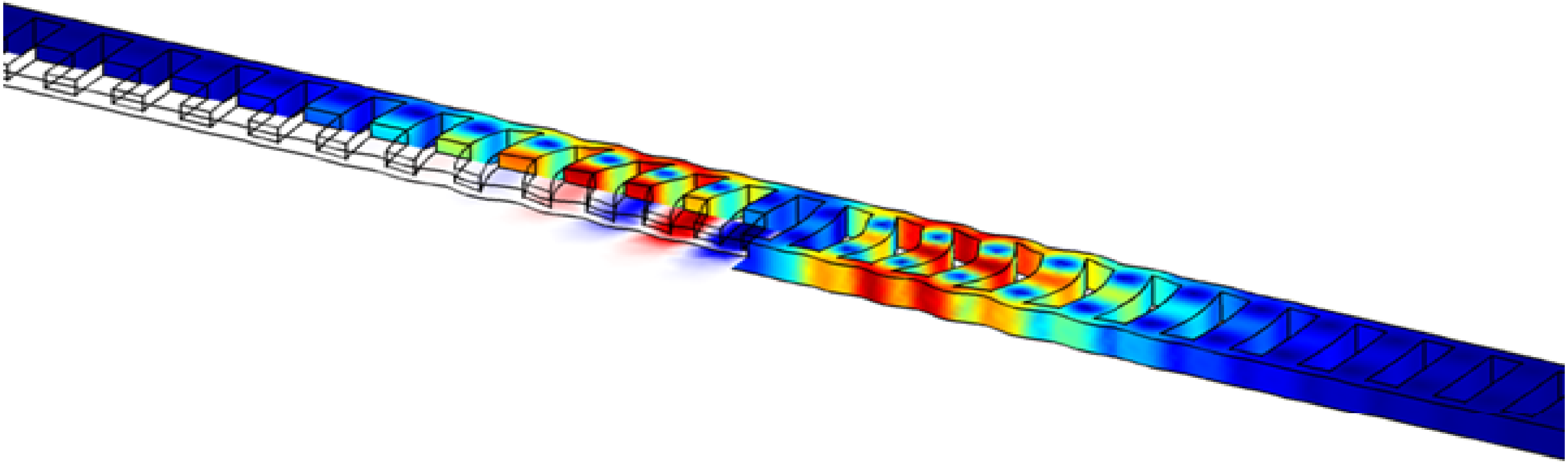
Nano-opto-mechanics: utilizing light forces within guided-wave nanostructures



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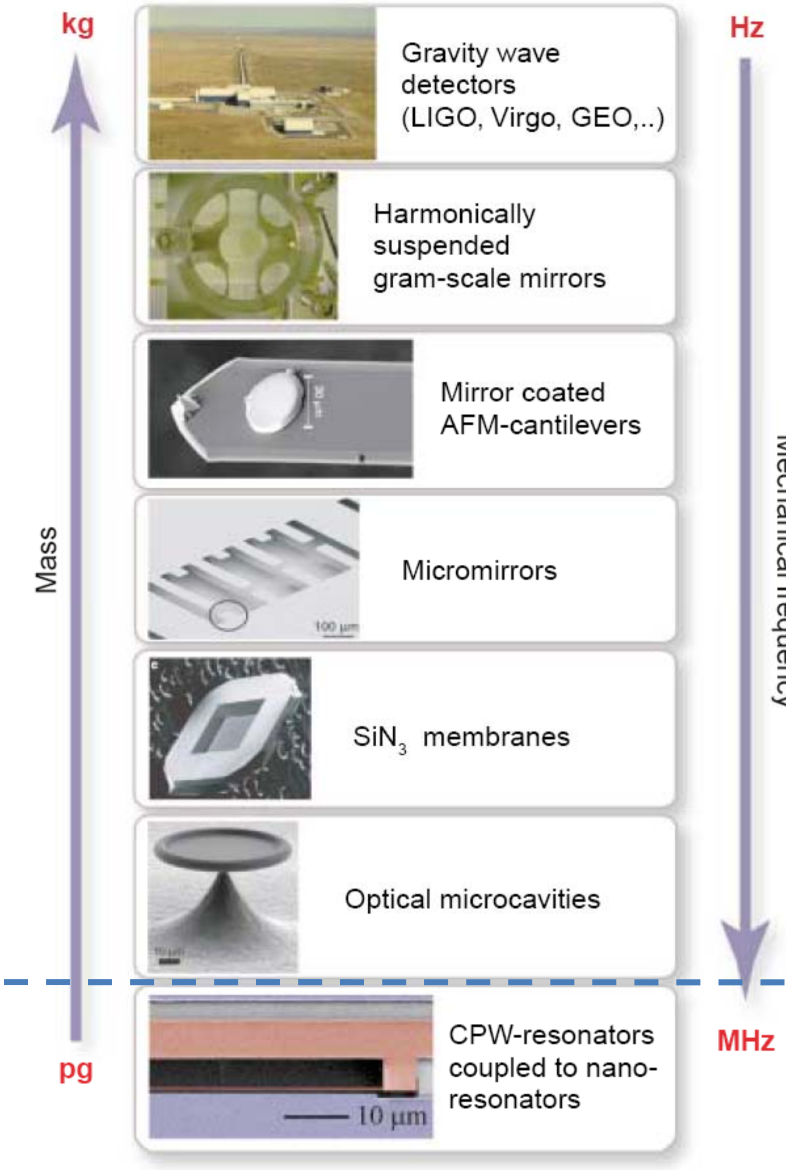
1/25/2010

Outline

- Brief introduction to various forms of optical forces and cavity-optomechanics
- "Zipper" photonic crystal optomechanical cavity
- Various applications of nano-optomechanical systems

cavity-optomechanics: scale and geometry



Gravity wave detectors (LIGO, Virgo, GEO,..)

Harmonically suspended gram-scale mirrors

Mirror coated AFM-cantilevers

Micromirrors

SiN_3 membranes

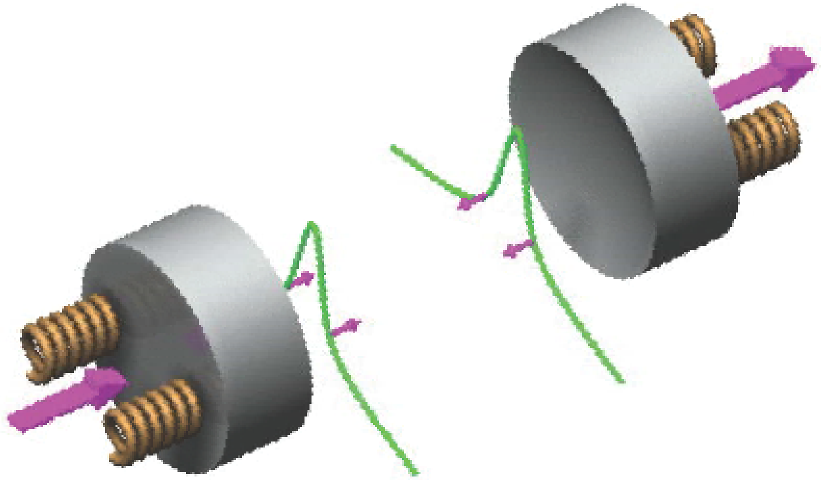
Optical microcavities

CPW-resonators coupled to nano-resonators

diffraction limit

Cavity Optomechanics: Back-Action at the Mesoscale
T. J. Kippenberg, *et al.*
Science **321**, 1172 (2008);
DOI: 10.1126/science.1156032

