Quantum Microwave Photonics:

Coupling quantum microwave circuits to quantum optics via cavity electro-optic modulators

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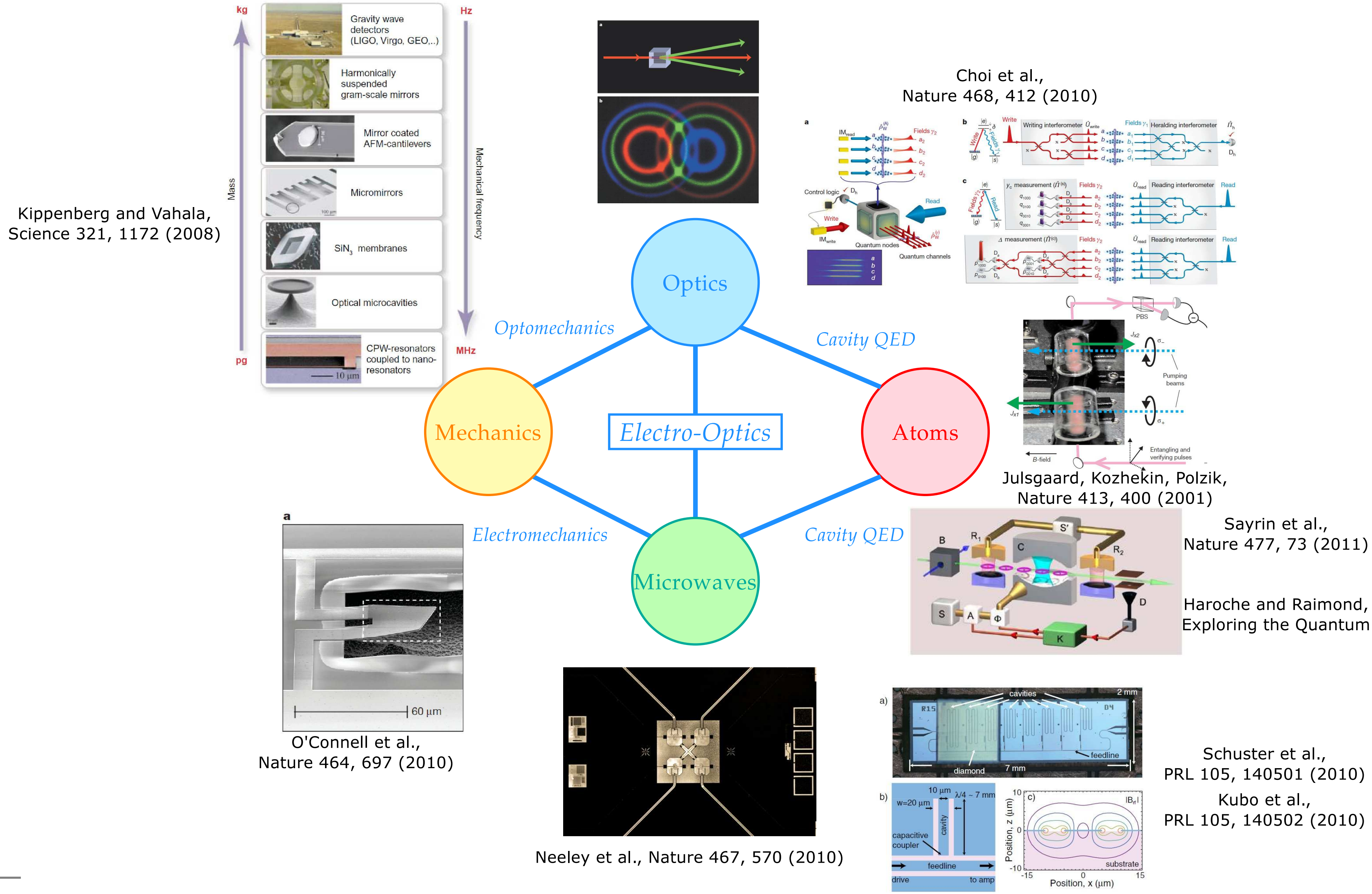
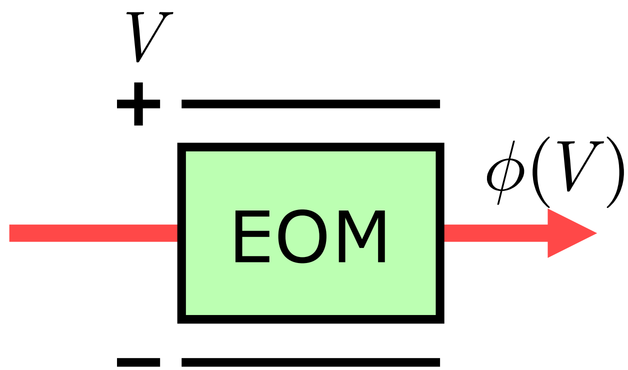
Hybrid Quantum Systems



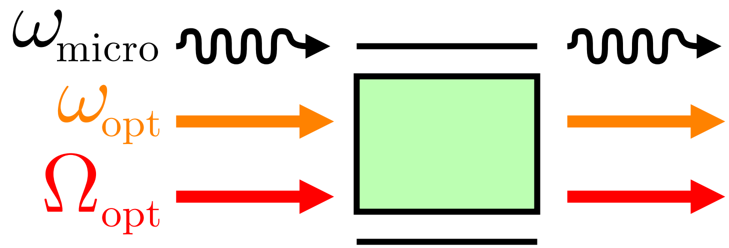
Electro-Optic Modulation



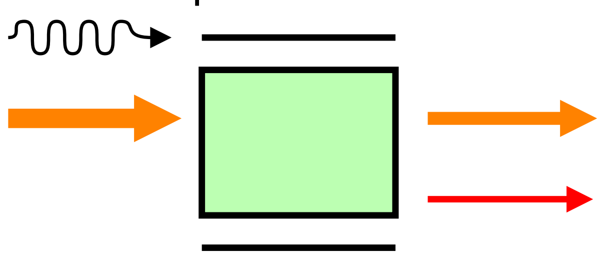
- $\boldsymbol{\epsilon} = \epsilon_0 \left(1 + \boldsymbol{\chi}^{(1)} + \boldsymbol{\chi}^{(2)}\boldsymbol{E} + \boldsymbol{\chi}^{(3)} : \boldsymbol{EE} + \ldots\right)$
- $\boldsymbol{\chi}^{(2)}$ (Pockels): $\Delta\phi(V) \propto V$: e.g., lithium niobate ($LiNbO_3$)
- Optical:
  - transparent between 350nm-5μm
  - intrinsic $Q \sim 10^6$ resonator at 1.55μm [Ilchenko *et al.*, JOSAB 20, 333 (2003)]
  - 10dB squeezing [Vahlbruch *et al.* PRL 100, 033602 (2008)]
- Microwave:
  - intrinsic $\epsilon_l \approx 28$, $\epsilon_t \approx 45$, $Q \approx 2.3 \times 10^3$ at 9GHz, 300K [Bourreau *et al.*, EL 22, 399 (1986)], loss should decrease with temp.
  - Cu half-wave resonator: $Q \approx 100$ at 9GHz, 300K [Ilchenko *et al.*]
  - 26.5GHz EOM with Nb electrode on $LiNbO_3$ at 4.2K [Yoshida *et al.*, IEEE TMTT 47, 1201 (1999)]

