RF Quantum Upconverters

DMRadio-50L Collaboration meeting

August 7, 2024

- Intro to SQL
- RF Quantum Upconverters
- RQU Design and Testing
- Outlook and Next Steps

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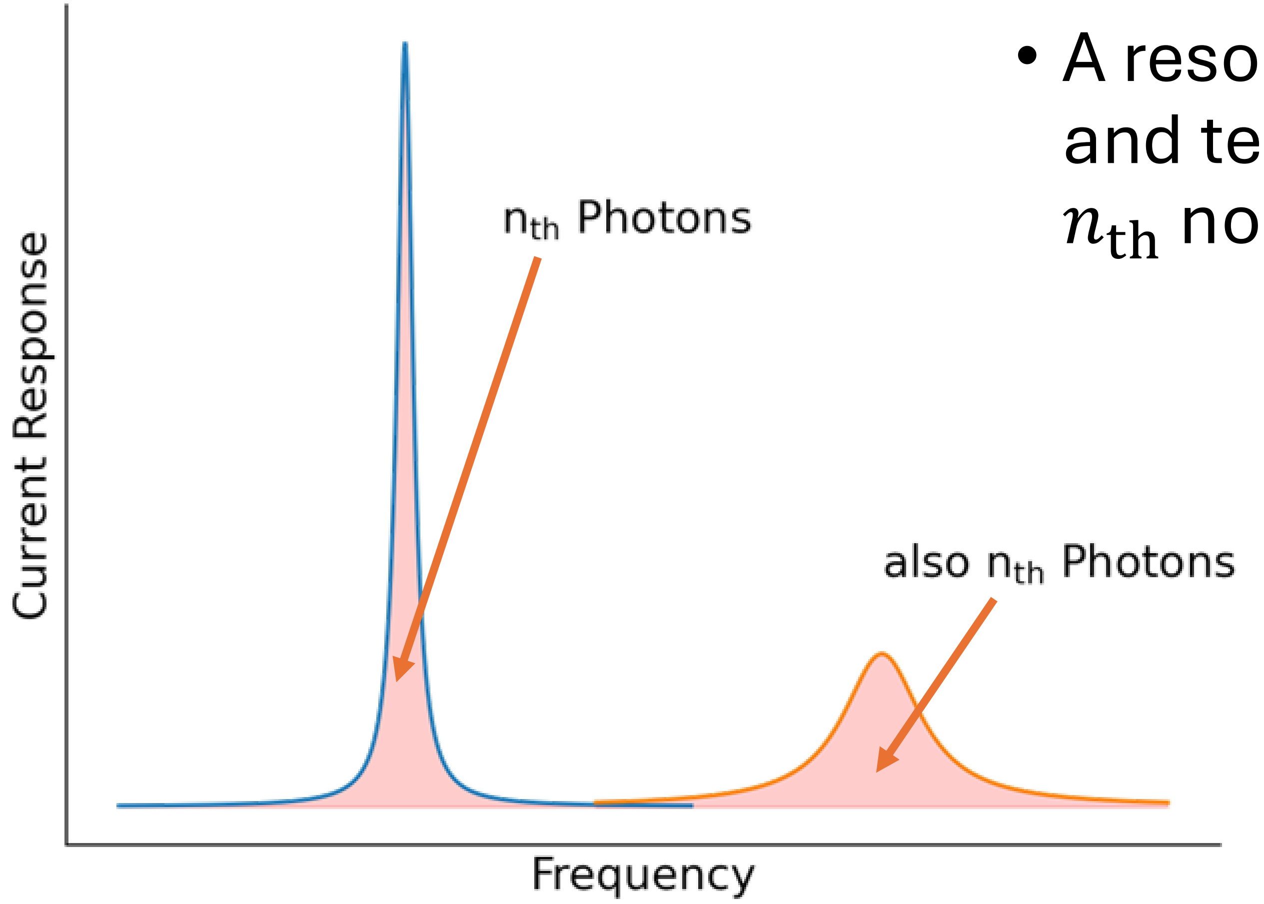
Thermal noise in resonator

