Control and measurement of an optomechanical system using a superconducting qubit

Florent Lecocq

PIs
Ray Simmonds
John Teufel
Joe Aumentado
Introduction: typical architecture

Non Gaussian resource

Quantum information processing

Two Level System

Cavity QED

Linear Harmonic Oscillator

Storage or Bus

Large Hilbert space
Long lifetime

$|e\rangle$

$|g\rangle$

$|0\rangle$

$|1\rangle$

$|2\rangle$

$|3\rangle$

$|n\rangle$
Introduction: typical architecture

Linear quantum information processing

Two Level System

Linear Harmonic Oscillator

Analog information processing

Linear Harmonic Oscillator
Introduction: cQED and optomechanics

Rydberg atoms - roughly 1,000 times larger than typical atoms - are sent through the cavity one by one. At the exit the atom can reveal the presence or absence of a photon inside the cavity.

Serge Haroche

Photon Cavity

Two Level System

David Wineland

Mechanical Oscillator

optomechanics

cQED
Introduction: cQED and optomechanics

What about superconducting circuit?
Introduction: cQED and optomechanics

**This talk:**

- Phase Qubit
- Mechanical Oscillator
- Microwave Cavity
- Circuit QED
- Microwave Opto-Mechanics

- Two Level System
- Photon Cavity
- Mechanical Oscillator
- 10 GHz
- 10 MHz
- cQED
Why mechanical oscillators?

Lifetime applied information storage

Precision measurement

\[ \sqrt{S_x} \approx 10^{-17} \text{ m}/\sqrt{\text{Hz}} \]
\[ \sqrt{S_F} \approx 10^{-17} \text{ N}/\sqrt{\text{Hz}} \]

\[ \sqrt{S_x S_F} \geq \hbar \]

Optical to microwave

Overview

• **Cavity QED:**
  Create and measure complex quantum photon states

• **Cavity Optomechanics:**
  Manipulate and measure mechanical motion using photons

• **Our Goal:**
  Implementation of a hybrid system to readout and prepare quantum state of light and motion
Overview

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Cavity QED: circuits and microwave photons

\( \frac{1}{2} \hbar \Omega \hat{\sigma}^z \)

\( \hbar g (\hat{a}^+ \hat{\sigma}^- + \hat{a} \hat{\sigma}^+) \)

Fock states

\( |0\rangle \quad \text{oscillations} @ \quad \sqrt{n} \times g \)

Hofheinz et al., Nature 454 (2008)
Hofheinz et al., Nature 459 (2009)
Cavity QED: circuits and microwave photons

\[\hbar g \left( \hat{a}^\dagger \hat{\sigma}^- + \hat{\sigma}^+ \hat{a} \right)\]

Coherent states

\[|\alpha\rangle \sim \sum_n \frac{\alpha^n}{\sqrt{n!}} |n\rangle\]

oscillations @ multiple frequencies

Hofheinz et al, Nature 459 (2009)
Cavity QED: circuits and microwave photons

\[ \frac{1}{2} \hbar \Omega \hat{\sigma}^z \]

\[ \hbar g (\hat{a}^\dagger \hat{\sigma}^- + \hat{a} \hat{\sigma}^+) \]

\[ \hbar \omega_m (\hat{a}^\dagger \hat{a} + \frac{1}{2}) \]

Arbitrary states

Hofheinz et al, Nature 459 (2009)
Cavity QED: circuits and mechanical oscillators


Overview

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  Implementation of a hybrid system to readout and prepare quantum state of macroscopic mechanical motion
Cavity optomechanics in a nutshell

Couple an electromagnetic resonance to a mechanical resonance

High Q cavity enhances the interaction
Cavity optomechanics: back-action forces

Pump detuning breaks the balance

\[ \omega_p = \omega_c - \omega_m \]

Damping & cooling

\[ \omega_p = \omega_c + \omega_m \]

Anti-damping & heating

Radiation pressure force does work
Cavity optomechanics: radiation pressure

\[ \hat{H}_c = \hbar \omega_c (\hat{a}^\dagger \hat{a} + \frac{1}{2}) \]

\[ \hat{H}_m = \hbar \Omega_m (\hat{b}^\dagger \hat{b} + \frac{1}{2}) \]

\[ \hat{H}_{RP} = \hbar \hat{a}^\dagger \hat{a} G x_{zpf} (\hat{b}^\dagger + \hat{b}) \]

Large coherent drive: \( \hat{a} \Rightarrow \hat{a} + \alpha \)

Single photon coupling rate \( g_0 = G x_{zpf} \)

\[ G = \frac{\partial \omega_c}{\partial x} \quad x_{zpf} = \sqrt{\frac{\hbar}{2m\Omega_m}} \]

Strong Coupling Regime (but linear)
Choose your Hamiltonian

\[ \hat{H}_{RP} = \hbar g (\hat{a}^\dagger + \hat{a})(\hat{b}^\dagger + \hat{b}) \]

\[ \omega_p = \omega_c - \omega_m \]

