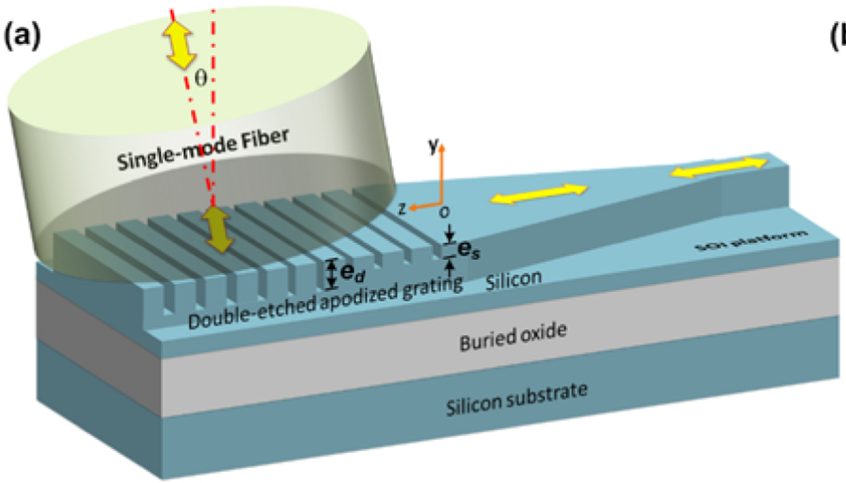


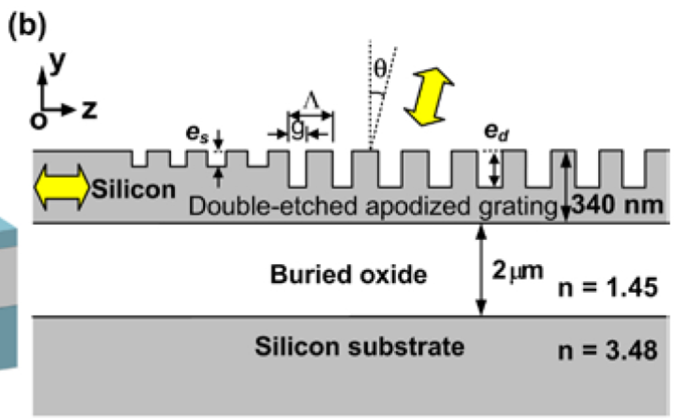
Grating coupler



Commercial FDTD software:

- Photon Design
- Numerical
- R-Soft
- …

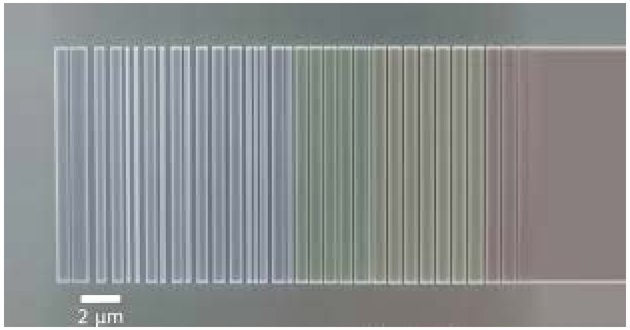




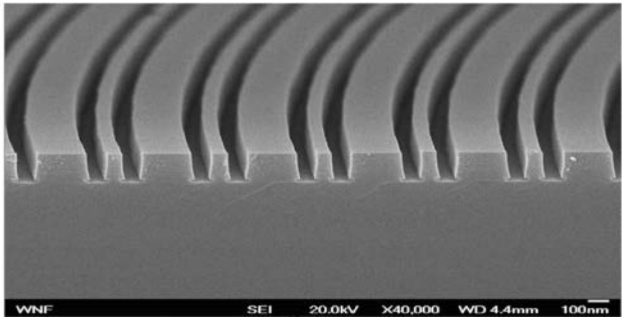
Chao Li, Huijuan Zhang, Mingbin Yu, and G. Q. Lo, "CMOS-compatible high efficiency double-etched apodized waveguide grating coupler," Opt. Express **21**, 7868-7874 (2013)

Other variations

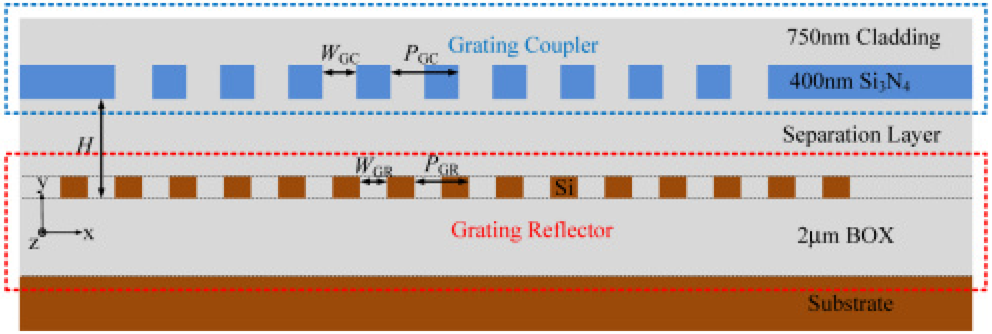
- Apodized grating coupler
- Double grating
- Grating couplers with back reflectors



Covey, J. et al, Optics express, 21(9), 10886-10896.



Wang Y. et al Opt. Express 22, 20652-20662 (2014)



Zou J. et al, Opt. Express 23, 26305-26312 (2015)

Pros and Cons of Different Coupling Schemes

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Facet coupling

Pro:

1) Higher coupling efficiency
2) Broadband

Con:

1) Many degrees of freedom in alignment
2) Take more foot print on a chip

Ideally suitable for nonlinear optics

Grating coupler

Pro:

1) Highly flexible; many inputs and outputs
2) Automatic alignment with lesser degrees of freedom – good for vacuum and cryogenic measurement

Con:

1) Lower coupling efficiency
2) Narrow band (30-100nm at telecom)

Good for optomechanics

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Design considerations

- Light to chip coupling
- Mechanics
  - Material
  - Quality factor (mechanical loss)
  - Resonant frequencies
  - Actuation (electrical or mechanical)
  - Readout
- Photonics
  - Material
  - Quality factor (optical loss)
  - Mode volume
  - Coupling strength (to mechanics)

SPSAS Nanophotonics

Campinas, Brazil

17th-29th July 2016

São Paulo School of Advanced Science on Nanophotonics and
XV Jorge Andre Swieca School on Nonlinear and Quantum Optics

IFGW CNPq FAPESP

Tutorial

Chipscale Cavity Optomechanics and Cavity Opto-Electro-Mechanics

Part 2

Hong Tang
Department of Electrical Engineering
Yale University

2016-07-25

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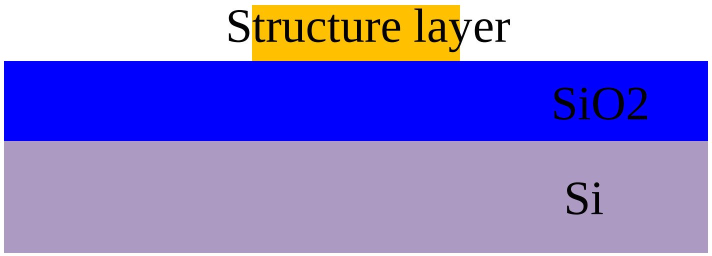
Electro-optomechanical device platforms

- Silicon electro-optomechanics
- Silicon nitride electro-optomechanics
- AlN-on-silicon piezo electro-optomechanics



Case Study: Silicon Optomechanics

Silicon optomechanics

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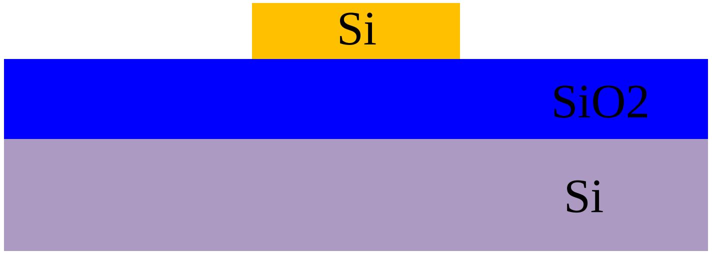
- Silicon on insulator



Waveguide to NEMS coupling

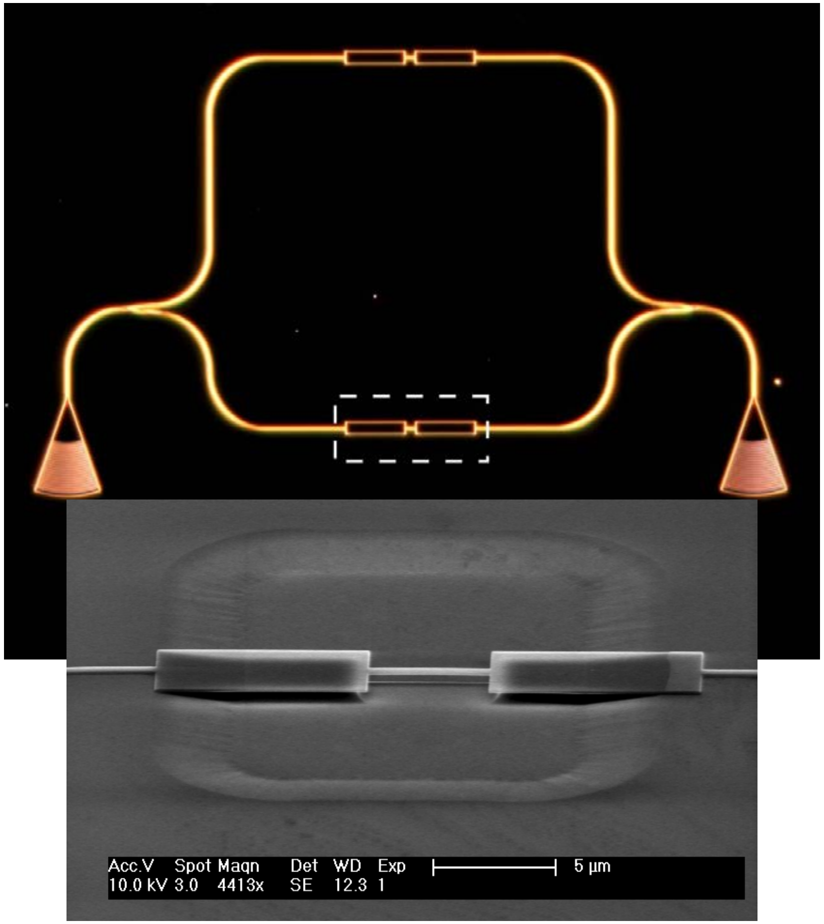
Design rules:

Mechanical design

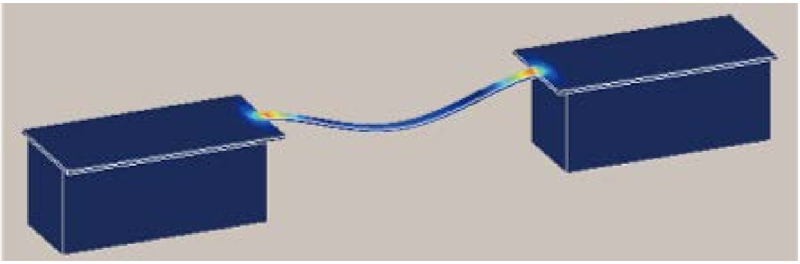
- High mechanical Q
- Low clamping
- Material etching selectivity
- Actuation

Optical design

- Low optical loss
- Single mode, strong optical confinement
- Right guiding and cladding material



Mechanical simulation



Li, M, et al. *Nature*, *456*(7221), 480-484 (2008)

Waveguide to NEMS coupling

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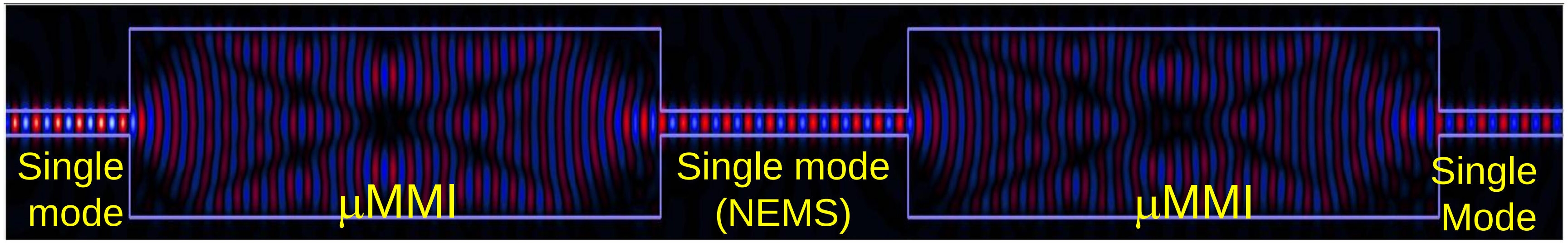
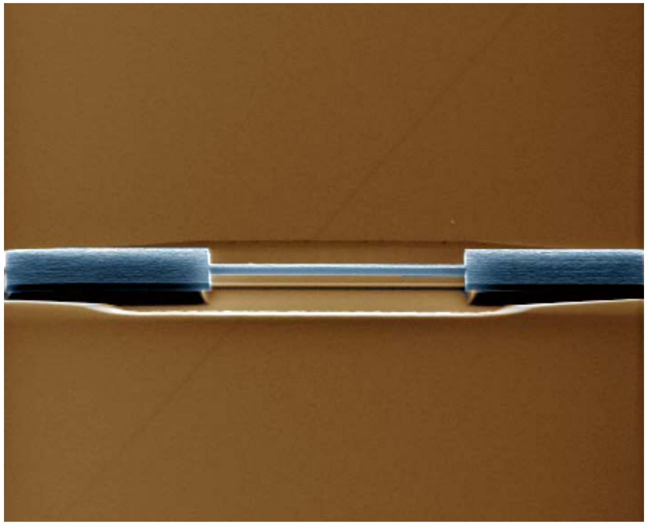
Optical simulation



<1dB loss



MMI = multimode interference coupler

Single mode silicon waveguide

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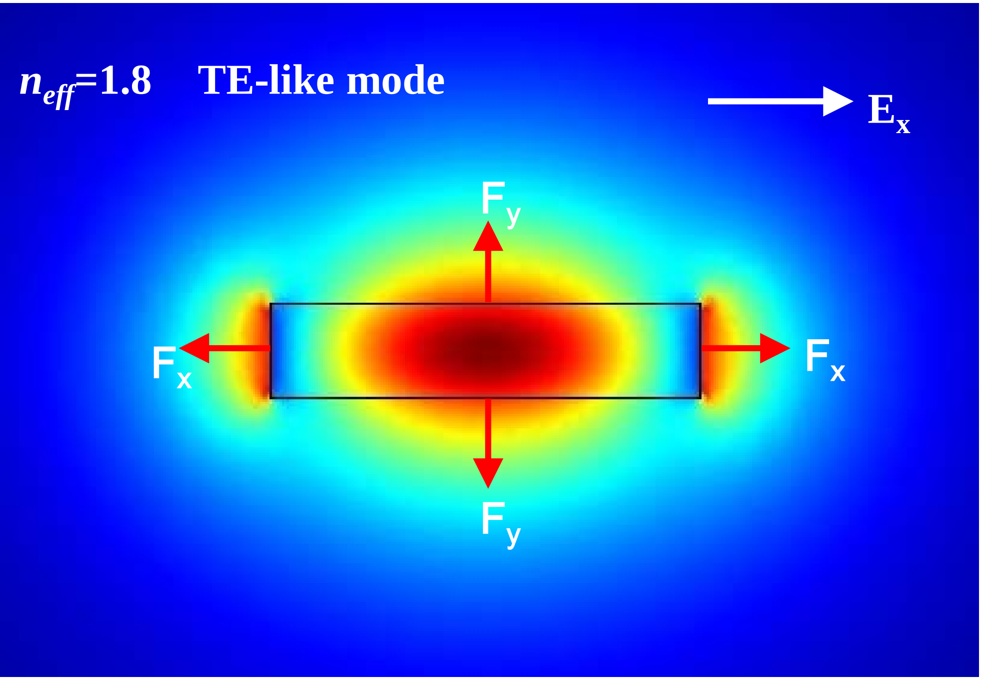
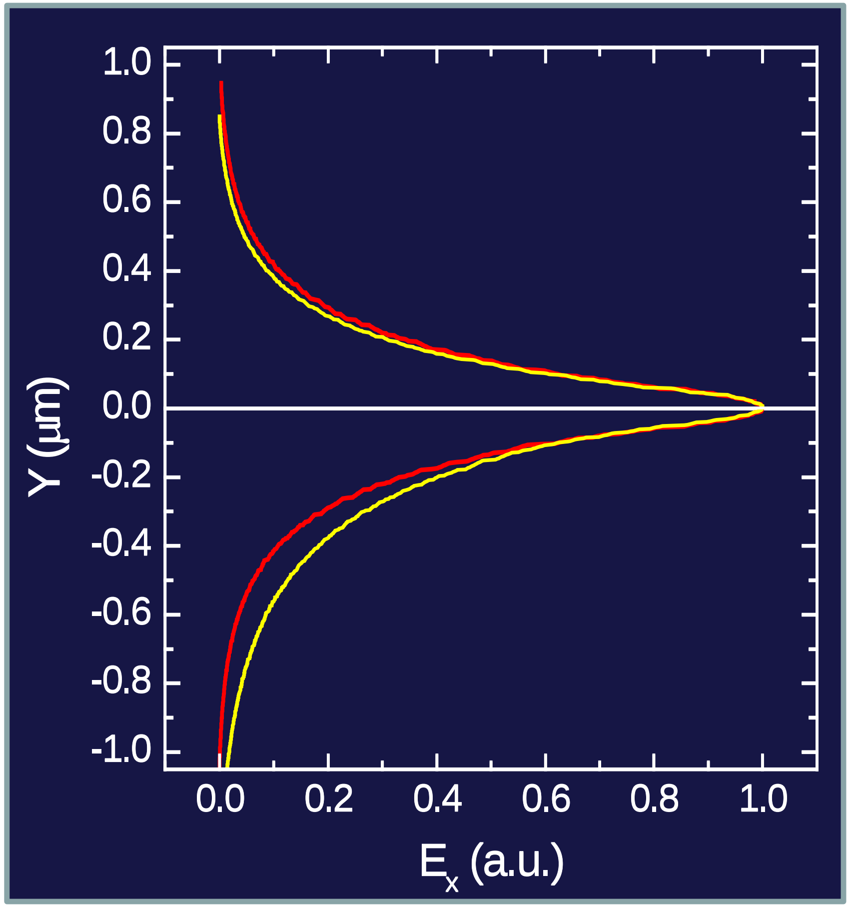




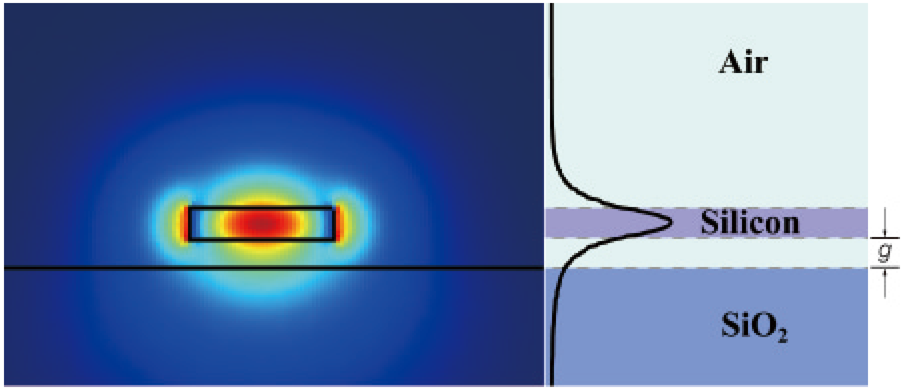
$$F_i = \oiint_s \sigma_{ik} dS_k \ , \quad F_{\text{total}} = \sum F_{1,2,3,4} = 0$$

Maxwell stress tensor:

$$\sigma_{ik} = \varepsilon_0 E_i E_k + \frac{1}{\mu_0} B_i B_k - \frac{1}{2}(\varepsilon_0 E^2 + \frac{1}{\mu_0} B^2)\delta_{ik}$$

Pernice, W. H. P., Li, M., Fong, K. Y., & Tang, H. X. (2009). Modeling of the optical force between propagating lightwaves in parallel 3D waveguides. *Optics express*, *17*(18), 16032-16037.