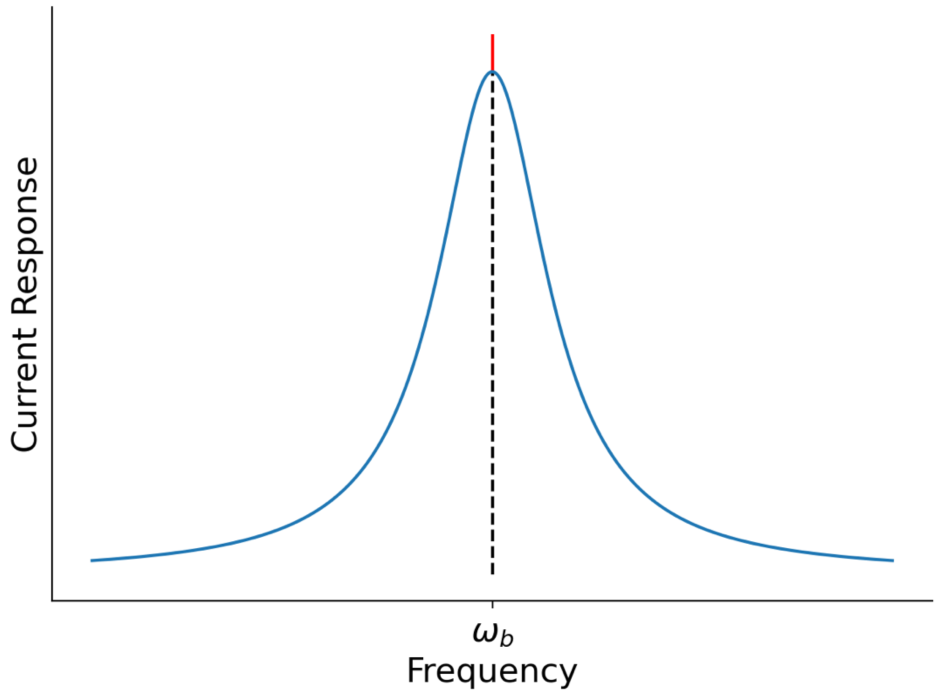


- A resonator with resonant frequency (ω_b) and temperature (T) will be occupied by n_{th} noise quanta:

$$n_{\text{th}} = \frac{1}{e^{-\hbar\omega_b/(k_{\text{B}}T)} - 1}$$

On-resonance Standard Quantum Limit (SQL)

- The SQL arises because the two quadrature operators of the electromagnetic signal are canonically conjugate.
- Precisely on resonance, the Standard Quantum Limit on noise temperature of a quantum sensor measuring a resonator is:



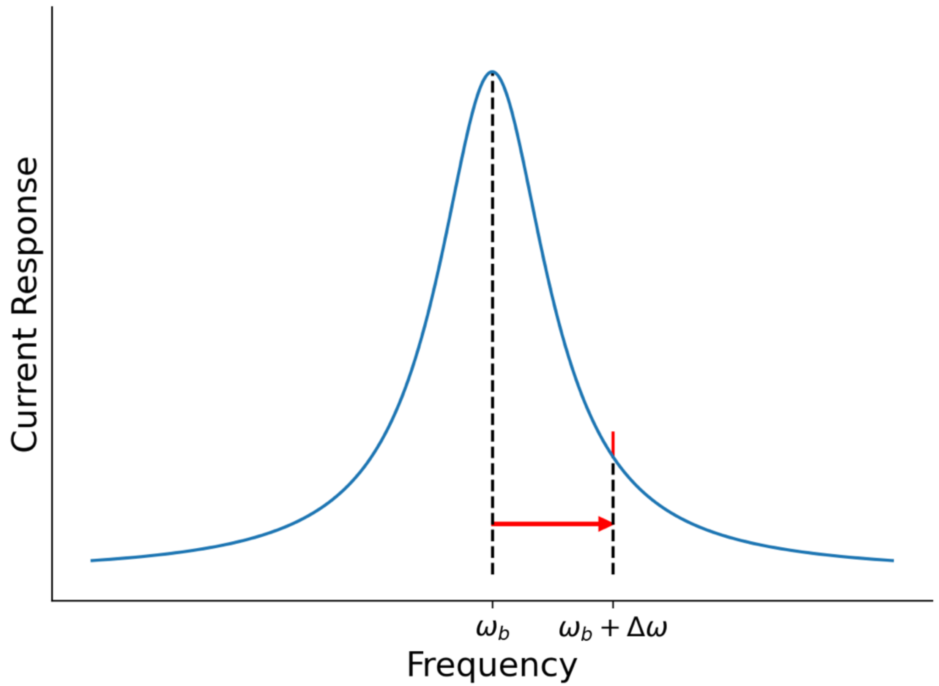
$$k_{\mathrm{B}} T_n = \hbar \omega_{\mathrm{b}} (n_{\mathrm{th}} + \frac{1}{2} + \frac{1}{2})$$