Damping & cooling

\[ \hat{a}^\dagger \hat{b} + \hat{b}^\dagger \hat{a} \]

Beam splitter

( Jaynes-Cummings: \( \hat{a}^\dagger \hat{\sigma}^- + \hat{a} \hat{\sigma}^+ \))

\[ \omega_p = \omega_c + \omega_m \]

Anti-damping & heating

\[ \hat{a}^\dagger \hat{b}^\dagger + \hat{a} \hat{b} \]

Two-mode squeezer

\[ \omega_m \]

swap

amplification
A zoo of optomechanical systems

Starving for coupling

\[ g = \frac{\partial \omega_c}{\partial x} \times x_{zp} \times \alpha \]

Single photon coupling rate

\[ g_0 = \frac{\partial \omega_c}{\partial x} \times x_{zp} \]

**Fabry-Perot Cavity**

\[ g_0 = \omega_c \frac{x_{zp} f}{L} \]

**LC Transducer Circuit**

\[ g_0 = \omega_c \frac{x_{zp} f}{2d} \left( \frac{C_m}{C_{total}} \right) \]

Braginsky & Khalili (1988)
mode volume $\approx 10^{-13} \lambda^3$

1 photon $\Rightarrow$ $\vec{E} \approx 1 \text{ kV/m}$

$m \approx 50 \text{ pg}$

$x_{zpf} \approx 4 \text{ fm}$

$g_0 \approx 2\pi \times 200 \text{ Hz}$

$\omega_m \approx 2\pi \times 10 \text{ MHz}$

Plate separation $\approx 50 \text{ nm}$

$\omega_c \approx 2\pi \times 10 \text{ GHz}$
Microwave optomechanics achievements

1. Continuous waves & driven response:

$\hat{H}_{RP} = \hbar g (\hat{a}^{\dagger} \hat{b} + \hat{b}^{\dagger} \hat{a})$

$T = 40\text{mK}$

$g = g_0 \sqrt{n_d}$

Probe transmission, $|T|^2$

Prove frequency, $\omega_p/2\pi$ (GHz)

Microwave optomechanics achievements

2. Continuous waves & noise spectrum:

\[ \langle n_m^{eq} \rangle \approx 35 \]

Beamsplitter

\[ \hat{H}_{RP} = \hbar g (\hat{a}^{\dagger} \hat{b} + \hat{b}^{\dagger} \hat{a}) \]

T = 40mK

Microwave optomechanics achievements

3. Pulsed interaction:

Beam Splitter $\hat{a}^+ \hat{b} + \hat{b}^+ \hat{a}$

Two-mode squeezer $\hat{a}^+ \hat{b}^+ + \hat{a} \hat{b}$

T = 40mK

How to go beyond Gaussian states and linear measurement?

Overview

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A nonlinear resource for optomechanics
A nonlinear resource for optomechanics

Qubit control

Qubit readout

Microwave control and readout

T = 40mK
Frequency domain: characterization

![Diagram of qubit and microwave cavity](image)

- Qubit drive, $\omega_d$ vs. Qubit detuning, $\omega_{qb} - \omega_c$ [MHz]
- Microwave field level, $P_{esc}$

**Phase**

Qubit  

Microwave  

Cavity
Frequency domain: characterization

![Circuit diagram and graph showing frequency response of a microwave cavity drive. The graph depicts the response of the cavity drive, $\omega_{d}^{cav}$, over a range of frequencies, with peaks and valleys indicating resonance. The labels $\omega_{qb}$, $\omega_{c}$, and $\omega_{m}$ represent different components of the circuit. The x-axis represents the cavity drive frequency, $\omega_{d}^{cav}$, in GHz, and the y-axis shows the amplitude in dB. The diagram includes a label "Microwave Cavity."
Frequency domain: characterization

\[ g = g_0 \sqrt{n_d} \]

Pump Power

Cavity drive, \( \omega_d^{\text{cav}} \)

Pump detuning, \( \omega_p - \omega_c \) [MHz]

Cavity drive

Microwave Cavity

Mechanical Oscillator

NIST
Frequency domain: characterization

Qubit bias

Qubit drive, $\omega_q^b$

Cavity drive

Cavity drive, $\omega_c^{\text{cav}}$

Pump

$\omega_p$

Qubit drive, $\omega_d$

Frequency domain:

\[ P_{\text{esc}} \]

Qubit detuning, $\omega_q^b - \omega_c$ [MHz]

\[ S_{11} \text{ [dB]} \]

Pump detuning, $\omega_p - \omega_c$ [MHz]

Phase

Qubit

Microwave

Cavity

Mechanical

Oscillator

[NIIST]
Time domain: cQED

(a) State Preparation
| \[ |\psi_{\text{init}}\rangle \rangle \] |
| --- |
| Microwave cavity

(b) Single Photon Fock State
<table>
<thead>
<tr>
<th>Interaction Time [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{\text{esc}}</td>
</tr>
</tbody>
</table>

