Integrated Photonic and Plasmonic Nanomechanical Transducers

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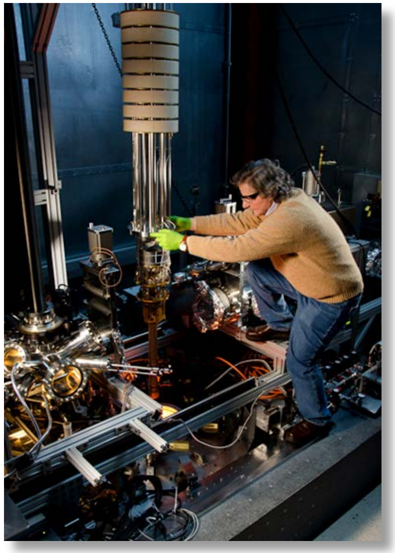
CNST Center for Nanoscale Science & Technology

Purdue University, January 2018

NIST National Institute of Standards and Technology • U.S. Department of Commerce

NIST Center for Nanoscale Science and Technology (CNST)

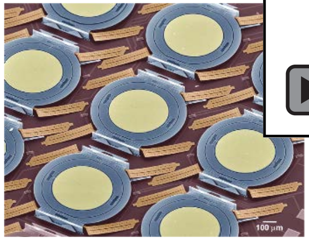
- NIST’s nanotechnology user facility.
- Enables innovation: Rapid access for all to tools for making and measuring nanostructures, with a particular emphasis on industry.
- Access in two ways:
  - **NanoFab:** Commercial state-of-the-art tool set at economical hourly rates, along with help from our dedicated, full-time technical support staff.



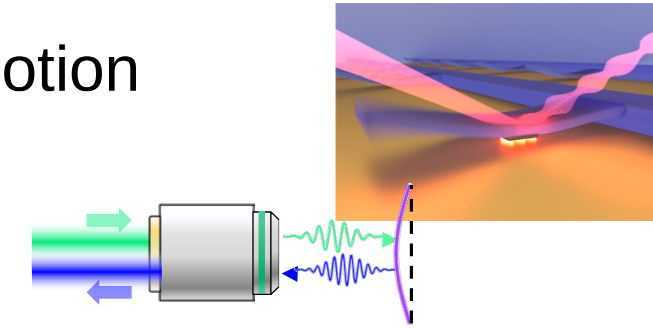
  - **NanoLab**: Next generation of tools and processes through collaboration with research staff, who develop new measurement and fabrication methods in response to national nanotechnology needs.
- The CNST also links the external community to nanotechnology-related measurement expertise at NIST (nano@nist.gov)

Optical MEMS and NEMS: Why?

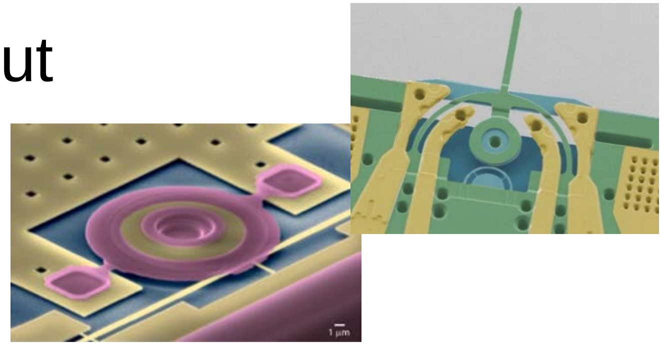
- Control light: many elements, near-zero power dissipation
  - Image projection with mirror arrays
  - Adaptive optics
  - Datacom switching



- Optical measurement of MEMS / NEMS motion
  - Fast: MHz – GHz frequencies
  - Sensitive: nanometer to picometer amplitudes
  - Noncontact method

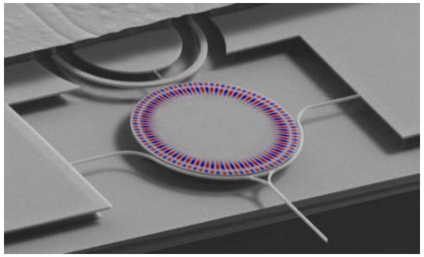


- MEMS / NEMS sensors with optical readout
  - Enhanced transduction at small scales (AFM, magnetization, etc)
  - Portability and robustness

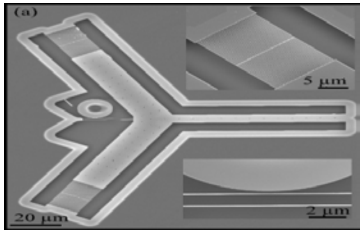


MEMS / NEMS + integrated photonics: Examples

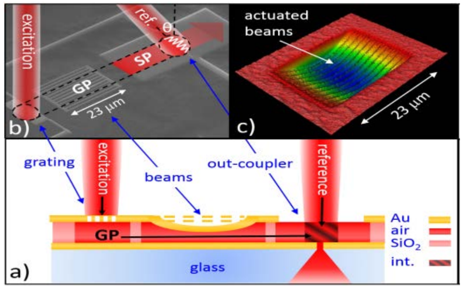
- Atomic Force Microscopy probe with a photonic cavity readout
  - High performance nanoscale measurement tool
  - PTIR application



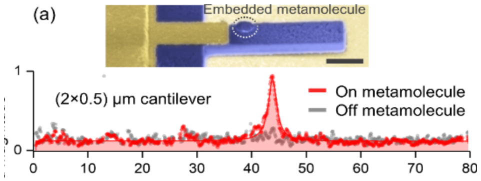
- High-Q NEMS for frequency-modulated sensing
  - Toward high bias stability and dynamic range

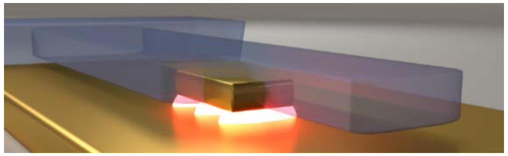


- Nanoscale gap plasmon NEMS phase modulator
  - Scaling of plasmonic-mechanical light control



- 100 nm scale gap-plasmon resonators coupled to NEMS
  - Precision, local motion sensing; optical modulation
  - Dynamics: regenerative oscillations and locking





Micro- and nano-mechanical transducers for nanoscale measurements

Measurement Principle:

- Nanoscale physical system is coupled to a micro- or nano-mechanical device
- Motion of the mechanical device is measured

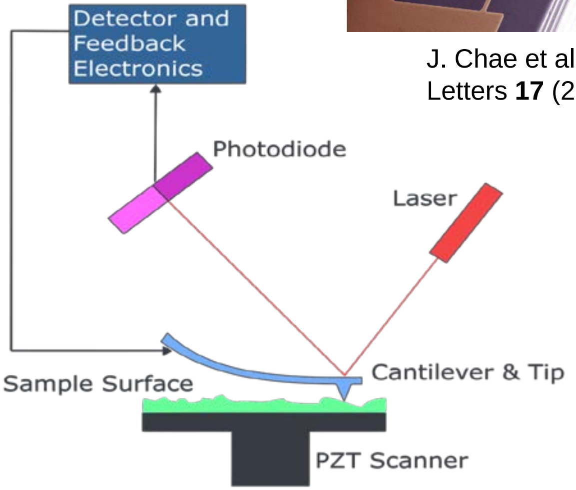
Low-dimensional or small systems – small transducers

Geometrical confinement enhances interactions

Precision motion readout – local optomechanical interaction

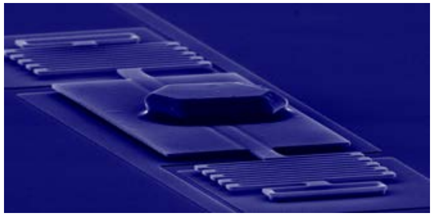
Atomic Force Microscopy

J. Chae et al, Nano Letters **17** (2017)



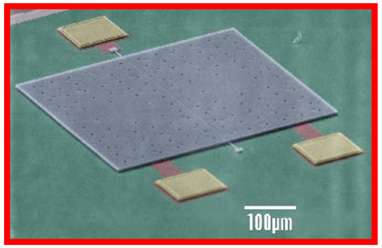
http://en.wikipedia.org/wiki/Atomic_force_microscopy

Magnetic Vortices



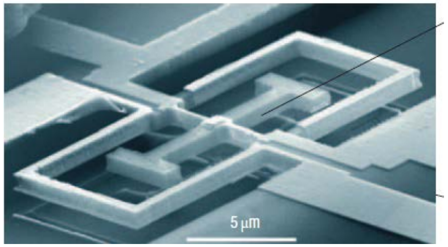
C. A. Bolle et al, *Nature* 399, 43-46 (1999)

Casimir Force



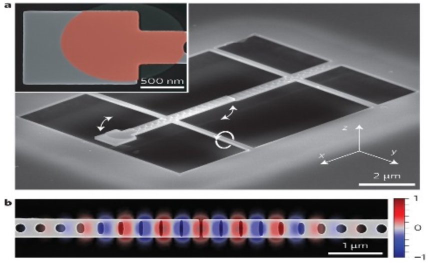
H. B. Chan et al, *Science* 291 no. 5510 (2001)

Spin Torque



G. Zolfagharkhani et al, *Nature Nanotechnology* 3,(2008)

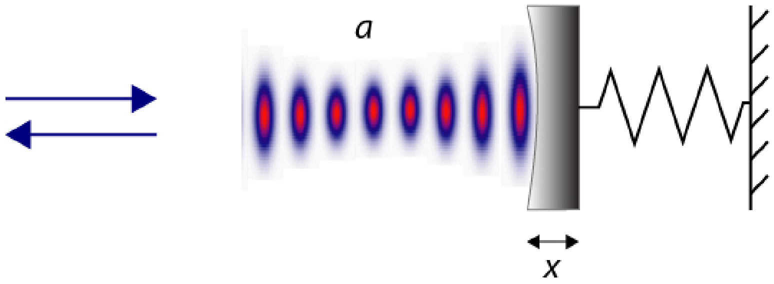
Nanoscale Magnetism

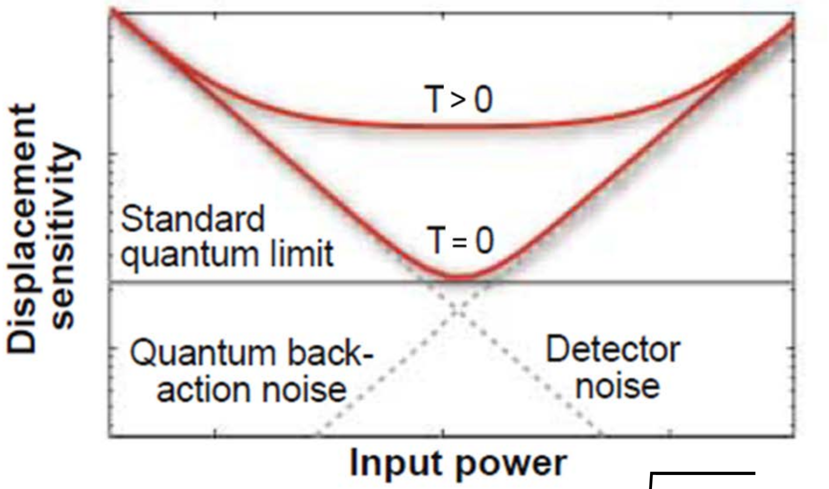


M. Wu et al, *Nature Nanotechnology 12*,(2017)

Optics is great for nanoscale motion measurement

- Power not dissipated in the transducer
- Small interaction region
  - Focal spot ~ λ (from far field)
  - Small devices can be measured
- Fast response
  - Excess bandwidth can be traded for sensitivity
- Precision at fundamental limits
  - Shot noise and backaction limited
  - No thermal noise in motion measurement
  - Standard Quantum Limit (SQL) can be reached





$$xp = {}^{\hbar}\!/_{2} \qquad x = \sqrt{\frac{\hbar}{2m\Omega}}$$

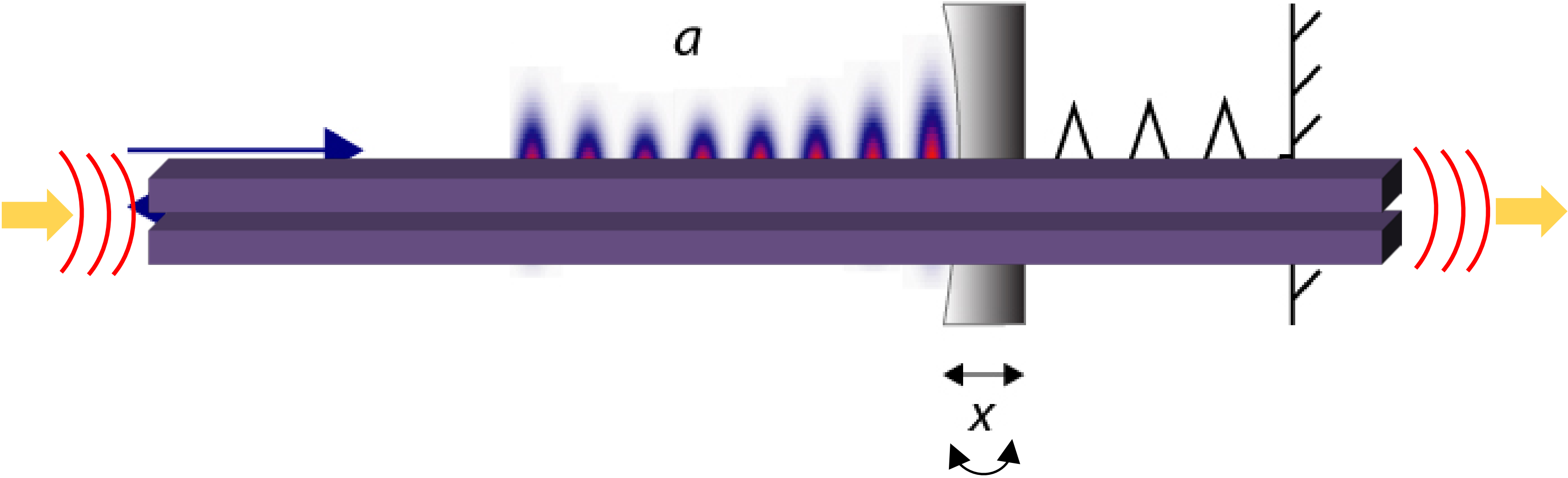
Sensing at fundamental thermo-mechanical limit

Thermal motion can be used and controlled

T.J.Kippenberg and K.J. Vahala, Cavity Optomechanics: Back action at the Mesoscale, Science, v. 321, p1172, 2008

V. B. Braginsky, F. Y. Khalili, *Quantum Measurement* (Cambridge Univ. Press, Cambridge, 1992).

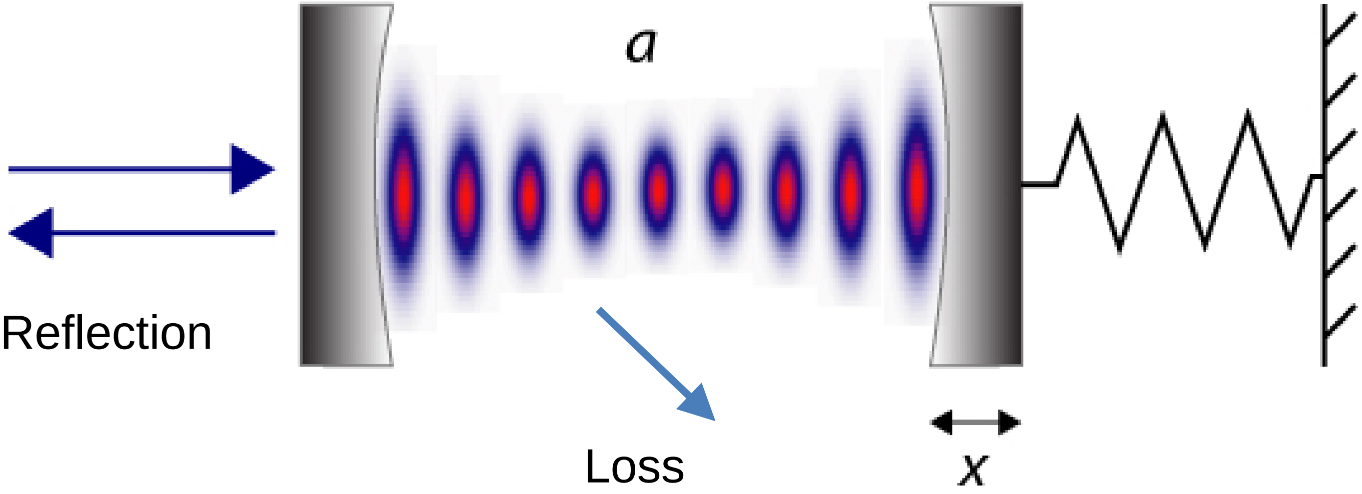
Basic optomechanical coupling



Transmitted phase or amplitude is a function of mechanical coordinate

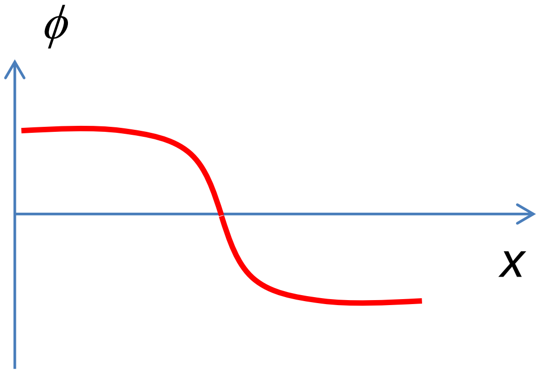
Different approaches are possible for on-chip transducers

Optical resonance enhancement



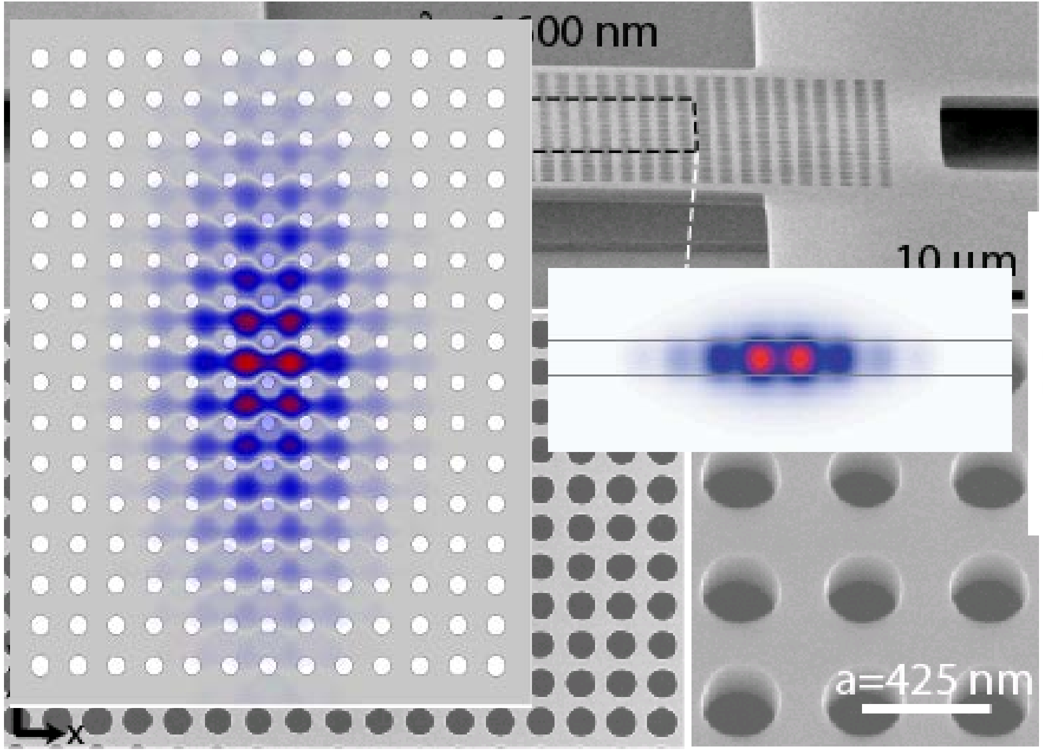
- A resonance increases the $d\phi/dx$ by the quality (Q) factor
- Optomechanical coupling is increased
- Delay is introduced

- Enables gain – bandwidth tradeoff
- E.g. cavity lifetime = mechanical timescale



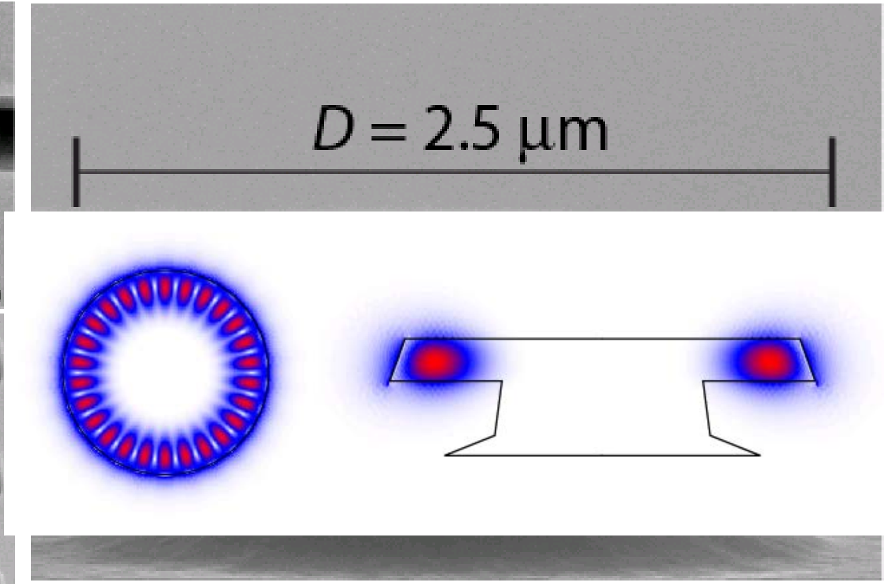
On-chip nanophotonic cavities for light confinement

Planar Photonic Crystal Cavity



Caltech -O. Painter, A. Scherer, J. Vuckovic, Kyoto University - S. Noda et al;
NTT Laboratories – M. Notomi et al
Specific design - K. Srinivasan and O. Painter, *Optics Express*, 2002

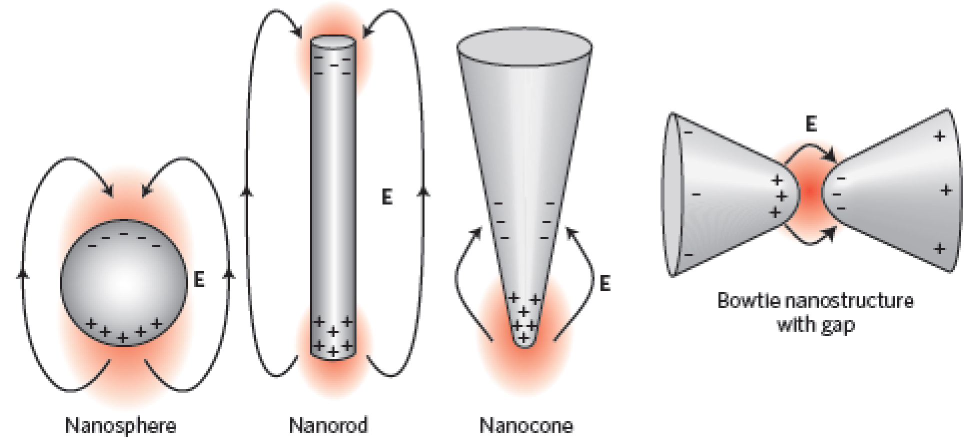
Microdisk Cavity



Bell Labs - R.E. Slusher, S.L. McCall, AFJ Levi, et al, early 1990s

- Confine field to volume $V \approx (\lambda/n)^3$
- Large per photon electric field strength
  - Enhanced interaction strength with matter
  - High cavity quality factor (Q) – enhanced interaction time with matter

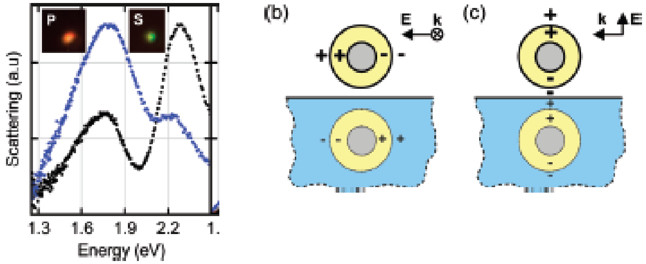
Sub-wavelength confinement: plasmonics




REVIEW ARTICLE | FOCUS
nature photonics

Plasmonics for near-field nano-imaging and superlensing

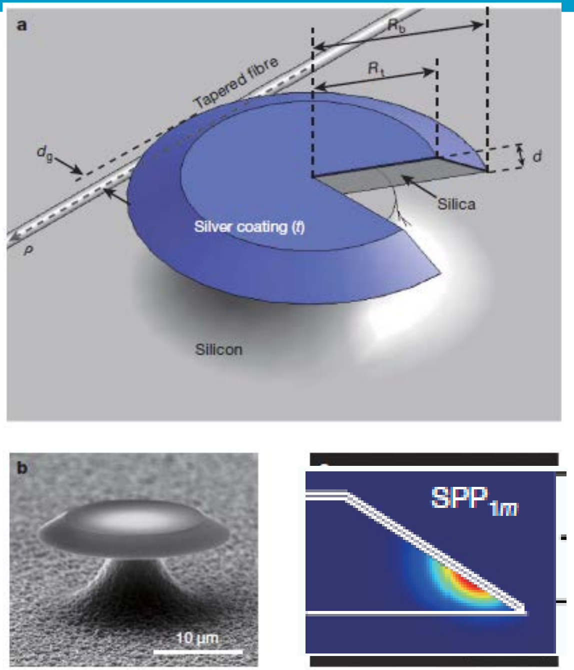
Satoshi Kawata[1,2], Yasushi Inouye[3] and Prabhat Verma[1,3]

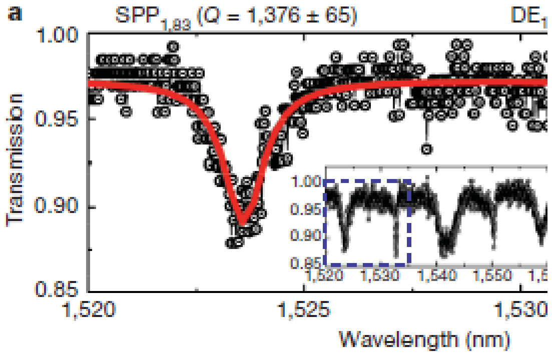



Substrates Matter: Influence of an Adjacent Dielectric on an Individual Plasmonic Nanoparticle

Mark W. Knight,†‡ Yanpeng Wu,‡§ J. Britt Lassiter,‡§ Peter Nordlander,*‡§ and Naomi J. Halas*,†,‡,§,∥

NANO LETTERS
2009
Vol. 9, No. 5
2188-2192






High-Q surface-plasmon-polariton whispering-gallery microcavity

Vol 457 | 22 January 2009 | doi:10.1038/nature07627

Bumki Min[1,2]†, Eric Ostby[1], Volker Sorger[2], Erick Ulin-Avila[2], Lan Yang[1]†, Xiang Zhang[2,3] & Kerry Vahala[1]

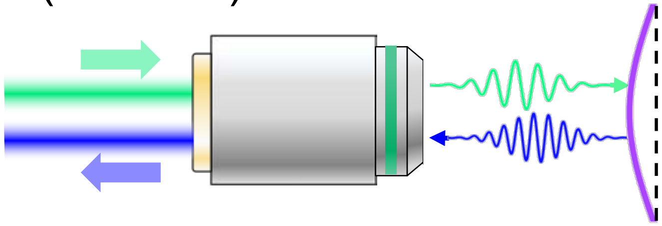
Microscale optical transduction schemes: dielectrics

Limits in light concentration ability obscure nanometer-localized measurements

- **Doppler vibrometry – far field**

Sensitivity ~ (30 to 50) fm·Hz$^{-1/2}$

$$\frac{\Delta\omega_{\text{optical}}}{2\pi} \propto \frac{2v(t)}{\lambda}$$

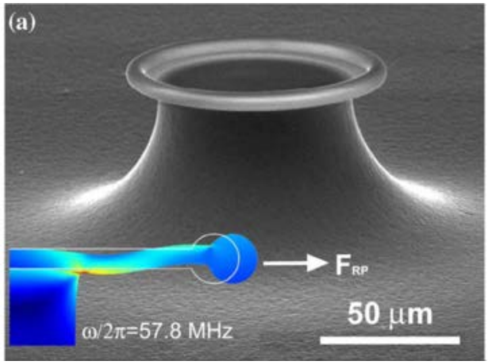


Vibrating microstructure
$v(t)$

- **Dielectric cavity optomechanical systems – resonance enhanced**

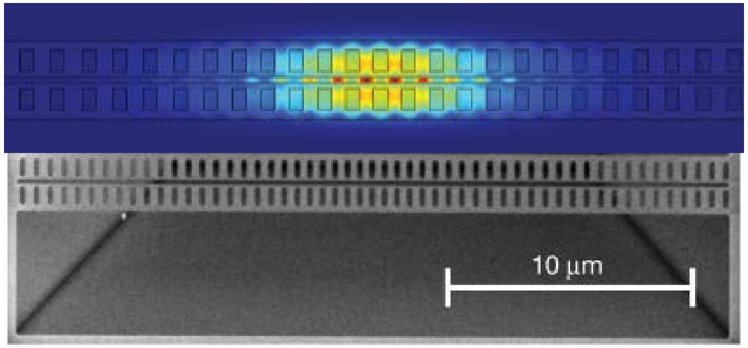
Quantum limited sensitivity ≈ am·Hz$^{-1/2}$

Whispering gallery resonators



PRL **97**, 243905 (2006)

Optomechanical crystals



Nature **459**, 550 (2009).