Effective index model



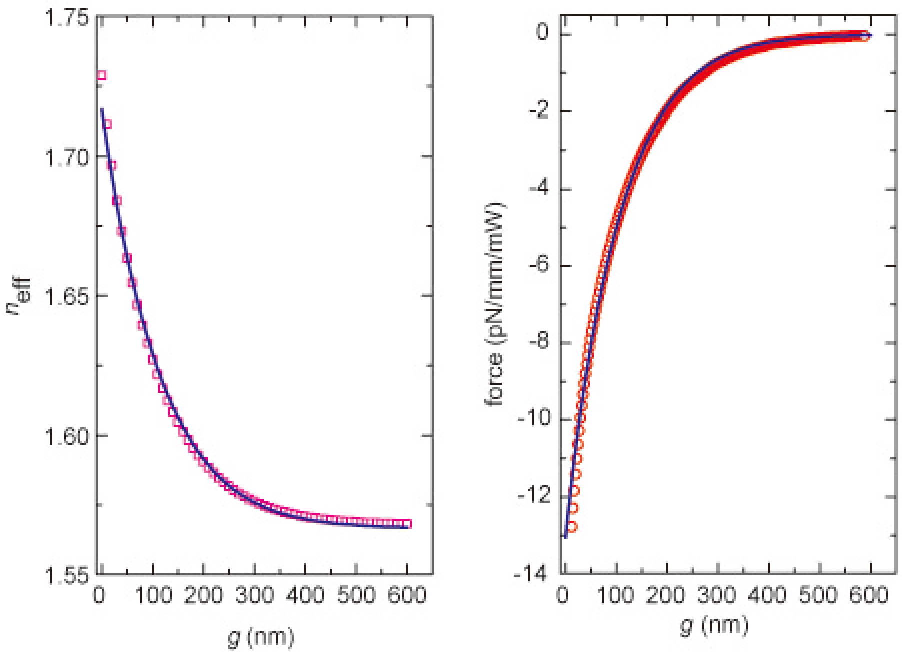
- Adiabatic expansion of "Photon Gas"

$$F = -\frac{1}{\omega}\frac{\partial \omega}{\partial g}U$$

$$F = \frac{1}{n_{eff}}\frac{\partial n_{eff}}{\partial g}U$$

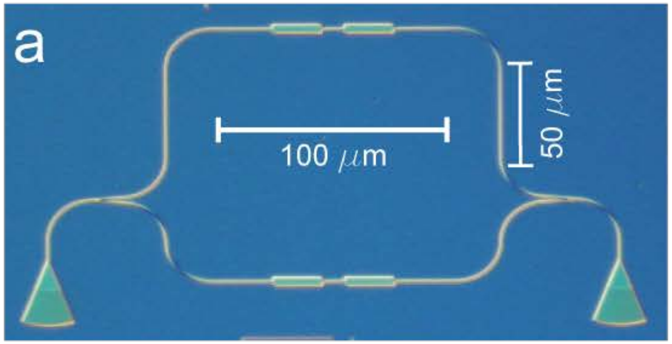
$$U = PLn_g/c$$

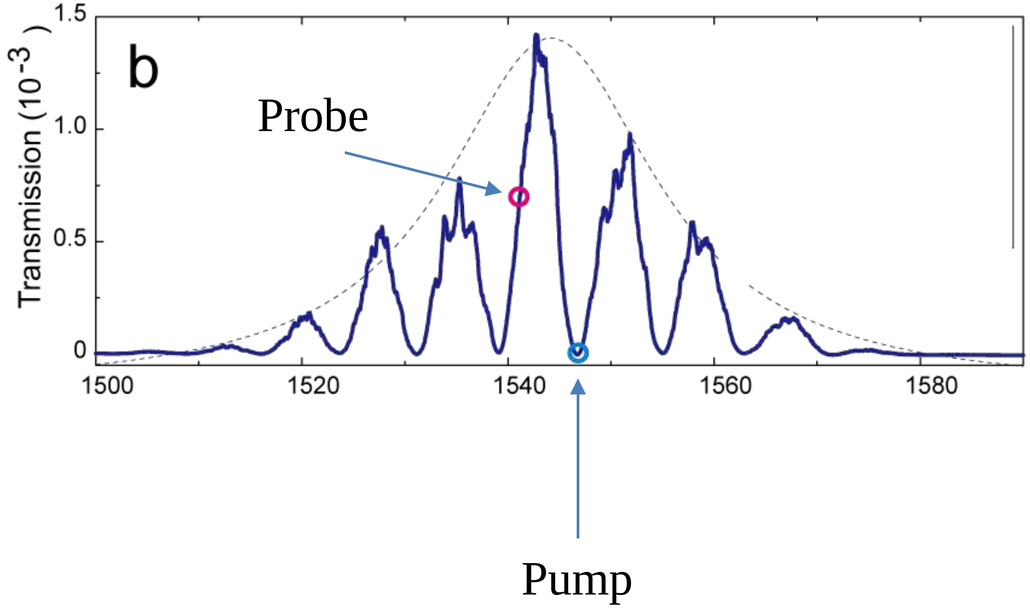
$$F_n = \frac{n_g}{cn_{eff}}\frac{\partial n_{eff}}{\partial g}$$



Li, M., Pernice, W. H. P., Xiong, C., Baehr-Jones, T., Hochberg, M., & Tang, H. X. (2008). Harnessing optical forces in integrated photonic circuits. *Nature*, *456*(7221), 480-484.

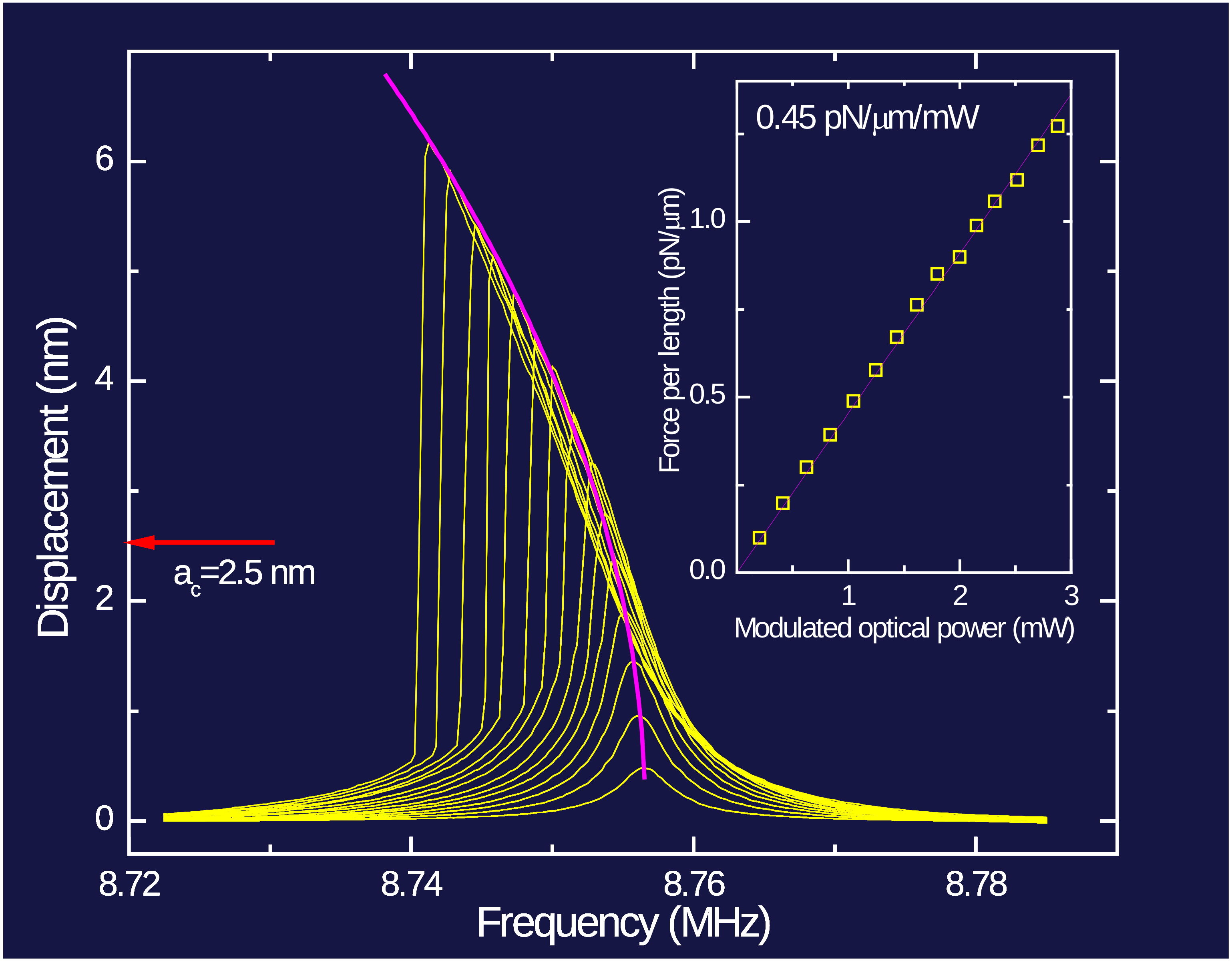
Pump-probe


a
100 μm
50 μm

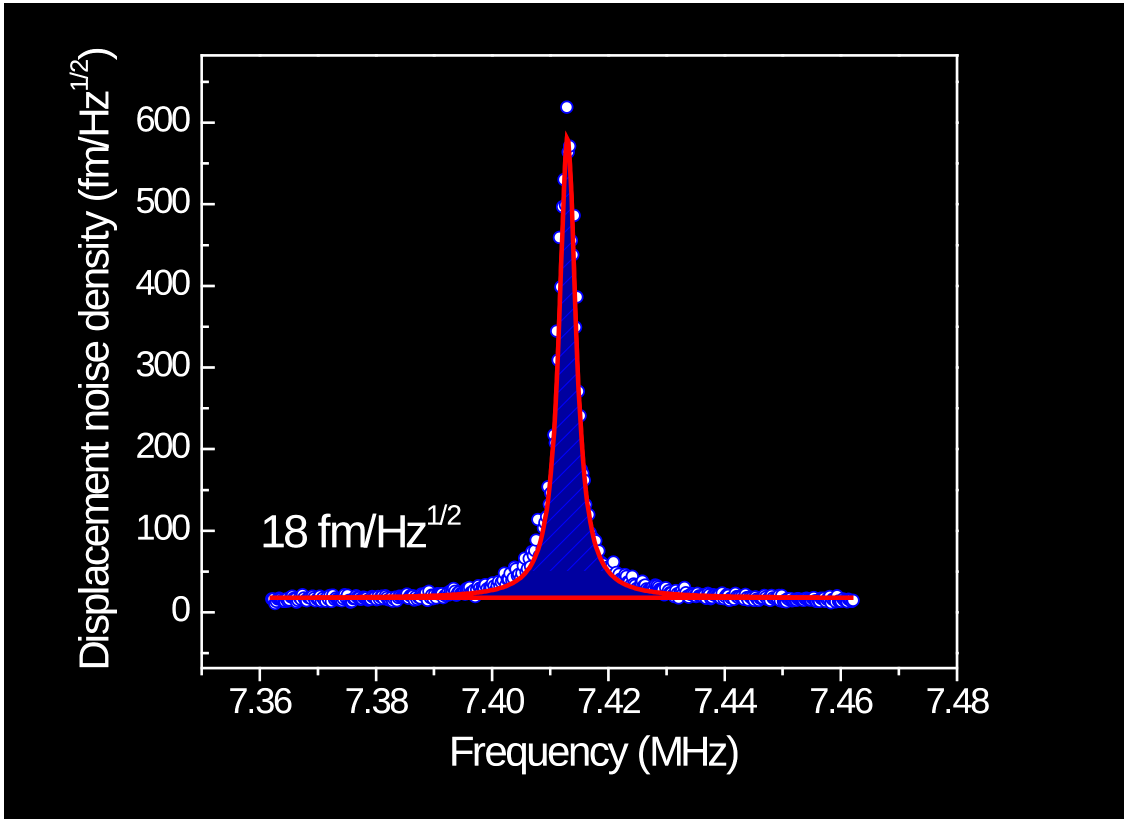

b
Probe
Pump
Transmission (10^-3)
1.5
1.0
0.5
0
1500
1520
1540
1560
1580

Quantify optical force with nanomechanical resonance

Yale



Thermomechanical Resonance



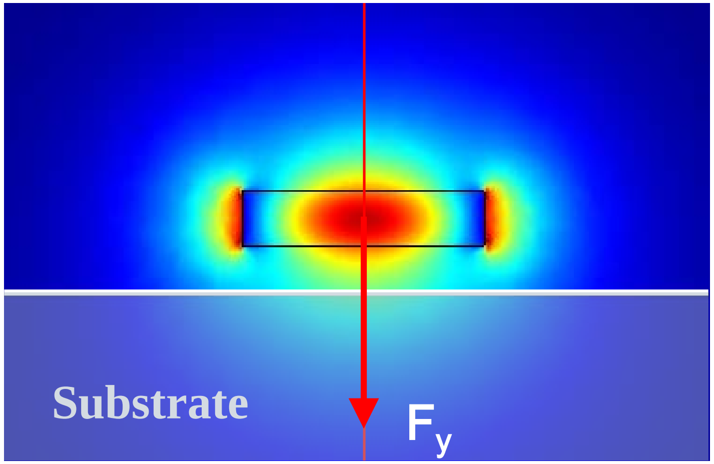
Detected brownian motion of mechanical device

Displacement sensitivity is 18fm/Hz$^{1/2}$ at room temperature

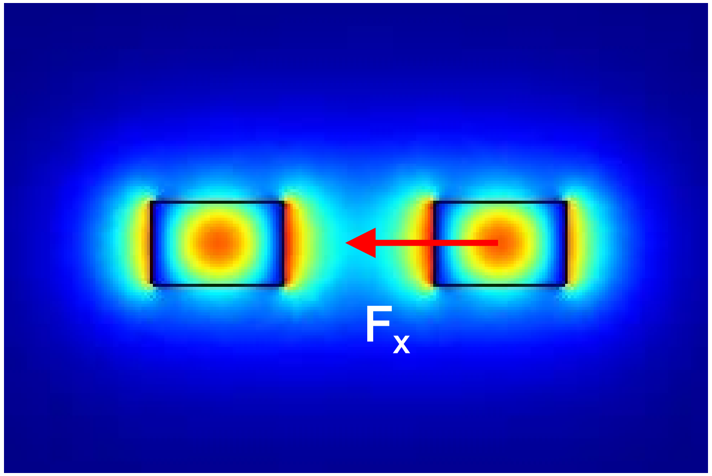
Optical mode engineering to allow optical actuation