Three-Wave Mixing

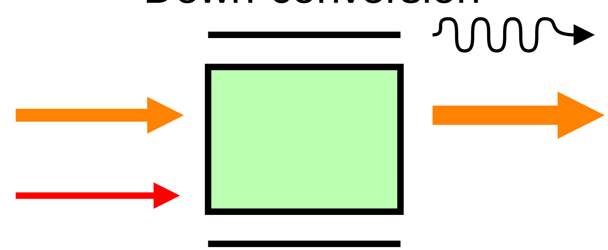
$$\boldsymbol{P}^{(NL)} \propto \boldsymbol{\chi}^{(2)} : \boldsymbol{E}\boldsymbol{E}, \quad \omega_{\text{micro}} + \omega_{\text{opt}} = \Omega_{\text{opt}}$$



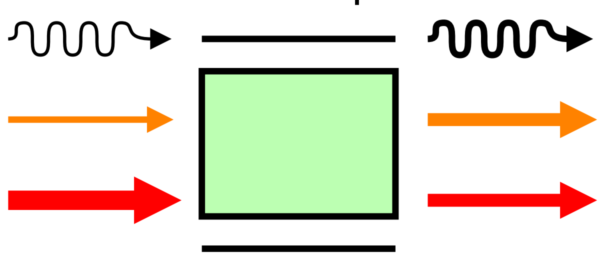
Up-conversion



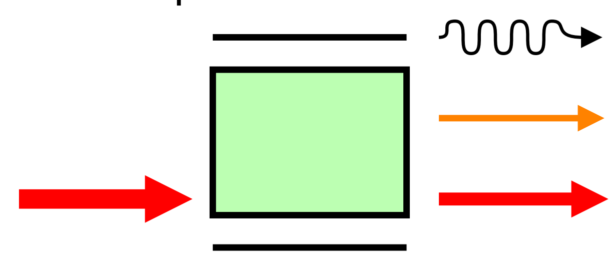
Down-conversion



Parametric amplification



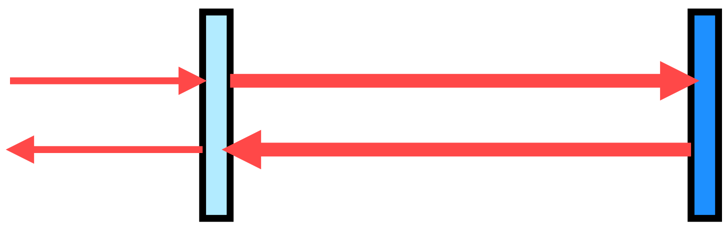
Spontaneous parametric down conversion

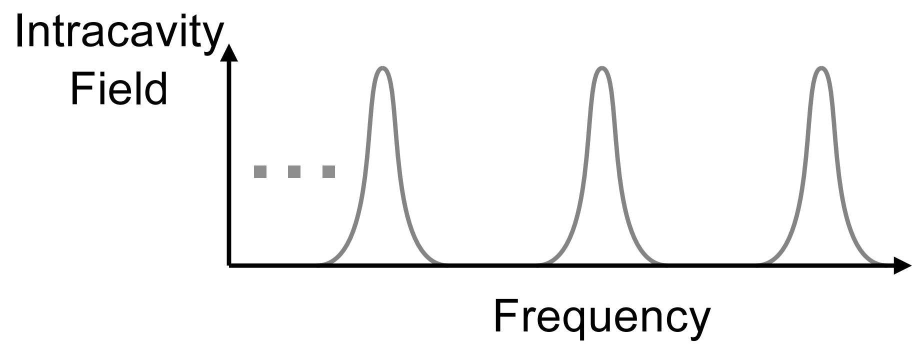


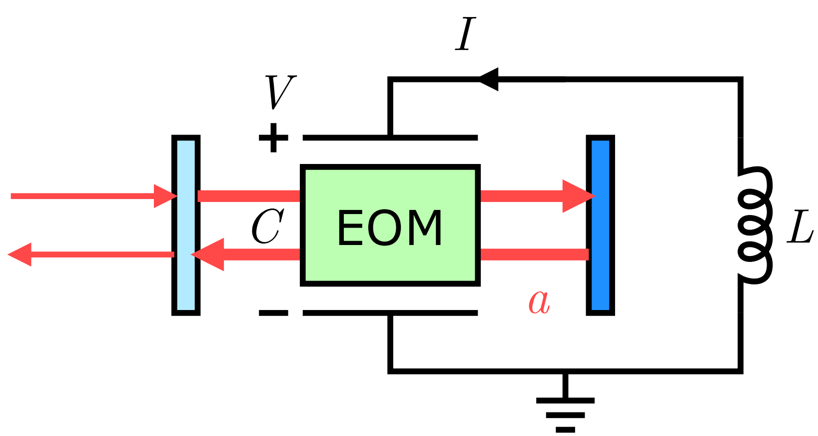
- Spatial mode matching

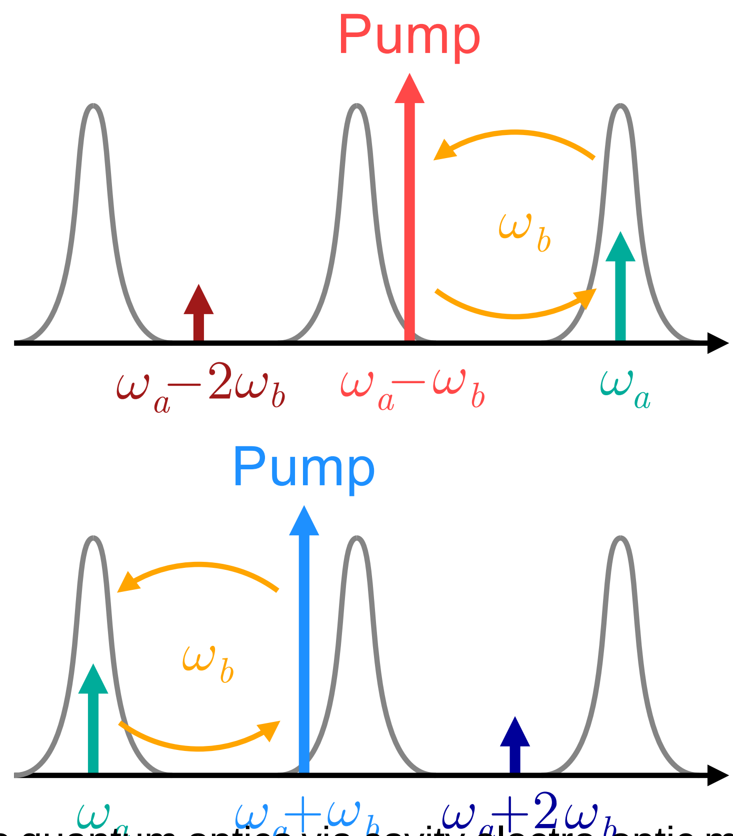
Resonant Enhancement

- How to enhance desired processes and suppress parasitic ones?