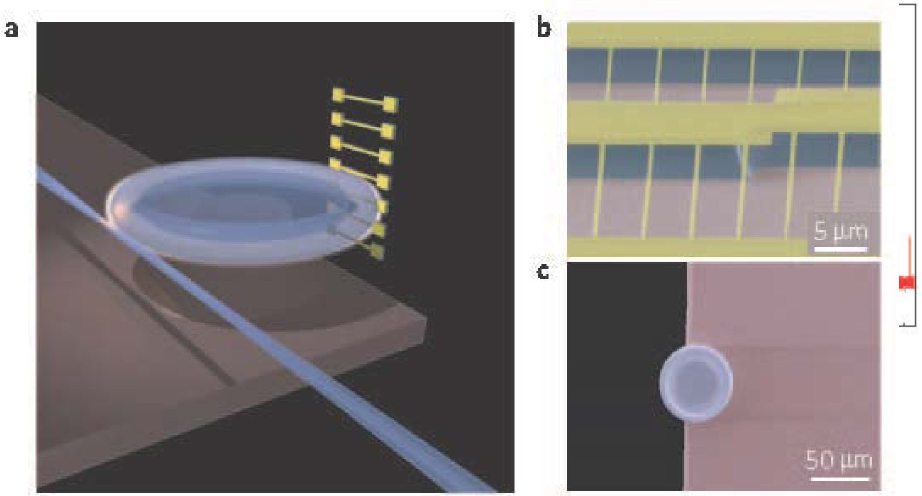
Sensitive transduction of NEMS motion

Microtoroid cavities

SiN cantilevers coupled to microtoroids

Displacement sensitivity=1x10^{-18} m/Hz$^{0.5}$

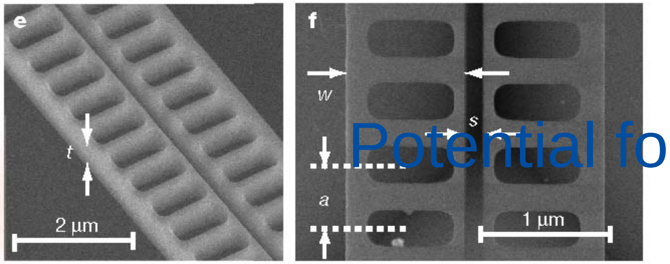
Displacement sensitivity=7x10^{-16} m/Hz$^{0.5}$



Coupled photonic crystal nanobeams

G. Anetsberger et al, *Nat. Phys.*, **5**, 909-914 (2009)

Displacement sensitivity=1x10^{-16} m/Hz$^{0.5}$

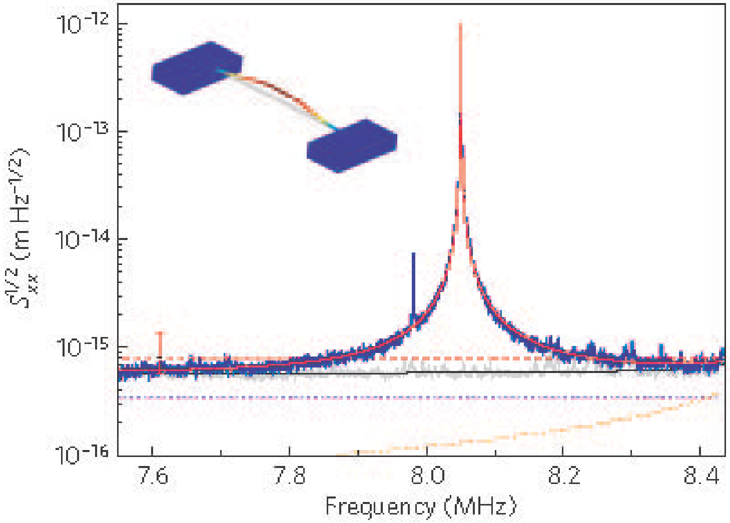


Potential for micro/nano instruments

M. Eichenfield et al, *Nature*, **459**, 550-555 (2009)

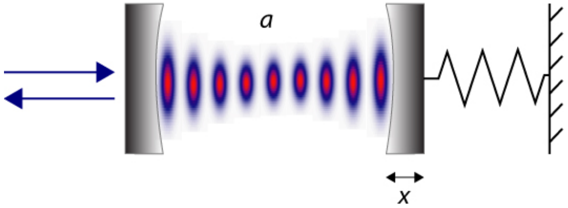
Double disk cavities

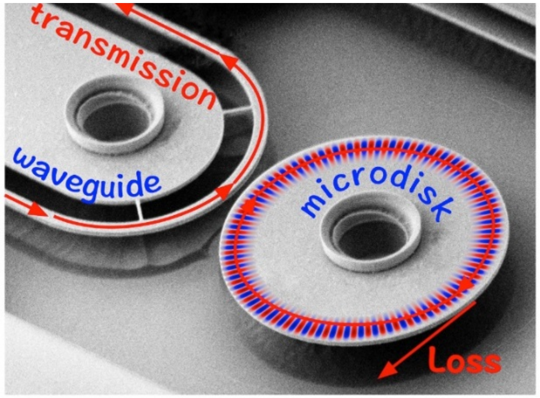
Displacement sensitivity=2x10^{-16} m/Hz$^{0.5}$

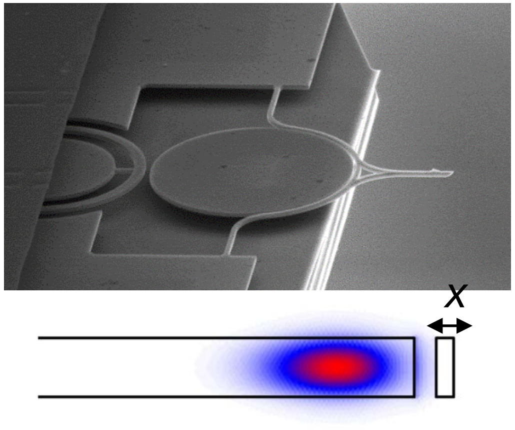


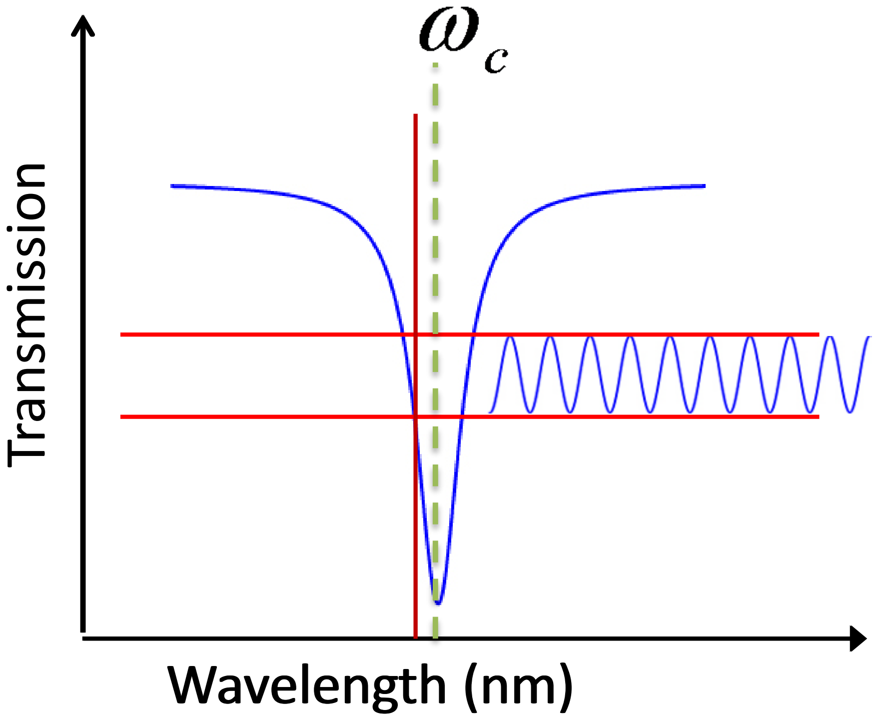
(2009)

Cavity-optomechanical motion sensing





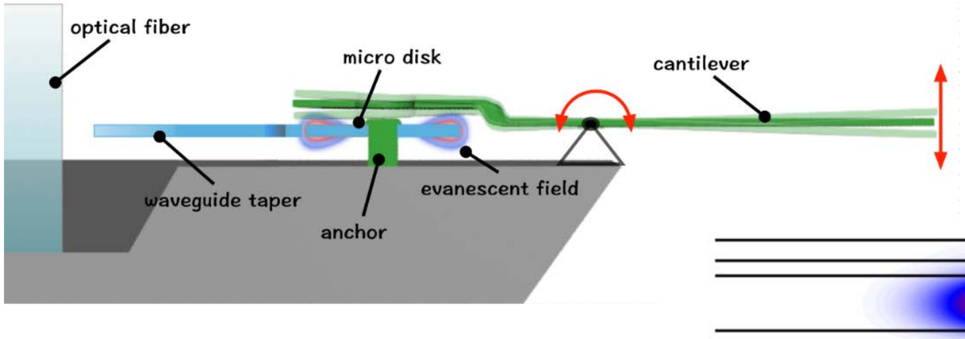


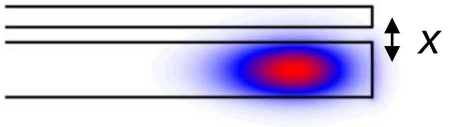


$$g_{OM} = \frac{d\omega_c}{dx}$$

$$\delta\omega_c = \omega_c / Q$$

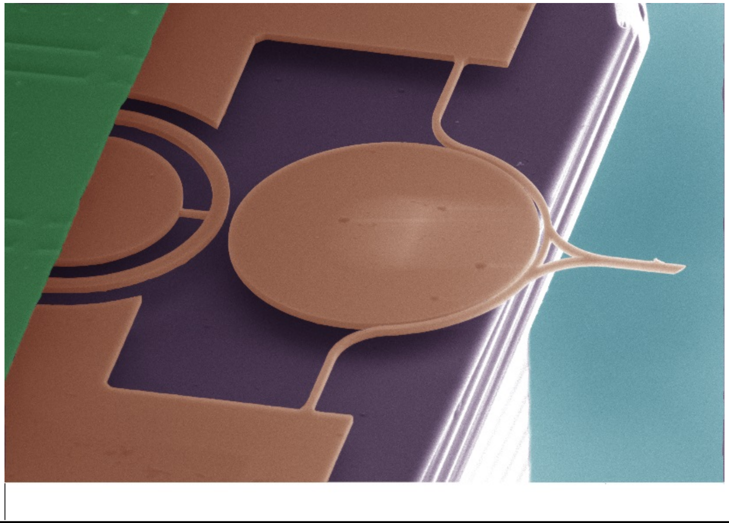
Displacement signal

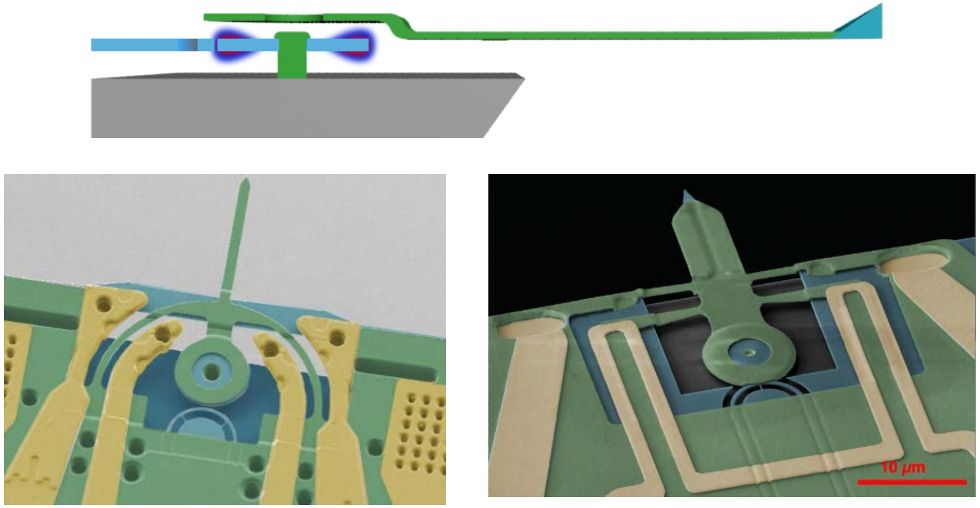




Integrated cavity optomechanical sensing

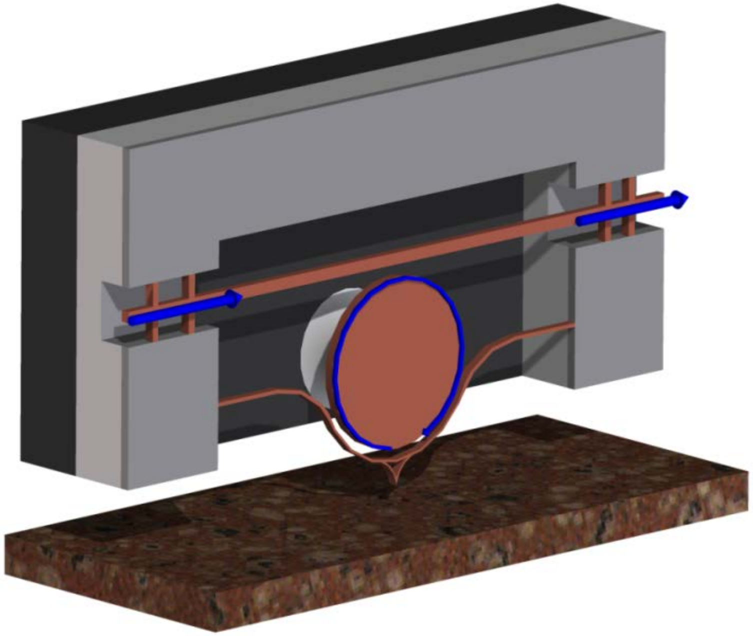
- FAST: measure motion at up to 100 MHz to 1 GHz mechanical frequency
  - Optical Q: 10^4 to 10^6
- SENSITIVE: sense ≈1 pm motion in 1 μs (1 MHz)
  - g_{om} = 1 GHz/nm to 30 GHz/nm; noise level (0.5 to 5) fm /$\sqrt{\text{Hz}}$
- Self-aligned and stable
- Compact, fiber connectorized, practical
- Electrostatic and thermo-electric actuation and tuning

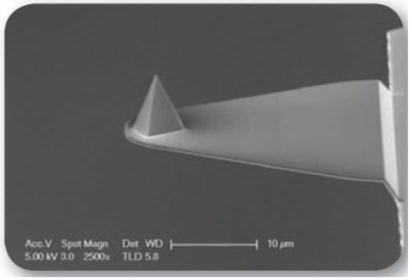




Nanoscale cantilevers for AFM

Atomic Force Microscopy





Nanoscale
Cantilever?

$k=m\omega^2$. High resonance frequency with a moderate stiffness

Larger bandwidth and faster scanning speed

Smaller cross section => smaller viscous drag

Fluctuation dissipation => smaller force noise

Far field / interferometry

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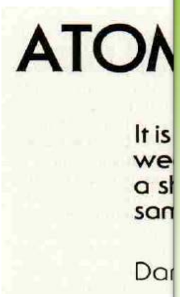

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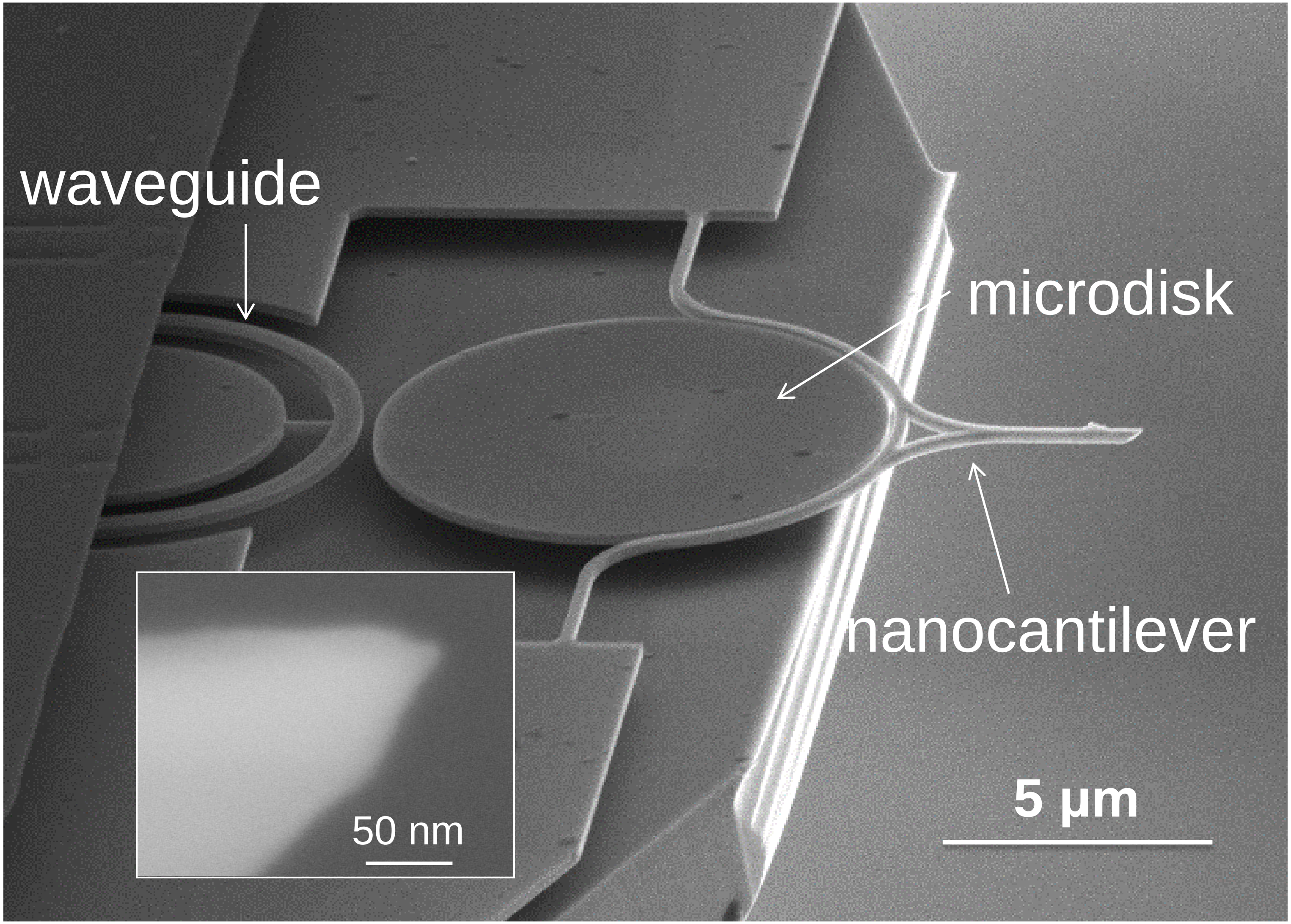
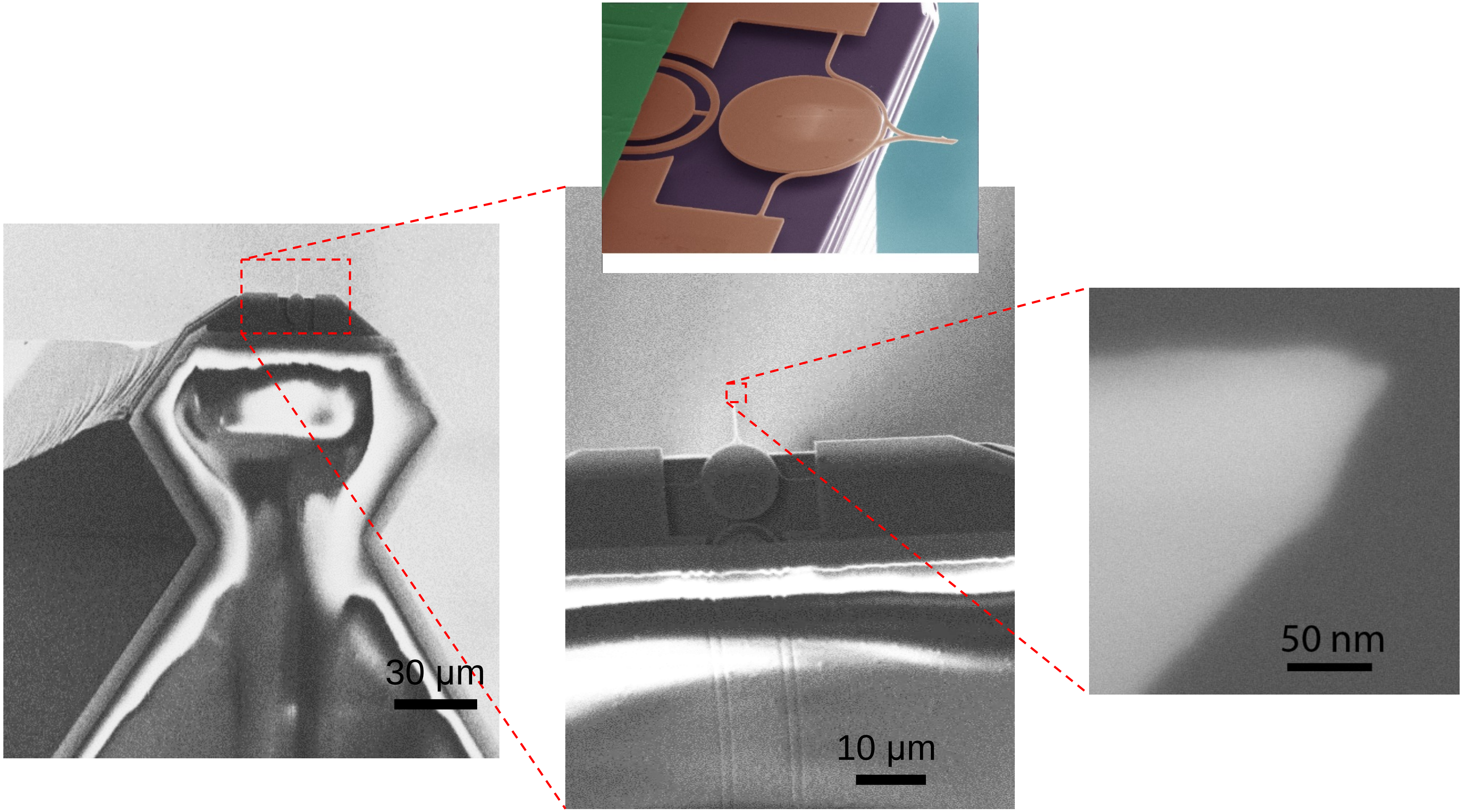
Nanoscale cantilever with integrated photonic cavity sensor

