Silicon optomechanics

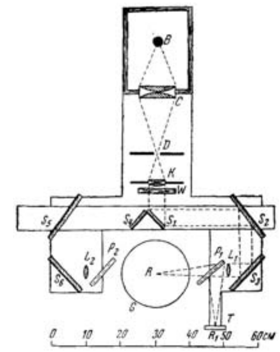
13th IEEE Photonics Society
Benelux Annual Workshop :
11/09/2009

Joris Roels, Dries Van Thourhout

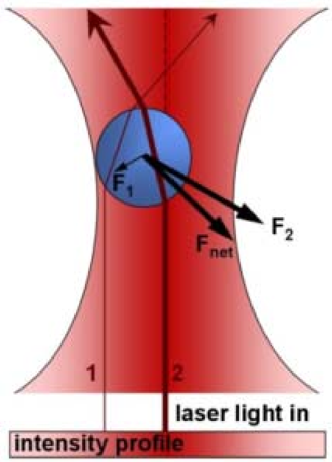
***Ghent University-IMEC, Dept. of information technology, Gent, Belgium**

Optomechanics: brief history

1871: theoretical prediction of 'radiation pressure' (James Clerck Maxwell)



1899: first experimental proof of tiny 'optical force' (Lebedev)



1986: optical trapping of polarizable microparticle (≈dipole), particle moves along field gradient towards region with highest intensity (beam waist)

Today: nanophotonic structures with shrinking device dimensions ⇒ enables relatively large forces

Exploitation of optical forces on a chip

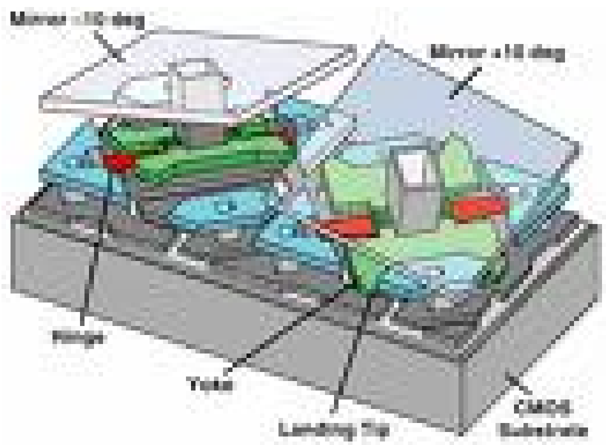
Optomechanics today

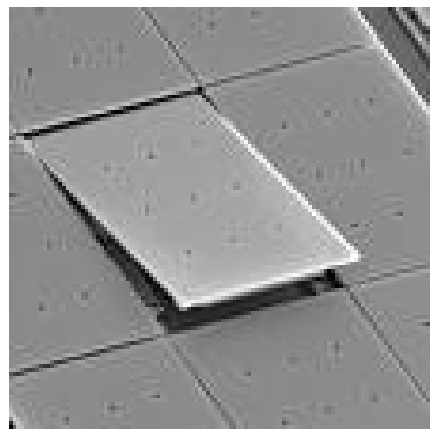
Possible applications:

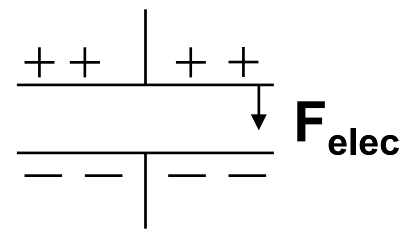
***optical cooling of micromechanical resonators (see further)**

***sensitive read-out of small displacement/vibration**

***light as ‘novel’ actuation force, from MEMS (Micro-Electro Mechanical Systems) to *NO*MS (*Nano-Opto* Mechanical Systems)**







***broad class of integrated optically tunable components possible**

…but first we need to understand the very basics

Outline

waveguide optomechanics

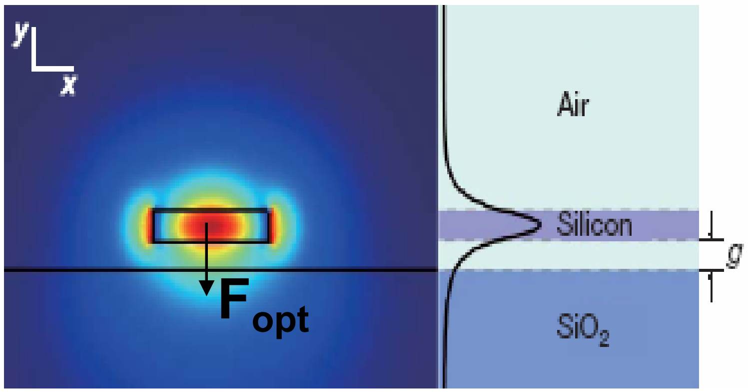
cavity optomechanics

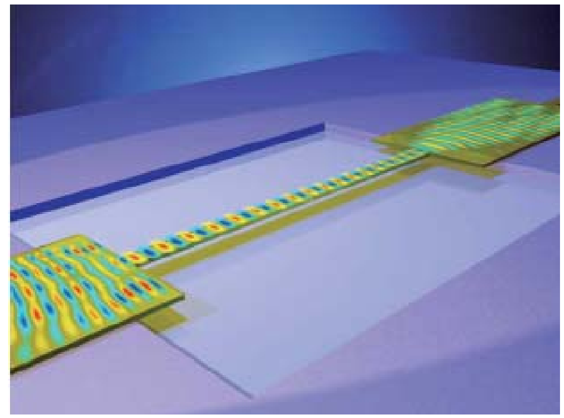
optical cooling

How to move a waveguide?

Physics similar to optical trapping: dipoles in field gradient

waveguide mode tries to increase its effective index





Experimental demonstration of *attractive* force between waveguide and substrate

Mo Li et al. , Harnessing optical forces, Nature (2008)

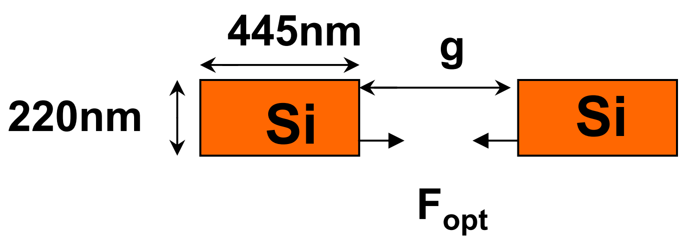
Waveguide-waveguide interaction (*repulsive* force?)

