Research overview

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Our group operates on the boundary of physics and engineering

The Physics

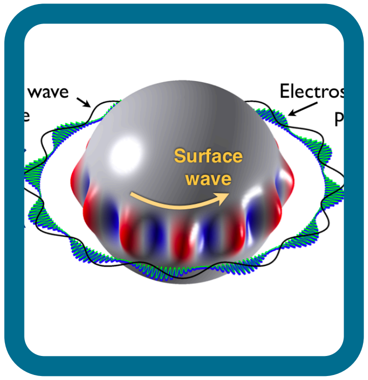
- Photonics
- Acoustics
- Electronics
- Quantum-optics analogues
- Nonreciprocal interactions and chirality (photons, phonons, electrons)
- Light-sound interactions
- Boundary forces
- Nonlinear optics

The applications

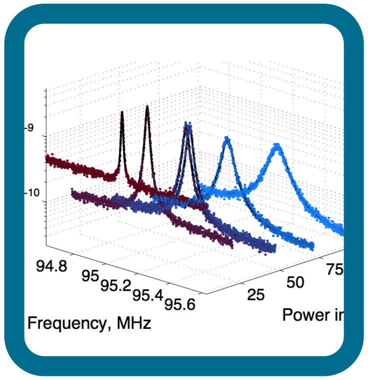
- Laser cooling of solids
- High-throughput sensing
- Optical isolators and circulators
- Signal processing, Oscillators

The team

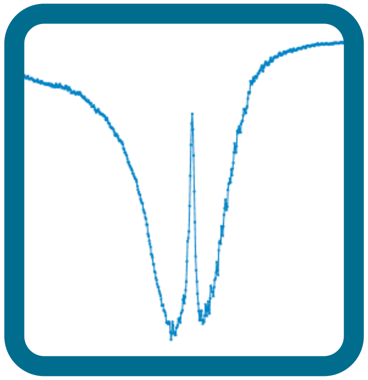
- 7 graduate students (we have openings)
- MechSE
- ECE
- Multiple undergrads



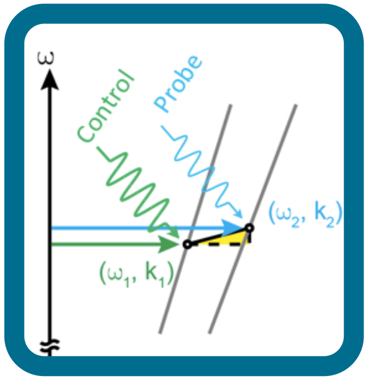
Brillouin optomechanics



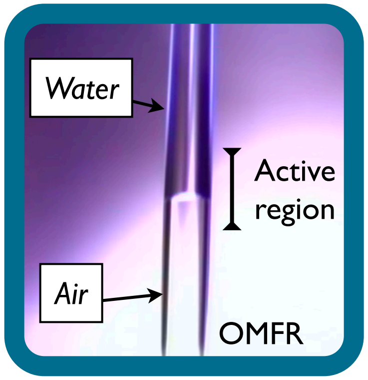
Brillouin and Raman cooling in solids



Brillouin Scattering Induced Transparency

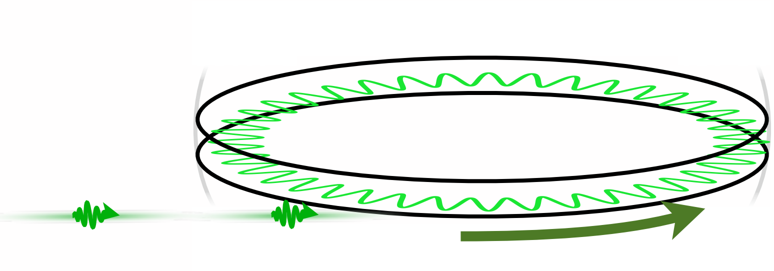


Nonreciprocal optomechanics

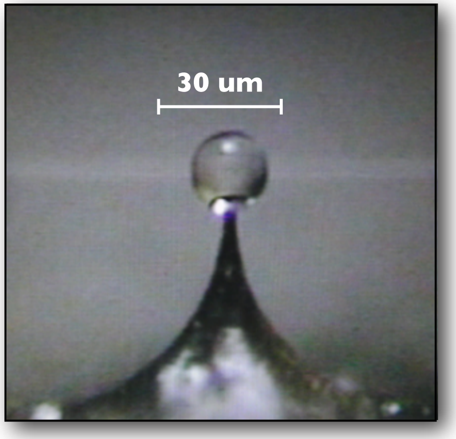


Microfluidic Optomechanics

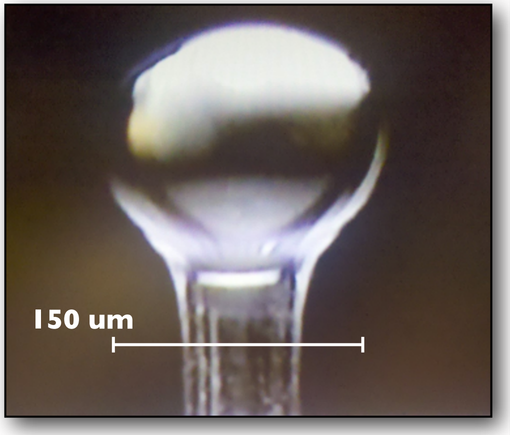
Microresonators as a platform for nonlinear optics



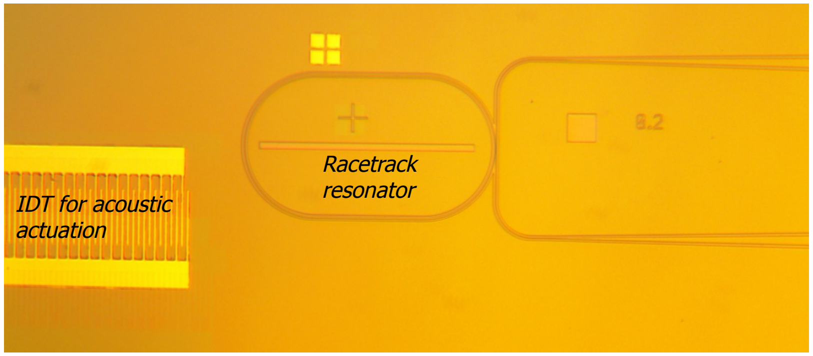
On chip spheres



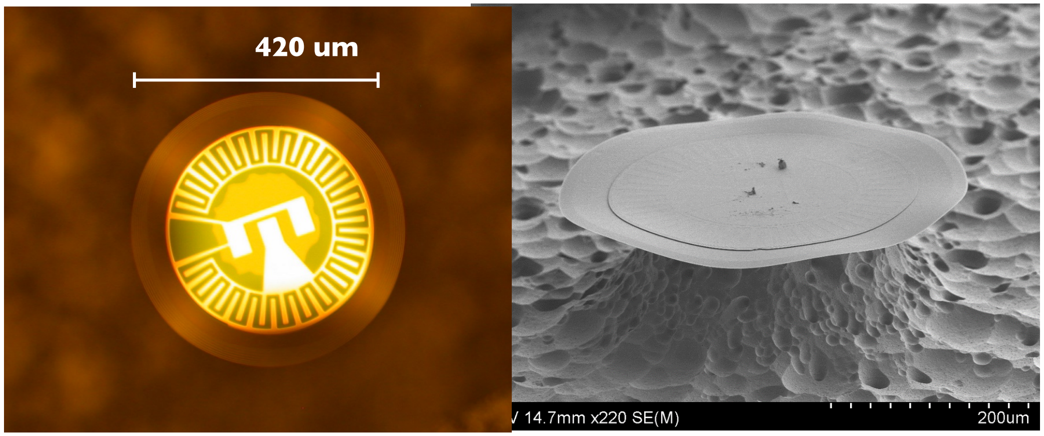
Fiber-tip spheres



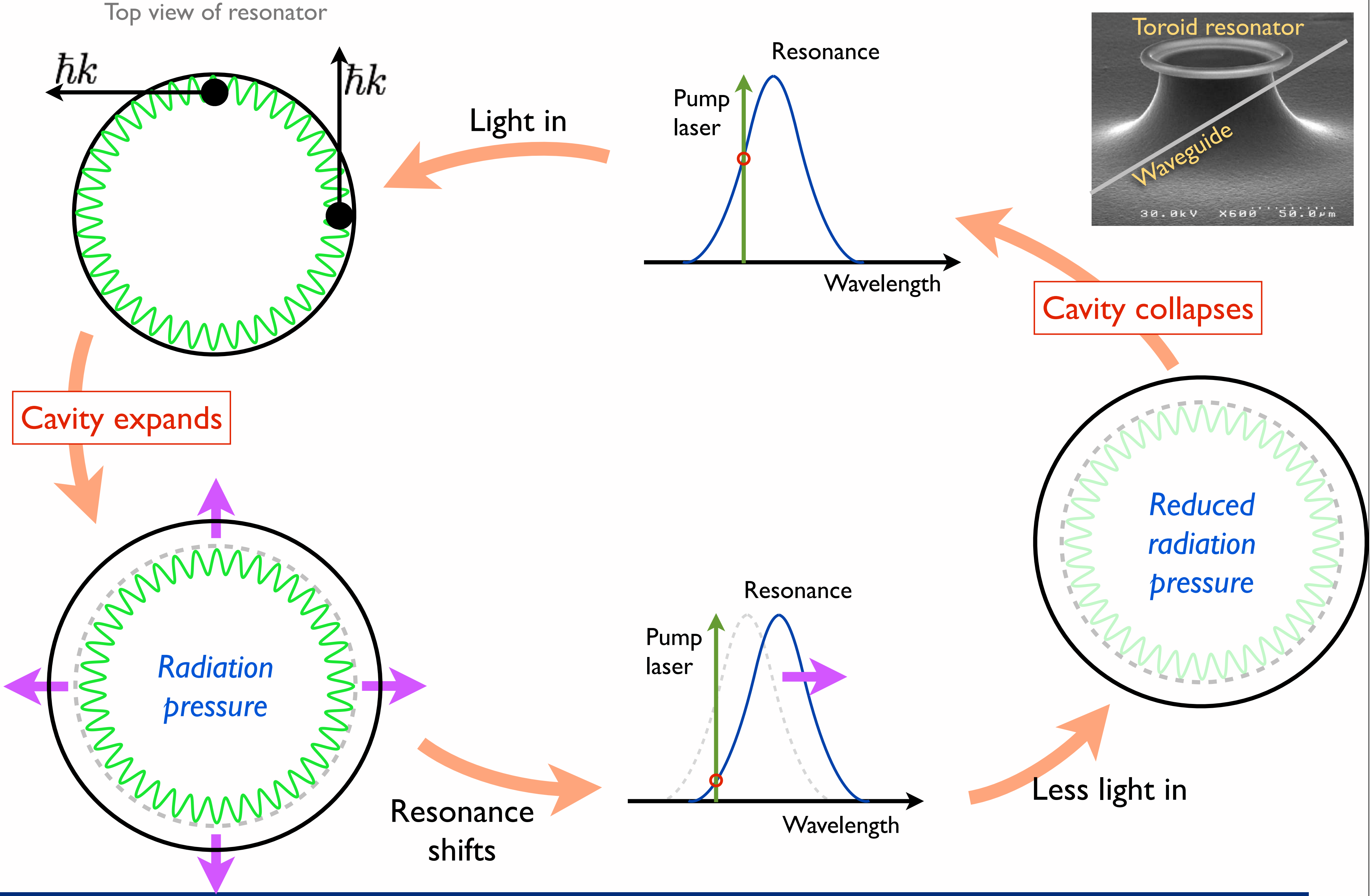
Chip-scale racetracks



AlN microdisks



Optomechanical coupling in resonators



Top view of resonator

Light in

Cavity expands

Radiation pressure

Resonance shifts

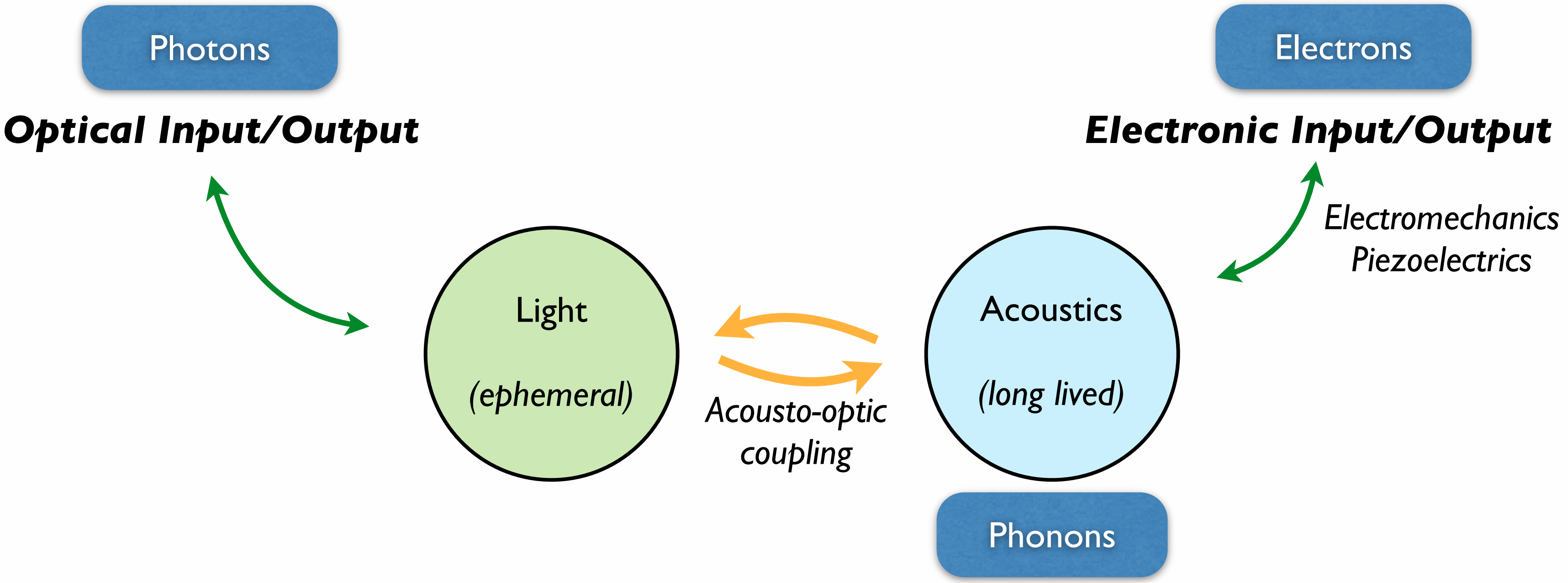
Less light in

Reduced radiation pressure

Cavity collapses

PRL 94, 223902 (2005) **Optics Express 13, 5293 (2005)** **PRL 95, 033901 (2005)**

What is optomechanics good for?