- Increase mechanical frequency while maintaining desired stiffness
- Improved force sensitivity and measurement bandwidth
    - Image acquisition rate
    - Fast force spectroscopy
    - Time-dependent forces

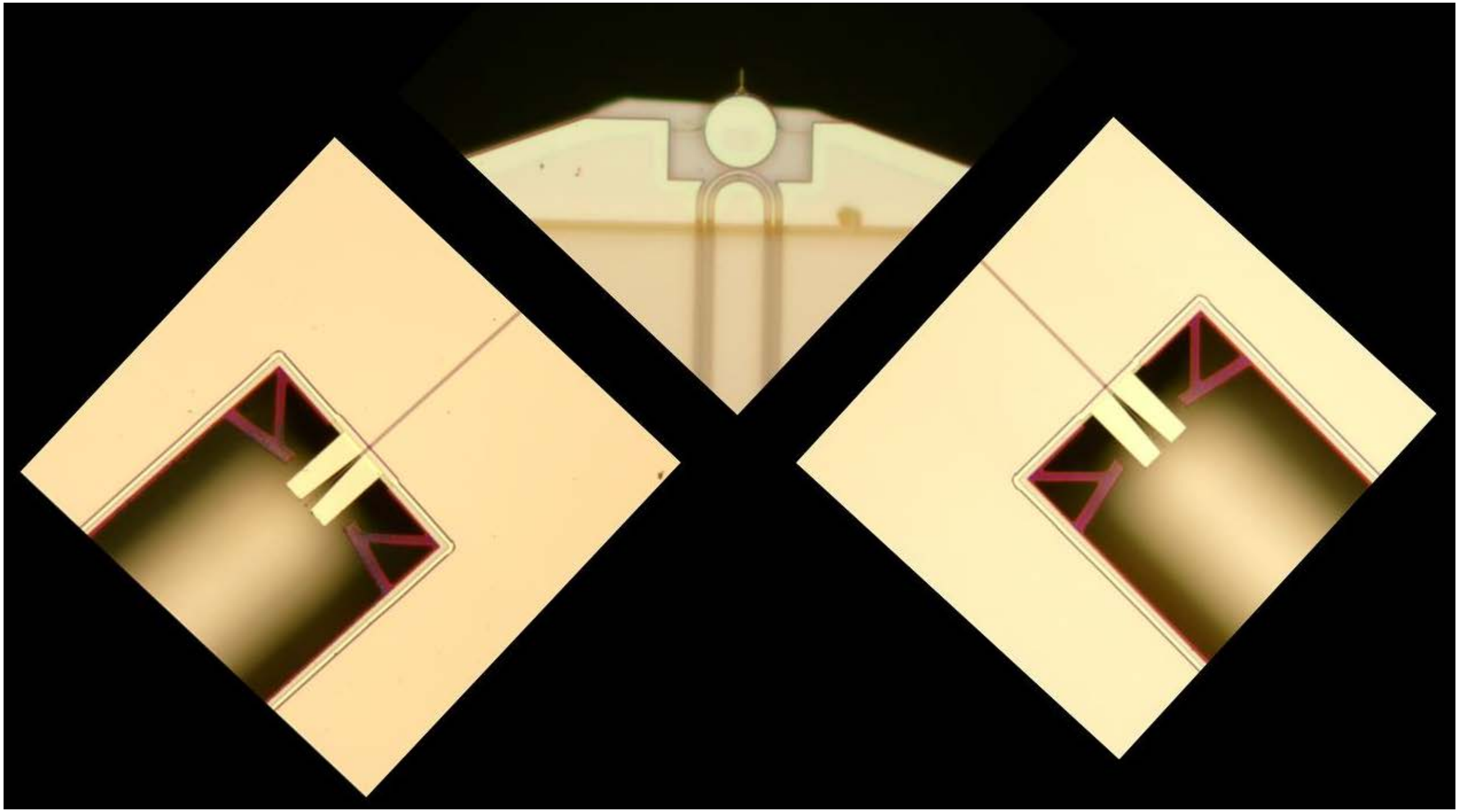
Operational AFM probe



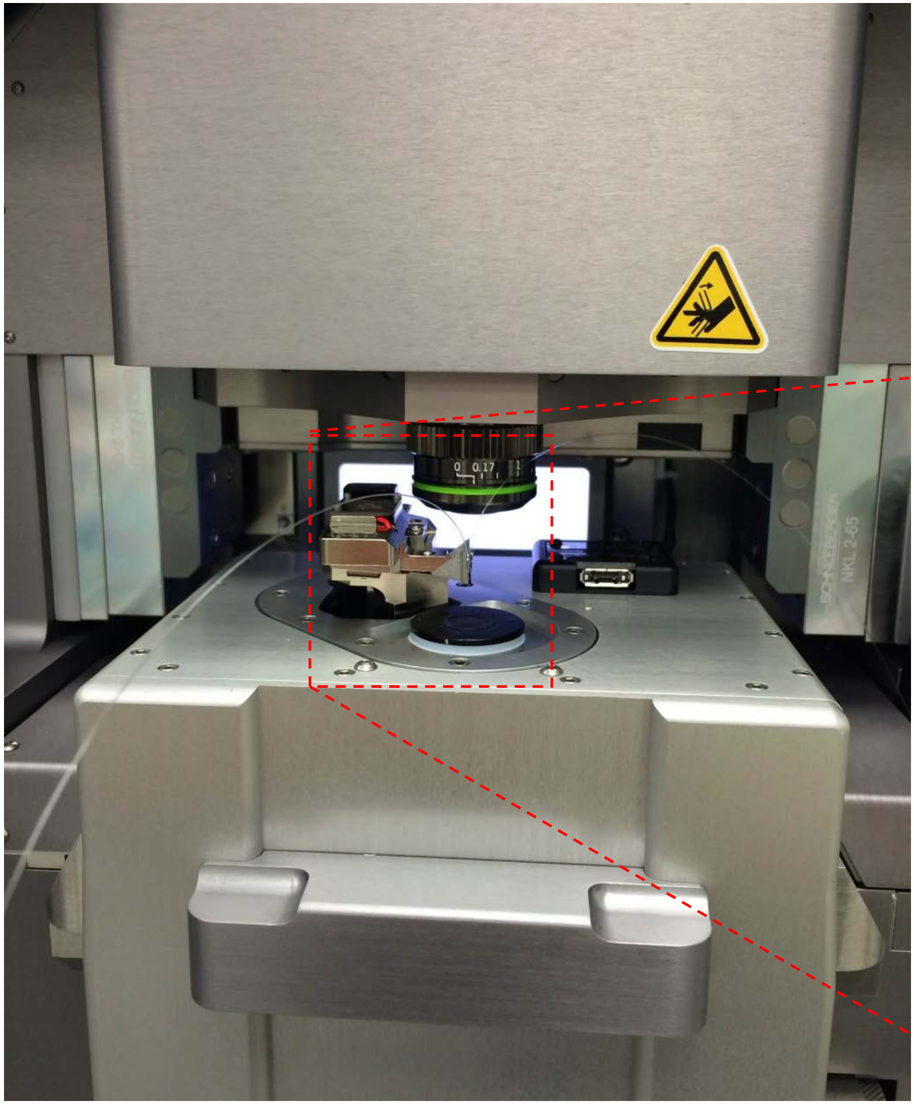
Integration with AFM

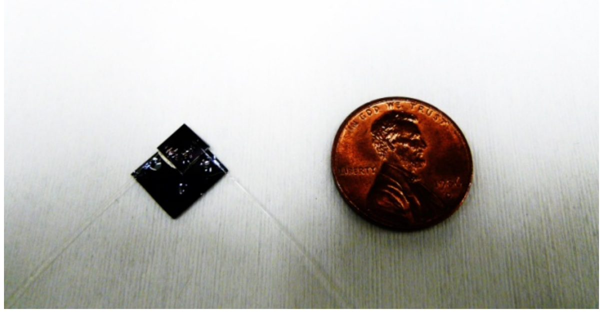


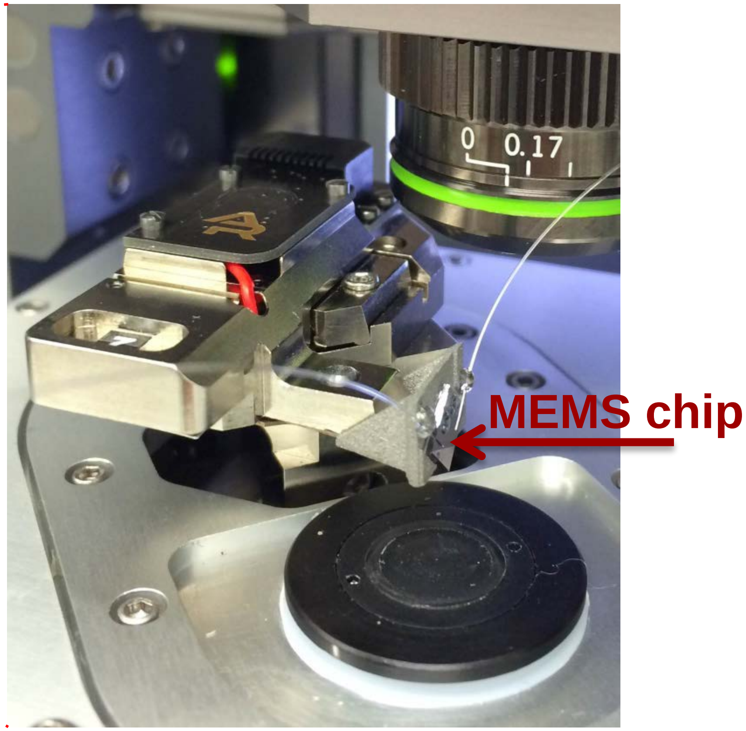
Integration with AFM



Integration with AFM

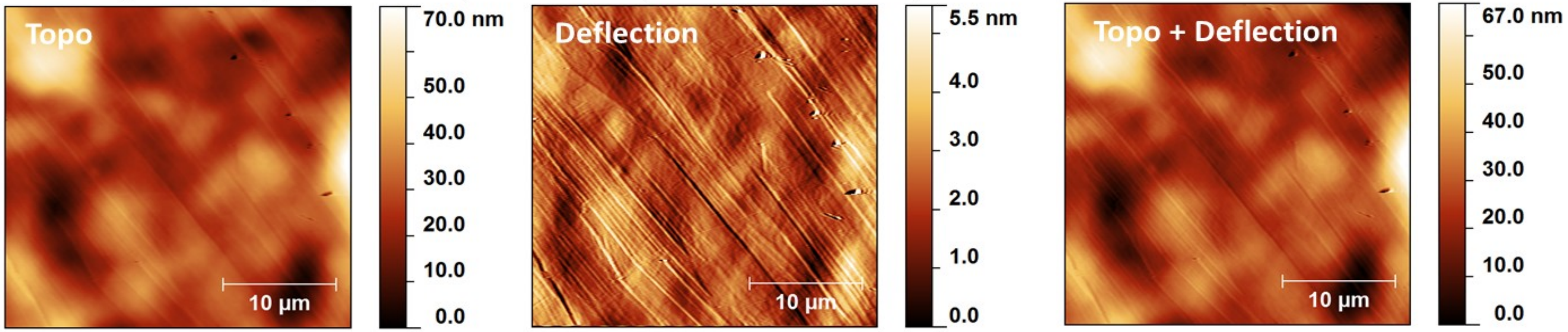




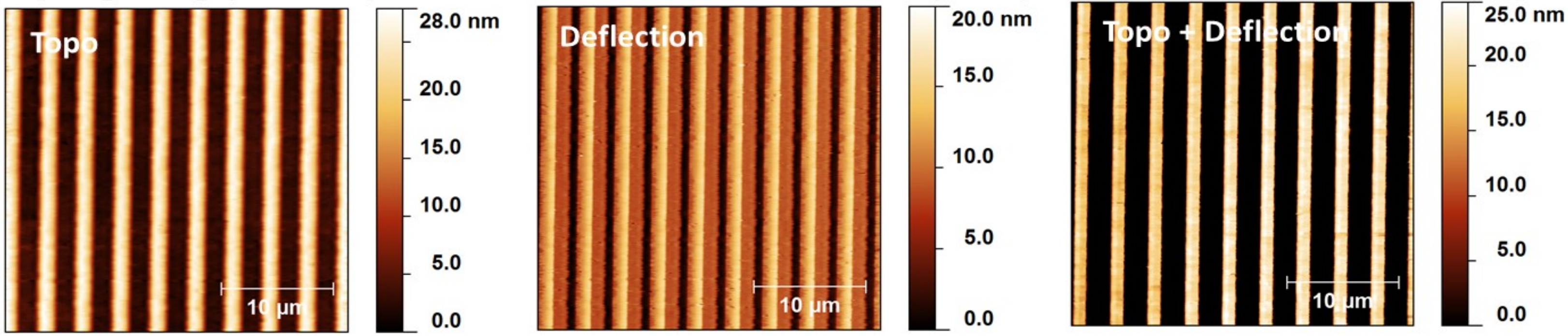


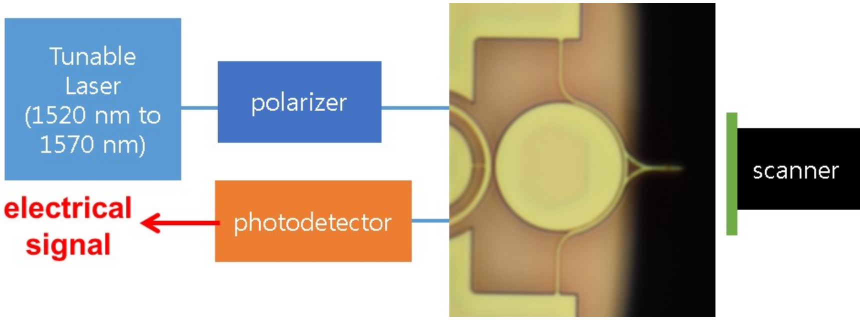
Fast, low noise contact-mode nanomechanical AFM

(a) **HOPG** (30 x 30 μm, **39.06 Hz**, **2.93 mm/s**, 512 × 512 pixels)



(b) **3 μm grating** (30 x 30 μm, **39.06 Hz**, **2.93 mm/s**, 512 × 512 pixels)




Tunable Laser (1520 nm to 1570 nm)

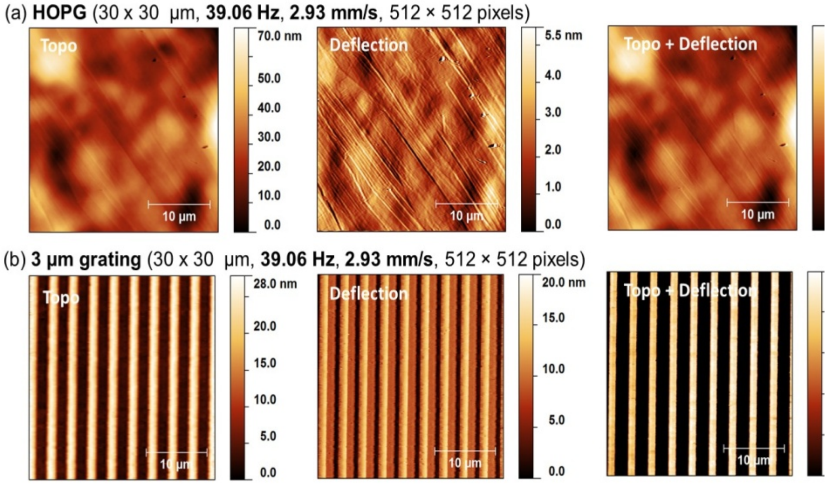
polarizer

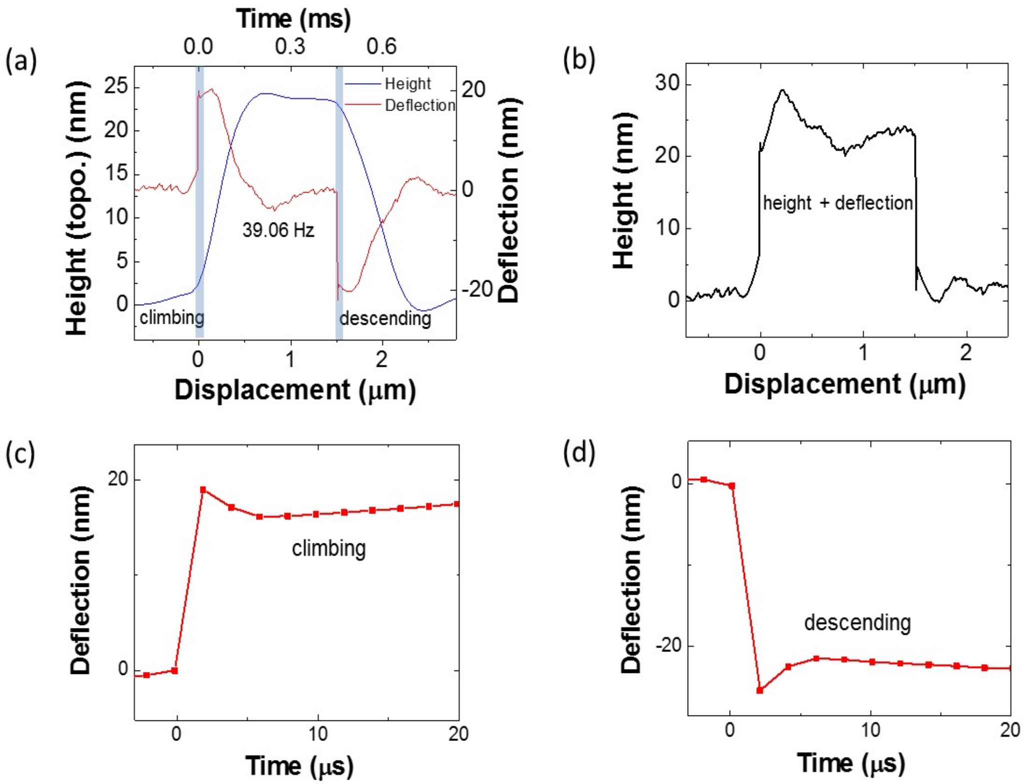
photodetector

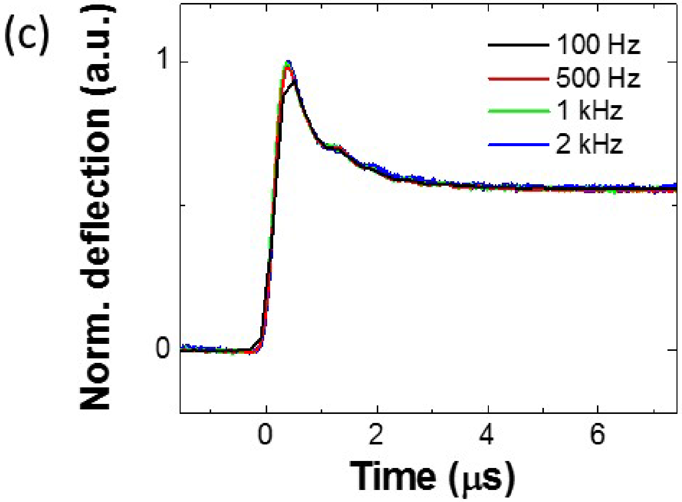
electrical signal

scanner

Fast, low noise contact-mode nanomechanical AFM







Microsecond response time
Few fm/Hz$^{0.5}$ displacement noise
Sub-10 nm resolution
Approx. 5 nN force

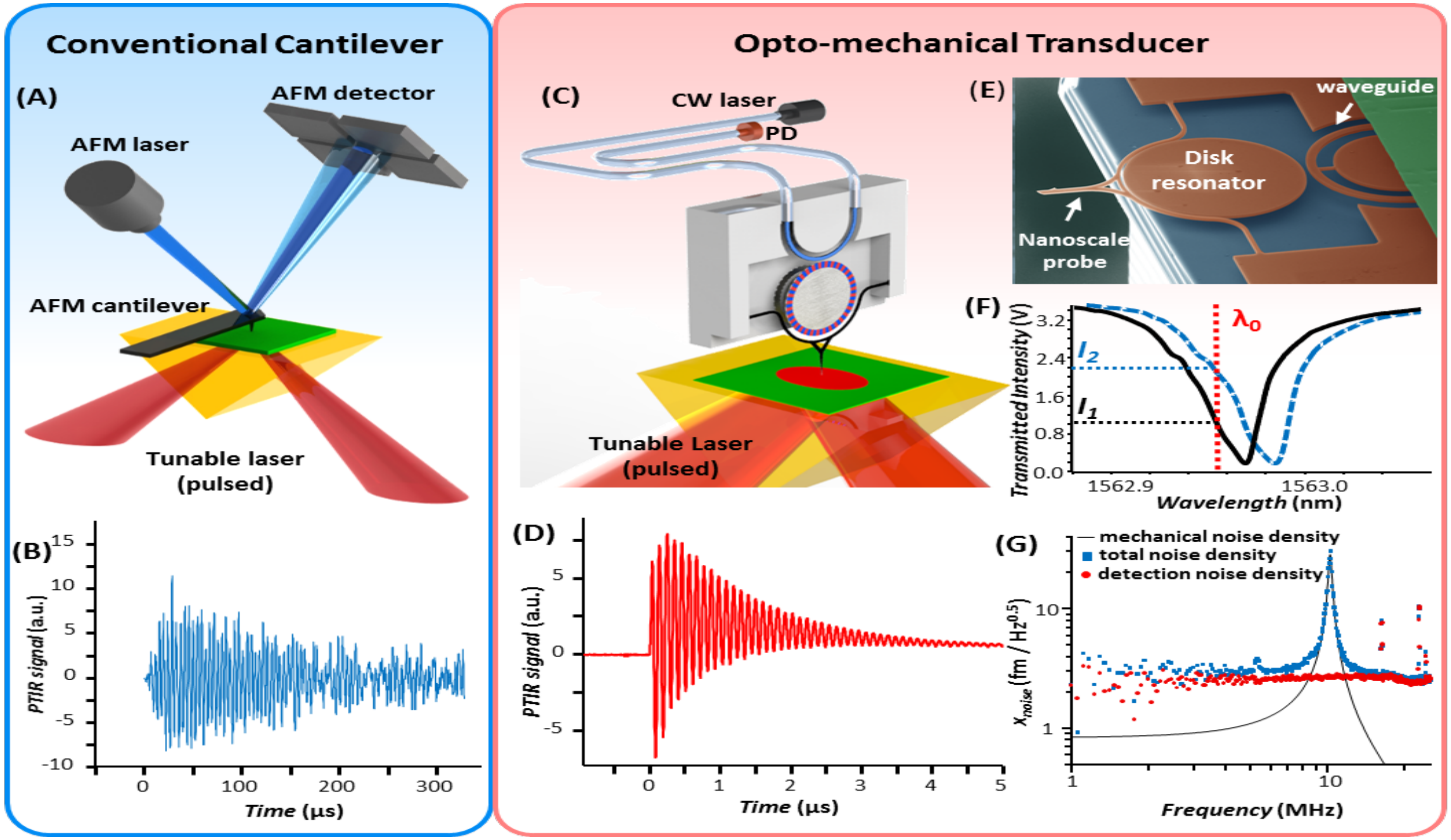
May enable HD, video-rate AFM

New science with nano-AFM probe: advanced PTIR

Photo Thermal Induced Resonance = IR spectroscopy with nanoscale resolution

Chemical mapping

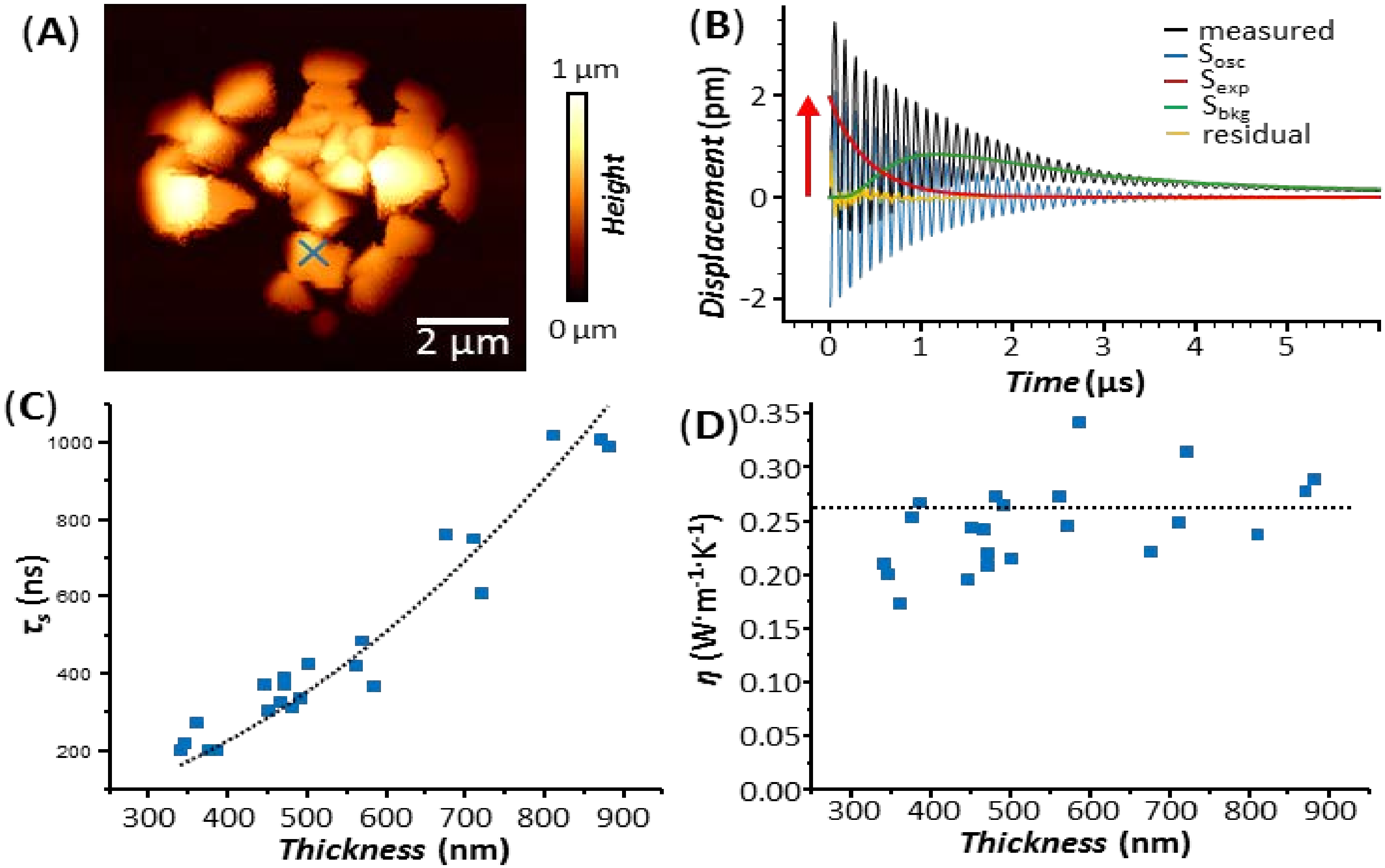
Optomechanical probe = 50x increased sensitivity for thin samples



J. Chae, S. An, G. Ramer, V. Stavila, G. Holland, Y. Yoon, A. Alec Talin, M. Allendorf, V. A. Aksyuk, A. Centrone, Nano Letters **17** (9), pp 5587–5594 (2017).