Quantum noise of the sensor

Zero-point noise of the resonator

Off-resonance Standard Quantum Limit

- The axion signal frequency is unknown and will generally be detuned from the detector resonance frequency.
- For large detuning, the SQL for the noise temperature of a sensor is set by the photon loss rate (bandwidth) of the resonance it couples to:



$$k_B T_n \approx \hbar\omega(n_{th} + 1 + \Delta\omega/\gamma)$$

Detuning
$\Delta\omega \equiv \omega - \omega_b$

Resonator bandwidth
$\gamma \equiv \omega_b/Q$

Defining the visibility bandwidth

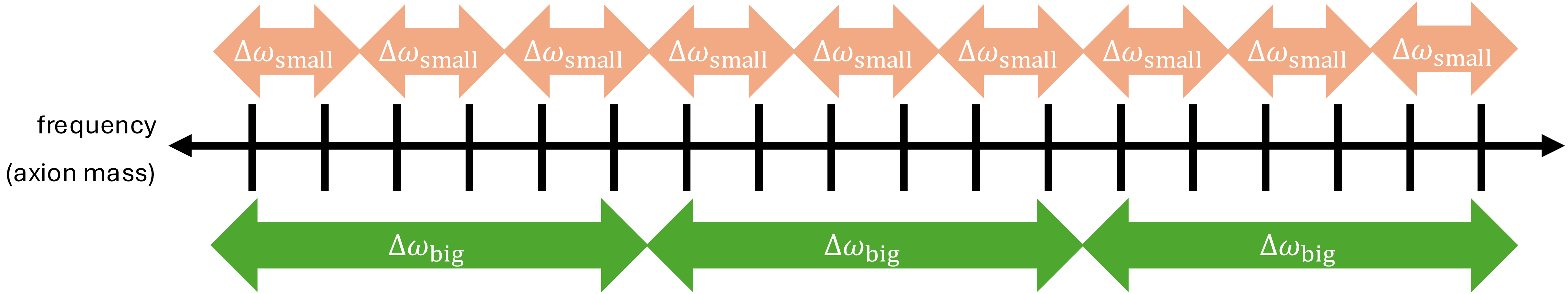
- **How far can the axion signal be detuned from the resonance without unduly degrading the SNR?**
- For an SQL amplifier and larger detuning:

$$k_{\mathrm{B}} T_n \approx \hbar\omega(n_{\mathrm{th}} + 1 + \Delta\omega/\gamma)$$

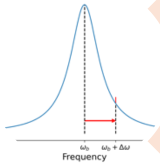
- The maximum detuning at which the total noise temperature is degraded by no more than a factor of two (in power):

$$\Delta\omega_{\mathrm{SQL}} \approx \gamma(n_{\mathrm{th}} + 1)$$

Why do we care about visibility bandwidth?



- **The same frequency span can be covered in fewer tuning steps with a wider visibility bandwidth. Increased scan rate!**



