Work Package 2: Photon-phonon interfaces

2nd year report
Tasks, Deliverables & Milestones

Task 2.1 Circuit optomechanics with graphene
Task 2.2 Hybrid circuit optomechanics with graphene
Task 2.3: Optomechanical Correlations and Photon-Phonon Conversion
Task 2.4: Strong Optomechanical Coupling for Single Photons

**due month 24:**
D2.2) Switching, slowing and advancing of microwave photons delivered by EPFL
D2.3) Detection of optomechanical correlations delivered by UNIVIE & LUH
D2.4) Coherent photon-phonon conversion postponed to month 36

MS6 Demonstration of strong optomechanical correlations reached by UNIVIE & LUH

**due month 36:**
D2.6) Strong charge-qubit-graphene resonator coupling approached by AALTO
List of publications contributing to WP2

- S. G. Hofer, K. Lehnert, K. Hammerer, „Violation of Bell’s Inequality in Electromechanics” arXiv:1506.08097
- M. Asjad et al., *Large Distance Continuous Variables Communication with Concatenated Swaps*, Phys. Scr. 90, 074055 (2015)
D2.2) Switching, slowing and advancing of microwave photons

False-colour scanning electron microscopy image of superconducting circuit nanoelectromechanical system.

a, A quarter-wavelength CPW resonator, coupled to a CPW feed line. The 6 μm gaps are patterned by etching through the Nb layer (yellow) down to the Si (green).
b, A 30 μm long bilayer mechanical beam integrated in the microwave cavity (yellow: Nb, green: Si, violet: Si₃N₄).
c,d, A magnified view, showing the mechanical beam released from the Si substrate.
Delayed and advanced microwave pulse propagation in a circuit electromechanical system in the presence of electromechanically induced transparency at 200 mK. Extracted group delay for pump powers between −89 and −49 dBm, with various detunings of the pump from the cavity red sideband $|\delta| = 2\pi \times (1.2 \text{ Hz}(1), 5.4 \text{ Hz}(2), 10 \text{ Hz}(3), 44 \text{ Hz}(4))$. The measured group delays are plotted (red data points) versus the input power together with the fittings from the full model (black).
Switching dynamics. a, Measurement. The pump tone is red-detuned (in red); the probe transmission readout is on resonance (in yellow); and the anti-Stokes scattering of the probe field is read out blue-detuned (in blue). b, Time constants of the ring-up (yellow dots) and ring-down (blue squares) of the individual pulse as a function of pump power. The curve (black) shows the calculation for the ring-up constant with $\Gamma_m = 2\pi \times 12$ Hz. Note the time constant $t_{\text{con}}$ is extracted from the voltage readout, and $t_{\text{con}} = 2/\Gamma_{\text{eff}}$. c,d, A train of red-detuned ($\Delta = -\Omega_m$) pulses is sent into the cavity, with a period of $T_{\text{on}} = T_{\text{off}} = 100$ $\mu$s that is shorter than $1/\Gamma_{\text{eff}}$ (c) and $T_{\text{on}} = T_{\text{off}} = 10$ ms that is on the same order of $1/\Gamma_{\text{eff}}$ (d), with a power descending from $-63$ dBm (green) to $-79$ dBm (blue) in steps of 4 dB. A weak probe tone ($-99$ dBm) is present on cavity resonance. Probe transmission on cavity resonance ($\omega_c$) measured with a spectrum analyzer in zero-span mode is plotted versus time, showing the dynamics of electro-mechanically induced transparency on cavity resonance.
An optical image of a dual-microwave-mode electromechanical system on sapphire substrate. Two superconducting (Al) lumped-element microwave resonators share the same mechanically compliant capacitor plate – a mechanical resonator.

(top) A network analyzer frequency offset measurement. The top panel shows positions of microwave tones used in the experiment and the VNA detector position in respect to the microwave modes of the electromechanical system. Both pumps are detuned from the neighboring microwave modes by the fundamental resonance frequency of the mechanical resonator.