Photons

Optical Input/Output

Electrons

Electronic Input/Output

Electromechanics
Piezoelectrics

Light

(ephemeral)

Acousto-optic coupling

Acoustics

(long lived)

Phonons

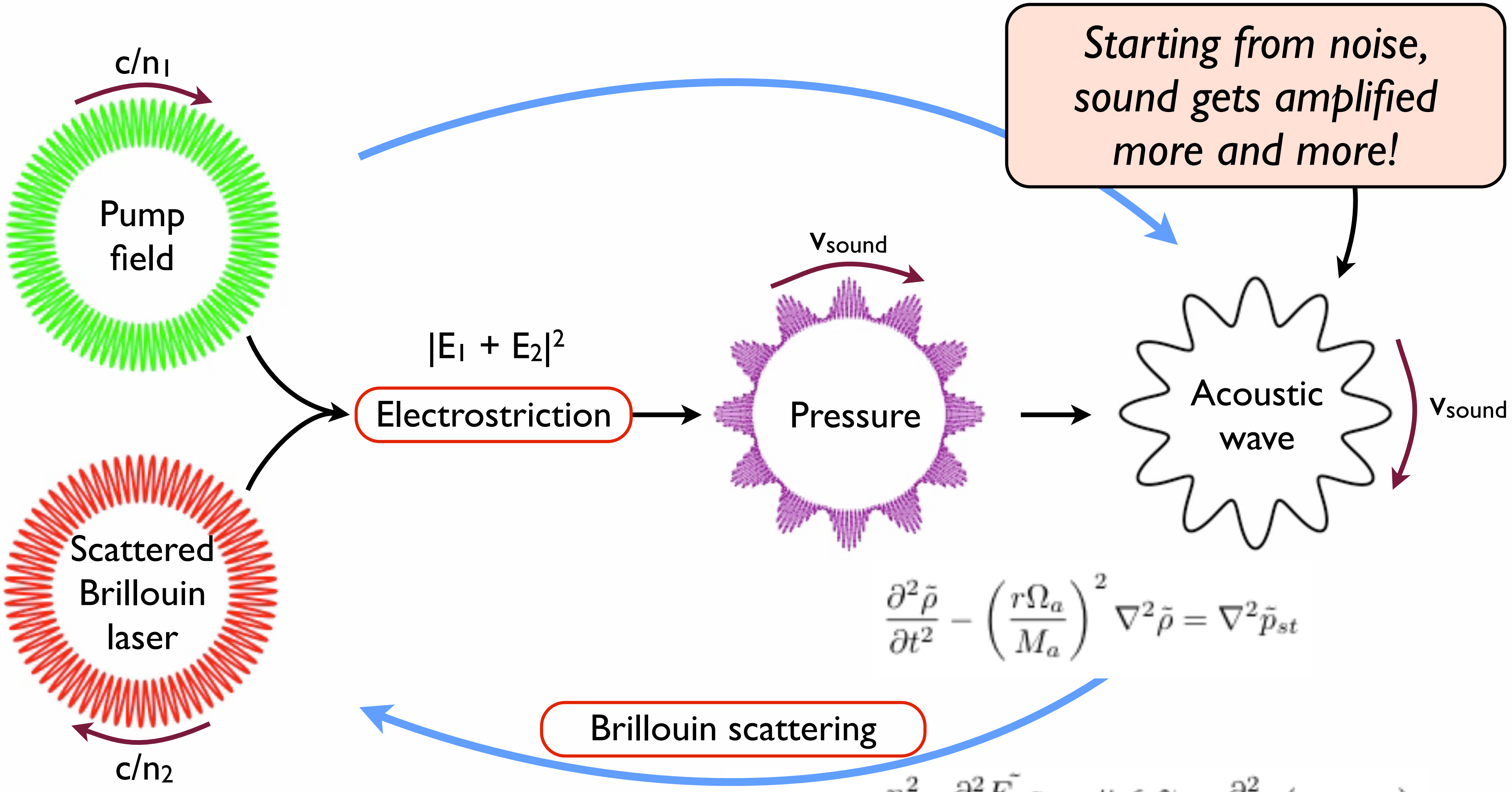
- Storing optical information (quantum states) for long periods of time.
  - *Potential qubits for quantum computation.*

- Generating acousto-optic transparency.
  - *Slowing down and speeding up light packets.*

- Annihilating phonons from a system.
  - *Laser cooling of solids.*
  - *Reaching quantum-mechanical ground state.*

Brillouin coupling visualized in a whispering gallery resonator

Nature Communications, 2:403, 2011



c/n_1

Pump field

$|E_1 + E_2|^2$

Electrostriction

v_{sound}

Pressure

Starting from noise, sound gets amplified more and more!

Acoustic wave

v_{sound}

$$\frac{\partial^2\tilde{\rho}}{\partial t^2} - \left(\frac{r\Omega_a}{M_a}\right)^2 \nabla^2\tilde{\rho} = \nabla^2\tilde{p}_{st}$$

Scattered Brillouin laser

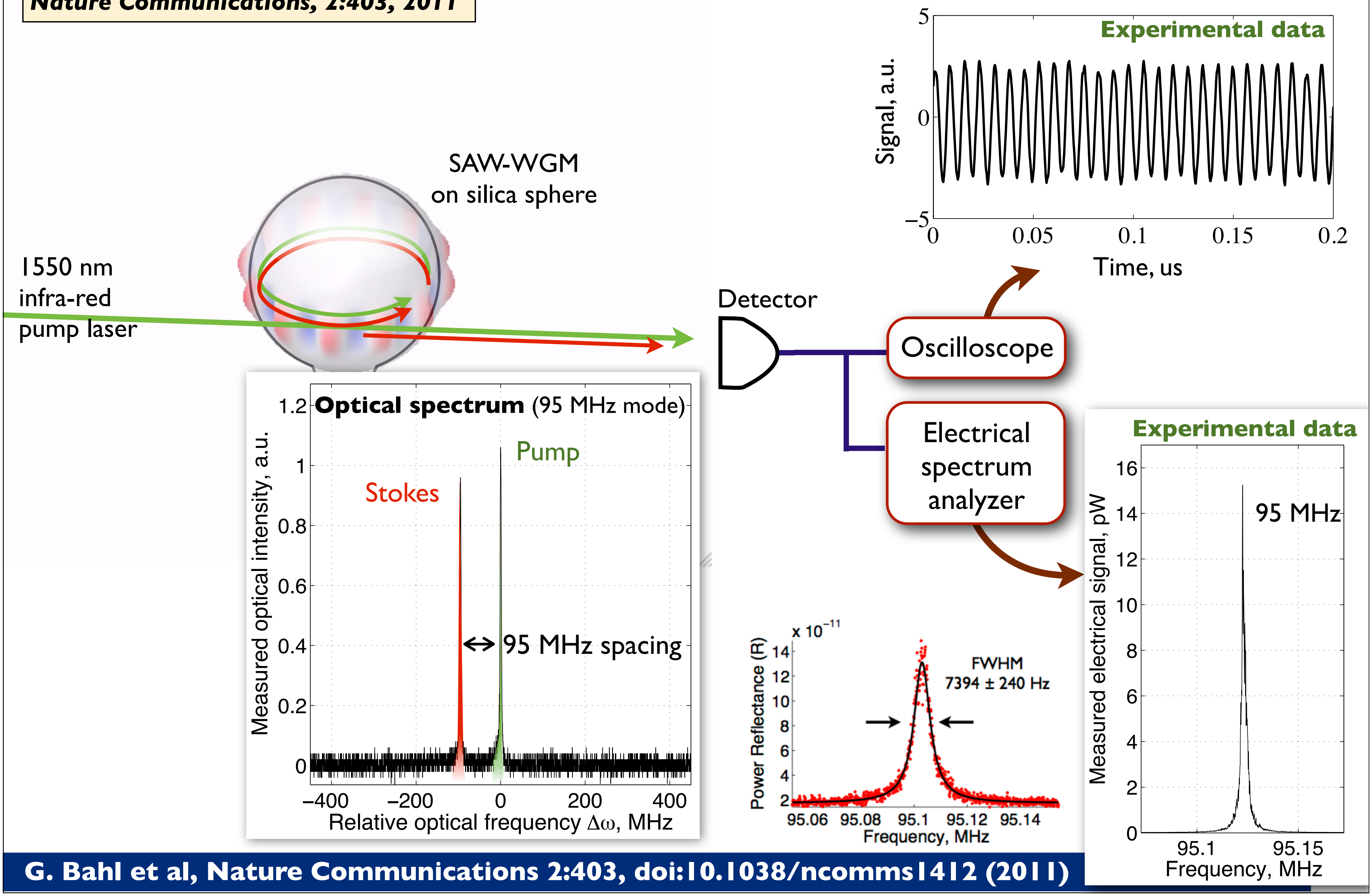
Brillouin scattering

c/n_2

$$\nabla^2 \tilde{E_{aS}} - \frac{n_o^2}{c^2}\cdot\frac{\partial^2 \tilde{E_{aS}}}{\partial t^2} = \frac{\mu_o\epsilon_o\gamma_e}{\rho_o}\cdot\frac{\partial^2}{\partial t^2}\left(\Delta\tilde{\rho}\ \tilde{E_P}\right)$$

Forward Brillouin scattering in microresonators

Nature Communications, 2:403, 2011



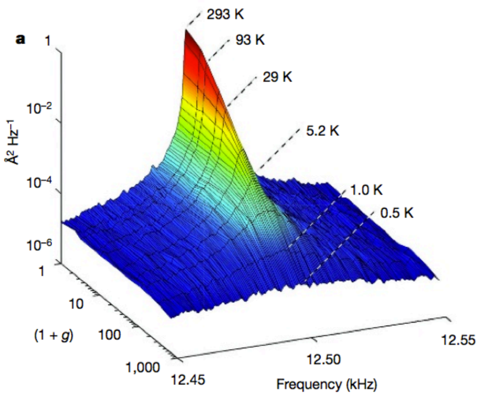
G. Bahl et al, Nature Communications 2:403, doi:10.1038/ncomms1412 (2011)

Laser cooling of vibrational modes in solids

Overview of optical cooling in solids

Structural interaction → Atomic interaction

Radiation pressure cooling of vibrational modes

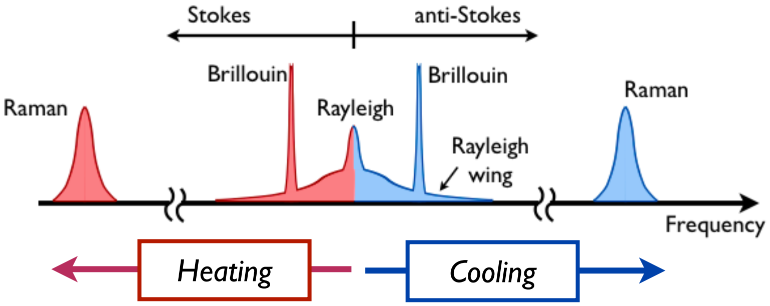


S. Gigan et al,
NATURE, Vol. 444, p. 67, 2006

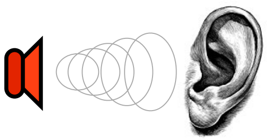
O. Arcizet et al,
NATURE, Vol. 444, p. 71, 2006

D. Kleckner et al,
NATURE, Vol. 444, p. 75, 2006

also
gradient force cooling (2009)
photothermal cooling (2004)
piezoresistive cooling (2010)



Brillouin scattering



Light interacts with sound

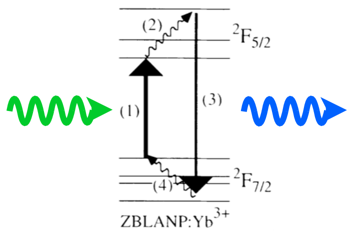
Raman scattering

Light interacts with molecular or atomic vibrations

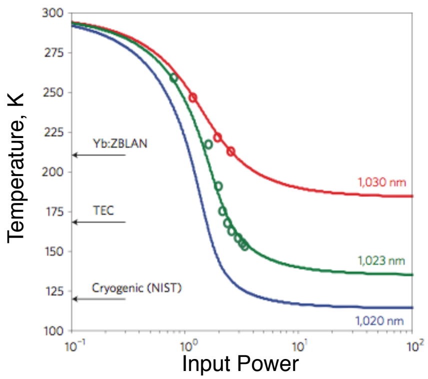
No demonstrations of Brillouin cooling in *__any__* *state of matter.*

NB: Raman cooling has been demonstrated in atomic gases, but *__not__* *solid phase.*

Fluorescence cooling



Observation of laser induced fluorescent cooling of a solid
Epstein et al, NATURE, Vol. 377, 1995