Intro to SQL

RF Quantum Upconverters

RQU Design and Testing

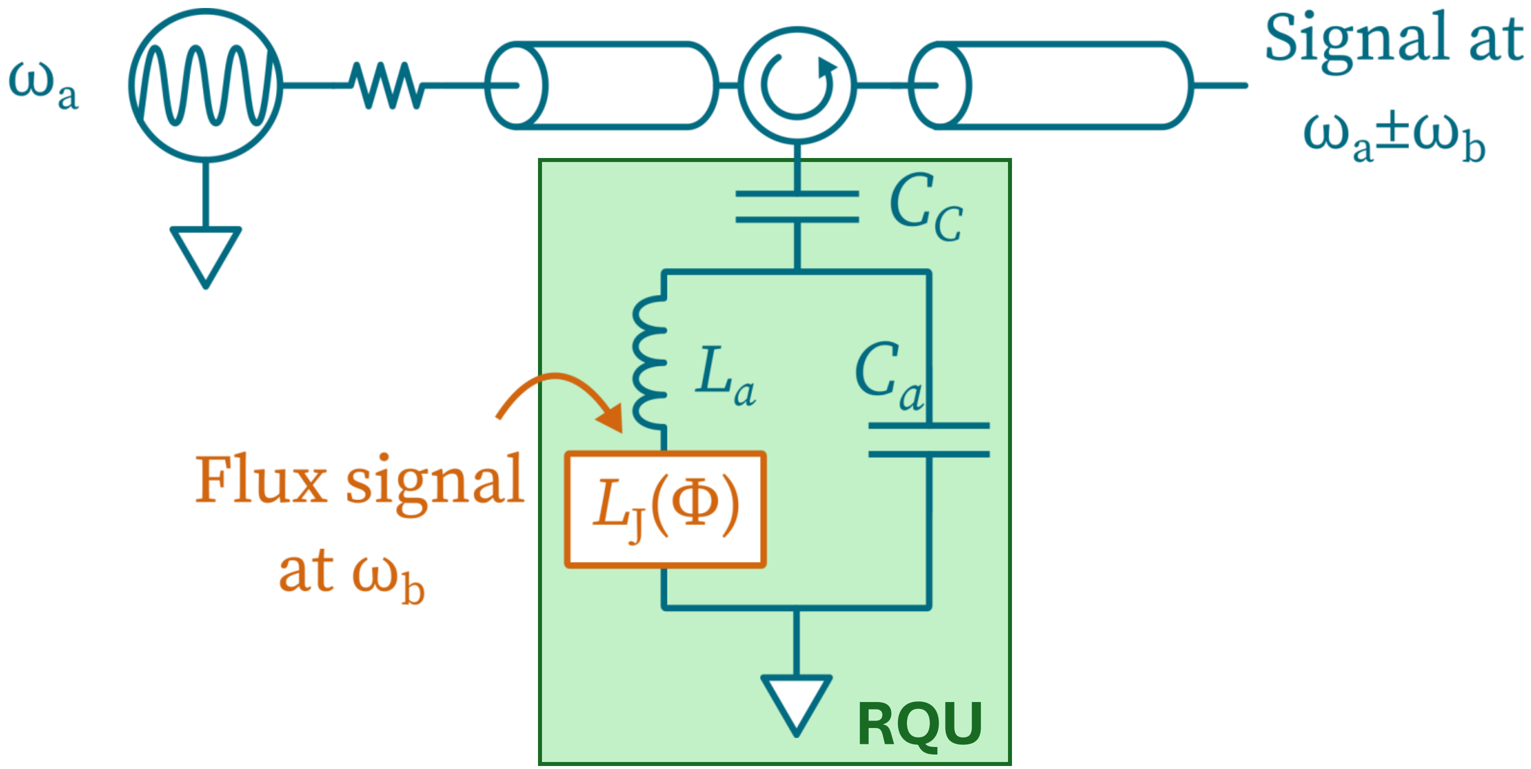
Outlook and Next Steps

RF Quantum Upconverters

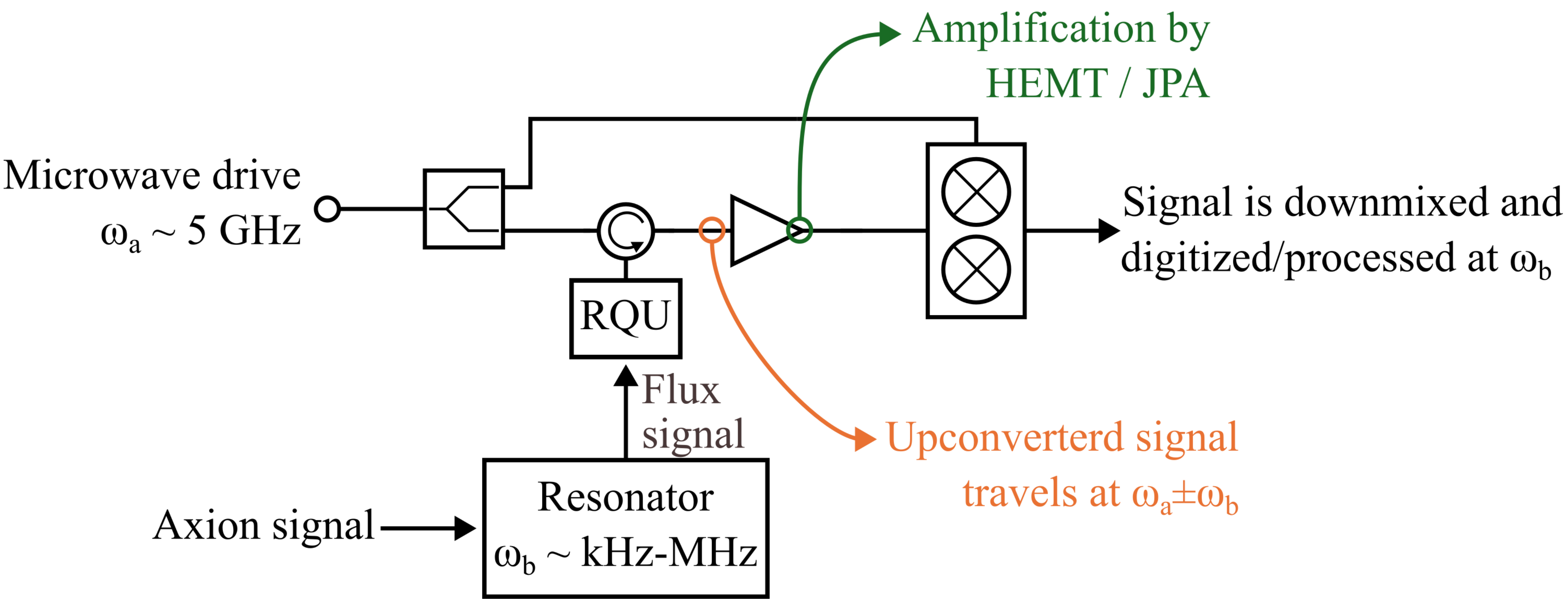
- Continuous-variables quantum sensor to measure axion-induced signals in electromagnetic resonators.
- Phase-preserving measurements (measuring both quadratures) can reach SQL.
  - Dramatically better sensitivity than is possible with existing dc SQUIDs.
- Single-quadrature measurement can perform better than SQL using quantum backaction-evasion (BAE) protocols.