(bottom) A train of microwave pulses exiting the higher frequency microwave mode when the VNA probe is resonant with the lower frequency cavity.
D2.3) Detection of optomechanical correlations
MS6 Demonstration of strong optomechanical correlations

Kalman filter system model
- Resonant probe field
- Red-detuned control field
- Quantum + classical noise
- Spurious mechanical modes

Correlations between the laser amplitude $y$ and the mechanical position $q$

Wieczoreck et al., PRL 114, 223601 (2015)
Feedback cooling

bad-cavity regime

resolved-sideband regime

Q = $10^7$
$n_{bath} = 3.5 \times 10^5$
$\kappa = 2 \omega_m$

Q = $10^7$
$n_{bath} = 3.5 \times 10^5$
$\kappa = \omega_m / 4$

LQG optimal feedback

resonant operation is optimal

off-resonant operation is optimal

Hofer & Hammerer, PRA 91, 033822 (2015)
Dissipative remote state preparation

\[ \dot{\rho} = D[J] \rho \quad t \to \infty \quad \rho_{ss} = |\psi_{\infty}\rangle \langle \psi_{\infty}| \]

Time-continuous teleportation

\[ |\psi_{\infty}\rangle = |\psi_{in}\rangle \]

Time-continuous entanglement swapping

\[ |\psi_{\infty}\rangle = |\psi_{EPR}\rangle \]

Hofer & Hammerer, PRA 91, 033822 (2015)
Violation of Bell inequality in optomechanical systems

Creation of entanglement

photon-phonon correlations

entanglement

photon-photon correlations

entanglement

Non-Gaussian measurement

observable:

\[ \sigma(\alpha) = |\alpha\rangle\langle\alpha| - (1 - |\alpha\rangle\langle\alpha|) \]

“no click” “click”

Resulting violation

CHSH inequality \( S \leq 2 \)

Hofer et al., arXiv:1506.08097

overall transmissivity (1-losses):

cooperativity:

\[ C = \frac{4g^2}{\kappa\gamma(n+1)} \]
Time-continuous teleportation

Ideal parameter regime:
\[ \Delta = \omega_m, \quad g < \kappa \lesssim \omega_m, \quad C > 1 \]

dissipative remote state preparation
\[ \dot{\rho} = \mathcal{D}[J] \rho \quad \text{as} \quad t \to \infty \quad \Rightarrow \quad \rho_{ss} = |\psi_{in}\rangle \langle \psi_{in}| \]

 teleportation of a squeezed state:

needs strong cooperativity!
\[ C = \frac{4g^2}{\kappa \gamma (n+1)} > 1 \]
Time-continuous entanglement swapping

Ideal parameter regime:

\[ \Delta = \omega_m \quad g < \kappa \lesssim \omega_m \quad C > 1 \]

dissipative remote state preparation

\[ \dot{\rho} = \mathcal{D}[J]\rho \quad t \to \infty \quad \rho_{ss} \approx |\psi_{EPR}\rangle \langle \psi_{EPR}| \]

Bipartite mechanical entanglement:

needs strong cooperativity!

\[ C = \frac{4g^2}{\kappa \gamma (\bar{n}+1)} > 1 \]
Pulsed optomechanical teleportation

CV Bell measurement = 2 homodyne detectors

I. Measures EPR modes "X_\text{--} = X_A - X_B" and "P_+ = P_A + P_B"
   with outcomes by \(m_x\) and \(m_p\)

II. Projects mechanics into displaced input state

III. Feedback = displacement by \(m_x\) and \(m_p\) recovers input state

Theory: Hofer et al., PRA 84, 052327 (2011)
Experiment: Palomaki et al., Science 342, 710 (2013)
Time-continuous quantum control

- Time-continuous Bell measurement
  - Generalisation of CV Bell measurement to time-continuous setting
  - Bell measurement + feedback $\rightarrow$ generate effective dissipative dynamics with engineered steady-state

