Optoelectromechanical quantum interfaces: from mechanical memory to nonreciprocal state conversion

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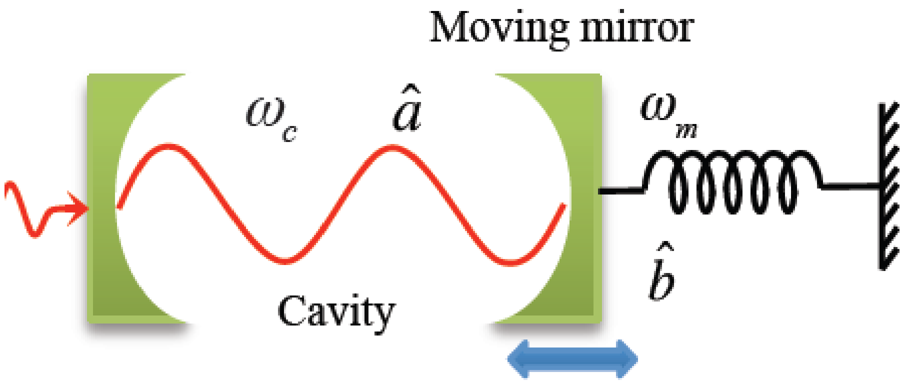
The 8th IWSSQC, NTU, Taiwan, Dec. 2016



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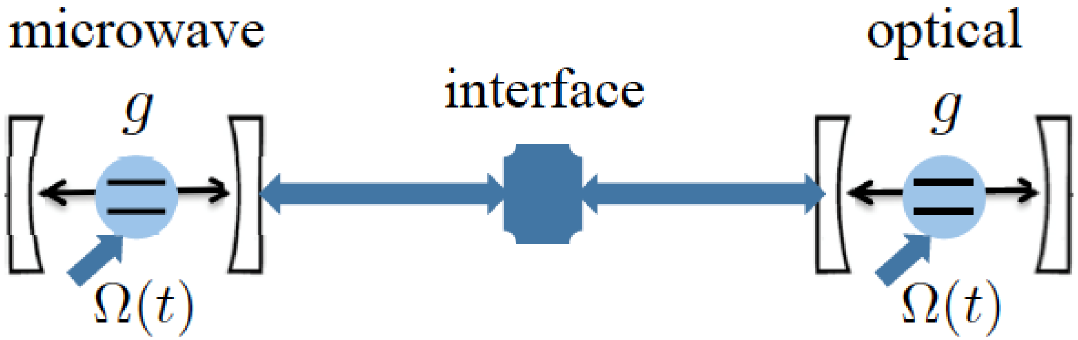
COINS

Outline of Talk

- Quantum network and hybrid quantum systems
- Mechanical systems in the quantum limit
- Electro- and opto-mechanical couplings
- Optoelectromechanical interface and state conversion
- Nonreciprocal quantum state conversion

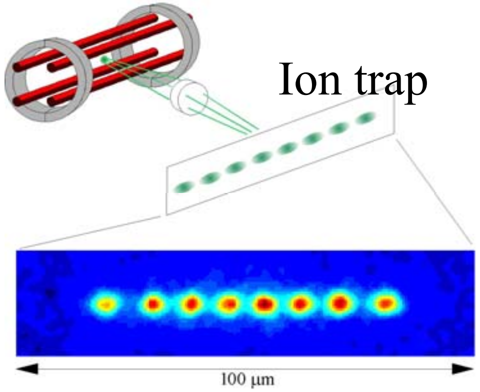
This talk covers basic concepts, recent theory and experiments

Quantum network and hybrid quantum systems

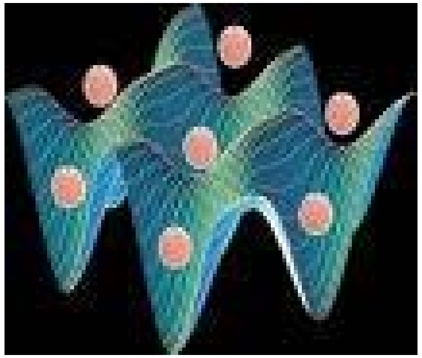


Quantum Technology - New Frontier

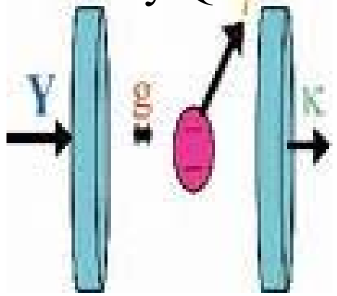
Ion trap



Atoms in lattice



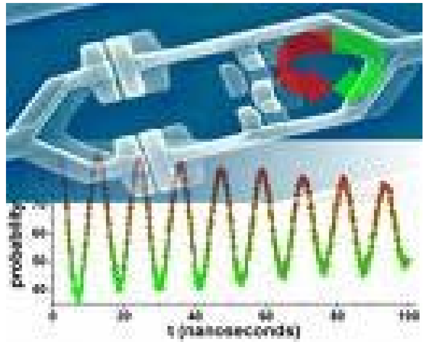
Cavity QED



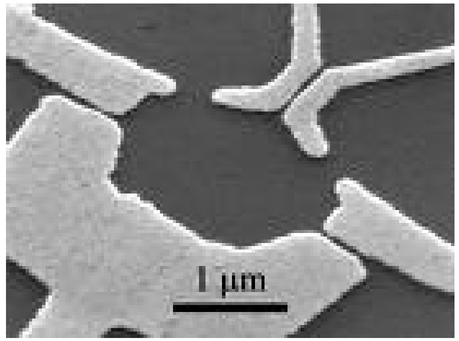
Exciting progress!

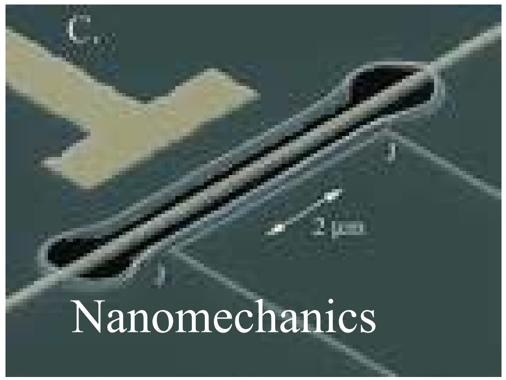
- Advances in system fabrication
- Coherence properties
- Merging of different technology
- Merging of microscopic and macroscopic physics
- Quantum applications (computing, security, communication, metrology, force detection, state engineering…)
- Conceptual issue (entanglement, quantum information, many body physics…)

Superconducting qubit



Quantum dots





Nanomechanics

Quantum Information Processing and Quantum Network

Quantum computers – nodes for computing formed by quantum bits (qubits); quantum logic gates performed

Quantum resources – entanglement, single photon sources, qubit preparation, ancilla systems

Classical resources – information processing units, external pumps

Technical difficulties -- noise and decoherence, quantum control issue, scalability

Channels for communication of quantum and classical information

- Connect quantum nodes – identical or hybrid systems
- Connect resources to quantum nodes
- Advance coherence and scalability

Hybrid quantum systems

- Combining the merits of different systems to build scalable quantum computers

  Atomic qubits – long live time – as quantum memories
  Solid-state qubits – tunable couplings – used to perform quantum logic gates
  e.g., L. Tian et al, PRL (2004) superconducting device + trapped ions

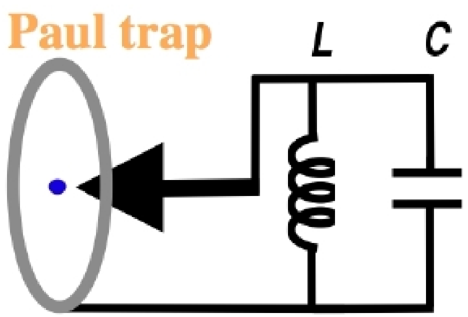
- Recent experiments on various hybrid systems

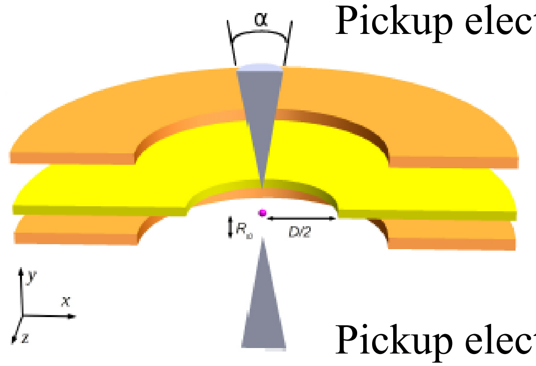
D. Petrosyan et al PRA 79, 040304 (2009) atomic ensemble + SCR
K. D. Petersson et al, Nature 490, 380 (2012) quantum dot + SCR
X. Zhu et al, Nature 478, 221 (2011) NV centers + SC flux qubit
S. Camerer et al, PRL 107, 223001 (2011) atoms + optomechanics

Hybrid quantum systems

Trapped particle and superconducting circuits

- Driven electron motion in nonlinear potential gives parametric coupling





Particle (electron) trapped by effective harmonic potential
- Careful trap simulation was done (micro-motion considered)
Coupling to pick-up electrode to connect with superconducting circuit
- Parametric driving on nonlinear potential to achieve energy conversion

$$U_{eff} = g x^2 \dot{\varphi}$$

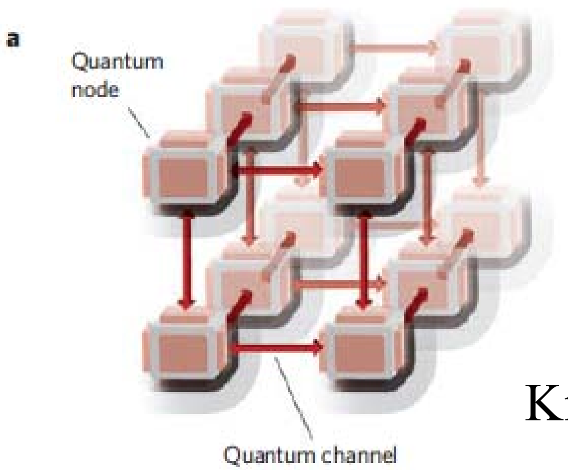
No extra circuit noise in our scheme
N. Daniilidis, D. Gorman, LT, H. Haeffner, NJP 15, 073017 (2013)

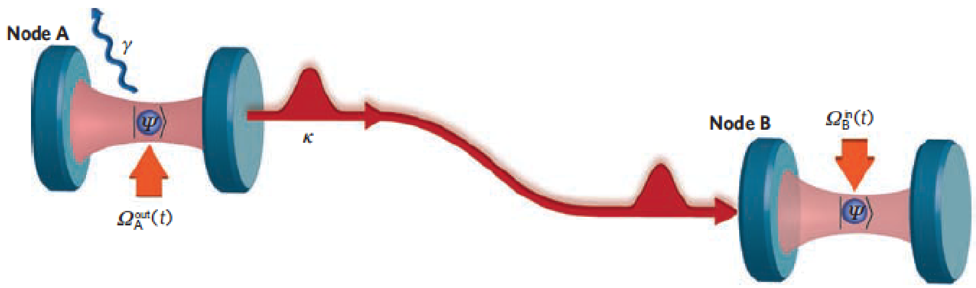
Quantum networks

- Scalable quantum computers: quantum nodes for storage and processing of quantum information