Measuring thermal conductivity at the nanoscale

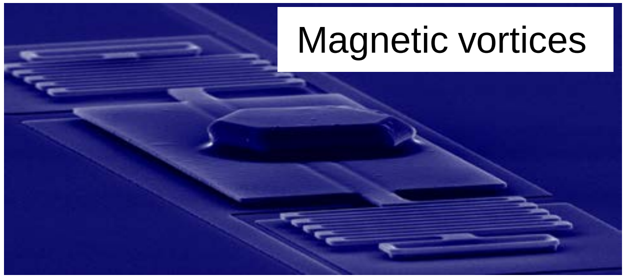
Speed + precision = dynamic thermal expansion relaxation



J. Chae, S. An, G. Ramer, V. Stavila, G. Holland, Y. Yoon, A. Alec Talin, M. Allendorf, V. A. Aksyuk, A. Centrone, Nano Letters **17** (9), pp 5587–5594 (2017).

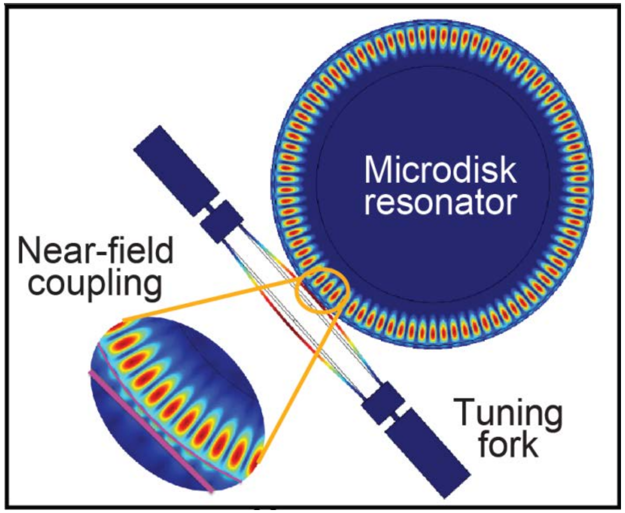
Transducing via a mechanical frequency change

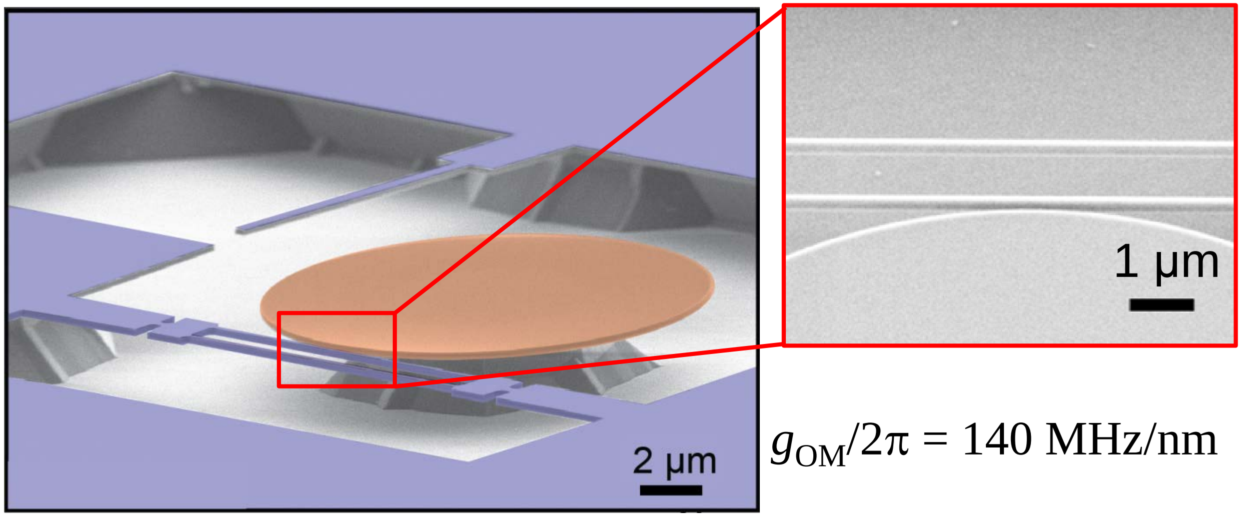
- Force, torque or motion => mechanical frequency change
- Advantages:
  - Insensitive to readout DC bias drift, 1/f noise
  - Very long averaging times for high sensitivity
  - Stable frequency/time references (e.g. vs. stable V or optical power)
  - Increased dynamic range
  - Mechanical element performance limits the transducer performance
- Applications:
  - Frequency-modulation atomic force microscopy (FM-AFM)
  - Physics: Magnetometers, Casimir force, etc…
  - Some macro- and micro-scale accelerometers



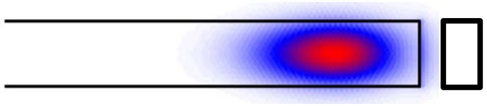
C. A. Bolle, *Nature* 399, 43-46 (1999)

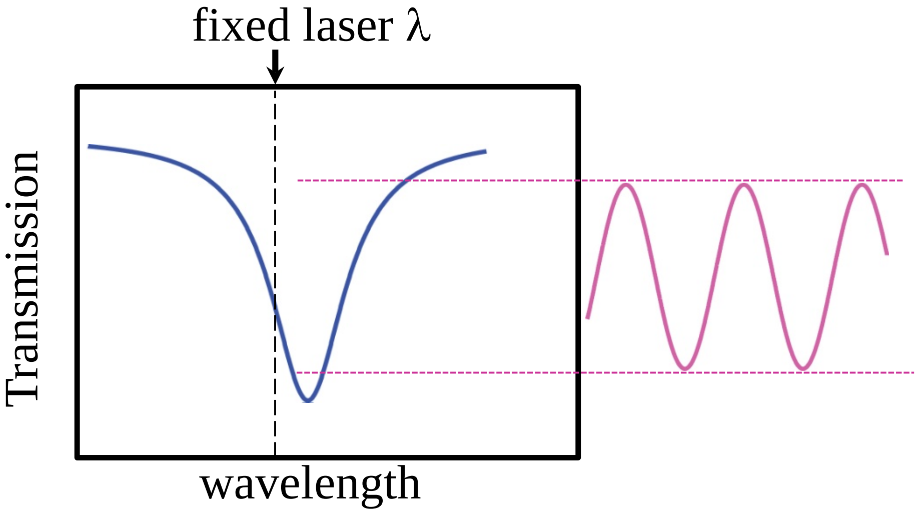
High mechanical $f_M Q_M$ tuning fork



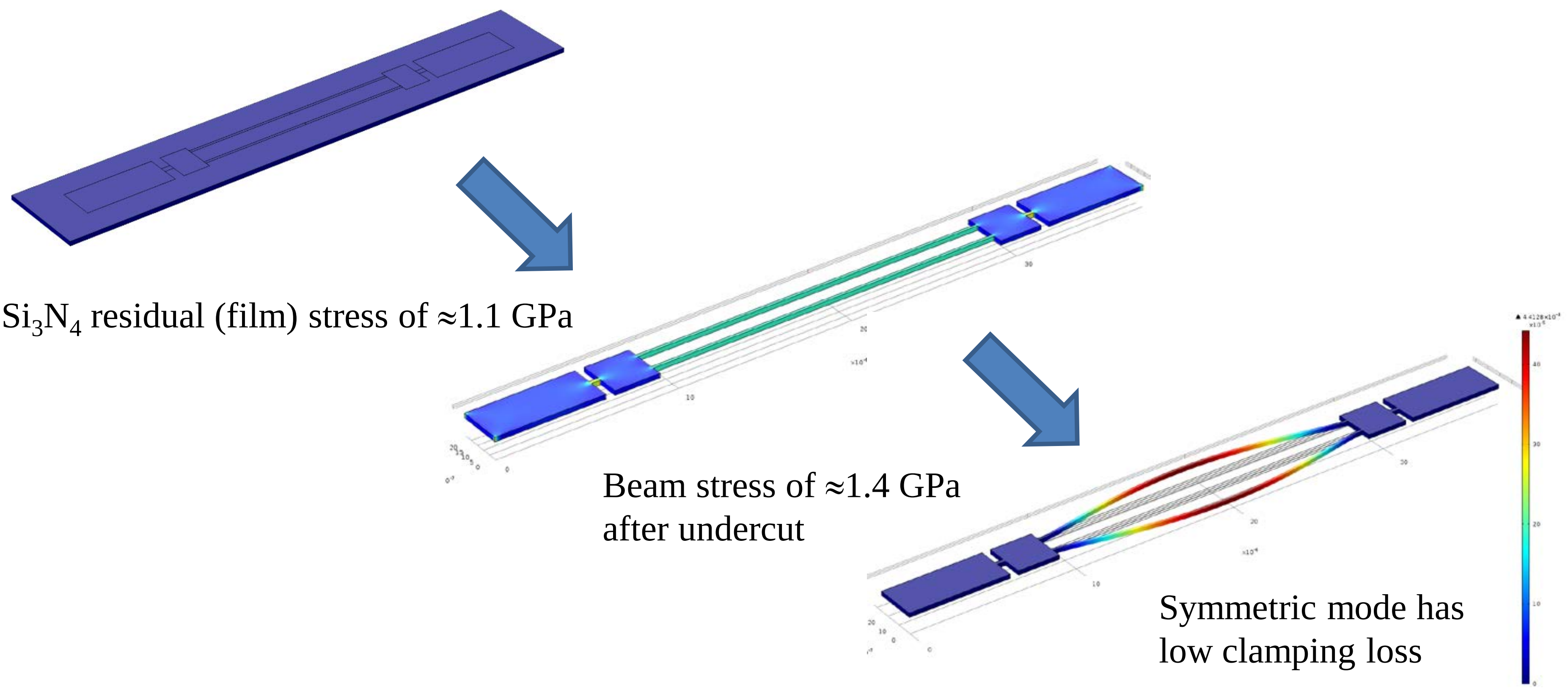


$g_{OM}/2\pi$ = 140 MHz/nm





Nanobeam tuning forks



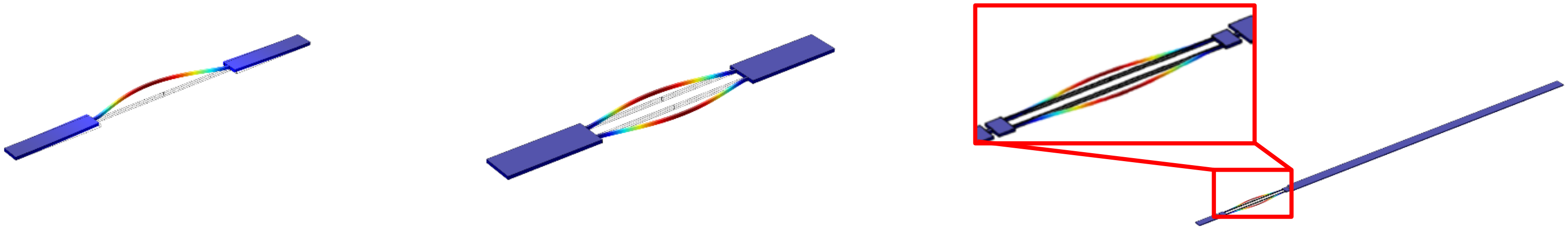
Si_3N_4 residual (film) stress of ≈1.1 GPa

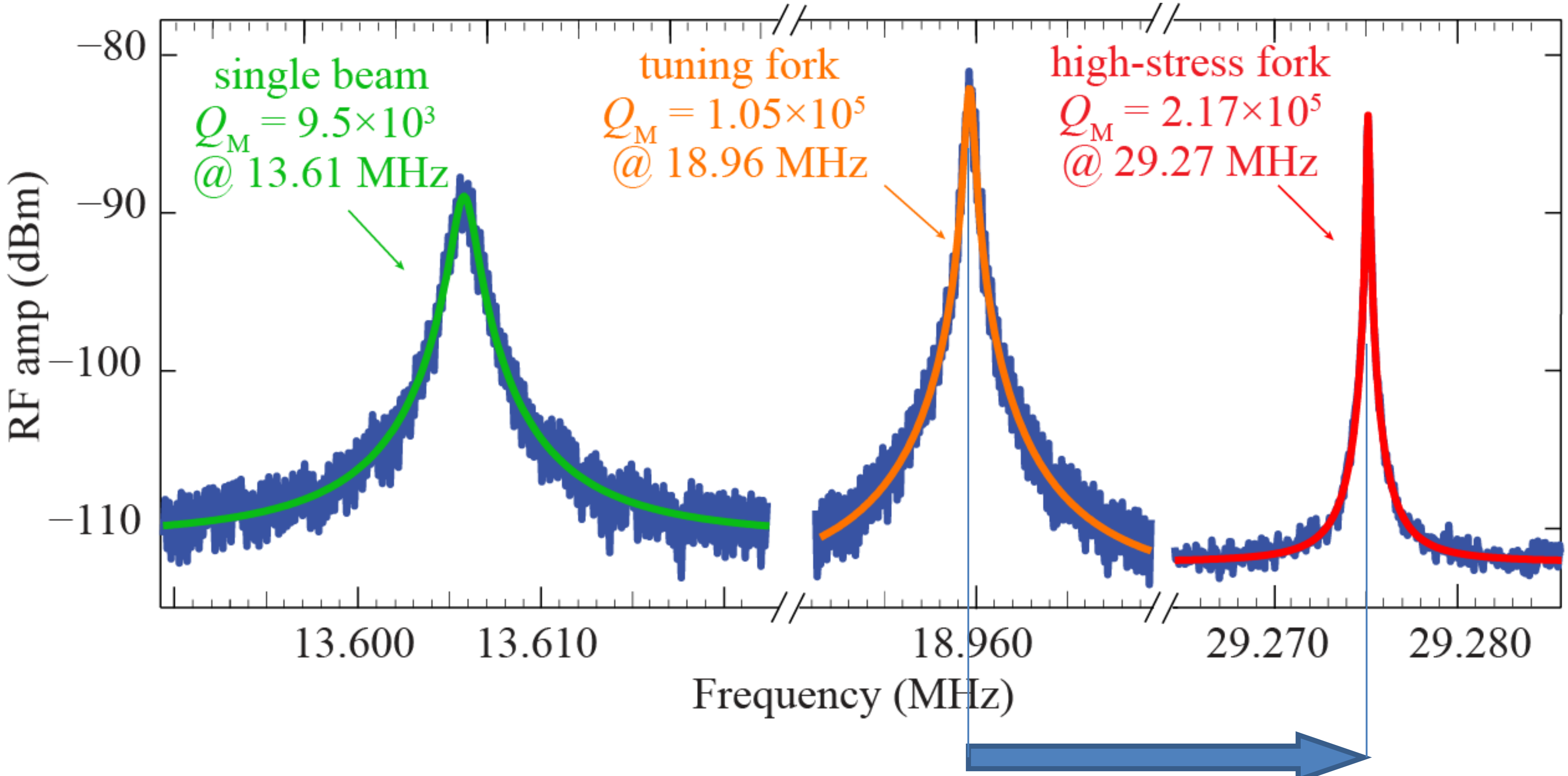
Beam stress of ≈1.4 GPa
after undercut

Symmetric mode has
low clamping loss

<u>Tension enhancement structure</u>: Beam stress of ≈3.0 GPa
for same residual (film) stress.

Measured Mechanical Spectra

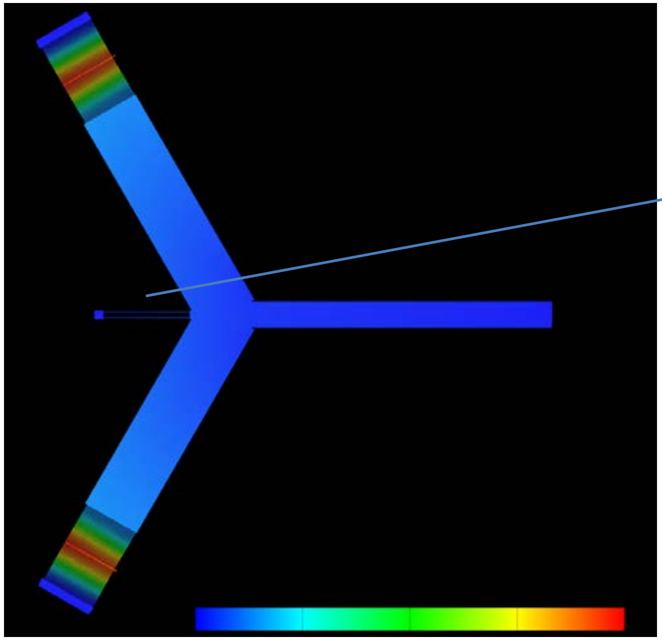


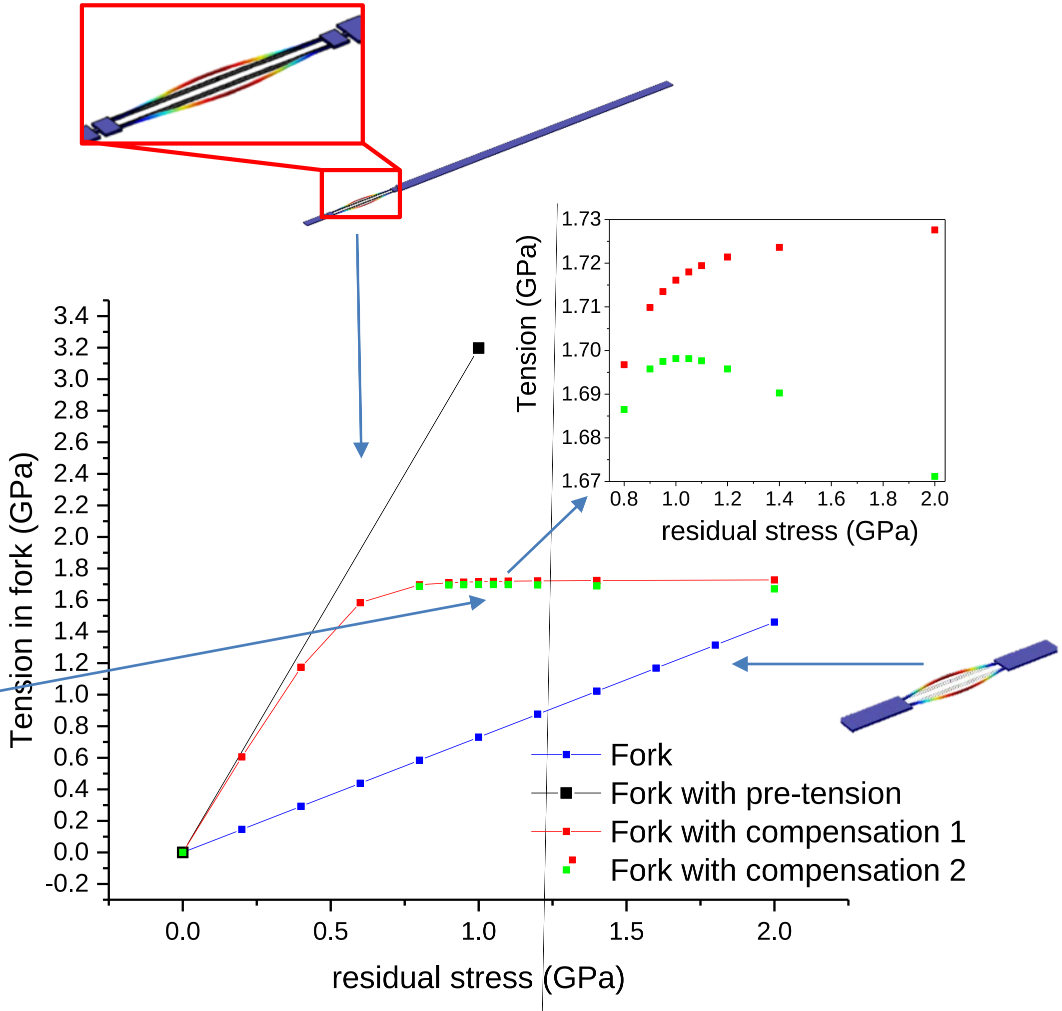


Tension enhancement

Compensation structures control tension in fork

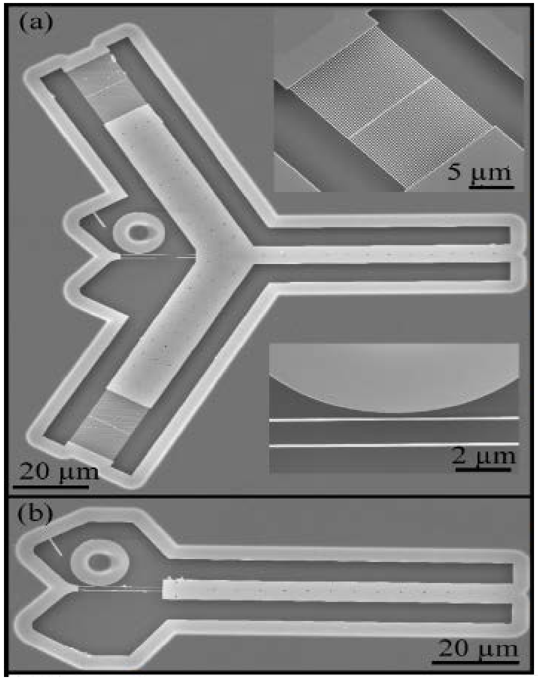
- Mechanical frequency is defined by tension
- Tension depends on
  - Residual stress
  - Differential thermal expansion
- Pre-tension structure increases tension for given residual stress (e.g. x4.4, black line)

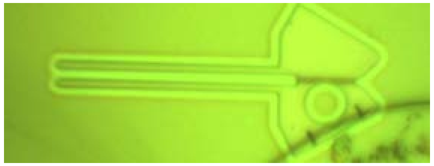


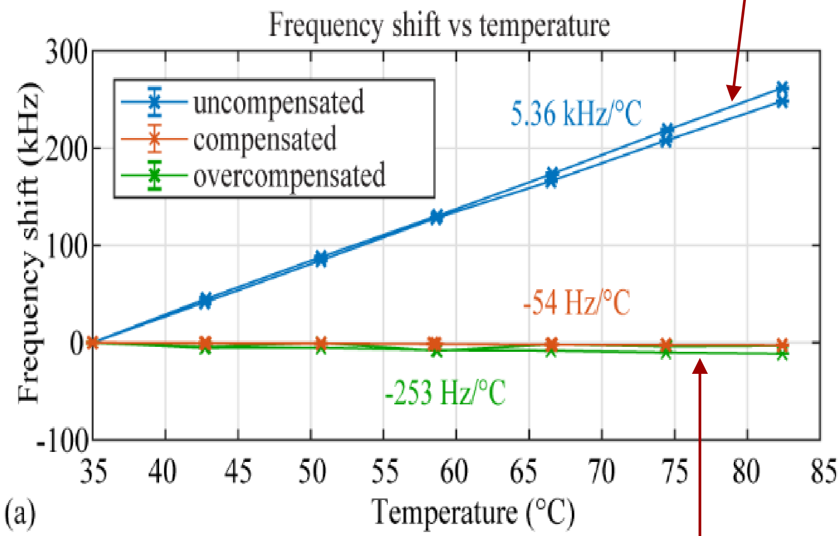


Compensation stabilizes tension to a predetermined value (reduced slope)