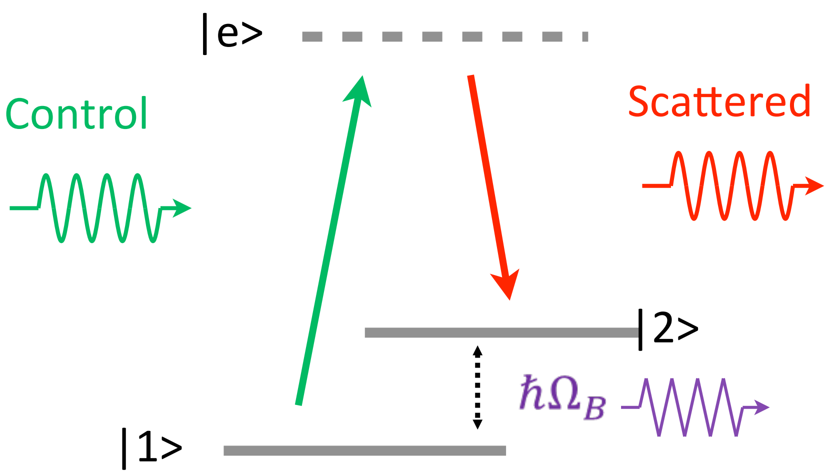


Laser cooling of solids to cryogenic temperatures
Seletskiy et al,
NATURE PHOTONICS, Vol. 4, 2010

Reached 110 K in 2011

Opto-acoustic interactions visualized as three-level systems

Stokes scattering



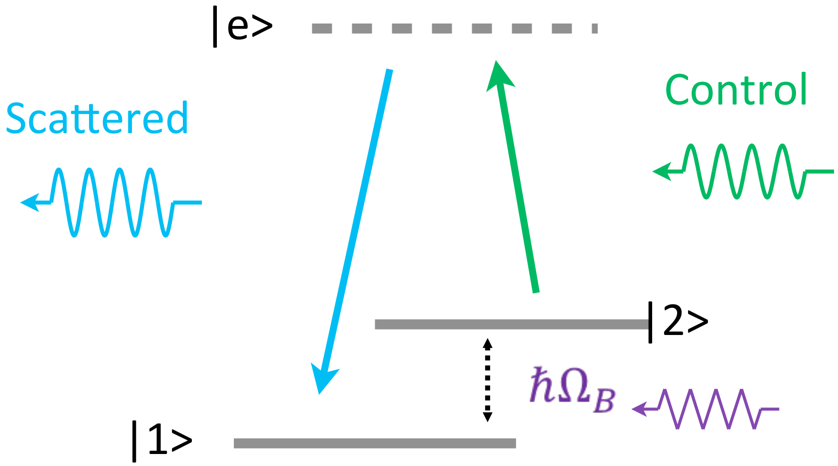
$|1\rangle = |n_p, n_m\rangle$

$|e\rangle = |n_p+1, n_m\rangle$

$|2\rangle = |n_p, n_m+1\rangle$

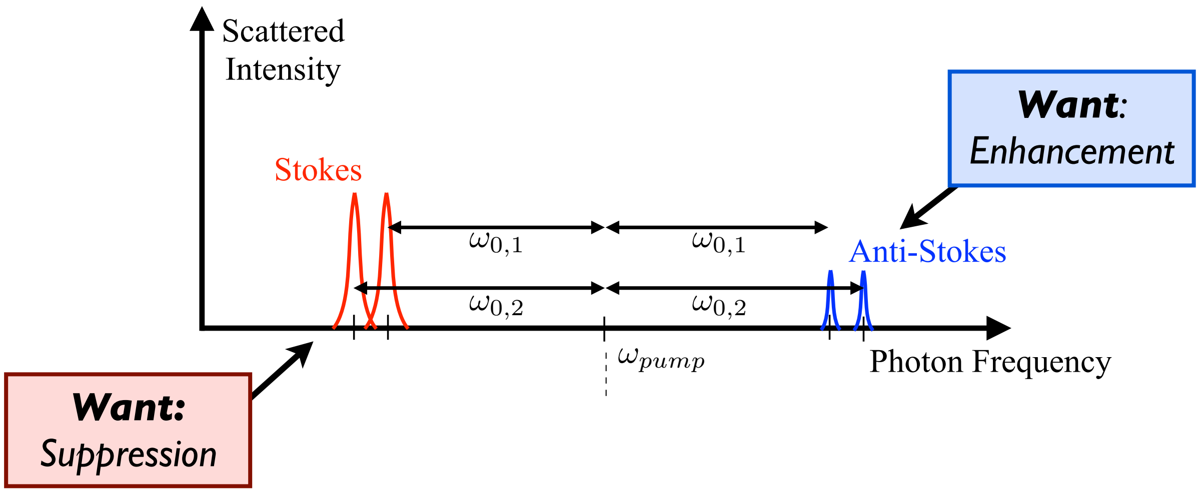
Stokes scattering with amplification of light and acoustic phonons

Anti-Stokes scattering



Anti-Stokes scattering with annihilation of acoustic phonons

Outlining the challenge of cooling with inelastic scattering processes



Want: *Enhancement*

Want: *Suppression*

Challenge 1 -- Selecting only anti-Stokes scattering

Stokes scattering is thermodynamically preferred in bulk materials!
Recall: Bose-Einstein distribution function $n_0 = (e^{\hbar\omega_0/k_BT} - 1)^{-1}$

Challenge 2 -- Removal of energy before repopulation of cooled modes

Light must be removed before it scatters back or is absorbed.

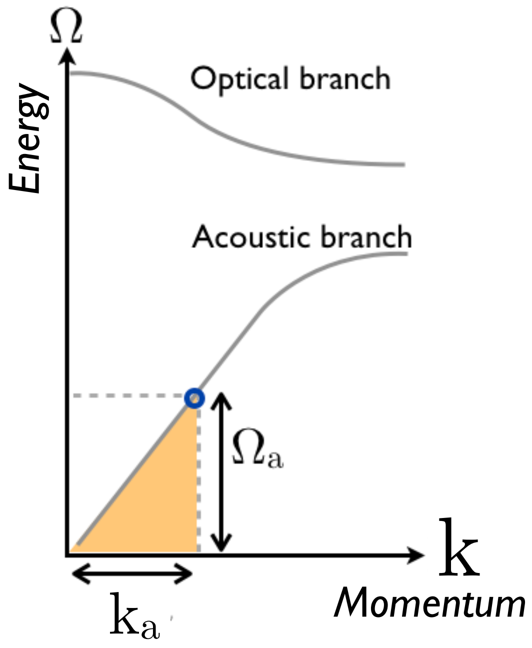
Challenge 3 -- Enhancing cooling above background absorption

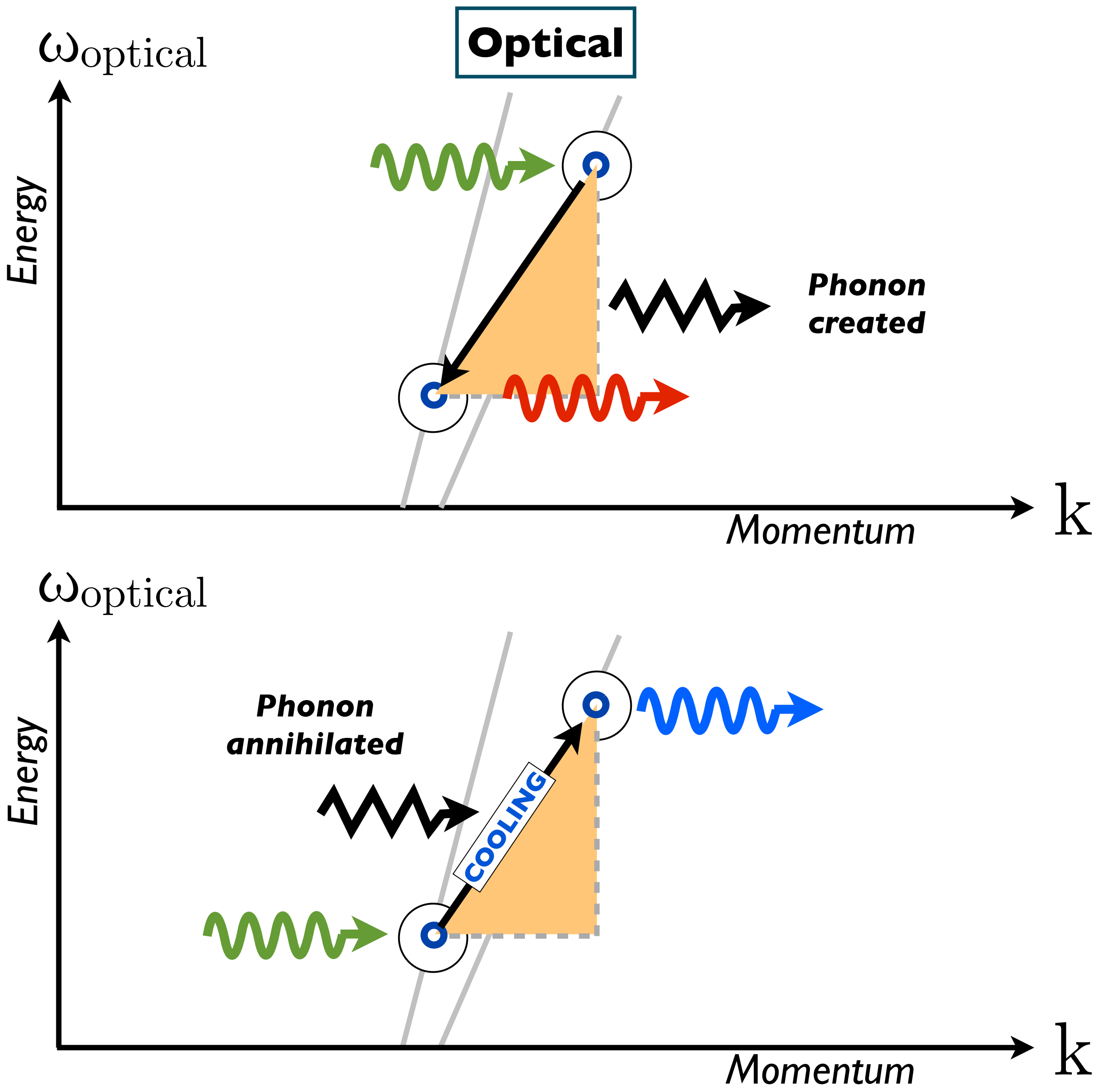
We must enhance the efficiency of anti-Stokes scattering above the intrinsic absorption efficiency in the material. Can we resonantly enhance it?

Rapidly annihilate phonons to acquire new thermodynamic balance (temperature)

Nature Physics, 8(3), p.203, 2012

Acoustic

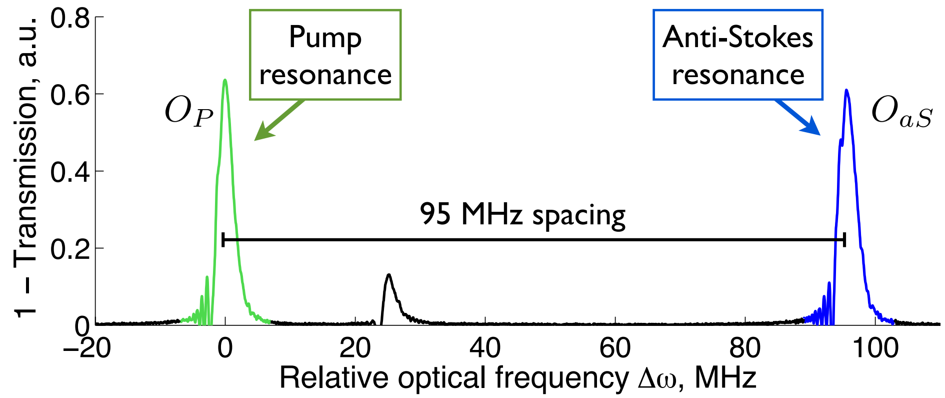




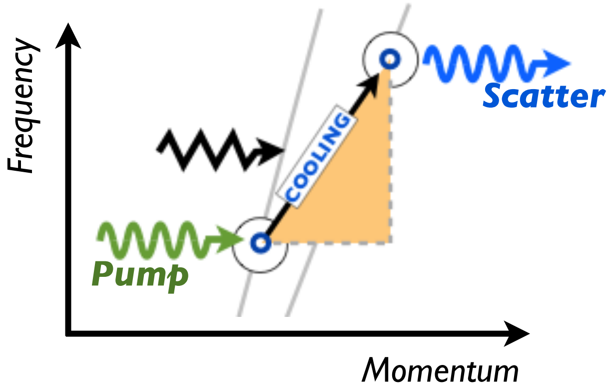
Experimental demonstration of Brillouin cooling

