Ultrahigh-Q microcavity photonics and optomechanical cooling

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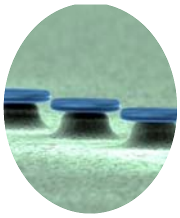

清华大学高等研究院 2015年3月11日

Microcavity photonics and quantum optics group@PKU
URL: www.phy.pku.edu.cn/~yfxiao/

Light-matter interaction plays the central role in both fundamental optical physics and applied photonics, ranging from quantum light source to functional photonic device.

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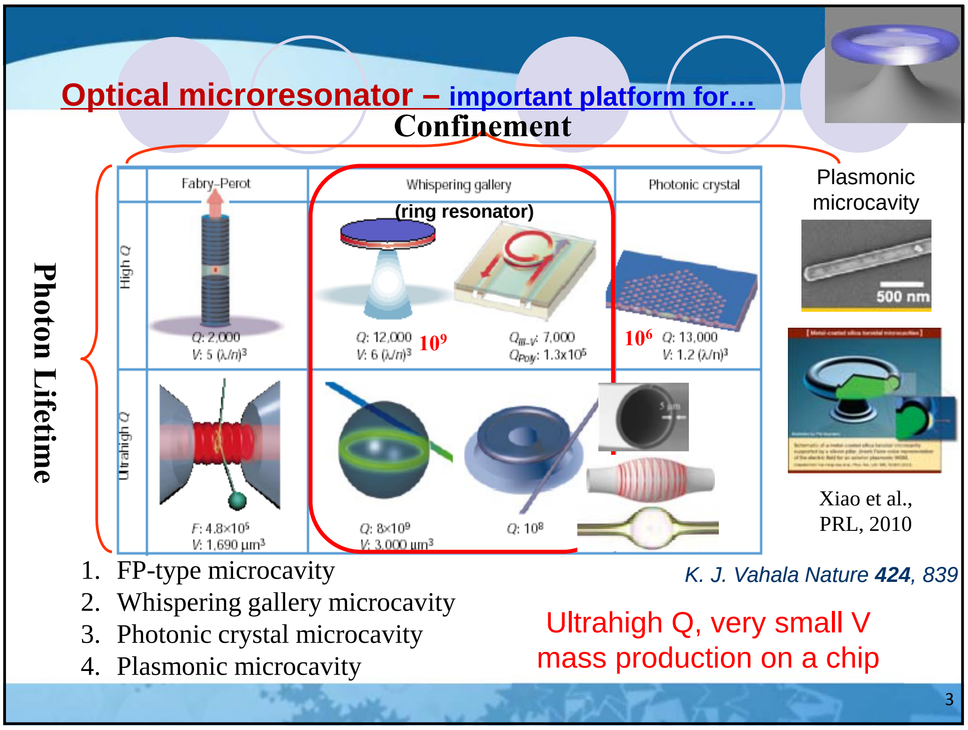
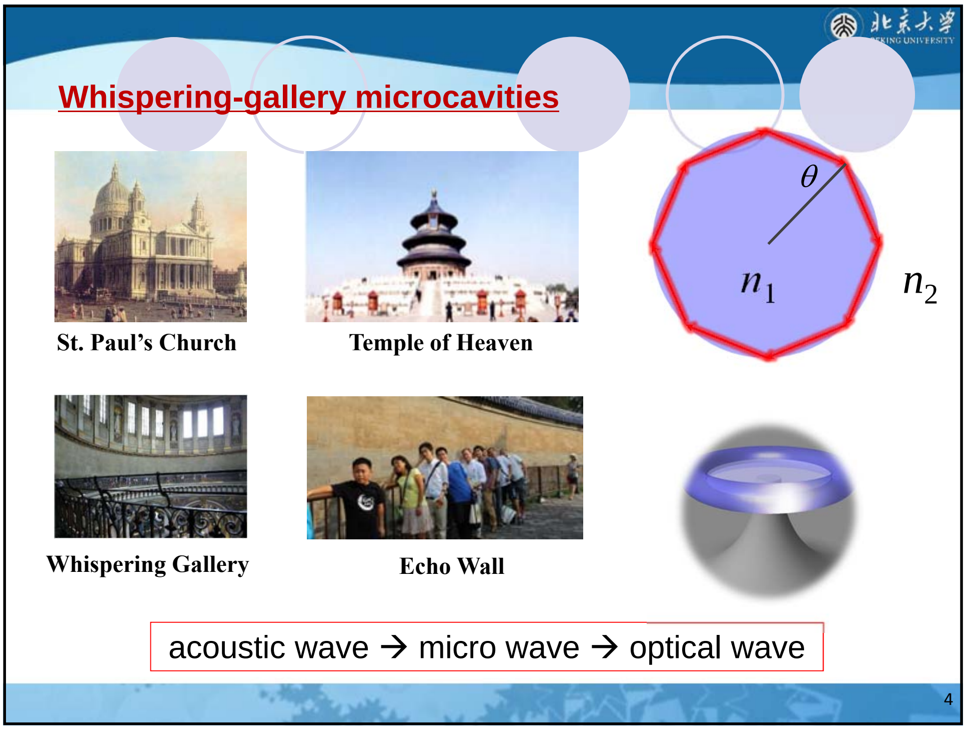

Optical microresonator – important platform for…
Confinement
Photon Lifetime
Fabry-Perot
Whispering gallery
(ring resonator)
Photonic crystal
Plasmonic microcavity
High Q
Ultrahigh Q
Q: 2,000
V: 5 (λ/n)³
Q: 12,000
V: 6 (λ/n)³
10⁹
10⁶
Q: 13,000
V: 1.2 (λ/n)³
500 nm
F: 4.8×10⁵
V: 1,690 μm³
Q: 8×10⁹
V: 3,000 μm³
Q: 10⁸
Xiao et al.,
PRL, 2010
1. FP-type microcavity
2. Whispering gallery microcavity
3. Photonic crystal microcavity
4. Plasmonic microcavity
K. J. Vahala Nature 424, 839
Ultrahigh Q, very small V
mass production on a chip
3