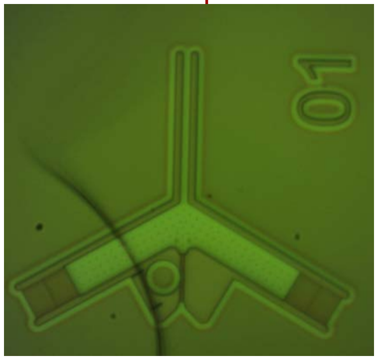
Temperature compensation: experimental



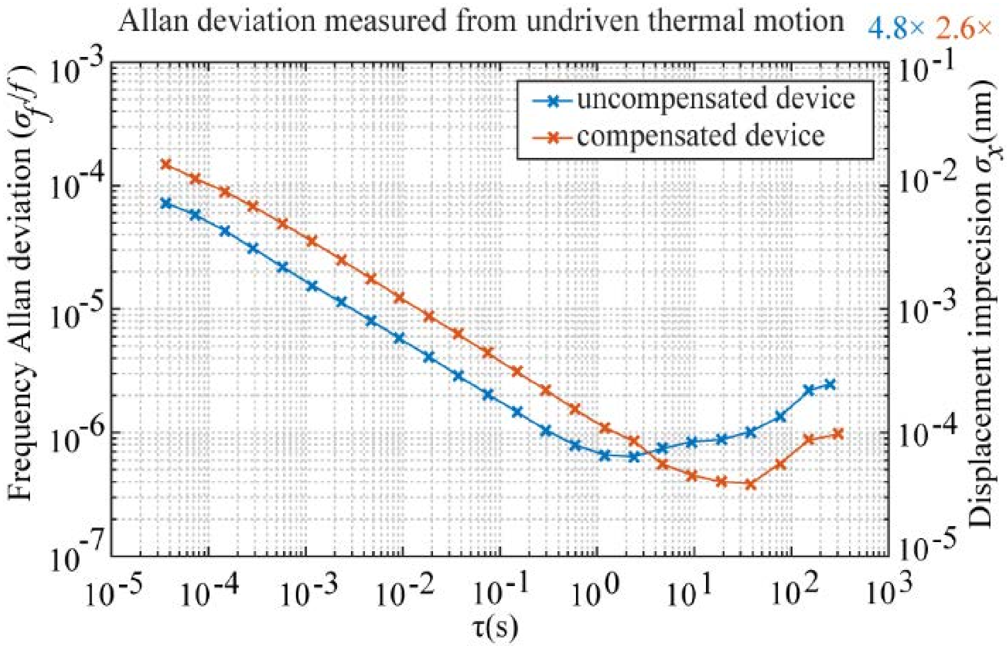


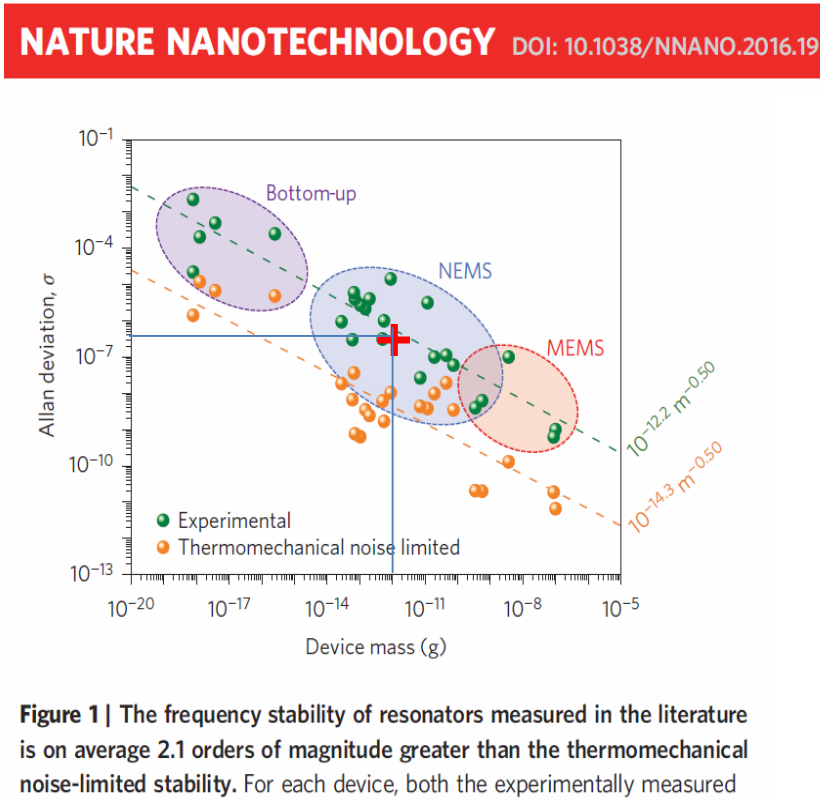


100x reduction of T dependence



Frequency stability: preliminary data



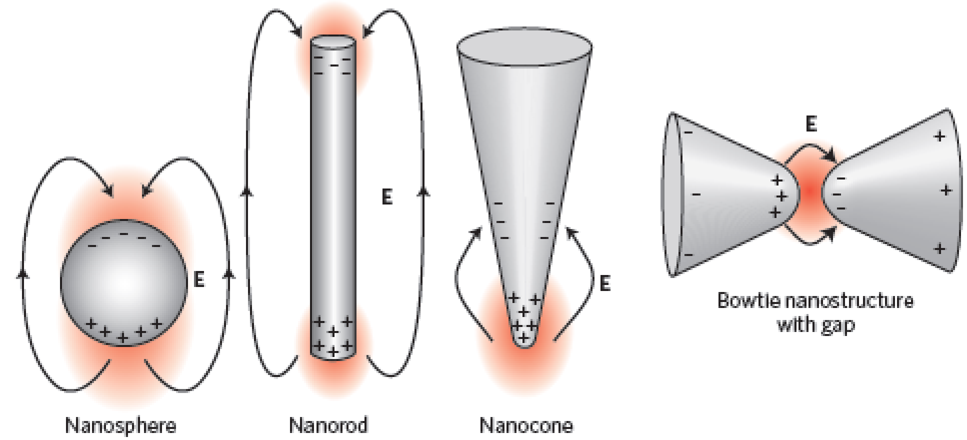


NATURE NANOTECHNOLOGY DOI: 10.1038/NNANO.2016.19

Figure 1 | The frequency stability of resonators measured in the literature is on average 2.1 orders of magnitude greater than the thermomechanical noise-limited stability. For each device, both the experimentally measured

- Undriven device (thermal noise only)
- ≈ thermodynamic limit up to 1s
  - Q ~ 30K, T_1 ~ 0.1 ms
- ≈ 1 ppm (≈ 0.3 pm) bias stability

Sub-wavelength confinement: plasmonics




REVIEW ARTICLE | FOCUS

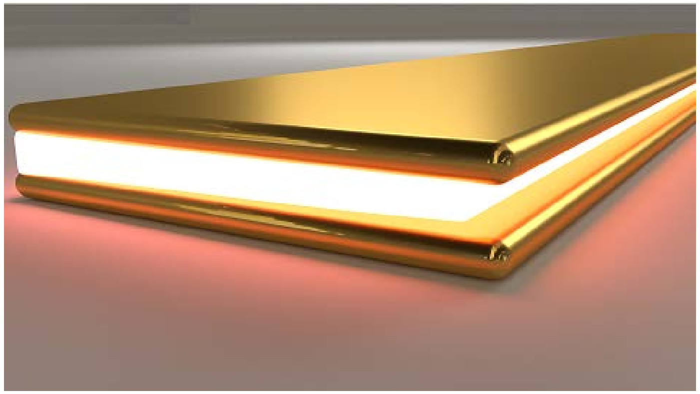
PUBLISHED ONLINE: 29 JUNE 2009 | DOI: 10.1038/NPHOTON.2009.111

nature photonics

Plasmonics for near-field nano-imaging and superlensing

Satoshi Kawata[1,2], Yasushi Inouye[3] and Prabhat Verma[1,3]

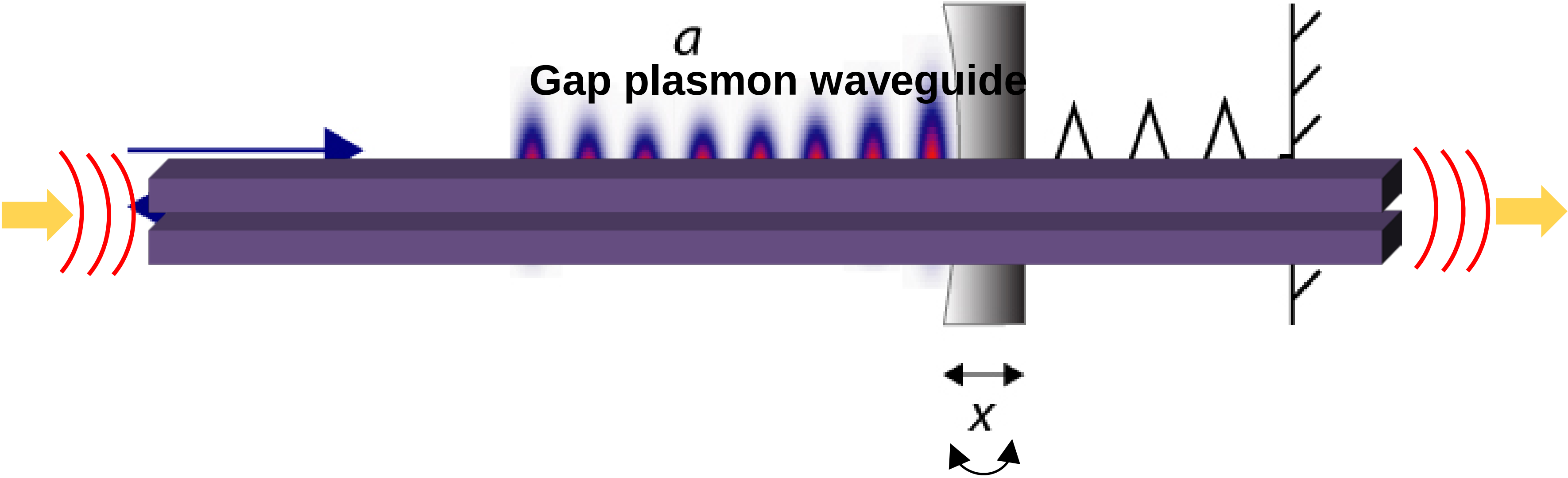
MIM waveguides: <10nm gaps



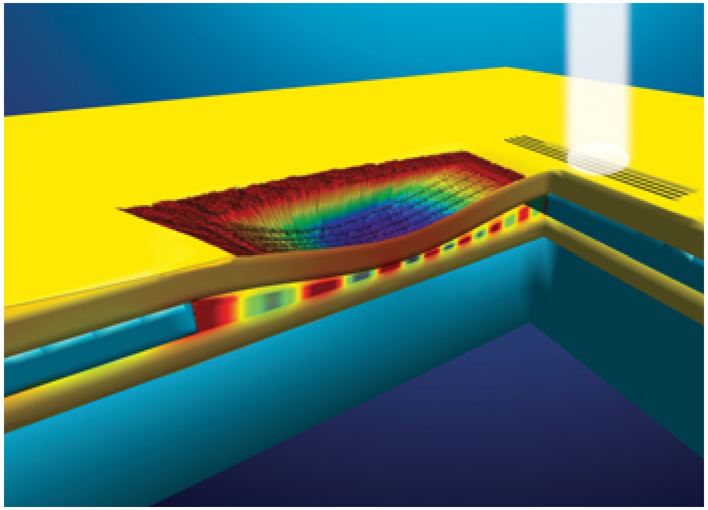
- Electron charge density oscillations
  - Strong interaction with light
- Nanometer energy confinement:
  - Electromagnetic energy → Electromechanical energy
- Favorable interaction/loss scaling

B. Dennis et al, Nature Photonics, 9, 267-273 (2015)

Deep sub-wavelength optical signal manipulation



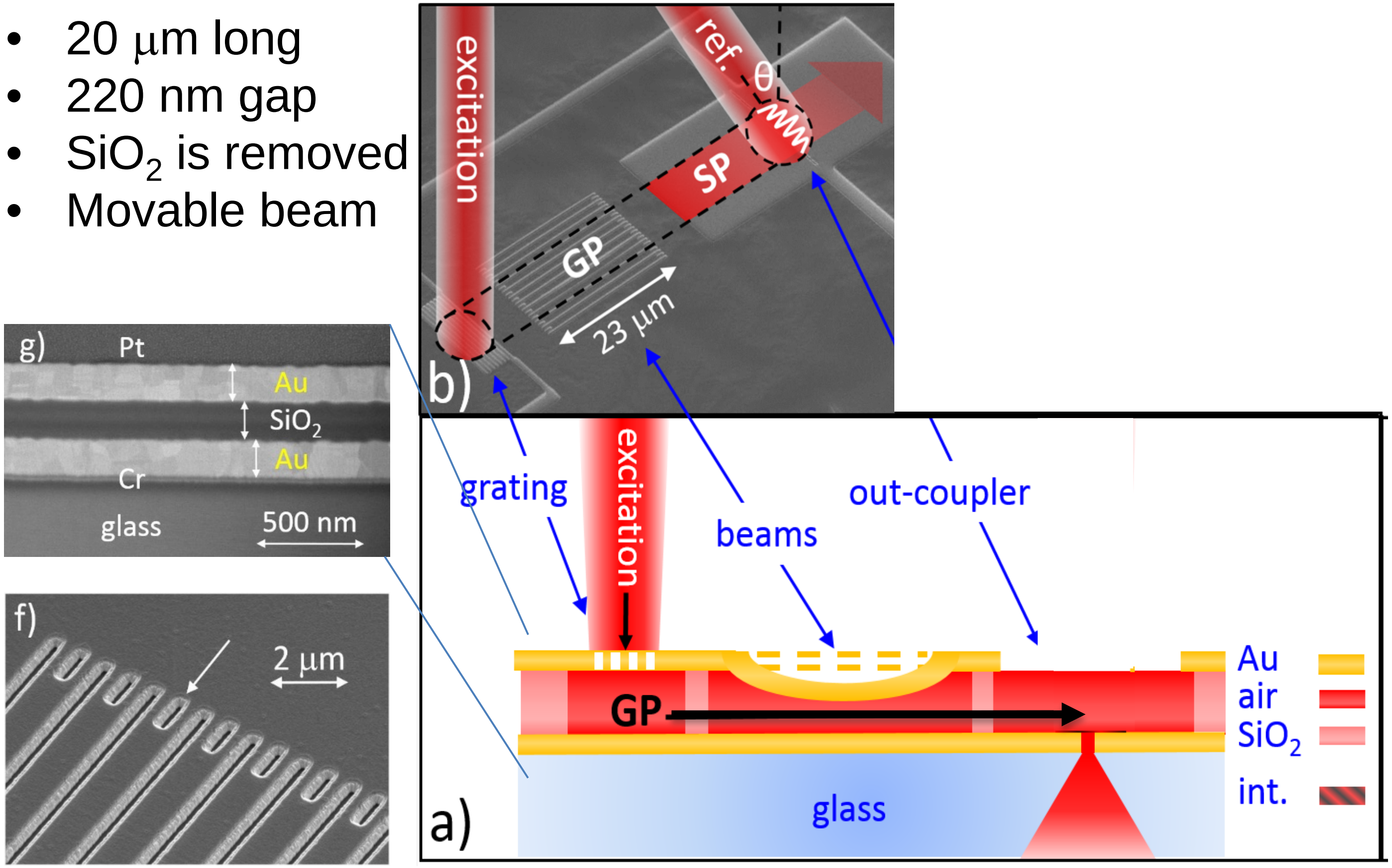
- Transmitted phase or amplitude is a function of mechanical coordinate
- Mechanically modulated effective index



Plasmonic nano-electro-mechanical transducer

NEMS Metal-Insulator-Metal plasmonic electrostatic transducer:

- 20 μm long
- 220 nm gap
- SiO_2 is removed
- Movable beam

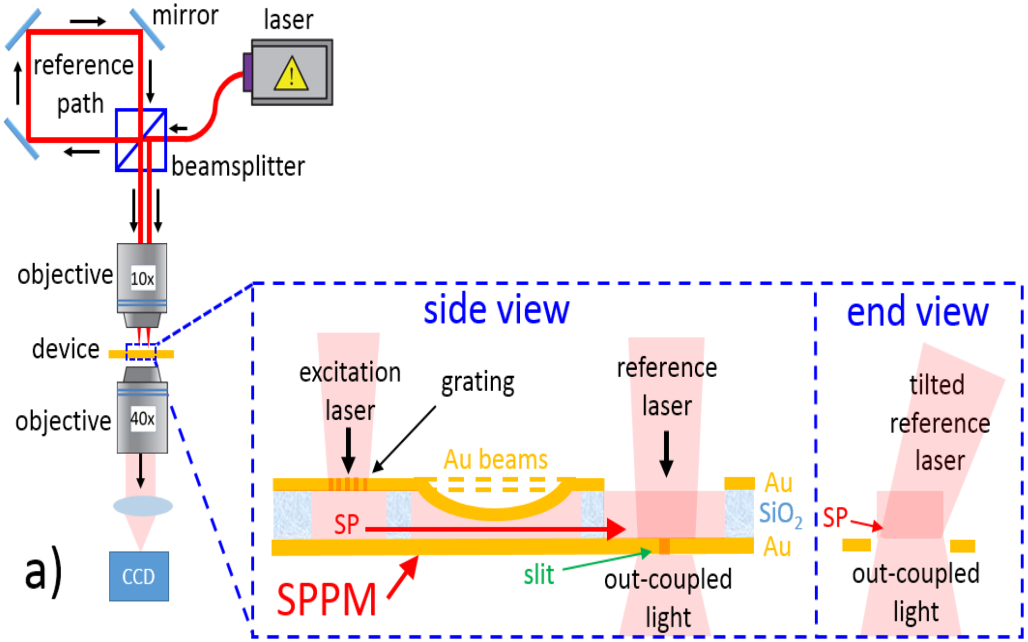


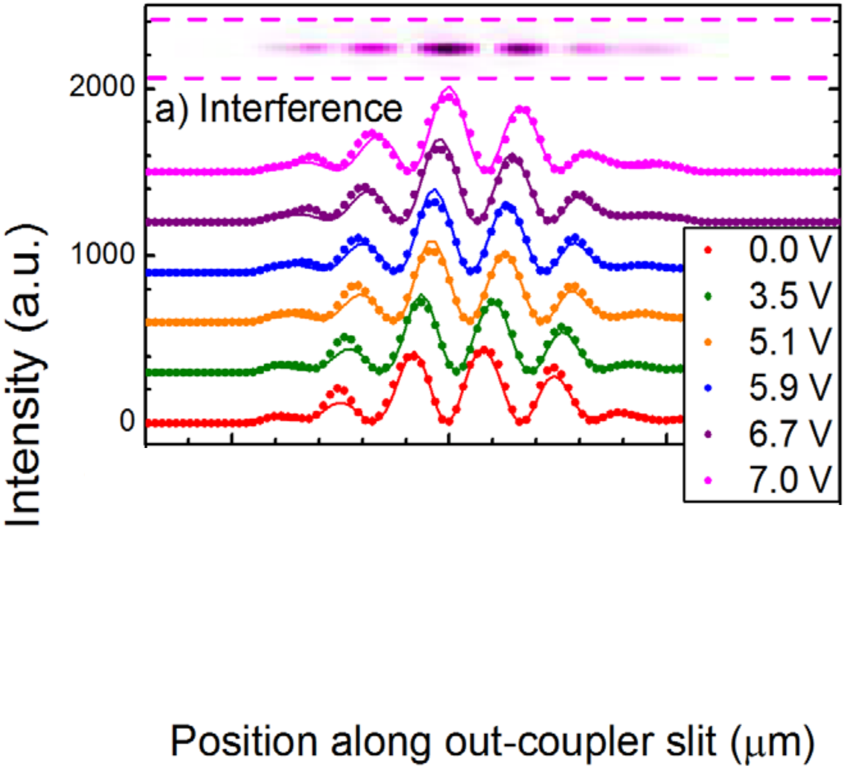
"Compact Nano-Mechanical Plasmonic Phase Modulators", B. Dennis et al, Nature Photonics, 9, 267-273 (2015)

Measured motion of Au nanobeams at 1 MHz

1 μm and 3 μm pitch suspended beams
≈ 4 V, 1 MHz actuation
≈ 100 nm amplitude

Measuring phase modulation





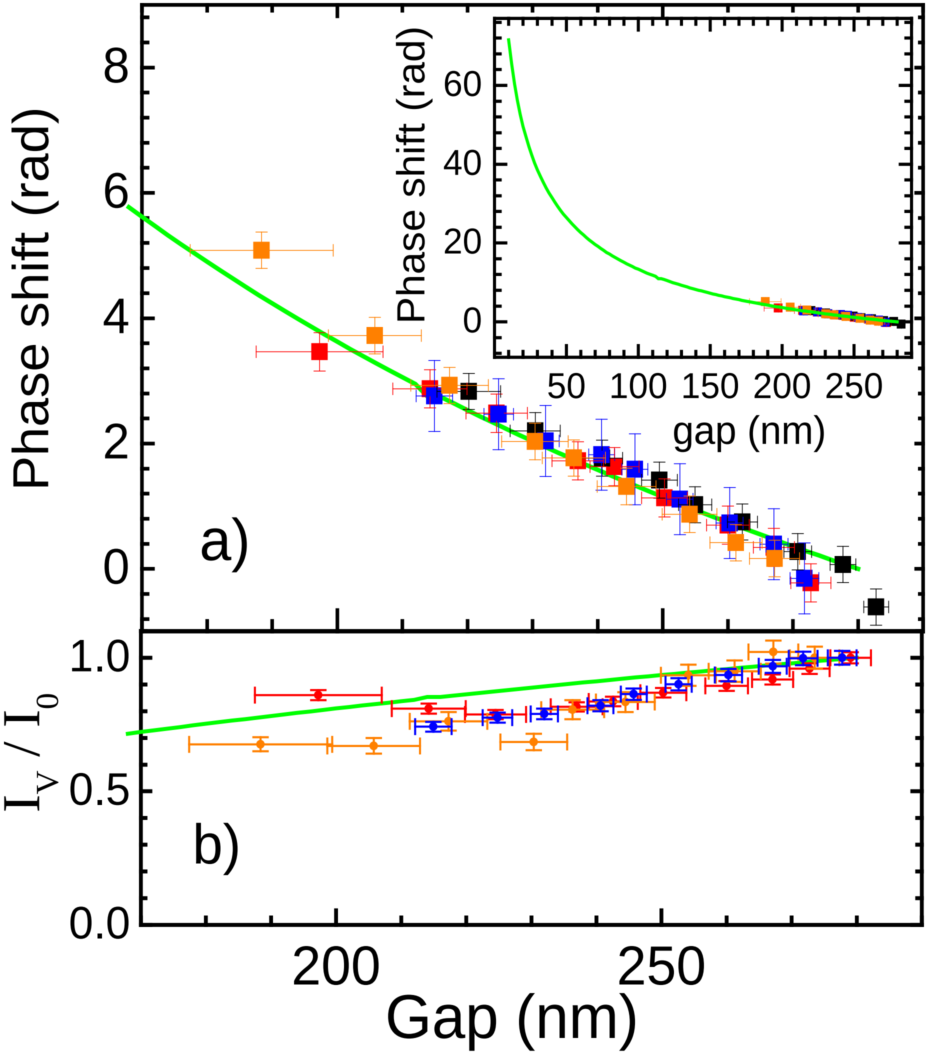
“Compact Nano-Mechanical Plasmonic Phase Modulators”, B. Dennis et al, Nature Photonics, 9, 267-273 (2015)

Phase modulation results

- > π rad phase modulation
- Excess loss below 70 %

Optical switching

Optical motion sensing



- Guided optical mode exists for gaps down to 1 nm
- Any wavelength longer than material absorption / surface plasma frequency
- Modulation vs. Loss?

