Optical Networking of Superconducting Quantum Nodes with Transduction Devices

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1. Abstract

- For superconducting quantum computers to continue to scale, multiple processors will need to be networked.
- Optical channels provide a low-loss link capable of spanning long distances.
- Combining hot optical photons with milliKelvin superconducting circuits at microwave frequencies in a dilution refrigerator would appear incompatible.

Question 1: How do we connect the microwave and optical regimes quantum mechanically?

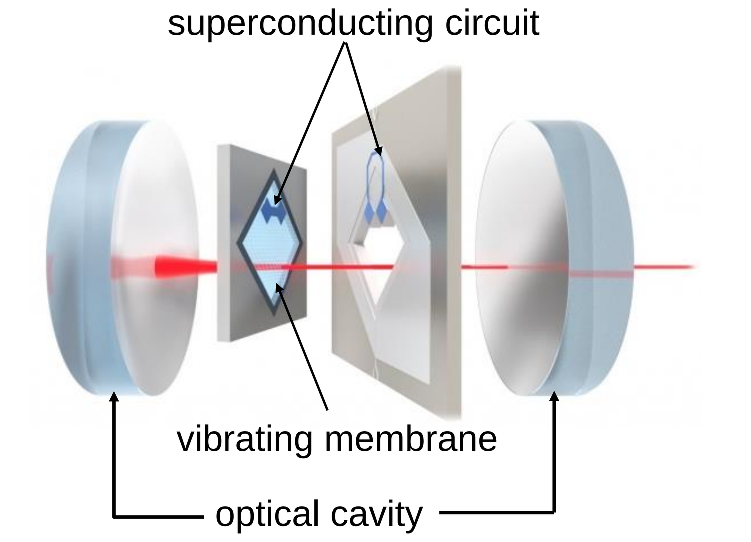
Question 2: What is the best way to use optical channels to entangle superconducting processor nodes?

Question 3: Will **YOU** be the first person in the world to experimentally demonstrate a "Quantum Internet" capable of distributing arbitrary quantum states?

2. Microwave-Optical Transduction

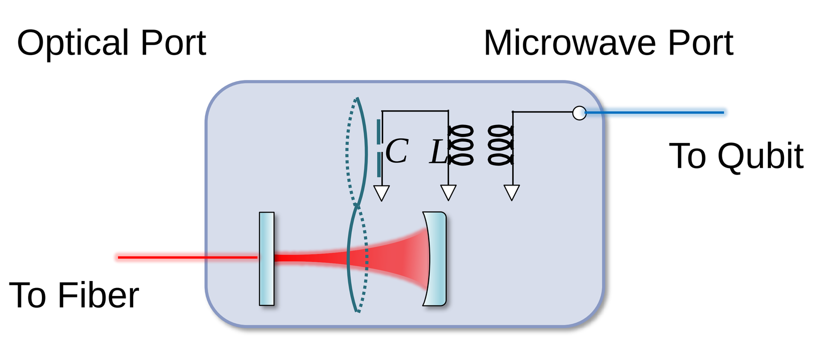
Collaborators at CU/JILA: Lehnert/Regal Lab

- Three coupled resonators (optical, mechanical, microwave): with "membrane in the middle"



- ✅ Efficiency: 47% (record)
- ❌ Added noise: 9 photons

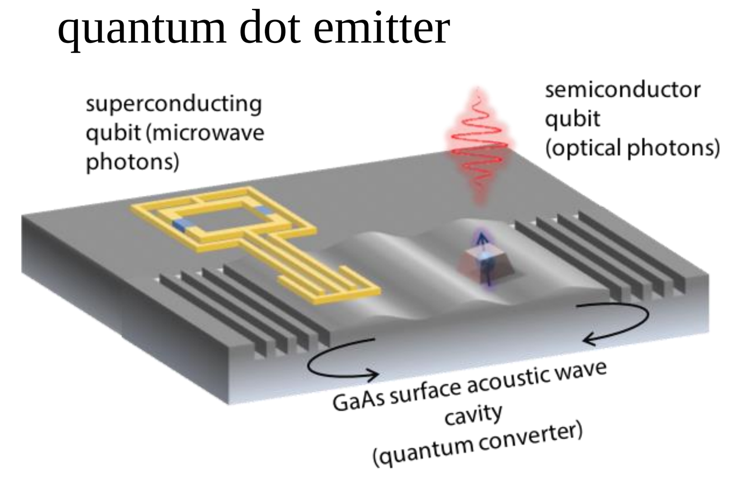
Target < 1 photon



- Bidirectional
- Can generate microwave-optical squeezing

Collaborators at NIST: Silverman/Mirin Lab

- Three coupled resonators (optical, acoustic, microwave): with quantum dot emitter