- Quantum data bus for transmission of quantum states and entanglement

Cirac et al PRL 78, 3221 (1997); Stannigel et al PRL 105, 220501 (2010)

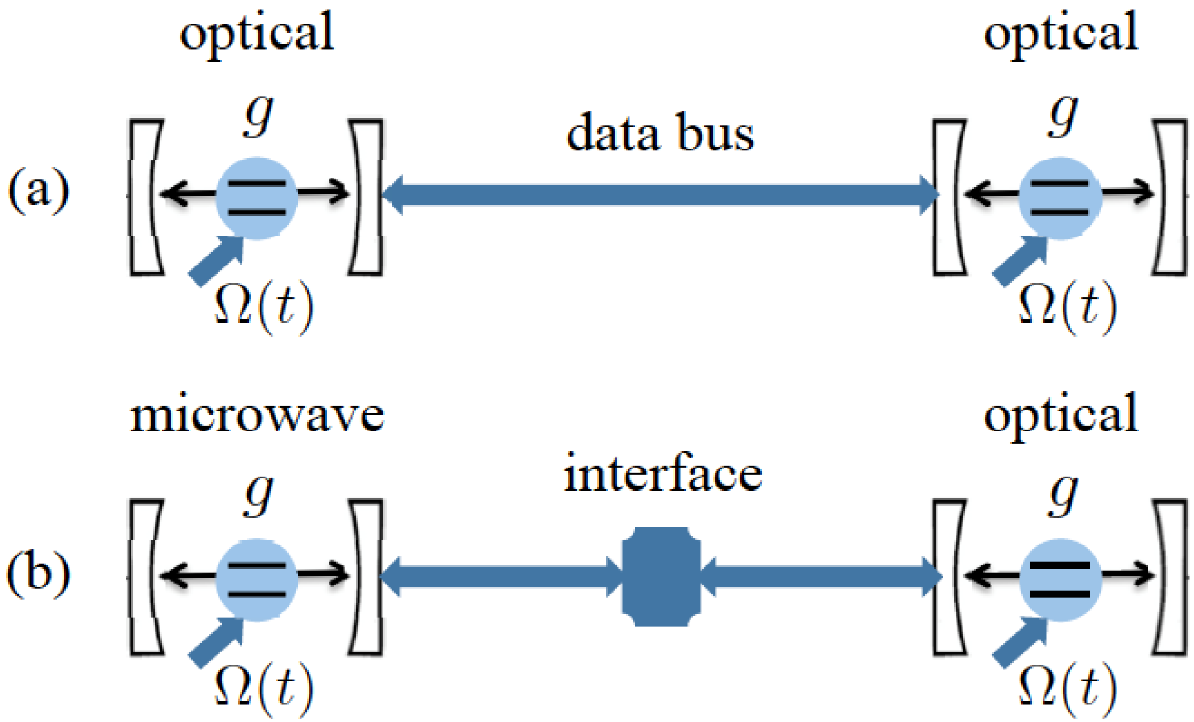




Kimble, Nature 453, 1023 (2008)

Quantum networks

- State transmission in hybrid quantum networks
- Requires interface to convert different frequencies



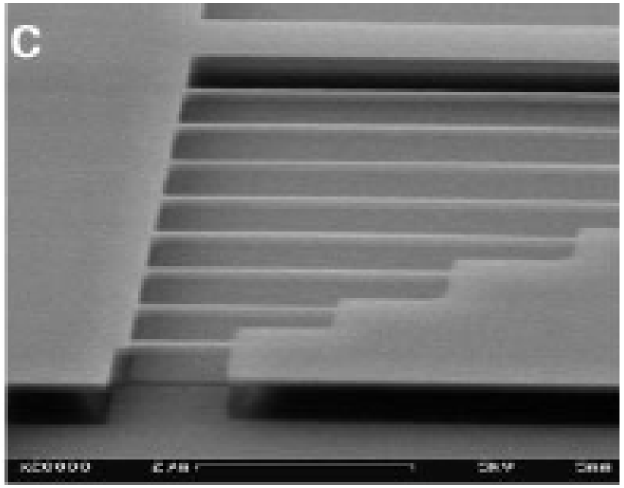
How to?

Mechanical systems in the quantum limit

Mechanical Resonator

1. Sometime ago

- Vibration of strings
- Dynamics – Euler-Bernoulli Eq.



2. Now, the decrease of size provides:

high frequency -- GHz

high $Q - 10^{5\text{-}7}$ & $\Gamma = \omega_0/Q$

$$f_0 = \frac{(4.730)^2}{2\pi}\frac{1}{l^2}\sqrt{\frac{EI}{\rho A}}$$

E: Young Modulus

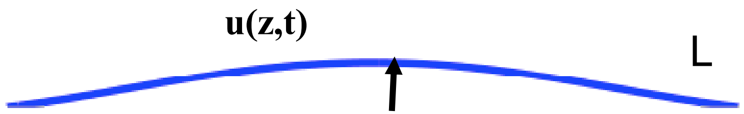
I: moment of inertia

ρ_a : linear density

3. Eigenmodes

a doubly clamped beam, flexural modes

$$H_v = \sum \frac{p_q^2}{2m} + \frac{m\omega_q^2 u_q^2}{2}$$



4. Can it be quantum mechanical?

Quantization of harmonic oscillator mode $[u_q, p_q] = i\hbar$ Quantum

High quality factor over 10,000,000

Keep coherence for a long time once it becomes coherent

Macroscopic quantum effects: with large number of atoms

Leggett (1980's)

Decoherence by gravitational wave, Blencowe PRL (2013)

Obstacles to become quantum:

- Thermal fluctuations, in dilution fridge with T=24 mK=500 MHz,

for resonator frequency 10 MHz, tens of excitations

- Preparation of quantum states: coupling with other system is weak

Approaching the quantum limit: cooling and other quantum tools

J. D. Teufel et al., Nature (2011); J. Chan et al., Nature (2011).

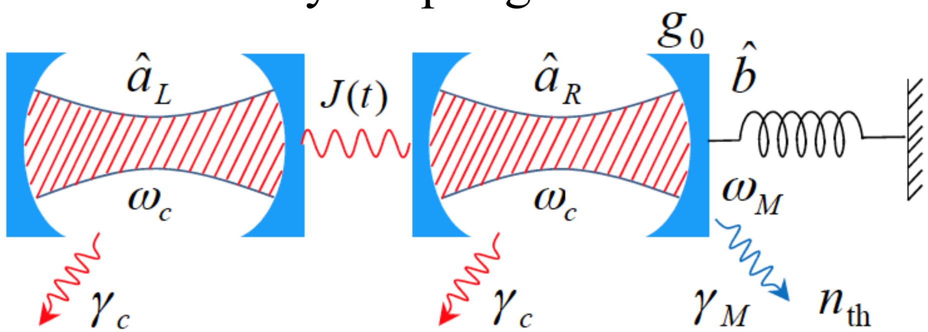
M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, RMP 86, 1391 (2014).

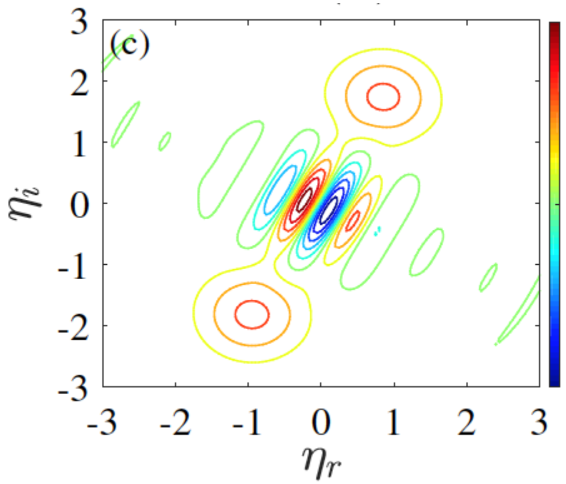
Superposition of Mechanical States

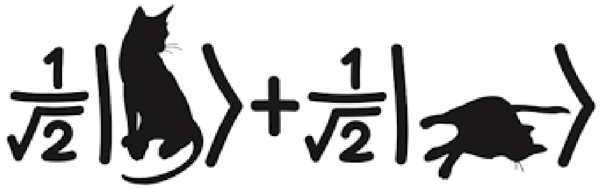
- Recent progress in cavity optomechanics enables state-of-art control of mechanical modes via cavity photon field (microwave, optical)
- Obstacle in direct optomechanical operations is the coupling strength,

Single photon coupling << cavity bandwidth and mechanical frequency

- Periodically modulated cavity coupling to enhance effective coupling





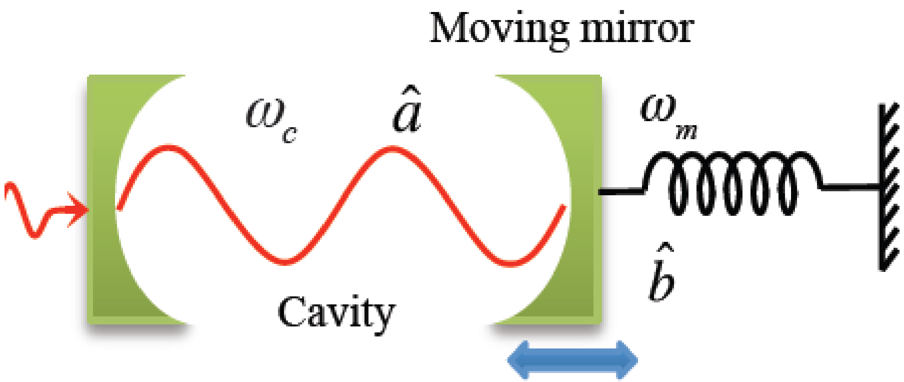


Picture from http://physics.stackexchange.com/

- Clear signature of quantum interference
- Fidelity not affected by cavity decay rate