Yale

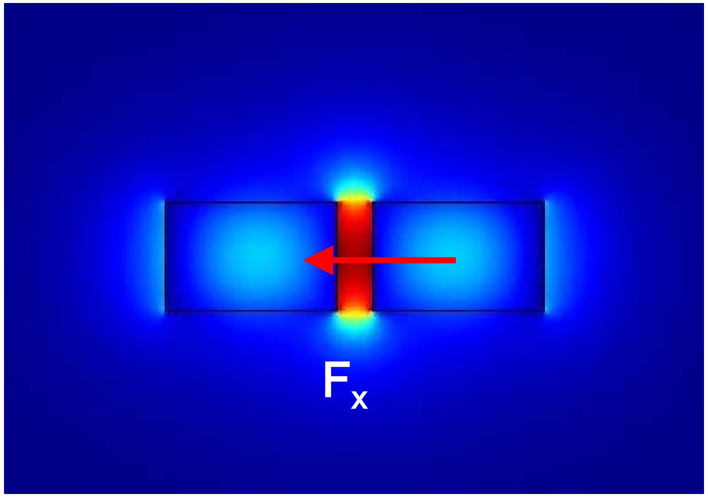
Substrate coupling



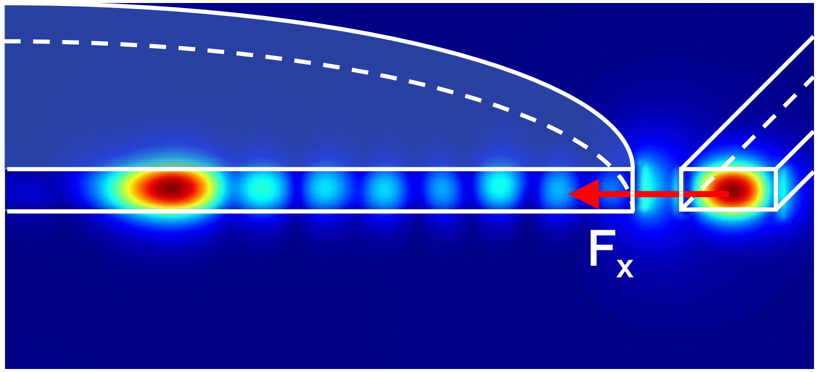
Coupled parallel waveguides



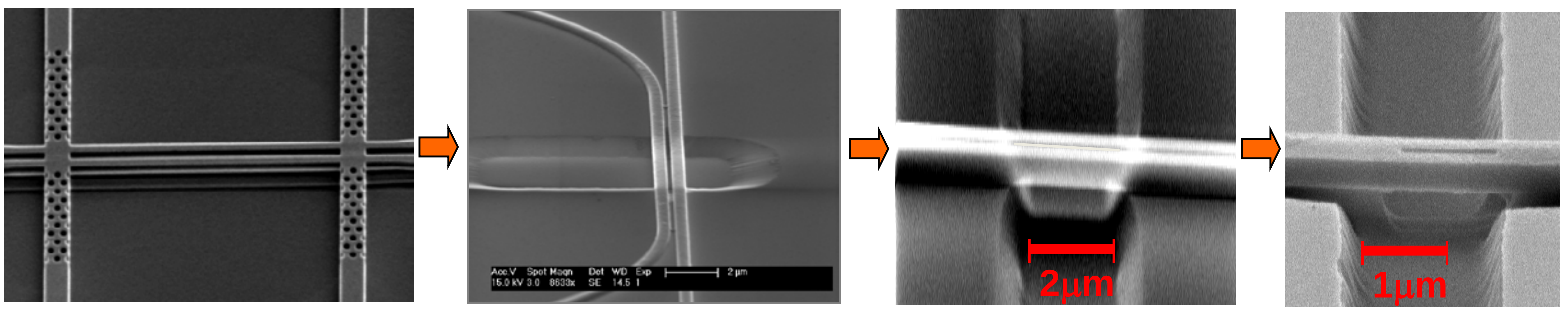
Slot waveguides



Couple with WGM resonator

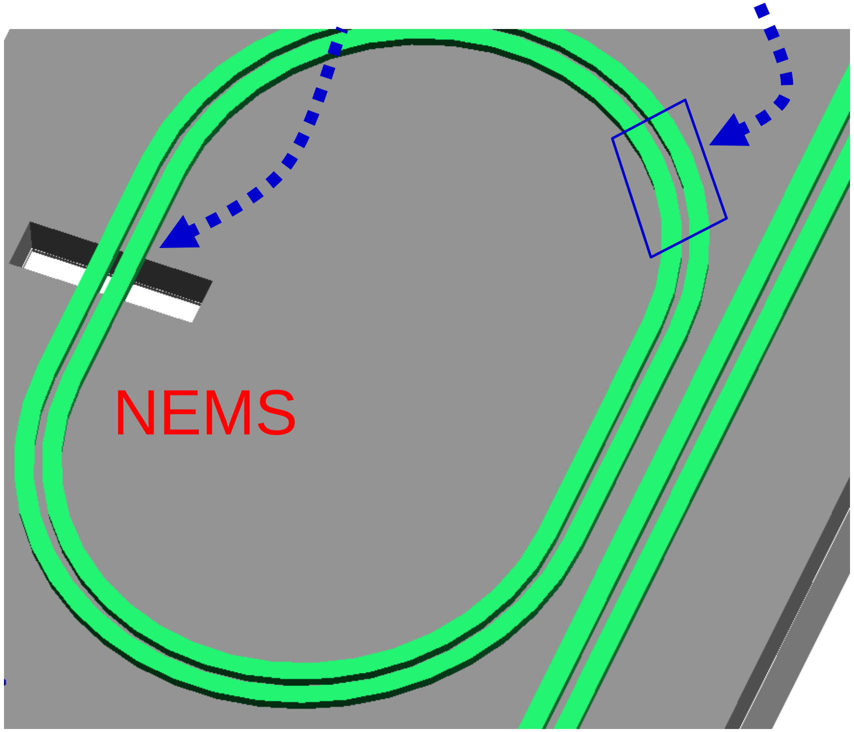


Smaller gap, stronger actuation

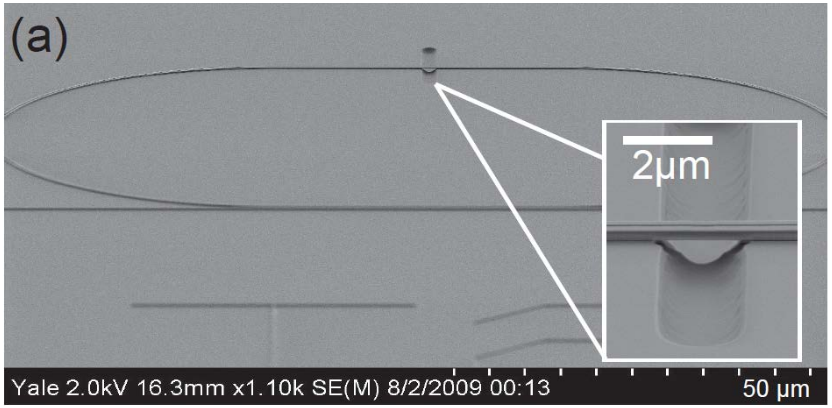


~18MHz ~30MHz ~310MHz ~1GHz

Light Rail



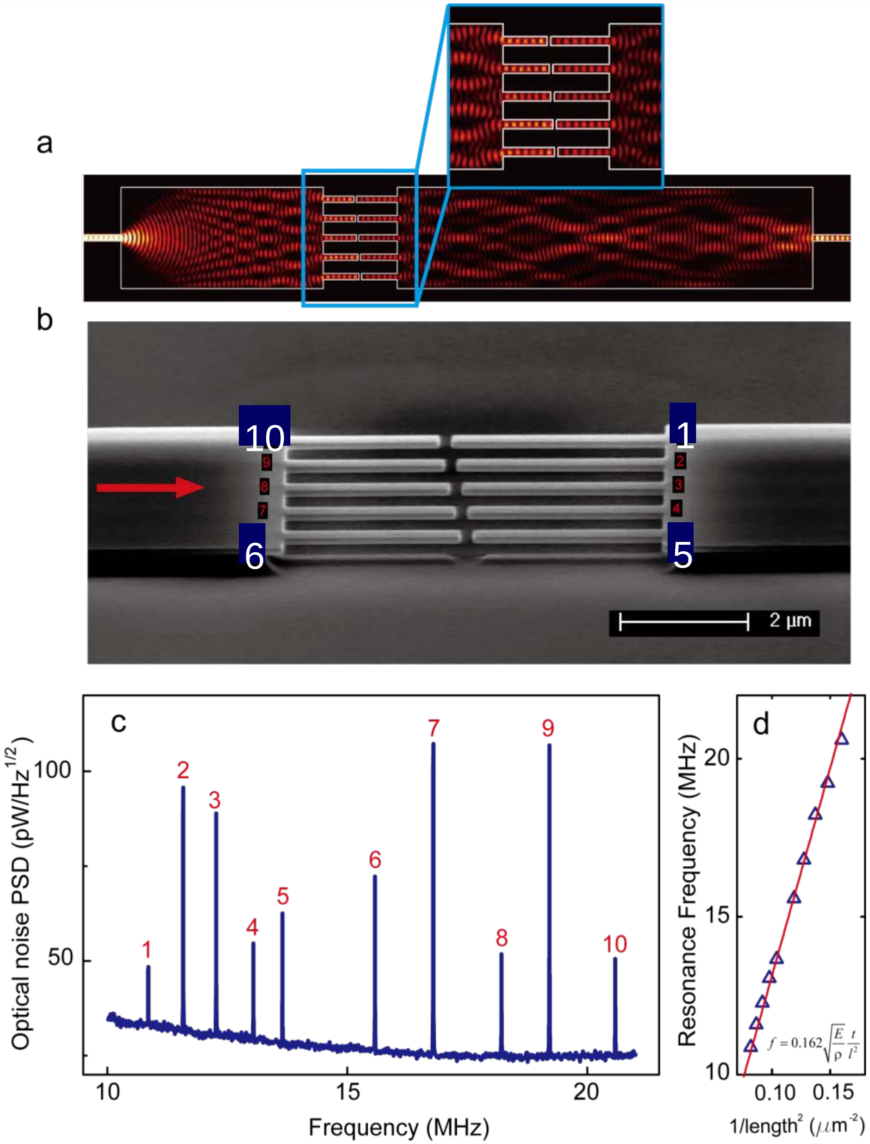
Light rail: Slot-ring circuit cavity



- Qo = 60,000
- Qm = 2400
- Sensitivity = 450am/rtHz
- Mass = 300fg

M. Li, W. Pernice, H. Tang, Applied Physics Letters, 2010

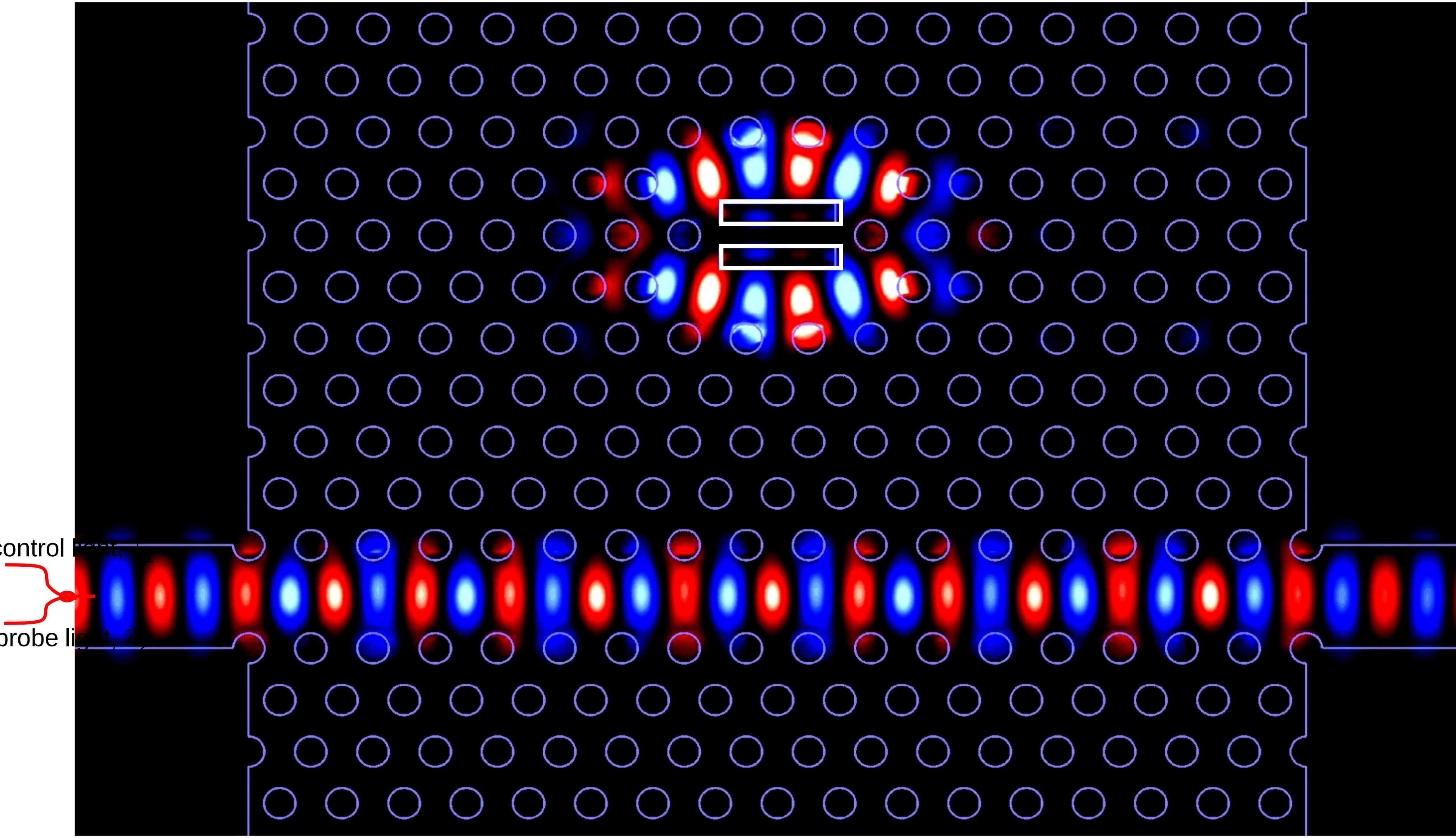
Cantilever arrays



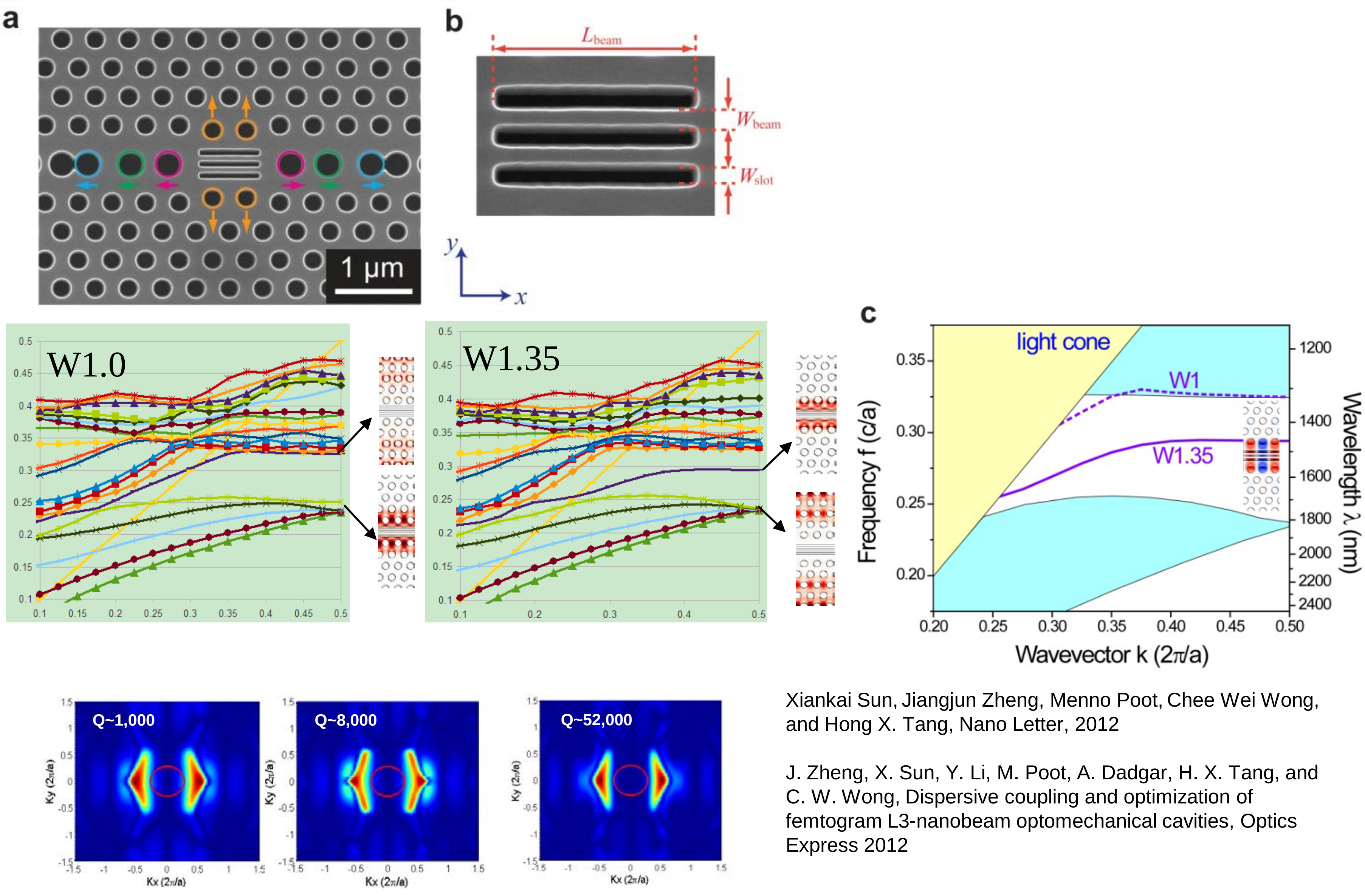
Multiplexing 10 optomechanical sensors on a photonic bus

Li, Pernice, Tang, Nature Nanotechnology (2009)