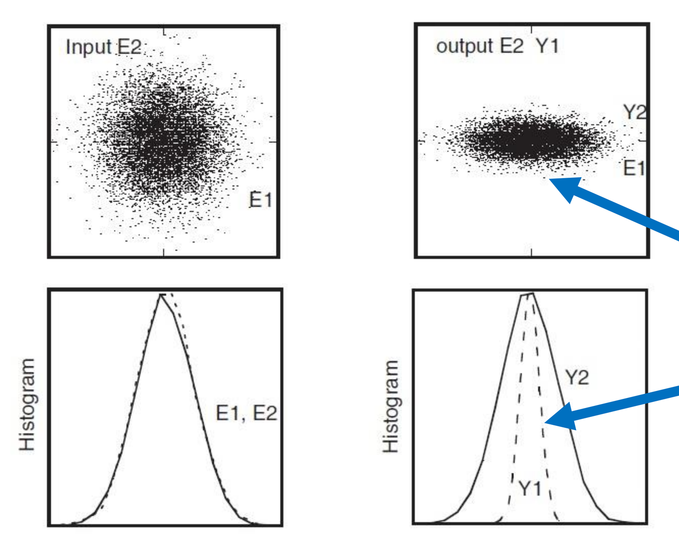
- High generation rates
- Integrated design
- Low power

3. Continuous Variables Approach

- Based on measuring continuous field quadratures instead of discrete number states. This is an infinite Hilbert Space ==> It's Analog!
- Practical preparation, manipulation, measurement of states. Protocols for teleportation and distillation known and feasible. Higher information capacity than discrete variables (DV). Can distill to DV if needed.
- Optics: A quantized electromagnetic field ==> use squeezed light.

4. Squeezed Light

Optical Quadratures:



Uncertainty Principle :

$\langle(\Delta E_1)^2\rangle \langle(\Delta E_2)^2\rangle \geq 1/4$

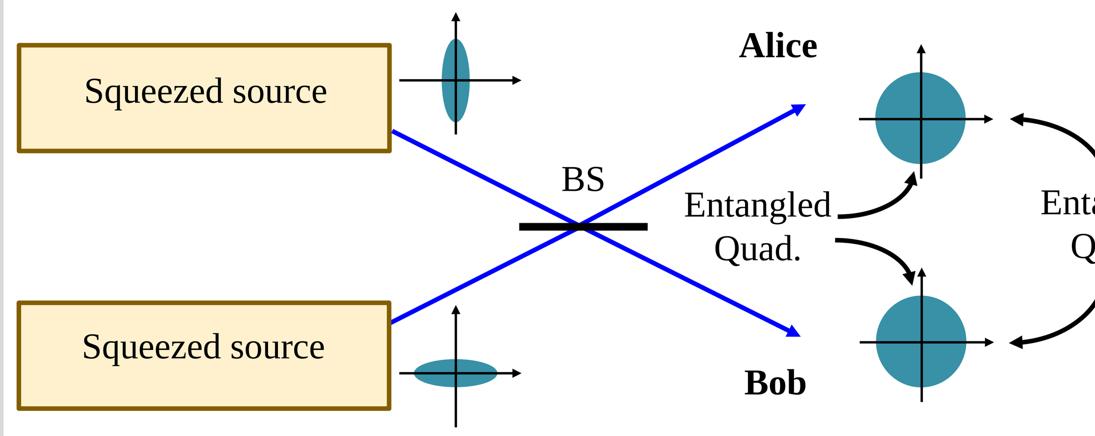
The proportion is not fixed.

Unequal is "squeezed."

Y1 quadrature noise is below vacuum fluctuations; Y2 is above.