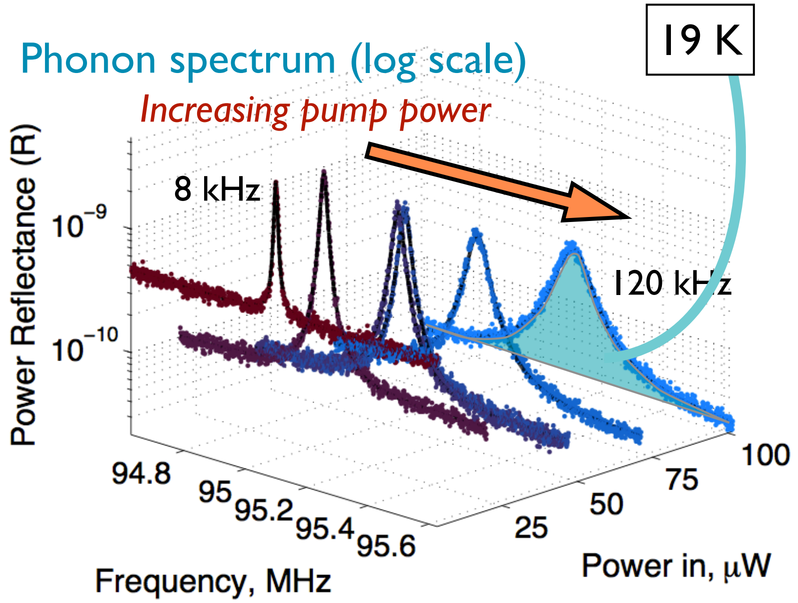
Nature Physics, 8(3), p.203, 2012

① *Find candidate optical modes*

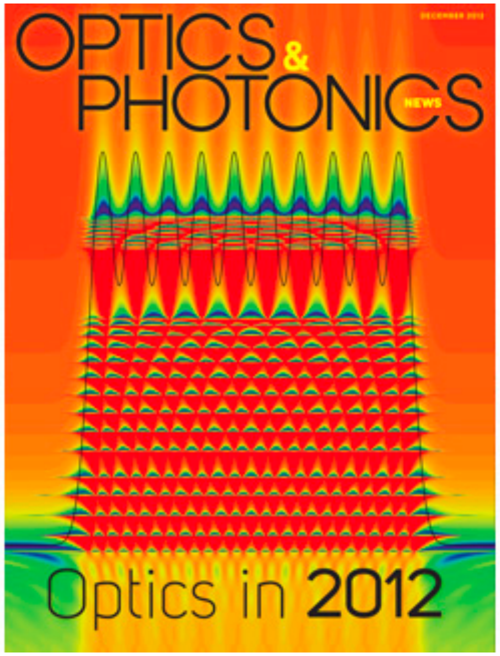


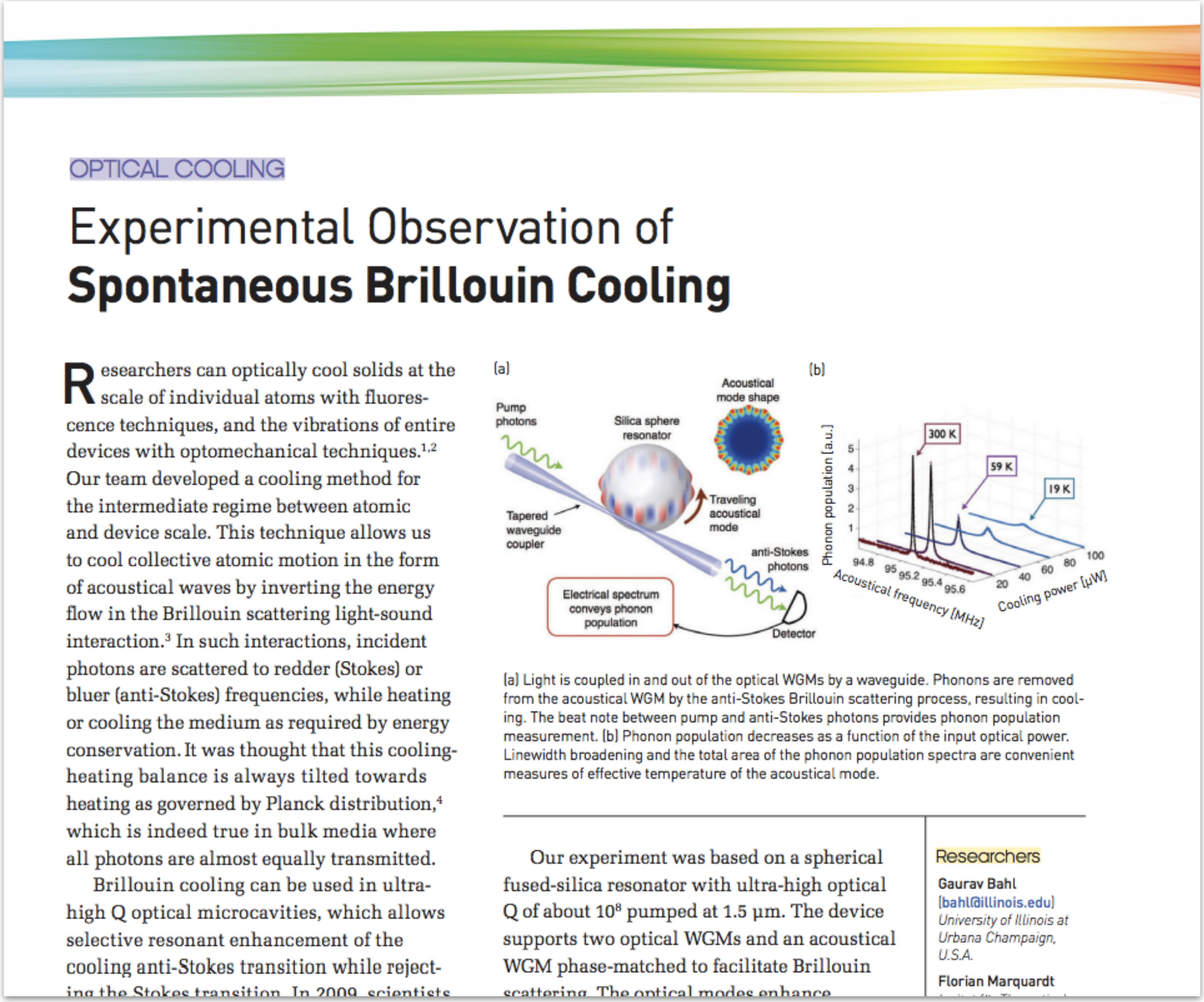
② *Cooling is achieved by pumping low frequency (energy) optical mode*





Top-30 Developments in Optics — 2012





OPTICAL COOLING

Experimental Observation of **Spontaneous Brillouin Cooling**

Researchers can optically cool solids at the scale of individual atoms with fluorescence techniques, and the vibrations of entire devices with optomechanical techniques.[1,2] Our team developed a cooling method for the intermediate regime between atomic and device scale. This technique allows us to cool collective atomic motion in the form of acoustical waves by inverting the energy flow in the Brillouin scattering light-sound interaction.[3] In such interactions, incident photons are scattered to redder (Stokes) or bluer (anti-Stokes) frequencies, while heating or cooling the medium as required by energy conservation. It was thought that this cooling-heating balance is always tilted towards heating as governed by Planck distribution,[4] which is indeed true in bulk media where all photons are almost equally transmitted.

Brillouin cooling can be used in ultra-high Q optical microcavities, which allows selective resonant enhancement of the cooling anti-Stokes transition while rejecting the Stokes transition. In 2009, scientists

(a) Light is coupled in and out of the optical WGMs by a waveguide. Phonons are removed from the acoustical WGM by the anti-Stokes Brillouin scattering process, resulting in cooling. The beat note between pump and anti-Stokes photons provides phonon population measurement. (b) Phonon population decreases as a function of the input optical power. Linewidth broadening and the total area of the phonon population spectra are convenient measures of effective temperature of the acoustical mode.

Our experiment was based on a spherical fused-silica resonator with ultra-high optical Q of about 10^8 pumped at 1.5 μm. The device supports two optical WGMs and an acoustical WGM phase-matched to facilitate Brillouin scattering. The optical modes enhance

Researchers

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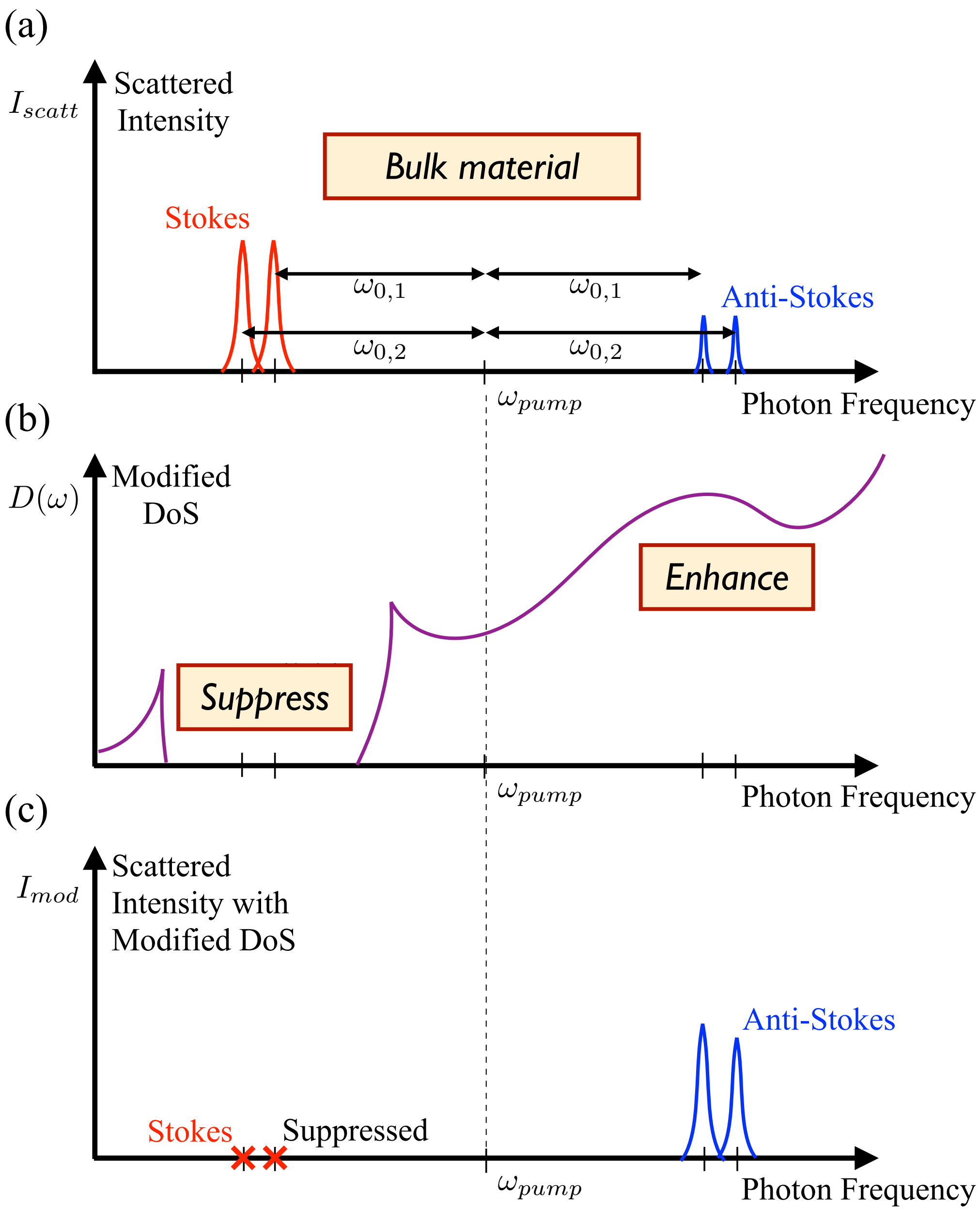
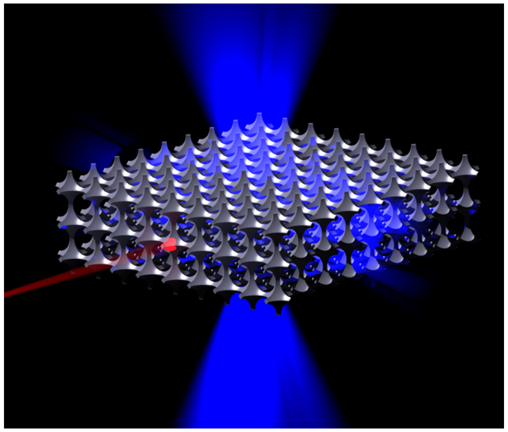
Florian Marquardt

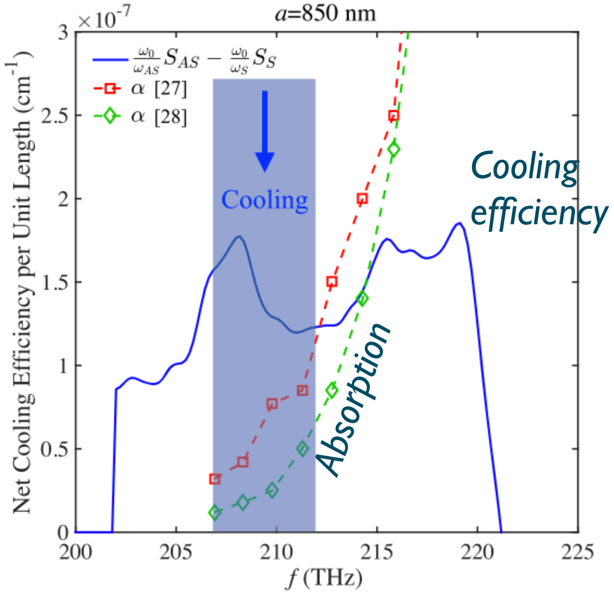
Extending photonic DoS concept to Raman cooling