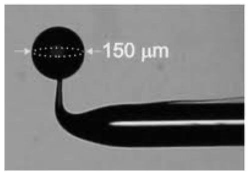

Whispering-gallery microcavities
St. Paul's Church
Temple of Heaven
Whispering Gallery
Echo Wall
θ
n1
n2
acoustic wave → micro wave → optical wave
4

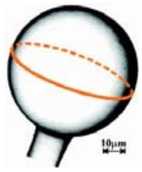
Optical WGMs in liquid and silica microspheres

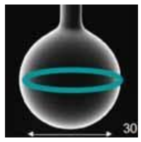
Early study: liquid droplets

many phenomena, e.g., nonlinear optical process
but, suffered from evaporation

From liquid to solid state







- *C. G. B. Garrett, W. Kaiser, and W. L. Bond, Phys. Rev. 124, 1807 (1961).*
- *A. Ashkin and J. M. Dziedzic, Phys. Rev. Lett. 38, 1351 (1977).*
- *P. Chylek, J. T. Kiehl, and M. K. W. Ko, Phys. Rev. A 18, 2229 (1978).*
- *V. B. Braginsky, M. L. Gorodetsky, and V. S. Ilchenko, Phys. Lett. A 137, 393 (1989).*
- *M. C. Kuzyk and H. Wang, SPIE Newsroom. DOI: 10.1117/2.1201208.004434*

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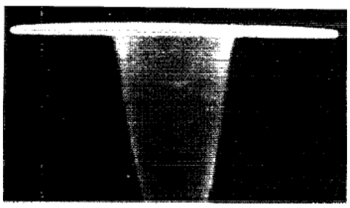
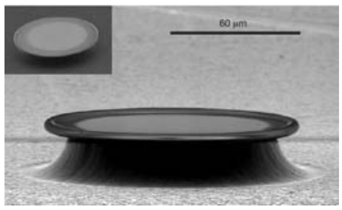
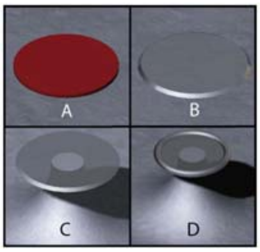
WGMs in silica microdisk and microtoroid on a chip



S. L. McCall et al., Appl. Phys. Lett. 60, 289 (1992)



Vahala Group, Nature **421**, 925-927 (2003)



- **Microtoroid resonator fabrication**
  - Photolithographically defined photo-resist disks
  - Silica etching using buffered HF and PR removal leaving silica disk
  - XeF_2 isotropical etch of Si and silica disk undercut
  - CO_2 laser activated reflow to form microtoroid

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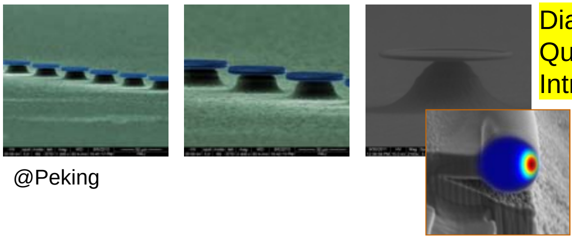
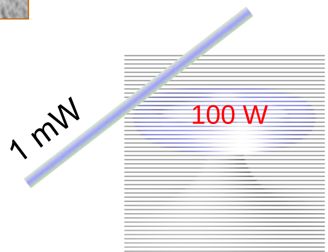
Why ultra-high-Q microcavities on a silicon chip



@Peking

Diameter: 20 μm – 200 μm
Quality factor > 10^8,
Intracavity lifetime > 100 ns

"Strongly enhanced light-matter interaction"



P_{in} = 1 mW ➔
P_{cav} ~ 100 W, I_{cav} > 2 GW/cm^2,

τ ~ 100 ns ➔ # of round trip > 10^5.

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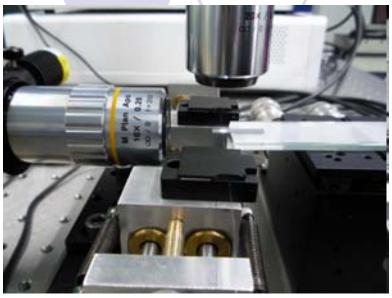
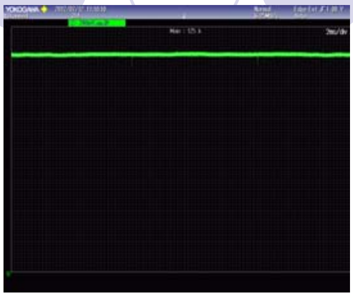
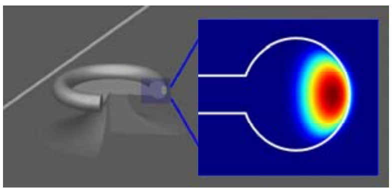
Our Group







Linewidth < 2 MHz
Quality factor > 2×10^8
From under coupling, critical coupling, to over coupling

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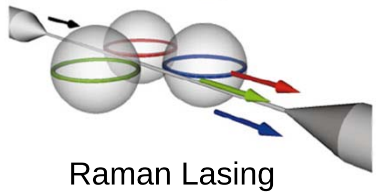
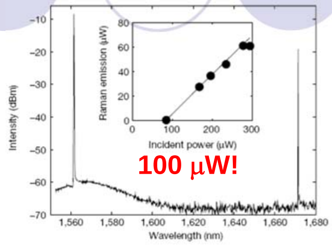
APPLICATION: Low-threshold lasing

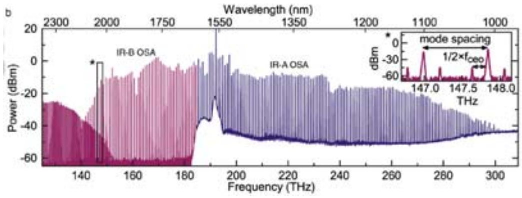


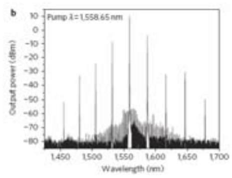
Raman Lasing



Vahala group, Nature (2002)

Single-frequency Pump → Microcomb





Kippenberg group, PRL (2008)

