The Boulder Cryogenic Quantum Testbed

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Community-Driven GitHub

Resonator fitting software

VNA control software

Workshops

https://github.com/Boulder-Cryogenic-Quantum-Testbed/measurement
The Boulder Cryogenic Quantum Testbed

Qi = 500,000
The Boulder Cryogenic Quantum Testbed

- Measurement of microwave devices at single photon powers is complex
- Which set-up decisions are critical and which have little effect?
- Transparent, community-driven effort to:
  - Perform experiments to optimize cryogenic set-up
  - Consolidate existing knowledge and create collaborative standards
  - Establish a facility where materials scientists can test new materials precisely and accurately
The Superconducting Quantum Circuit

Qubits (concentric transmons)

Test resonator

Readout resonators

Feedline

Qubits (planar plate capacitor qubits)
The Superconducting Quantum Circuit

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Collin (1992)
The Superconducting Quantum Circuit

Qubits (concentric transmons)

Readout resonators

Test resonator

Qubits (planar plate capacitor qubits)

Feedline

7.5 mm
The Boulder Cryogenic Quantum Testbed

- Simple superconducting quantum computing experiment:
  - Measure a resonator
- Information we can gain:
  - Material performance
  - Fabrication recipe change
  - Process benchmarking
- Great tool to measure losses that also affect qubits
The Superconducting Microwave Resonator

- Mazin, B. Microwave kinetic inductance detectors (2004).

\[ Q = 1001000.0 \pm 4000.0 \]
\[ Q_l = 4520000.0 \pm 100000.0 \]
\[ Q_c = 1175800.0 \pm 4000.0 \]
\[ 1/Re[1/Q_c] = 1284900.0 \pm 4000.0 \]
\[ \phi = -0.416 \pm 0.003 \text{ radians} \]
\[ f_c = 6.05127025 \pm 2e-08 \text{ GHz} \]
The Superconducting Microwave Resonator

- Mazin, B. Microwave kinetic inductance detectors (2004).

### Model Name
<table>
<thead>
<tr>
<th>Model Name</th>
<th>Citations</th>
<th>Model Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circle fit with e rotation method (WIM)</td>
<td>Gao, J. The physics of superconducting microwave resonators (2008).</td>
<td>$E_{e} = \frac{a e^{-2 i \theta}}{1 + e^{-2 i \theta} R_{e}}$</td>
</tr>
<tr>
<td>Circle fit with diameter correction method (DCM)</td>
<td>Mazin, B. Microwave kinetic inductance detectors (2004).</td>
<td>$S_{21} = (1 - e^{-2 i \theta}) R_{e}$</td>
</tr>
<tr>
<td>Inverse S21 fit</td>
<td>Mazin, B. Microwave kinetic inductance detectors (2004).</td>
<td>$S_{21}^{-1} = 1 + \frac{2 e^{-2 i \theta} R_{e}}{1 - 2 e^{-2 i \theta} R_{e}}$</td>
</tr>
<tr>
<td>Closest Pole and Zero Method</td>
<td>Mazin, B. Microwave kinetic inductance detectors (2004).</td>
<td>$S_{21, \text{res}} = \frac{1 + 2 i Q_{c} R_{e}}{1 + \frac{Q_{c}}{Q_{2}} + \frac{2 i Q_{c} R_{e}}{1 + \frac{Q_{c}}{Q_{2}}}}$</td>
</tr>
</tbody>
</table>

**Example Calculations:**

- $Q = 1001000.0 \pm 4000.0$
- $Q_{c} = 1175800.0 \pm 4000.0$
- $1/\text{Re}[1/Q_{c}] = 1284900.0 \pm 4000.0$
- $\phi = -0.416 \pm 0.003$ radians
- $f_{c} = 6.05127025 \pm 2e-08$ GHz

Community Resonator Fitting Survey

- 8 research groups fit the same set of resonator data
- 5 groups used DCM (red)
- 1 group used φRM (purple)
- 2 groups used INV (green)
- Results for $Q_i$ and $Q_c$ varied significantly, even within a single fit group

https://github.com/Boulder-Cryogenic-Quantum-Testbed
IR Filter Placement Experiment

- True effect of IR filtering?
- Al on Si CPW resonators
- Preliminary results

\[
Q_{\text{HP,filter}} = (4.5 \pm 0.2) \times 10^{-6}
\]

\[
Q_{\text{HP,NF}} = (5 \pm 1) \times 10^{-6}
\]

\[
\tan\delta_{\text{TLS,filter}} = (1.12 \pm 0.02) \times 10^{-6}
\]

\[
\tan\delta_{\text{TLS,NF}} = (1.34 \pm 0.07) \times 10^{-6}
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Very little effect!
Epitaxial GaAs Trilayer Measurement

\[ \tan \delta_{\text{TLS}} = (1.83 \pm 0.07) \times 10^{-5} \]

\[ Q_{\text{HP}} = (1.73 \pm 0.01) \times 10^4 \]
Epitaxial GaAs Trilayer Measurement

\[ \tan \delta_{TLS} = (1.83 \pm 0.07) \times 10^{-5} \]

\[ Q_{HP} = (1.73 \pm 0.01) \times 10^4 \]

Dominated by high power loss
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