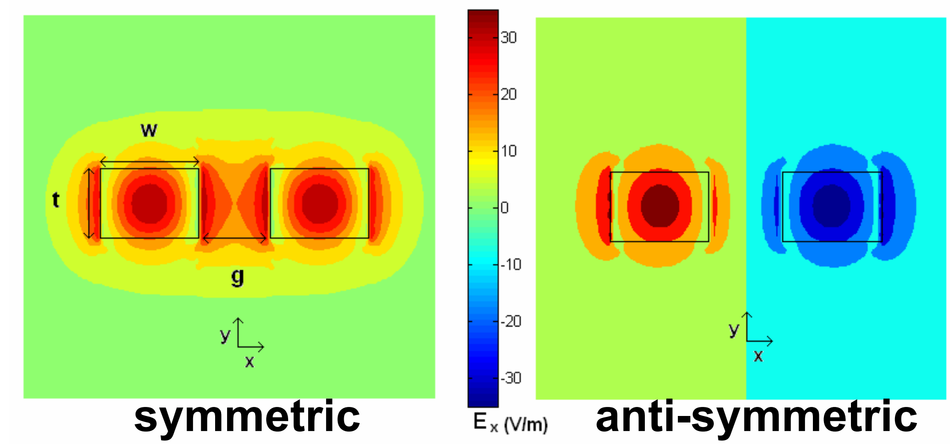
Povinelli et. al, Optics Express, (2005)

Theory

Two single mode Si nanophotonic waveguides in close proximity ⇒ bimodal: symmetric/anti-symmetric eigenmode

Light couples back-and-forth between waveguides





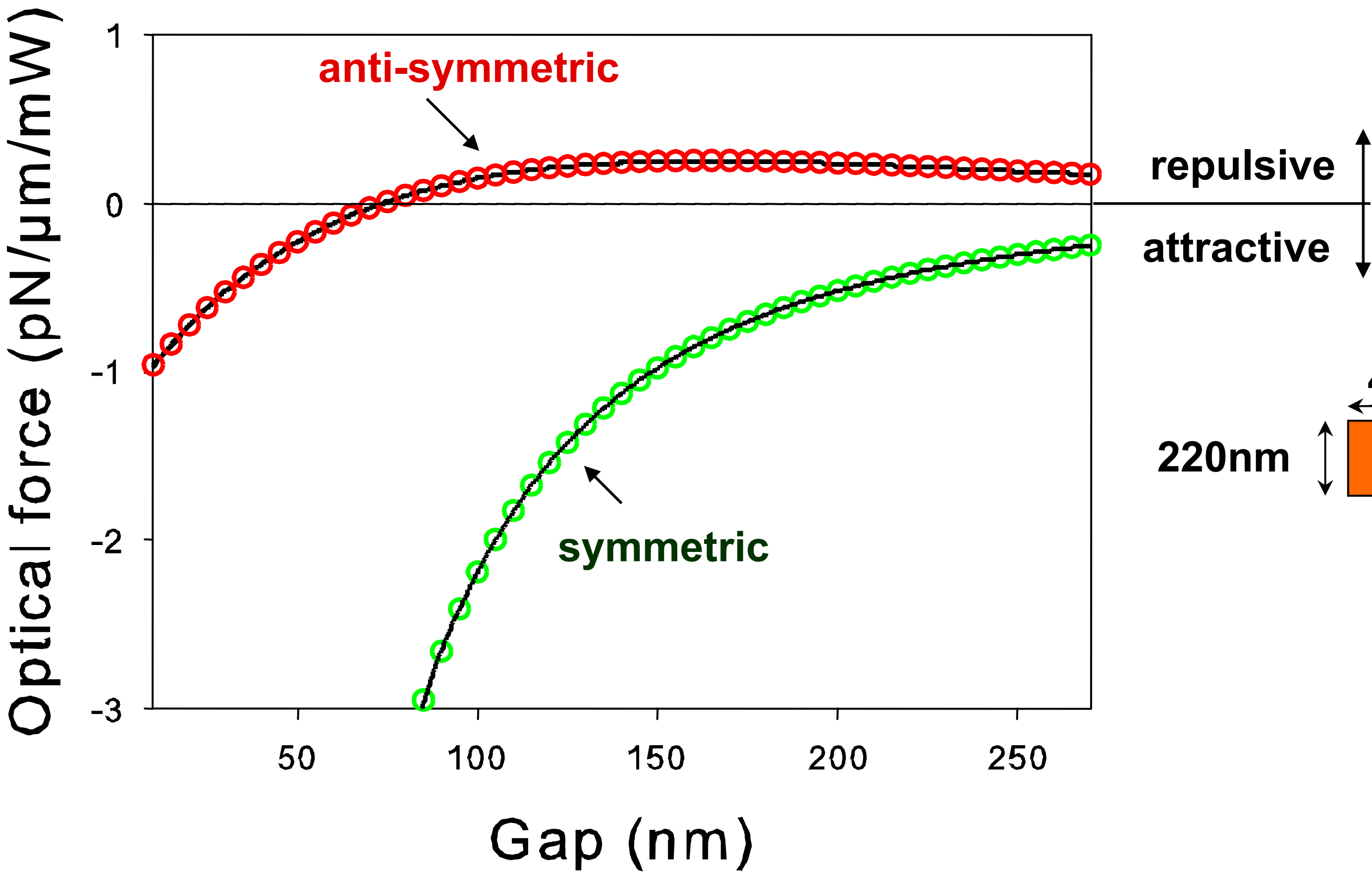
symmetric → **attractive force**

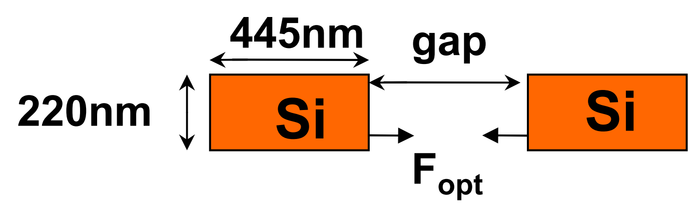
anti-symmetric → **repulsive force**

$$F_{opt} = \frac{\overset{\text{power}}{-P}}{c}\boxed{\frac{d\omega}{dg}}\,\frac{n_{group}^{\text{group index}}}{\underset{\text{eigenmode frequency}}{\omega}}\,\overset{\text{waveguide length}}{L}\Bigg|_{k}$$

symm vs. anti-symm mode: different (force) sign

Force simulation





@gap = 220nm

- $F_{symm,att} \approx$ -0.23pN/µm/mW
- $F_{antisymm,rep} \approx$ 0.1pN/µm/mW

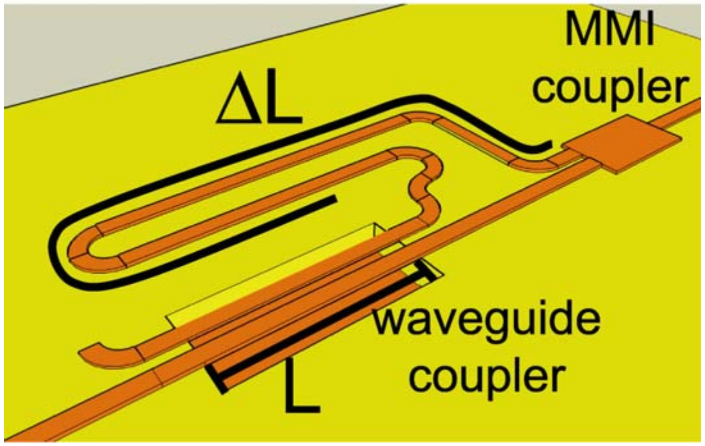
Superposition of 2 modes:

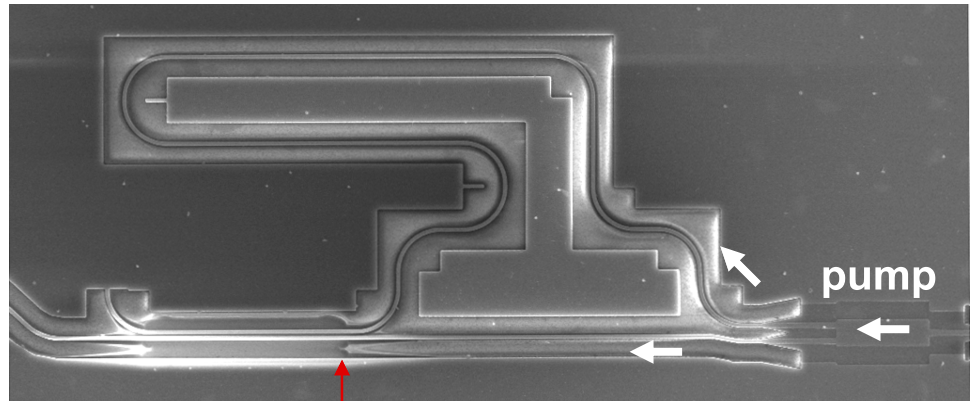
- Beating force up to 20% of the total force magnitude
- Beat period ≈ 120µm

controlling symm/anti-symm mode excitation = controlling force

Device

3-dB optical power splitter (MMI) + two waveguides (delay length $\Delta L \approx 113\mu m$) + freestanding waveguide coupler (length $L \approx 25\mu m$)

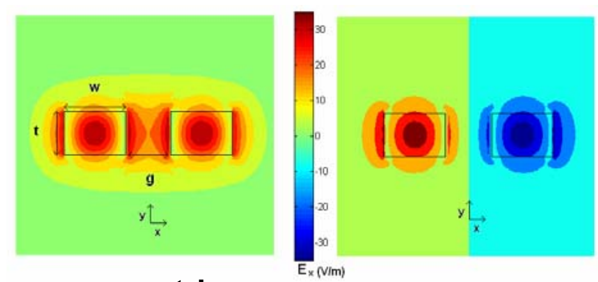




sweeping pump λ ⇒ fields arrive with different phase at waveguide coupler entrance

in phase fields favor symmetric (attractive) mode

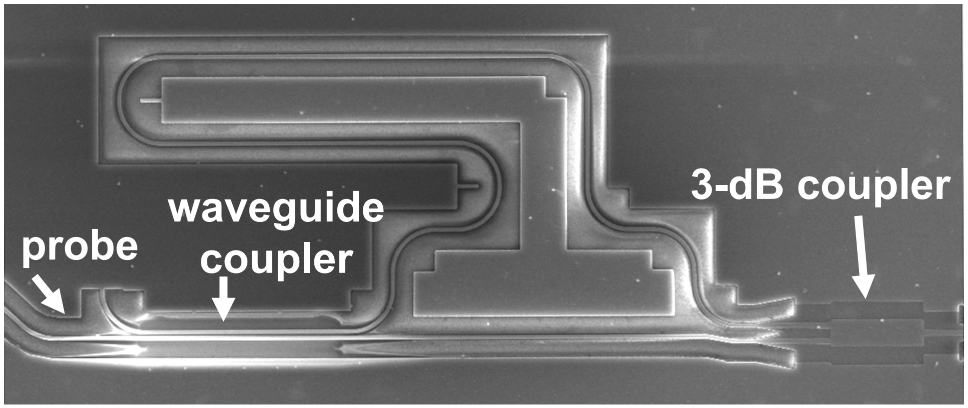
counter phase fields favor anti-symmetric (repulsive) mode



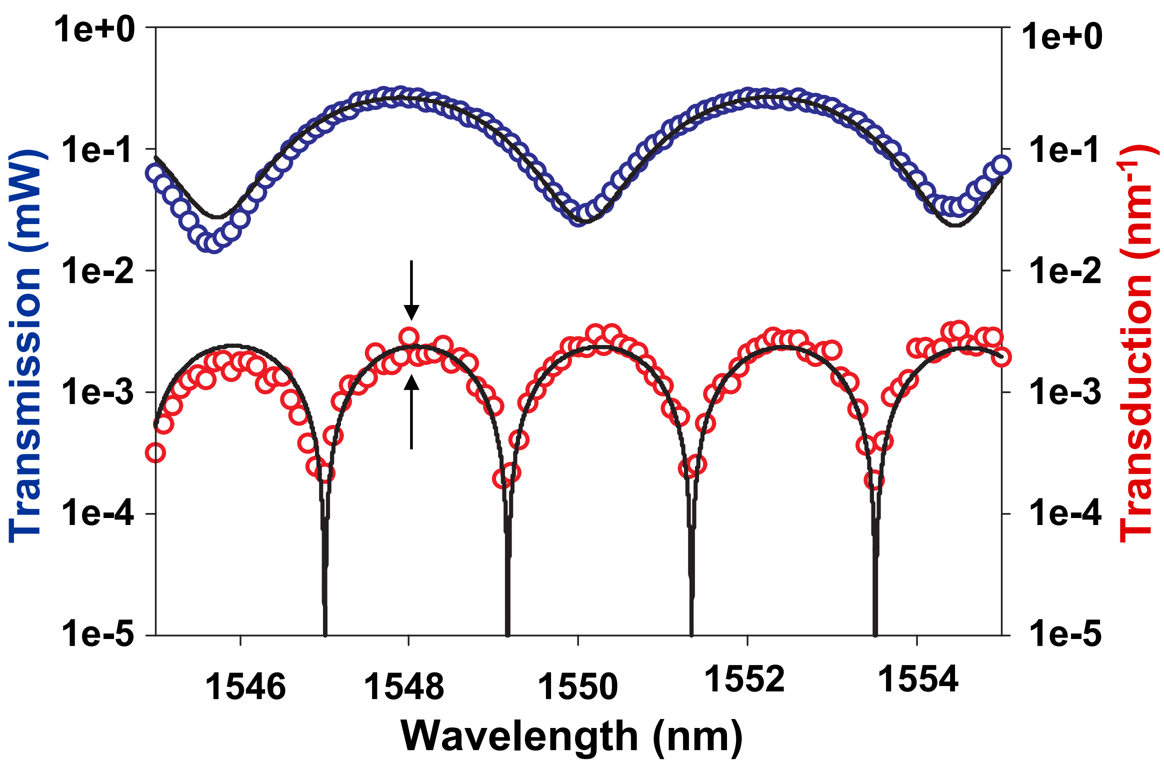
symmetric **anti-symmetric**

sweeping wavelength enables tuning: attractive ↔ repulsive

Transduction scheme



full device = unbalanced Mach-Zehnder Interferometer (delay length ΔL) with one MMI coupler and one waveguide coupler



