Towards a quantum interface between light and microwave circuits
Quantum information network built from nodes linked by propagating modes

quantum network

nodes

process and store

links

transmit

physically secure communication

uncopiable information
Quantum transduction connects disparate physical systems

**optical light:**
- long distance communication
- ambient temperature

**microwave circuits:**
- process quantum information
- ultralow temperature $T < 250$ mK
Quantum state preserving convertor is a unitary device

quantum state preserving => bidirectional, lossless, reflectionless network

$T_{\text{up}} = T_{\text{down}} = 1 \quad R_{\text{elec}} = R_{\text{opt}} = 0$
Mechanical oscillator creates coherent coupling between microwaves and light

- Electrical
  - 7 GHz

- Mechanical
  - 1 MHz

- Optical
  - 280 THz

Microwaves flow from left to right, and light flows from right to left.
Mechanical oscillator creates coherent coupling between microwaves and light

- Electrical: 7 GHz
- Mechanical: 1 MHz
- Optical: 280 THz

Lehnert group: quantum electromechanics
Regal group: quantum optomechanics
Suspended membrane in optical cavity forms optomechanical system

Si₃N₄ membrane (50 nm)

Harris group (YALE)
Suspended membrane in optical cavity forms optomechanical system

Si$_3$N$_4$ membrane (50 nm)

Harris group (YALE)

Optomechanical coupling ($g$)
Position alters optical phase
Optical amplitude alters momentum

Harris group (YALE)
Superb coherent control creates optomechanical system in quantum regime

Optical
quantum bath
cavity
vacuum

Mechanical
oscillator
warm bath

optomechanics in the quantum regime \( \frac{g^2}{4\kappa_o} > n_{\text{env}} \gamma_m \)
Resonant circuit with compliant capacitor creates electromechanical system

Electromechanical system

- superconducting LC circuit
- quantum circuit for $T < 250 \text{ mK}$

GHz “laser” detector

$\nu_m \sim 10 \text{ MHz}$

$\nu_e \sim 7 \text{ GHz}$
Microwave fields control the quantum state of a mechanical oscillator.

State transfer

Entanglement
Science 342, 710 – 713 (2013)
Opto-electromechanical system formed from “flip-chips” in optical cavity

mirrors: high-finesse optical cavity

top chip: membrane and one plate of capacitor

bottom chip: remainder of electrical circuit
Image of assembled flip-chip structure
Diagram of optical cavity assembly
Image of optical cavity assembly

- Optical port
- Microwave port
4 K sufficiently cold to test electro-optic conversion in a classical regime

4 K cryostat with optical access

$T_c$ of Nb: 9.2 K

$\frac{k_B T}{\hbar \omega_e} \approx 12$
Conversion requires both optical and microwave pumps.
Power absorbed at the microwave port is converted to optical light.
Bidirectional operation a prerequisite for quantum state transfer

\[ T = 4 \text{ K} \]

The future of mechanical systems in the quantum regime

quantum operation of electro-optomechanical convertor

impact: create quantum networks
Reaching the regime of quantum state preservation: cooling the environment

optical access dilution refrigerator in low vibration environment

\[ T < 100 \text{ mK} \]
Conclusions

transfer between microwave and optical fields
classical
bidirectional
cryogenic

poised for quantum operation

microelectromechanics: a new quantum technology
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