Optica 2(10), pp.893-899, 2015

Nature Photonics 10, p.566, 2016



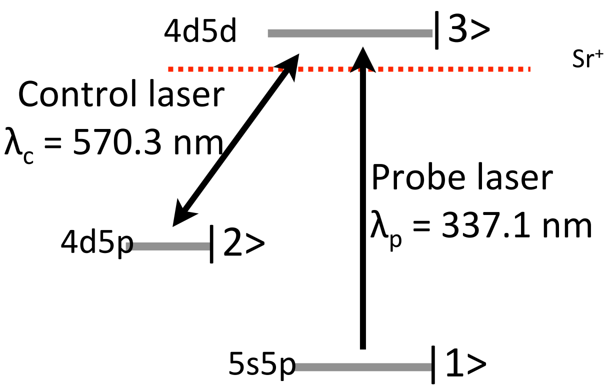


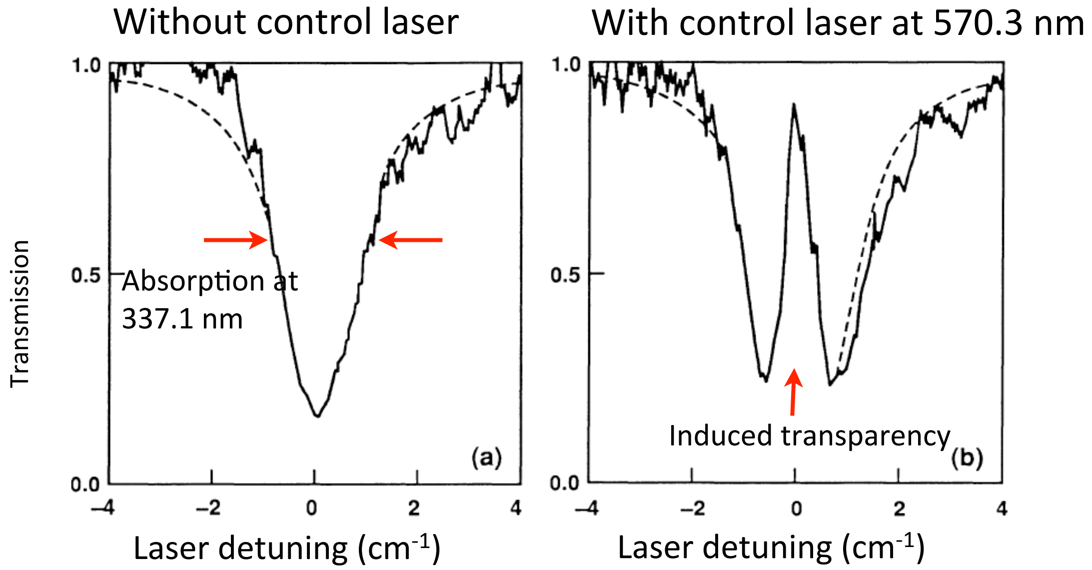


Induced transparency
&
nonreciprocity

Electromagnetically Induced Transparency (EIT) in atomic gases

Energy levels of Strontium





The material is opaque in a range of optical frequencies.

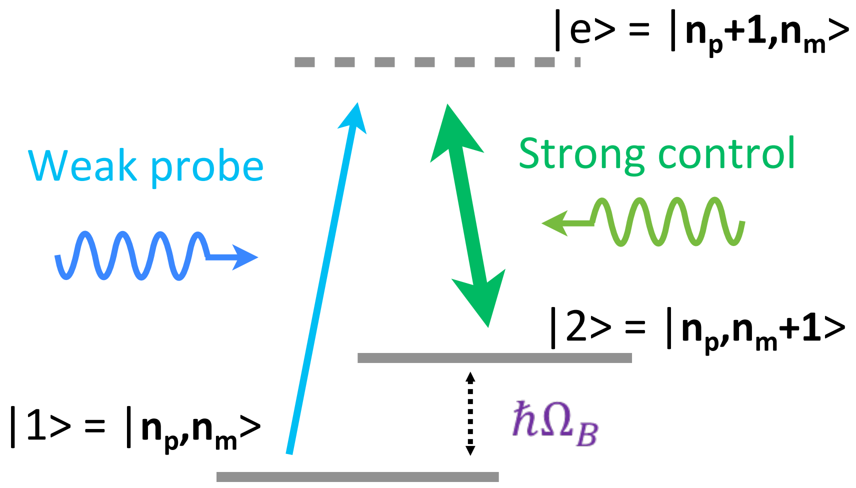
… but exhibits transparency when control field is on.

- Requires 3-level system where (in this example) **lower states are not directly coupled**.
- Coupling state |2> must have **high coherence**.
- EIT occurs due to interference of two options for electronic excitation via optical absorption |1>→|3> and |1>→|3>→|2>→|3>

Boller et. al., Phys. Rev. Lett., vol. 66, pp. 2593, 1991

EIT-like 3-level picture in opto-acoustic systems

Opto-acoustic coupling looks like EIT system



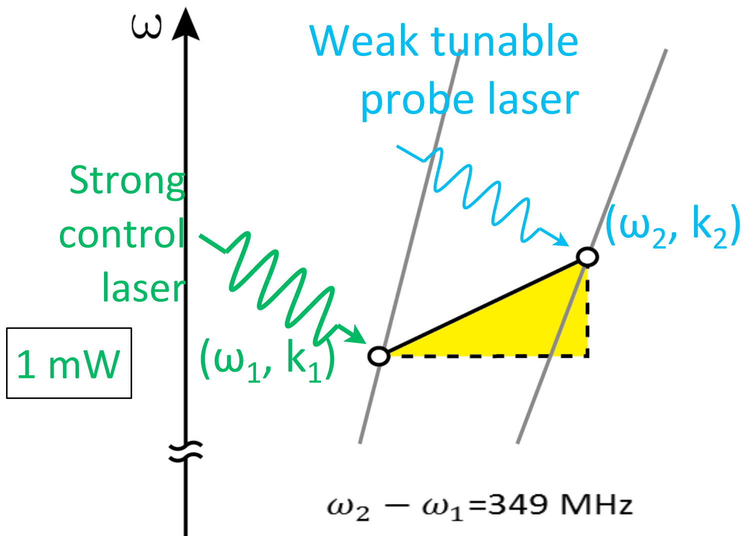
- Interference occurs between the two excitation pathways :

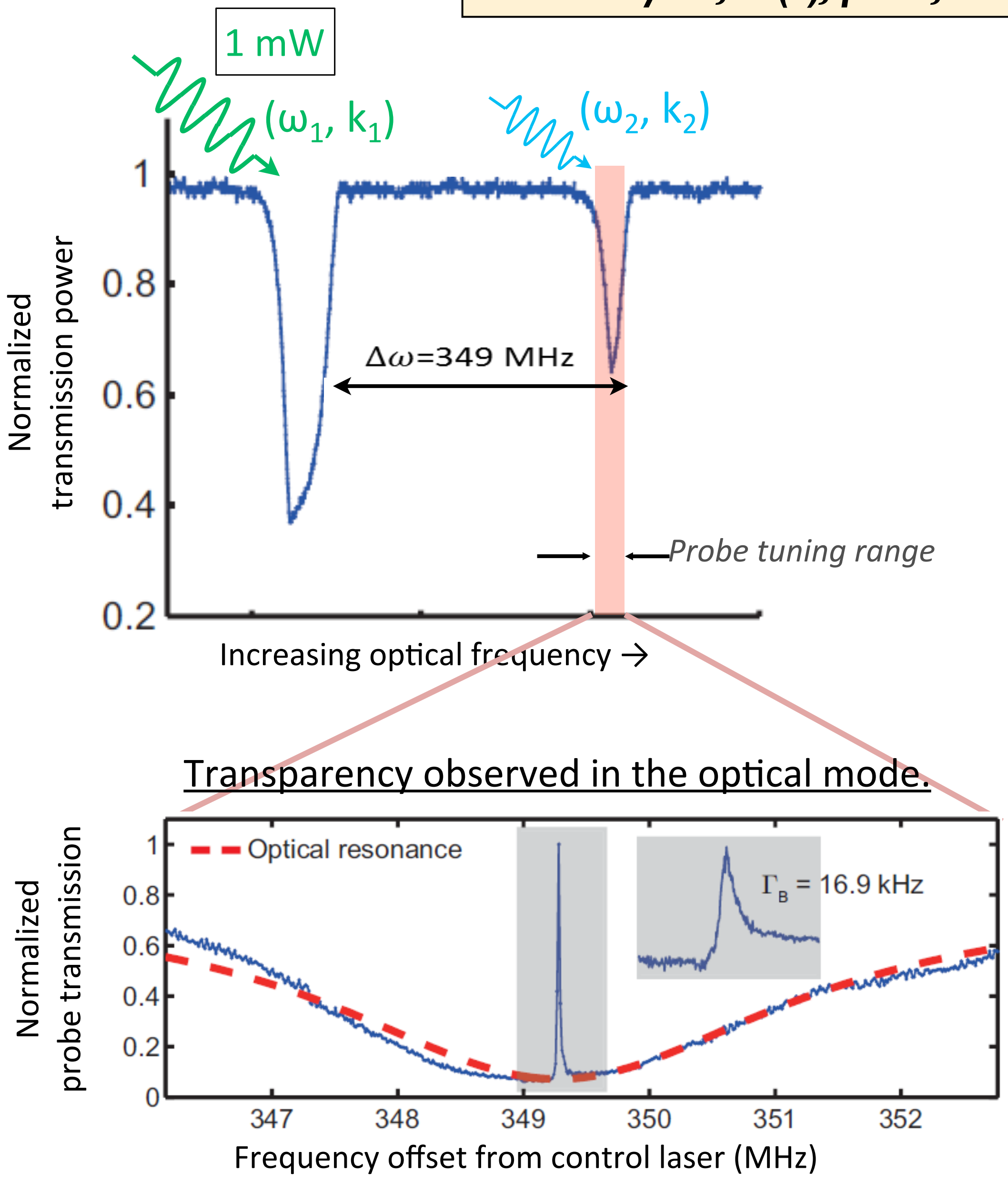
  |1>→|e> and |1>→|e>→|2>→|e>
- Probe absorption is inhibited due to destructive interference
- This illustration is identical to optomechanically induced transparency (OMIT) [1,2]

[1] S. Weis, et. al., Science, vol. 330, pp. 1520-1523, 2010.
[2] A. H. Safavi-Naeini, et. al., vol. 472, pp. 69-73, 2011.

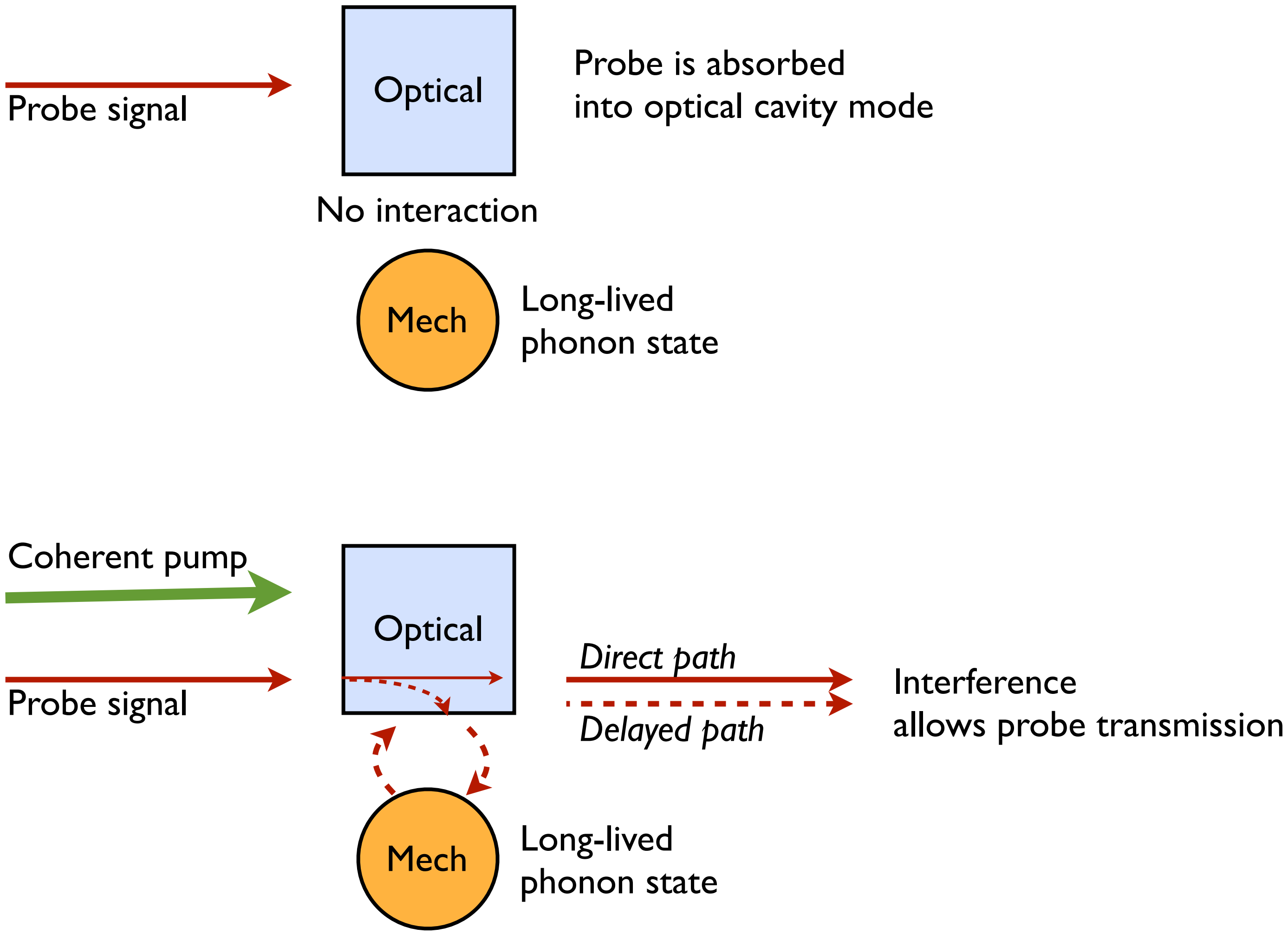
Observation of Brillouin scattering induced transparency (BSIT)