Precision metrology: LIGO

Entanglement from Two Mode Squeezing:



$$\frac{var(E_{1a} - E_{1b})}{\sqrt{2}} < 1/2$$

$$\frac{var(E_{2a} + E_{2b})}{\sqrt{2}} < 1/2$$

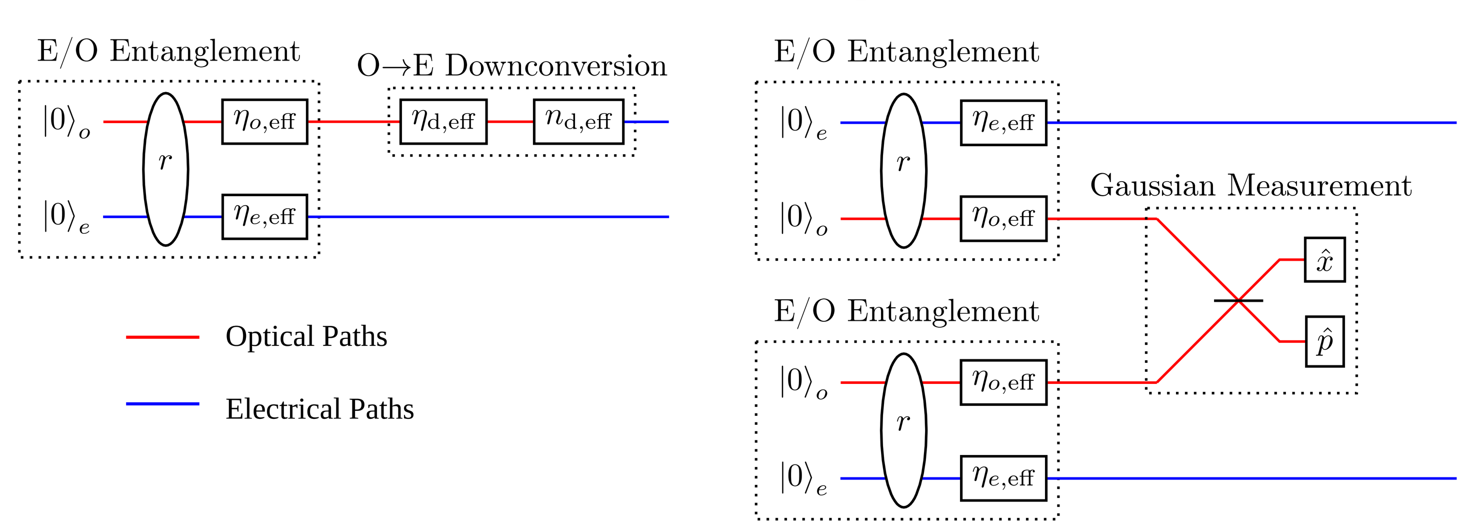
Entangled Pair of EPR Beams ➡ CV Quant. Networking Resource

5. Network Topology Study

For imperfect transducers, lossy channel, Gaussian operations, is it better to:

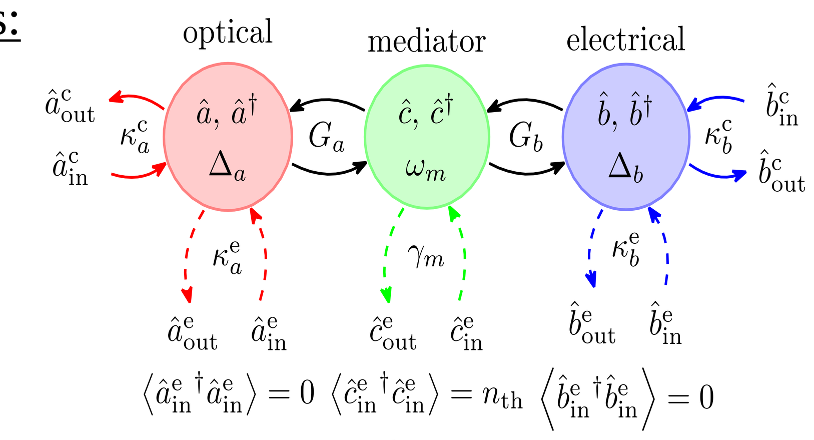
- Distribute or swap entanglement?
- Squeeze in the optical, microwave, or combined optical/microwave domain?
- Introduce squeezing intrinsic or extrinsic to transducers?