L. Razzari *et al*., Nature Photon. 4, 41 (2010)

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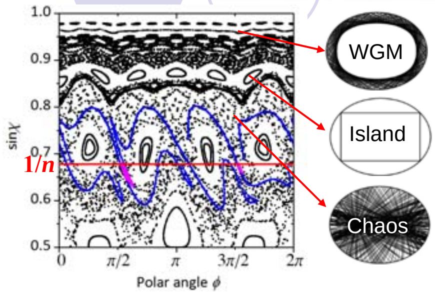
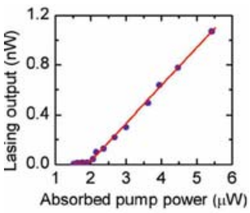
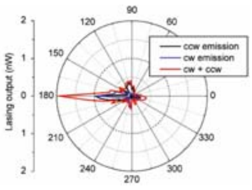
APPLICATION: Low-threshold lasing



Question: Ultrahigh-Q factor + Highly directional emission





X. F. Jiang, Y.-F. Xiao* et al., *Advanced Materials* 24, OP260-OP264 (2012)

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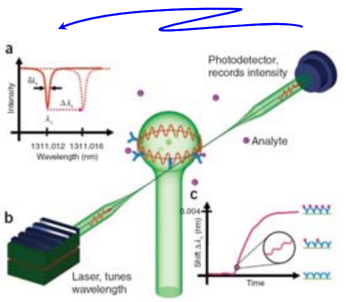
APPLICATION: Highly sensitive optical biosensing

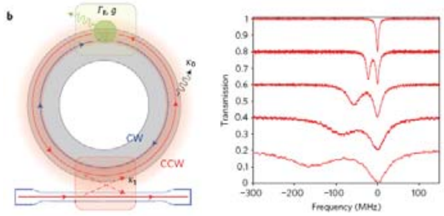
Mode shift



Thermal and probe noise

Mode splitting

Rayleigh scattering
→ mode coupling
→ mode splitting (splitting > linewidth)
(immune to thermal noise)



F. Vollmer & S. Arnold, Nature Methods 5, 591 (2008)
M. A. Santiago-Cordoba et al., APL 99, 073701 (2011)
J. D. Swaim, J. Knittel, and W. P. Bowen, APL 99, 243109 (2011)
V. R. Dantham et al., APL 101, 043704 (2012)
Y.-F. Xiao et al., Phys. Rev. A 85, 031805(R) (2012)
V. R. Dantham et al., Nano Lett. 13, 3347 (2013)

J. Zhu et al. Nature Photonics 4, 46 (2010).
L. He et al., Nature Nanotech. 6, 428 (2011).
A. Mazzei et al. Phys. Rev. Lett. 99, 173603 (2007).
L. Chantada et al., JOSA B 25, 1312 (2008).
X. Yi, Y.-F. Xiao* et al., APL 97, 203705 (2010); PRA 83 , 023802 (2011); JAP 111, 114702 (2012)

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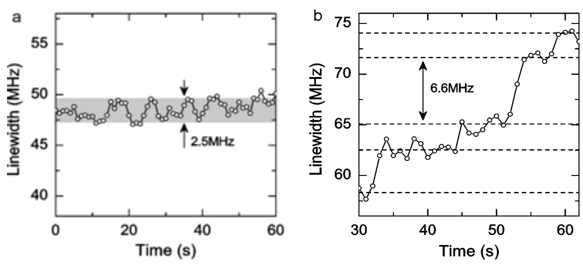
APPLICATION: Highly sensitive optical biosensing

Mode broadening:

- Temperature insensitive
- High sensitivity
- No requirement of ultra-high Q factors



Pure water (w/o virus)

PS nanoparticles

L. Shao, X.-F. Jiang (Y.-F. Xiao*) et al., Advanced Materials 25(39), 5615 (2013)

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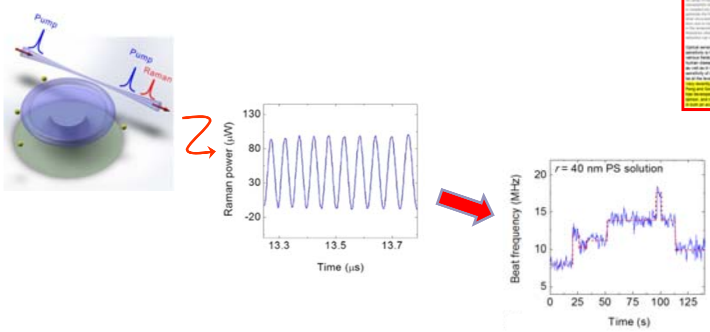
APPLICATION: Highly sensitive optical biosensing

Microcavity Raman laser:

- Temperature insensitive
- Higher sensitivity than passive cavity
- No requirement of doping



B.-B. Li, Y.-F. Xiao* et al., PNAS 111, 14657 (2014)

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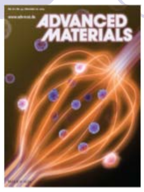
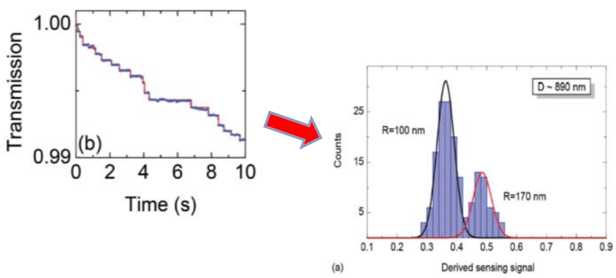
APPLICATION: Highly sensitive optical biosensing

Nanofiber array sensor:

- No requirement of tunable laser
- Single nanoparticle response
- Lager sensor area





X.-C. Yu, Y.-F. Xiao* et al., Adv. Mater. 26, 7462 (2014)

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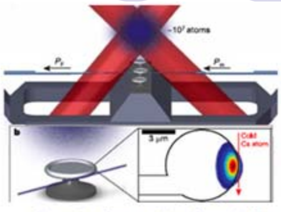
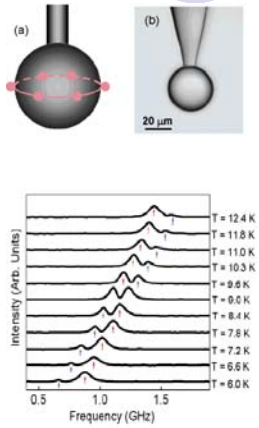
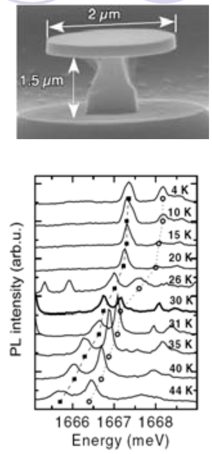
APPLICATION: Quantum optics & quantum information



"Strong coupling"

$g/2\pi \sim 50$ MHz
$\kappa/2\pi \sim 18$ MHz
$\gamma/2\pi \sim 2.6$ MHz





Cavity QED for implementation of quantum computation, quantum routers, ...