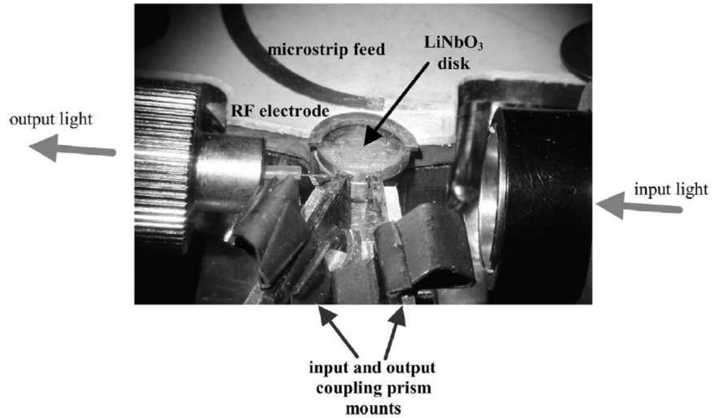




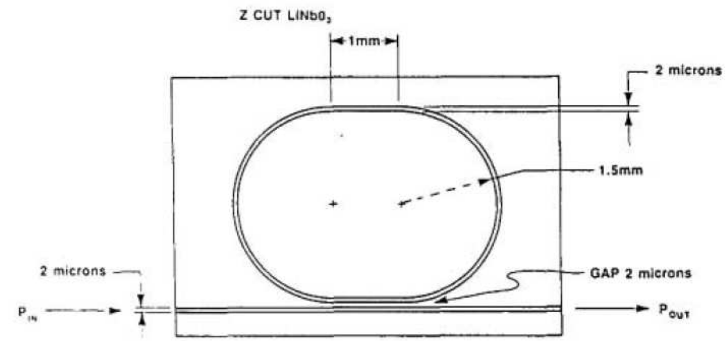




Device Geometry



Cohen *et al.* (USC), "High-Q microphotonic electro-optic modulator," Solid-State Electronics **45**, 1557 (2001)



Mahapatra and Robinson, "Integrated-optic ring resonators made by proton exchange in lithium niobate," Appl. Opt. **24**, 2285 (1985).

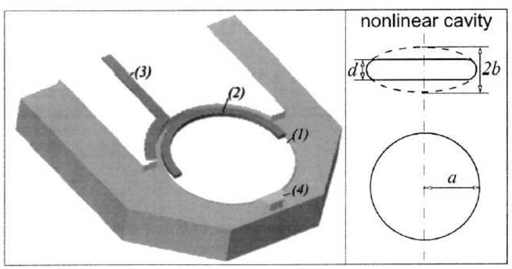
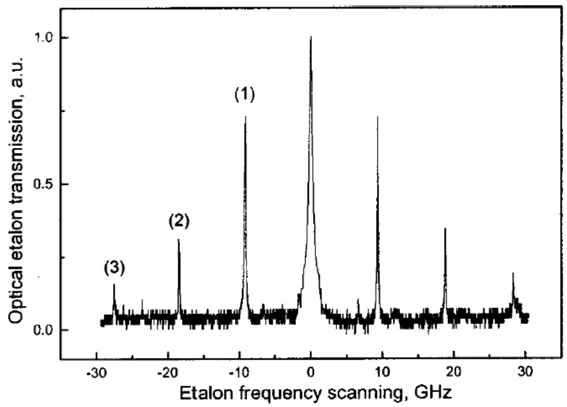
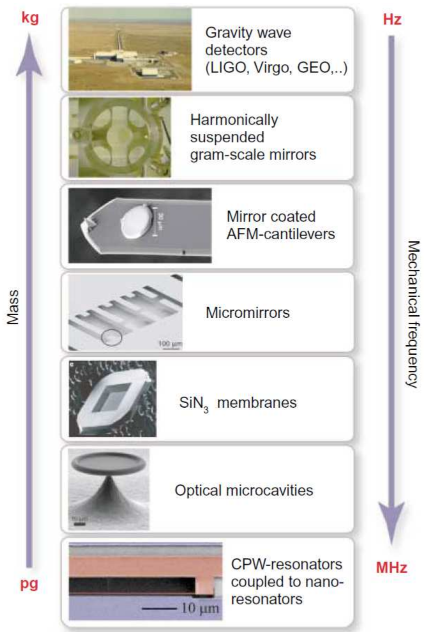


Fig. 1. Experimental setup: (1) $LiNbO_3$ optical cavity, (2) microwave resonator, (3) microwave feeding strip line, and (4) diamond coupling prism. Inset: geometric characteristics of the nonlinear optical cavity.