canonical "mirror on a spring" system



Optical NEMS?
- (sub)-picogram mass
- GHz frequencies

cavity-optomechanics: a review

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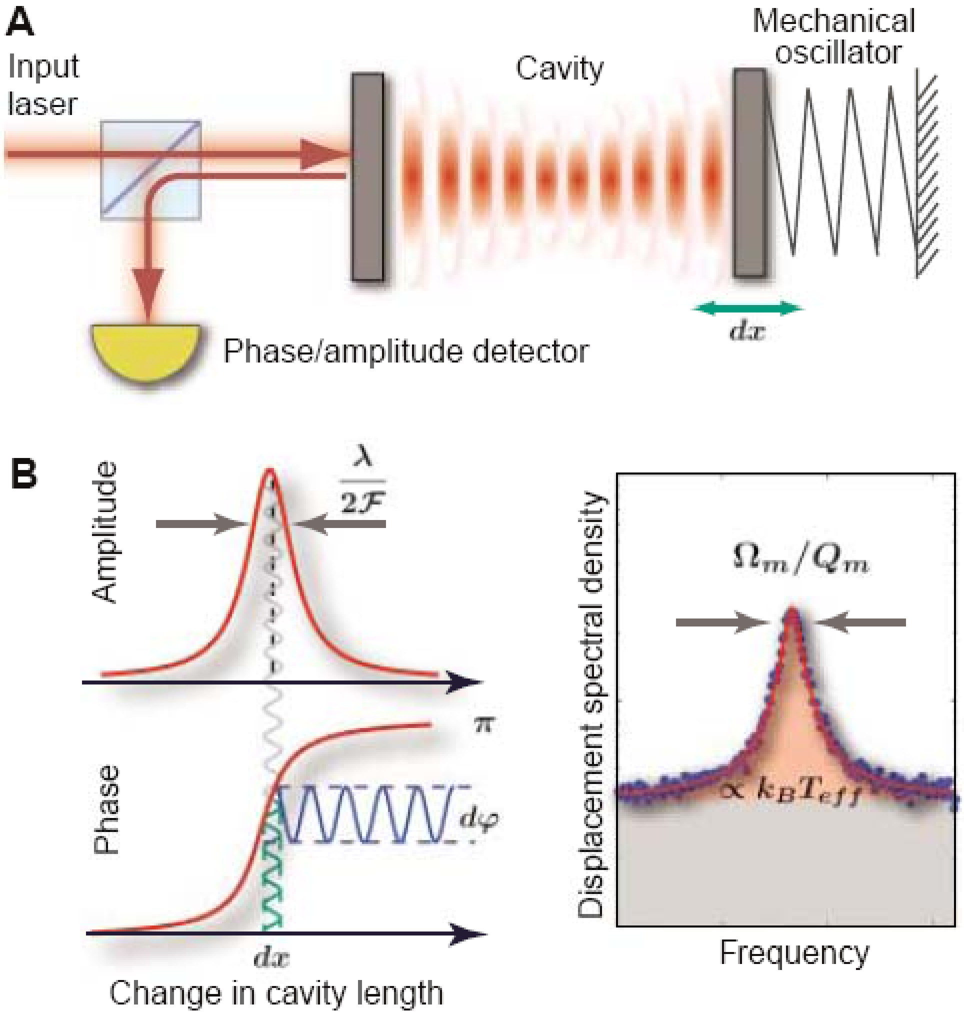
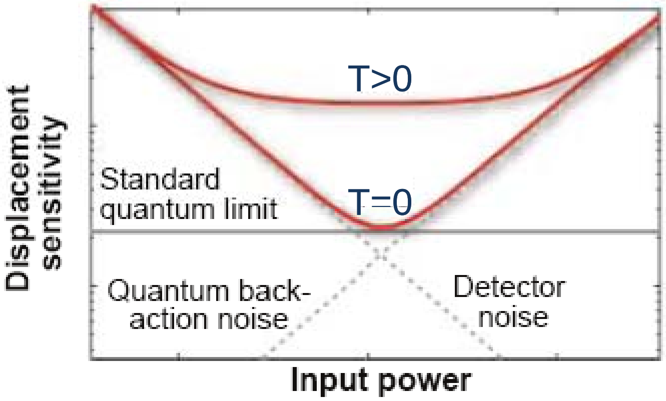
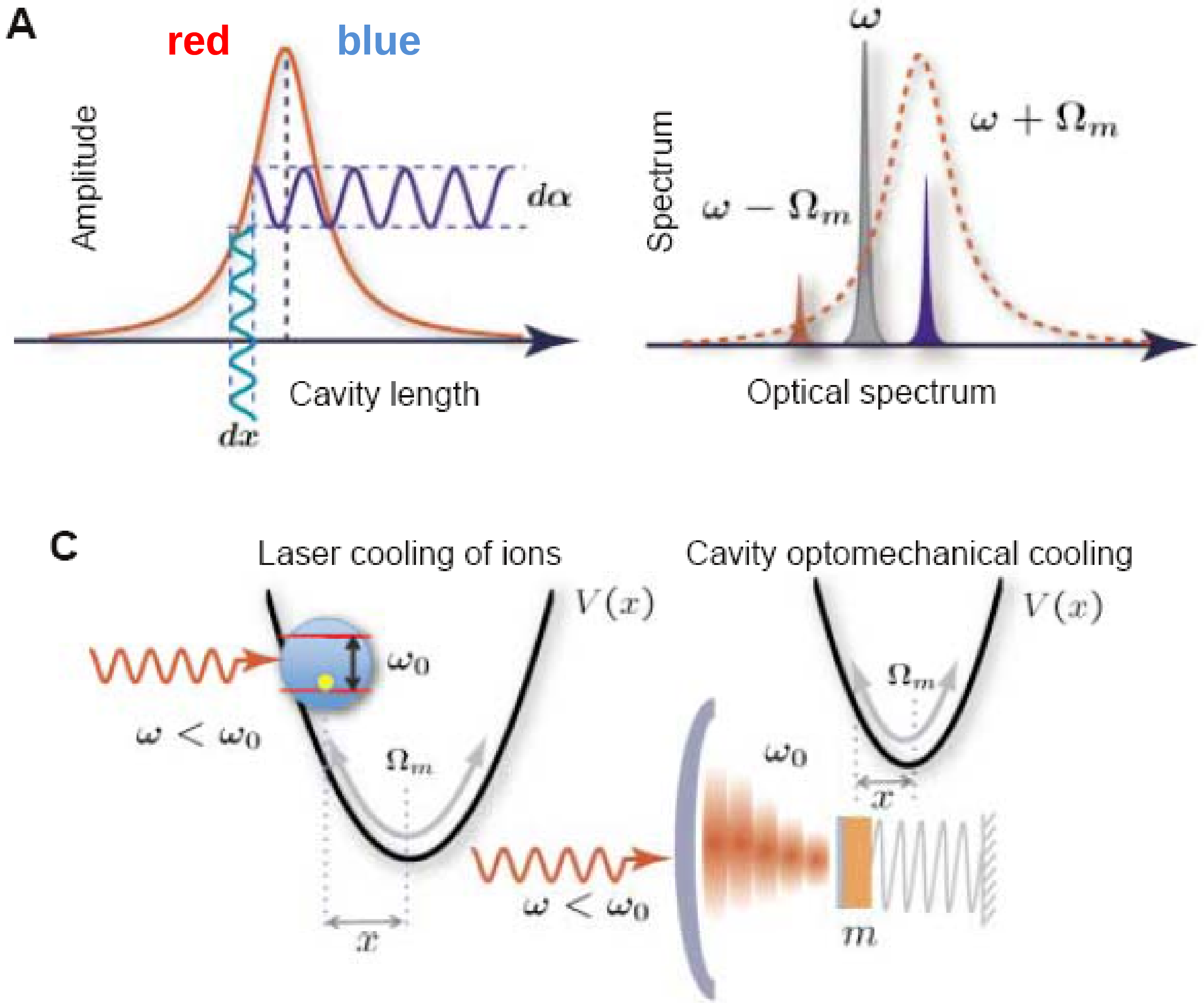




optical spring and damping



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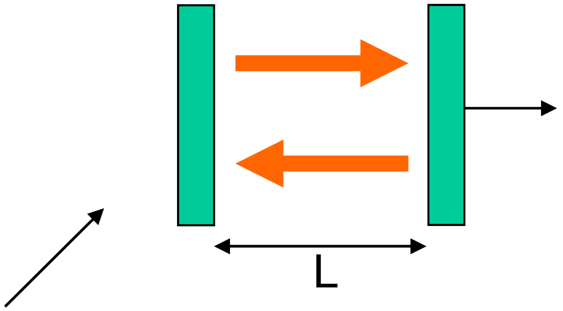
Radiation Pressure in Microcavities