Nature **443**, 671 (2006); *Science* 319, 1062 (2008); *PRL* 95, 067401 (2005); *Nano Lett.* **6**, 2075 (2006)

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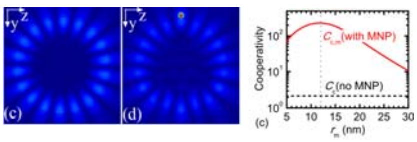
APPLICATION: Quantum optics & quantum informati

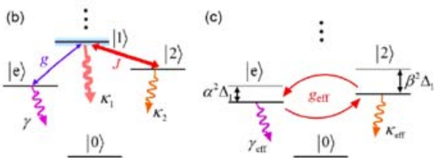
Plasmonics enhanced interaction



Nature Physics (2013)

Xiao*, Liu* *et al.*, Phys. Rev. A 85, 031805(R) (2012) (Rapid Communications)

Strong coupling in coupled dissipative cavities



Jun 10, 2014

New design surpasses the coherent interaction limit **www.phys.org**

Liu *et al.*, Phys. Rev. Lett. 112(21), 213602 (2014)

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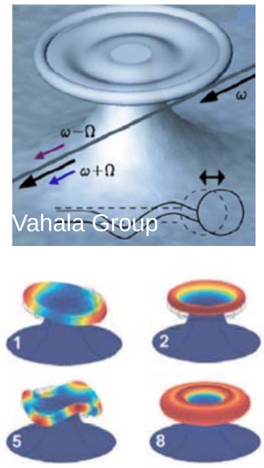
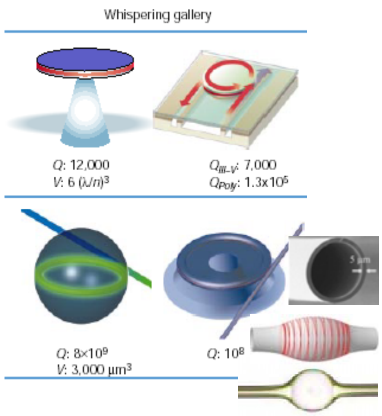
APPLICATION: Cavity optomechanics



Applications of whispering gallery microcavities

Vahala, Nature, 2003



Ultrahigh Q, very small V,
and mass production on a chip

Excellent platform for

Fundamental physics:

Quantum optics
Cavity quantum electrodynamics (QED)
Quantum information
Quantum chaos
Cavity quantum optomechanics
……

Microphotonics:

Highly sensitive bio/chemical sensing
All-optical low-threshold switching
On-chip microlasing (includ. Raman)
Optical microcomb
Optical filtering…

Outline

1. **Introduction**
2. **Cooling in the strong coupling regime**
   - Dynamic dissipative cooling
3. **Cooling in the intermediate coupling regime**
   - Room-temperature ground-state cooling
4. **Summary**

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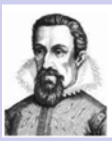
Cavity optomechanics

Mechanical effect of light

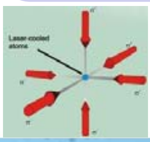
Astronomic scale

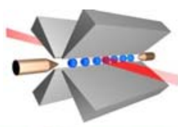


Comet's tail **Kepler**

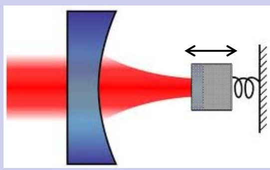
Microscopic scale

Laser cooling, Nobel 1997





Macro and Mesoscopic scale



Opto-mechanical coupled system

Optical force acts on the mirror;

Mirror’s motion state changes;

Cavity length changes;

Cavity field changes;

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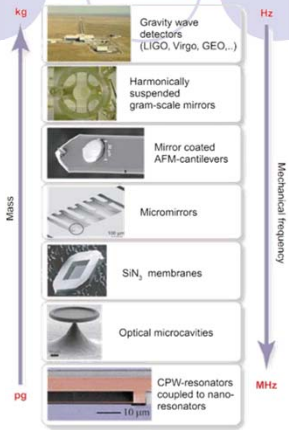
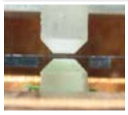
Applications

- Fundamental studies of quantum theory
  - Macroscopic quantum state, superposition and entanglement
  - Quantum-classical boundary
- Precision measurement
  - Gravitational waves detection
  - Mass, force and displacement
- Quantum information processing platform



Kippenberg & Vahala Science, 321, 1172 (2008)



Trapped particle
Cold atoms/BEC

Weiping Zhang group, PRL 108, 240405 (2012)

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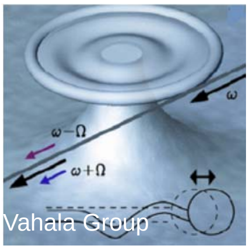
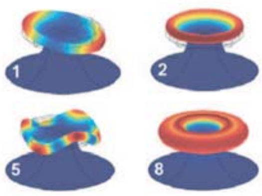
WGM Cavity optomechanics





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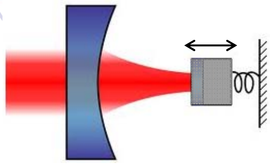
Optomechanical coupling (dispersive)