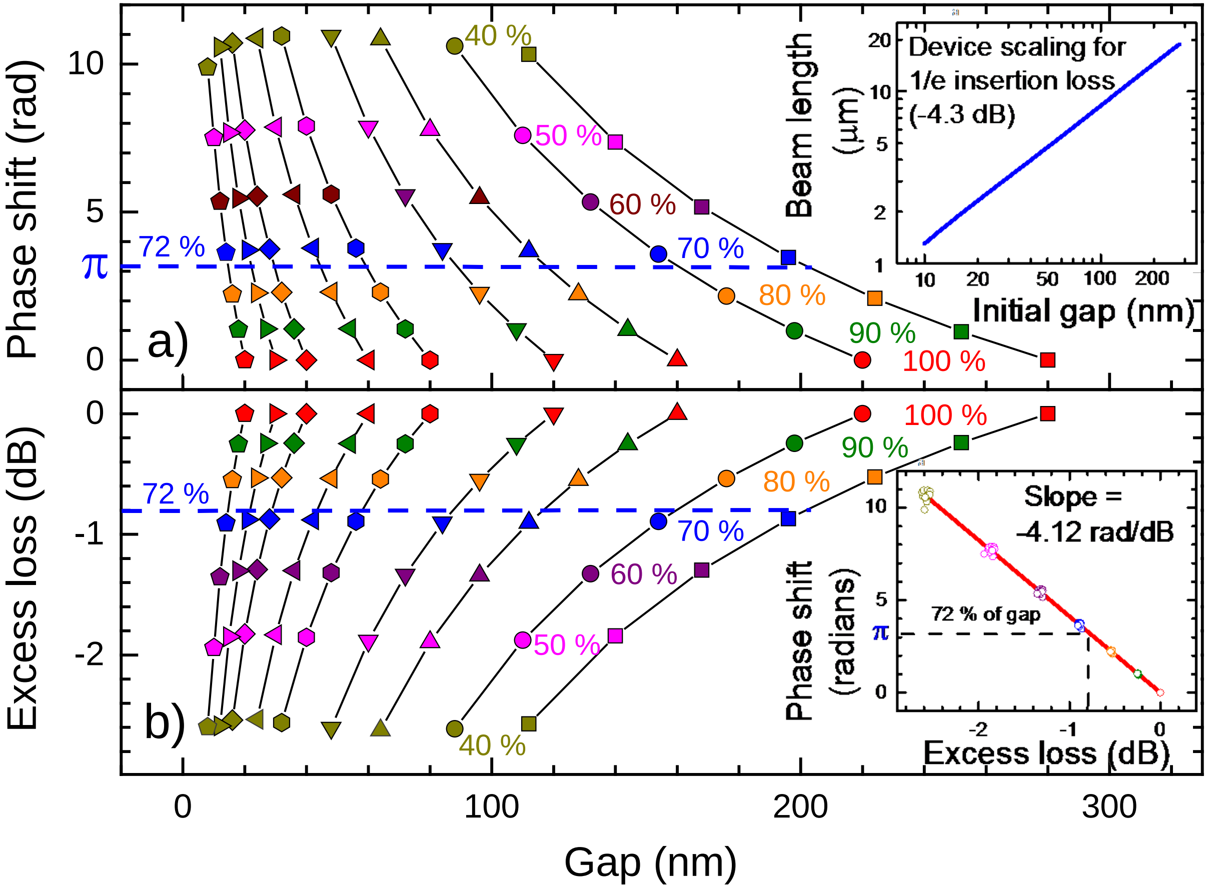
"Compact Nano-Mechanical Plasmonic Phase Modulators", B. Dennis et al, Nature Photonics, 9, 267-273 (2015)

Theoretical: reducing device size

- Maintain constant low loss
- Length ~ Gap$^{0.8}$
- Achieve π phase range?
  - Yes.
- Same relative actuation

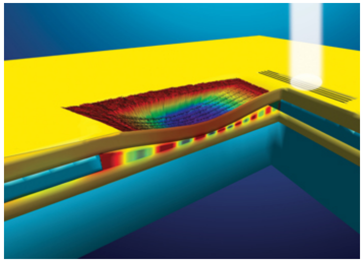
Gap: 100 nm -> 20 nm

Footprint: 2 µm x 100 nm

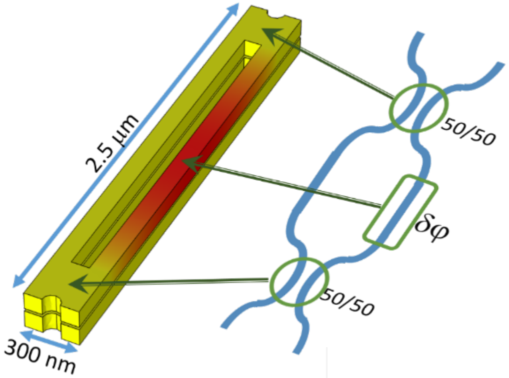


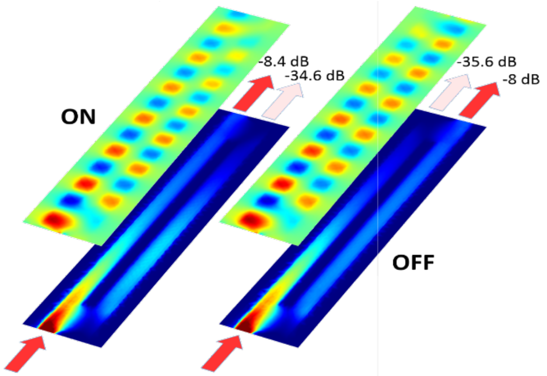
“Compact Nano-Mechanical Plasmonic Phase Modulators”, B. Dennis et al, Nature Photonics, 9, 267-273 (2015)

Gap plasmonic modulation



- Nano-mechanically tunable gap plasmons
  - Large coupling – large tuning with small motion
  - Scalable to very small size – efficiency is maintained
- Nano-electro-mechanical plasmon phase modulators
  - > π range, low losses
  - Compact: 20 μm scalable down to 2 μm
- Path to optical devices with deep subwavelength footprint
  - Plasmonic switch model: 2.5 μm x 0.5 μm

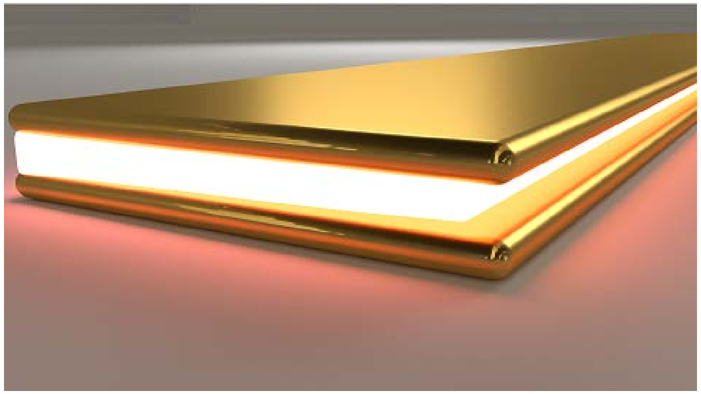




From 2D to 3D confinement

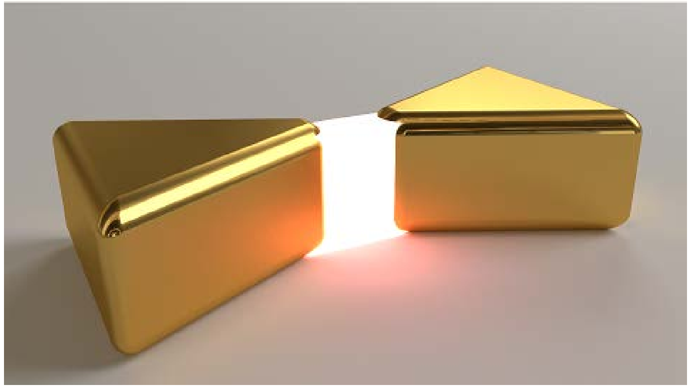
- Confine to smallest volume => max mechanical modulation
- NOT field enhancement at a single point but max average field
  - NOT the usual mode volume metric

MIM waveguides



Gap plasmons

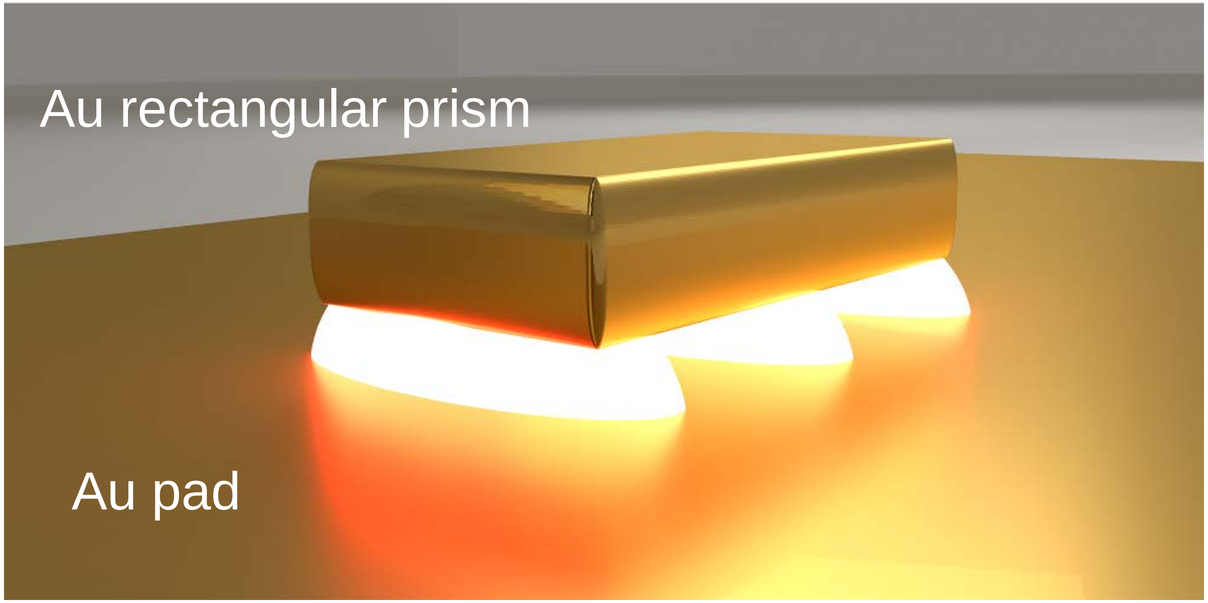
Antennas



Localized plasmon resonances

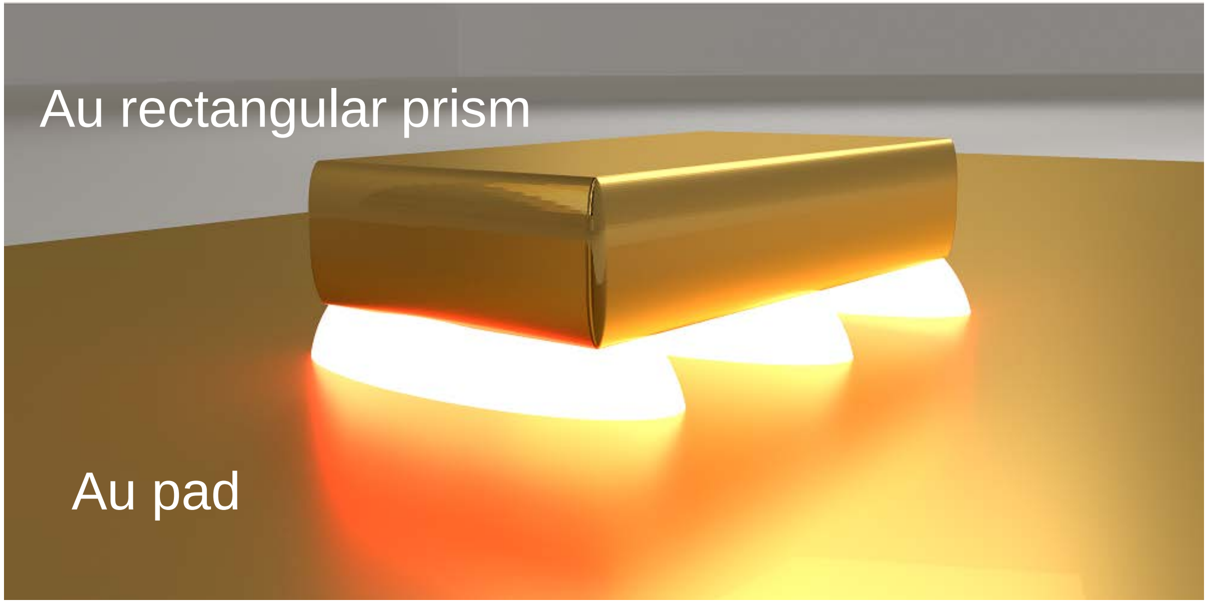
Localized gap-plasmon resonators

- Beneficial combination of MIM and antennas
- LGP mode is a standing-wave gap plasmon
- Reduced radiation loss vs. antennas → higher optical *Q*



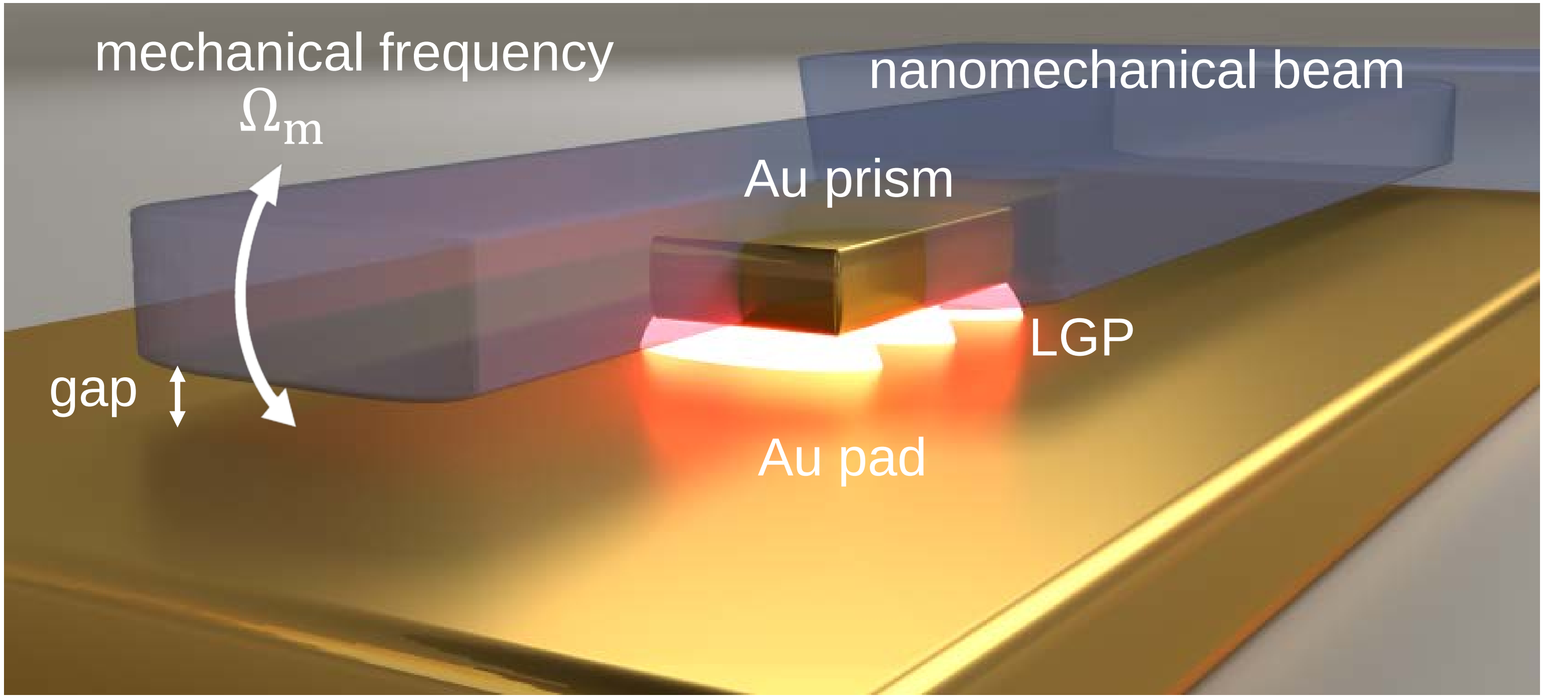
Localized gap-plasmon resonators

- LGP mode is a standing-wave gap plasmon
  - 100 nm to 300 nm typical lateral size
- Mode order, shape controls radiation coupling →
  - higher optical *Q*
  - Nanoscale resonator near-optimally coupled to free space
- ~ 10 nm gaps – extremely sensitive to vertical mechanical motion



Plasmonic-NEMS resonators

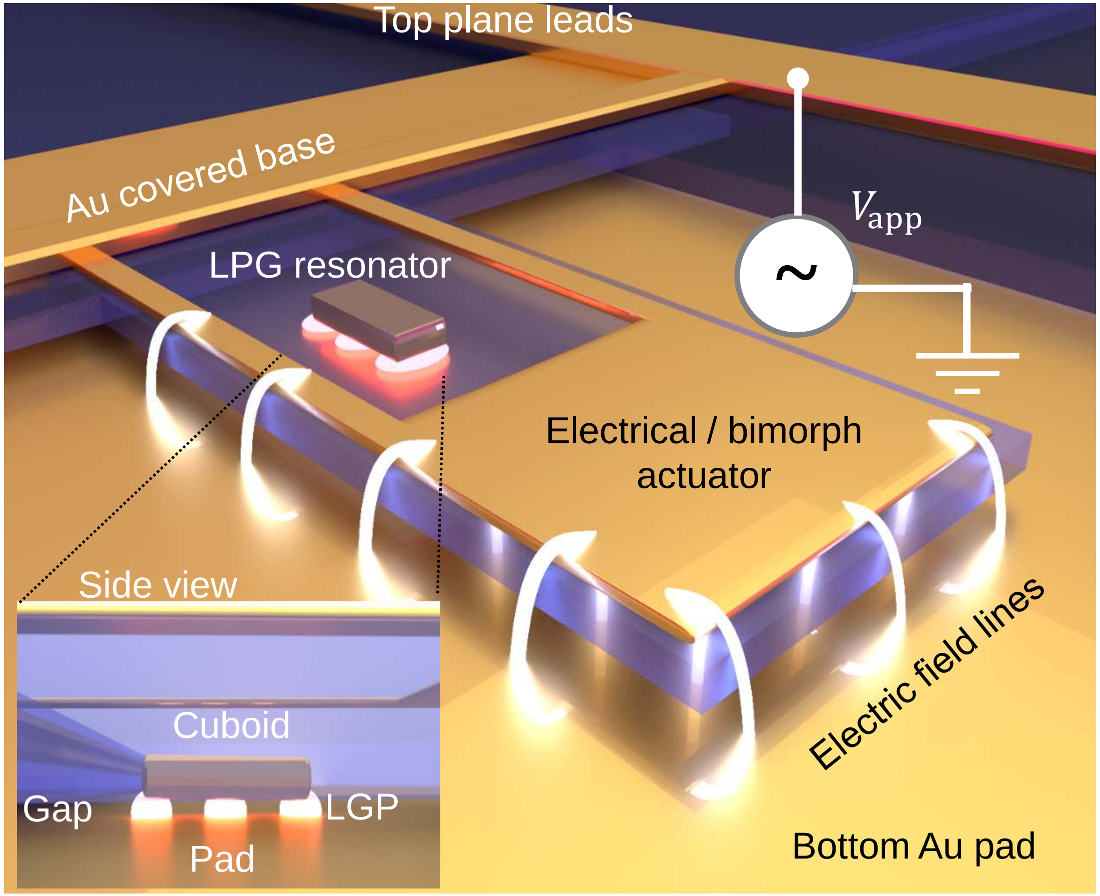
- Plasmonic prisms embedded into nanomechanical structures
- Dynamic localized gap plasmons (LGPs)
  - Produce strong, nanometer-localized optomechanical coupling



B. J. Roxworthy & V. A. Aksyuk, *Nature Comm.* **7**, 13746 (2016).

The full plasmonic-NEMS (pNEMS) architecture

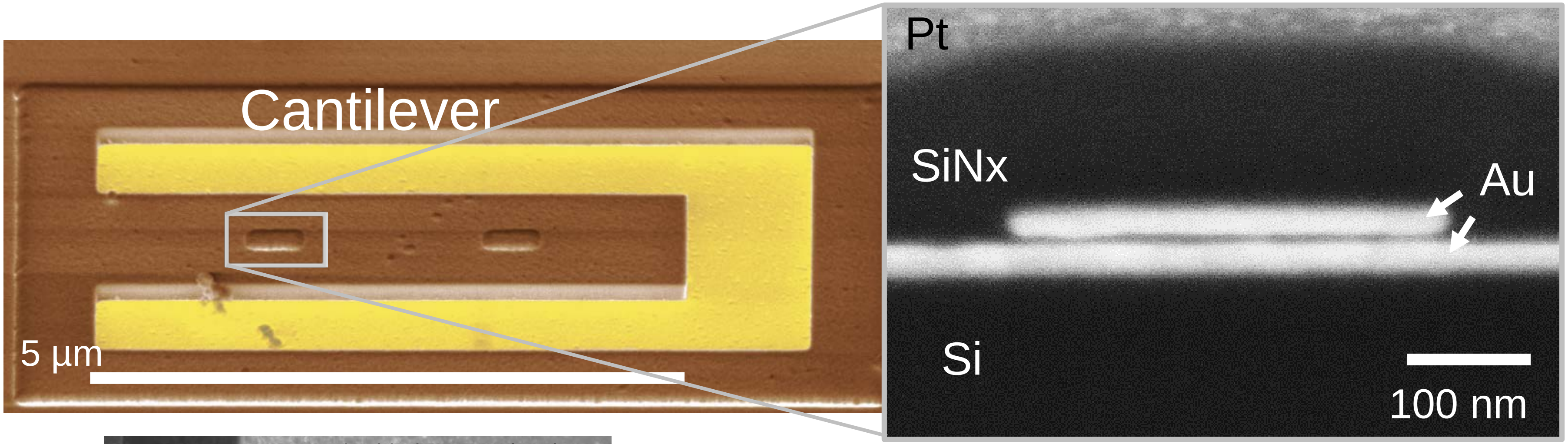
- Added metal layer optimized for electrostatic and thermo-mechanical
- Couple nanoscale optical resonance to mechanical, thermal, electrical DOFs

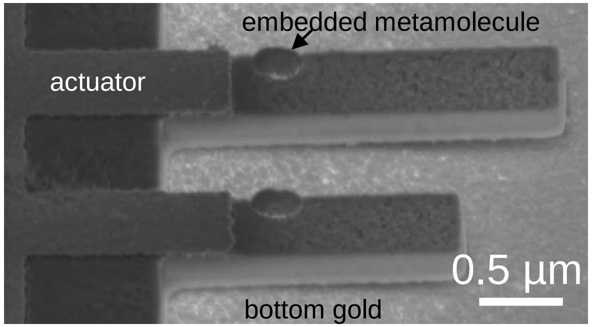


B. J. Roxworthy & V. A. Aksyuk, Optica **5**(1), 71-79 (2018)

Localized gap plasmon resonator + nanocantilever

- Silicon nitride cantilever: (5×1.25×0.175) µm^3
- Embedded gold prism: ($\underbrace{350\times165}_{\text{Prism footprint}}\times35$) nm^3 and ($\underbrace{90\times75}_{\text{Prism footprint}}\times40$) nm^3

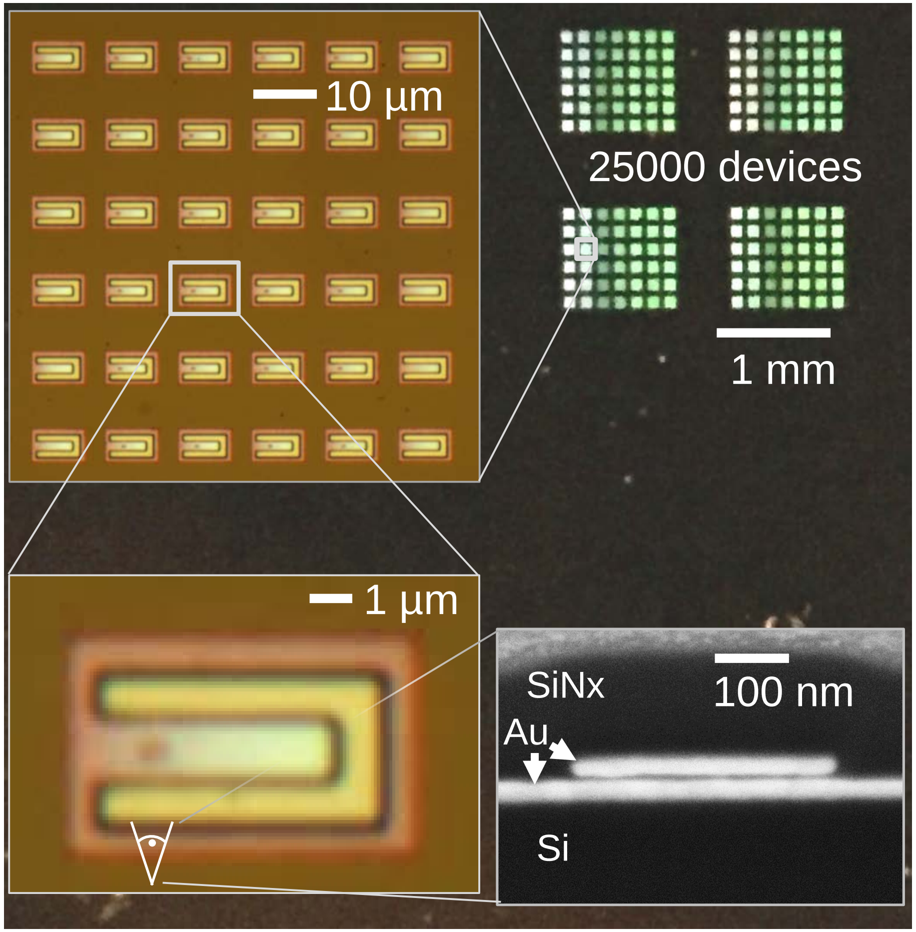


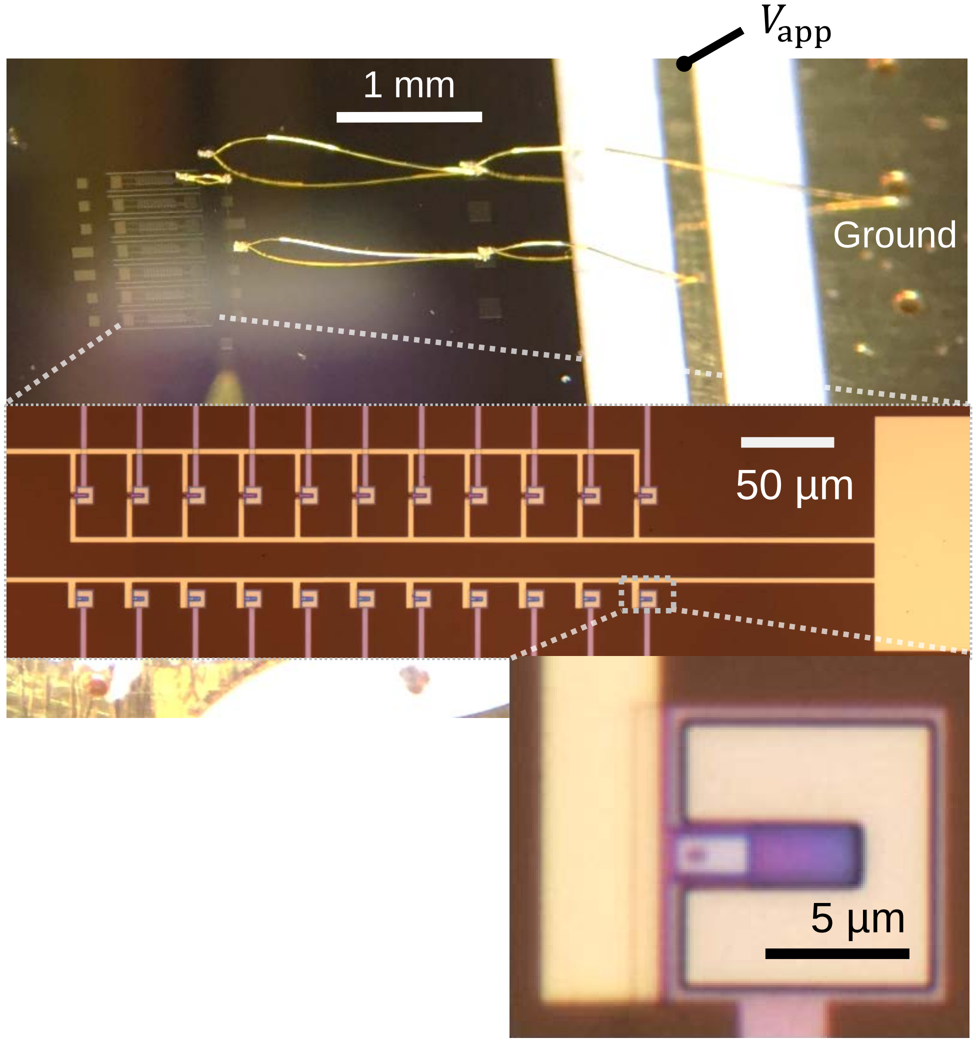


B. J. Roxworthy & V. A. Aksyuk, *Nature Comm.* **7**, 13746 (2016).

B. J. Roxworthy & V. A. Aksyuk, Optica **5**(1), 71-79 (2018)

pNEMS: scalable platform for plasmomechanics





B. J. Roxworthy & V. A. Aksyuk, *Nature Comm.* **7**, 13746 (2016).

B. J. Roxworthy & V. A. Aksyuk, Optica **5**(1), 71-79 (2018)

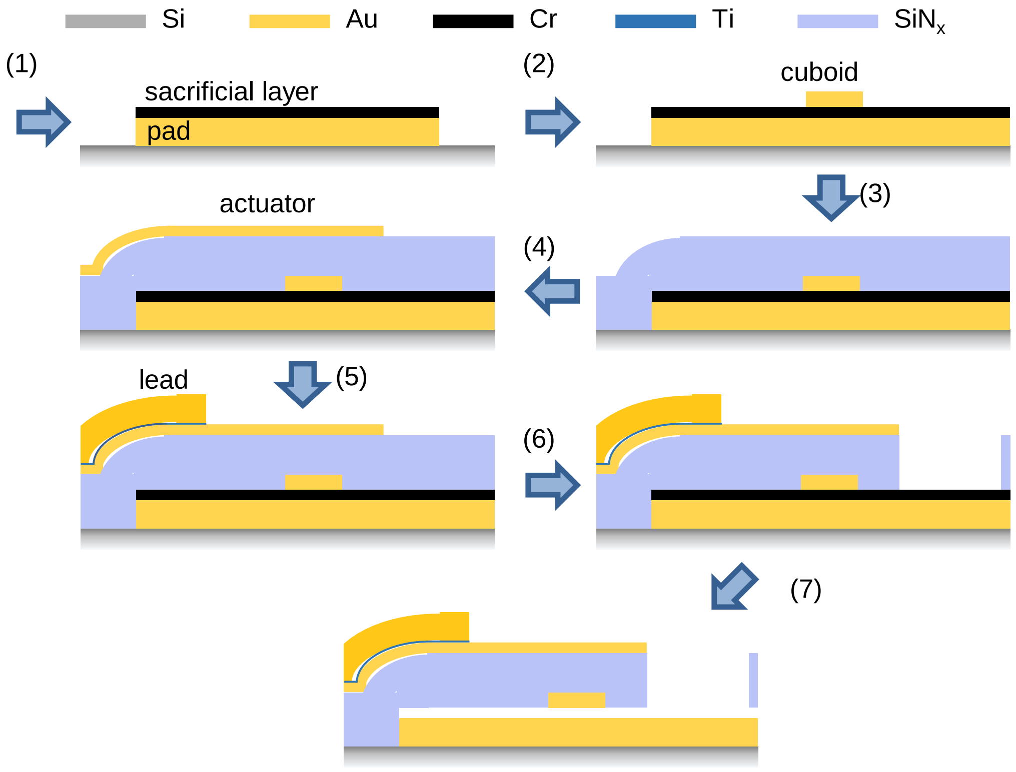
Process flow for plasmonic-NEMS platform