J. Q. Liao and L. Tian, PRL 116, 163602 (2016)

Electro- and opto-mechanical couplings

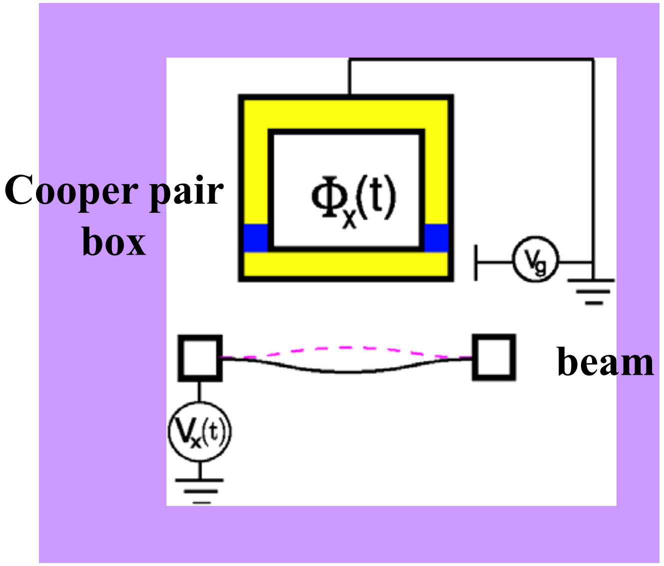


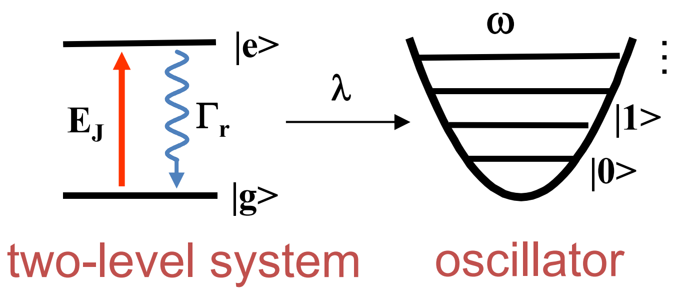
Mechanical Systems Coupled to …

Mechanical modes can be coupled to a broad range of systems

- Very different types of systems: solid-state devices, AMO system
- Systems in vastly different frequency regimes: microwave, optical
- Different forms of coupling models

It makes them useful in many applications, such as engineering quantum states and preparing system to ground state

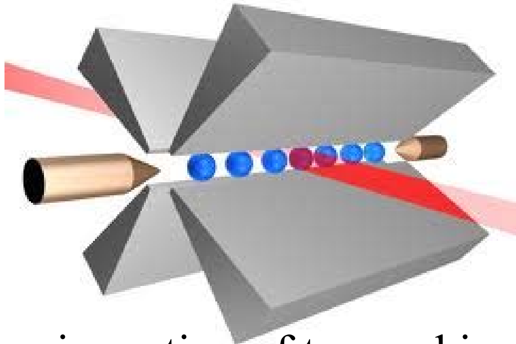




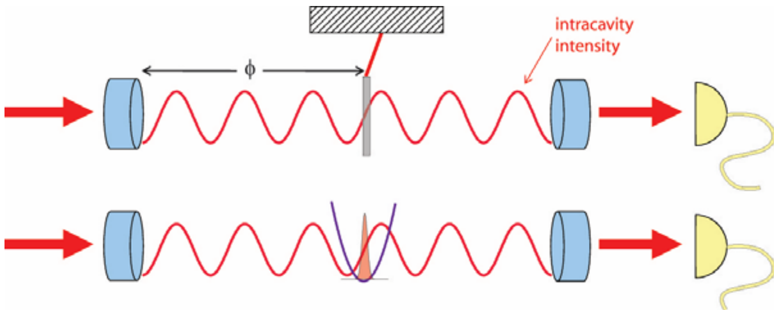
Armour, Blencowe, Schwab, PRL (2002)

Various forms of mechanical systems

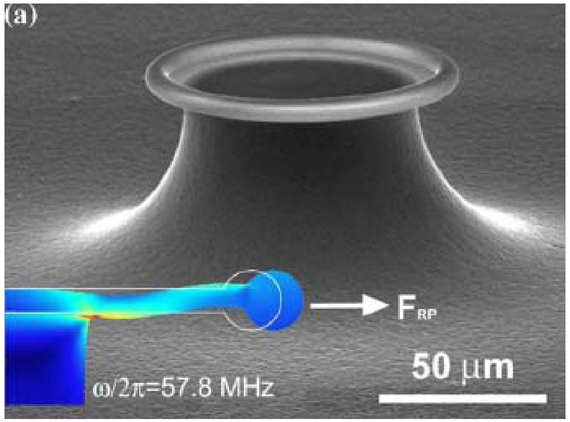
Several examples of mechanical systems



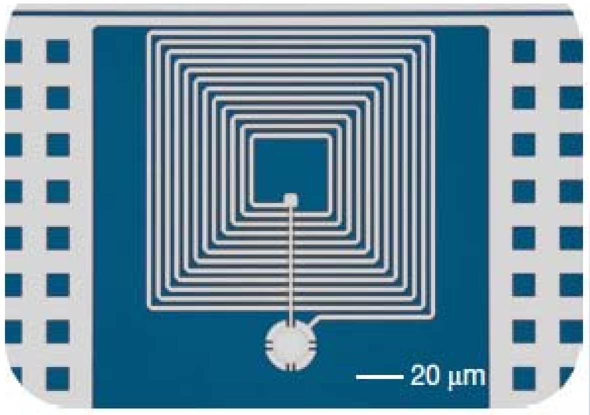
Harmonic motion of trapped ions
(Brown et al, Nature 2011)



Atomic cloud in optical cavity
(Brahms et al, 1109.5233)



Optomechanical systems
(Kippenberg,Vahala, Science 2008, review)



Nanoelectromechanical systems
(Teufel et al, Nature 2011)

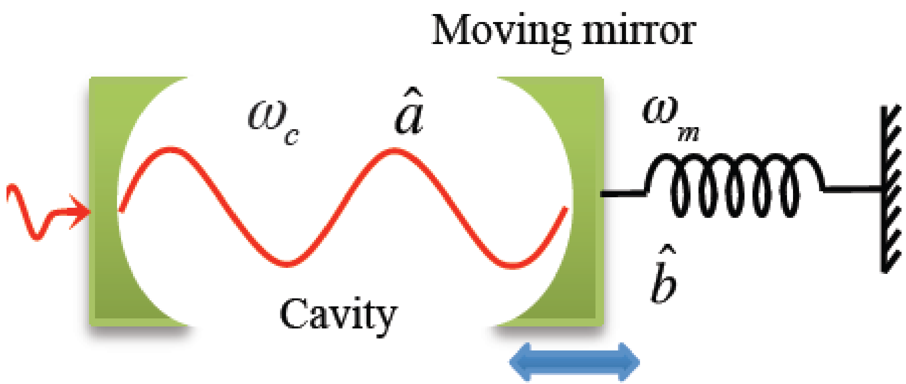
M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, RMP 86, 1391 (2014).

Electro- and opto-mechanical coupling

- Radiation-pressure force on mirror proportional to photon number

$$H_G = -G_i a_i^\dagger a_i q$$

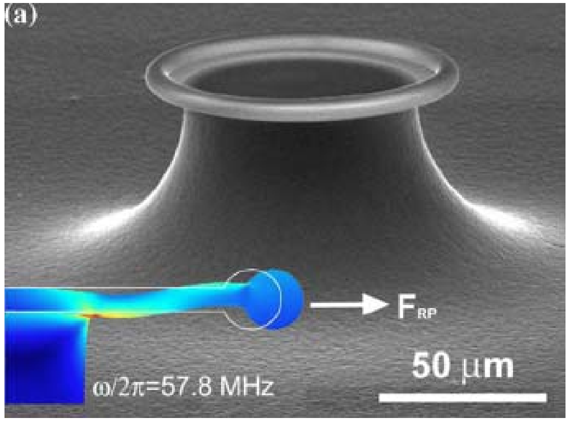
C. K. Law, PRA 51, 2537 (1995).



- Shifts photon frequency with mechanical displacement

- Shifts mirror position by photon number

- Often single-photon coupling strength G is 1-100 kHz, much weaker than other energy scales



Electro- and opto-mechanical coupling

- Different forms of coupling can be studied

Coupling between different cavity modes

$$H_{int} = \hbar G \hat{a}_1^\dagger \hat{a}_2 (\hat{b}_m + \hat{b}_m^\dagger) + h.c.$$

H. Cheung and C. K. Law, Phys. Rev. A 84, 023812 (2011).

Quadratic coupling between phonon number and photon number

$$H_{int} = \hbar G \hat{a}^\dagger \hat{a} \hat{b}_m^\dagger \hat{b}_m$$

J. D. Thompson et al, Nature (London) 452, 72 (2008).

Electro- and opto-mechanical coupling

- Apply strong driving field on cavity and linearize coupling

steady state amplitude a_{is}; laser detuning Δ_i; cavity damping κ_i

$$a_{is} = \frac{-iE_i}{\kappa_i/2 - i(\Delta_i + G_i q_s)}$$

$$\boxed{a_i \rightarrow a_i + a_{is}}$$

Red sideband driving – effective linear coupling $\omega_d = \omega_{ci} - \omega_m$

Beam splitter operation

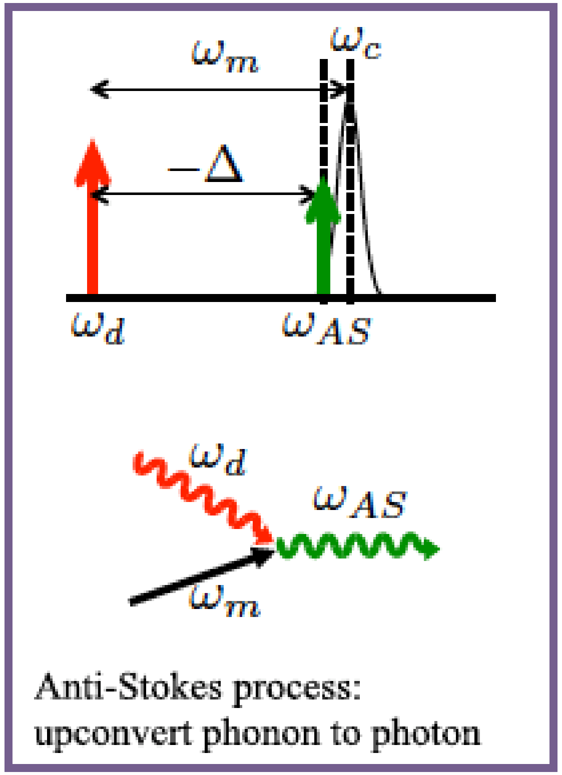
$$\boxed{H_{eff} = \epsilon_i a_i^\dagger b_m + \epsilon_i^\star b_m^\dagger a_i}$$

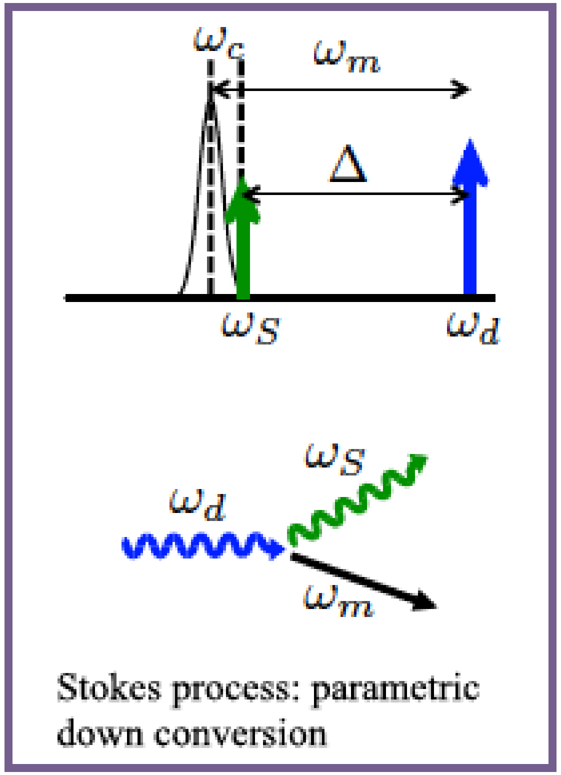
Blue sideband driving – effective bilinear coupling $\omega_d = \omega_{ci} + \omega_m$

Parametric down conversion

$$\boxed{H_{eff} = i\epsilon_i \left(a_i^\dagger b_m^\dagger - b_m a_i\right)}$$

Linearized couplings





Red detuned driving

$$\omega_d = \omega_{ci} - \omega_m$$

- Cooling
- State conversion

Blue detuned driving

$$\omega_d = \omega_{ci} + \omega_m$$

- Entanglement
- Two-mode squeezing

Review: L. Tian, Ann. Phys. (Berlin) 527, 1 (2015).