Nature Physics, 11(3), p.275, 2015





Physical intuition for the induced transparency process



Probe signal

Optical

Probe is absorbed
into optical cavity mode

No interaction

Mech

Long-lived
phonon state

Coherent pump

Probe signal

Optical

Direct path

Delayed path

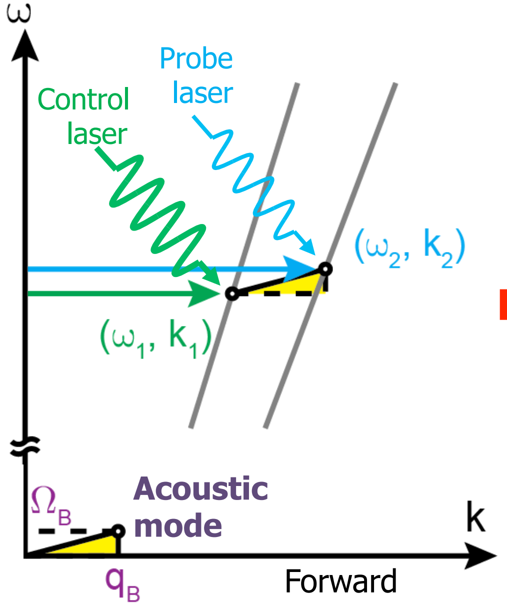
Interference
allows probe transmission

Mech

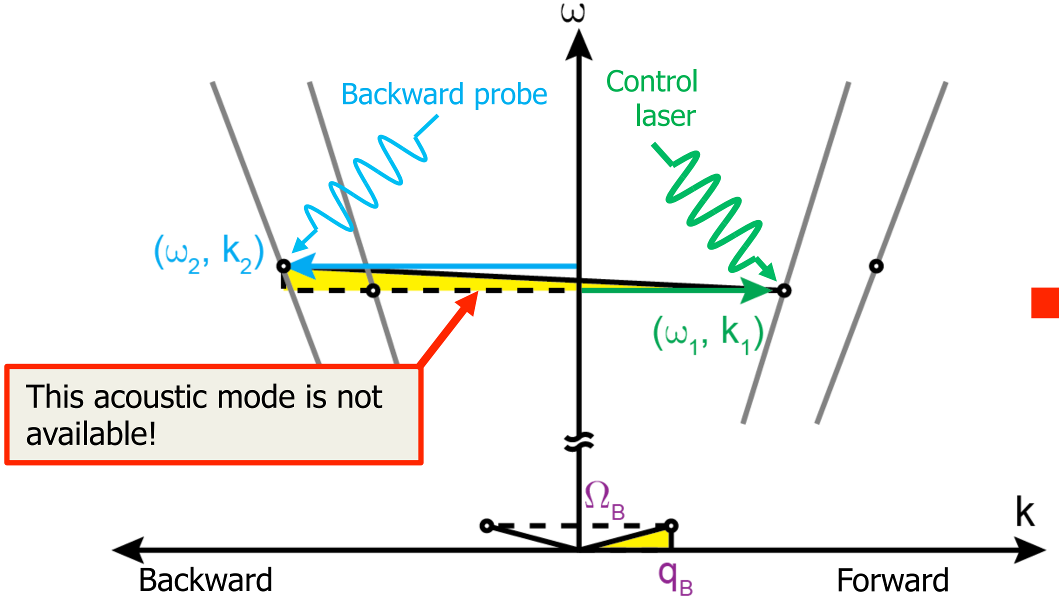
Long-lived
phonon state

Brillouin interactions are nonreciprocal since momentum rules apply

Nature Physics, 11(3), p.275, 2015



Acousto-optic interaction
+
Brillouin Scattering Induced Transparency (BSIT)

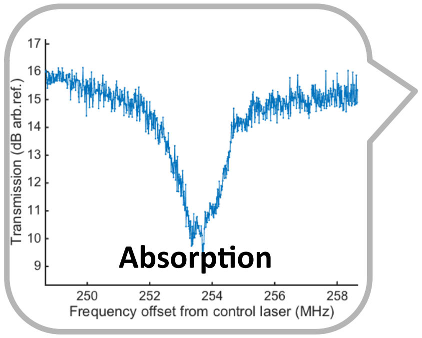


This acoustic mode is not available!

System is not T-symmetric upon probe reversal
+
Interaction will not take place and light will be absorbed.

Observing nonreciprocal light transmission

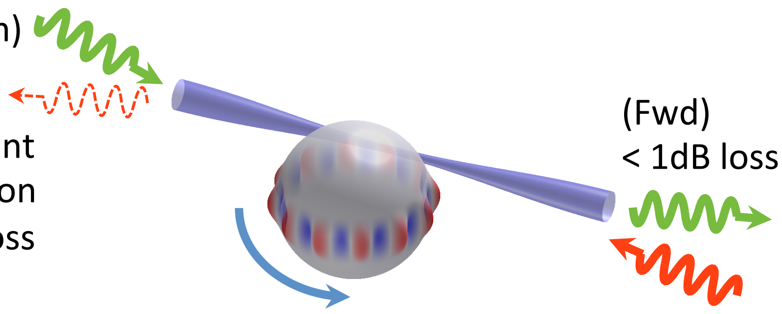
Nature Physics, 11(3), p.275, 2015



Absorption

Forward input
(780 nm)

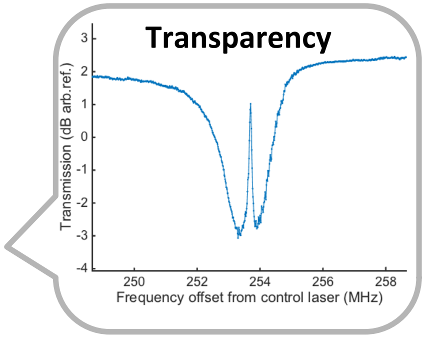
(Rev) Resonant
absorption
> 30 dB loss



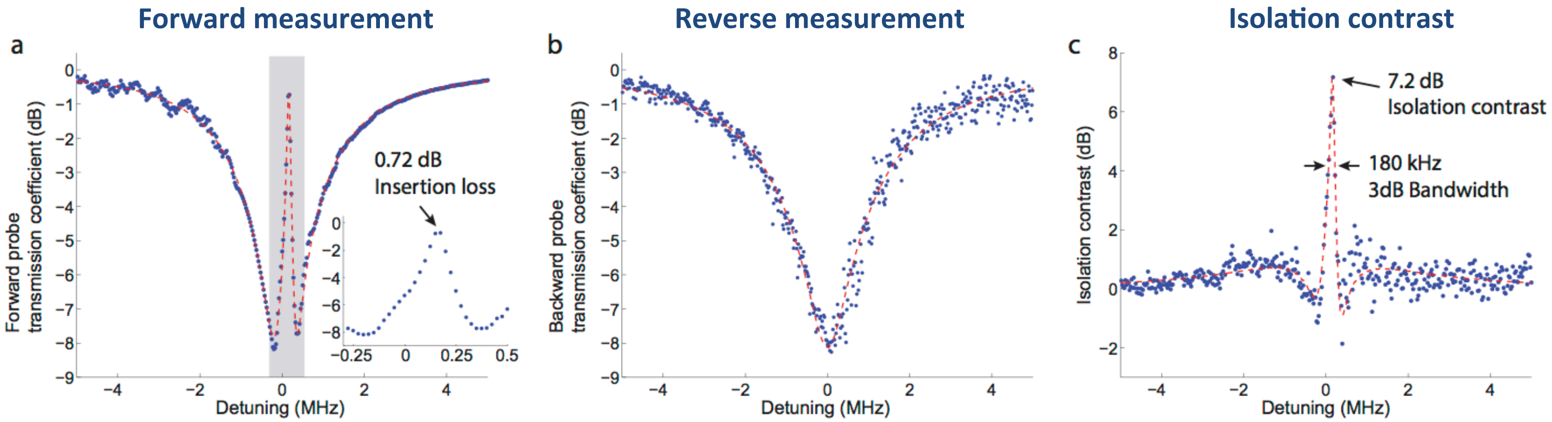
(Fwd)
< 1dB loss

Opto-acoustic
Coupling
(Brillouin Scattering)

Reverse
input (780 nm)



Transparency



Forward measurement

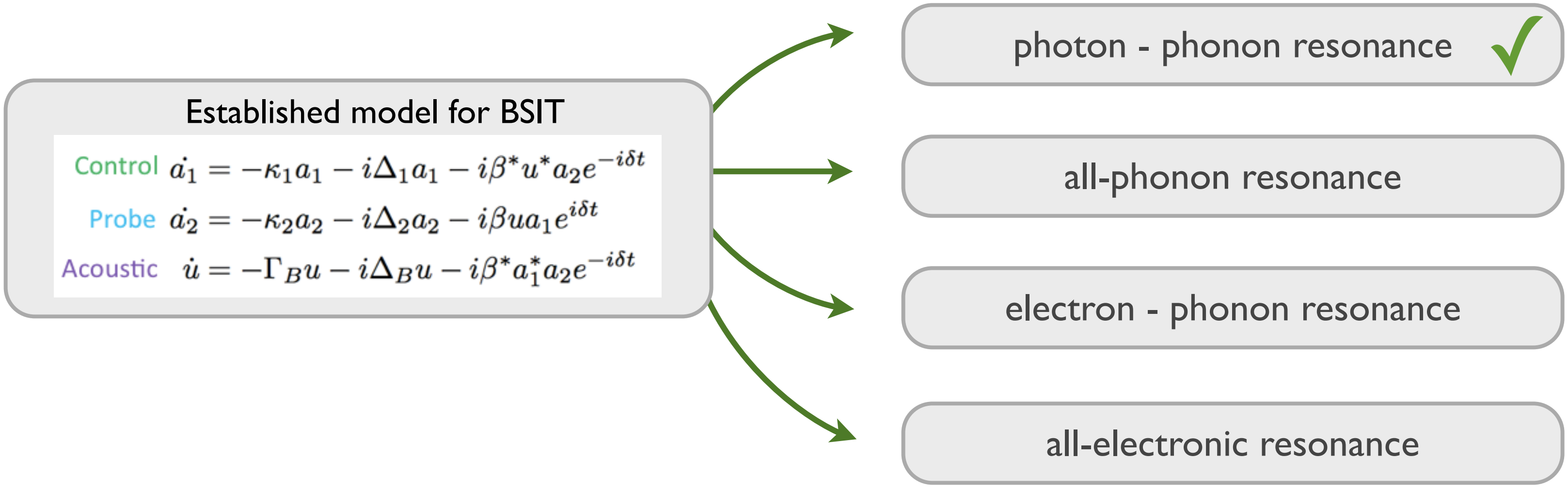
Reverse measurement

Isolation contrast

⇧
Induced transparency

⇧
Absorption only

- We know how to map other coupled-wave systems to the same set of fundamental equations. *Electromagnetic/RF fields included! Acoustic systems too.*



Established model for BSIT

Control $\dot{a_1} = -\kappa_1 a_1 - i\Delta_1 a_1 - i\beta^* u^* a_2 e^{-i\delta t}$

Probe $\dot{a_2} = -\kappa_2 a_2 - i\Delta_2 a_2 - i\beta u a_1 e^{i\delta t}$

Acoustic $\dot{u} = -\Gamma_B u - i\Delta_B u - i\beta^* a_1^* a_2 e^{-i\delta t}$

photon - phonon resonance ✓

all-phonon resonance

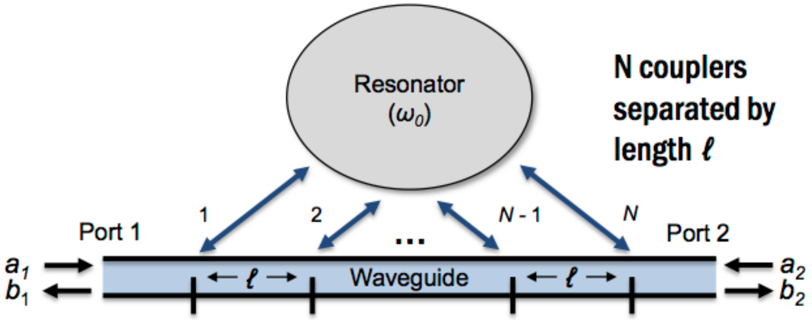
electron - phonon resonance

all-electronic resonance

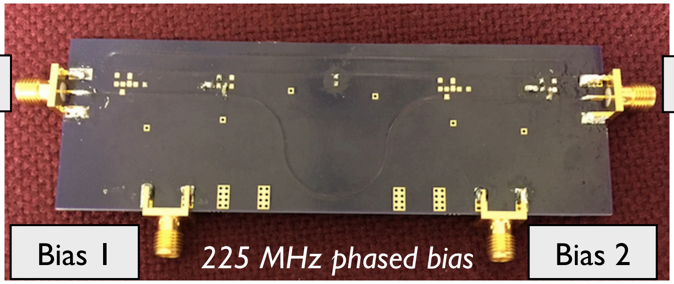
<u>IMPACT</u>

- Manipulating the flow of photons
- Non-magnetic optical isolators for cold-atom systems (position, navigation, timing)
- Manipulating the flow of <u>phonons</u> (one-way heat transfer, sound isolation)
- Possibility of non-reciprocal active surfaces, with implications for cloaking / active stealth