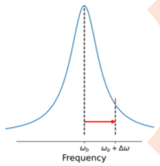
RQU circuit model

- Tunable inductance modifies electrical length of GHz resonator.
- Analogous to optomechanics– three-wave mixing upconverts signal mode to sidebands around microwave drive tone.

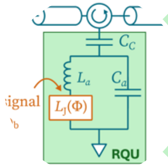


RQU readout chain (simplified!)





Intro to SQL



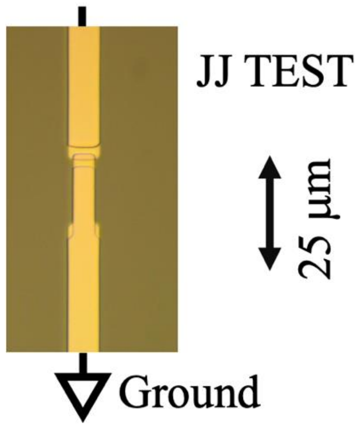
RF Quantum Upconverters

RQU Design and Testing

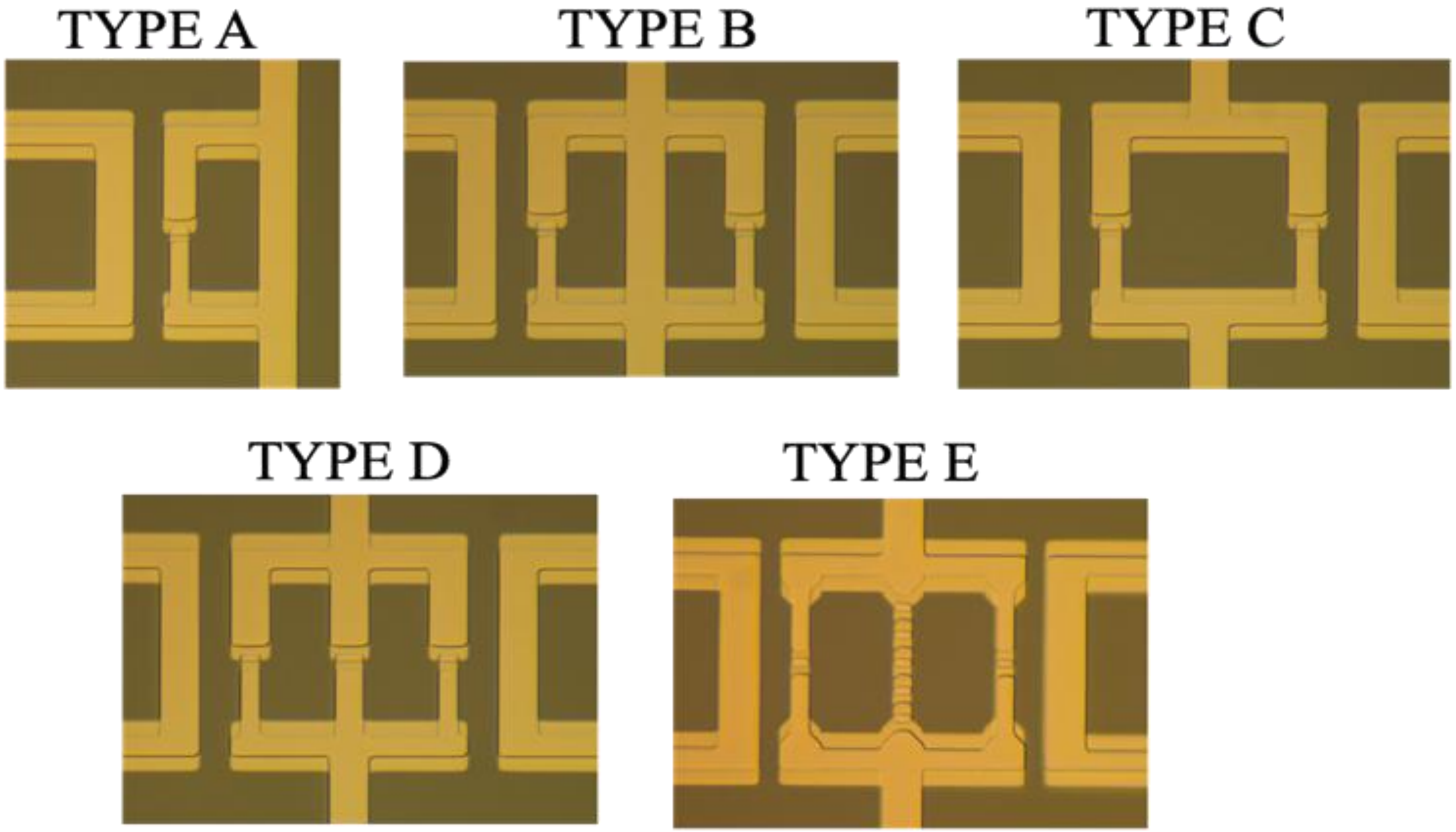
Outlook and Next Steps

Aluminum RQU fabrication

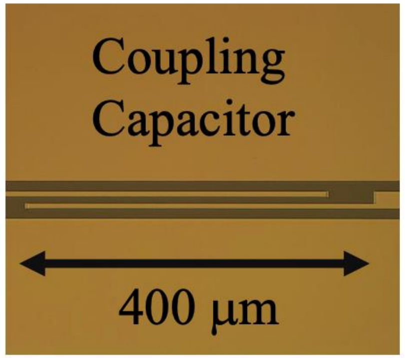
- Fab process is fast and flexible, enabling a range of designs.