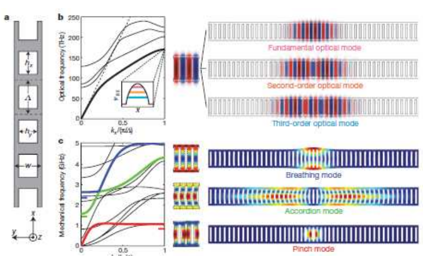
Ilchenko *et al.* (JPL), "Whispering-gallery-mode electro-optic modulator and photonic microwave receiver," J. Opt. Soc. Am. B **20**, 333 (2003), $r = 2.4$ mm, $d = 150\ \mu$m, half-wave 9 GHz resonator



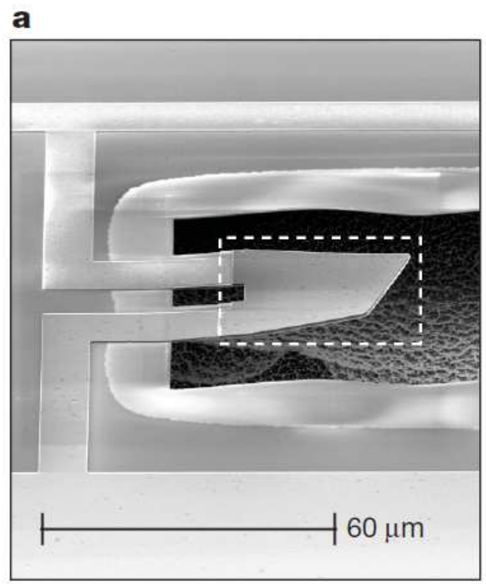
Analogy with Cavity Optomechanics



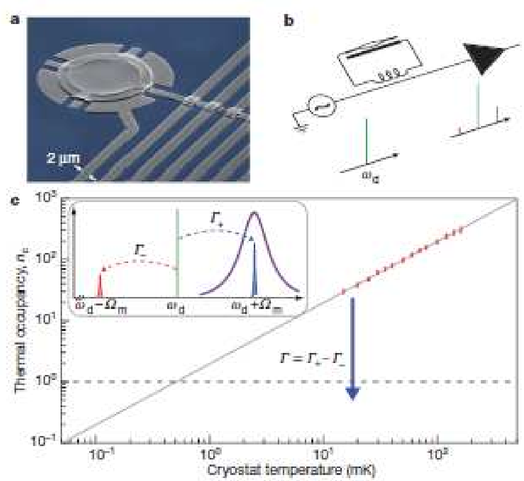
Kippenberg and Vahala, Science **321**, 1172 (2008)



Eichenfield *et al.*, Nature **462**, 78 (2009)

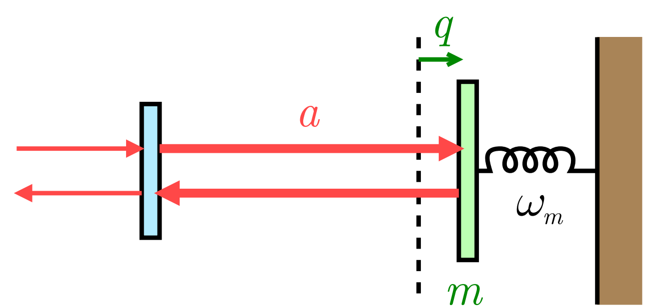


O'Connell *et al.*, Nature **464**, 697 (2010)

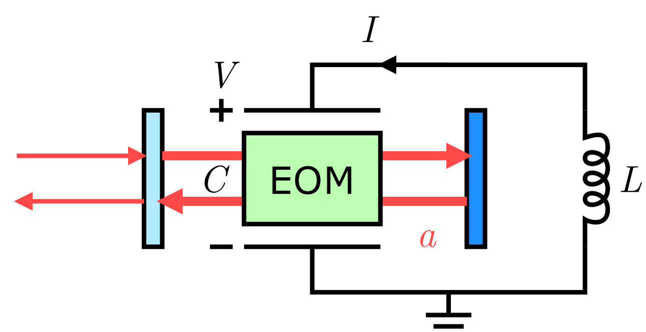


Teufel *et al.*, Nature **464**, 697 (2010)

Optical/microwave photons $\leftrightarrow$ microwave/RF phonons:

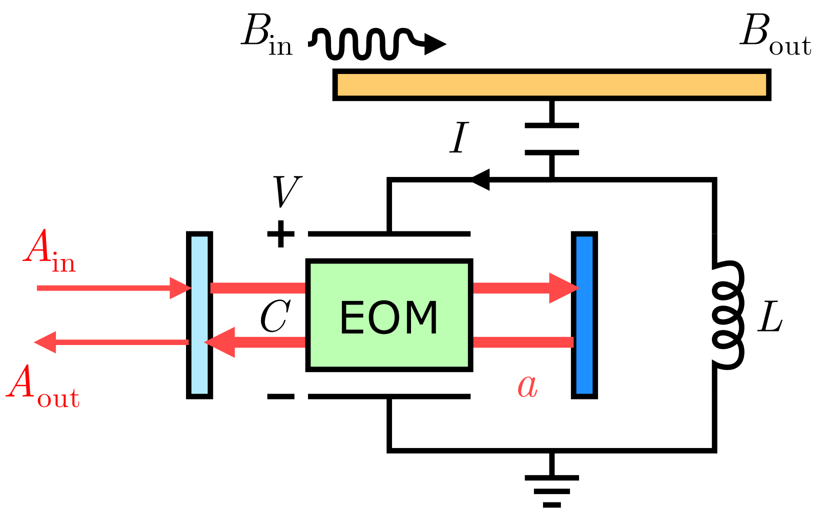


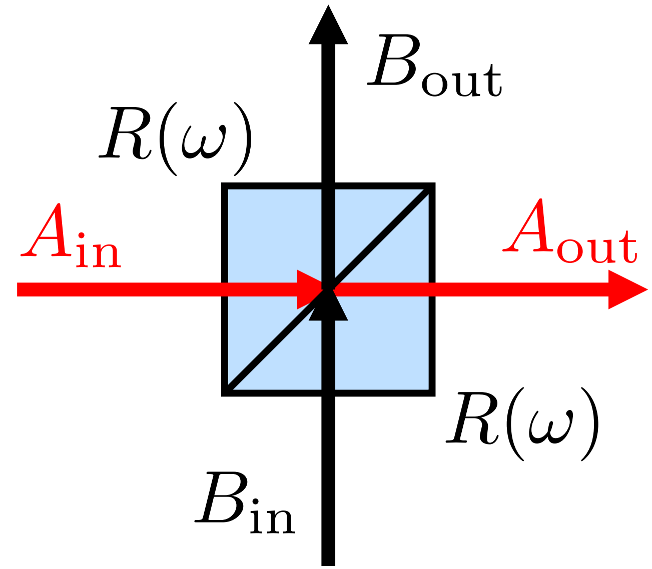
optical photons $\leftrightarrow$ microwave/RF photons:



Tsang, Phys. Rev. A **81**, 063837 (2010); e-print arXiv:1108.1829 (2011)

Laser Cooling and Noiseless Frequency Conversion





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$$\frac{da}{dt} = ig\alpha b - \frac{\Gamma_a}{2}a + \sqrt{\gamma_a}A_{\rm in} + \sqrt{\gamma_a'}A', \quad (1)$$