waveguide displacement Δg

↓

coupling Δκ

↓

Transmission ΔT

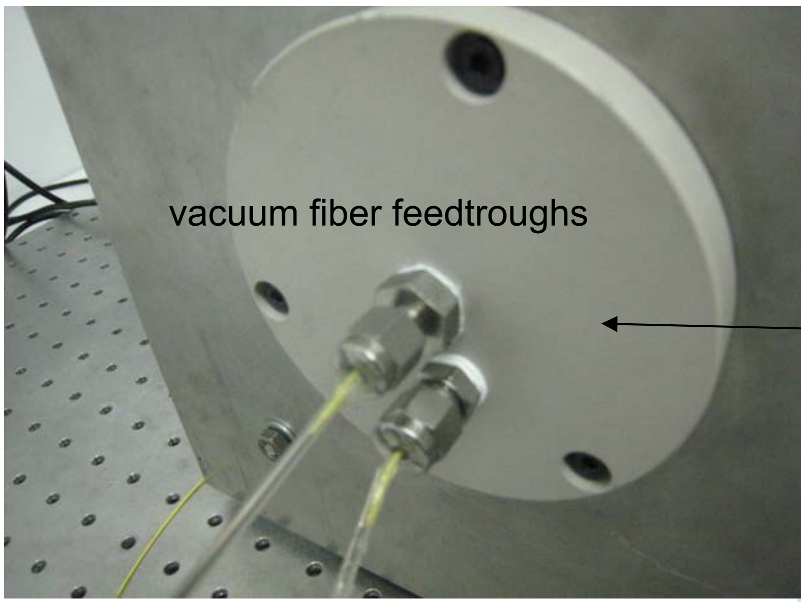
Probe laser @1548nm

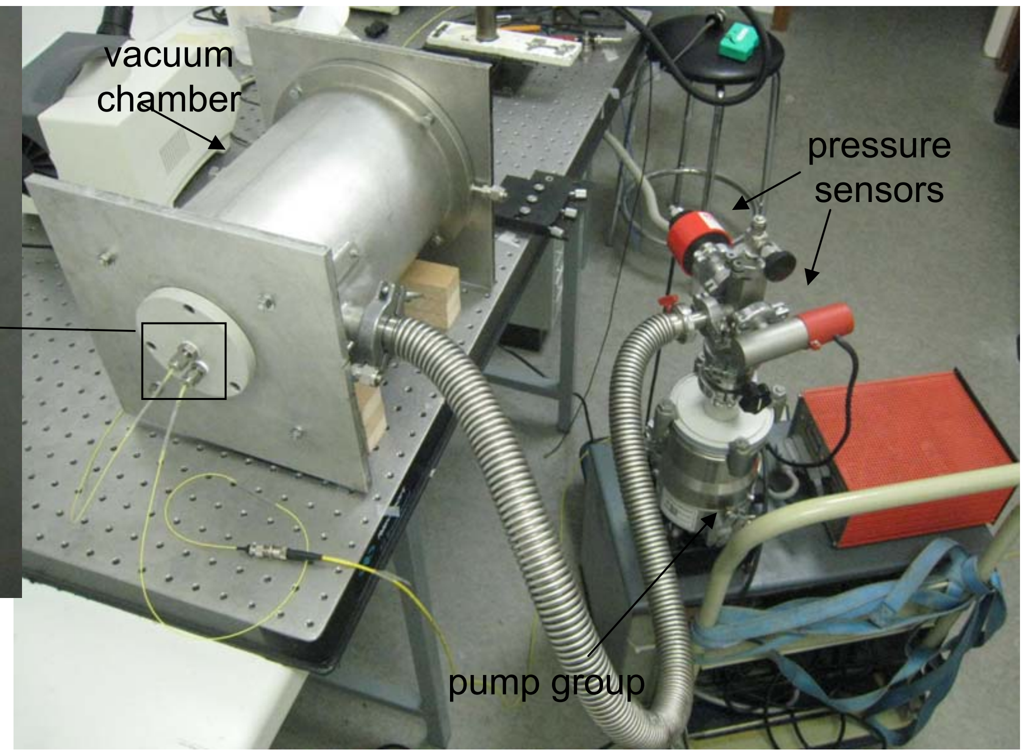
Calibration

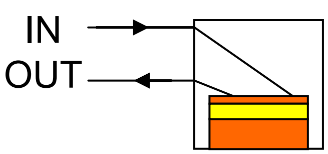
Calibration: *thermal* forces (can be calculated with known params e.g. T, oscillator mass)

both optical and thermal forces are very small (≈fN-pN): mechanical resonator ⇒ vibration amplitude x Q_{mech} for given AC-force

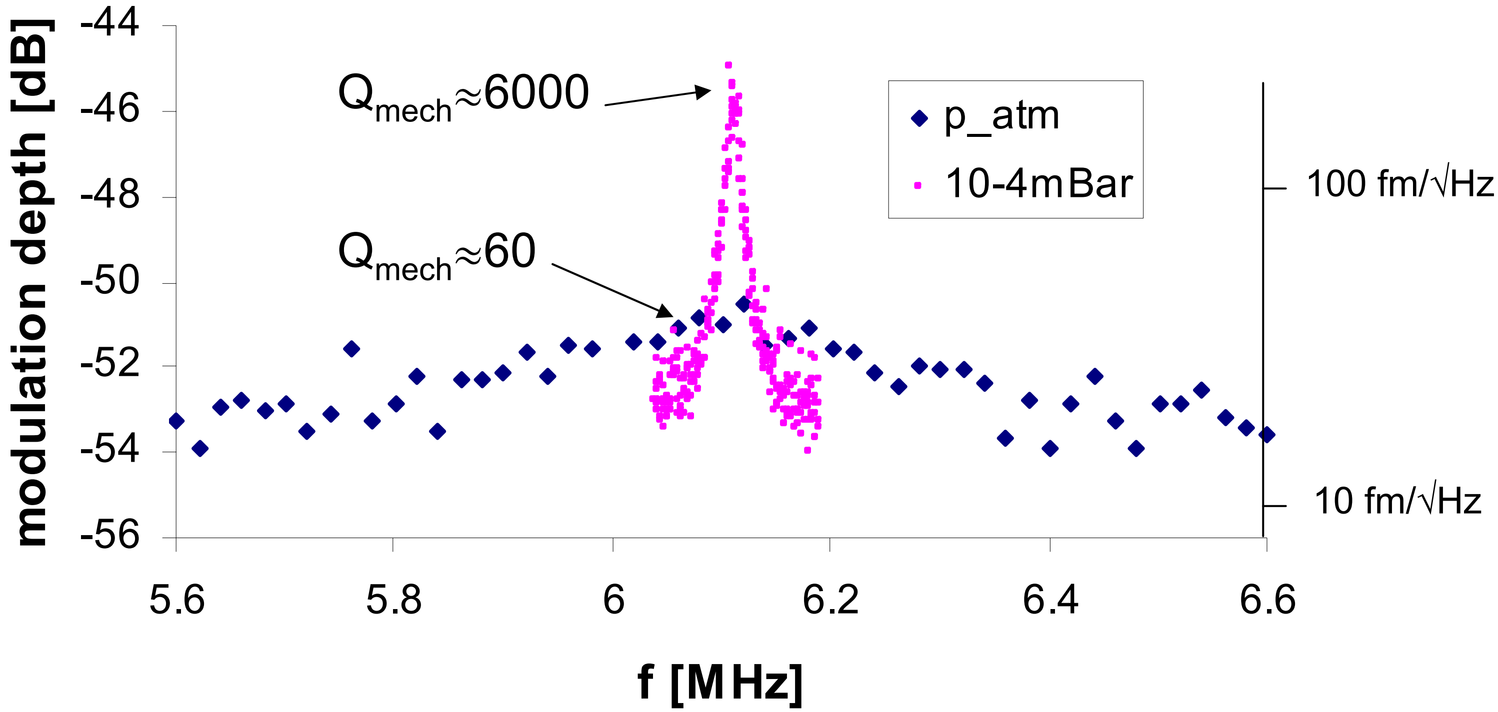
main damping factor: air ⇒ vacuum conditions: $Q_{mech}\uparrow$