- Time-continuous teleportation
  Goal: Teleportation of Gaussian state from light to mechanics

- Time-continuous teleportation
  Goal: Generation of bipartite mechanical entanglement

Hofer et al., PRL 111, 170404 (2013)
Hofer & Hammerer, PRA 91, 033822 (2015)
Optomechanical phase diagram

conditioned on homodyne detection of phase quadrature

Entanglement (log Neg)

Steady-state phonon number

Q = $10^7$
$n_{\text{bath}} = 3.5 \times 10^5$
$\kappa = \omega_m/4$

red detuning = cooling

$\Delta$ (units of $\omega_m$)

blue detuning = heating

conditional phonon number

$\rho$
Preconditions for Coherent Photon-Phonon Conversion:

- mechanical oscillator in the quantum ground state
- for state swaps, entanglement: Resolved sideband regime

System of choice:

- fiber coupled Photonic crystals
- high frequency mechanical breathing modes
- cryogenic initialization to mechanical ground state utilizing a dilution refrigerator (base T \sim 0.02K)
D2.4 Coherent Photon Phonon Conversion

Thermalization of optical fibers on every stage

Main challenge: Update of control software to Windows 7

Dilution Fridge

Cryo fiber coupling

$n_{th}@5\text{GHz} < 0.01\text{ Phonons}$
D2.4 Coherent Photon Phonon Conversion

Lensed fiber
Allows for optical coupling in dilution fridge

Device array
Fabricated from silicon on isolator chip

Simulated mechanical mode
$f_{mech} \approx 5.3 \, \text{GHz}$

Structures in collaboration with Prof. Gröblacher, TU Delft

Scanning Electron Microscope Image (TUD)
D2.4 Coherent Photon Phonon Conversion

System is ready for low temperature experiments in M36
D2.4 Coherent-photon-phonon conversion

Optomechanical coupling for the generation of entangled optical output beams for long distance quantum communication
The common interaction with a nanomechanical resonator allows to entangle output fields at different wavelengths: it is a consequence of the combination of the optomechanical parametric interaction $(ab + \text{h.c.})$ and of the beam-splitter interaction $(ab^+ + \text{h.c.})$

- The common interaction with a nanomechanical resonator establishes quantum correlations which are strongest between the output Fourier components \textit{exactly at resonance} with the respective cavity field (narrowband entanglement)
The entangled beams can be combined via an entanglement swapping protocol realizing a quantum relay; by suitably concatenating a number of such optomechanical devices one can create a long-distance continuous variable entangled link.

The optomechanical device at a node could generate entanglement between a near-infrared field for free space propagation (810 nm) and a field at telecom wavelengths (1550 nm).
Teleportation fidelity for a coherent state after one (a) and three (b) concatenated swapping versus the central frequency of one of the two output modes, in the case of optomechanical nodes with high-Q $10^7$ (red line) and $Q = 10^5$ (blue dotted line). The associated black curves gives the upper bound of the fidelity at a given logarithmic negativity.

The present scheme still exponentially decreases with distance due to the effect of loss and to the lack of quantum memories; nonetheless, it could represent a starting point for a quantum repeater scheme

[M. Asjad et al., —Large Distance Continuous Variables Communication with Concatenated Swaps, Phys. Scr. 90, 074055 (2015)]
Coherent photon-phonon conversion for entangling MECHANICAL modes

• A single, bichromatically-driven, optical cavity mode coherently mediating the interaction between two mechanical resonators with different frequencies $\omega_1$ and $\omega_2$

[J. Li et al, Generation and detection of large and robust entanglement between two different mechanical resonators in cavity optomechanics, New. J. Phys. 17 103037 (2015)]
Extremely **large mechanical entanglement** can be generated, in a robust way with respect to temperature, at large cooperativities $C$ (and optimising $C_1/C_2$)

\[
E_N \sim \frac{1}{2} \ln \left[ \frac{C_1}{2 \left( 1 + \bar{n}_1 + \bar{n}_2 \right)} \right]
\]