Microwave circuits inspired by nonlinear optics



N couplers separated by length ℓ



Input

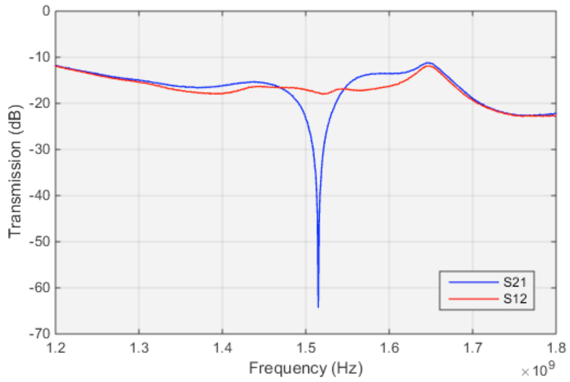
Output

Bias 1

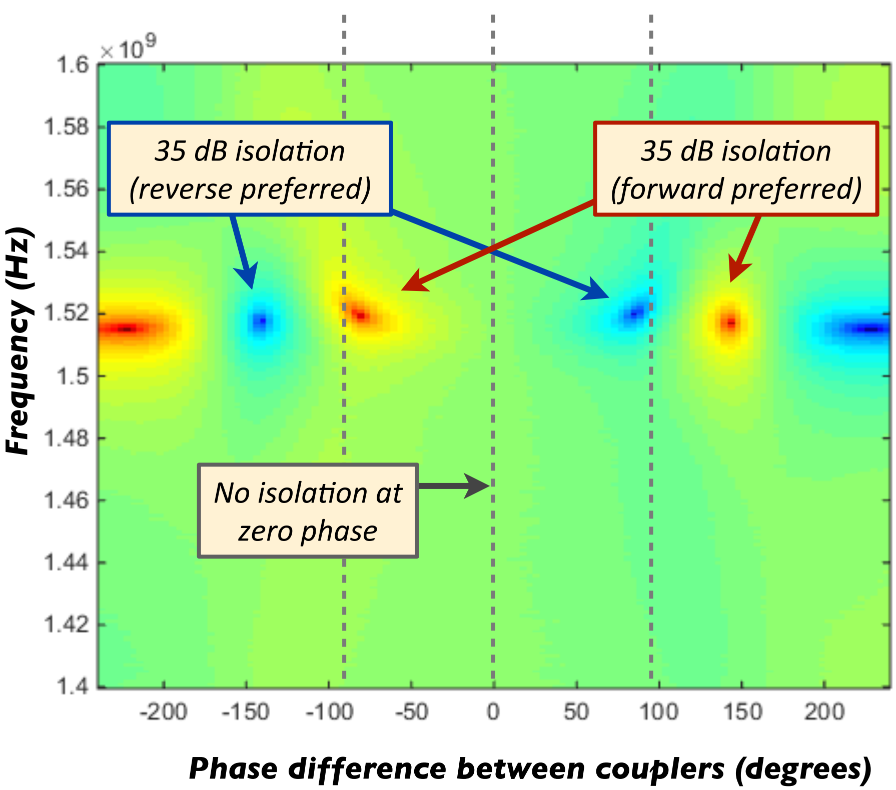
225 MHz phased bias

Bias 2

Example S_{21} and S_{12} measurement



Reconfigurable isolation (S_{21}/S_{12}, dB)



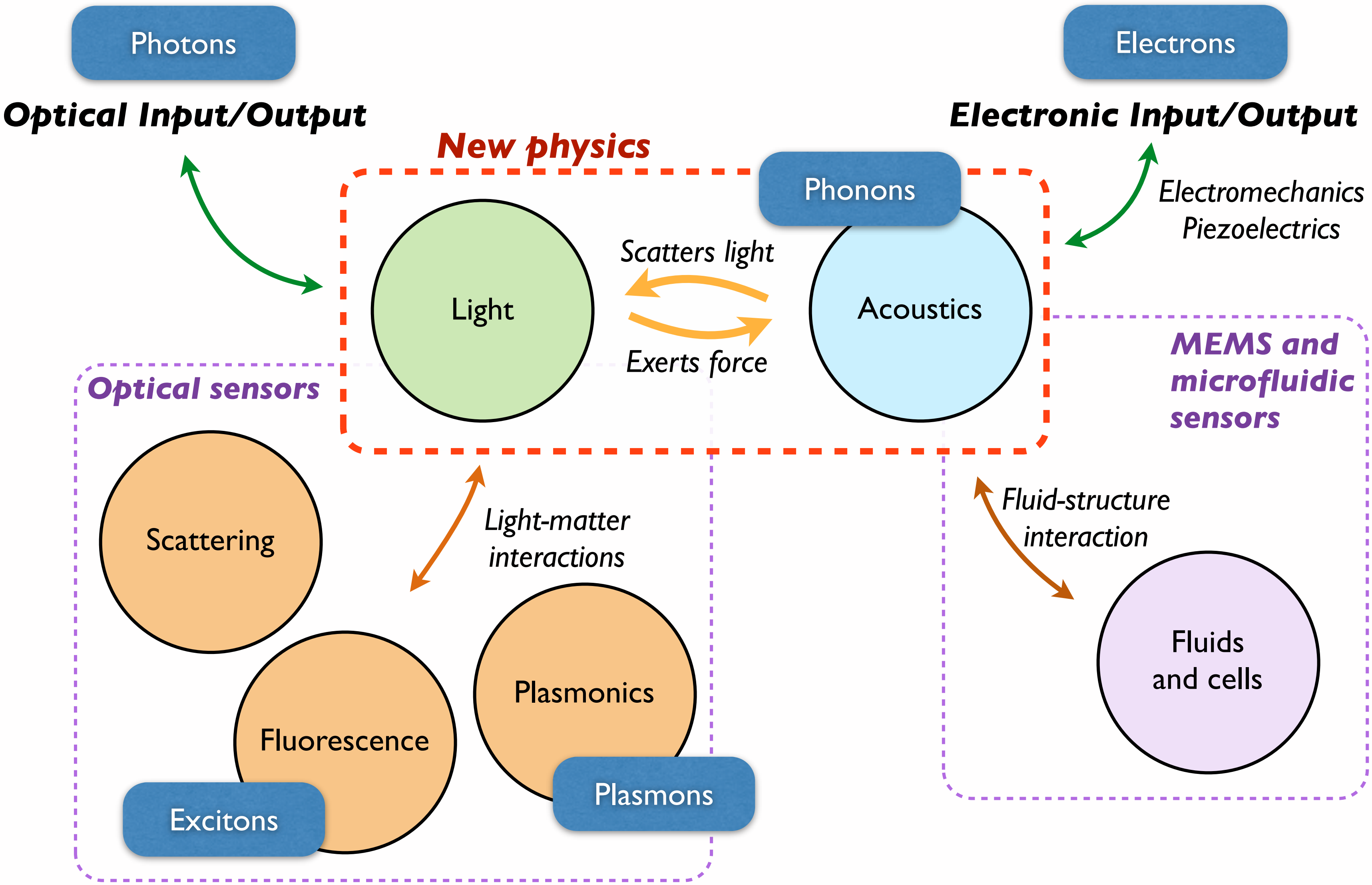
35 dB isolation (reverse preferred)

35 dB isolation (forward preferred)

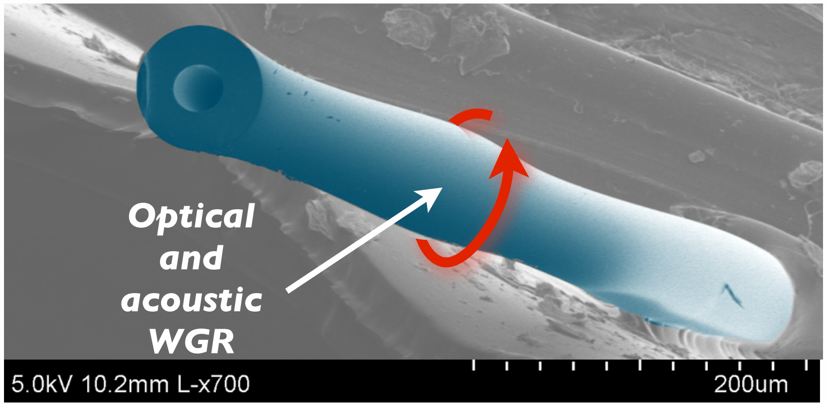
No isolation at zero phase

Extreme throughput optomechanical microfluidics

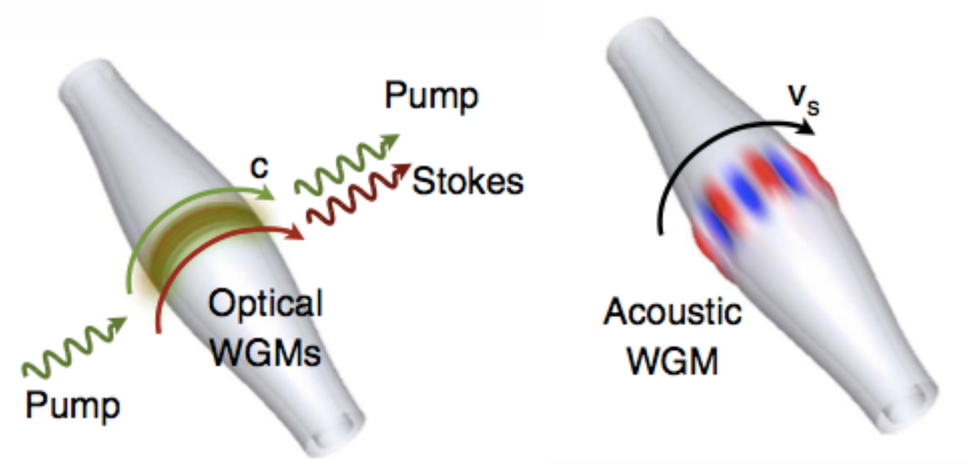
Bridging existing biosensing modalities with optomechanics/SBS



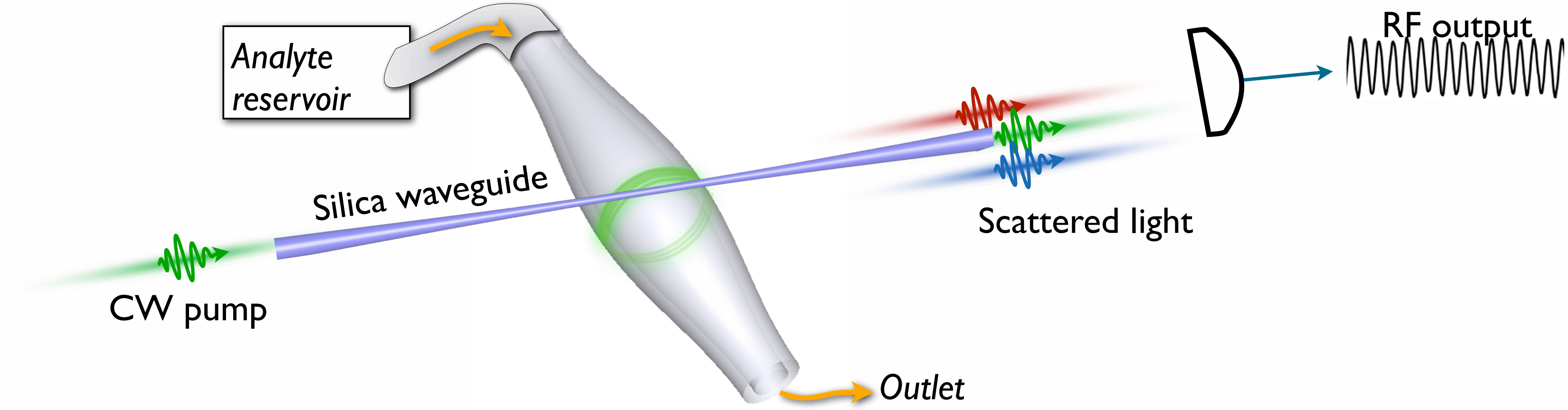
Opto-mechano-fluidic microresonators



$Q_{optical}$ = 160 million



Bottle shape enables simultaneous confinement of optical and acoustic WGMs



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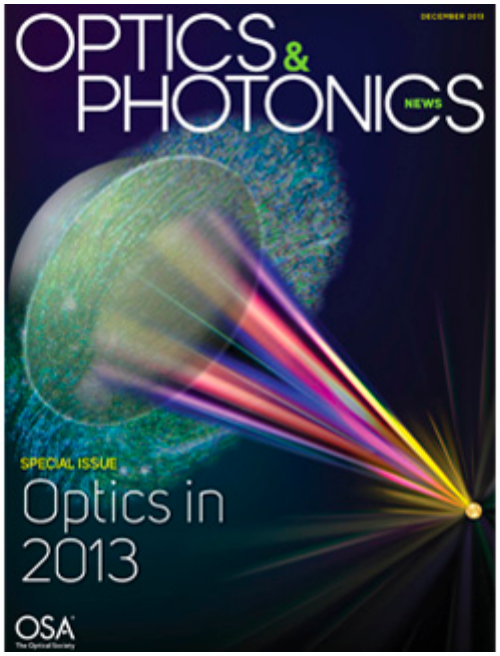