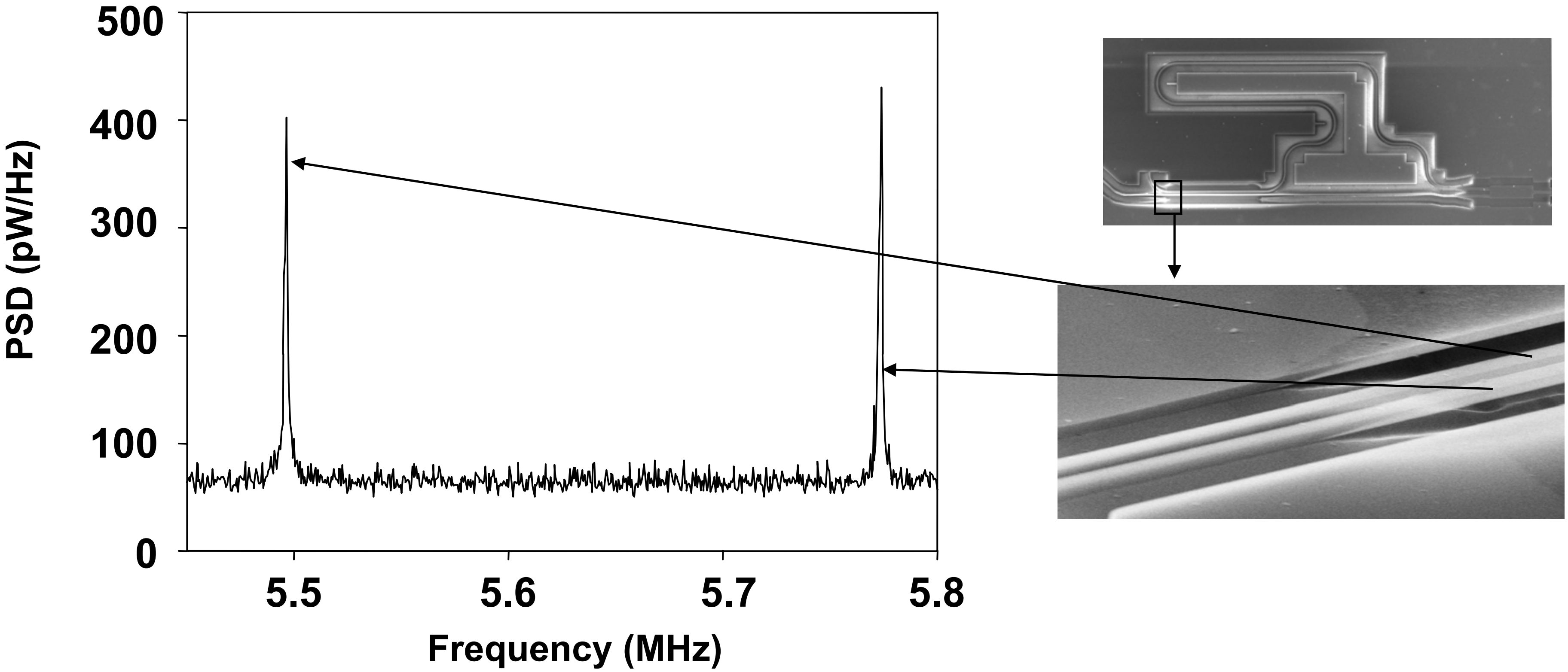
Mechanical Q



vacuum conditions boost up Q_{mech} x100

max expected optically induced displacement (Hooke's law):
Q_{mech} x F/k ≈ nm

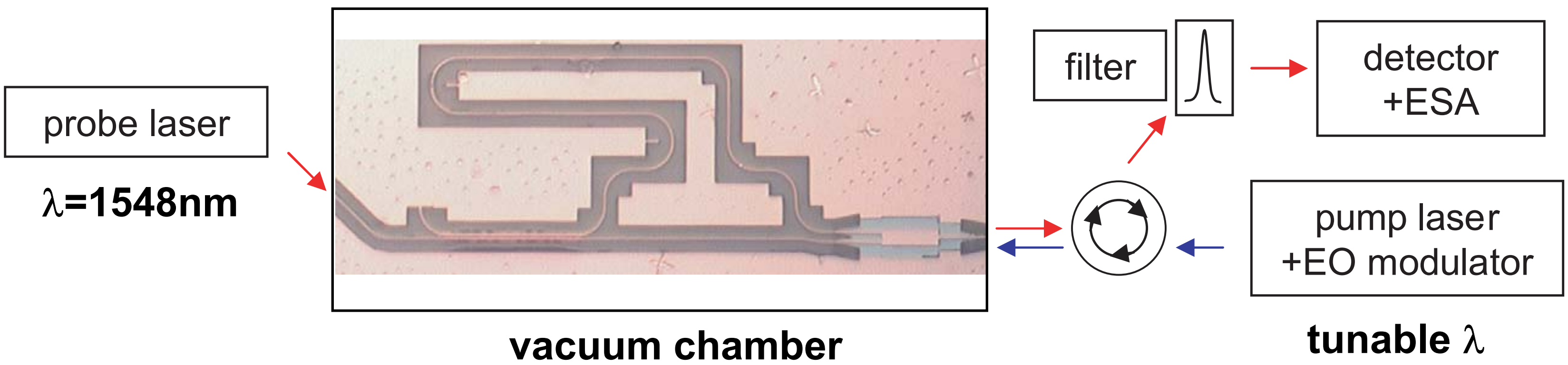
Calibration (2)



Transduction (without pump) is measured/calibrated by recording thermal vibration noise (peak spectral density PSD)