C. K. Law et al., 1990s

System Hamiltonian

$$H = \omega_c(x) a^\dagger a + \omega_m b^\dagger b$$



The cavity resonance frequency is modulated by the mechanical motion

$$\omega_c(x) = \omega_c + x\partial\omega_c(x)/\partial x + \mathcal{O}(x)$$

$$x = x_{ZPF}(b^\dagger + b)$$

Zero-point fluctuation: $x_{ZPF} = \sqrt{\hbar/(2m_{eff}\omega_m)}$

$$H_{int} = g a^\dagger a (b^\dagger + b)$$
$$H_0 = \omega_c a^\dagger a + \omega_m b^\dagger b$$

Optomechanical coupling: $g = [\partial\omega_c(x)/\partial x] x_{ZPF}$

Coherent laser input

$$H_{drive} = \Omega^* e^{i\omega_{in}t} a + \Omega e^{-i\omega_{in}t} a^\dagger \qquad \Omega = \sqrt{\kappa_{ex} P/(\hbar\omega_{in})}\, e^{i\phi}$$

Linearization $a \to a_1 + \alpha,\ b \to b_1 + \beta$

$$H_L = -\Delta' a_1^\dagger a_1 + \omega_m b_1^\dagger b_1 + (G a_1^\dagger + G^* a_1)(b_1 + b_1^\dagger)$$

$$G = \alpha g \qquad \Delta' = \omega - \omega_c + 2|G|^2/\omega_m$$

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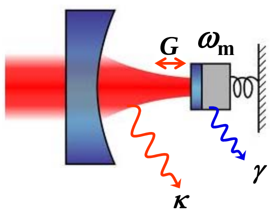
Optomechanical coupling

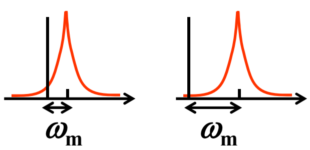
Important parameters

- ω_m: mechanical frequency
- G: coupling strength
- κ: optical decay
- γ: mechanical decay
- n_{th}: thermal phonon number



Unresolved sideband regime : $\omega_m < \kappa$

Resolved sideband regime : $\omega_m > \kappa$



Weak coupling regime: $G < \kappa$

Strong coupling regime: $G > \kappa$

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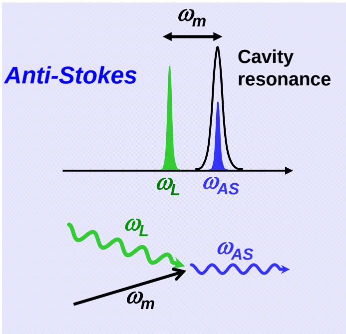
Cooling and amplification

$$H_L = -\Delta' a_1^\dagger a_1 + \omega_m b_1^\dagger b_1 + (G a_1^\dagger + G^* a_1)(b_1 + b_1^\dagger)$$

Red detuning



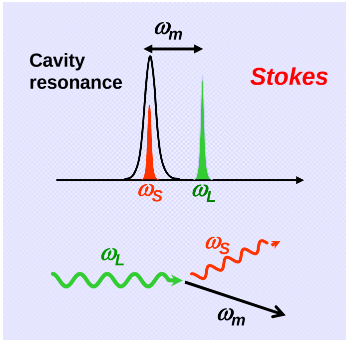
Converts phonons to photons

$$H \approx \hbar G(\hat{a}_s^+ \hat{b} + \hat{a}_s \hat{b}^+)$$

Beam-splitter interaction

Cooling

Blue detuning



Similar to parametric down conversion

$$H \approx \hbar G(\hat{a}_s^+ \hat{b}^+ + \hat{a}_s \hat{b})$$

2-mode squeezing interaction

Amplification

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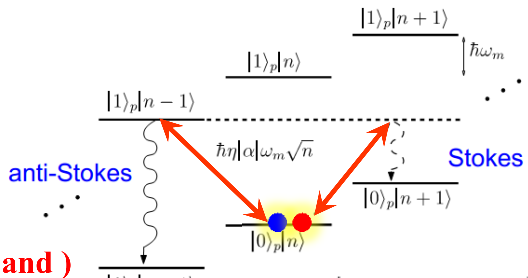
Laser cooling of mechanical resonators

Red detuned laser input, imbalanced Stokes & anti-Stokes sidebands.

Anti-Stokes >> Stokes

➔ Cooling but with limit



$$H_I = (G a_1^\dagger + G^* a_1)(b_1 + b_1^\dagger)$$

Cooling limit (resolved sideband)

Theories:

Wilson-Rae *et al*, *PRL* 99, 093901 (2007)
Marquardt *et al*, *PRL* 99, 093902 (2007)

Experiments:

Nature 444,67 (2006); Nature 444, 71 (2006)
Nat. Phys.4 , 415 (2008); Nat. Phys.5 , 485 (2009)
Nat. Phys.5, 489 (2009); Nat. Phys.5, 509 (2009)
Nature 463,72 (2010); Nature 475, 359 (2011)
Nature 478, 89 (2011); Nature 482 , 63 (2012)

Weak coupling ($G < \kappa$): Optomechanical coupling is considered as perturbation.

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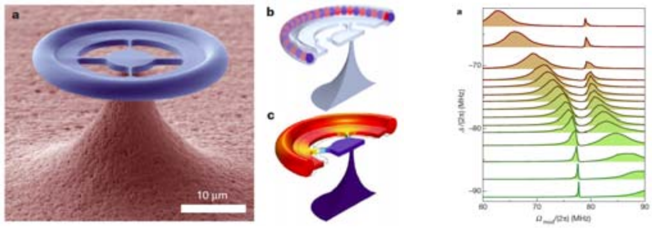
Cooling beyond the weak coupling regimes

From weak to intermediate or even strong coupling regime ($G > \kappa$)



Theory: Dobrindt *et al*, PRL 101, 263602 (2008);
Experiment: Verhagen *et al*, Nature (2012); Palomaki *et al*, Nature (2013).