Cavity to enhance the optical force:



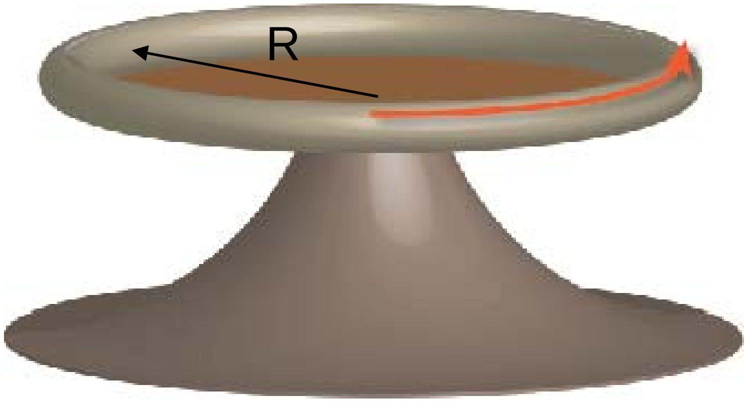
$$F = \frac{2P_d}{c}\frac{\tau_0}{T_r} = Nf$$

τ_0	Cavity photon lifetime
T_r	Round-trip time
P_d	Dropped optical power
N	Photon number
f	Per-photon force

$$f = \frac{2\hbar k}{T_r} = \hbar\frac{\omega_0}{L}$$

Per-photon force

$$f = \frac{2\pi\hbar k}{T_r} = \hbar\frac{\omega_0}{R}$$



High-Q microtoroid

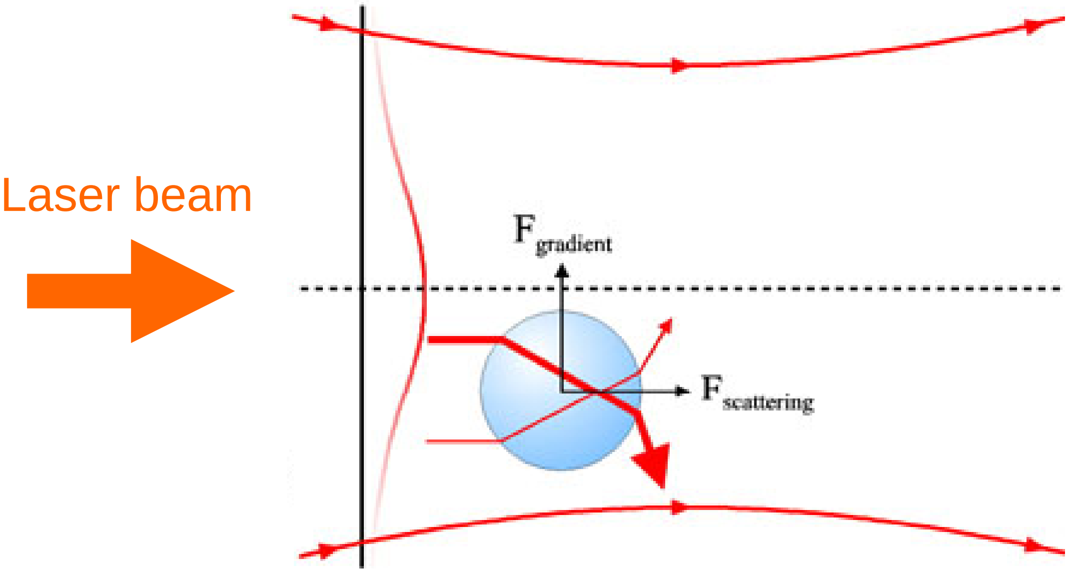
Per-photon force: scales inversely with cavity length.

T. J. Kippenberg & K. J. Vahala, Opt. Express **15**, 17172 (2007).
T. J. Kippenberg & K. J. Vahala, Science **321**, 1172 (2008).
I. Favero & K. Karrai, Nat. Photon. **3**, 201 (2009).

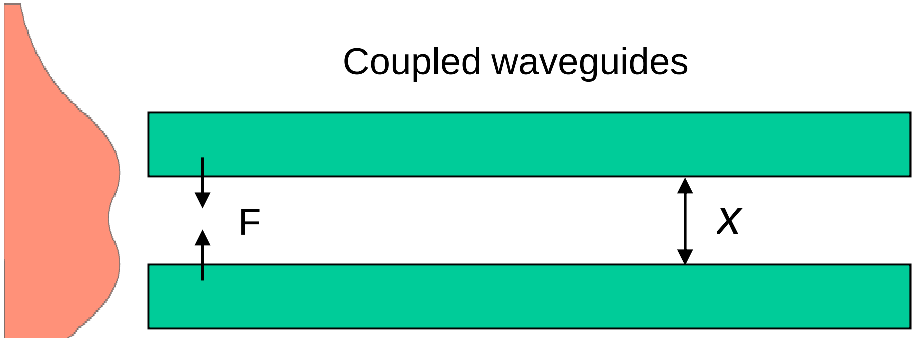
Optical Force: Gradient Force

$$F \propto \nabla \left| E \right|^2$$

Laser beam



Coupled waveguides



Optical self-tweezing

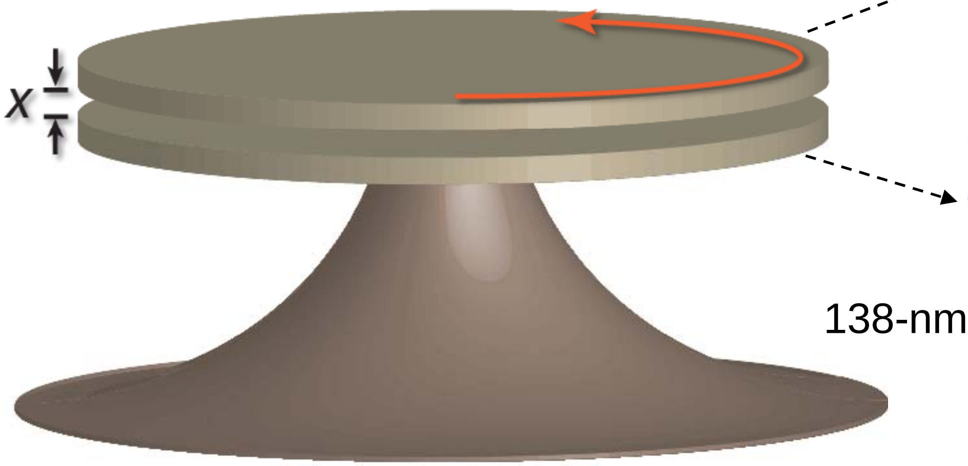
$$F \propto e^{-\alpha x}$$

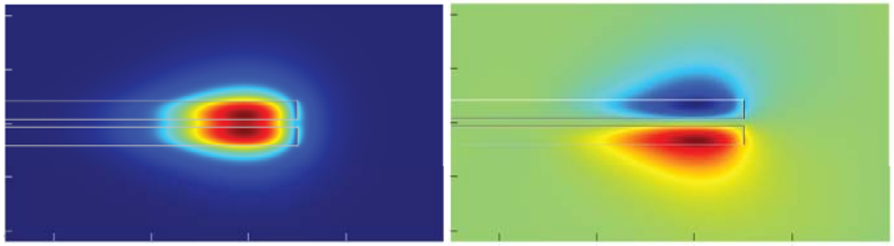
Independent of waveguide length.