Two peaks = two suspended waveguides

Pump probe set-up

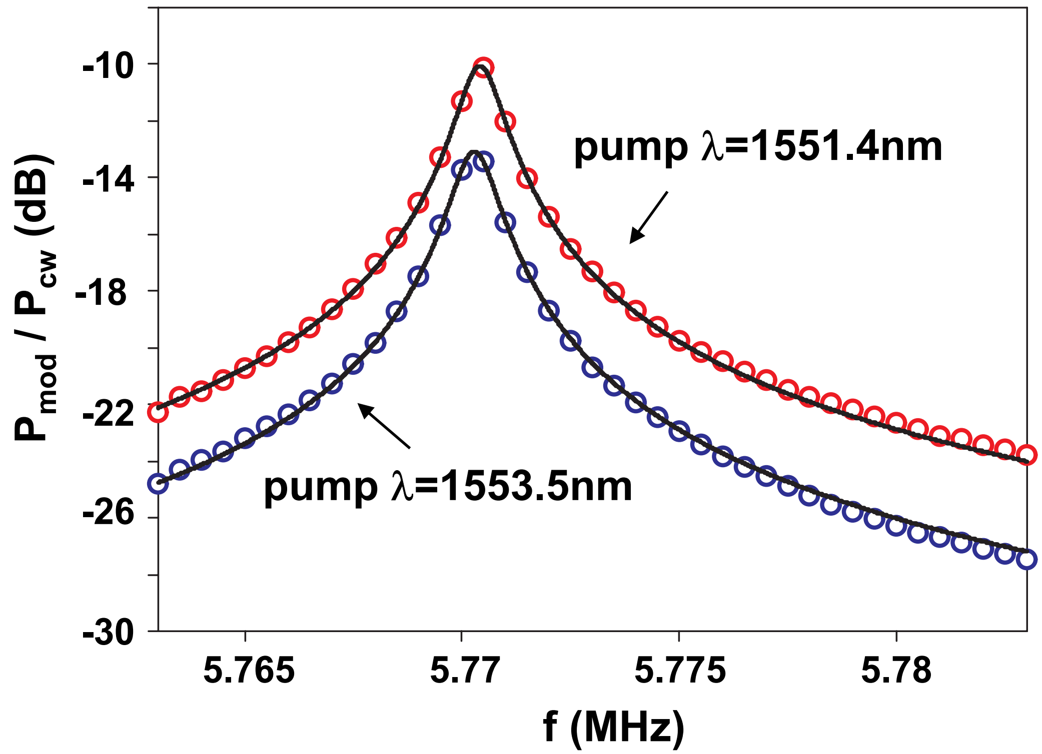


probe laser light is detected and analyzed with electrical spectrum analyzer

pump laser light is modulated with electro-optical modulator and injected simultaneously (circulator)

sweeping modulation frequency enables to record driven displacement spectra for different pump λ

Displacement spectra



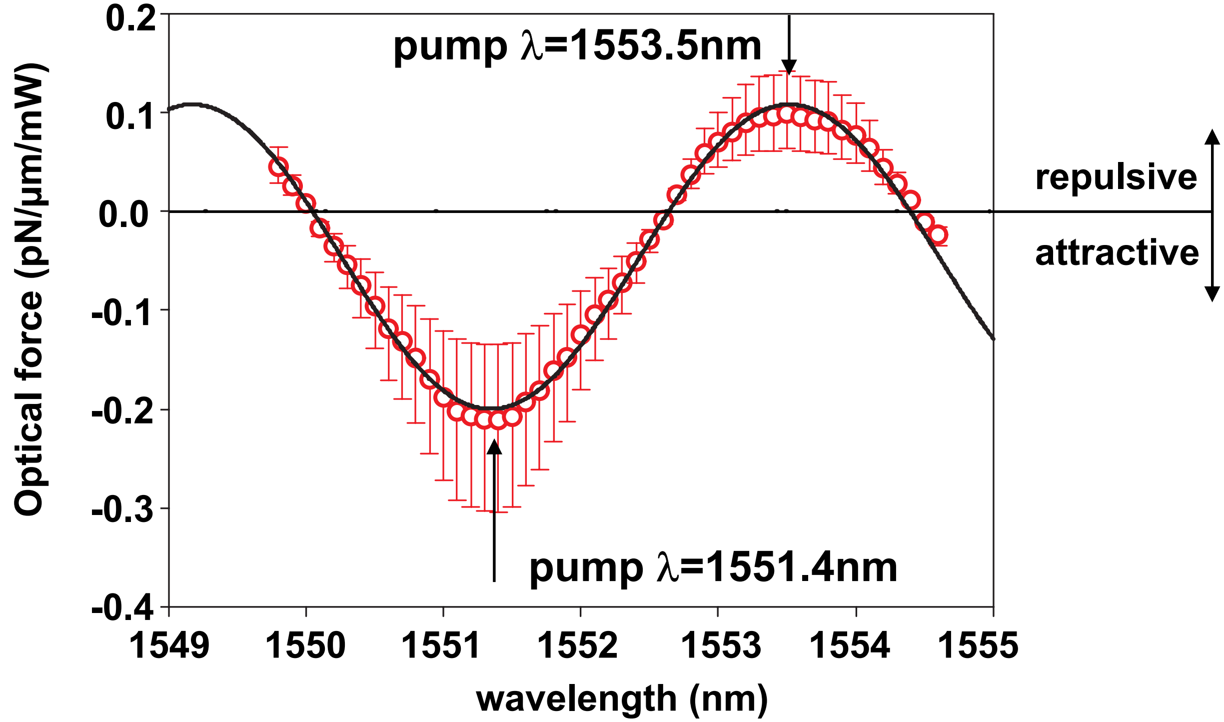
red circles for λ=1551.4 (attractive), blue circles for λ=1554nm (repulsive)

@gap = 220nm

- **$F_{symm,att} \approx$ -0.23pN/μm/mW**
- **$F_{antisymm,rep} \approx$ 0.1pN/μm/mW**

curves are phase-shifted 180°

Optical force



Excellent agreement theory vs. experiment

- **$F_{symm,att} \approx$ -0.2pN/µm/mW**
- **$F_{antisymm,rep} \approx$ 0.1pN/µm/mW**