Device 2: PhC nanobeam cavity



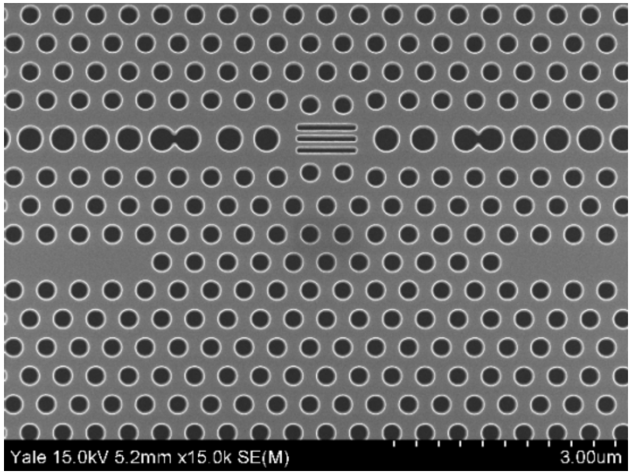
High-Q femtogram beam cavities

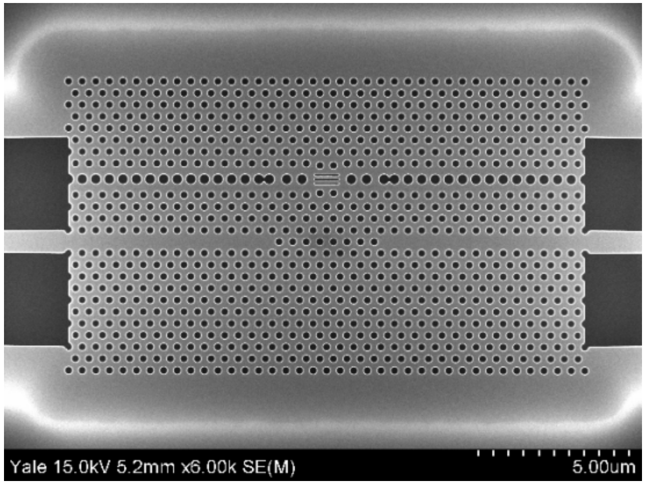


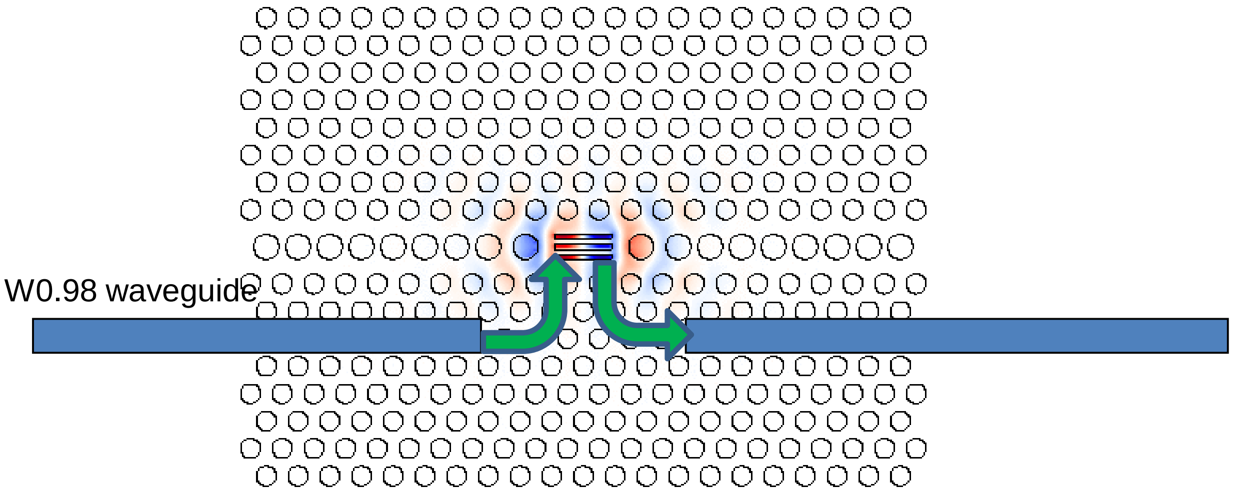
Xiankai Sun, Jiangjun Zheng, Menno Poot, Chee Wei Wong, and Hong X. Tang, Nano Letter, 2012

J. Zheng, X. Sun, Y. Li, M. Poot, A. Dadgar, H. X. Tang, and C. W. Wong, Dispersive coupling and optimization of femtogram L3-nanobeam optomechanical cavities, Optics Express 2012

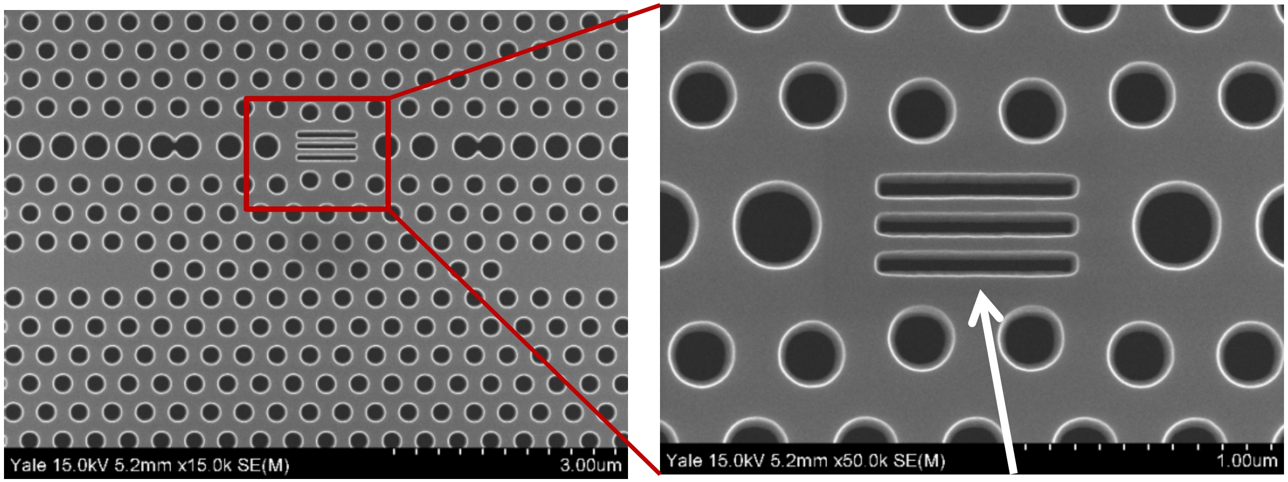
Fabrication and measurement







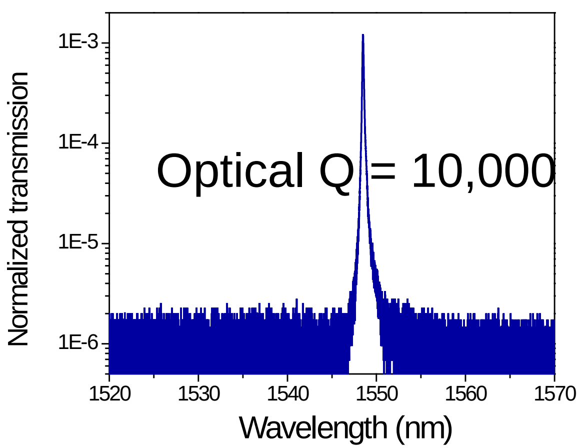
Fabrication and measurement

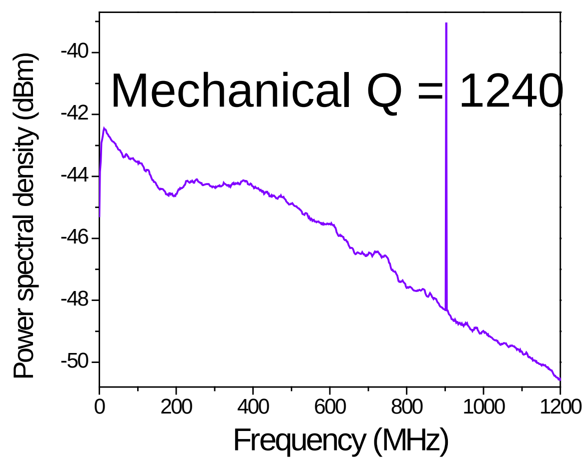


Dual optomechanical resonators

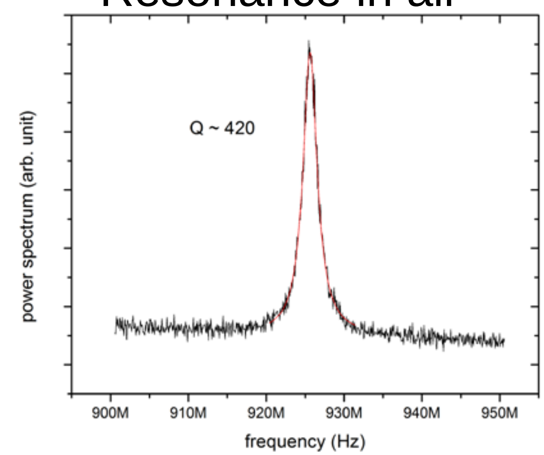
Main features

- Qo = 10,000 (>52,000 possible)
- Vo = $0.022(\lambda_{air})^3$
- Q_m = 1240
- **M = 25 fg**
- Minimum resolvable mass ~ **50 zg**

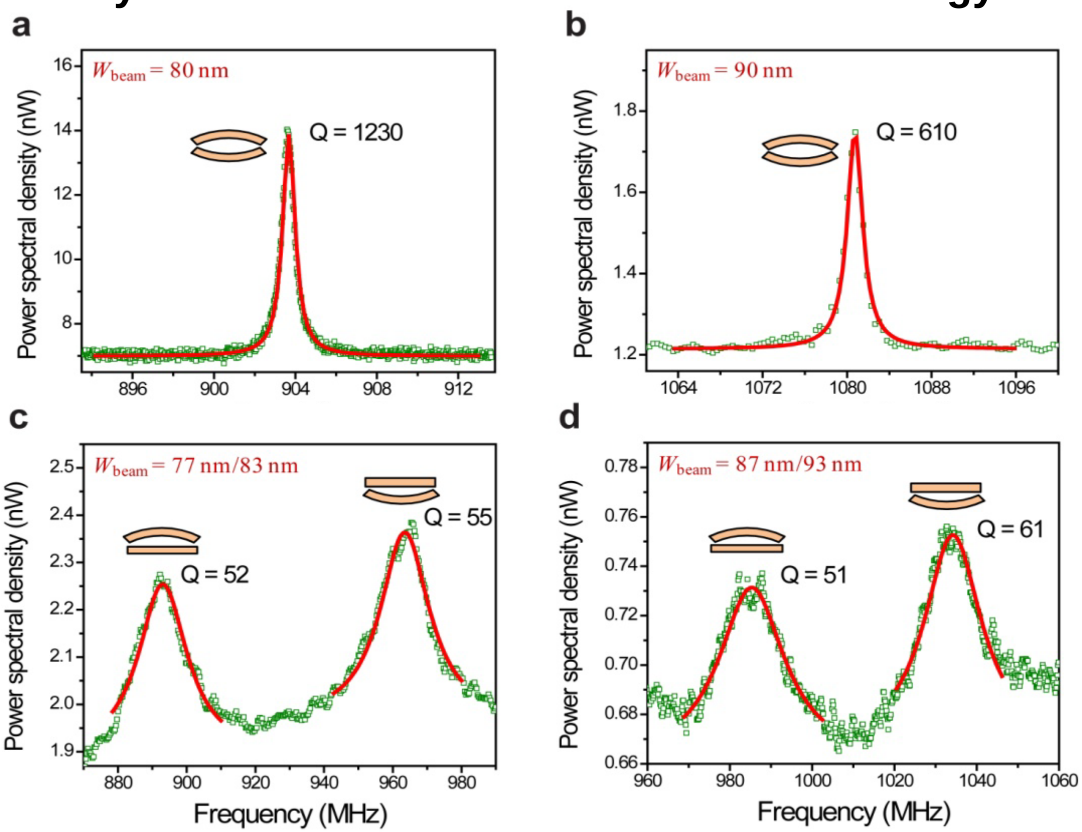




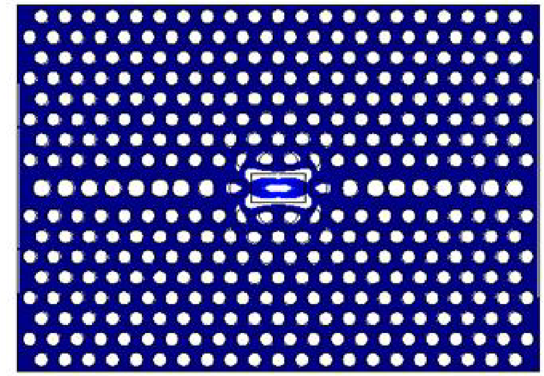
Resonance in air



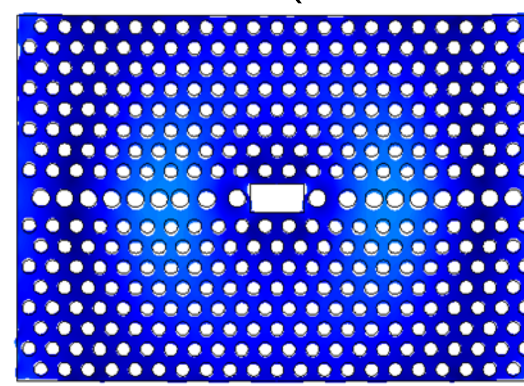
Symmetric mode radiates less elastic energy

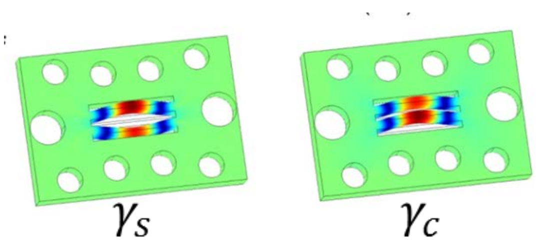


differential mode (longitudinal waves)



common mode(shear waves)





Plan for the next five days

Yale

Chipscale Cavity
Optomechanics and Electro-Optomechanics, part 1
Monday, 12:00PM NP

Chipscale Cavity
Optomechanics and Electro-Optomechanics, part 2
Tuesday, 8:30AM NP

Hybrid Silicon Photonic Circuits
for Chip-Scale Nonlinear and Quantum Optics, part 1
Wednesday, 9:30AM NP

Hybrid Silicon Photonic Circuits
for Chip-Scale Nonlinear and Quantum Optics, part 2
Friday, 9:30AM NP

Plan for the next five days

Yale

Chipscale Cavity
Optomechanics and Electro-Optomechanics, part 1
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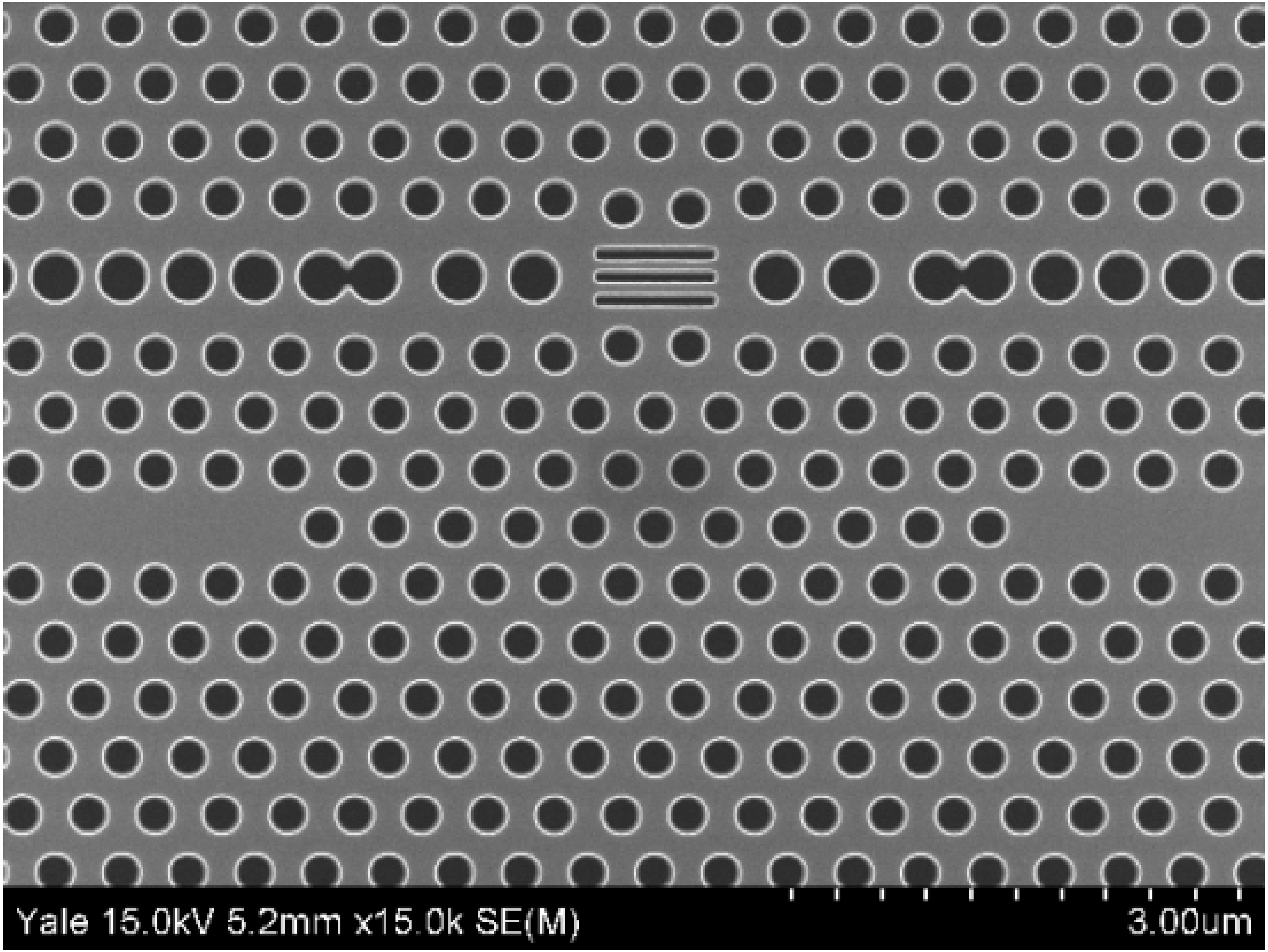
Tuesday, 8:30AM NP