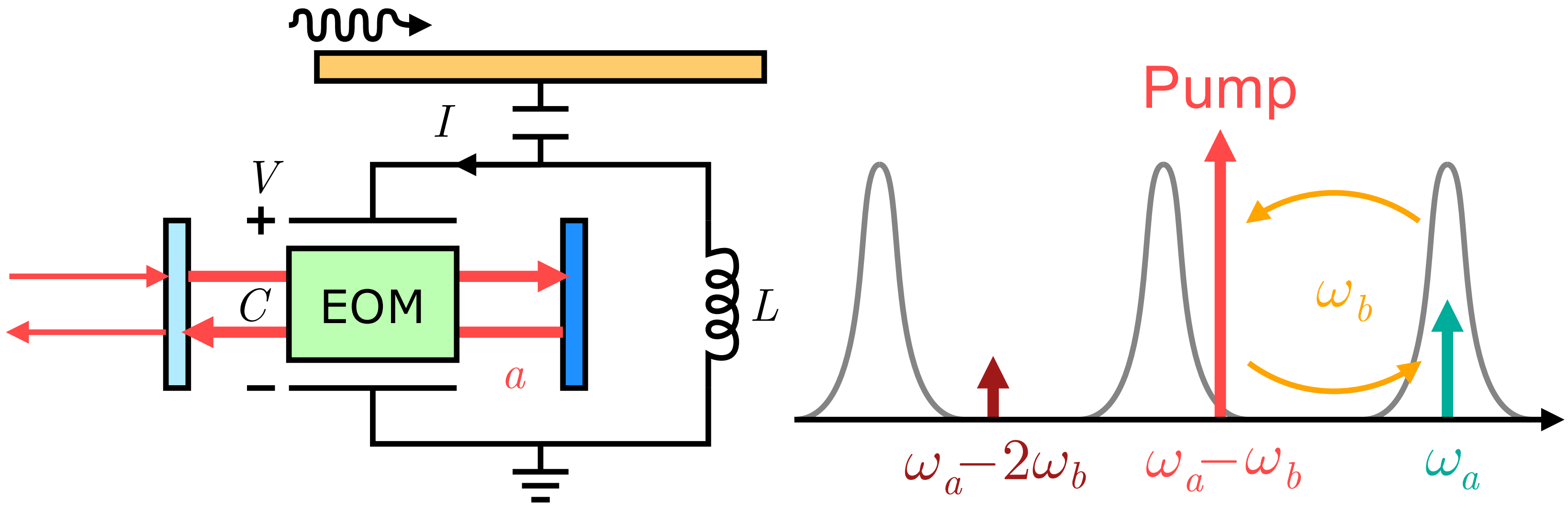
$$\frac{db}{dt} = ig\alpha^* a - \frac{\Gamma_b}{2}b + \sqrt{\gamma_b}B_{\rm in} + \sqrt{\gamma_b'}B', \quad (2)$$

$$A_{\rm out} = \sqrt{\gamma_a}a - A_{\rm in}, \quad (3)$$

$$B_{\rm out} = \sqrt{\gamma_b}b - B_{\rm in}. \quad (4)$$

- Effective microwave resonator temperature $\propto \langle b^\dagger b\rangle$

Laser Cooling and Noiseless Frequency Conversion



$$H_I \approx g\sqrt{N_{\text{pump}}}\left(a^\dagger b + a b^\dagger\right) \quad (5)$$

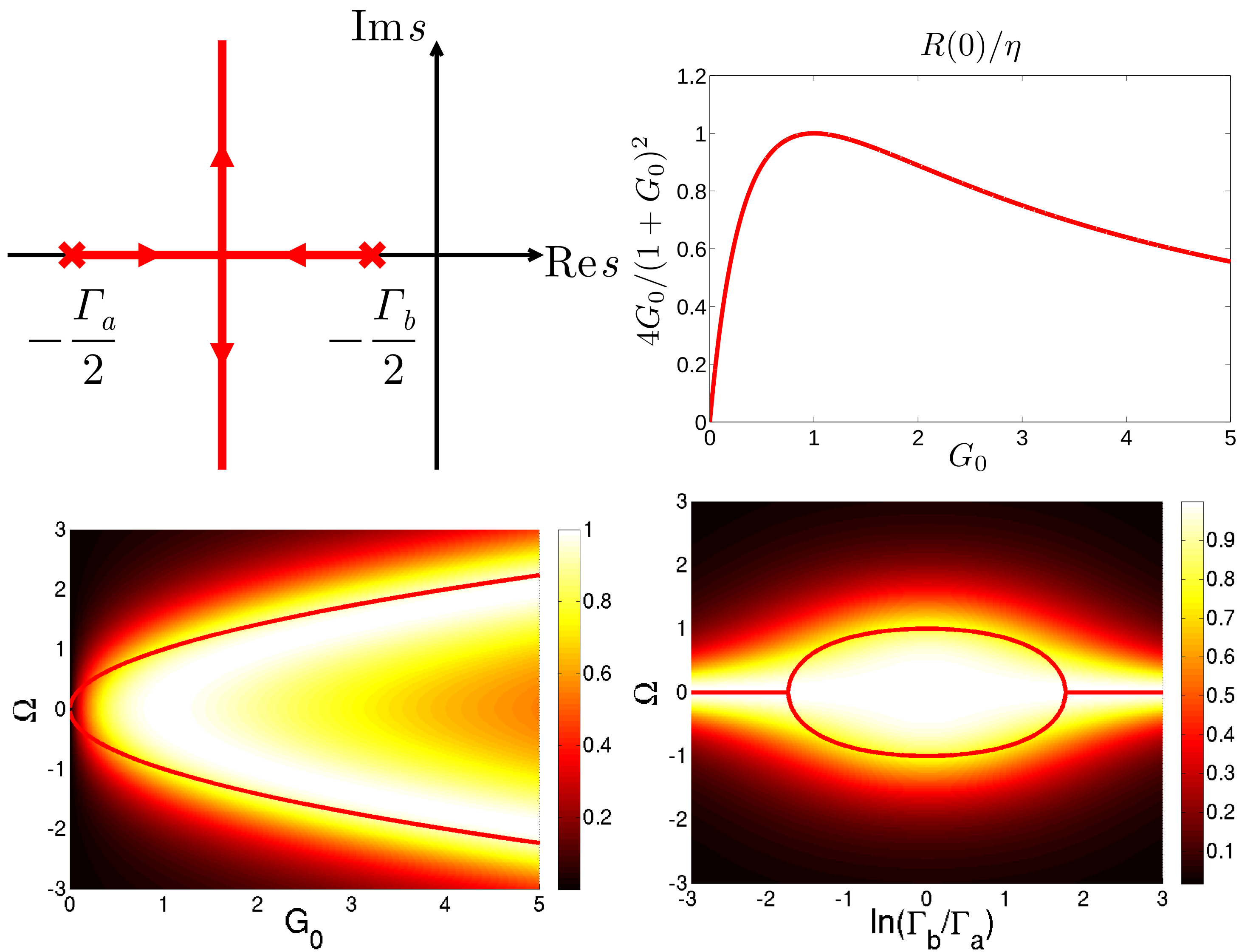
$$g = \eta \frac{\omega_a n^3 r}{2d}\sqrt{\frac{\hbar\omega_b}{2C}}, \quad (6)$$