Lithographic layers:

- Plasmonic resonator
- Mechanical device
- Actuator

Modes / degrees of freedom:

- Optical
- Mechanical
- Thermal
- Electrical



(1) EBL + LO **(2)** aEBL + LO **(3)** PECVD **(4)** aEBL + LO

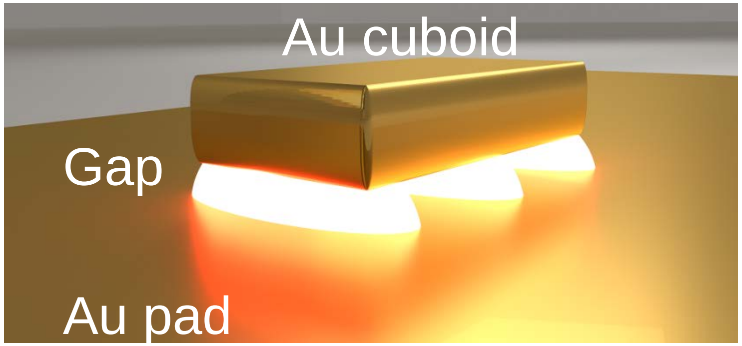
(5) aEBL + LO **(6)** aEBL + RIE **(7)** Etch + CPD + package

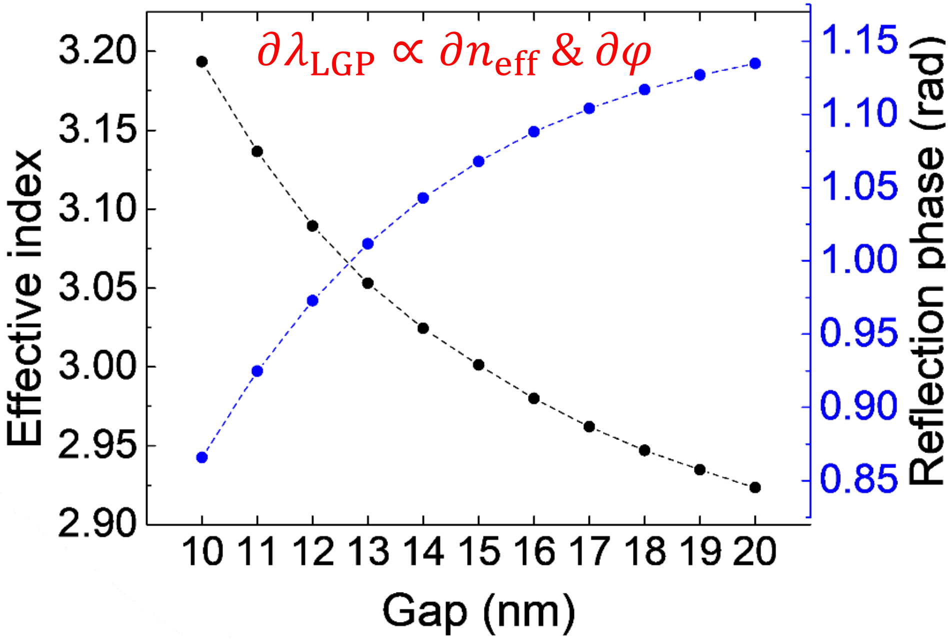
- Key processing features
  - **Chromium** sacrificial layer ≤ 15 nm – build plasmonic resonator vertically
  - **PECVD** silicon nitride (SiNx) – low temperature of 180 °C

B. J. Roxworthy & V. A. Aksyuk, Optica **5**(1), 71-79 (2018)

Localized gap-plasmon resonators

- LGP mode is a standing-wave gap plasmon
- LGP resonance depends sensitively on gap size





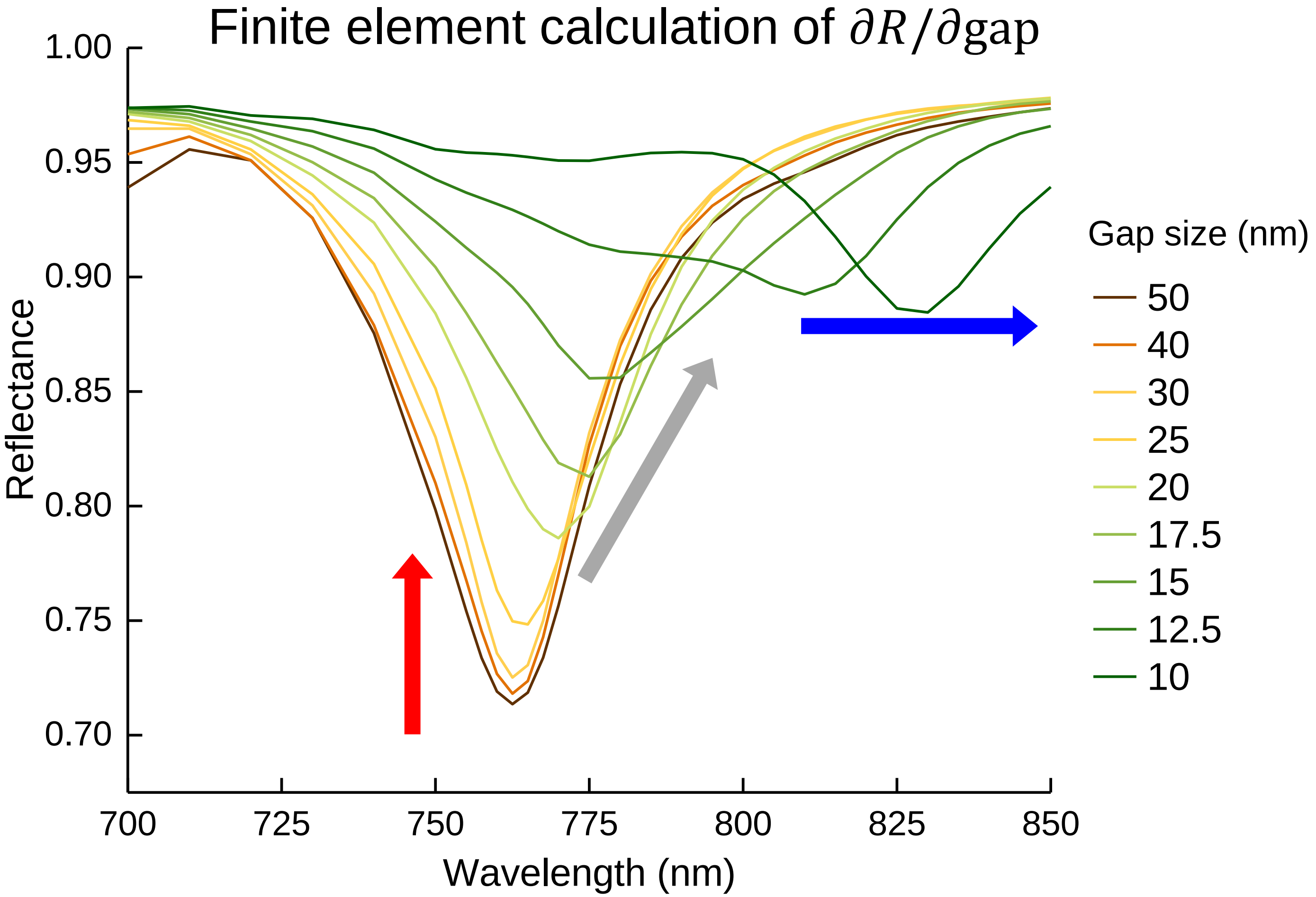
$\partial \lambda_{\mathrm{LGP}} \propto \partial n_{\mathrm{eff}} \,\&\, \partial \varphi$

$\varphi_{\mathrm{RT}} = m \cdot 2\pi$

$m = 1$

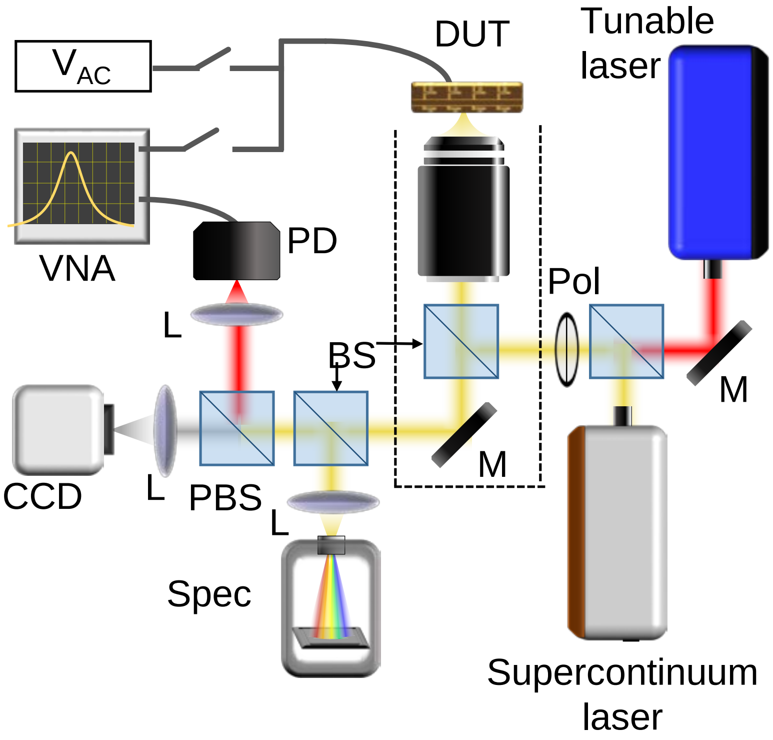
$m = 3$

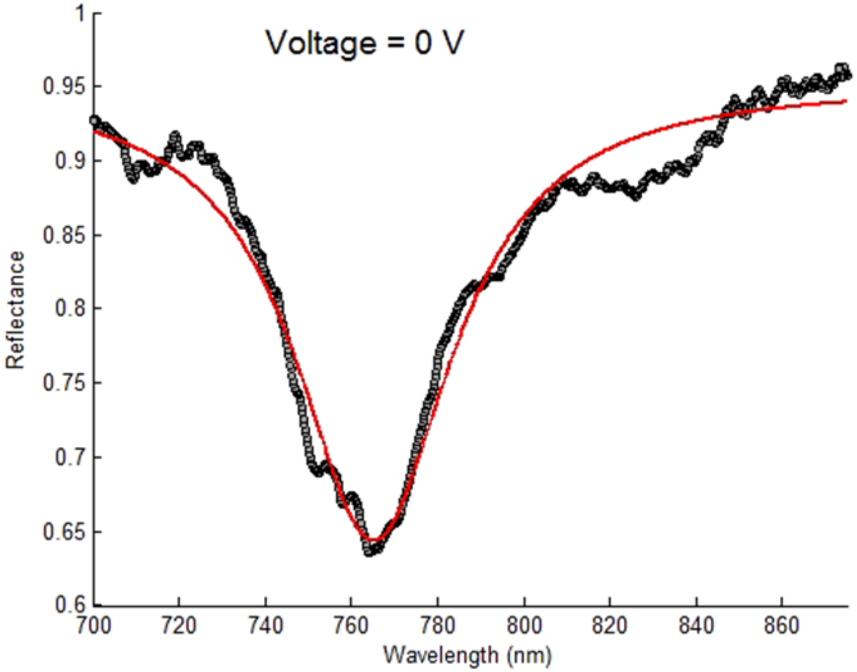
Shrinking gap = plasmon red shift + reduced coupling



Measured g_{om} up to ≈ 2 THz/nm; (g_0 ≈ 70 MHz)

Electrostatic actuation provides facile LGP tuning





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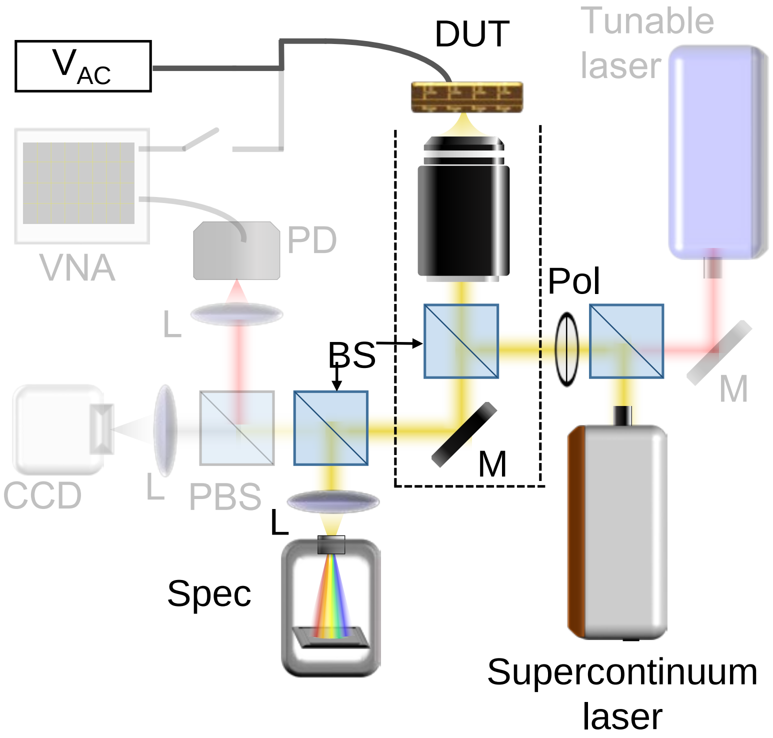
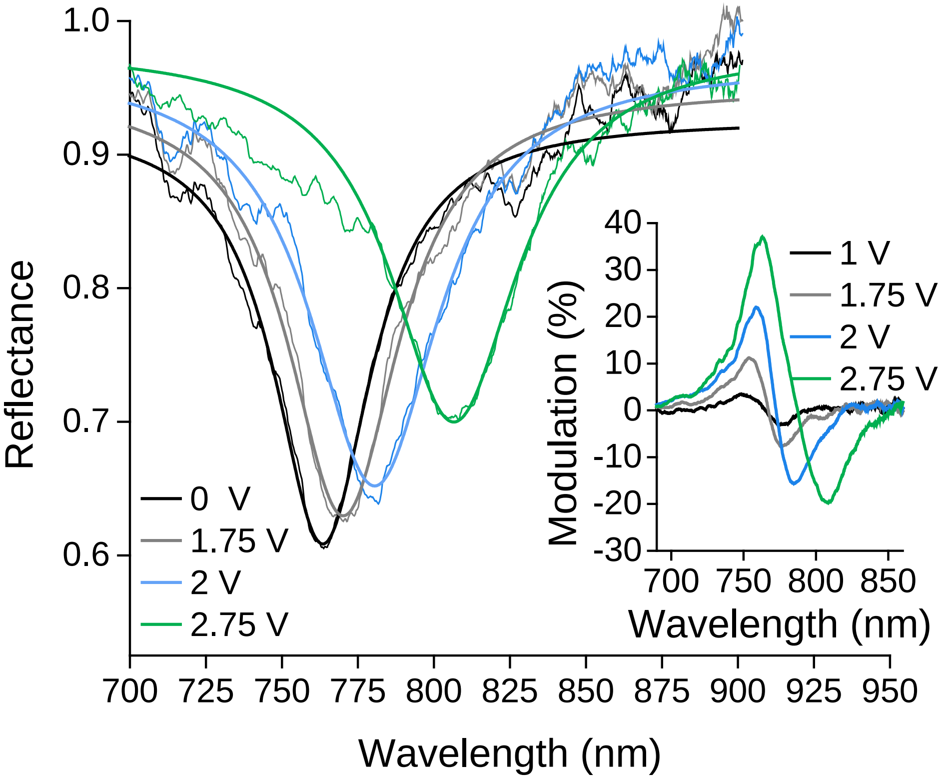
Electrostatic actuation provides facile LGP tuning

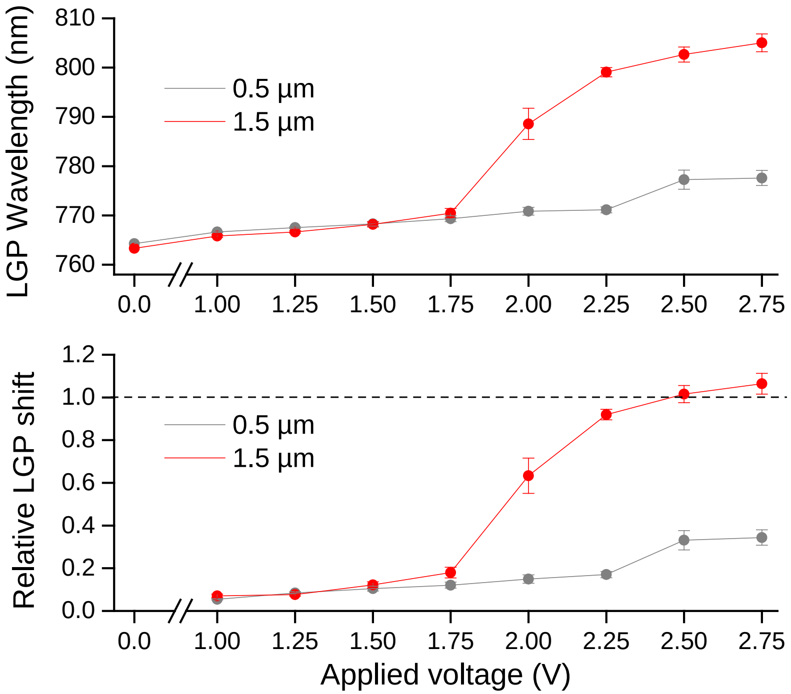


B. J. Roxworthy & V. A. Aksyuk, Optica **5**(1), 71-79 (2018)

Electromechanical LGP resonance tuning

- $\Delta\lambda_{\mathrm{LGP}} > \mathrm{FWHM}_{\mathrm{LGP}}$ and 40 % (4 dB) amplitude modulation





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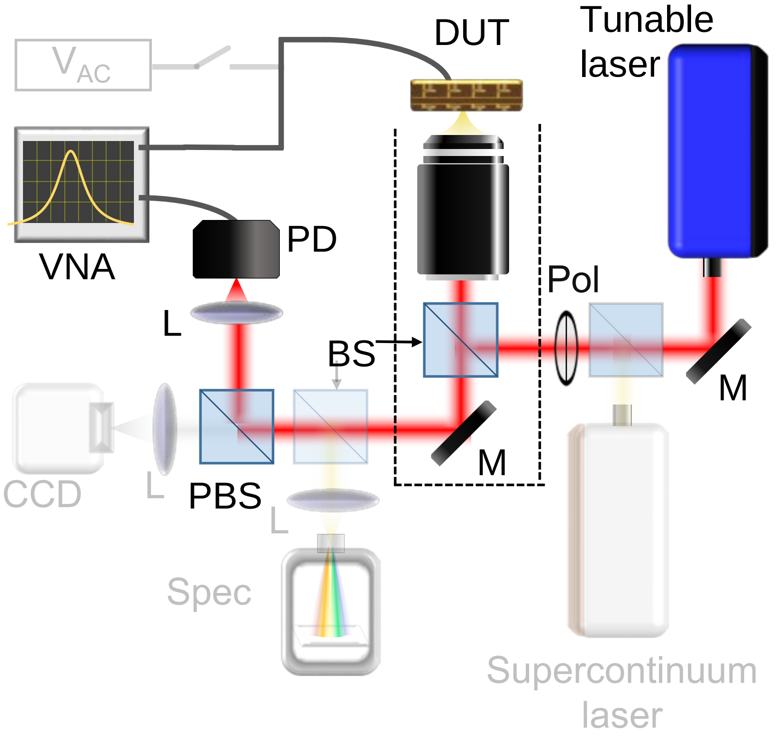
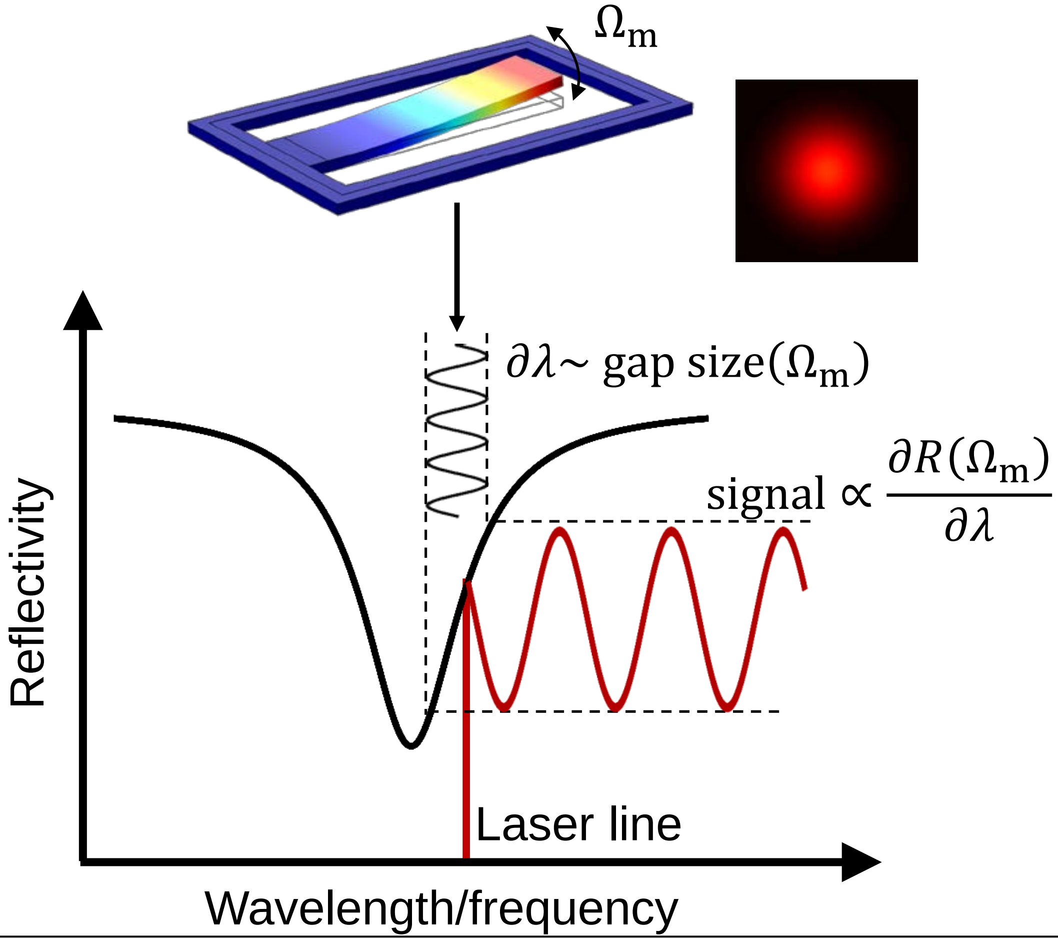
Dynamic motion measurement using amplitude modulation