Linearized couplings

Bean-splitter Operation at red-detuned driving field

$$\boxed{H_{eff} = \epsilon_i a_i^\dagger b_m + \epsilon_i^\star b_m^\dagger a_i}$$

- Corresponds to anti-Stokes process
- Time evolution of the system operators

$$a_i(t) = \cos(\epsilon_i t) a_i(0) + i \sin(\epsilon_i t) b_m(0)$$
$$b_m(t) = \cos(\epsilon_i t) b_m(0) + i \sin(\epsilon_i t) a_i(0)$$

- Generates swapping between two modes with π/2 pulse

$$a_i(\pi/2) = i b_m(0)$$

$$b_m(\pi/2) = i a_i(0)$$

- State swapped up to a phase factor

Heisenberg-Langevin Equation

Effects of cavity and mechanical noise

- Input noise/signal on cavity and mechanical modes
- Dynamics described by Heisenberg-Langevin equation, g linearized coupling

$$\dot{\hat{a}} = i\Delta\hat{a} - ig\left(\hat{b}_m + \hat{b}_m^\dagger\right) - \frac{\kappa}{2}\hat{a} + \sqrt{\kappa}\,\hat{a}_{in}(t);$$

$$\dot{\hat{b}}_m = -i\omega_m\hat{b}_m - ig\left(\hat{a} + \hat{a}^\dagger\right) - \frac{\gamma_m}{2}\hat{b}_m + \sqrt{\gamma_m}\hat{b}_{in}(t).$$

a_{in} includes signal and noise $\hat{a}_{in}(t) = \sqrt{\kappa_{ext}/\kappa}\,\hat{a}_{p,in}(t) + \sqrt{\kappa_{in}/\kappa}\,\hat{a}_{s,in}(t)$

Internal damping rate and external damping rate $\kappa = \kappa_{ext} + \kappa_{in},$

Many discussions set $\kappa_{in} = 0$

- Output photon using input-output formalism $\hat{a}_{p,out}(t) = \hat{a}_{p,in}(t) - \sqrt{\kappa_{ext}}\hat{a}(t)$

  Strong-coupling limit $g \gg \kappa$, dominated by linearized couplings

  Weak-coupling limit $g \ll \kappa$ ımping plays important role

  Can be converted to frequency domain for constant couplings

Heisenberg-Langevin Equation

Converting itinerant photon into mechanical mode

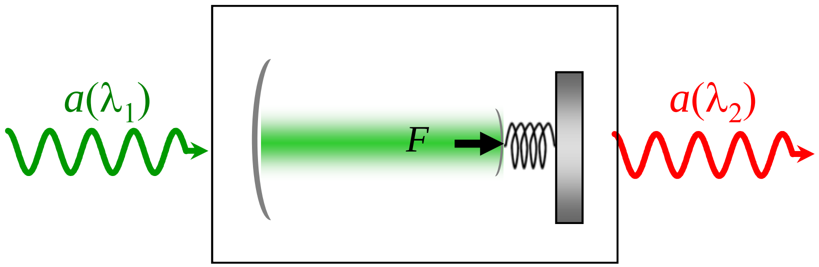
- Weak coupling regime $g \ll \kappa$ and $\kappa_{in} = 0$
- Adiabatically eliminate the cavity mode

- Under rotating-wave approximation

$$\boxed{\dot{\hat{b}}_m = i\sqrt{\Gamma}\hat{a}_{in}(t)} - \frac{\Gamma + \gamma_m}{2}\hat{b}_m + \sqrt{\gamma_m}\hat{b}_{in}(t) \qquad \Gamma = 4g^2/\kappa$$

Similar to beam-splitter operation, conversion between b_m and a_{in}

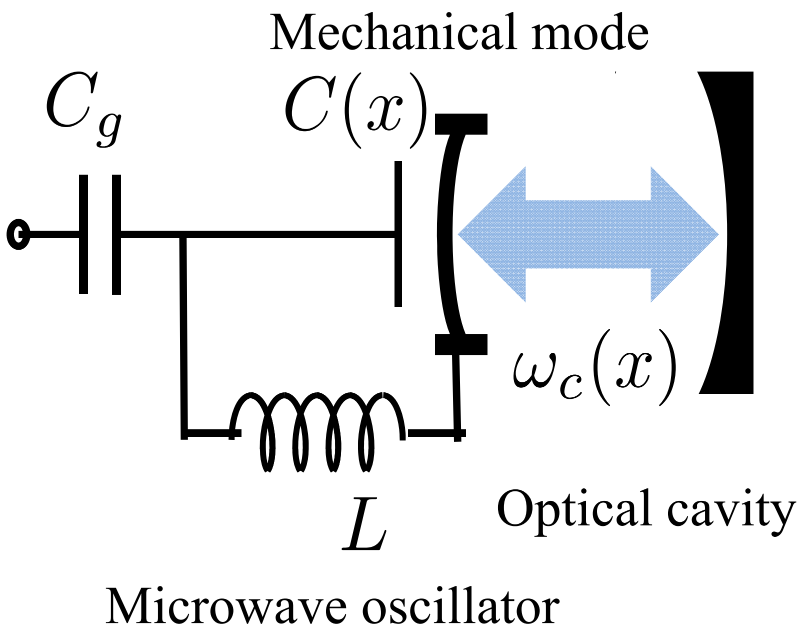
Without driving field, vacuum is converted to resonator – cooling



- Experimental demonstration of state transfer and cavity-mechanical mode entanglement; effect of mechanical noise

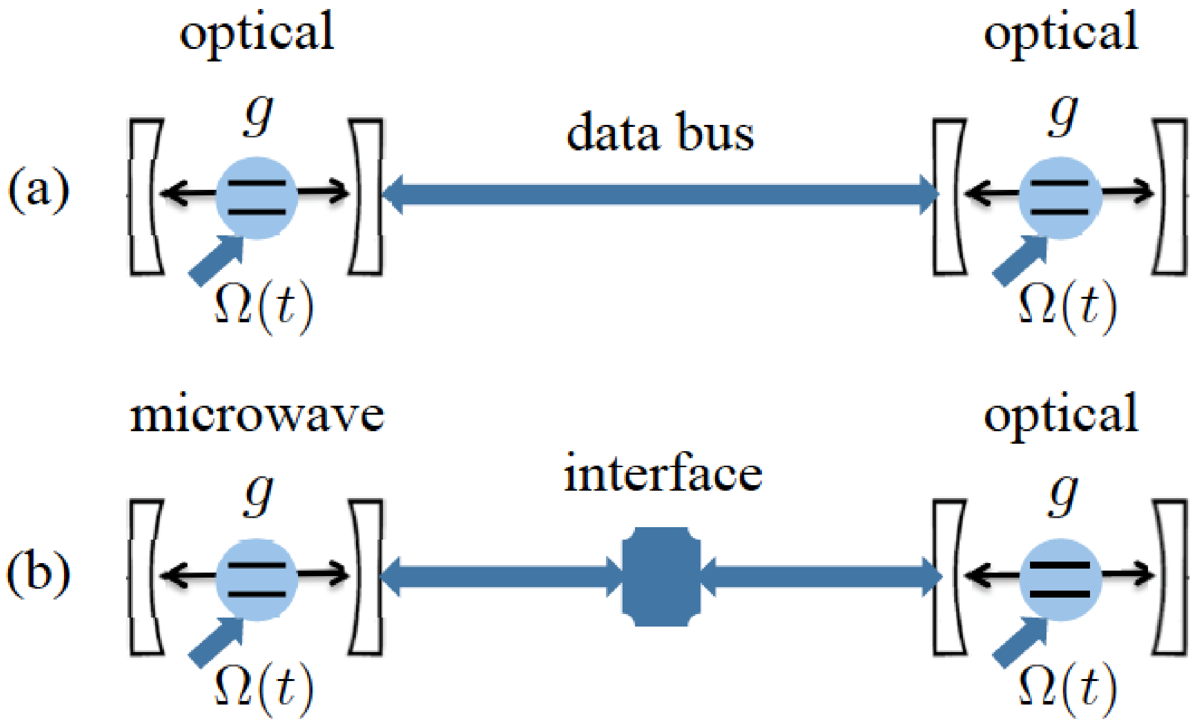
T. A. Palomaki et al., Nature (London) 495, 210 (2013).

Optoelectromechanical interface and state conversion



Quantum networks

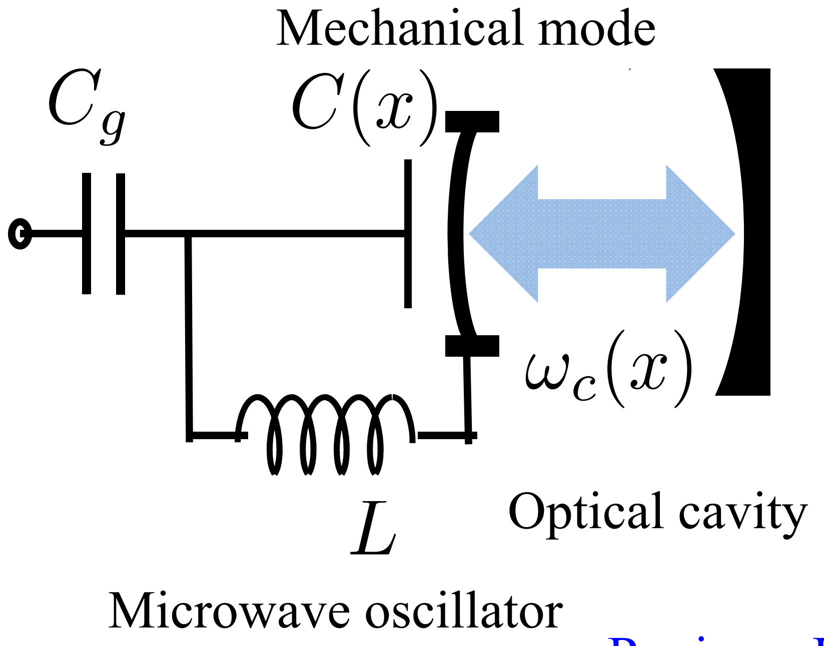
- State transmission in hybrid quantum networks
- Requires interface to connect systems of different frequencies