Distribute: Swap:

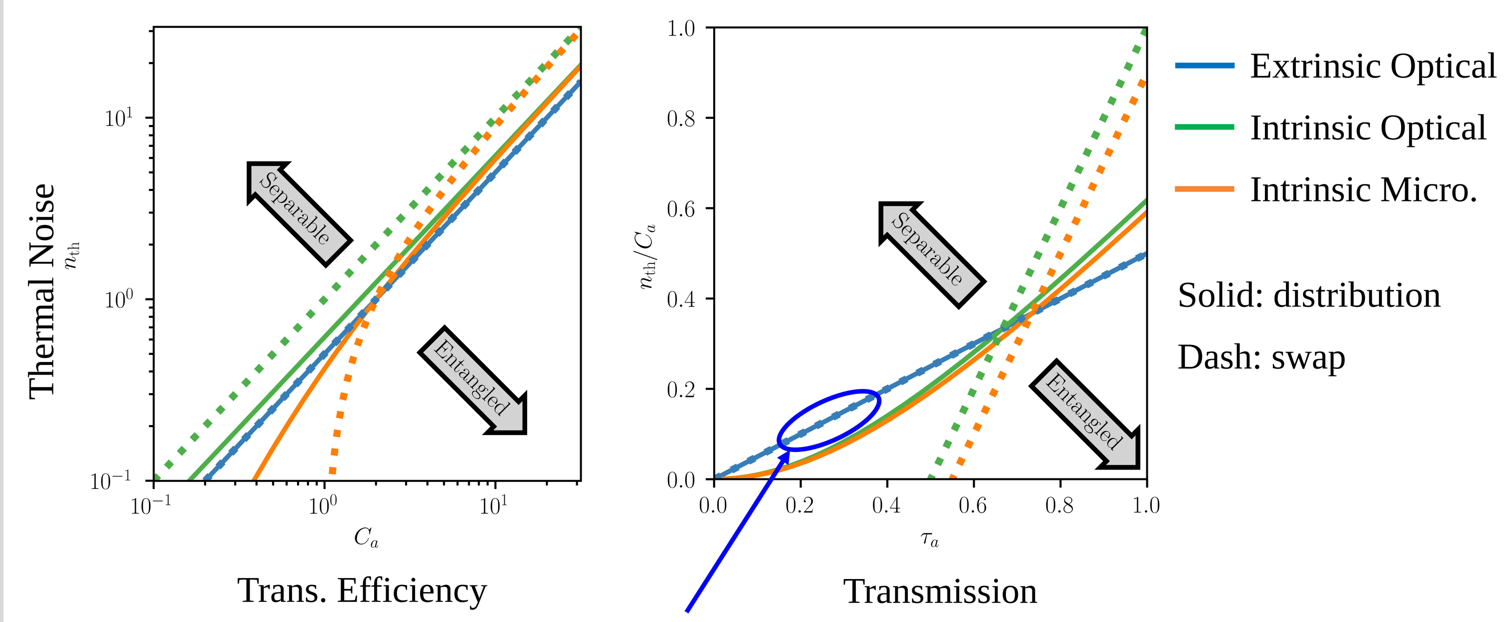


Modeling the Network Topologies:

- Transducer cooperativities, transmissivities, thermal noise (Temp. > 0).
- Optical channel Loss.
- Calculate entanglement thresholds.