$$\boxed{G \equiv \frac{g^2 N_{\text{pump}}}{\Gamma_a \Gamma_b}} \quad (7)$$

$$\text{Cooling} : G \gg 1 \quad (8)$$

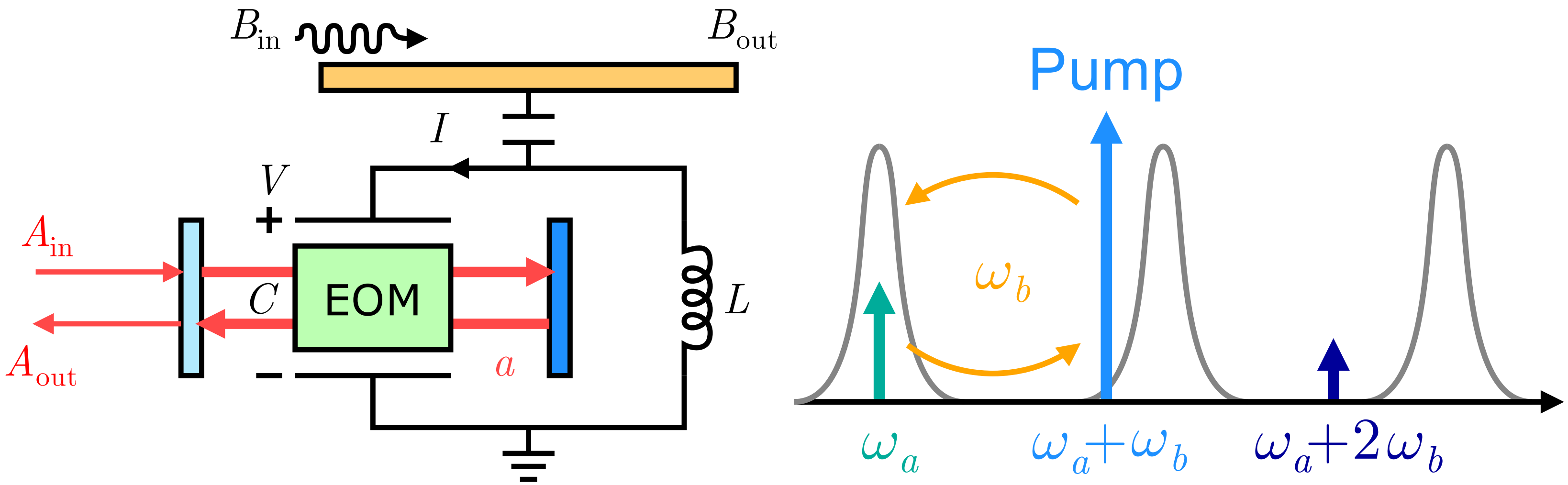
$$\text{Conversion} : G = 1 \quad (9)$$

Plots



Im s
Re s
$-\frac{\Gamma_a}{2}$
$-\frac{\Gamma_b}{2}$
$R(0)/\eta$
$4G_0/(1+G_0)^2$
G_0
Ω
G_0
Ω
$\ln(\Gamma_b/\Gamma_a)$

Parametric Amplification/Oscillation



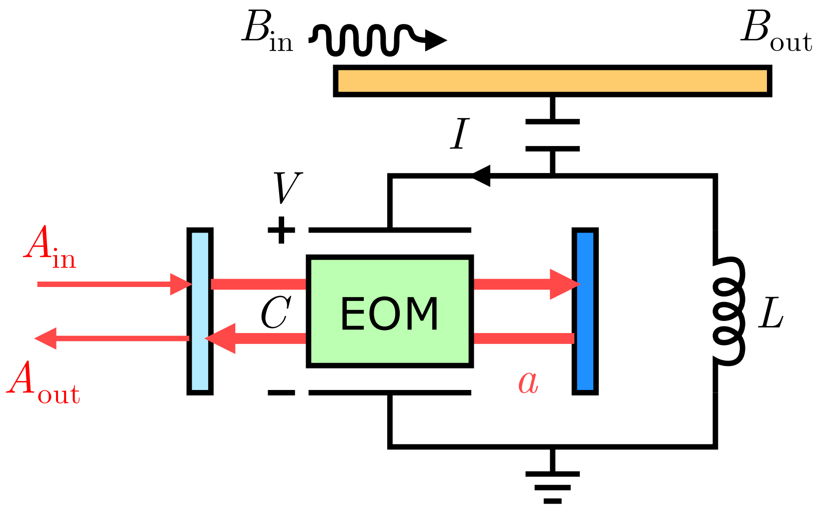
$$\frac{da}{dt} = ig\alpha b^* - \frac{\Gamma_a}{2}a + \sqrt{\gamma_a}A_{\text{in}} + \sqrt{\gamma'_a}A', \tag{10}$$

