Quantum Microwave Photonics: Coupling quantum microwave circuits to quantum optics via cavity electro-optic modulators

Mankei Tsang
eletmk@nus.edu.sg

1 Department of Electrical and Computer Engineering
2 Department of Physics
National University of Singapore
3 Center for Quantum Information and Control
University of New Mexico
http://mankei.tsang.googlepages.com/
Hybrid Quantum Systems

Kippenberg and Vahala, Science 321, 1172 (2008)

Optomechanics

Choi et al., Nature 468, 412 (2010)

Mechanics

Julsgaard, Kozhekin, Polzik, Nature 413, 400 (2001)

Electro-Optics

Sayrin et al., Nature 477, 73 (2011)

Cavity QED

Haroche and Raimond, Exploring the Quantum

Atoms

Schuster et al., PRL 105, 140501 (2010)

Kubo et al., PRL 105, 140502 (2010)

Optics

Neeley et al., Nature 467, 570 (2010)

Microwaves


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Electro-Optic Modulation

\[ \epsilon = \epsilon_0 \left( 1 + \chi^{(1)} + \chi^{(2)} E + \chi^{(3)} : EE + \ldots \right) \]

- \( \chi^{(2)} \) (Pockels): \( \Delta \phi(V) \propto V \): e.g., lithium niobate (LiNbO\(_3\))

Optical:
- transparent between 350nm-5\( \mu \)m
- intrinsic \( Q \approx 10^6 \) resonator at 1.55\( \mu \)m [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)]
Analogy with Cavity Optomechanics

Optical Photons ↔ Microwave/RF Photons:

\[ \hat{H}_I \propto \phi(\hat{V})\hat{a}^\dagger \hat{a} \]
\[ \hat{V} \propto \hat{b} + \hat{b}^\dagger \]

Optical Photons ↔ Microwave/RF Phonons:

\[ \hat{H}_I \propto \phi(\hat{q})\hat{a}^\dagger \hat{a} \]
\[ \hat{q} \propto \hat{b} + \hat{b}^\dagger \] (1)

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Laser Cooling and Noiseless Frequency Conversion

\[ H_I \approx g \sqrt{N_{\text{pump}}} \left( a^\dagger b + ab^\dagger \right) \]  
\[ g = \eta \frac{\omega_a n^3 r}{2d} \sqrt{\frac{\hbar \omega_b}{2C}}, \]  
\[ G \equiv \frac{g^2 N_{\text{pump}}}{\gamma_a \gamma_b} \]  
Cooling : \( G \gg 1 \)  
Conversion : \( G = 1 \)
**Parametric Amplification/Oscillation**

\[ H_I \approx g \sqrt{N_{\text{pump}}} \left( a^\dagger b^\dagger + ab \right), \quad G \equiv \frac{g^2 N_{\text{pump}}}{\gamma_a \gamma_b} \]

Oscillation: \( G \geq 1 \),

Entangled Photons: \( G \ll 1 \)

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

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Coupling Strength

\[ G = \frac{g^2 N_{\text{pump}}}{\gamma_a \gamma_b}, \quad g = \eta \frac{\omega_a n^3 r}{2d} \sqrt{\frac{\hbar \omega_b}{2C}}. \] (11)

Ilchenko et al., JOSAB 20, 333 (2003) (\(\gamma_a \approx 2\pi \times 90 \text{ MHz}, \gamma_b \approx 2\pi \times 50 \text{ MHz}, d \approx 150 \mu\text{m})

\[ g \approx 20 \text{ Hz}, \quad G \approx 2 \times 10^{-5} \text{ at 2 mW pump} \] (12)

- \(g\) can be improved by \(\sim 10^1 - 10^2\), \(\gamma_b\) 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


Regal and Lehnert, J. Phys.: Conf. Series 264, 012025 (2011);
Safavi-Naeini and Painter, NJP 13, 013017 (2011); Taylor et al., PRL 107, 273601 (2011)

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

<table>
<thead>
<tr>
<th>Effect</th>
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<th>Mechanics</th>
<th>Atoms</th>
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<tr>
<td>Pumps</td>
<td>$\chi^{(2)}$</td>
<td>$\chi^{(3)}$</td>
<td>$\chi^{(3)}$</td>
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<td>Resonators</td>
<td>optical + microw.</td>
<td>microw. + optical + mech.</td>
<td>microw. + optical + atoms</td>
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<tr>
<td>Experiment</td>
<td>$g = 20$ Hz (Ilchenko)</td>
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Summary

- Analogous to cavity optomechanics
- **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.
- eletmk@nus.edu.sg
- http://mankei.tsang.googlepages.com/
- Funding: NSF (UNM), Singapore National Research Foundation NRF-NRFF2011-07 (NUS)