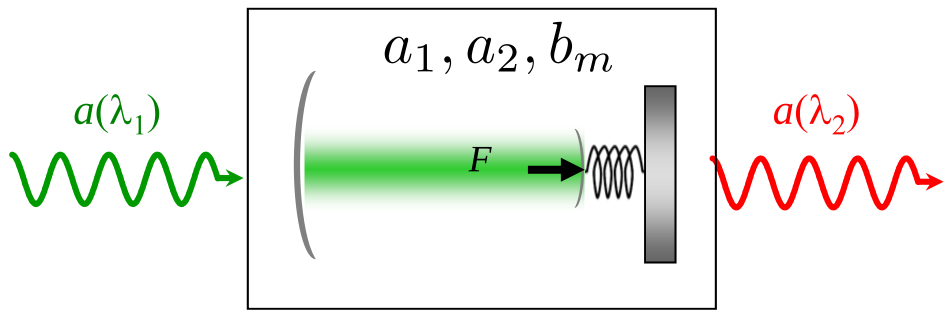


Optoelectromechanical quantum interface

- Controllable and strong light-matter coupling enhanced by driving
- Mechanical mode connects very different systems

  optical channel – mechanical mode - microwave channel
- Connect different parts of a hybrid quantum network
- Other forms with multiple cavity and mechanical modes can be studied

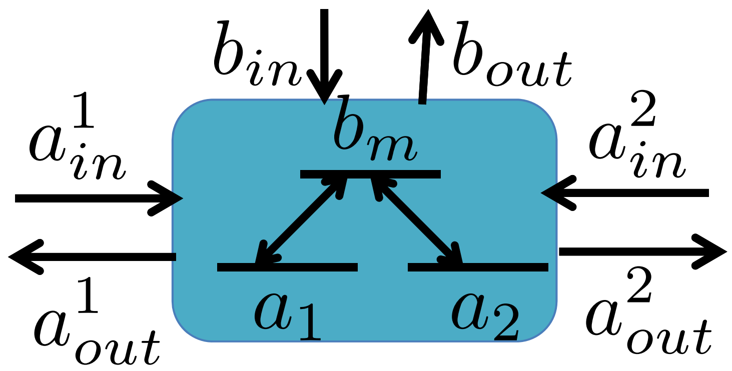




Review: L. Tian, Ann. Phys. (Berlin) 527, 1 (2015)

Optoelectromechanical quantum interface

Two cavity modes (quantum channels) and a mechanical mode (interface)
Cavity modes can have distinct frequency – microwave, optical … (hybrid)
Input, output channels for all three modes – mechanical thermal noise

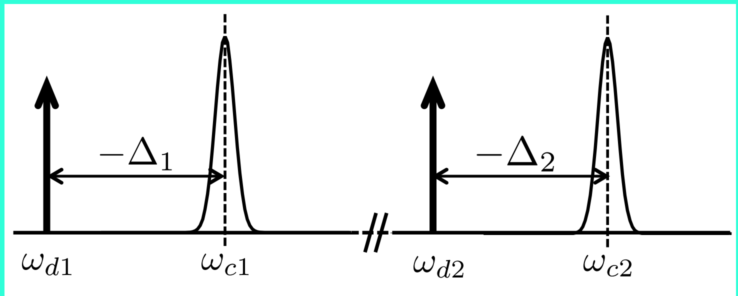


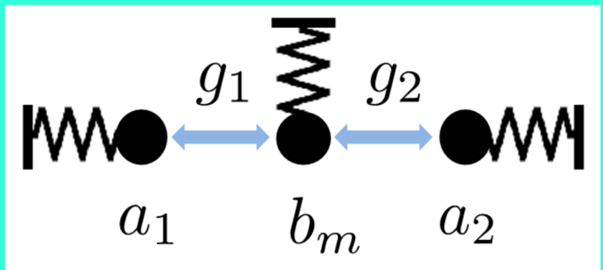
What can be achieved for cavity and itinerant photon states

1. Quantum states can be converted between microwave and optical photons
2. Entanglement can be generated between microwave and optical photons
3. Challenge: thermal noise can degrade fidelity of quantum schemes (??)

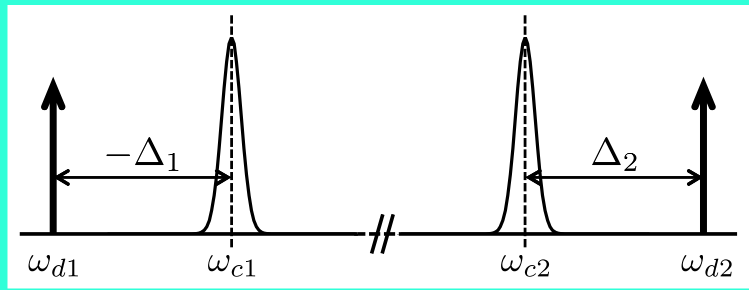
Red- and blue-detuned driving fields

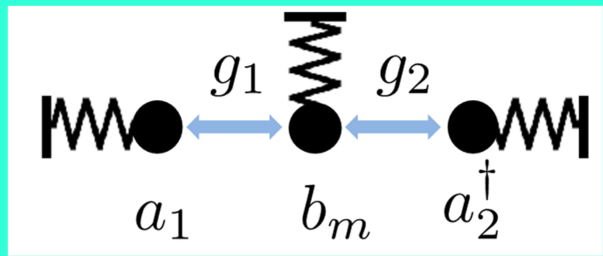
Red-detuned – Red-detuned
- quantum wavelength conversion





Red-detuned – Blue-detuned
- continuous variable entanglement





Review: L. Tian, Ann. Phys. (Berlin) 527, 1 (2015).

Conversion of quantum state : transient scheme by 2 swap pulses

PRL **107**, 133601 (2011) PHYSICAL REVIEW LETTERS week ending 23 SEPTEMBER 2011

Storing Optical Information as a Mechanical Excitation in a Silica Optomechanical Resonator

Victor Fiore,[1] Yong Yang,[1] Mark C. Kuzyk,[1] Russell Barbour,[1] Lin Tian,[2] and Hailin Wang[1]

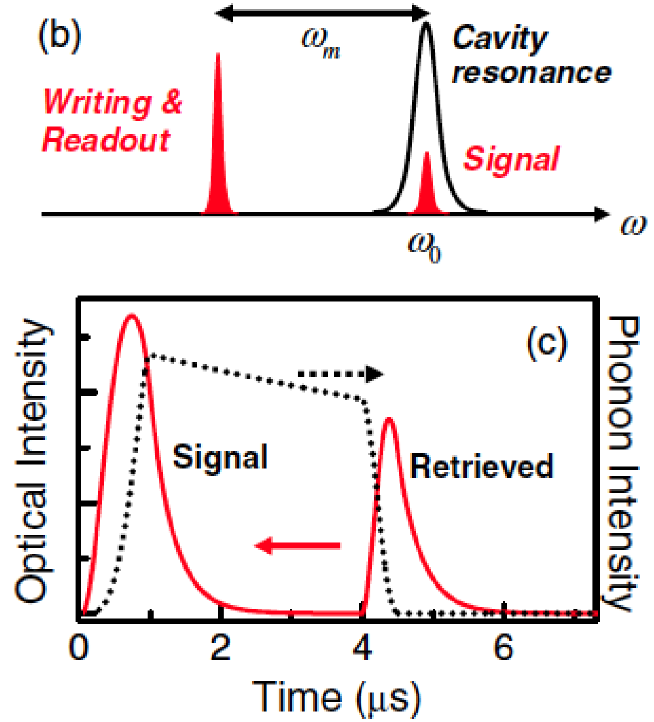
1. Matter of principle demonstration of Optomechanical swap operation

- Optical and mechanical signal swap

- Signal swap back to cavity after some free time – retrieved by another swap

2. Scheme subject to mechanical noise

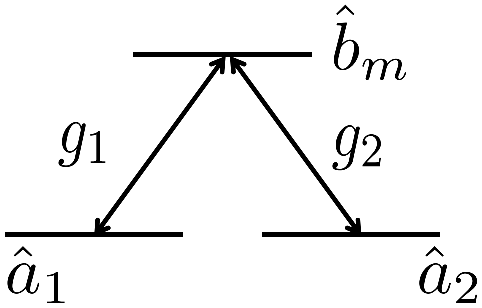
Theory: Tian, Wang, PRA 82, 053806 (2010)



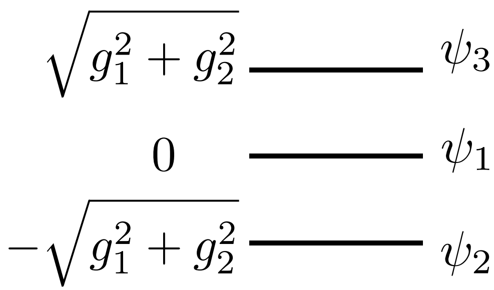
<u>Quantum state conversion robust against mechanical noise</u>

- Simultaneous couplings generate state swapping between

$$H = \sum_{i=1,2} -\hbar\Delta_i a_i^\dagger a_i + \boxed{\hbar g_i (a_i^\dagger b_m + b_m^\dagger a_i)} + \hbar\omega_m b_m^\dagger b_m$$



Eigenmodes at $-\Delta_i = \omega_m$



<u>No damping:</u> mechanical dark mode

$$\psi_1 = (-g_2 a_1 + g_1 a_2)/g_0$$

Dark mode energy separated from other modes $g_0 = \sqrt{g_1^2 + g_2^2}$

$$\lambda_1 = 0,\ \lambda_{2,3} = \pm\sqrt{g_1^2 + g_2^2}$$

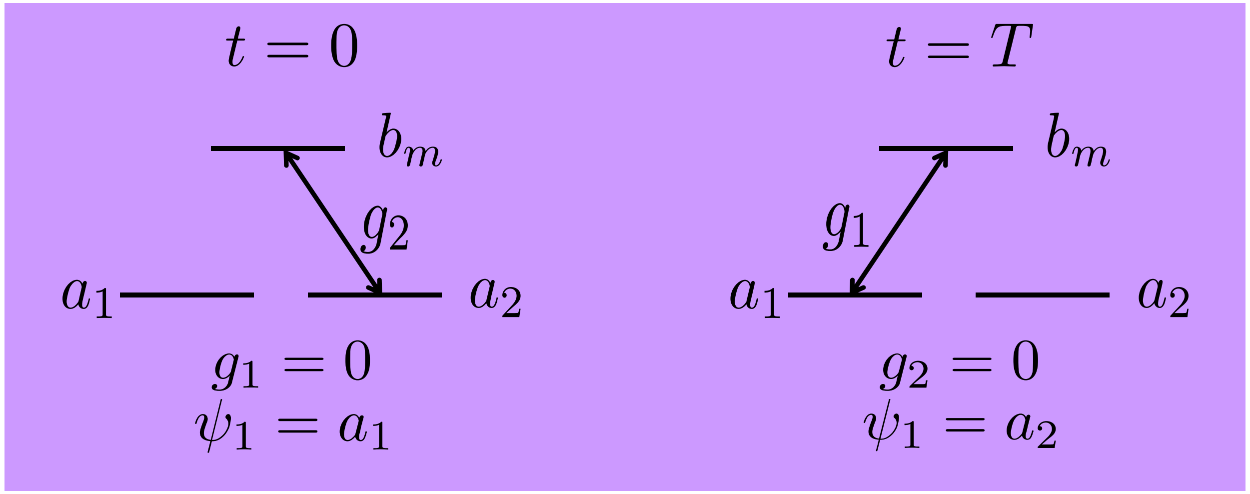
Remains in dark mode when adjusting coupling $g_{1,2}$ adiabatically (Landau-Zener condition)

$$|dg_i/dt|/g_0 \ll g_0$$

Quantum state conversion robust against mechanical noise

- Adiabatic variation of couplings; state stored in mechanical dark mode

$$\psi_1 = (-g_2 a_1 + g_1 a_2)/g_0$$



At time t=0, g_1=0, g_2=-g_0, dark mode $a_1(0)$
at time t=T, g_1=g_0, g_2=0, dark mode $a_2(T)$
Initial state in mode a_1 is transferred to mode a_2
Basic idea related to electromagnetically induced transparency (EIT) in AMO

$$\boxed{a_2(T) = a_1(0)}$$

L. Tian, PRL 108, 153604 (2012); see also
Y. D. Wang & A. A. Clerk, PRL 108, 153603 (2012)

Quantum state conversion robust against mechanical noise

- Experiment that demonstrates mechanical dark mode

Sciencexpress Reports

Optomechanical Dark Mode

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Thermal mechanical motion hinders the use of a mechanical system in applications such as quantum information processing. While the thermal motion can be overcome by cooling a mechanical oscillator to its motional ground state, an alternative approach is to exploit the use of a mechanically-dark mode that can protect the system from mechanical dissipation. We have realized such a dark mode by coupling two optical modes in a silica resonator to one of its mechanical breathing modes in the regime of weak optomechanical coupling. The dark mode,