A. Ashkin, IEEE JSTQE **6**, 841 (2000).
M. L. Povinelli, *et al*, Opt. Lett. **30**, 3042 (2005).

Gradient Force in Double-Disk

Bend the coupled-waveguide into a double-disk





Bonding (attractive) Anti-bonding (repulsive)

138-nm gap ⇒ 1520nm 1297nm

Substantial resonance splitting by 34 THz!

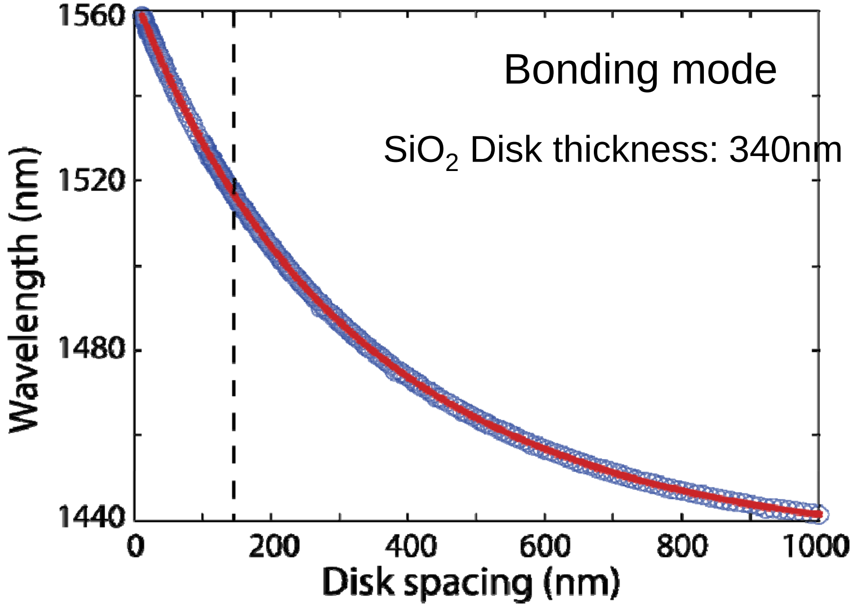
A nano-optomechanical system (NOMS)

Per-photon force: energy perspective

$$f = -\frac{d\left(\hbar\omega_0\right)}{dx} \equiv -\hbar g_{om}$$

Force metric: $g_{om} \equiv \frac{d\omega_0}{dx}$

(Determined by cavity dispersion)



figures of merit

- Optical force per photon: $F_{ph} = \hbar g_{\mathrm{OM}} \equiv \hbar \frac{\mathrm{d}\omega_{\mathrm{c}}}{\mathrm{dx}}$

$\Omega_M \ll \Gamma$

- Optical Spring: $(\Omega'_M)^2|_{\Delta T_1=0} = \Omega_M^2 + \left(\frac{2|a_0|^2 g_{\mathrm{OM}}^2}{\Delta^2 \omega_o m_x}\right) \Delta'_o$

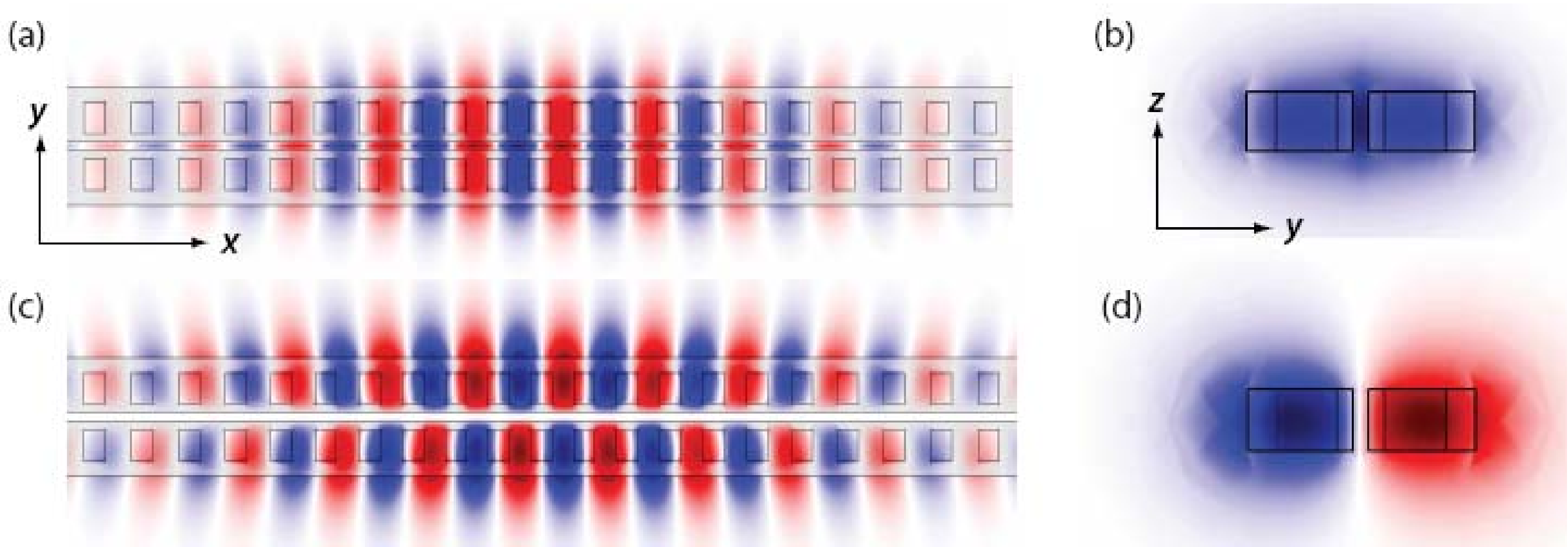
- Damping/amplification rate:

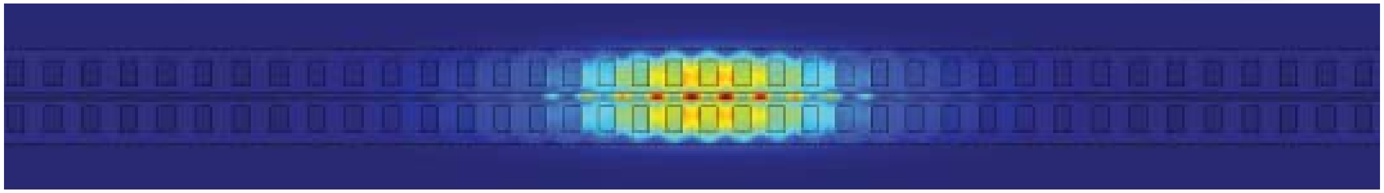
$$\gamma'_M|_{\Delta T_1=0} = \gamma_M - \left(\frac{2|a_0|^2 g_{\mathrm{OM}}^2 \Gamma}{\Delta^4 \omega_o m_x}\right) \Delta'_o.$$

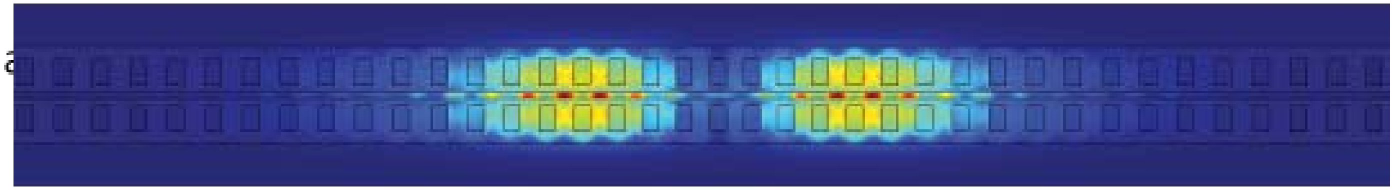
- Maximum damping/amplification rate:

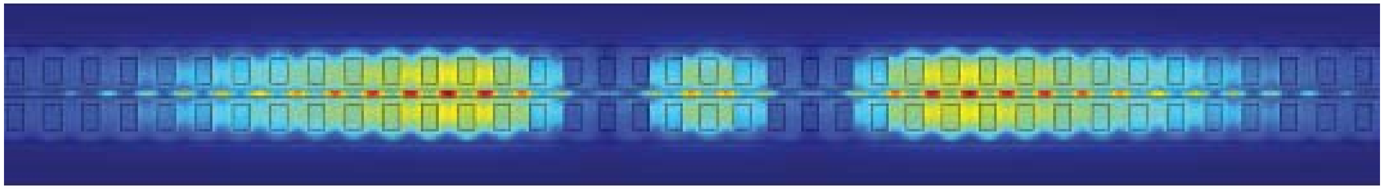
$$\sim \Gamma_{\mathrm{optical}}$$

zipper cavity design



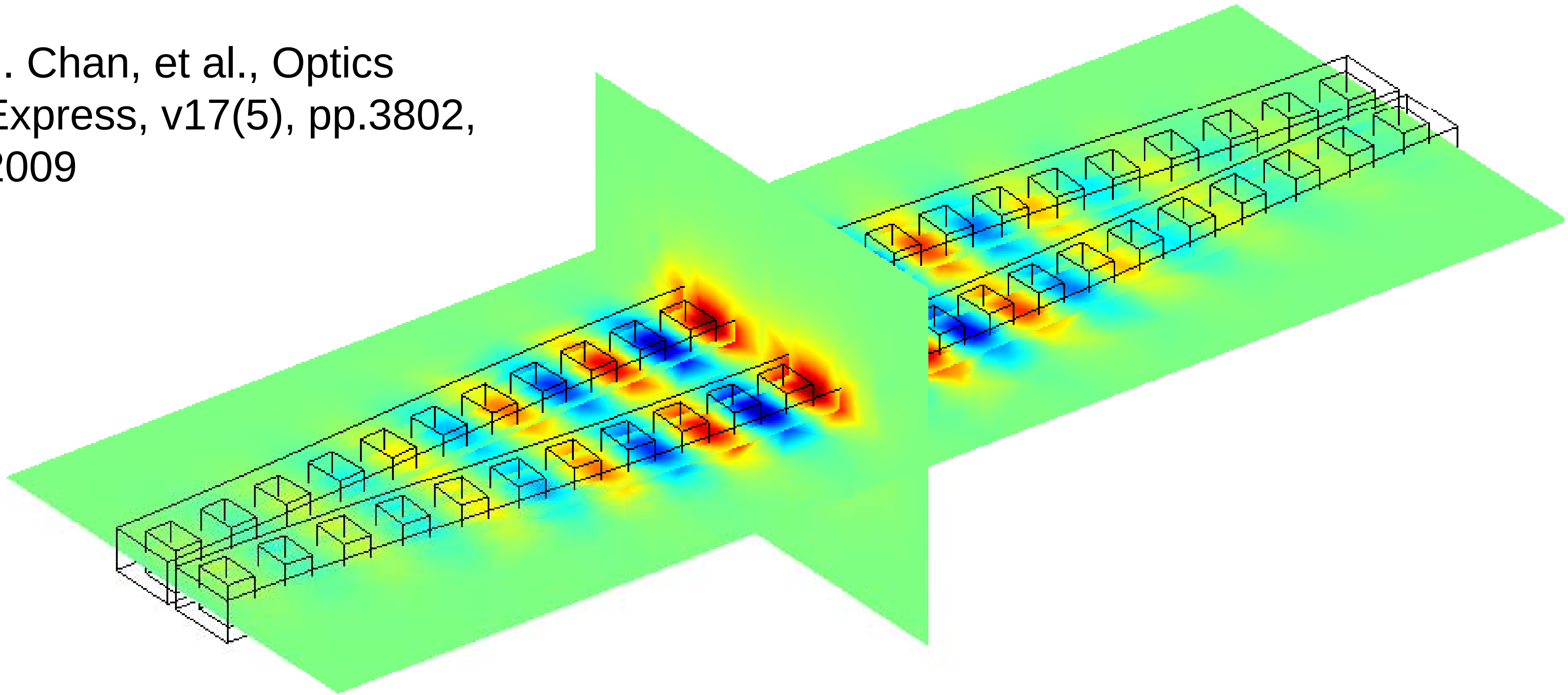

$TE_{0,+}$


$TE_{1,+}$


$TE_{2,+}$

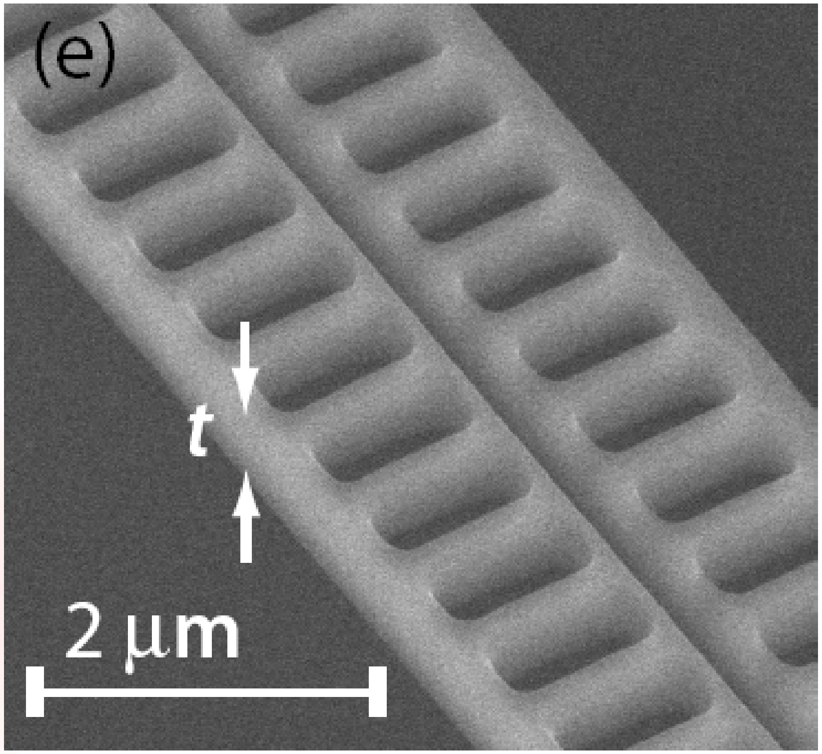
zipper optomechanical cavity

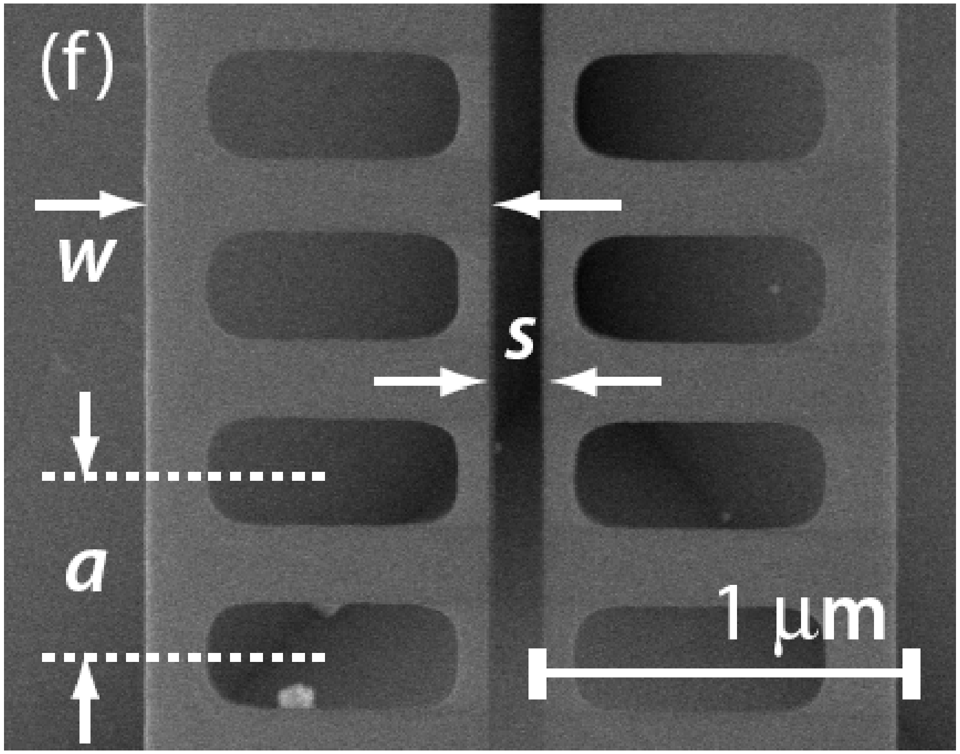
J. Chan, et al., Optics Express, v17(5), pp.3802, 2009