(i) $n_1 = n_2 = 0$ (black line);
(ii) $n_1 = 200 \ n_2 = 100$, (blue line);
(iii) $n_1 = 1000 \ n_2 = 500$, (green line);
(iv) $n_1 = 2000 \ n_2 = 1000$, (red line);
D2.6) Strong charge-qubit-graphene resonator coupling

Optomechanics with artificial atoms (D2.6)
Josephson junction quantum circuits

\[ E = E_J \cos (\varphi) + \frac{Q^2}{2C} \]

\[ \hat{Q} = 2e \hat{a} \]

Superconducting qubit

“Artificial atom”
Cooper-pair box = charge qubit

- Small capacitance \( E_J / E_C < 1 \)

\[
H_{QB} = 2E_C(1 - 2n_g) \hat{\sigma}_z - \frac{1}{2} E_J \hat{\sigma}_x
\]

\[
E_J(\hat{\sigma}_e) = (E_{J1} + E_{J2}) \cos \frac{e}{2}\sqrt{E_J^2 - E_C^2}
\]

\[
n_g = \frac{C_g V_{dc}}{2e}
\]

\[
E_C = \frac{e^2}{2C}
\]
Circuit optomechanics + qubit?
Cooper-pair box coupled to a phonon

\[ H_{QB} = 2E_C \left( 1 - 2n_g \right)^z \frac{1}{2} E_J^x \]

Motion affects gate charge (scaled by 2e)

\[ n_g(x) = \frac{V_{dc}}{2e} C_{g0} + \frac{V_{dc}}{2e} \frac{dC_g}{dx} \]

\[ \hat{H} = \hat{H}_{QB} + m \hat{b}^+ \hat{b} + \frac{1}{2} g_m \left( \hat{b}^+ \hat{b} \right)^z \]

\[ g_m = \frac{2E_C}{e} x_{ZP} V_{dc} \frac{C_g}{x} \approx 1 \ldots 100 \text{ MHz} \]


iQuOEMS 2nd review, Aalto University
Qubit coupled to two cavities

### Qubit

### Photonic cavity

\[ H_c = c \hat{a}^\dagger \hat{a} + \frac{1}{2} \]

### Phononic cavity

\[ H_m = m \hat{b}^\dagger \hat{b} + \frac{1}{2} \]

\[ H = H_{QB} + H_c + H_m + H_{QB-c} + H_{QB-m} \]

\[ H_{QB-c} = g_c \left( \hat{a}^\dagger + \hat{a} \right)^x \]

\[ H_{QB-m} = g_m \left( \hat{b}^\dagger + \hat{b} \right)^z \]

\[ g_m \approx 100 \text{ MHz} \quad f_m \]

\[ g_c \approx \sqrt{\frac{Z_0}{R_Q} E_J} \approx 1 \text{ GHz} \]
Effective optomechanical system

- Qubit-cavity coupling very large

\[
H_{QB-c} = g_c (\hat{a}^+ + \hat{a})^x
\]

\[
H_{QB-m} = g_m (\hat{b}^+ + \hat{b})^z
\]

\[
g_m \quad 100 \text{ MHz} \quad f_m
\]

\[
g_c \quad \sqrt{\frac{Z_0}{R_Q}} E_J \quad 1 \text{ GHz}
\]
Effective optomechanical system