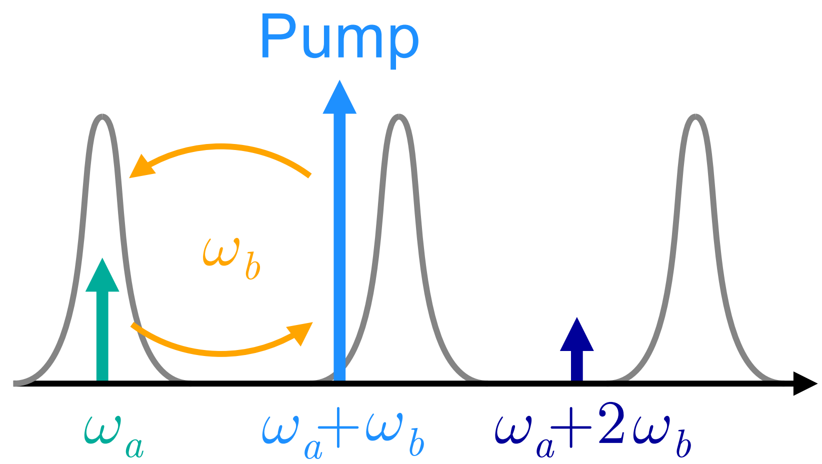
$$\frac{db}{dt} = ig\alpha a^* - \frac{\Gamma_b}{2}b + \sqrt{\gamma_b}B_{\text{in}} + \sqrt{\gamma'_b}B', \tag{11}$$

$$A_{\text{out}} = \sqrt{\gamma_a}a - A_{\text{in}}, \tag{12}$$

$$B_{\text{out}} = \sqrt{\gamma_b}b - B_{\text{in}}. \tag{13}$$

Parametric Amplification/Oscillation





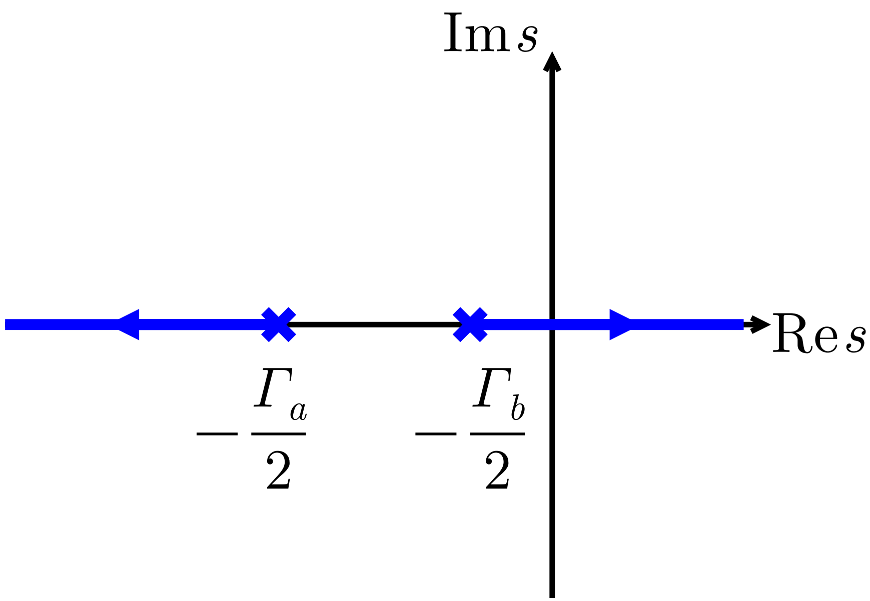
$$H_I \approx g\sqrt{N_{\text{pump}}}\left(a^\dagger b^\dagger + ab\right), \quad \boxed{G \equiv \frac{g^2 N_{\text{pump}}}{\Gamma_a \Gamma_b}} \tag{14}$$

$$\text{Oscillation} : G \geq 1, \tag{15}$$

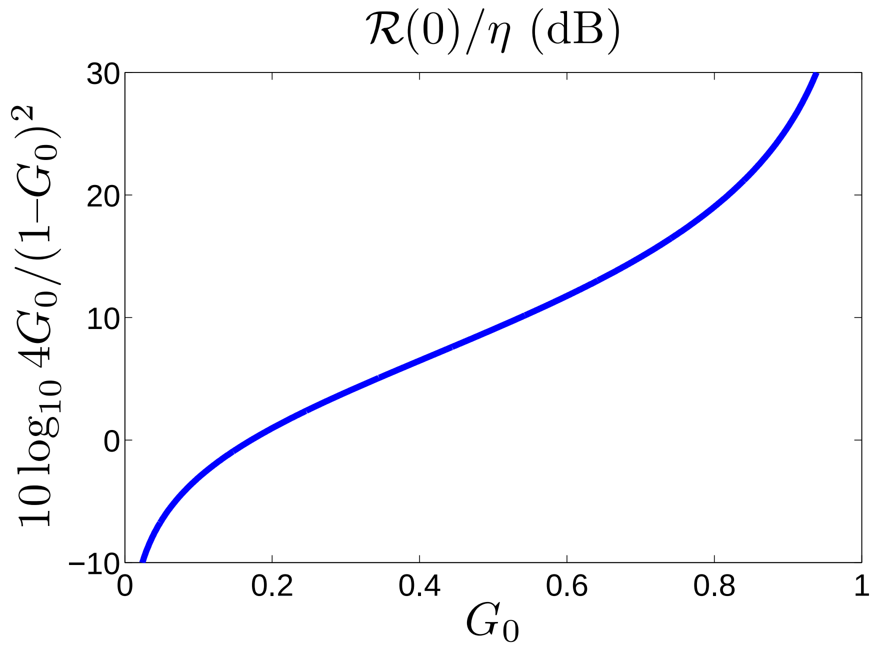
$$\text{Spontaneous Down Conversion/Entangled Photons} : G \ll 1 \tag{16}$$

- Double-sideband pumping: backaction-evading microwave quadrature measurement
- $\chi^{(3)}$ (Kerr): $\phi(V) \propto V^2$, backaction-evading microwave energy measurement

Plots



Im s
Re s
$-\frac{\Gamma_a}{2}$
$-\frac{\Gamma_b}{2}$



$\mathcal{R}(0)/\eta$ (dB)
$10\log_{10} 4G_0/(1-G_0)^2$
30
20
10
0
−10
0
0.2
0.4
0.6
0.8
1
G_0

Coupling Strength

$$G = \frac{g^2 N_{\rm pump}}{\gamma_a \gamma_b}, \qquad g = \eta \frac{\omega_a n^3 r}{2d}\sqrt{\frac{\hbar\omega_b}{2C}}. \tag{17}$$

- Ilchenko *et al.*, JOSAB 20, 333 (2003) ($\gamma_a \approx 2\pi \times 90$ MHz, $\gamma_b \approx 2\pi \times 50$ MHz, $d \approx 150\mu$m):