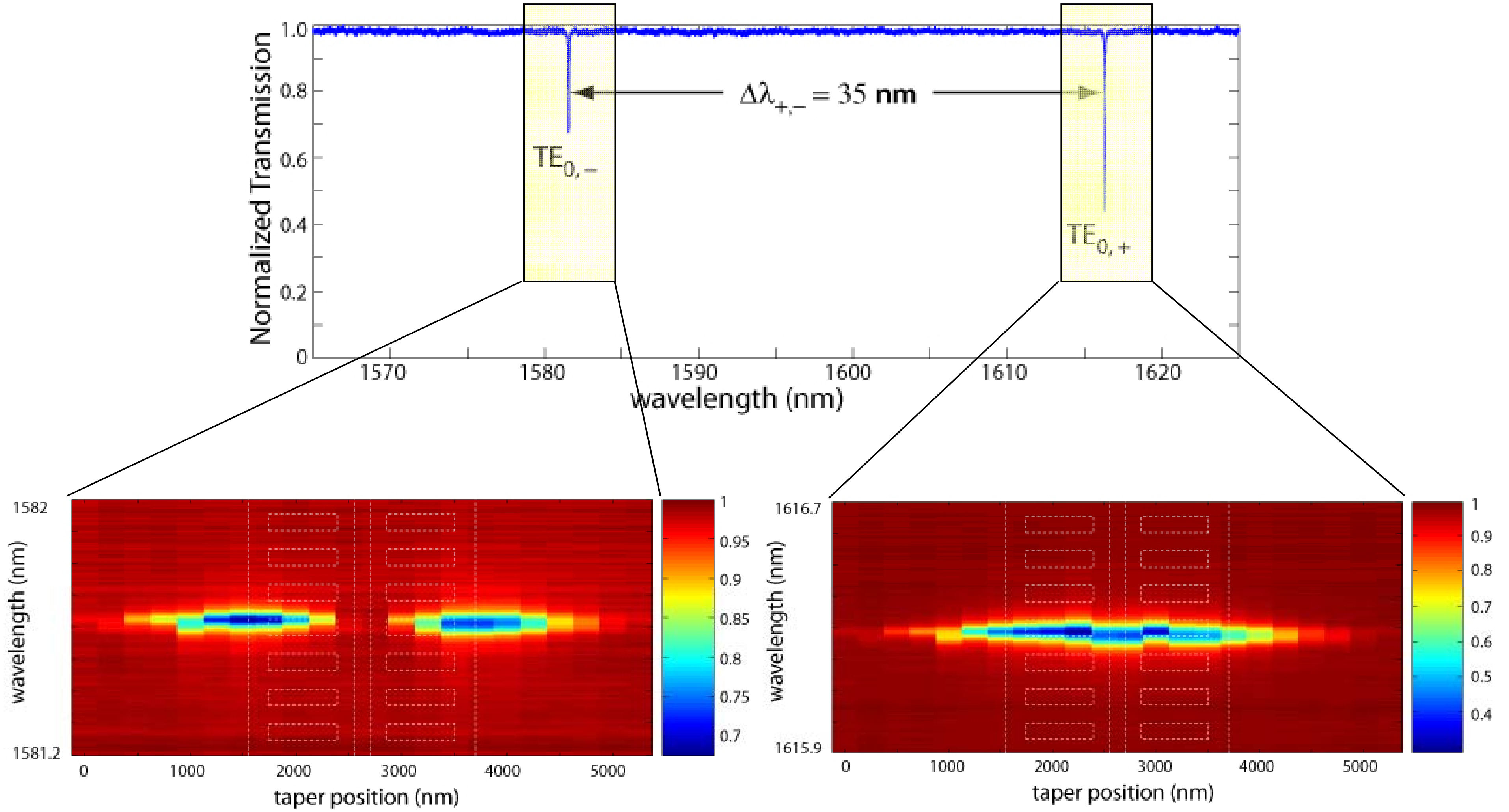
- effective motional mass, m_x = 20 picograms
- optomechanical coupling factor, $g_{OM}/2\pi$ = 123 GHz/nm ($L_{OM} \cong \lambda_0$)