- **Important for quantum applications**
- **Requires non-perturbative calculation**

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Cooling beyond the weak coupling regimes

Non-perturbative approach:

$$\dot{\rho} = i[\rho, H_L] + \kappa\mathcal{D}[a_1]\rho + \gamma(n_{\rm th}+1)\mathcal{D}[b_1]\rho + \gamma n_{\rm th}\mathcal{D}[b_1^\dagger]\rho$$

$$\dot{\mathbf{V}} = \mathbf{M}\mathbf{V} + \mathbf{N},$$

$$\mathbf{V} = (\bar{N}_a, \bar{N}_b, \langle a_1^\dagger b_1\rangle, \langle a_1 b_1^\dagger\rangle, \langle a_1 b_1\rangle, \langle a_1^\dagger b_1^\dagger\rangle, \langle a_1^2\rangle, \langle a_1^{\dagger 2}\rangle, \langle b_1^2\rangle, \langle b_1^{\dagger 2}\rangle)^T$$

$$\mathbf{N} = (0, \gamma n_{\rm th}, 0, 0, -iG, iG^*, 0, 0, 0, 0)^T$$

- **Valid in weak, intermediate and strong coupling regimes**
- **Can study dynamics behavior, in addition to steady state**

Y.-C. Liu et al., PRA 89, 053821 (2014)

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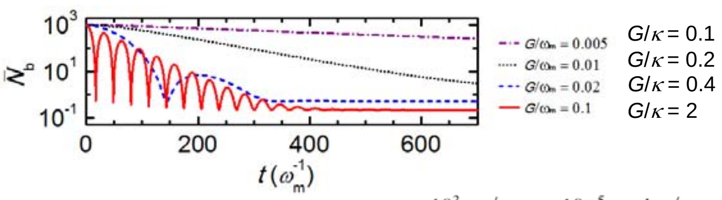
Outline

Cooling in the strong coupling regime

Time evolution of average phonon number in weak and strong coupling regimes (numerical result)



$n_{th} = 10^3$, $\gamma/\omega_m = 10^{-5}$, and $\kappa/\omega_m = 0.05$

Characteristics of cooling in strong coupling regime

- **Oscillation and cooling rate saturation**
- **Instantaneous-state cooling limit**

Cooling in the strong coupling regime

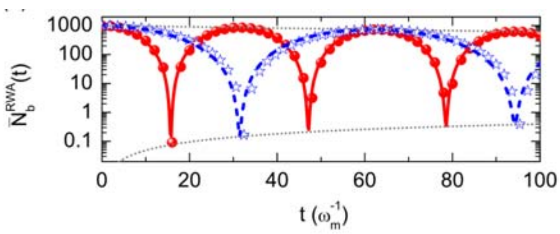
Under rotating-wave approximation (RWA) $|G| \ll \omega_m$

$$\bar{N}_b^{RWA}(t) \simeq n_{th} \frac{\gamma + e^{-\frac{\kappa+\gamma}{2}t}\left[\kappa\cos^2(|G|t) - \gamma\sin^2(|G|t)\right]}{\kappa+\gamma}$$

$$n_{ins}^{RWA} \simeq \frac{\pi\gamma n_{th}}{4|G|}$$

$t \sim \pi/(2G)$

n_{th} = 1000 G/ω_m = 0.1; G/ω_m = 0.05



“研究热环境的影响”

N_b, $n_{ins} \propto n_{th}$

Data: numerical result;
Curve: analytical result (RWA)

Y.-C. Liu et al., PRA 89, 053821 (2014)

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Cooling in the strong coupling regime

Without RWA, n_{th} = 0 “研究反旋波的影响”

$$\bar{N}_b^{(0)}(t) \simeq \frac{|G|^2\left[1 - e^{-\frac{\kappa+\gamma}{2}t}\cos(\omega_+ + \omega_-)t\cos(\omega_+ - \omega_-)t\right]}{2(\omega_m^2 - 4|G|^2)}$$

$$\omega_\pm = \sqrt{\omega_m^2 \pm 2|G|\omega_m}$$

Frequency matching condition:

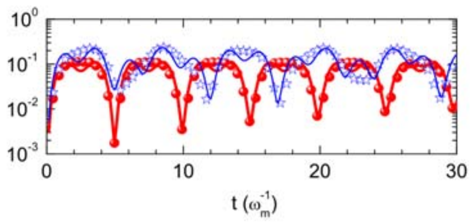
$(\omega_+ + \omega_-)t = p\pi,$

$(\omega_+ - \omega_-)t = q\pi,$

p, q both odd or even

$$|G| = \frac{pq}{p^2+q^2}\omega_m,$$

$$n_{ins}^{(0)} \simeq \frac{\pi\kappa|G|}{8(\omega_m^2 - 4|G|^2)}$$



G/ω_m = 0.3
G/ω_m = 0.35

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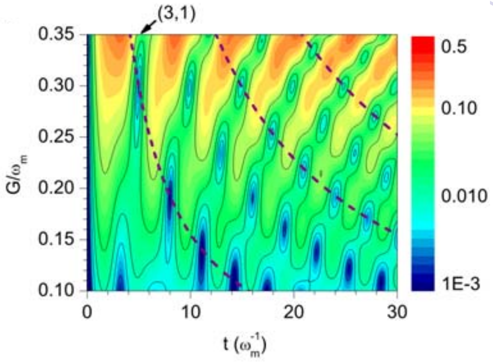
Cooling in the strong coupling regime

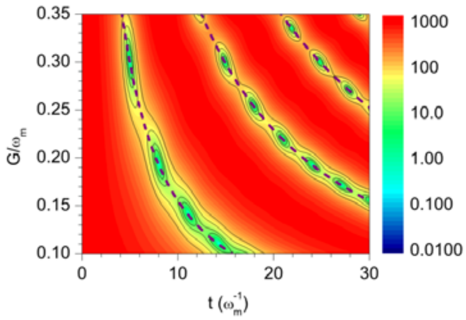


Time evolution of phonon number

$$|G| = \frac{pq}{p^2+q^2}\omega_{\rm m},$$
$$t = \sqrt{p^2+q^2}\,\frac{\pi}{2\omega_{\rm m}}.$$