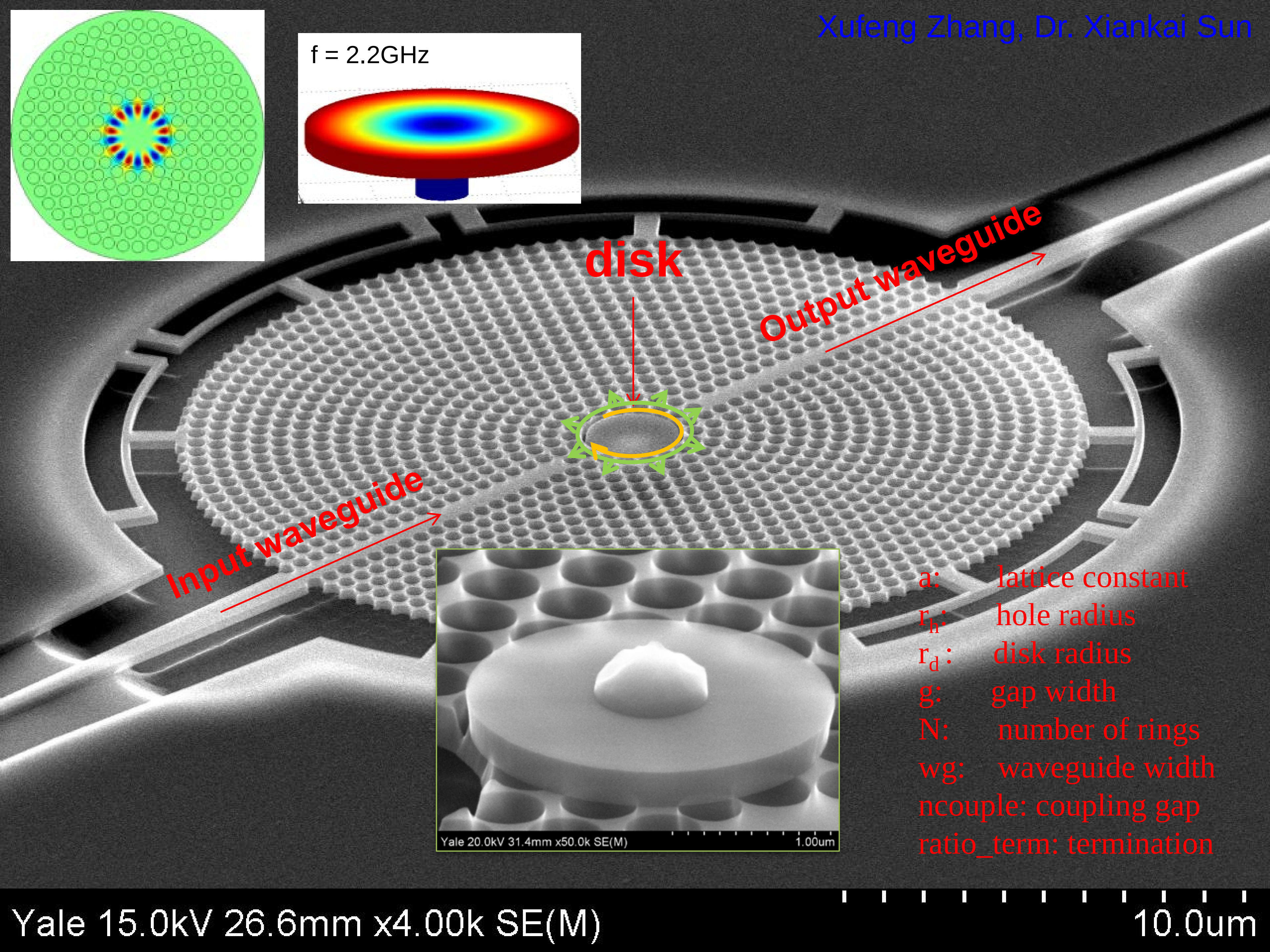
Chipscale Cavity
Optomechanics and Electro-Optomechanics, part 3
Wednesday, 8:30AM NP

Hybrid Silicon Photonic Circuits
for Chip-Scale Nonlinear and Quantum Optics
Friday, 9:30AM NP

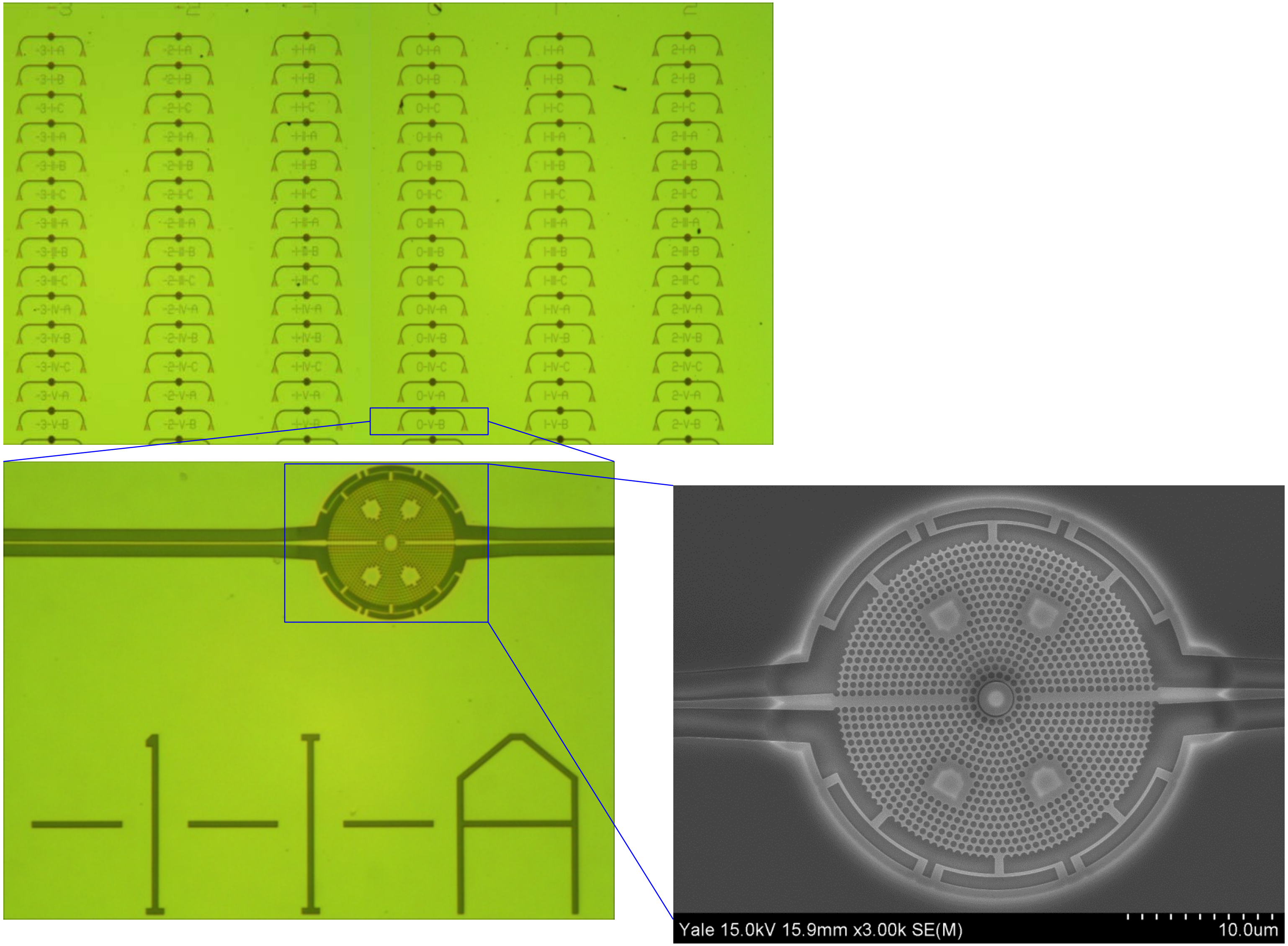
A record-small nanomechanical resonator

Yale




Xufeng Zhang, Dr. Xiankai Sun
f = 2.2GHz
disk
Output waveguide
Input waveguide
a: lattice constant
r_h: hole radius
r_d : disk radius
g: gap width
N: number of rings
wg: waveguide width
ncouple: coupling gap
ratio_term: termination
Yale 20.0kV 31.4mm x50.0k SE(M) 1.00um
Yale 15.0kV 26.6mm x4.00k SE(M) 10.0um

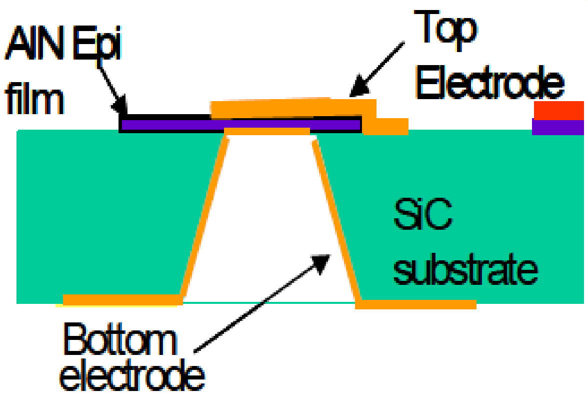
Sunflower

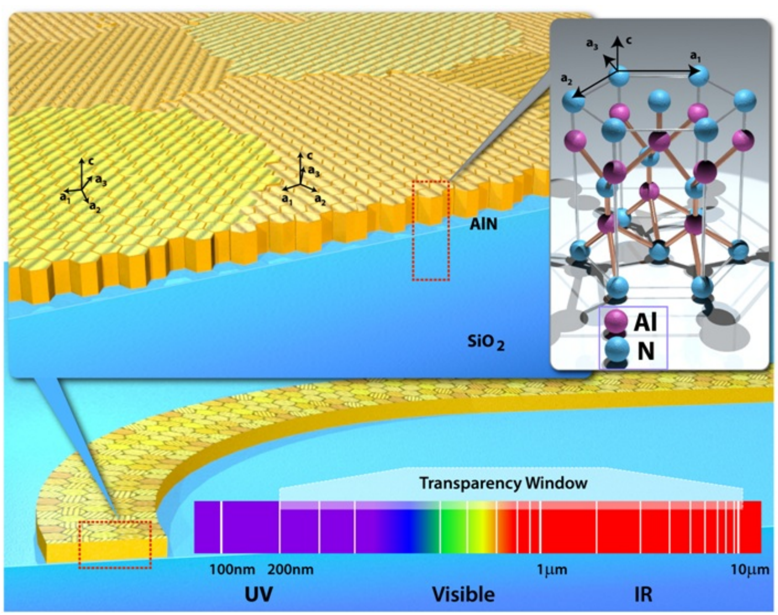


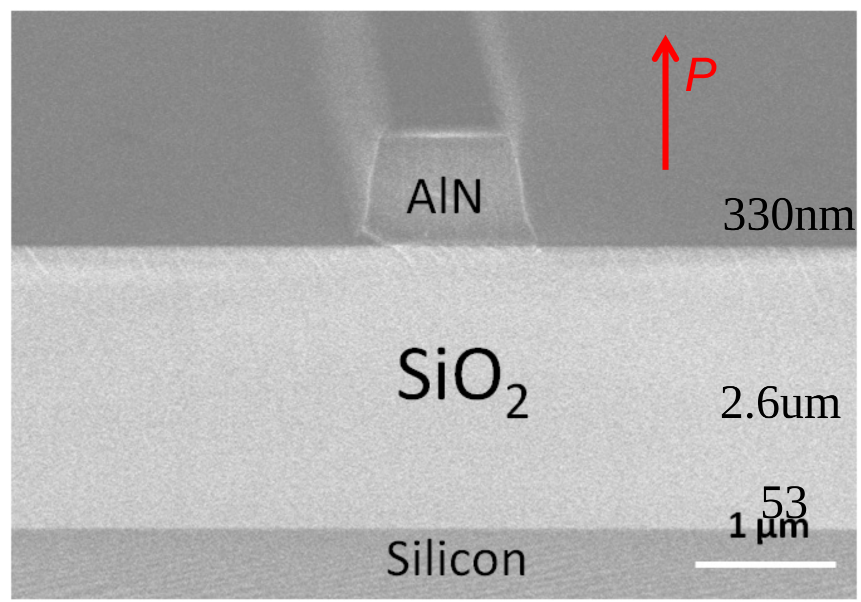
Case Study: AlN Piezo-optomechanics

AlN on silicon for photonics

- RF sputter deposition
  - Excellent *c*-axis orientation
  - Low temperature deposition (350 °C)
  - Low surface roughness (rms a few nm)
  - Wafer-scale deposition
  - Versatile substrates (Metal, silicon, silicon dioxide and etc.)



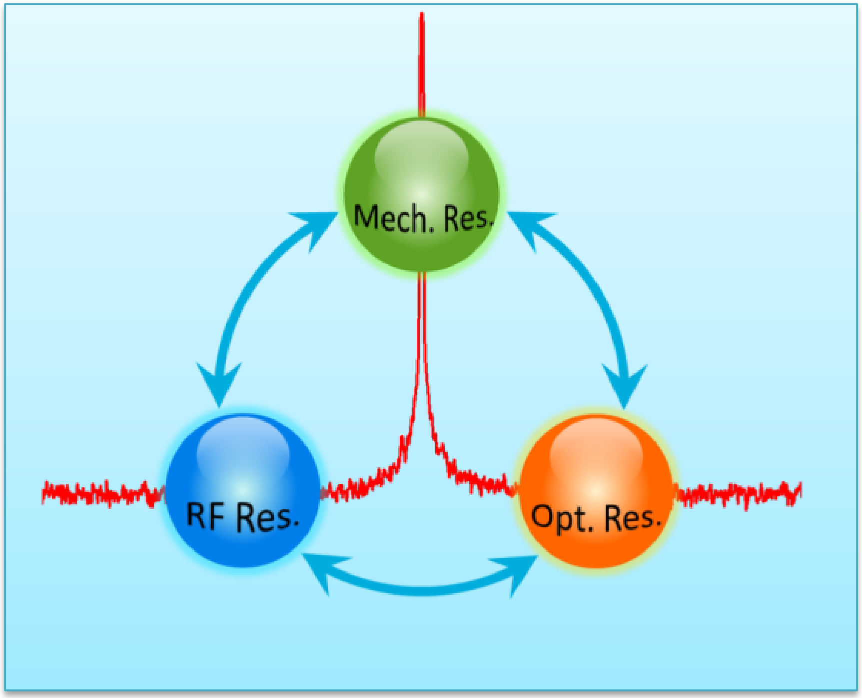




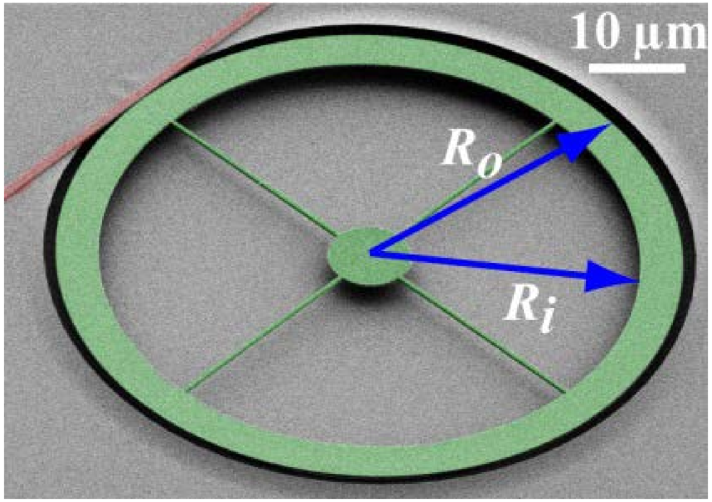
Electro-optic and piezoelectric properties of AlN

- electro-mechanical tensor

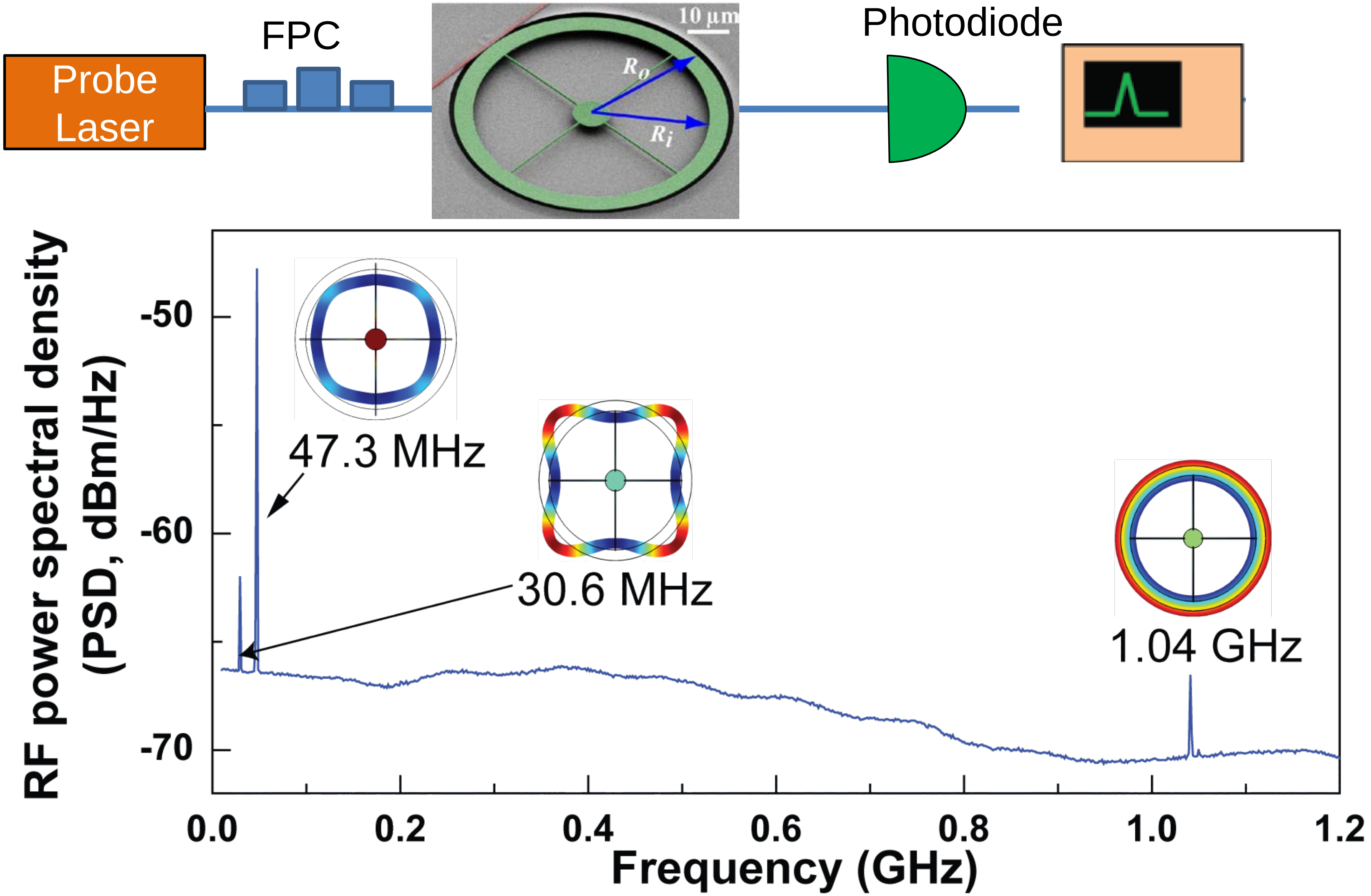
$$\begin{pmatrix} S_{xx} \\ S_{yy} \\ S_{zz} \\ S_{yz} \\ S_{xz} \\ S_{xy} \end{pmatrix} = \begin{pmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{31} \\ 0 & 0 & d_{33} \\ 0 & d_{51} & 0 \\ d_{51} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} = \begin{pmatrix} d_{31}E_z \\ d_{31}E_z \\ d_{33}E_z \\ d_{51}E_y \\ d_{51}E_x \\ 0 \end{pmatrix}$$