Error bars originate from uncertainty on exact power level in device

Experimental demonstration: attractive vs. repulsive force

J. Roels et al., Tunable optical forces between nanophotonic waveguides, Nat. Nanotechnology (2009)

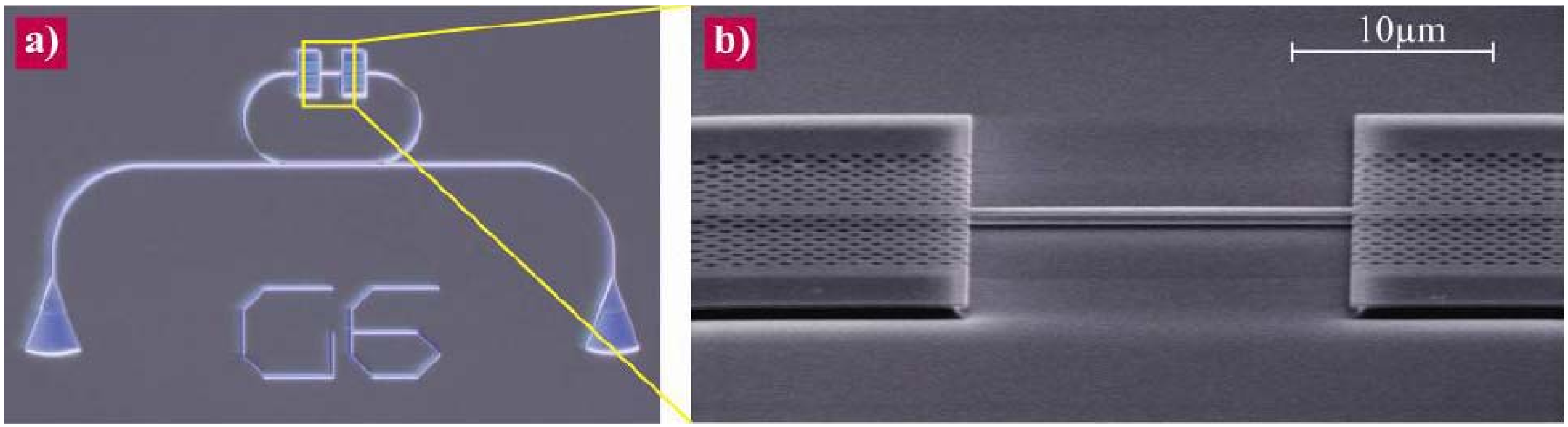
Outline

waveguide optomechanics

cavity optomechanics

optical cooling

Cavity optomechanics



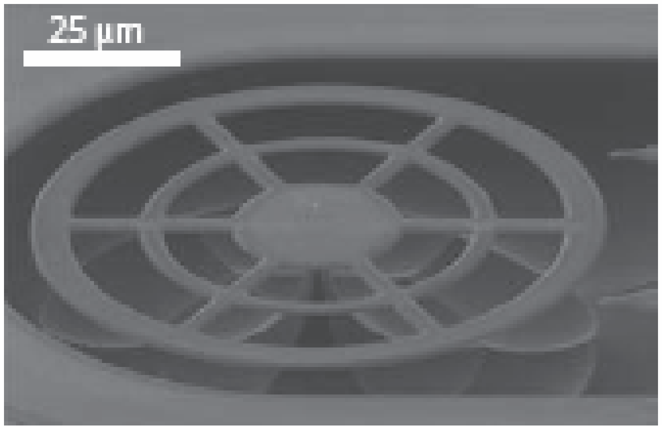
Mo Li et al., Optomechanical coupling in photonic crystal supported nanomechanical waveguides, Opt. Express (2009)

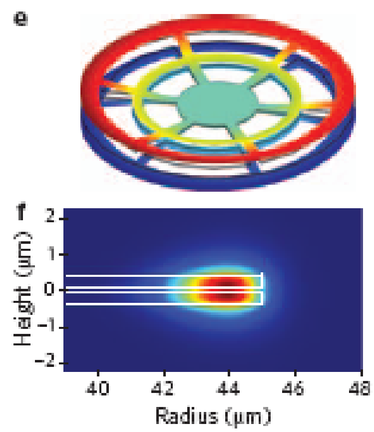
power enhancement

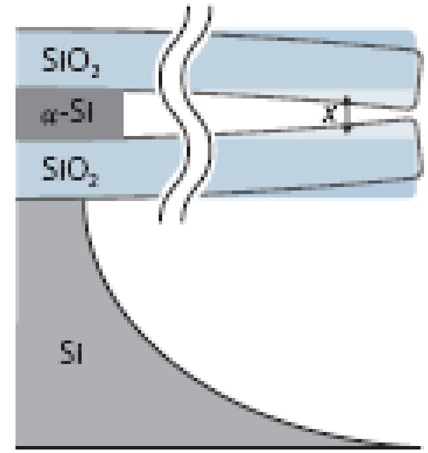
larger force per photon $F_{opt} \sim d\omega_{cav}/dx$

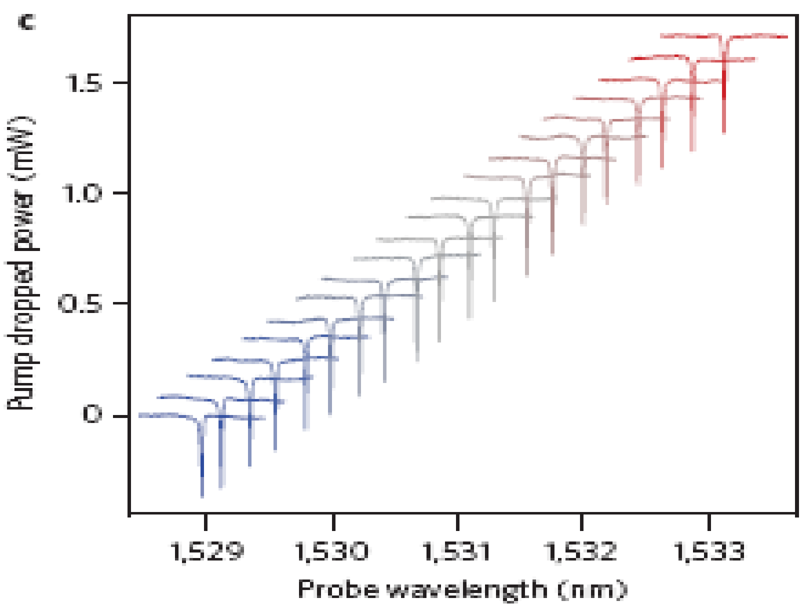
optomechanically tunable filters

Coupled resonators









2 vertically stacked ring resonators (spider web)

filter tuning over 4nm range

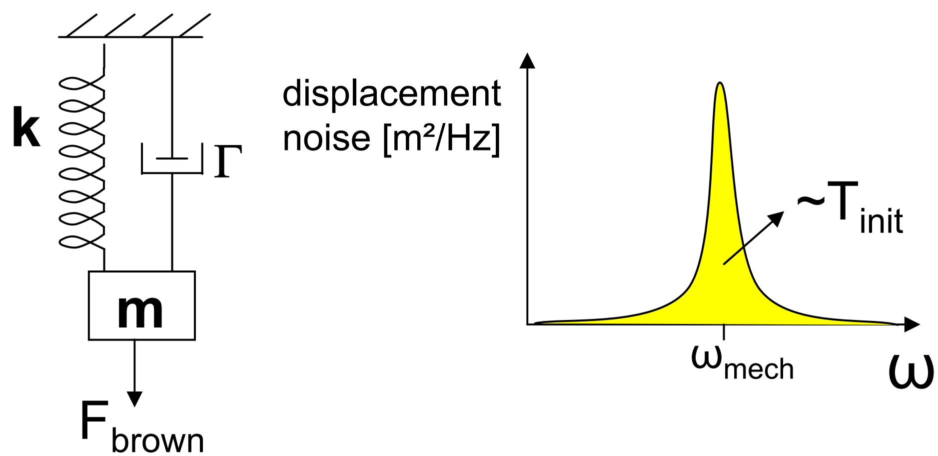
Rosenberg et al., Static and dyamic wavelength routing via the optical force, Nature Photonics, (2009)