Cooling in the strong coupling regime

Without RWA, $n_{\rm th} = 1000$



$$\bar{N}_b^{\rm str} = \bar{N}_{b,1}^{\rm str} + \bar{N}_{b,2}^{\rm str},$$
$$\bar{N}_{b,1}^{\rm str} \simeq n_{\rm th}\frac{\gamma + \frac{1}{2}e^{-(\kappa+\gamma)t/2}[\kappa-\gamma+(\kappa+\gamma)\cos(\omega_+-\omega_-)t]}{\kappa+\gamma},$$
$$\bar{N}_{b,2}^{\rm str} \simeq \frac{|G|^2[1-e^{-(\kappa+\gamma)t/2}\cos(\omega_++\omega_-)t\cos(\omega_+-\omega_-)t]}{2(\omega_m^2-4|G|^2)},$$

- Suppress oscillation
- Reduce instantaneous-state cooling limit (frequency mismatched)

Dynamic dissipative cooling approach

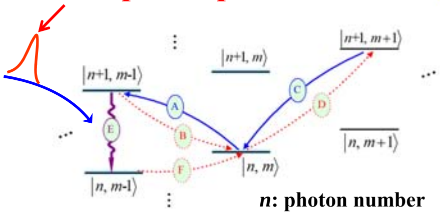
Cooling processes:

A: Energy swapping
C: Counter-rotating-wave interaction
E: Cavity dissipation

Heating processes:

B: Swap heating
D: Quantum backaction heating
F: Thermal heating

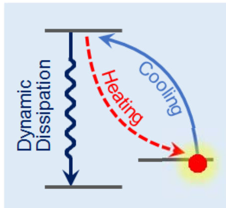
Dissipation pulses



***n*: photon number**
***m*: phonon number**

Strong coupling: *E* is slower than *A/B*.

Dynamically modulate *E* process.



Y.-C. Liu *et al.*, *Phys. Rev. Lett.* 110, 153606 (2013)

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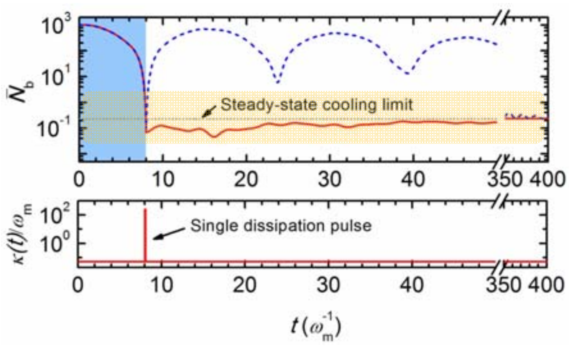
Fast cooling to the steady-state limit

A single dissipation pulse



$G/\omega_m=0.2$
$\kappa/\omega_m=0.05$

Blue: w/o dissipation pulse
Red: with dissipation pulse

Modulation scheme and mean phonon number.

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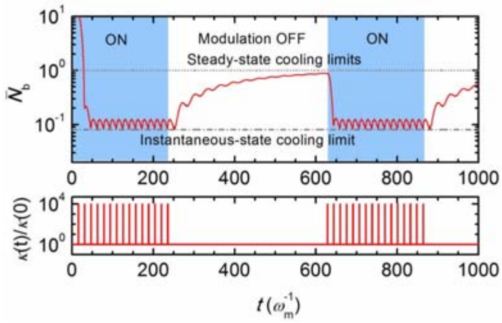
Breaking the cooling limit @ frequency mismatched

Periodic dissipation pulses **Period:** $\pi/(\omega_+ - \omega_-)$



$G/\omega_m = 0.1$
$\kappa(0)/\omega_m = 0.01$

Instantaneous-state cooling limit:

$$\bar{N}_{ins} \simeq \frac{\pi\gamma n_{th}}{4|G|} + \frac{\pi^2|G|^4}{(\omega_m^2-|G|^2)(\omega_m^2-4|G|^2)}$$

经典 量子

Modulation is switchable.
ON: Instantaneous-state limit
OFF: Steady-state limit

Steady-state cooling limit:

$$\bar{N}^{str}_{std} \simeq \gamma n_{th}/(\kappa+\gamma) + |G|^2/[2(\omega_m^2-4|G|^2)]$$

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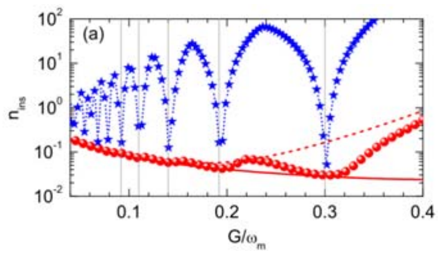
Breaking the cooling limit @ frequency mismatched

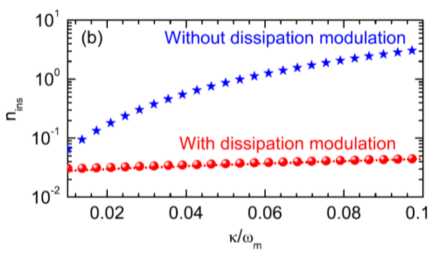
Comparison of cooling limits



声子数 vs. 耦合强度(G)

蓝色：无周期性调制
红色：有周期性调制

—— Frequency matched
- - - - Frequency mismatched



声子数 vs. 腔膜耗散(κ)

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Experimental realization

Modulation of cavity decay rate

- **By modulating the free-carrier plasma density.**
  - The absorption is affect by injection of charge carriers into an undoped sample.
- **By using a light absorber/scatterer.**
  - The position change of a light absorber/scatterer leads to the change of the cavity dissipation by absorption of photons and Rayleigh scattering photons out of the cavity.

Q. Xu *et al.*, *Nat. Phys.* **3**, 406 (2007); K. Kondo *et al.*, *Phys. Rev. Lett.* **110**, 053902 (2013); I. Favero *et al.*, *New J. Phys.* **10**, 095006 (2008).