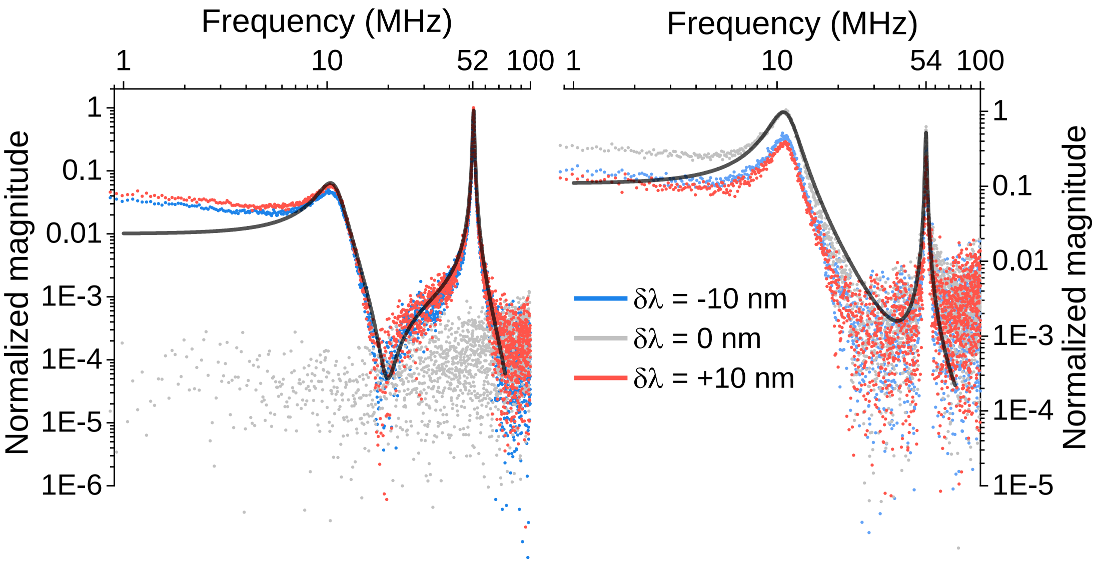
- Modulated reflectivity→photodiode→spectrum analyzer

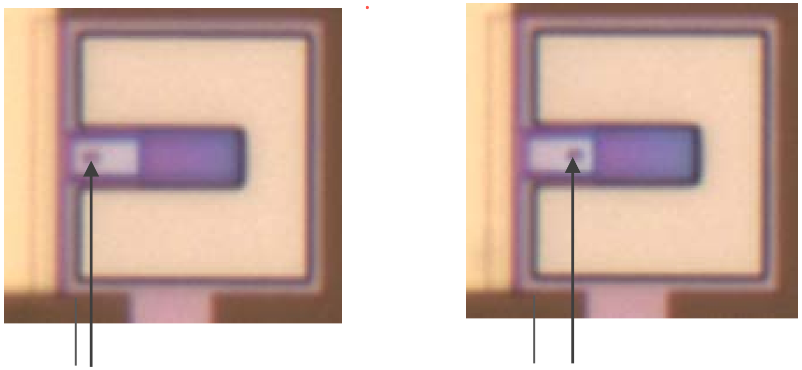




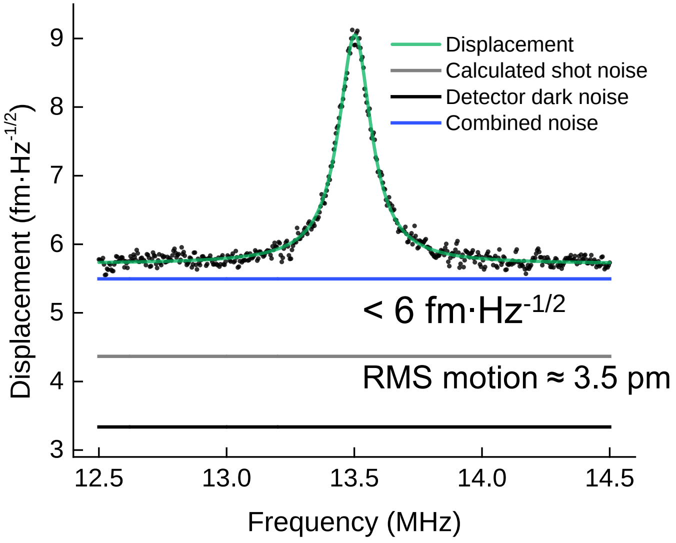
LGPs selectively transduce mechanical modes

Ambient, electrostatic drive





Vacuum, thermodynamic fluctuations

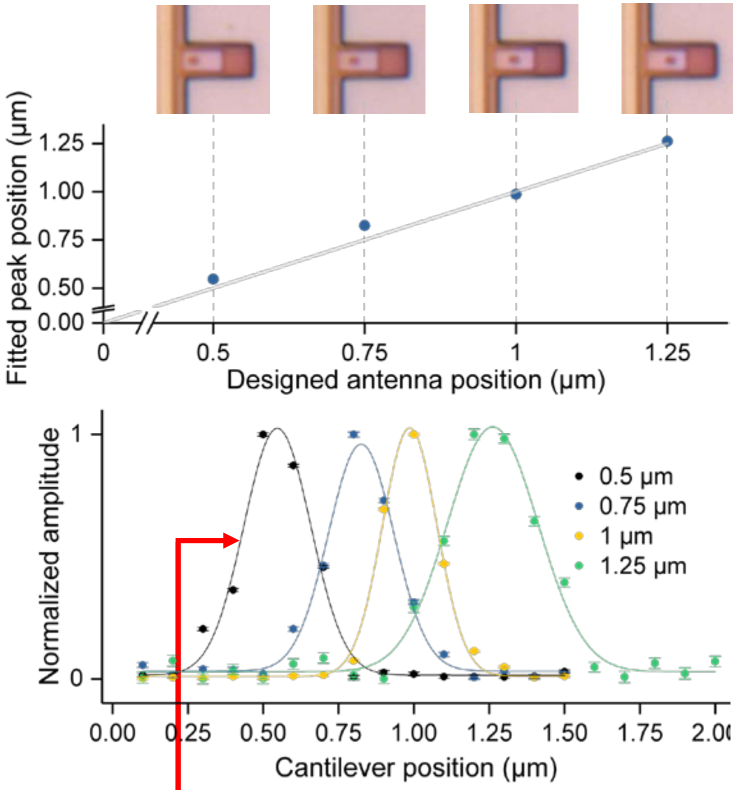


- Measured $g_{\mathrm{OM}} \approx 2$ THz·nm^{-1}
- Sensitivity > 40× improvement
  - 4× ideal Doppler
  - Limited by photon shot noise
- Transduction region <150× diffraction limit

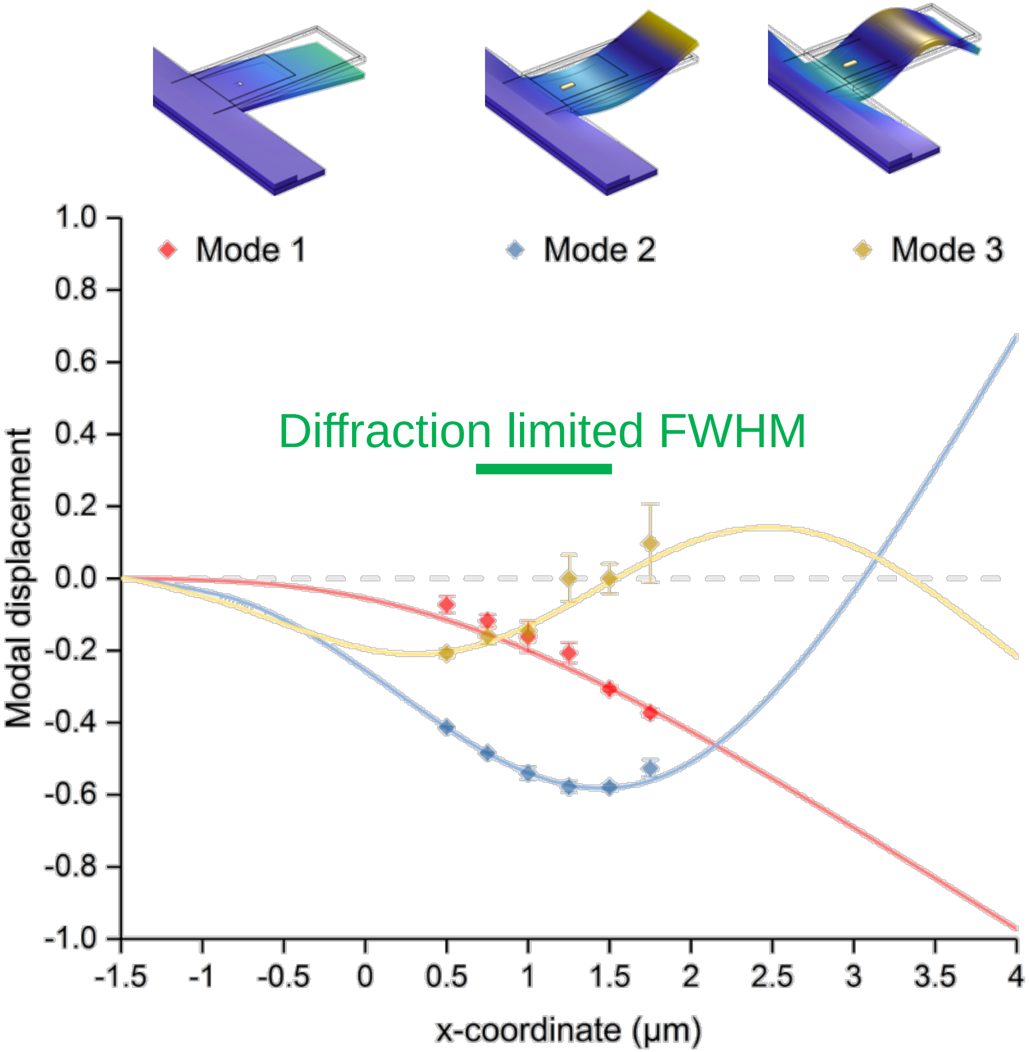
B. J. Roxworthy & V. A. Aksyuk, Optica **5**(1), 71-79 (2018)

B. J. Roxworthy & V. A. Aksyuk, *Nat. Commun* **7**, 13746 (2016).

Localized interactions enable sub-λ mode mapping

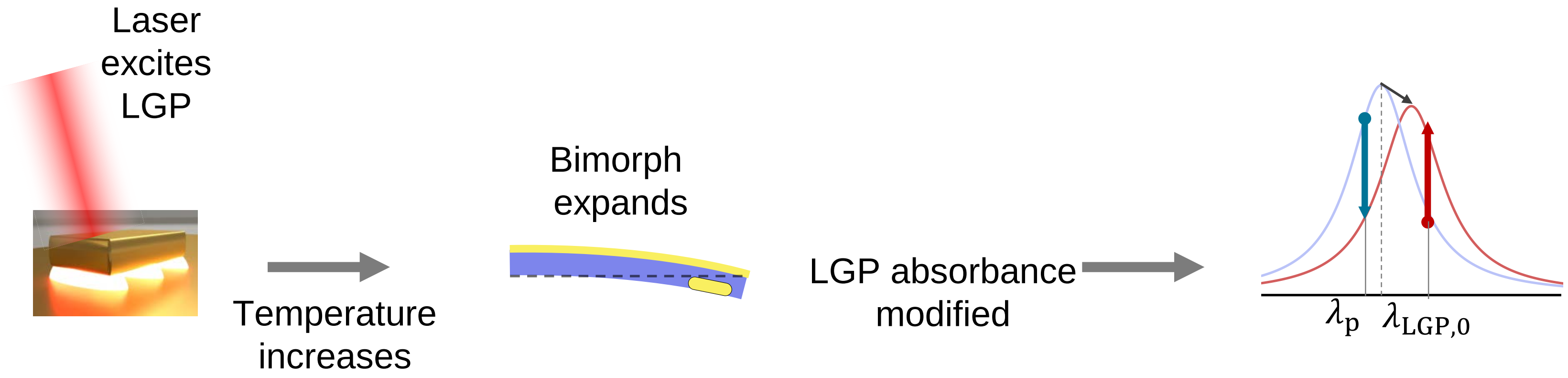


FWHM ≈ 280 nm



Bimorph enables Plasmomechanical Oscillators (PMOs)

- Optomechanical interactions via absorption, thermal actuation: delayed feedback



Laser excites LGP

Temperature increases

Bimorph expands

LGP absorbance modified

Amplification/Oscillation
via
time-delayed
positive spring

↓

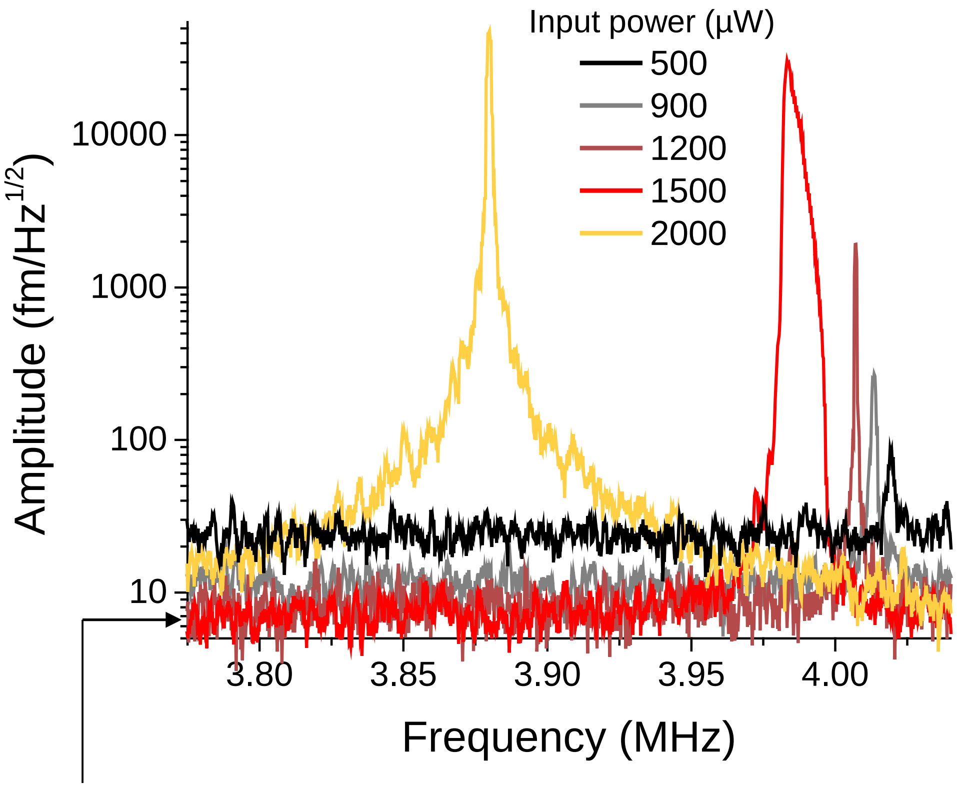
blue detuning

Damping
via
time-delayed
negative spring

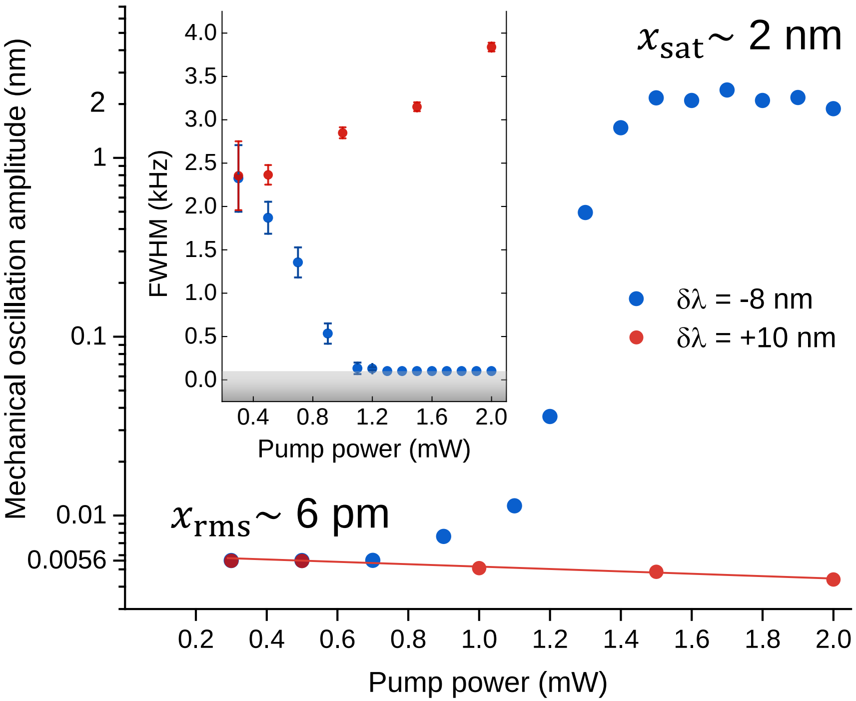
↓

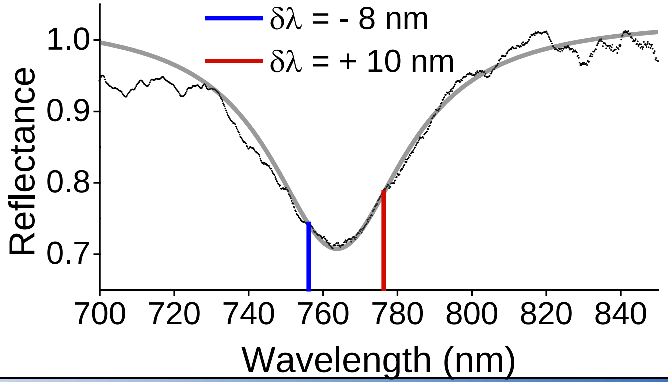
red detuning

Single-element Plasmomechanical Oscillators



Noise floor: ~ 10 fm·Hz$^{-1/2}$





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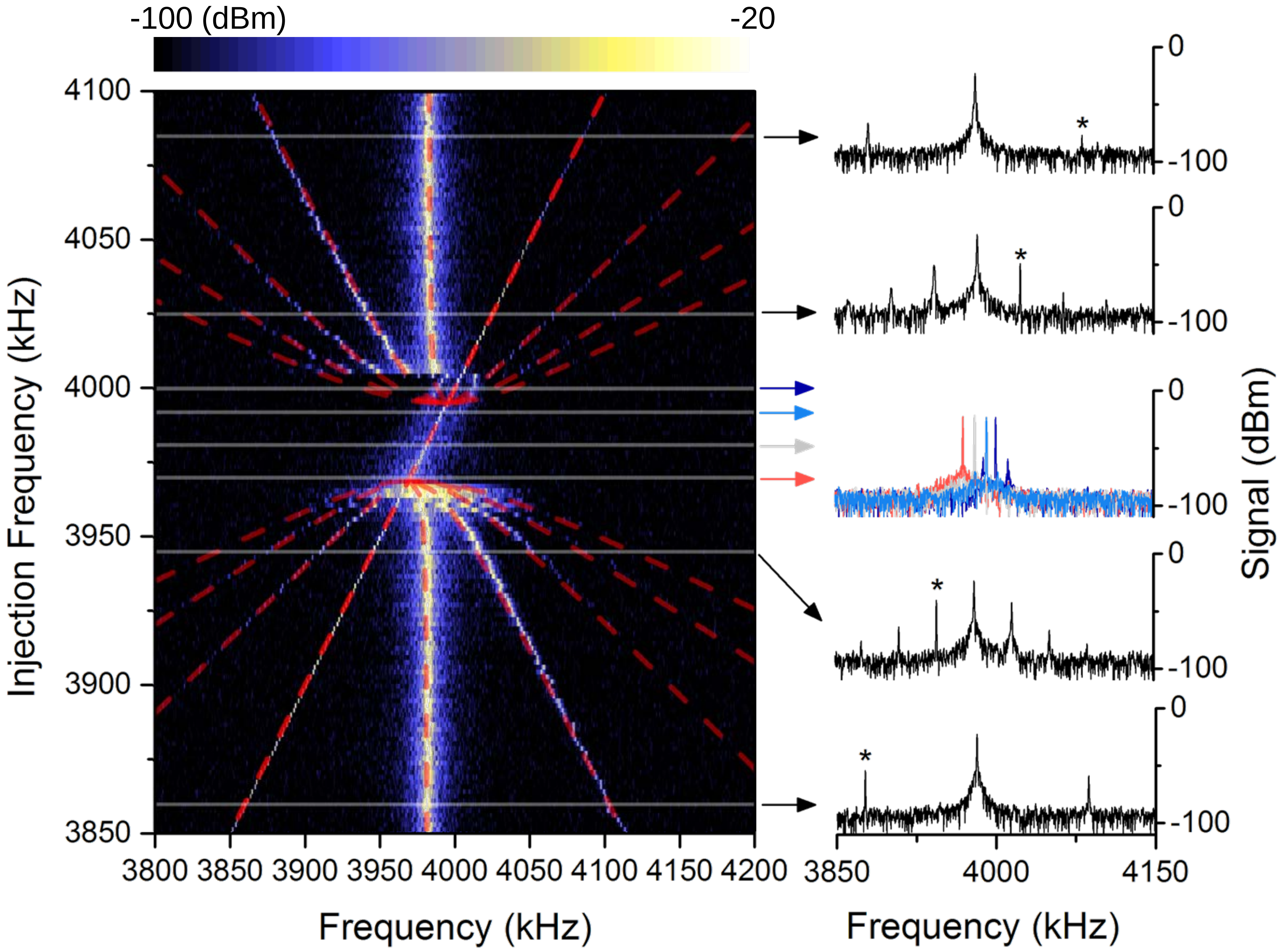
Oscillation injection-locked onto a weak stimulus



NIST Center for Nanoscale Science & Technology

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Nanoscale plasmonic NEMS

- New type of plasmomechanical platform
  - Arbitrary planar shape, small gap, vertical motion
- High-sensitivity, localized optical motion measurements
  - 40× > state of art
  - ~ 100 nm interrogation area
- Optomechanical coupling ≈ 2 THz·nm^{-1}
  - New regime of light-motion interaction enabled
- Electrostatic actuation for excitation and strong tuning
  - Toward dynamically tunable metasurfaces
- Nanomechanical oscillators driven by individual plasmonic particles
- Engineered modes and couplings:
  - Plasmonic, mechanical, thermal, electrical
- Injection locking of nanomechanical oscillator
  - Frequency readout of week periodic stimul

Acknowledgements

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NIST/Rutgers

Photonics

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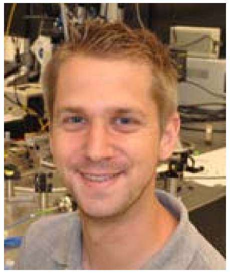
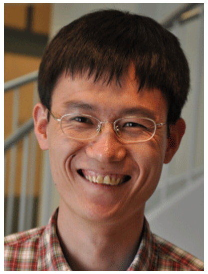
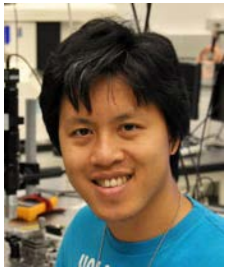


Thomas Michels



Houxun Miao



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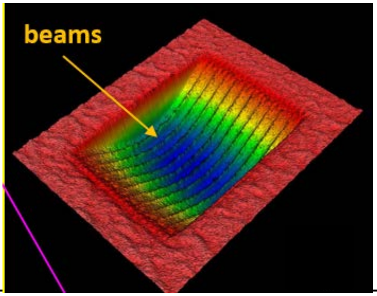
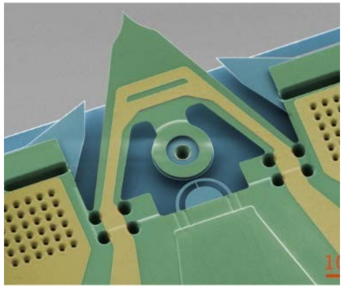
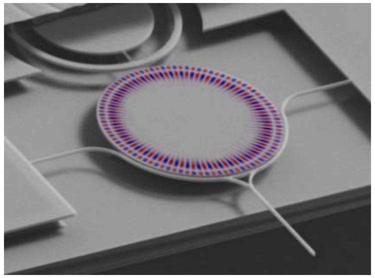
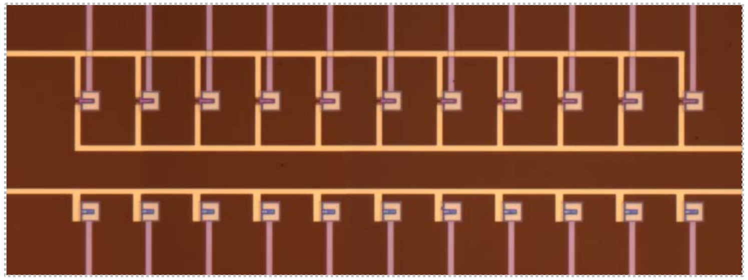


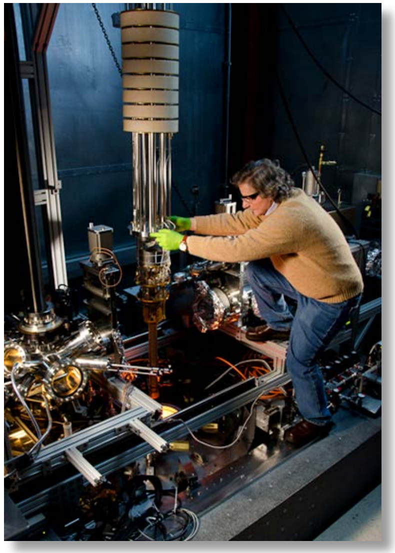






NIST Center for Nanoscale Science and Technology (CNST)

- NIST's nanotechnology user facility.
- Enables innovation: Rapid access for all to tools for making and measuring nanostructures, with a particular emphasis on industry.
- Access in two ways:
  - **NanoFab:** Commercial state-of-the-art tool set at economical hourly rates, along with help from our dedicated, full-time technical support staff.



  - **NanoLab**: Next generation of tools and processes through collaboration with research staff, who develop new measurement and fabrication methods in response to national nanotechnology needs.

Seeking collaboration opportunities
Postdoc positions are available