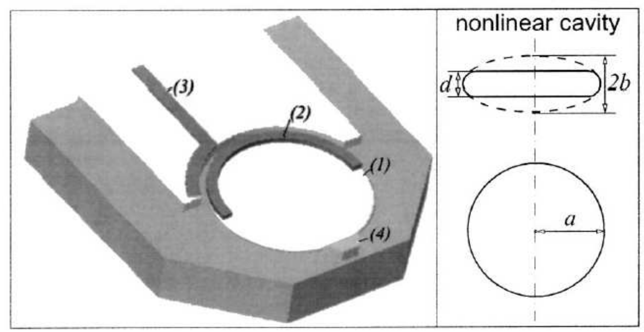
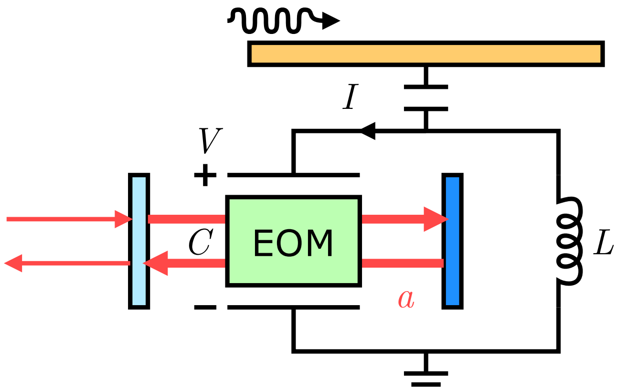


Fig. 1. Experimental setup: (1) $LiNbO_3$ optical cavity, (2) microwave resonator, (3) microwave feeding strip line, and (4) diamond coupling prism. Inset: geometric characteristics of the nonlinear optical cavity.

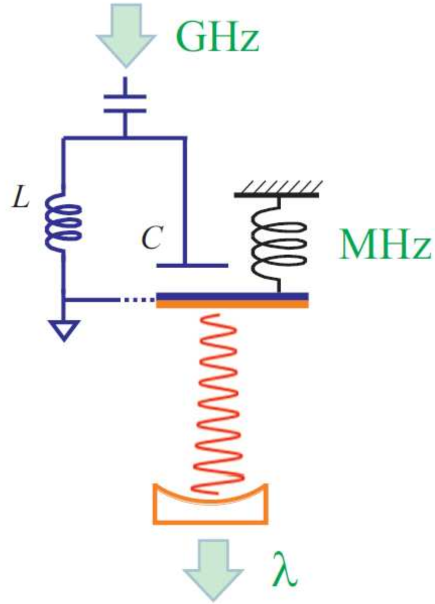
$$g \approx 20 \text{ Hz}, \qquad G \approx 2 \times 10^{-5} \text{ at 2 mW pump} \tag{18}$$

- g can be improved by $\sim 10^1 - 10^2$, γ_b reduced by $\sim 10^3$ using superconducting microwave resonator
- r in $BaTiO_3$ and KTN is higher than $LiNbO_3$ by $10^1 - 10^2$

Competition: electro-optomechanics, atoms



M. Tsang, "Cavity quantum electro-optics," Phys. Rev. A **81**, 063837 (2010); **84**, 043845 (2011).



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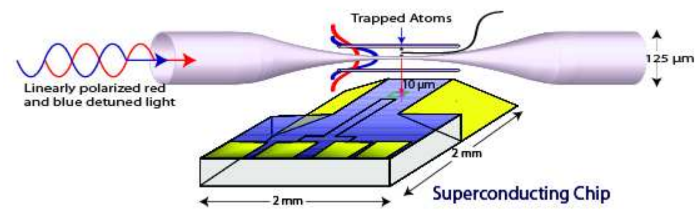

Hoffman *et al.*, arXiv:1108.4153 (2011); Hafezi *et al.*, PRA 85, 020302(R) (2012)

	Electro-optics	Mechanics	Atoms
Effect	$\chi^{(2)}$	$\chi^{(3)}$	$\chi^{(3)}$
Pumps	optical	optical + microw.	optical + microw.
Resonators	microw. + optical	microw. + optical + mech.	microw. + optical + atoms
Experiment	$g = 20$ Hz (Ilchenko)	N/A	N/A

Summary

- Cooling, frequency conversion, parametric amplification/oscillation, entangled photons, BAE quadrature/energy measurements, . . .
- Quantum apps require $G \sim 1$, technology not there yet but not impossible
- More advanced than mechanics/atoms
- Classical apps: microwave photonics, sensing, metrology, etc.
- M. Tsang, "Cavity quantum electro-optics," Phys. Rev. A **81**, 063837 (2010); **84**, 043845 (2011).
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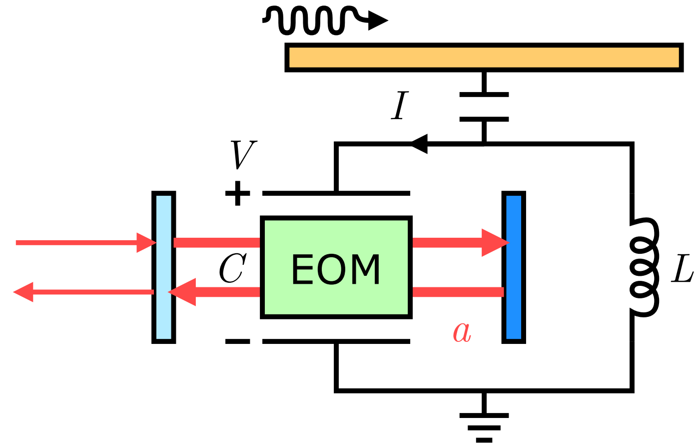
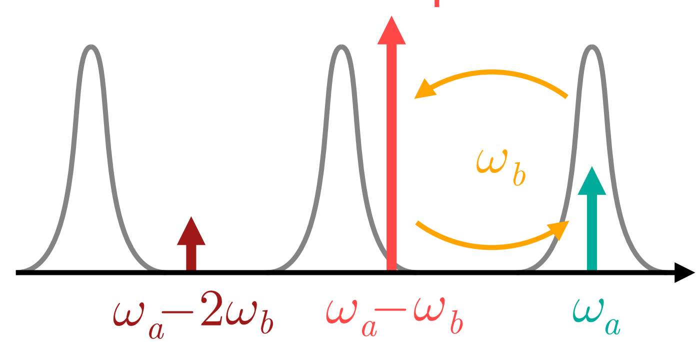
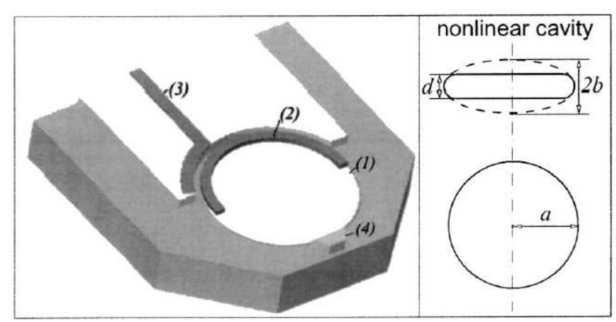
- Funding: Singapore National Research Foundation NRF-NRFF2011-07







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