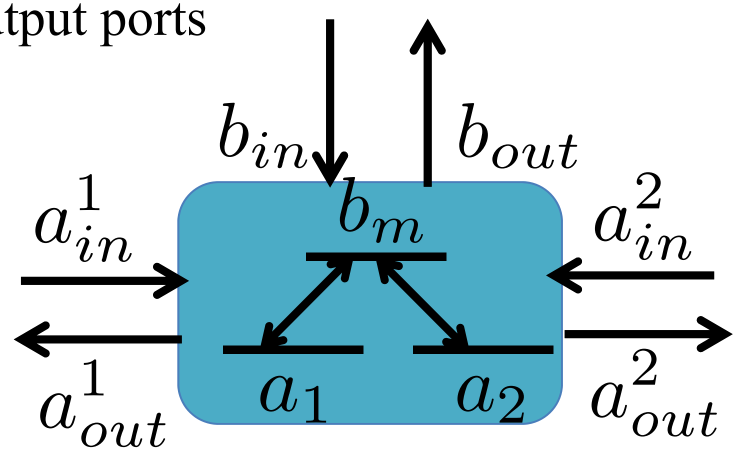
other, effectively mediating an optomechanical coupling between the two optical modes. This type of mechanically-mediated coupling can be immune to thermal mechanical motion, providing a promising mechanism for interfacing hybrid quantum systems (*9*, *14*, *15*).

To introduce the optomechanical dark mode, we consider an optomechanical system, in which two optical modes couple to a mechanical oscillator with optomechanical coupling rates G_1 and G_2, respectively (see Fig. 1B). As illustrated in Fig. 1C, the optomechanical coupling is driven by

Quantum state conversion for itinerant photons via the interface

- Transmission matrix between input and output ports

e.g., Input mode $a^1_{in}(t)$ to be transferred to output mode $a^2_{out}(t)$ with noise operators $a^2_{in}(t)$ and $b_{in}(t)$

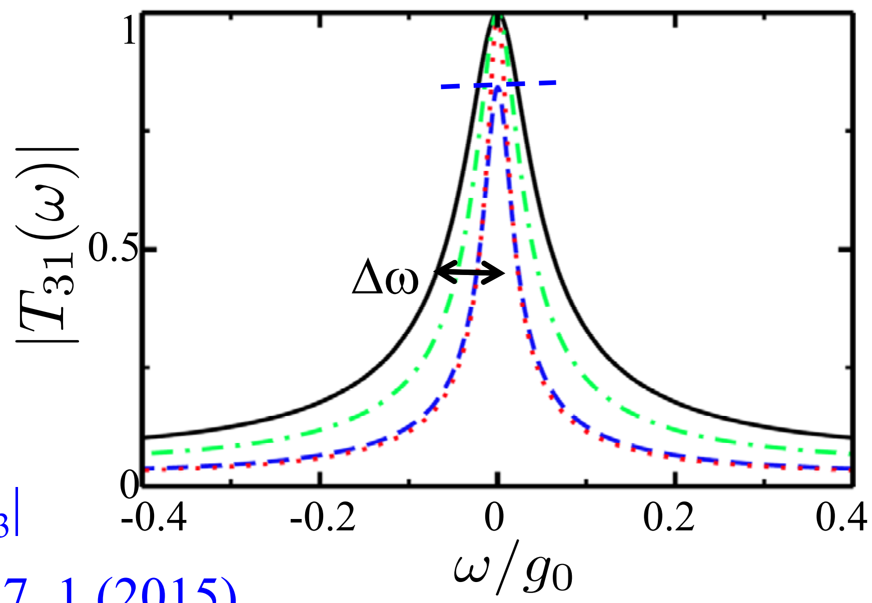


- Heisenberg-Langevin equation in frequency domain for constant couplings

$$\vec{v}_{out}(\omega) = \widehat{T}(\omega)\vec{v}_{in}(\omega)$$

$$\widehat{T}(\omega) = \left(I - i\sqrt{K}\,(I\omega - M_0)^{-1}\sqrt{K}\right)$$

- Frequency dependence T_{31}



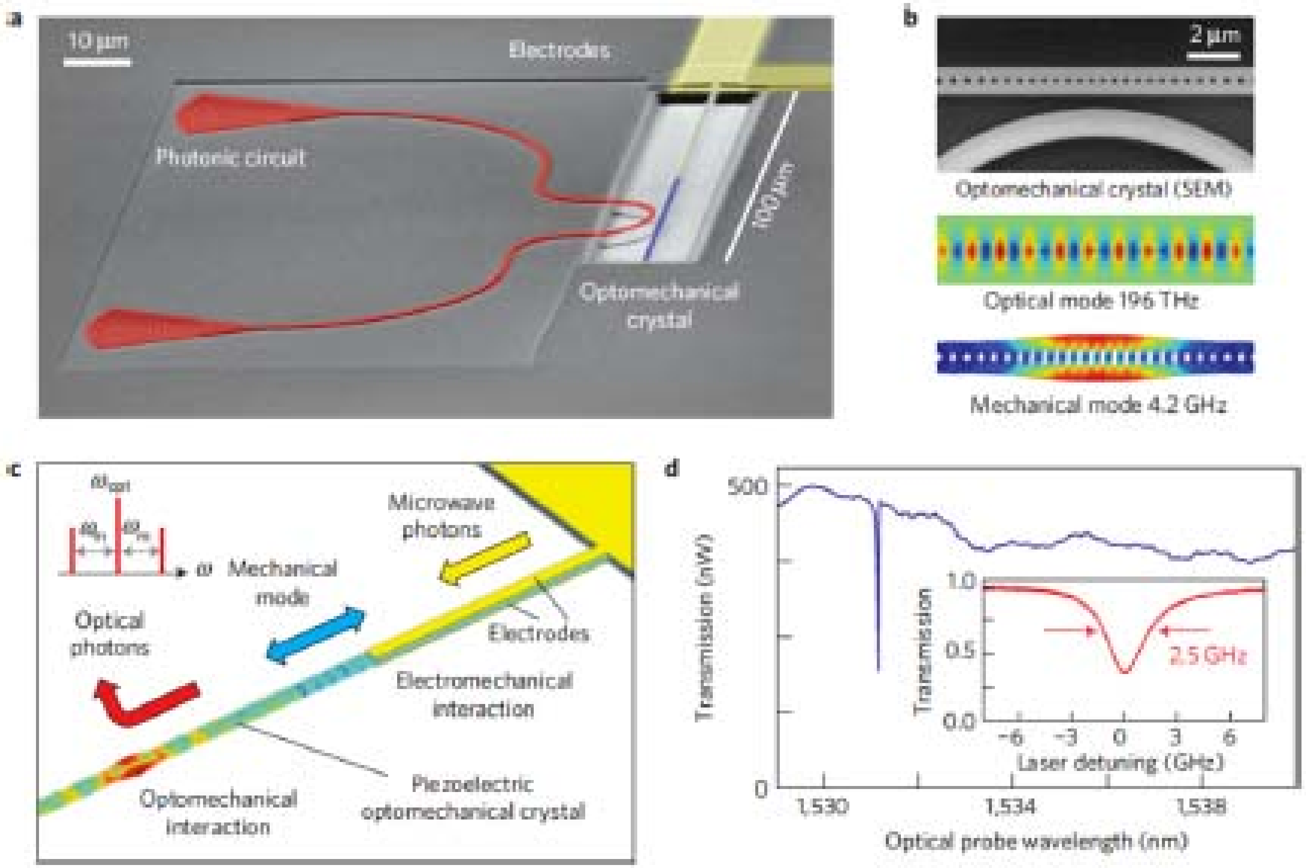
- At ω=0, when $g_1^2\kappa_2 = g_2^2\kappa_1$

$$\widehat{T}_{31}(\omega) \to 1$$

- Conversion is bidirectional $|T_{31}|=|T_{13}|$

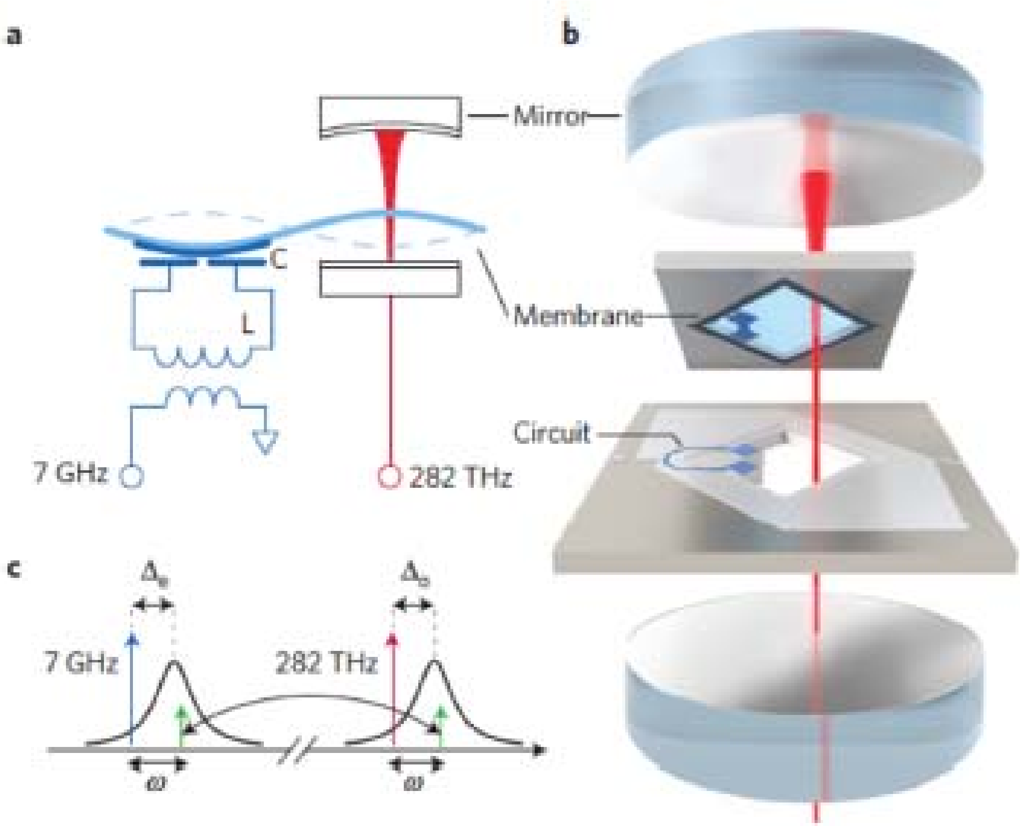
Review: L. Tian, Ann. Phys. (Berlin) 527, 1 (2015).