zipper cavity fabrication

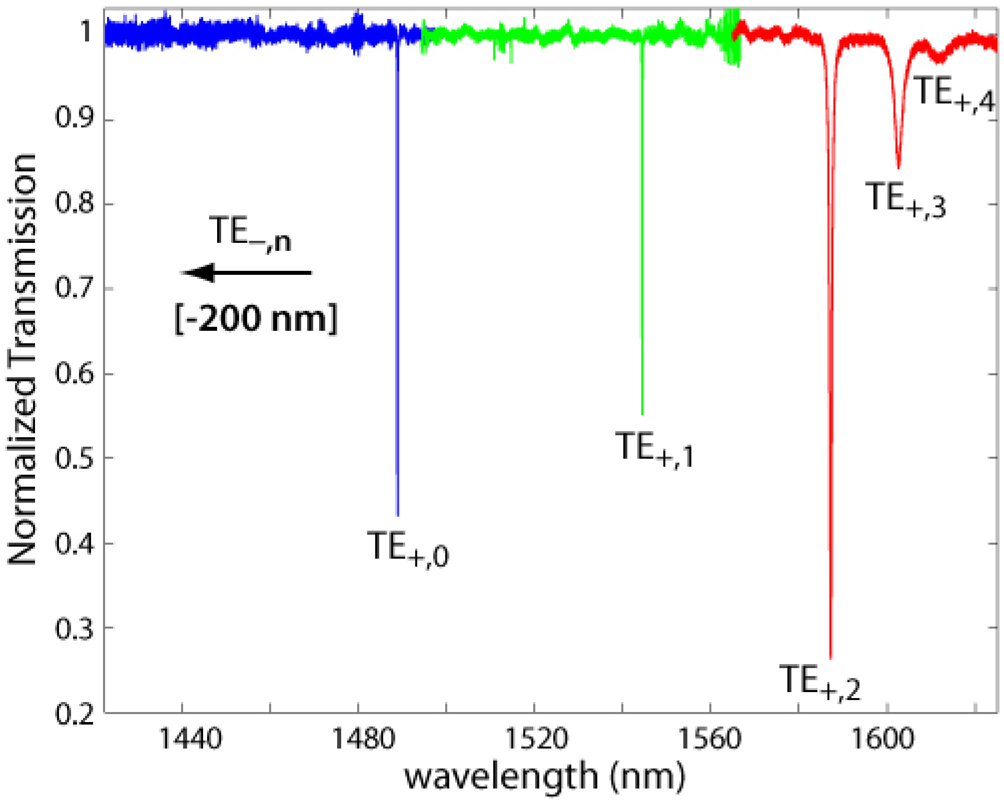


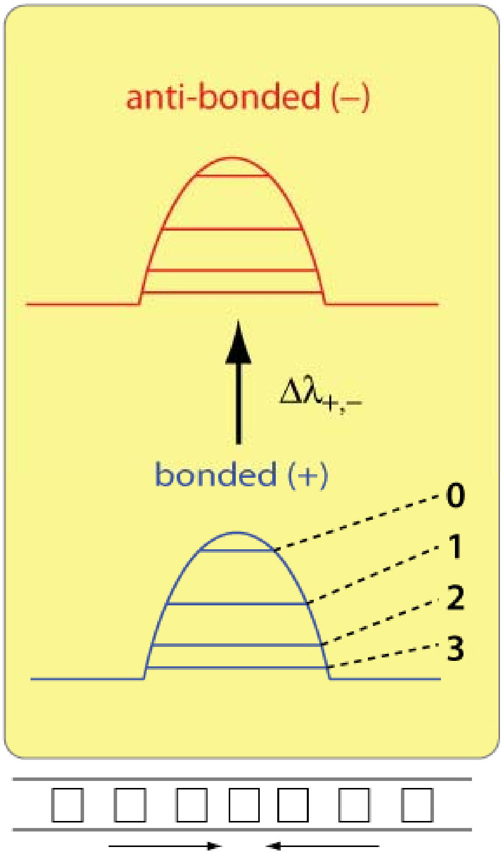


spatial symmetry of zipper modes

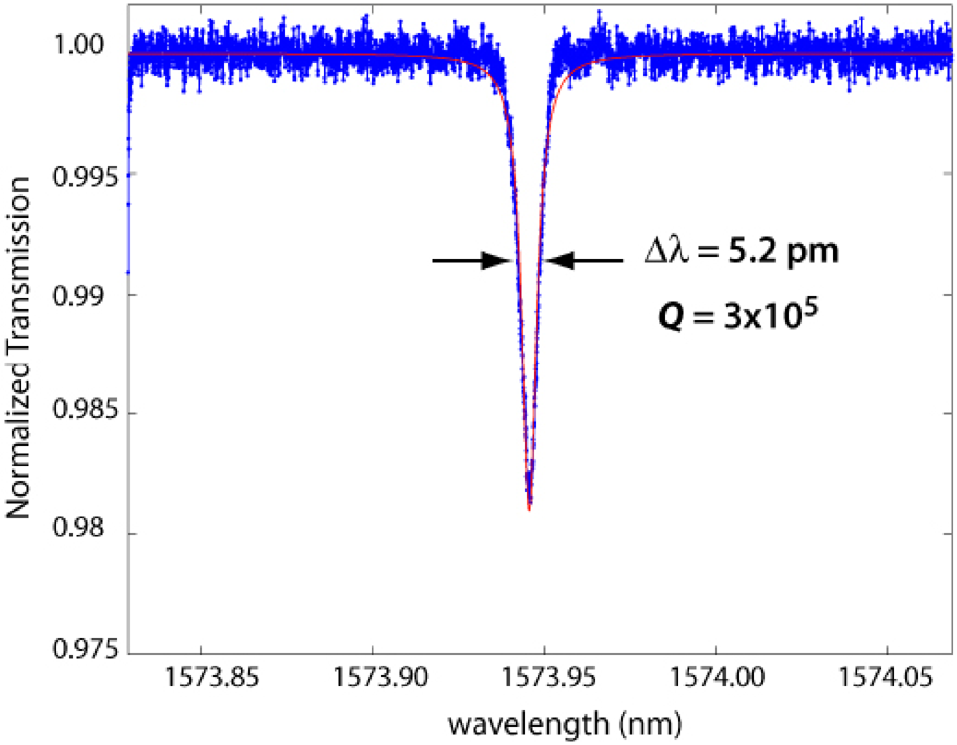


zipper mode “spectroscopy”





what about the optical Q ?