- **Qubit tweaks a linear coupling into** $\sigma_z$ coupling
- Trace out the qubit with Schrieffer-Wolff
- **Effective cavity** couples to effective mechanics via radiation-pressure

$$H_{\text{eff}} = c a^+ a + m b^+ b + g a^+ a x + g_{xx} x c x + g_4 a^+ a b^+ b$$

$$\frac{g}{g_0} = \frac{C_g V_{dc} L_{tot}}{2e n_g} \frac{L_J^1}{C_g V_{dc}} \frac{E_C}{E_J}.$$  

$$V_{dc} = 10 \text{ V} \quad E_J / E_C = 0.1 \quad \frac{g}{g_0} \sim 10^6$$

- $g_{xx} < g_m$
- $g_4 \frac{g_0}{E_J Z_0} < g$
Radiation-pressure coupling

$$V_{dc} = 10 \ V$$
**Bridge type micromechanical resonator**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>60 nm</td>
</tr>
<tr>
<td>Sapphire</td>
<td></td>
</tr>
<tr>
<td>negative PMMA</td>
<td>40...80 nm</td>
</tr>
<tr>
<td>Al</td>
<td>300 nm</td>
</tr>
<tr>
<td>O₂ plasma</td>
<td></td>
</tr>
</tbody>
</table>

- $L = 5 \text{ m}$
- $W = 2 \text{ m}$
- $d = 40 \text{ nm}$
- $x_{ZP} = 6.2 \text{ fm}$
Josephson junction cavity

\[ f_c = 4.93 \text{ GHz} \]
\[ C = 0.33 \text{ pF} \]
\[ L = 3.2 \text{ nH} \]
\[ C_g = 1.8 \text{ fF} \]
\[ C = 4.9 \text{ fF} \]
\[ \frac{E_J}{E_C} = 2.1 \]
Cavity charge modulation

- Tune down effective $E_j/E_C \rightarrow 0.6$ by flux bias
- Cavity frequency is sensitive to charge
- Low-power $n_c < 1$

One-e. Both parities visible the same time.
Pump cavity at very high power (kill Josephson effect)

Drive mechanics

Recording of intrinsic mechanical frequency and linewidth

\[ m/2 \quad 15 \text{kHz} \]

\[ g_0 \quad 1 \text{Hz} \]

\[ n_c \quad 10^9 \]

\[ V_{dc} = 1 \text{V} \]

\[ x \quad 15 \text{pm} \]
Josephson cavity optomechanics

- Measure thermal motion
  - Incoherent emission from cavity
  - Motion imprinted in thermal sidebands \( \pm f_m \) around \( f_P \)
  - \( T \sim 25 \text{ mK}, \ n_m \sim 8 \)
- \( g(n_g), \Delta(n_g), \kappa(n_g) \) vary with gate point

\[
\frac{\gamma_{\text{eff}}}{2} = 40 \text{ MHz}
\]

\[
n_g \approx \frac{1}{4} \\
f_c \approx 4.82 \text{ GHz} \\
\approx m \\
n_c \approx 0.05 \\
P_p \approx 1 \text{ fW}
\]

\[
\gamma_{\text{eff}} / 2\pi \approx 41 \text{ kHz} > \gamma_m
\]
Cavity charge modulation

- Tune down effective $E_J/E_C \to 0.6$ by flux bias
- Cavity frequency is sensitive to charge

\[
g \propto \frac{f_c}{x} \frac{x_{ZP}}{x} \frac{V_{dc}}{2e} \frac{f_c}{n_g} \frac{x}{C_g} = \frac{x_{ZP}}{x} \frac{V_{dc}}{2e} \frac{C_g}{x} \]

\[V_{dc} = 4.6 \text{ V}\]

1 Hz $\to$ 0.5 MHz
Hybrid qubits: graphene vs. CNT

Microwave cavity with proximity carbon junction in transmon

- D2.6 deals with a hybrid graphene device

- CNT grown on Mo/Re cavity sounds the most promising route

- Drop D2.6? Or realize using a CNT?
1/f noise in suspended graphene bilayer

\[ S_I = A \frac{I^2}{f} \]

Contact noise

\[ \frac{\delta G^2}{G^2} \propto \frac{\delta G^2}{N^2} \]

Gas sensor

With Ne gas