(c) Coherent State
<table>
<thead>
<tr>
<th>Interaction time [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{\text{esc}}</td>
</tr>
</tbody>
</table>

\[ n_c = 2.65 \]
\[ n_c = 0.67 \]
\[ n_c = 0.10 \]

(d) Thermal State
<table>
<thead>
<tr>
<th>Interaction time [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{\text{esc}}</td>
</tr>
</tbody>
</table>

\[ n_c = 4.35 \]
\[ n_c = 1.15 \]
\[ n_c = 0.21 \]
Nonlinear readout of an optomechanical system

Microwave cavity

$|0\rangle$

$|\phi\rangle$

Mechanical oscillator

$\tilde{H}_{\text{int}} = \hbar g (\hat{a}^\dagger \hat{a}) (\hat{b}^\dagger + \hat{b})$

Qubit sensor

$\omega_p$

$\omega_m$

Pump detuning, $\omega_p - \omega_c$ [MHz]

$n_c$ [a.u.]

$10^{-2} < n_c < 10^1$

$n_d \gg 10^5$

$\langle n_m^{\text{init}} \rangle \approx 25$

$\tilde{H}_{\text{int}} = \hbar g (\hat{a}^\dagger \hat{b} + \hat{b}^\dagger \hat{a})$

$\omega_p = \omega_c - \omega_m$

$\omega_p = \omega_c + \omega_m$

Qubit sensor

$\tilde{H}_{\text{int}} = \hbar g (\hat{a}^\dagger \hat{b} + \hat{b}^\dagger \hat{a})$

$\hat{a}$

$\hat{a}^\dagger$

$\hat{b}$

$\hat{b}^\dagger$
Simulation of optomechanical interaction

\[ \langle n_m \rangle = \text{No Cooling} \]

\[ \langle n_c \rangle \]

\[ \langle n_m^{\text{init}} \rangle \approx 25 \]

\[ \omega_p = \omega_c - \omega_m \]

\[ \theta = \int g(t) \]

\[ \hat{H}_{\text{int}} = \hbar g (\hat{a}^\dagger \hat{b} + \hat{b}^\dagger \hat{a}) \]

Microwave Cavity

Mechanical Oscillator

No Loss

= No Cooling
Simulation of optomechanical interaction

\[ \langle n^\text{init}_m \rangle \approx 25 \]

\[ \omega_p = \omega_c - \omega_m \]

\[ \theta = \int g(t) \]

\[ \hat{H}_{\text{int}} = \hbar g (\hat{a} \hat{b} + \hat{b}^\dagger \hat{a}) \]
Simulation of optomechanical interaction

Microwave Cavity

Mechanical Oscillator

\[ \langle n_m \rangle \approx 25 \]

\[ \langle n_c \rangle \]

Interaction angle, \( \theta \) [rad]

Photon number

\[ \omega_p = \omega_c + \omega_m \]

\[ \hat{H}_{int} = \hbar g (\hat{a}^{\dagger} \hat{b}^{\dagger} + \hat{a} \hat{b}) \]
Simulation of optomechanical interaction

\[ \omega_p = \omega_c - \omega_m \]

\[ \theta = \int g(t) \]

\[ \hat{H}_{int} = \hbar g (\hat{a}^\dagger \hat{b} + \hat{b}^\dagger \hat{a}) \]
Nonlinear readout of an optomechanical system

\[ \langle n_m^{\text{init}} \rangle \approx 25 \]

\[ \hat{H}_{\text{int}} = \hbar g (\hat{a}^\dagger + \hat{a}) (\hat{b}^\dagger + \hat{b}) \]

\[ n_c = 4.35 \]
\[ n_c = 1.15 \]
\[ n_c = 0.21 \]
Nonlinear readout of an optomechanical system

\[ \langle n_m \rangle \approx 25 \]
\[ \langle n_m^{\text{init}} \rangle \approx 0.8 \]
Nonlinear readout of an optomechanical system

\[ \omega_p = \omega_c - \omega_m \]

Coherent SWAP photon/phonon down to a fraction of a quantum

Future:
Process reversible

\[ \langle n_m \rangle = 0.2 \]
Nonlinear readout of an optomechanical system

\[ \omega_p = \omega_c + \omega_m \]
\[ \theta = \int g(t) \]
\[ \hat{H}_{int} = \hbar g (\hat{a}^\dagger \hat{b}^\dagger + \hat{a} \hat{b}) \]

“near quantum-limited” amplification monitoring

**Future:**

Sequence interaction and tomography

Dual mode squeezing and entanglement

\[ \Delta_{EPR}^{estimated} < 10^{-2} \]

Photon number

Interaction angle, \( \theta \) [rad]

Phase

Qubit

Microwave

Cavity

Mechanical

Oscillator

Future:

Sequence interaction and tomography

Dual mode squeezing and entanglement

Phase

Qubit

Microwave

Cavity

Mechanical

Oscillator
Conclusion & future directions

Architecture for quantum information using mechanical resonator

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