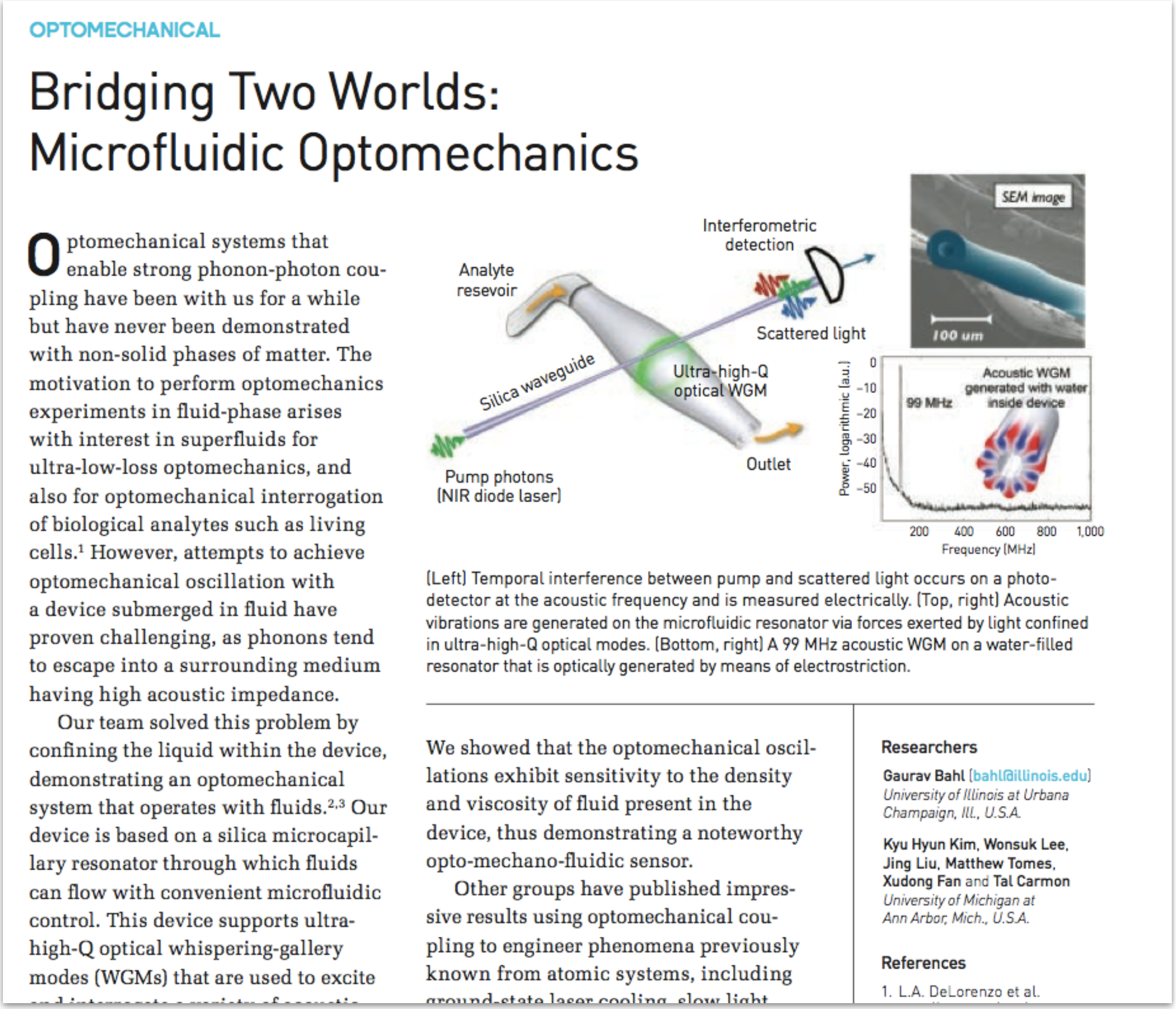

OPTOMECHANICAL

Bridging Two Worlds: Microfluidic Optomechanics

Optomechanical systems that enable strong phonon-photon coupling have been with us for a while but have never been demonstrated with non-solid phases of matter. The motivation to perform optomechanics experiments in fluid-phase arises with interest in superfluids for ultra-low-loss optomechanics, and also for optomechanical interrogation of biological analytes such as living cells.[1] However, attempts to achieve optomechanical oscillation with a device submerged in fluid have proven challenging, as phonons tend to escape into a surrounding medium having high acoustic impedance.

Our team solved this problem by confining the liquid within the device, demonstrating an optomechanical system that operates with fluids.[2,3] Our device is based on a silica microcapillary resonator through which fluids can flow with convenient microfluidic control. This device supports ultra-high-Q optical whispering-gallery modes (WGMs) that are used to excite

(Left) Temporal interference between pump and scattered light occurs on a photodetector at the acoustic frequency and is measured electrically. (Top, right) Acoustic vibrations are generated on the microfluidic resonator via forces exerted by light confined in ultra-high-Q optical modes. (Bottom, right) A 99 MHz acoustic WGM on a water-filled resonator that is optically generated by means of electrostriction.

We showed that the optomechanical oscillations exhibit sensitivity to the density and viscosity of fluid present in the device, thus demonstrating a noteworthy opto-mechano-fluidic sensor.

Other groups have published impressive results using optomechanical coupling to engineer phenomena previously known from atomic systems, including

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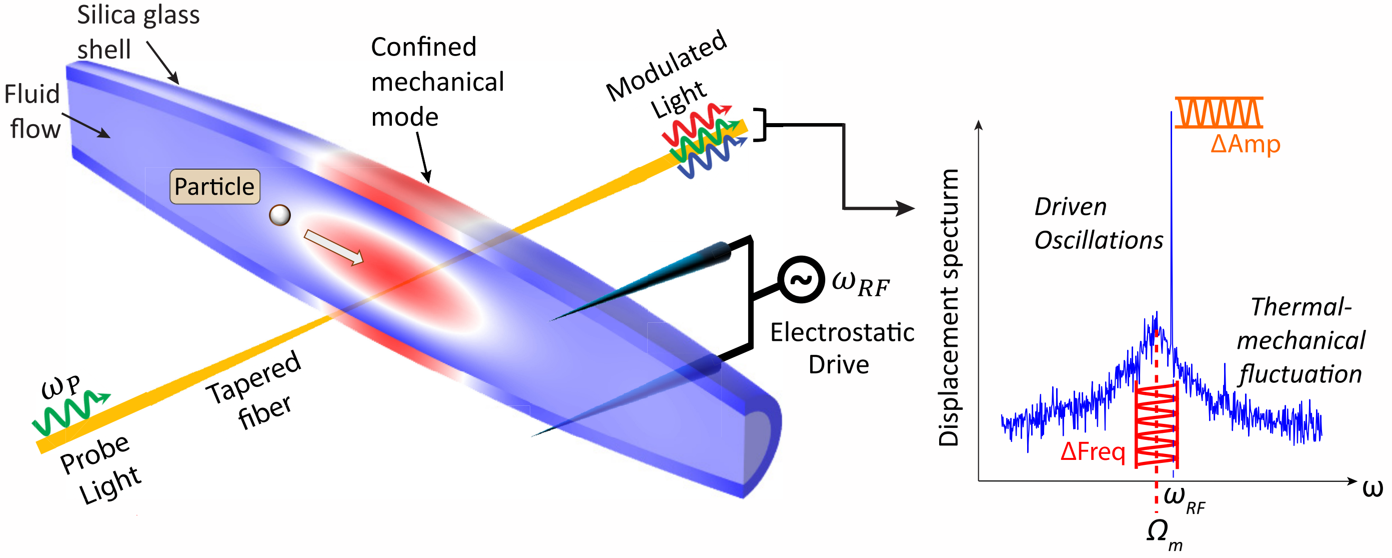
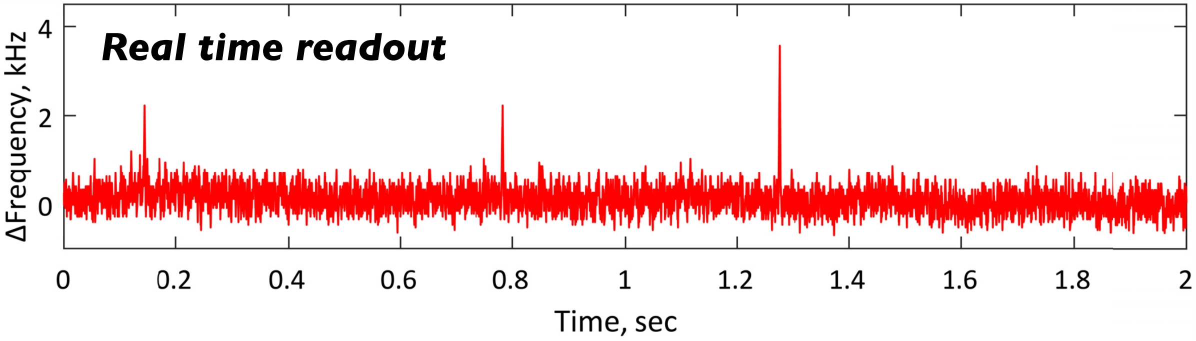
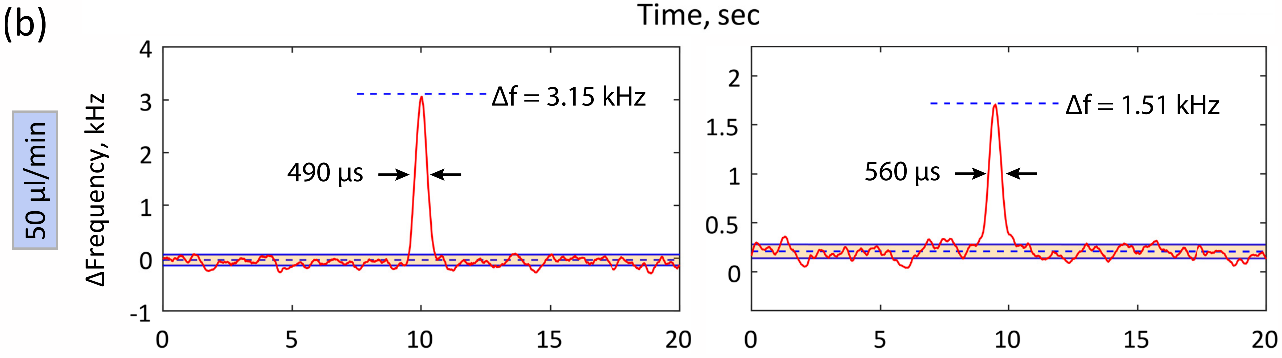
References

1. L.A. DeLorenzo et al.

Current effort -- Extreme throughput sensing of microparticles







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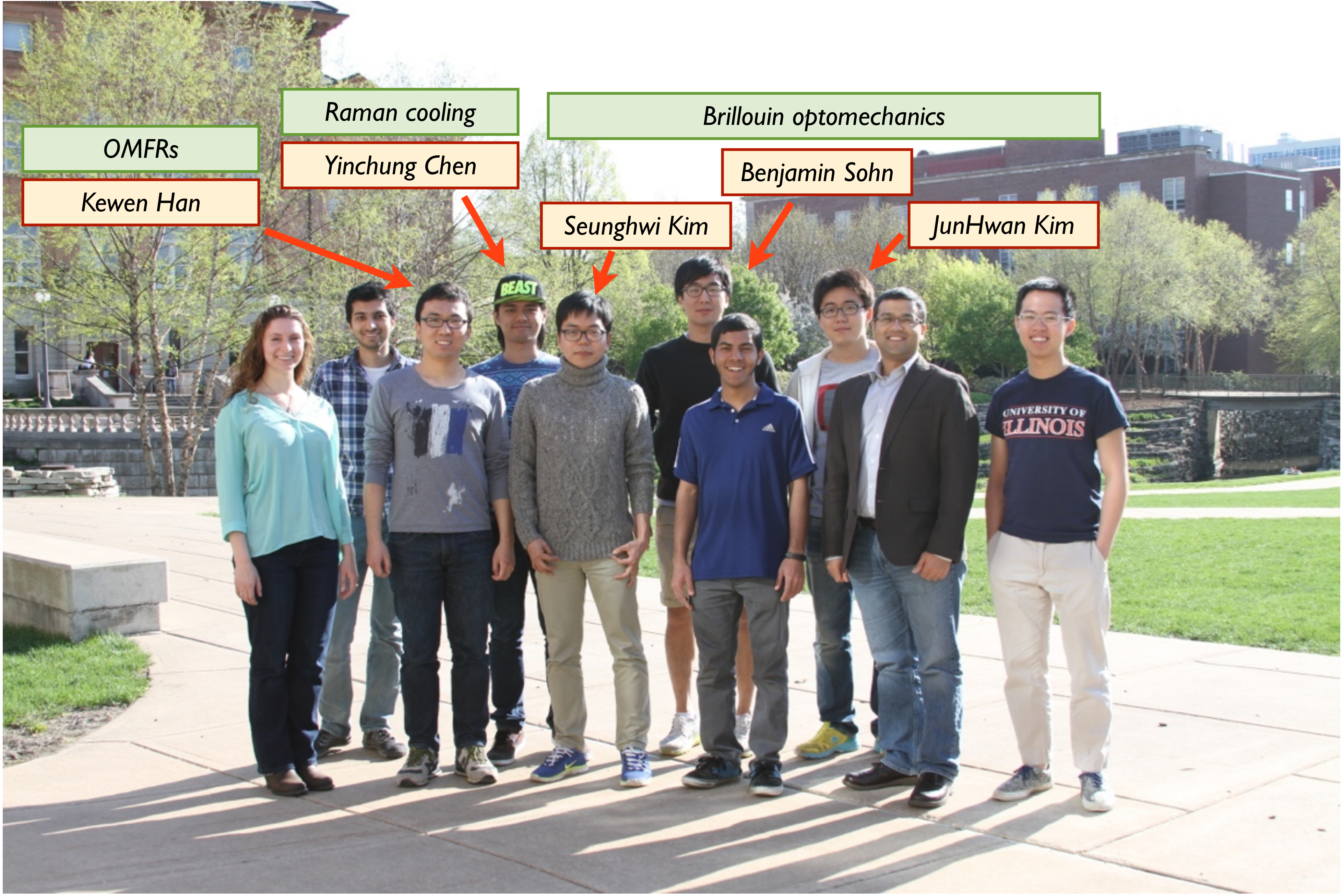

OMFRs

Kewen Han

Raman cooling

Yinchung Chen

Brillouin optomechanics

Seunghwi Kim

Benjamin Sohn

JunHwan Kim

Key citations

Brillouin optomechanics, Cooling, Nonreciprocal BSIT

Brillouin cooling	Observation of spontaneous Brillouin cooling G. Bahl, M. Tomes, F. Marquardt, T. Carmon Nature Physics, Vol.8, doi:10.1038/nphys2206 (2012)
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SBS microfluidic optomechanics	Brillouin cavity optomechanics with microfluidic devices G. Bahl, K.H. Kim, W. Lee, J. Liu, X. Fan, T. Carmon Nature Communications, 4:1994 (2013)
Theory for Raman cooling	Raman cooling of solids through photonic density of states engineering Y. Chen, G. Bahl Optica 2(10), pp.893-899 (2015)