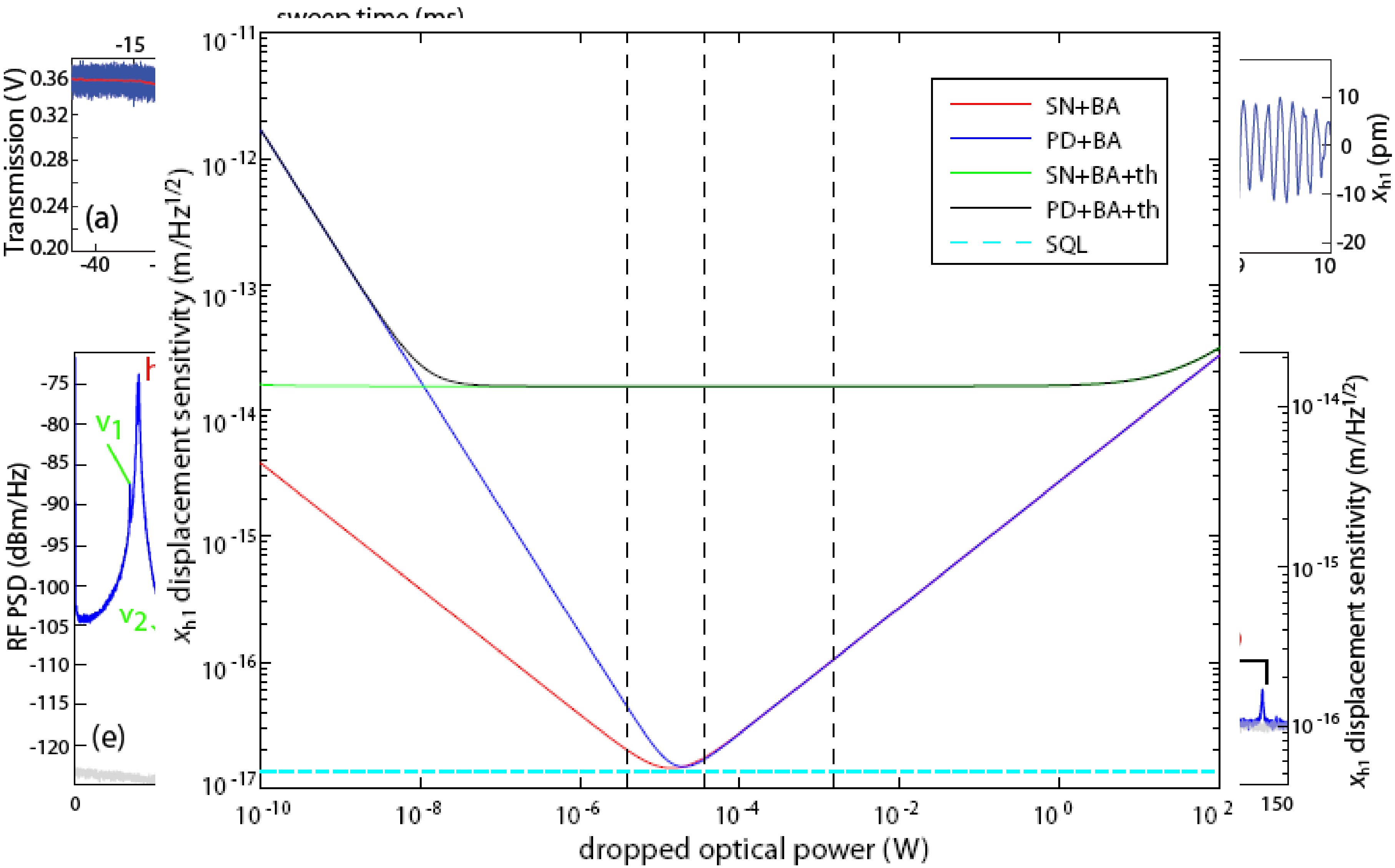


- ❑ theoretical $Q \cong 10^7$

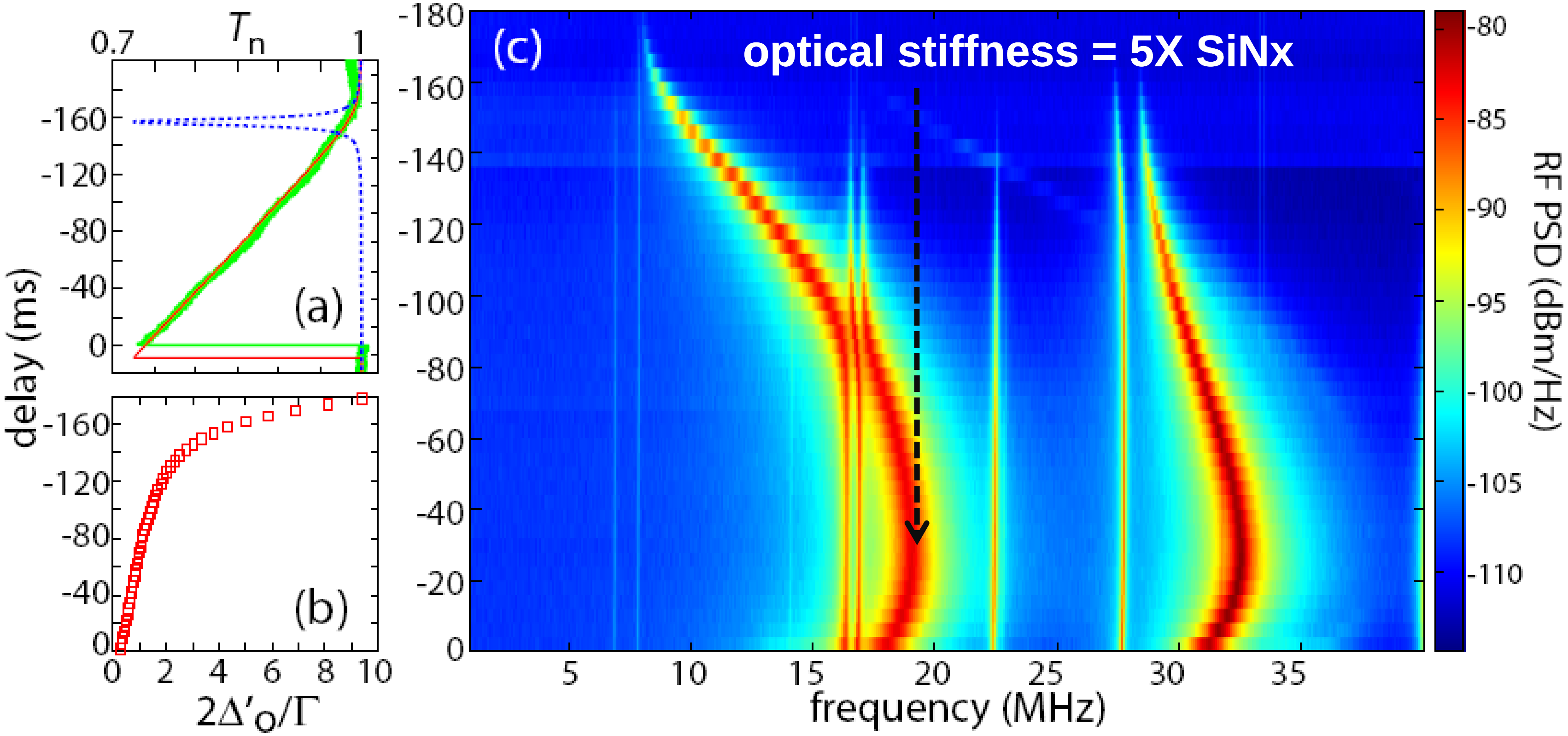
J. Chan, et al., Optics Express, v17(5), 2009; M. W. McCutcheon, et al, Optics Express, v16, 2008

→ fabrication limited, possibly surface absorption

optical transduction



motion-selective optical stiffness



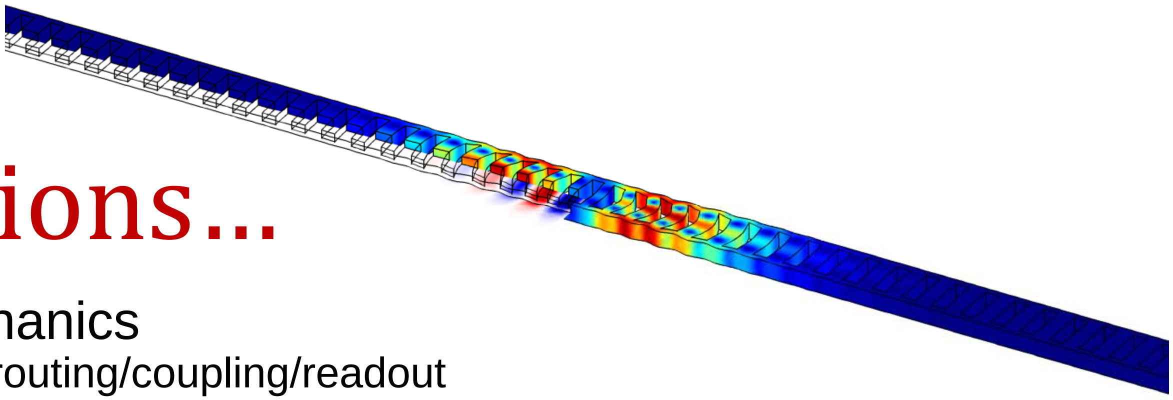
zipper cavity summary

- g_{OM} = 123 GHz/nm (L_{OM} = 1.5 μm)
- m_x = 20 picograms

g_{OM}^2/m_x is 10^5 X greater than previous OM systems

- $\Omega_M/2\pi$ = 10-150 MHz (for 1st to 9th order)
- $Q_o = 3\text{x}10^5$
- $Q_M = 2\text{x}10^4$ (in vacuum; 100 in 1 atm. air)
- Regenerative oscillation (threshold is uW-level)
- Cooling → >100 MHz cooling rate is possible

Future Directions…



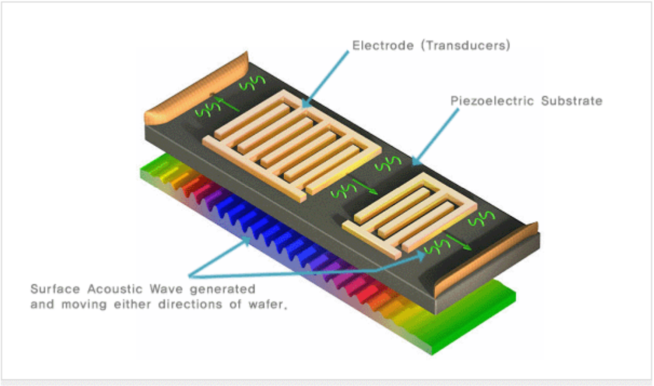
Quantum Cavity-Optomechanics

... Chip-scale platform for routing/coupling/readout
... High frequency, low thermal population
... Mechanical mode control, squeezing

Optically tunable components

... Filters, modulators, couplers, lasers,

... RF-photonics, SAW-like digital filters



Sensors

... Non-invasive, all-optical position detection and actuation

Non-linear dynamical effects

... Optical-to-mechanical energy conversion (e.g. Notomi et al., PRL 97 2006)

... Optical frequency conversion

... Laser modulation, mode-locking, etc.

Light detection methods

... Single-photon-level sensitivity (?) with a non-demolition measurement (?)

Optomechanical Photon "Detection"?

- ❑ Large g_{OM} ~ 150 GHz/nm yields a force per photon of roughly 1 picoNewton

- ❑ Mass and stiffness can be engineered over many orders of magnitude (m_x =100-5000 femtograms, $k=10^{-2}$ – 1000 N/m)

- ❑ Laser field *cannot* (?) be used to sensitively measure mechanical position/applied force, due to shot-noise and quantum back-action of the laser field → capactive "DC" electrical measurement.

- ❑ Must consider photon pulse shape, cavity ring-up time, mechanical resonance frequency, etc. For example, for a photon pulse much longer than the cavity lifetime, want to operate in the critically-coupled regime

- ❑ More effective (exotic) ways of utilizing optomechanical coupling to read out photons "mechanically"…

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