Josephson Junction tunable inductance designs

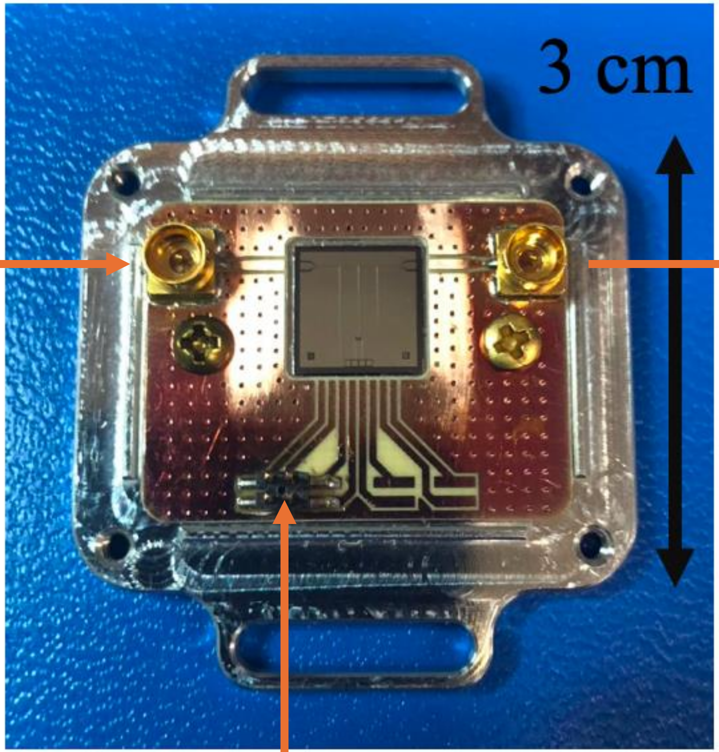


Microwave components



Packaging and readout

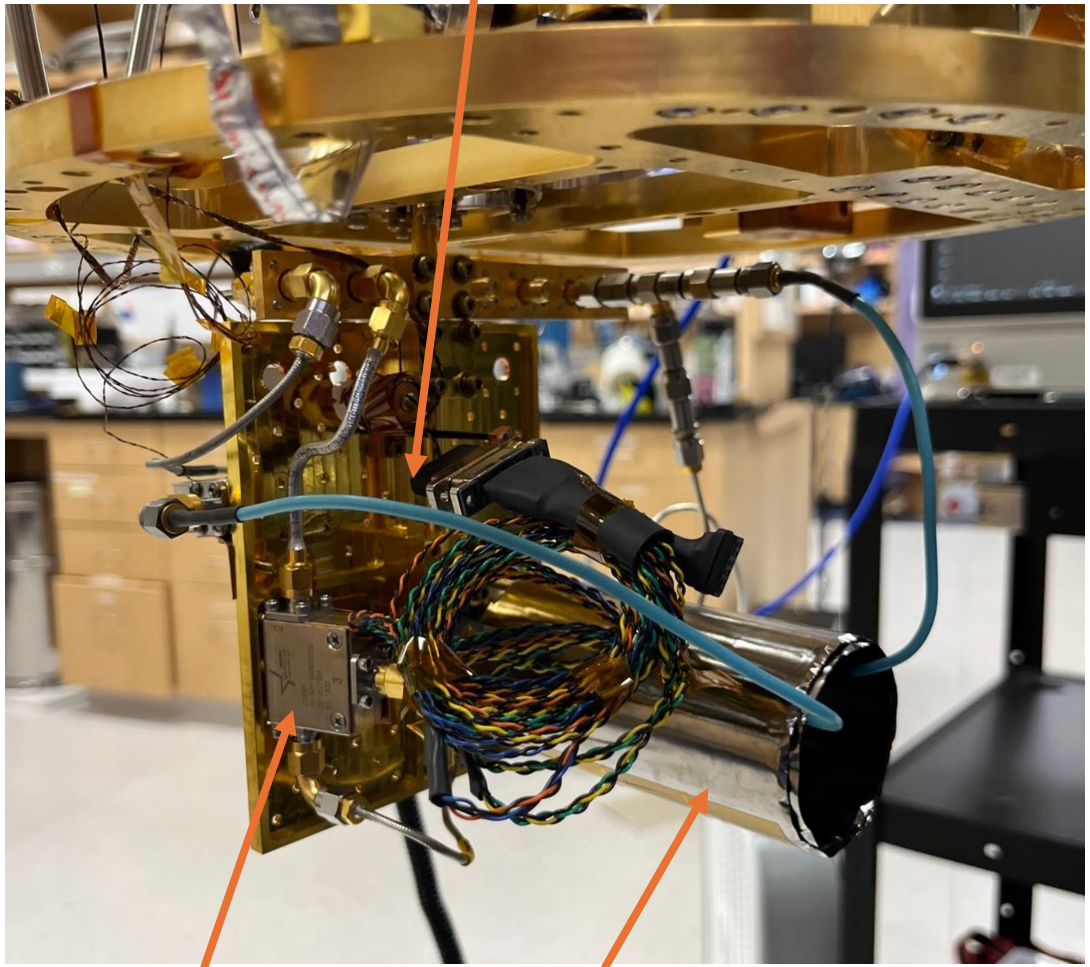