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Outline

1. Introduction
2. Cooling in the strong coupling regime
   - Dynamic dissipative cooling
3. Cooling in the intermediate coupling regime
   - Room-temperature ground-state cooling
4. Summary

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Cooling in the intermediate coupling regime

Exact results of the steady-state cooling limit:

$$n_s = n_s^{(1)} + n_s^{(0)}$$

Classical cooling limit

Originates from the mechanical dissipation and is proportional to n_{th}

Quantum cooling limit

Originates from the quantum backaction and does not depend on n_{th}

Approximate analytical results under resolved sideband limit:

$$n_s^{(1)}|_{\Delta'=-\omega_m} \simeq \frac{4|G|^2+\kappa^2}{4|G|^2\kappa}\gamma n_{th},$$

$$n_s^{(0)}|_{\Delta'=-\omega_m} \simeq \frac{\kappa^2+8|G|^2}{16(\omega_m^2-4|G|^2)}.$$

ω_m: mechanical frequency
G: coupling strength
κ: optical decay
γ: mechanical decay
n_{th}: thermal phonon number

at G→0, agree to previous result (微扰)   *Y.-C. Liu et al., unpublished*

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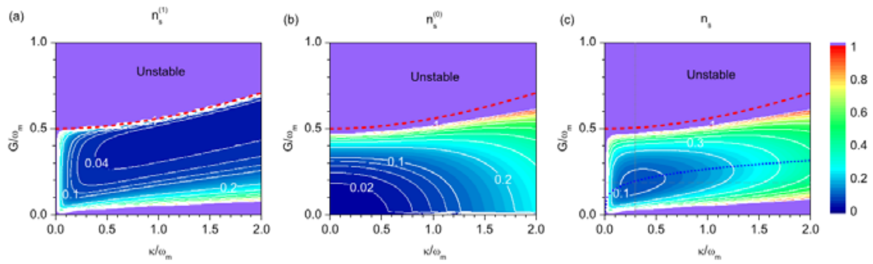
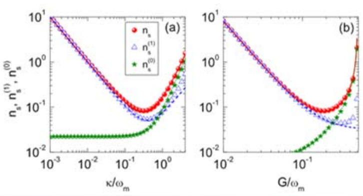
Cooling in the intermediate coupling regime

Exact numerical simulation

Classical cooling limit **Quantum cooling limit** **Total cooling limit**



- Classical cooling limit dominates for small *k* and *G*,
- while quantum limit becomes important as *k* and *G* increase.



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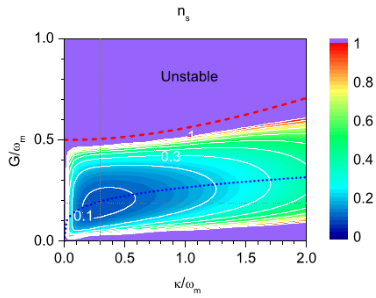
Cooling in the intermediate coupling regime

Optimal cooling limit:

$$n_{\rm opt} \simeq 1.8\left(\frac{n_{\rm th}}{Q_{\rm m}}\right)^{\frac{2}{3}}$$

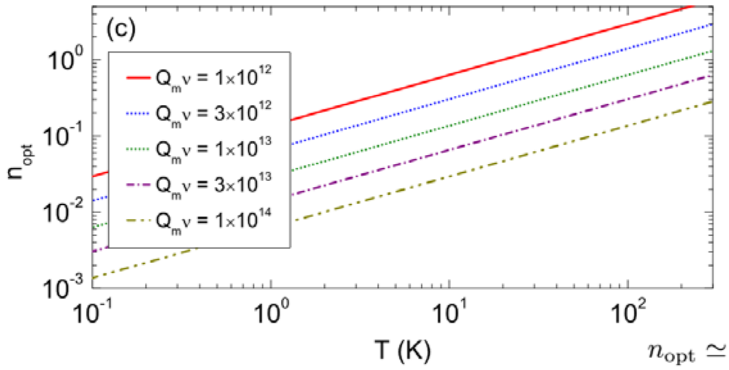
Optimal parameters:

$$\kappa_{\rm opt} \simeq 1.5\omega_{\rm m}\left(\frac{n_{\rm th}}{Q_{\rm m}}\right)^{\frac{1}{3}},$$
$$G_{\rm opt} \simeq 0.9\omega_{\rm m}\left(\frac{n_{\rm th}}{Q_{\rm m}}\right)^{\frac{1}{3}},$$



The optimal cooling limit is obtained in the intermediate coupling regime.

Cooling in the intermediate coupling regime

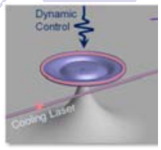


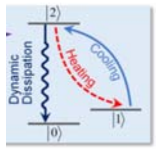
$$n_{\rm opt} \simeq 1.8\left(\frac{n_{\rm th}}{Q_{\rm m}}\right)^{\frac{2}{3}}$$

Ground state: $n_{opt} < 1 \rightarrow Q_m > 2.4n_{th}$
Room temperature: $T = 300K \rightarrow Q_m \nu > 1.5\times10^{13}$
ν = 100 MHz, $Q_m = 1.5\times10^5$

Summary

1. **Ultra-high-Q microcavity photonics**
2. **Cooling in the strong coupling regime**
   - Dynamic dissipative cooling
3. **Cooling in the intermediate coupling regime**
   - Room-temperature ground-state cooling





- *Y.-C. Liu, Y.-F. Xiao*, et al., PRL 112, 213602 (2014).*
- *Y.-C. Liu, Y.-F. Xiao* et al., PRL 111, 083601 (2013).*
- *Y.-C. Liu, Y.-F. Xiao* et al., PRL 110, 153606 (2013).*
- *Y.-C. Liu, Y.-F. Xiao* et al., Science China, in press*
- *Y.-C. Liu, Y.-F. Xiao* et al., PRA 89, 053821 (2014).*
- *H.-K. Liu, Y.-F. Xiao* et al., PRA 88, 053850 (2013).*
- *M.-Y.Yan, Y.-F. Xiao* et al., PRA 88, 023802 (2013).*
- *X.-X. Ren, Y.-F. Xiao* et al., PRA 87(3), 033807 (2013).*
- *H.-K. Li, Y.-F. Xiao* et al., PRA 85, 053832 (2012)*
- *Y.-F. Xiao* et al., PRA 85, 031805(R) (2012). Rapid Comm.*
- *Y.-C. Liu, Y.-F. Xiao* et al., PRA 84, 011805(R) (2011). Rapid Comm.*
- *Y.-C. Xiao* et al., PRA 81(5), 053807 (2010).*
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Thank you for your attention!

For more information:
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http://www.phy.pku.edu.cn/~yfxiao/

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