Experiments



J. Bochmann, A. Vainsencher, D. D. Awschalom, and A. N. Cleland, Nat. Phys. 9, 712 (2013).

Experiments

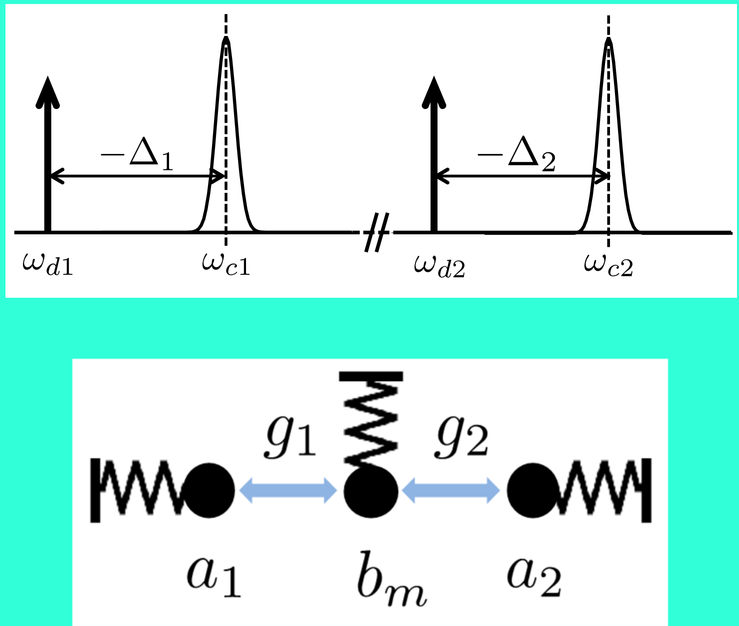


R.W. Andrews, R.W. Peterson, T. P. Purdy, K. Cicak, R. W. Simmonds, C. A. Regal, and K.W. Lehnert, Nat. Phys. 10, 321 (2014).

Red- and blue-detuned driving fields

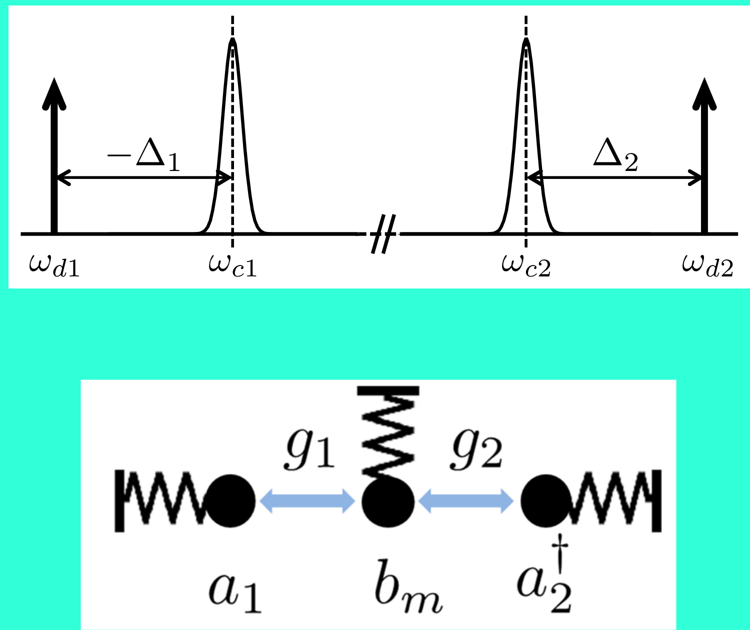
Red-detuned – Red-detuned

- quantum wavelength conversion
- discrete state entanglement



Red-detuned – Blue-detuned

- continuous variable entanglement



Review: L. Tian, Ann. Phys. (Berlin) 527, 1 (2015).

Entanglement generation between microwave and optical photons

- Linear (red-detuned) and bilinear (blue-detuned) couplings

Cavity mode a1 – red-detuned drive $-\Delta_1 = \omega_m$
Cavity mode a2 – blue-detuned drive $\Delta_2 = \omega_m$
Both coupling with mechanical mode bm

System Hamiltonian in the strong coupling regime under RWA

$$H_I = \hbar g_1 (a_1^\dagger b_m + b_m^\dagger a_1) + i\hbar g_2 (a_2^\dagger b_m^\dagger - a_2 b_m) + H_{I,diss}$$

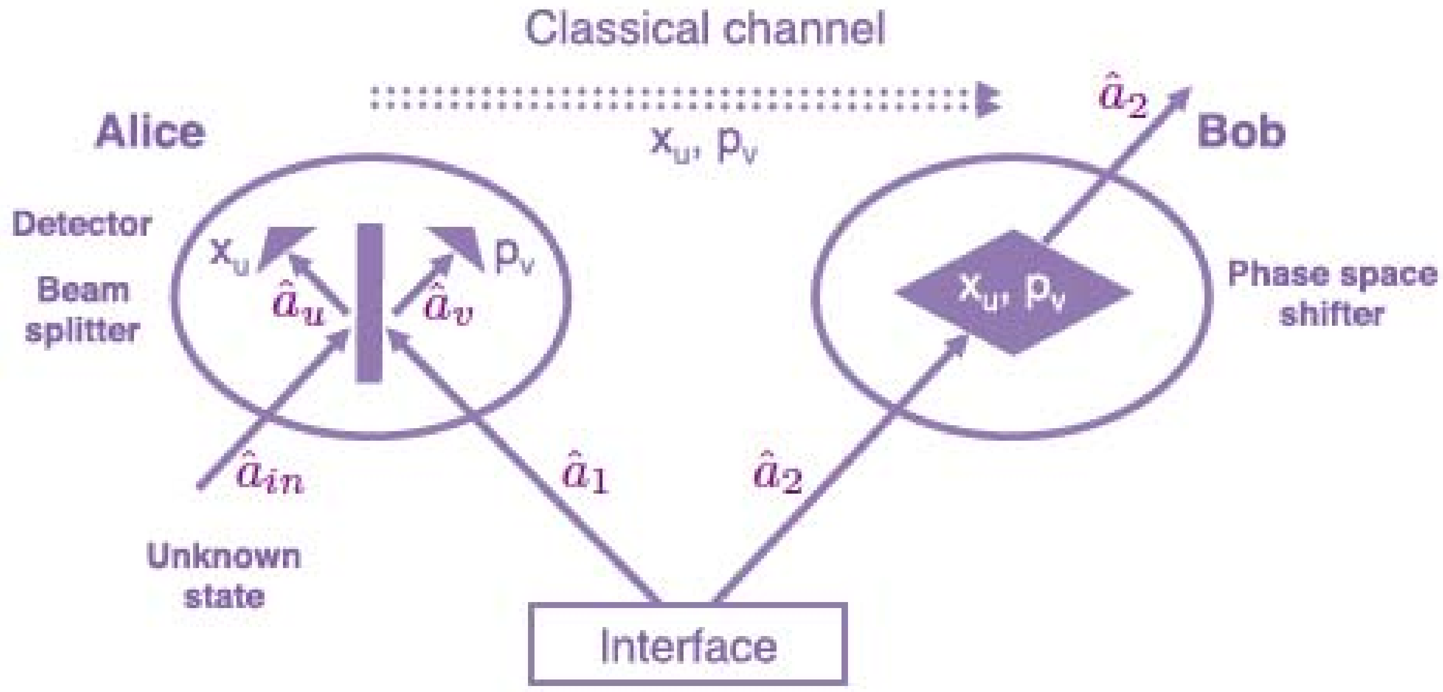
Stability conditions in strong coupling regime: $\frac{g_1^2}{g_2^2} > \max\left\{\frac{\kappa_2}{\kappa_1}, \frac{\kappa_1}{\kappa_2}\right\}$
Which indicates $g_1 > g_2$

$$g_1 = g_0 \cosh(r) \quad g_2 = g_0 \sinh(r) \quad g_0 = \sqrt{g_1^2 - g_2^2}$$

L. Tian, PRL 110, 233602 (2013); related work Y.D. Wang, A.A. Clerk, PRL (2013), H. Tan, G. Li, and P. Meystre, PRA (2013)

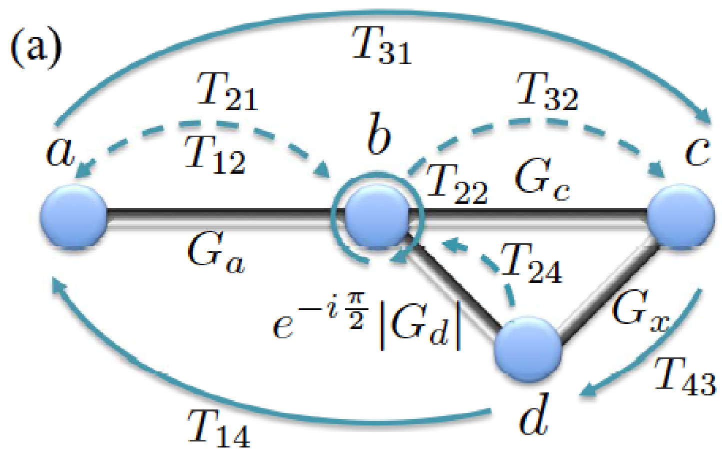
Quantum teleportation from microwave to optical photons

- Entangled photons a1 and a2 distributed to distant nodes



S. Barzanjeh, M. Abdi, G. J. Milburn, P. Tombesi, and D. Vitali, Phys. Rev. Lett. 109, 130503 (2012).

Nonreciprocal quantum state conversion



Nonreciprocal state conversion in quantum networks

- Directing quantum information to desired node; separate input and output channels; avoid noise to propagate in the quantum network
- Requirements: lossless and noiseless
- Previous works (breaking time-reversal symmetry or time dependence)

Farady effect in magneto-optical crystal, C. E. Fay (1956)…
Time-dependent reactive elements, N. A. Estep et al Nat Phys (2014)