AlN piezo-optomechanical oscillator

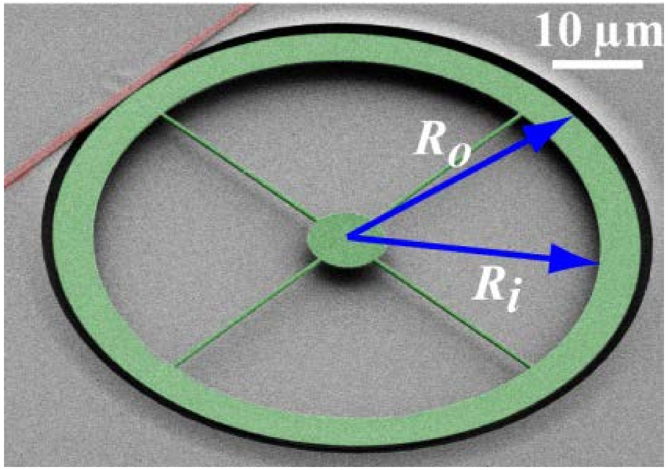


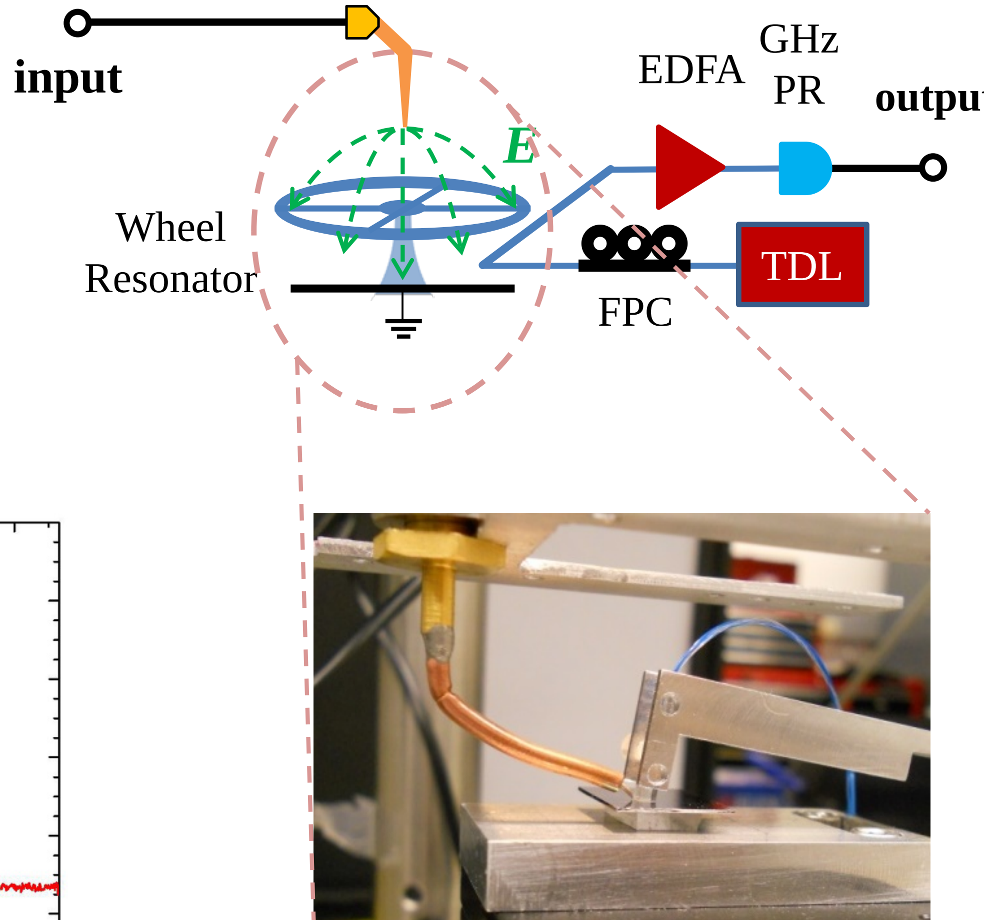
AlN micro-ring resonator



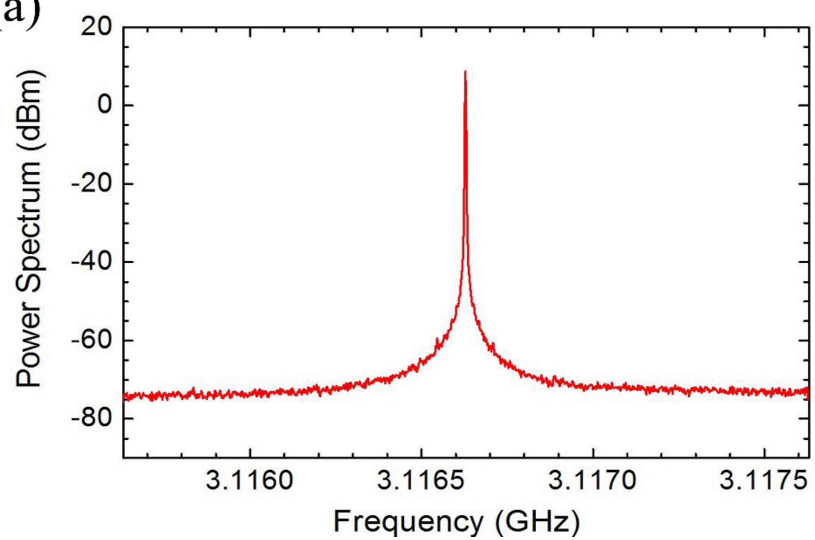
Xiong, Sun, King, Tang, *App. Phys. Lett.* **100**,171111 (2012)

AlN piezo-optomechanical oscillator

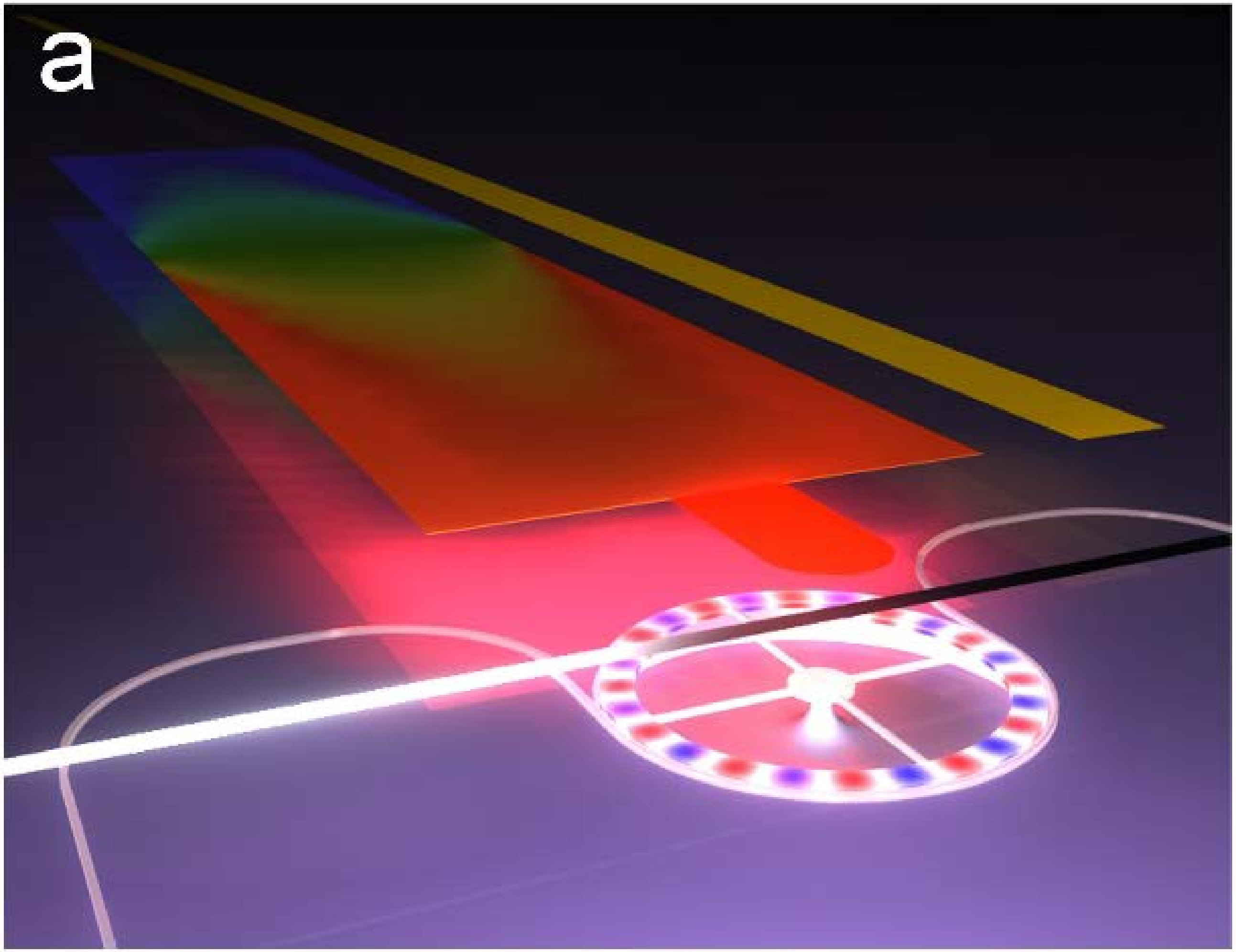




(a)



Triple resonant electro-opto-mechanical oscillator

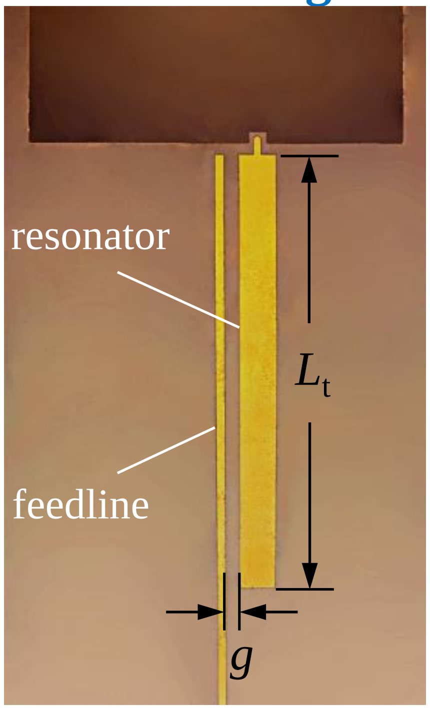


High frequency optomechanics

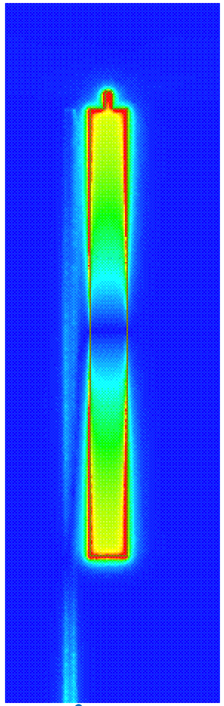
Triple resonant electro-opto-mechanical oscillator

Yale

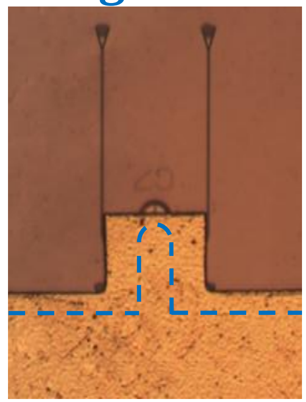
Photo Image



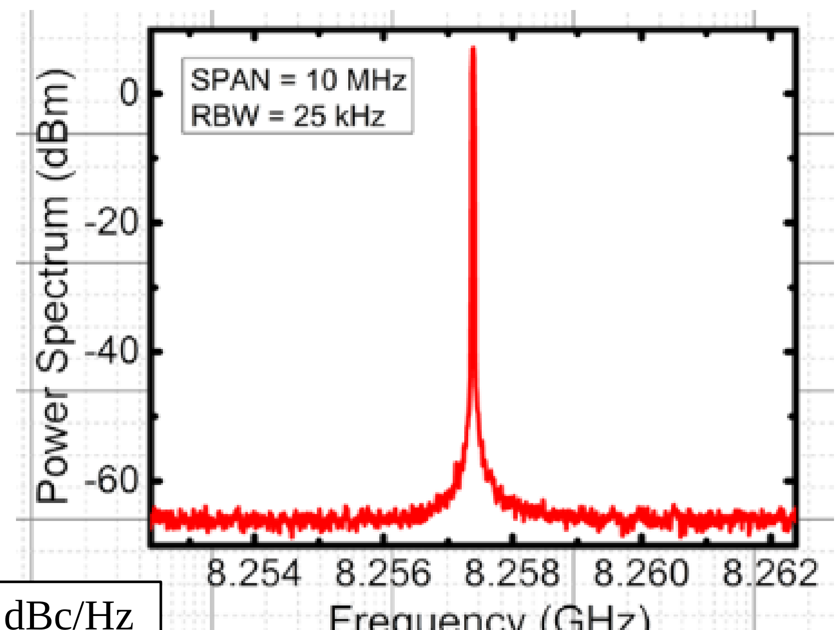
Simulation



Alignment



Packaging



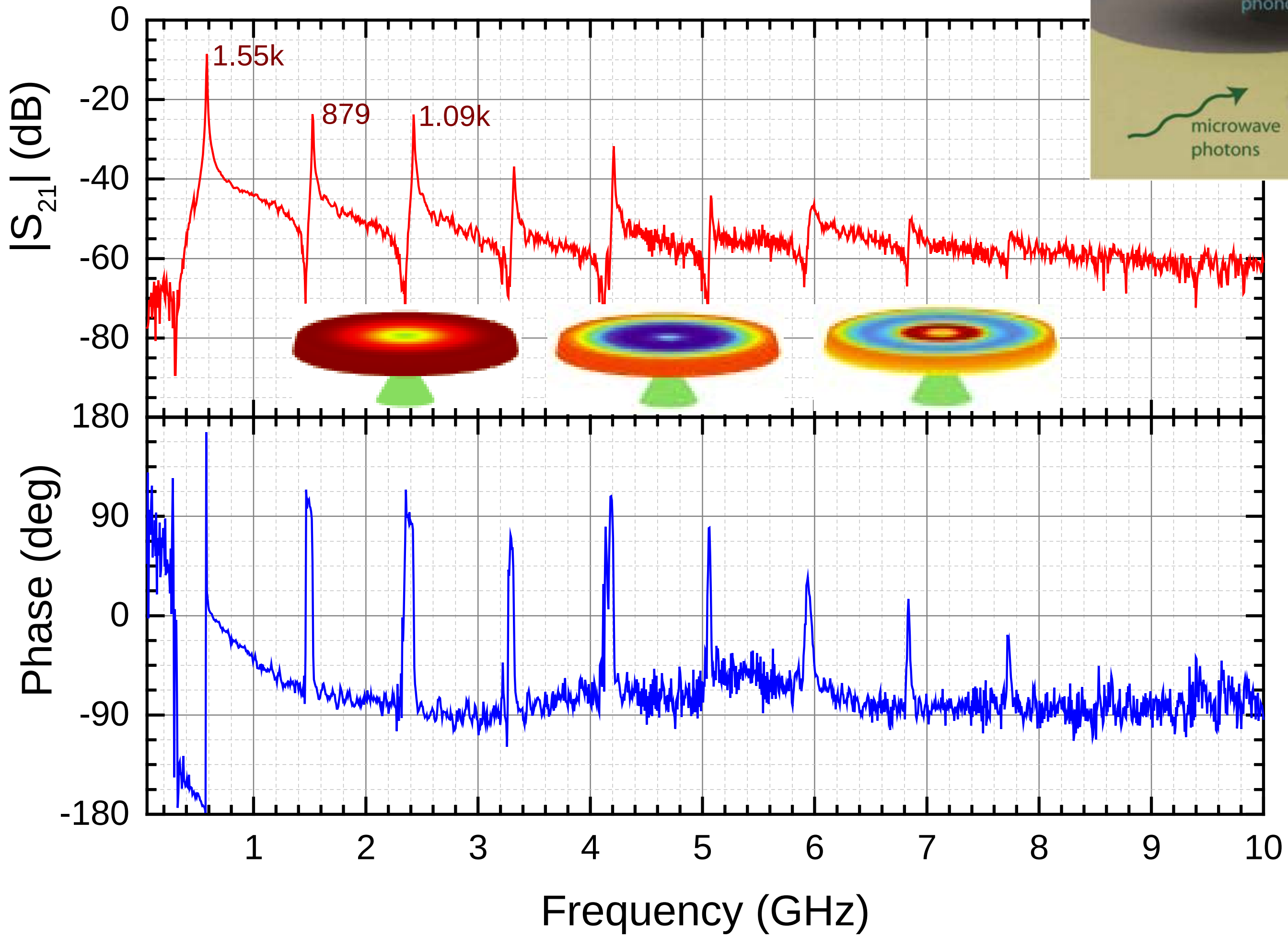
-88 dBc/Hz

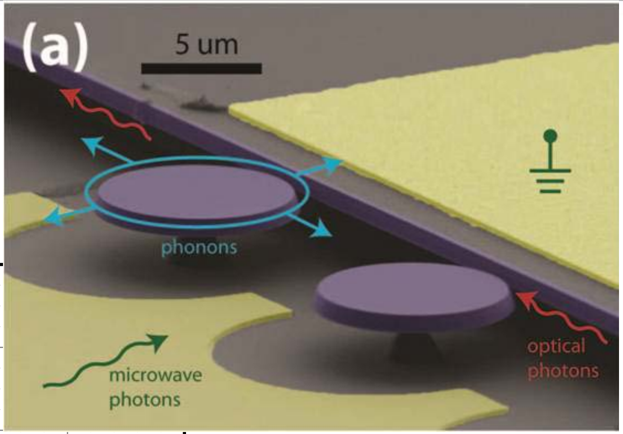
"Triply resonant cavity piezo-optomechanics at X-band", X. Han, C. Xiong, K. Y. Fong, X. F. Zhang, H. X. Tang, New Journal of Physics 16, 063060 (2014).