Microwave drive IN



Readout tone OUT

Low-frequency flux signal IN

30 mK ADR base stage

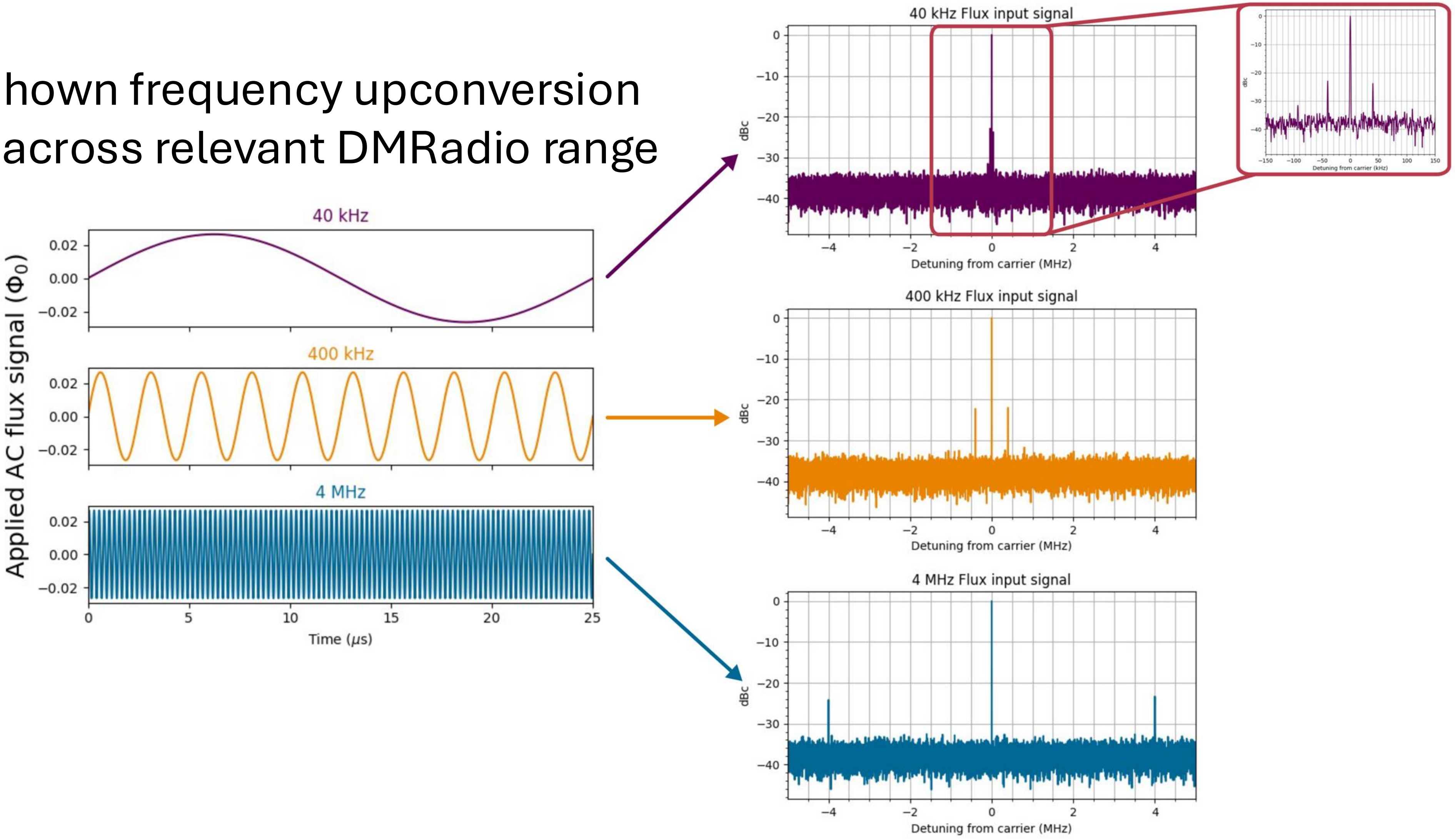


Circulator

Multi-layer magnetic shielding