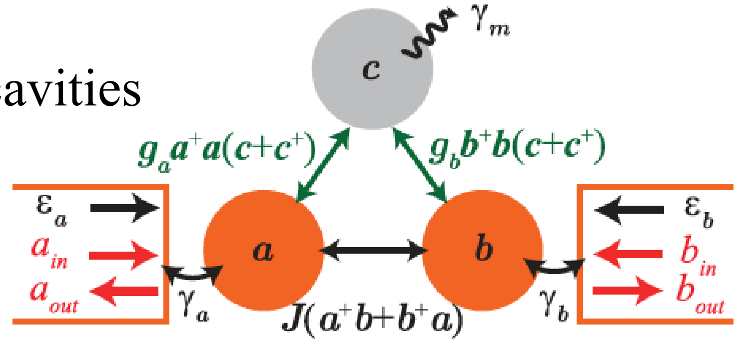
Parametric active microwave device, A. Kamal et al, N Phys (2011), L. Ranzani and J. Aumentado NJP (2015), J. Kerckhoff et al K. W. Lehnert, Phys. Rev. Appl. (2015); K. M. Sliwa et al, PRX (2015) …

Photonic devices: K. Fang et al, Nat Photonics (2012)

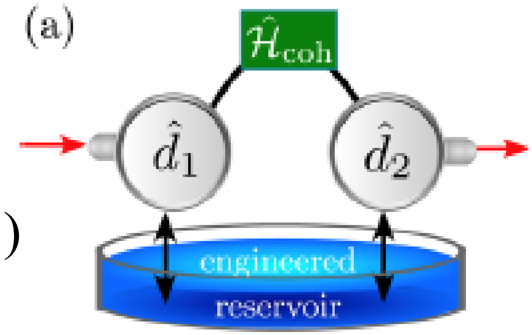
Hall effect: G. Viola and D. P. DiVincenzo PRX (2014)

Recent works via mechanical or cavity modes

- Direct coupling between input and output cavities or via strongly damped mechanical mode; and engineering phase difference in couplings
X.-W. Xu and Y. Li, PRA 91, 053854 (2015)
X.-W. Xu et al., PRA 93, 023827 (2016).



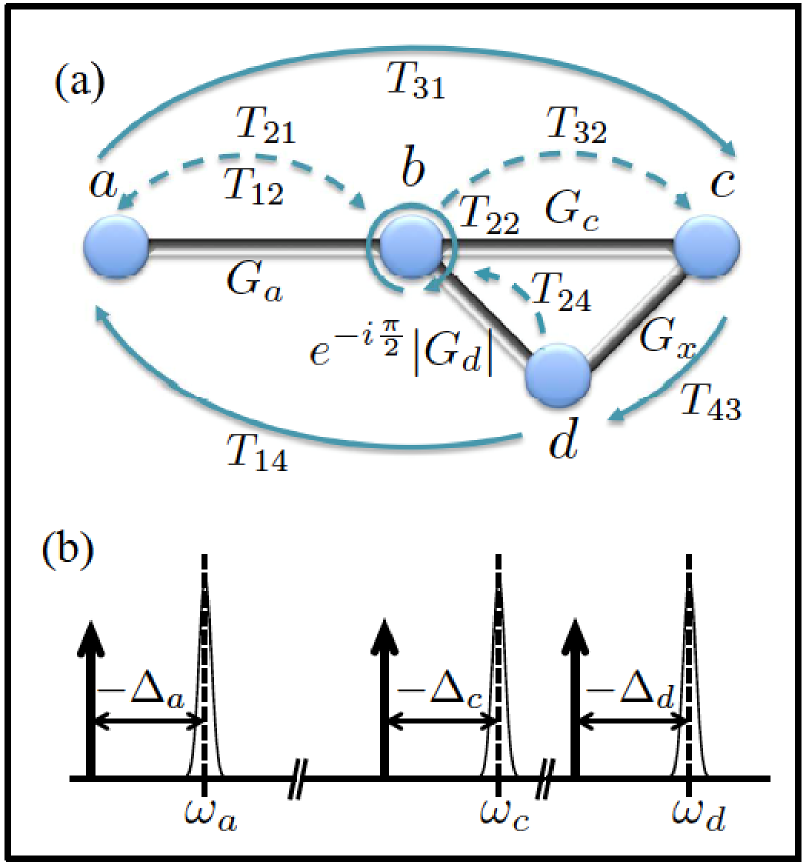
- Quantum cascade systems approach
Coupling between cavities via reservoir
Wide bandwidth scheme
A. Metelmann and A. A. Clerk, PRX 5, 021025 (2015)
K. J. Fang et al., eprint arxiv.1608.03620.



High-fidelity nonreciprocal state conversion

- Using an optoelectromechanical interface with an auxiliary cavity mode

- No direct coupling between microwave and optical cavities. Auxiliary mode of the same type as cavity c, coupled to c



- Cavities are driven in the red-sideband. Effective gauge phase in the b-c-d loop is used to control flow of information

- Interface acts as circulators a-c-d-a or c-a-d-c, depending on phase

- Interface acts as a two-way switch

- Mechanical noise cancels in the lowest order. And conversion is high fidelity

High-fidelity nonreciprocal state conversion

- Coupling Hamiltonian. Optomechanical coupings $G_{a,c,d}$ controlled by external driving

$$\hat{H}_{int} = G_a\left(\hat{a}^\dagger\hat{b} + \hat{b}^\dagger\hat{a}\right) + G_c\left(\hat{c}^\dagger\hat{b} + \hat{b}^\dagger\hat{c}\right)$$
$$+G_d\left(\hat{d}^\dagger\hat{b} + \hat{b}^\dagger\hat{d}\right) + G_x\left(\hat{c}^\dagger\hat{d} + \hat{d}^\dagger\hat{c}\right)$$

- Requirement on couplings

$$G_x = (\sqrt{\kappa_1\kappa_2})/2 \qquad G_d = -iG_c\sqrt{\kappa_d/\kappa_c}$$

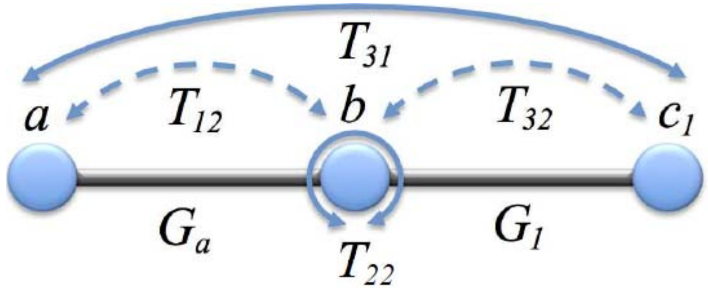
Nonreciprocity requirement

$$|T_{13}/T_{31}| = 0$$

Lossless requirement

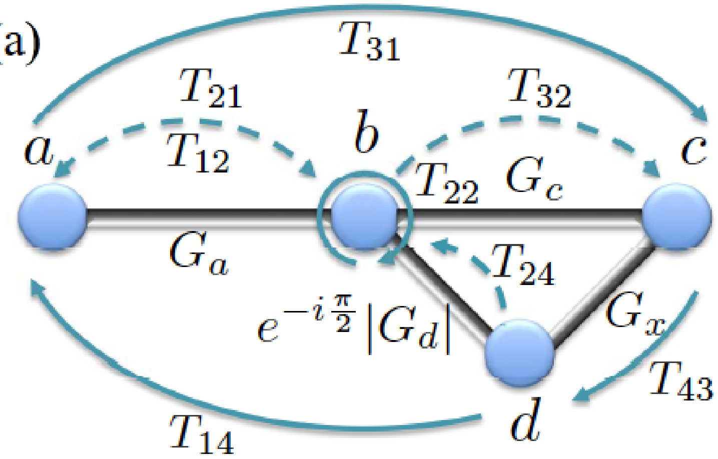
$$|T_{i1}/T_{31}| \ll 1$$

Previous interface for bidirectional state conversion



Nonreciprocal interface

(a)



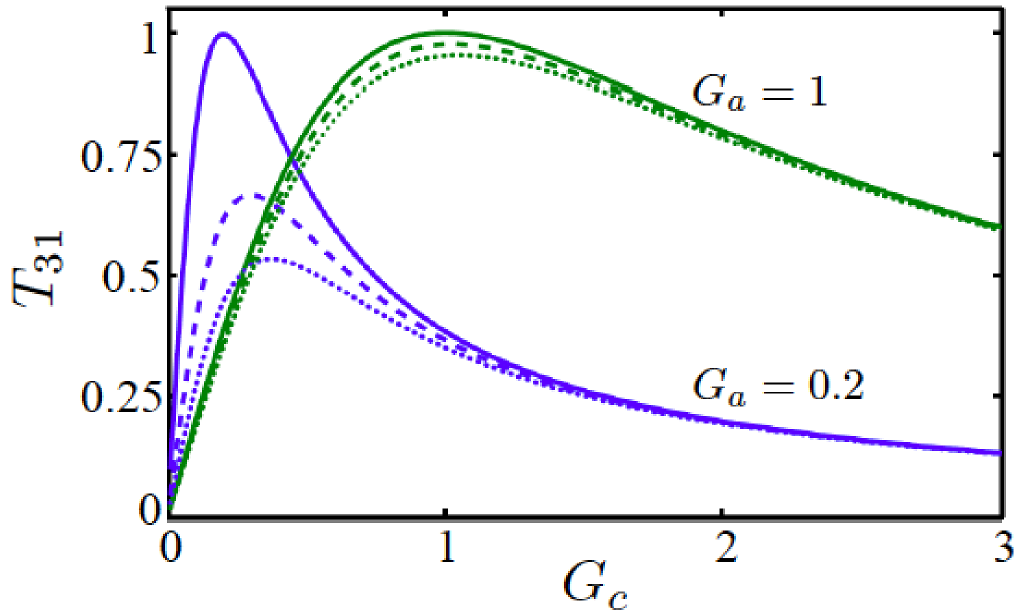
High-fidelity nonreciprocal state conversion

- Transmission matrix element

$$T_{31} = \frac{2\sqrt{\Gamma_c \Gamma_a}}{\Gamma_c + \Gamma_a + \gamma_m}$$

- Optimal condition

$$\Gamma_a \approx \Gamma_c = \Gamma_d$$



- Output field

$$\hat{c}_{out} = (1 - \gamma_m / 2\Gamma_a)\hat{a}_{in} + i\sqrt{\gamma_m / \Gamma_a}\hat{b}_{in}$$

- Single-photon-level state transmission $\Gamma_a / \gamma_m n_{\mathrm{th}} \gg 1$

L. Tian and Z. Li, arXiv:1610.09556

Summary

- Quantum network and hybrid quantum systems

What are the challenges for scalable quantum computing; why hybrid systems; why quantum interface in hybrid systems

- Mechanical systems in the quantum limit; electro- and opto-mechanics

Overview of mechanical systems; what operations can be performed and how to

- Optoelectromechanical interface and state conversion

High fidelity interface to convert and entangle microwave and optical photons; suppress mechanical noise

- Nonreciprocal quantum state conversion

Noiseless and losses state conversion with controlled information flow

Thank you

New postdoc and student openings on many-body effects in two-dimensional materials starts mid next year

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