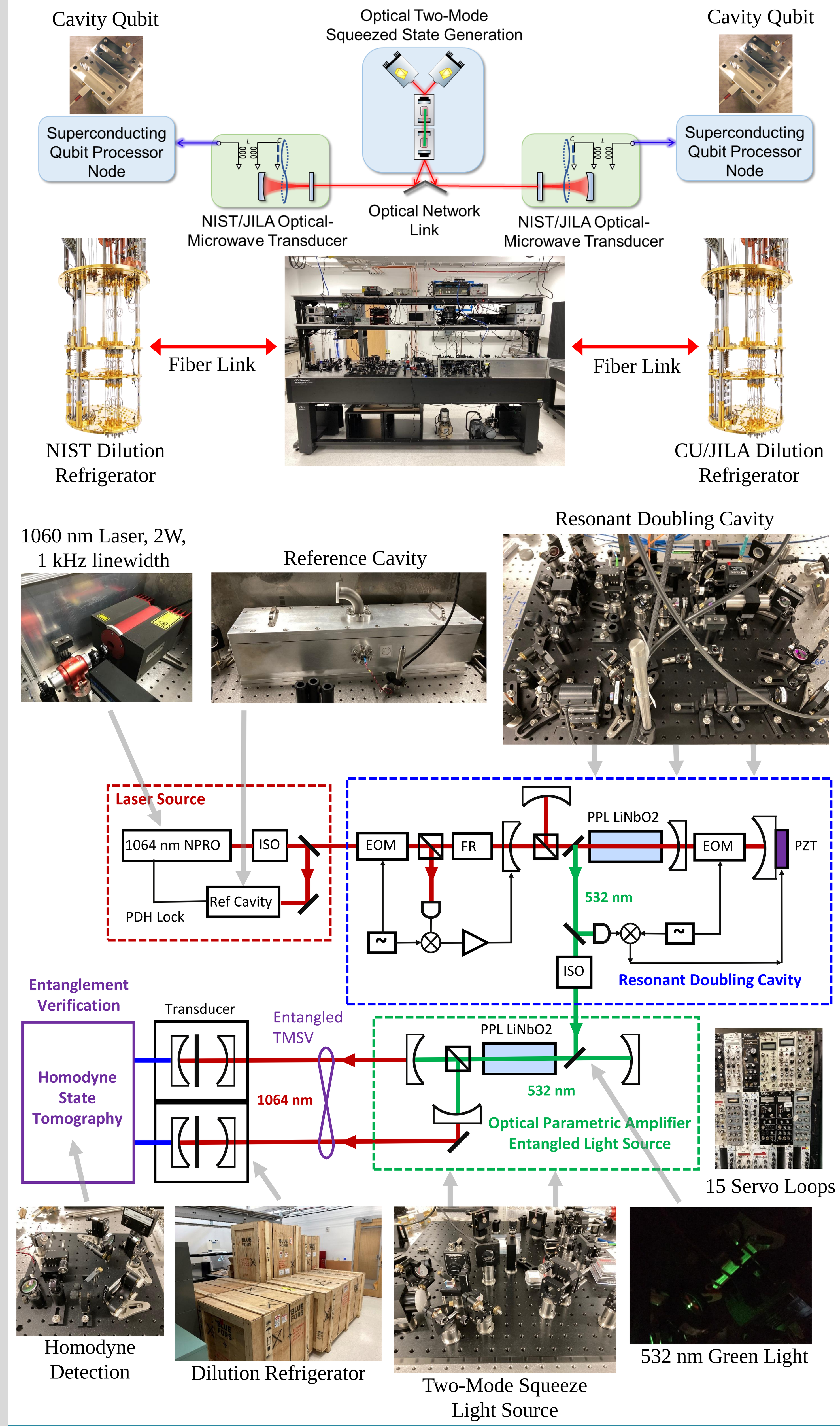


Transducer Hamiltonian of coupled resonators



- Extrinsic Optical Distribution is best choice for (realistic!) high loss.

6. Experimentally Making it Work



7. Future Research Topics

- Demonstration of extrinsic optical distribution through transducers.
- Demonstration of short-distance entanglement of superconducting nodes.
- Demonstration of long-distance entanglement of superconducting nodes.
- Demonstration of entanglement across a free-space channel.
- Heterogenous quantum network demonstration between superconducting qubits and trapped ion nodes.
- Networking with exotic optical states with non-Gaussian processes.
- Networking with distillation of weak Gaussian states or coherent feedback control to overcome noise and loss.

Bidirectional and Efficient Conversion Between Microwave and Optical Light, R. W. Andrews, R. W. Peterson, T. P. Purdy, K. Cicak, R. W. Simmonds, C. A. Regal, and K. W. Lehnert, Nature Physics **10**, 321-326, 2014.

Harnessing Electro-Optic Correlations in an Efficient Mechanical Converter, A. P. Higginbotham, P. S. Burns, M. D. Urmey, R. W. Peterson, N. S. Kampel, B. M. Brubaker, G. Smith, K. W. Lehnert, and C. A. Regal, Nature Physics **14**, 1038-1042, 2018.

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