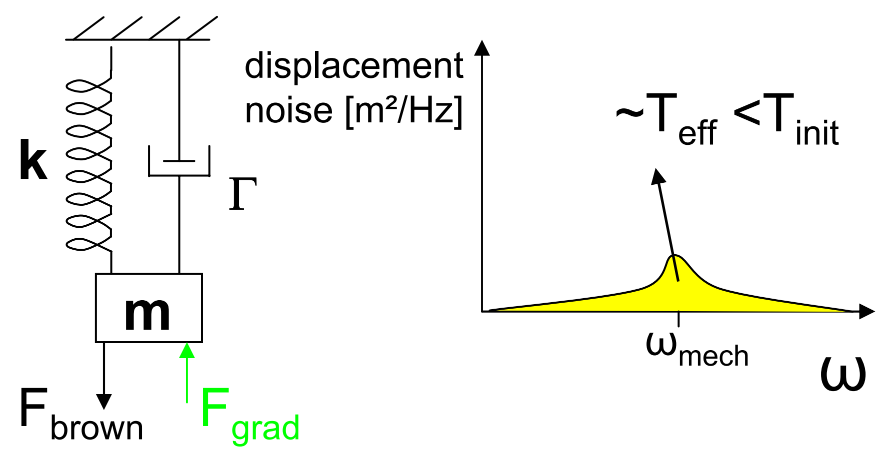
Mechanical resonator optical cooling

vibrating atoms cause force $F_{brown} \sim \sqrt{T} \Rightarrow$

***thermal* motion at resonance frequency ω_{mech}**

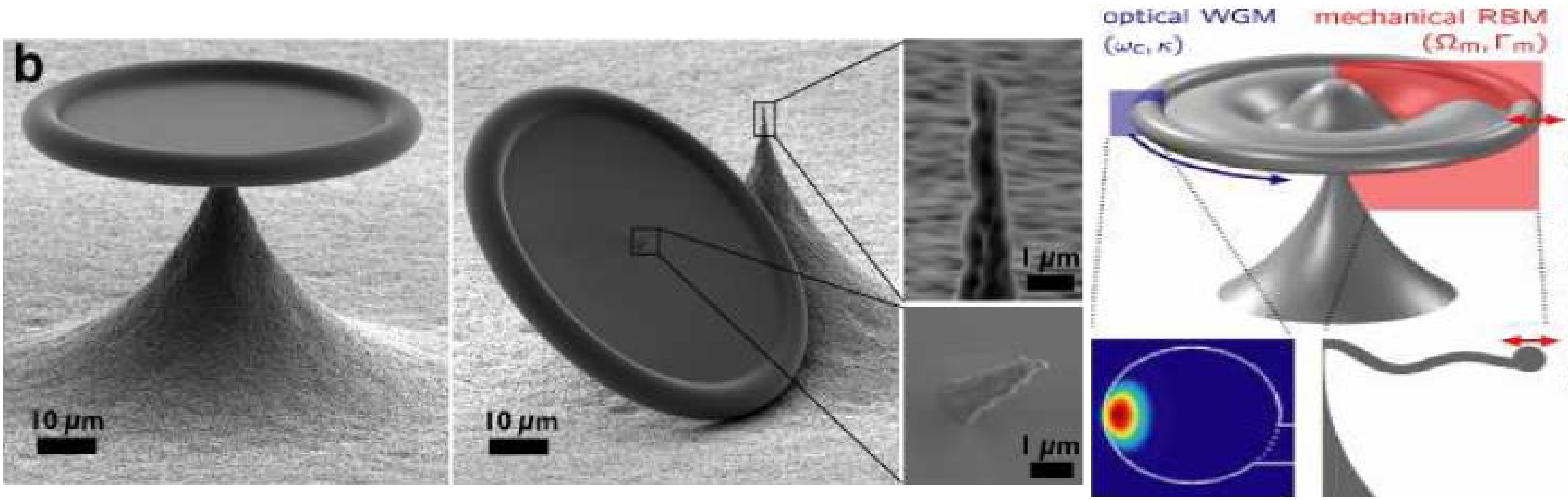
photon life time cavity ≈ mechanical period (high optical Q!) ⇒ optical force F_{grad} creates drag force





optical cooling = reducing thermal vibration

Cavity cooling (1)



Schliesser, Kippenberg et. al, Nature Physics, 4, 415-419 (2008)

microtoroids on tiny pillar

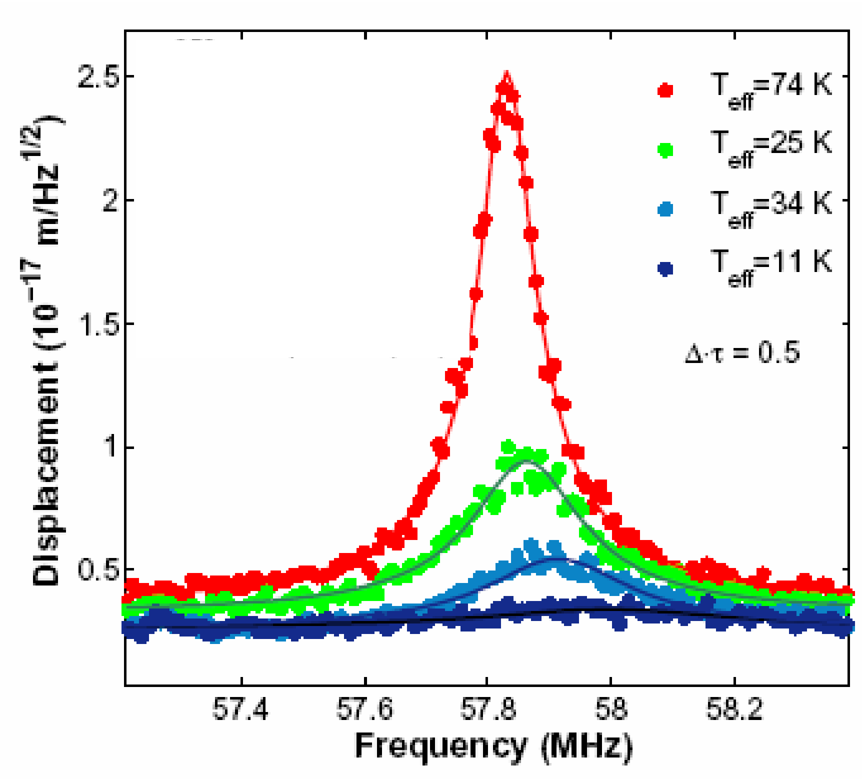
radial mechanical modes

$Q_{opt} \approx 10^8$, finesse > 10^5

$Q_{mech} \approx 10^5$

having both high mechanical and optical Q is very challenging!

Cavity cooling (2)



Implications:

-fundamental (quantum mechanics in microscale objects!)

-ultrasensitive displacement sensing

-quantum computing/cryptography

-on chip photonic clocks

Conclusions & perspectives

Recent advances have enabled exploitation of optical forces on chip

Optically tunable components/ optical cooling

Immature research field, much more work needs to be done towards practical applications.