High frequency electro-opto-mechanical oscillator

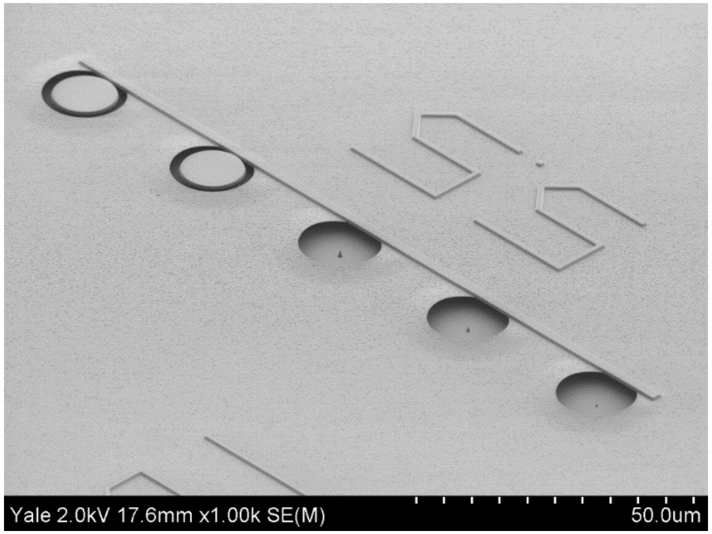
Yale

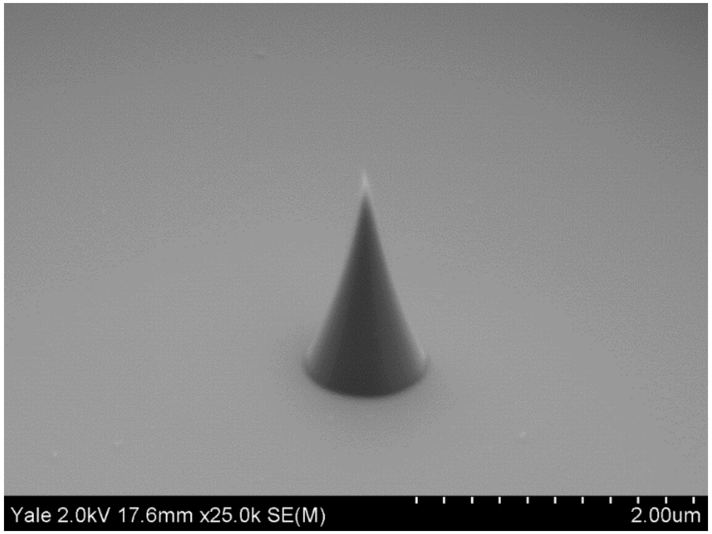
r=6um disc
spectrum 50 MHz ~ 10 GHz



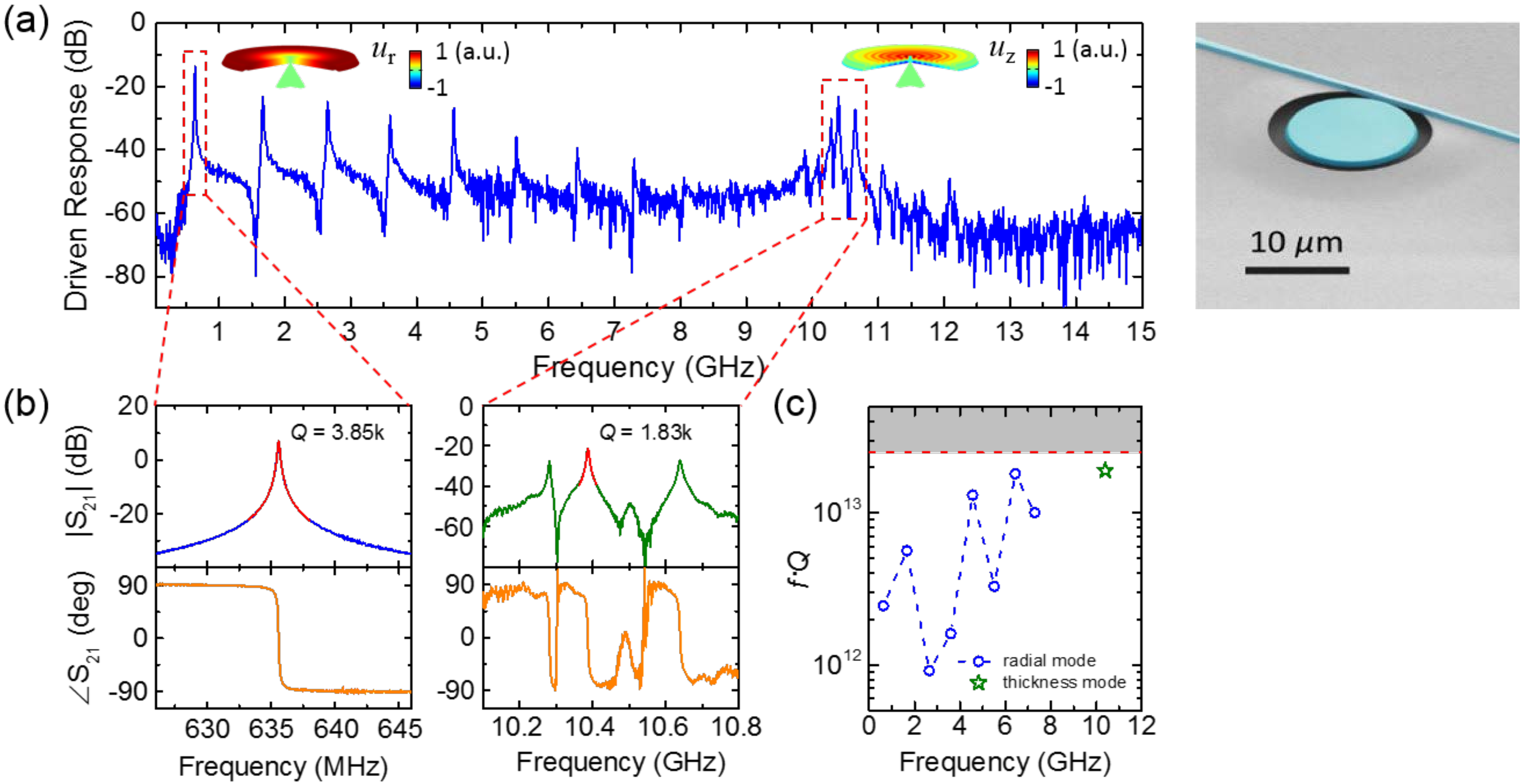


Reduction of clamping loss





Frequency response and fQ product

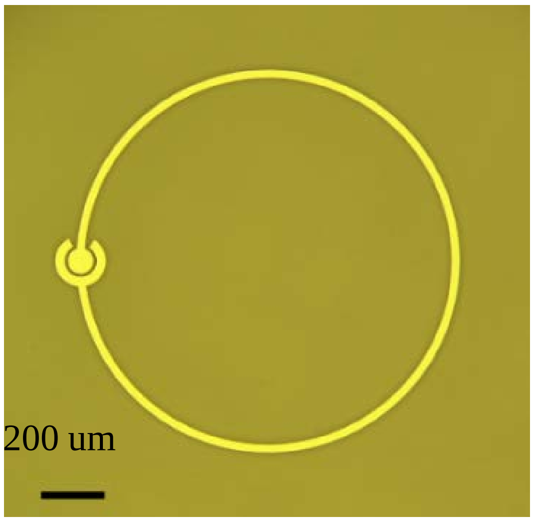


f·Q producet = 2x10^{13}, at the theoretical limit

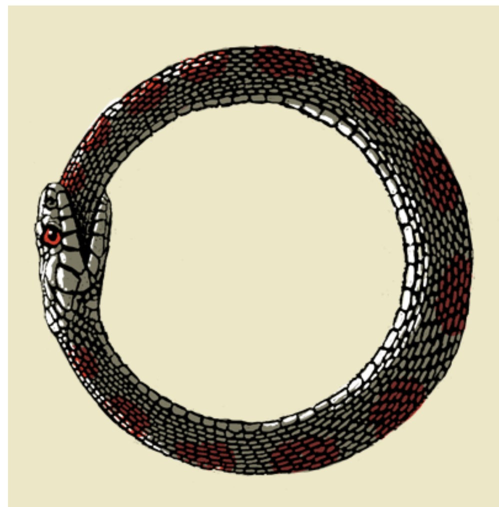
X. Han, et al, "A 10-GHz film-thickness-mode cavity optomechanical resonator", Applied Physics Letters 108, 161108 (2015)

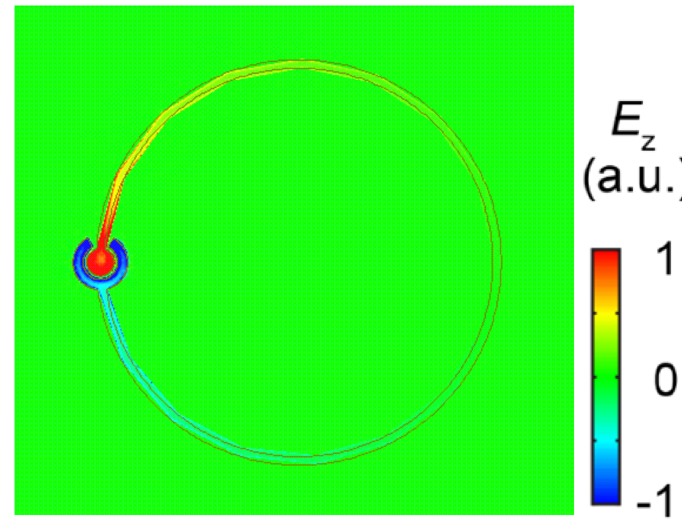
“Ouroboros” Superconducting Resonator

Optical Image



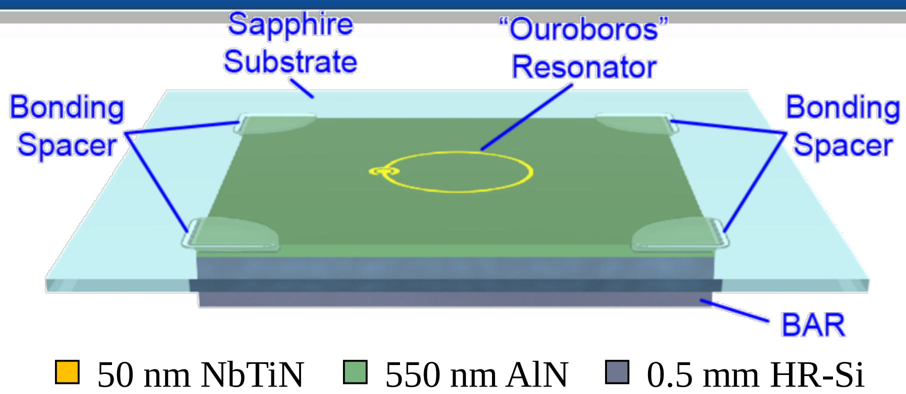
HFSS Simulation

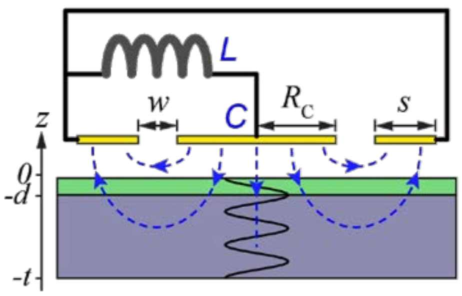




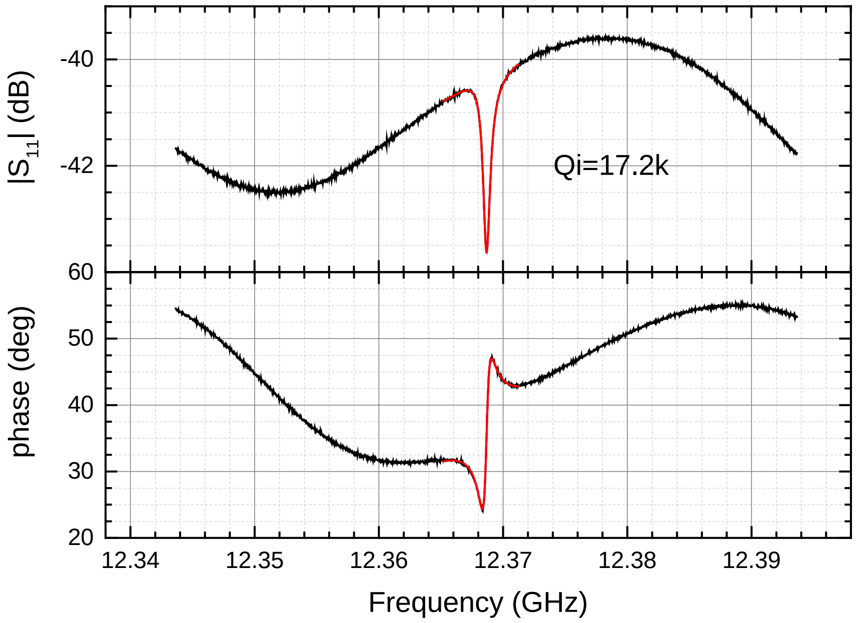
50 nm NbTiN (Tc = 13 K) on
127 μm sapphire substrate

"Ouroboros" + Bulk Acoustic Resonator (BAR)



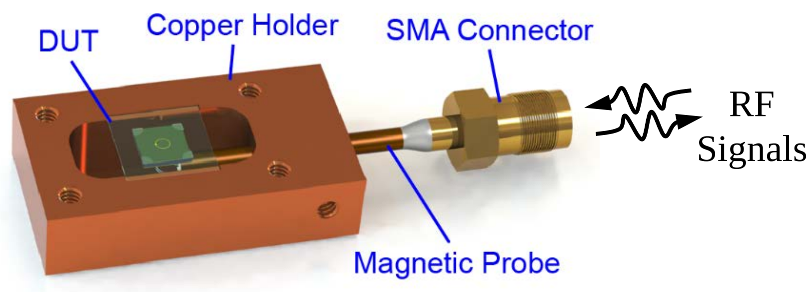


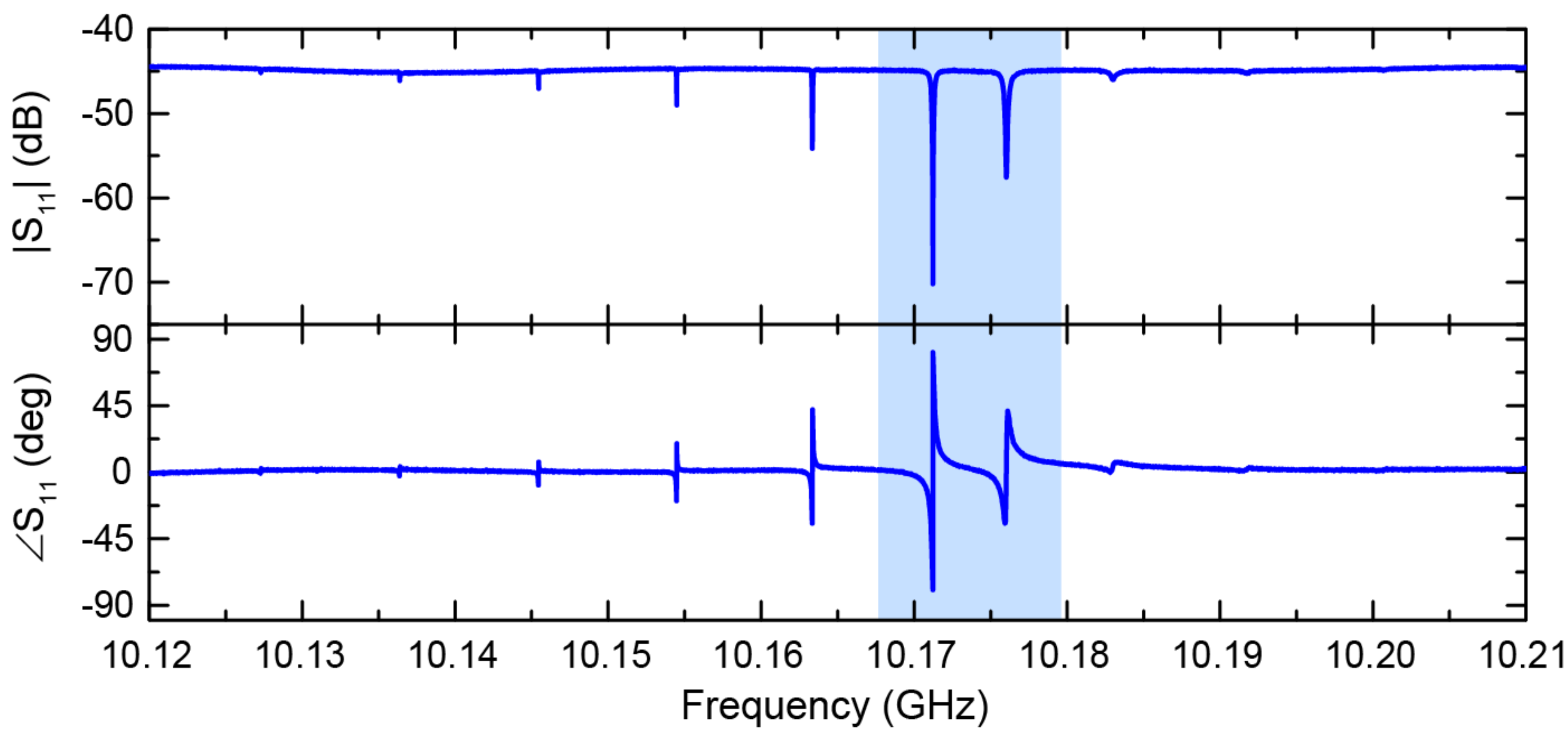
❑ Characterization in liquid helium (4.2 K)



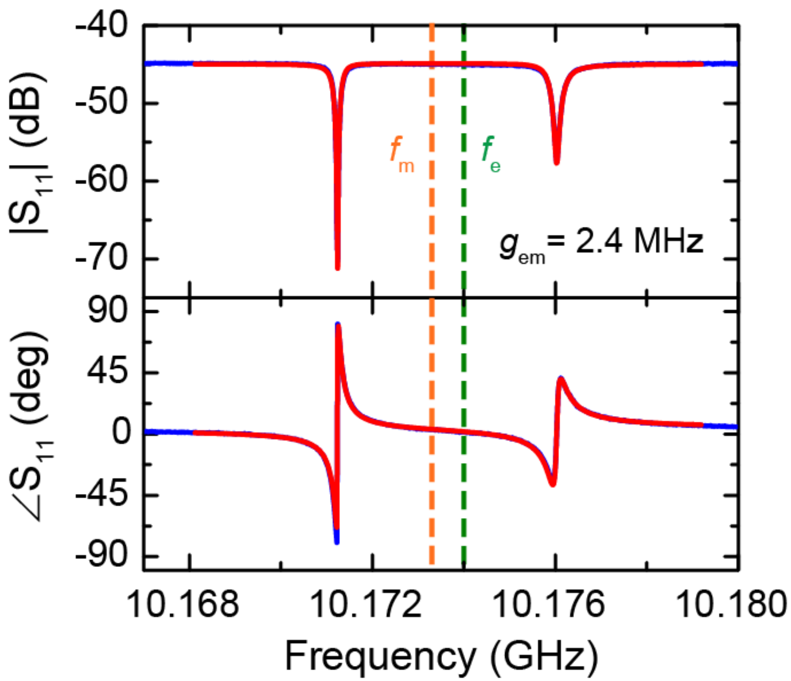
Piezo-electromechanical Strong Coupling

❑ **Reflection Spectrum (@ 1.7 K)**





Piezo-electromechanical Strong Coupling



Fitting Results:

$f_a \approx 10.1740$ GHz $\quad f_b \approx 10.1733$ GHz

$Q_{a,e} \approx 52.8\text{k} \quad Q_{a,i} \approx 19.0\text{k} \quad Q_m \approx 49.7\text{k}$

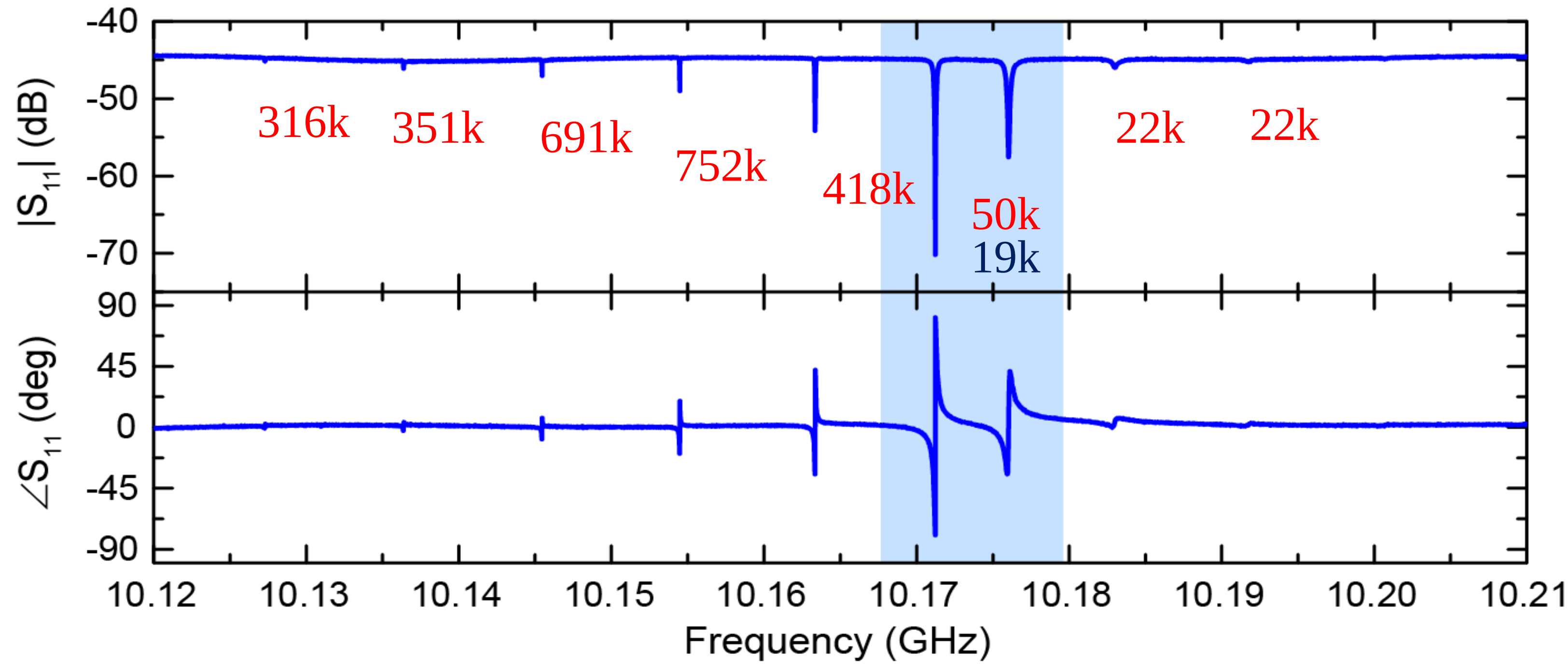
$\kappa_{bn}/2\pi \approx 0.10$ MHz $\quad \kappa_{a,i}/2\pi \approx 0.27$ MHz

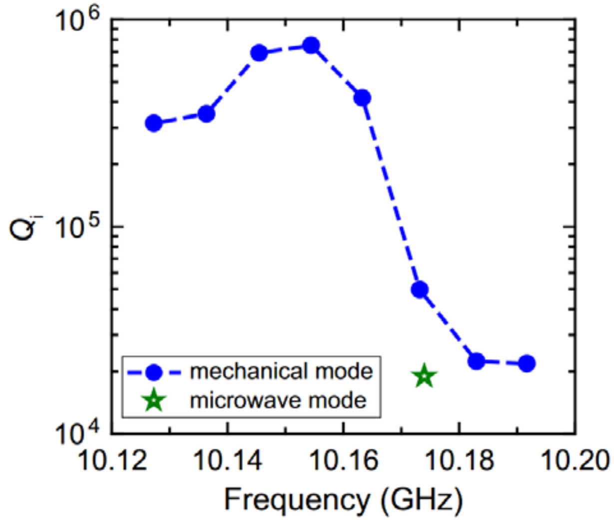
$\kappa_a/2\pi \approx 0.39$ MHz $\quad \kappa_{a,e}/2\pi \approx 0.12$ MHz

$g_{n_0} \approx 2.4 \text{ MHz} \times 2\pi > (\kappa_a, \kappa_{bn})$

→ ***Strong Coupling***

Quality Factor Extraction

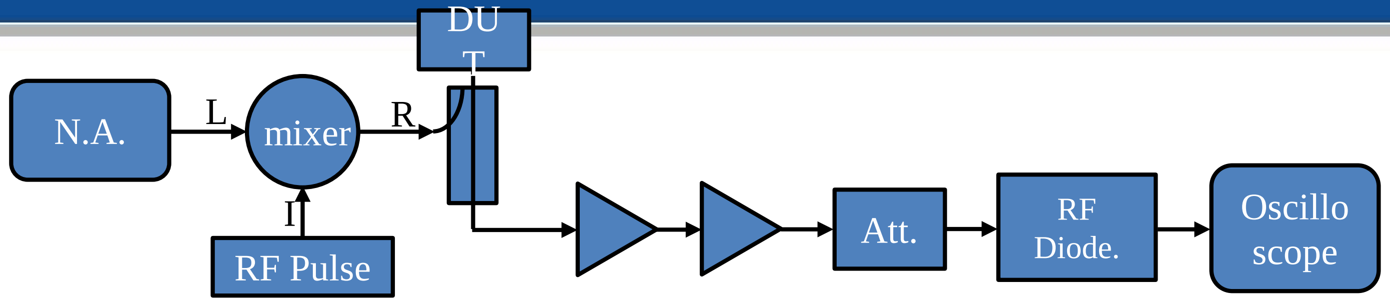


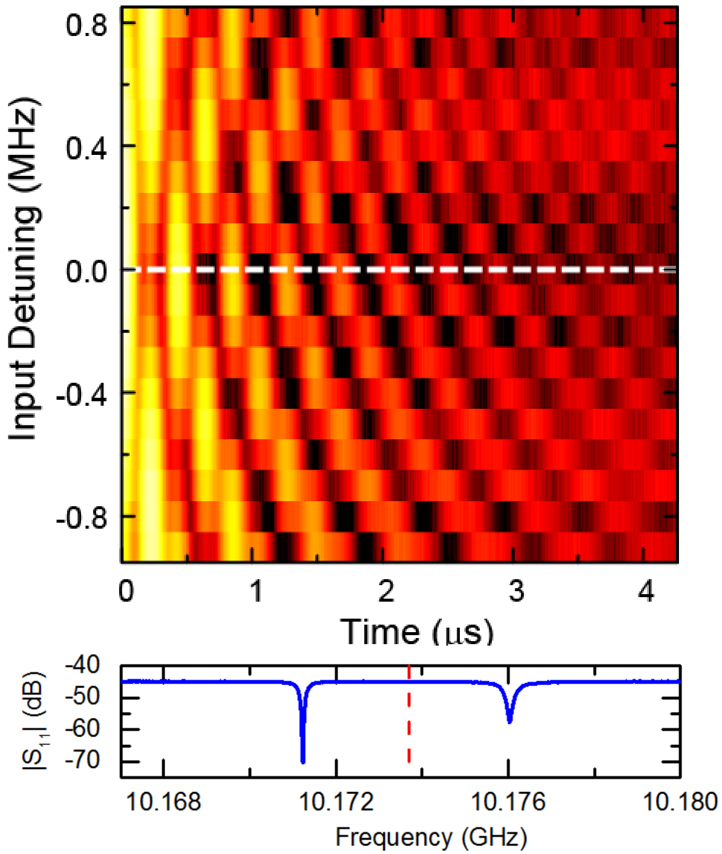


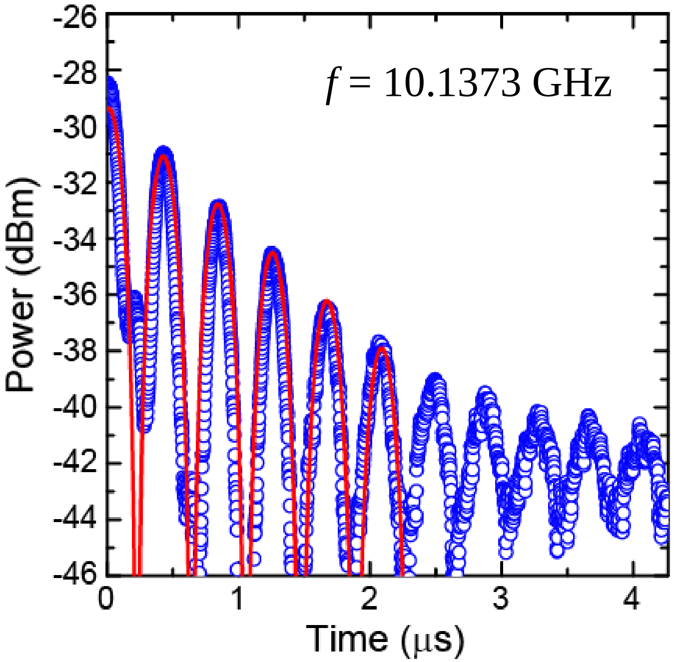
- A highest mechanical Q of 7.5×10^5 is obtained, corresponding to $\kappa_{bn}/2\pi \approx 0.007$ MHz ;
- Hence, we get an ultra-high cooperativity of: $C = g_n^2/(\kappa_a \kappa_{bn}) \approx 2100.$

Our system is in the multimode strong coupling (MMSC) regime

Time-domain Measurement

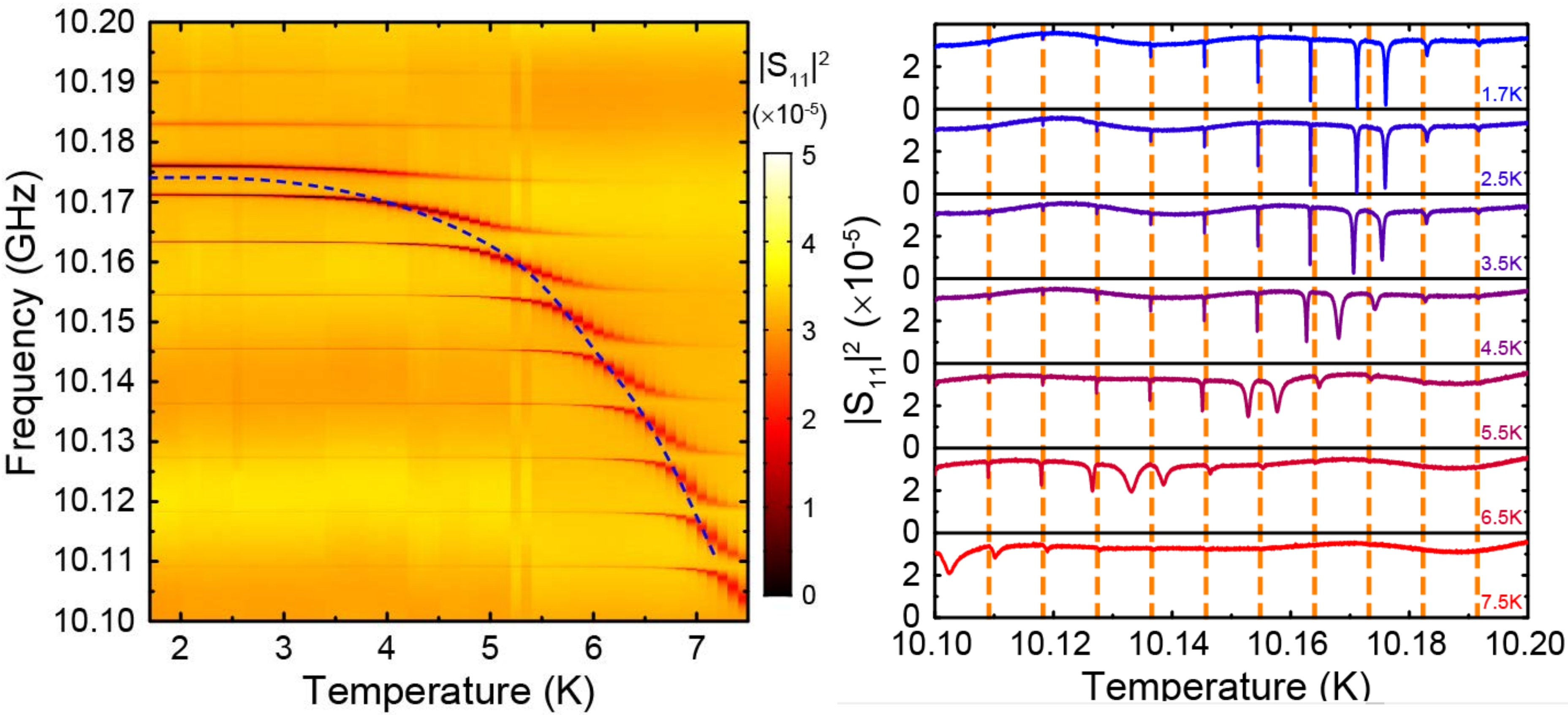






Yale

❑ Spectra at Different Temperatures



As the temperature increases, the “Ouroboros” resonate frequency decreases as indicated as the dashed blue line.

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Yale

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- Chipscale optomechanics and design guidelines
- Case studies
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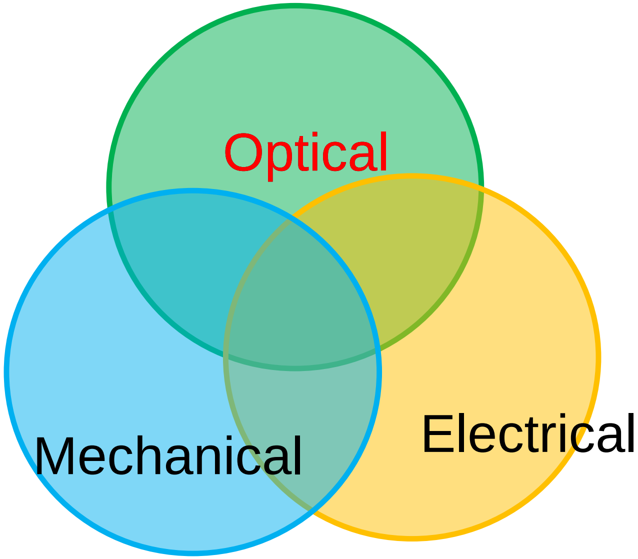
  - Si_3N_4 (electro-)optomechanics
  - AlN (electro-)optomechanics
- Summary



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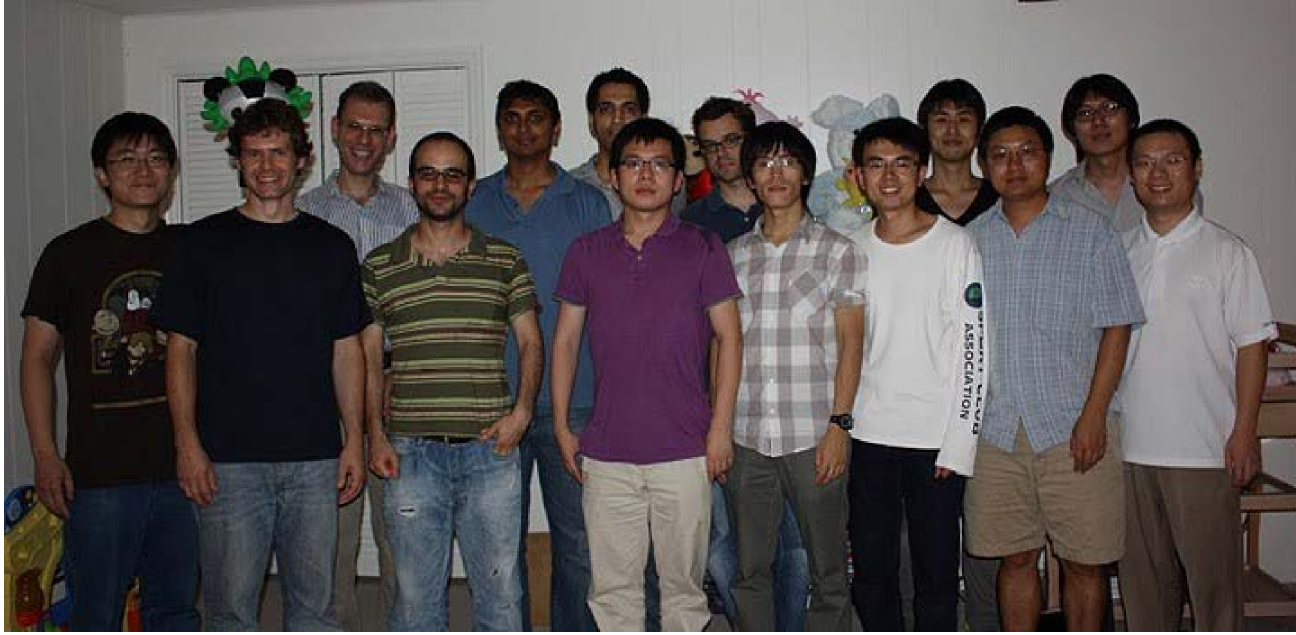

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Thank you!

Funded by:DARPA, ARO, AFOSR, NSF, Packard Foundation, BSF, Humboldt Foundation, Marie Curie Foundation, Rubicon Foundation, DAAD