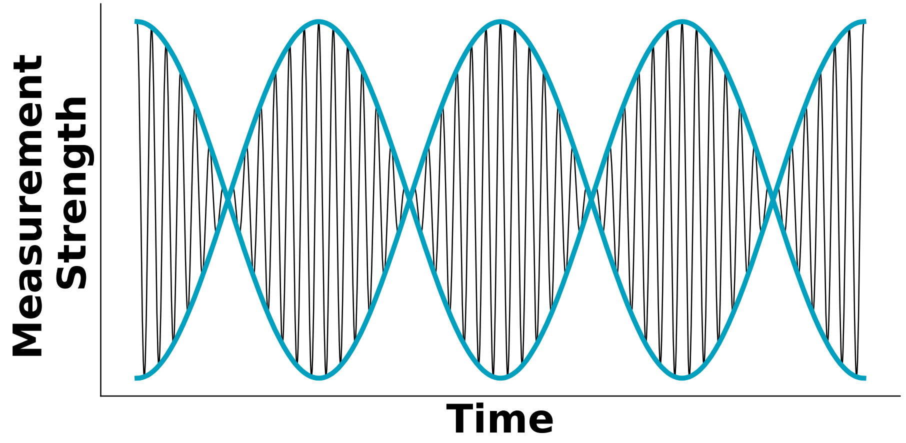
Demonstration of upconversion

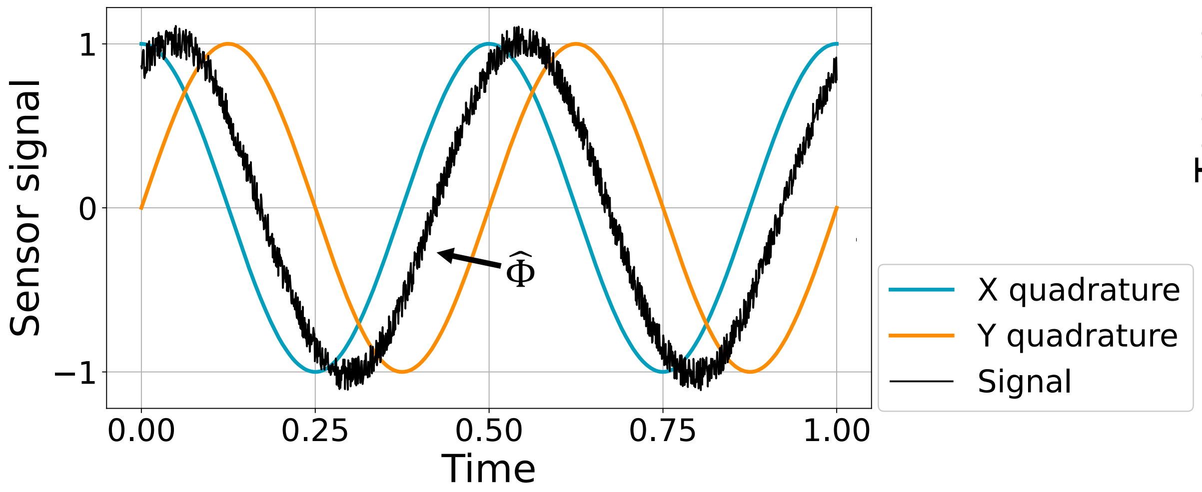
We have shown frequency upconversion of signals across relevant DMRadio range

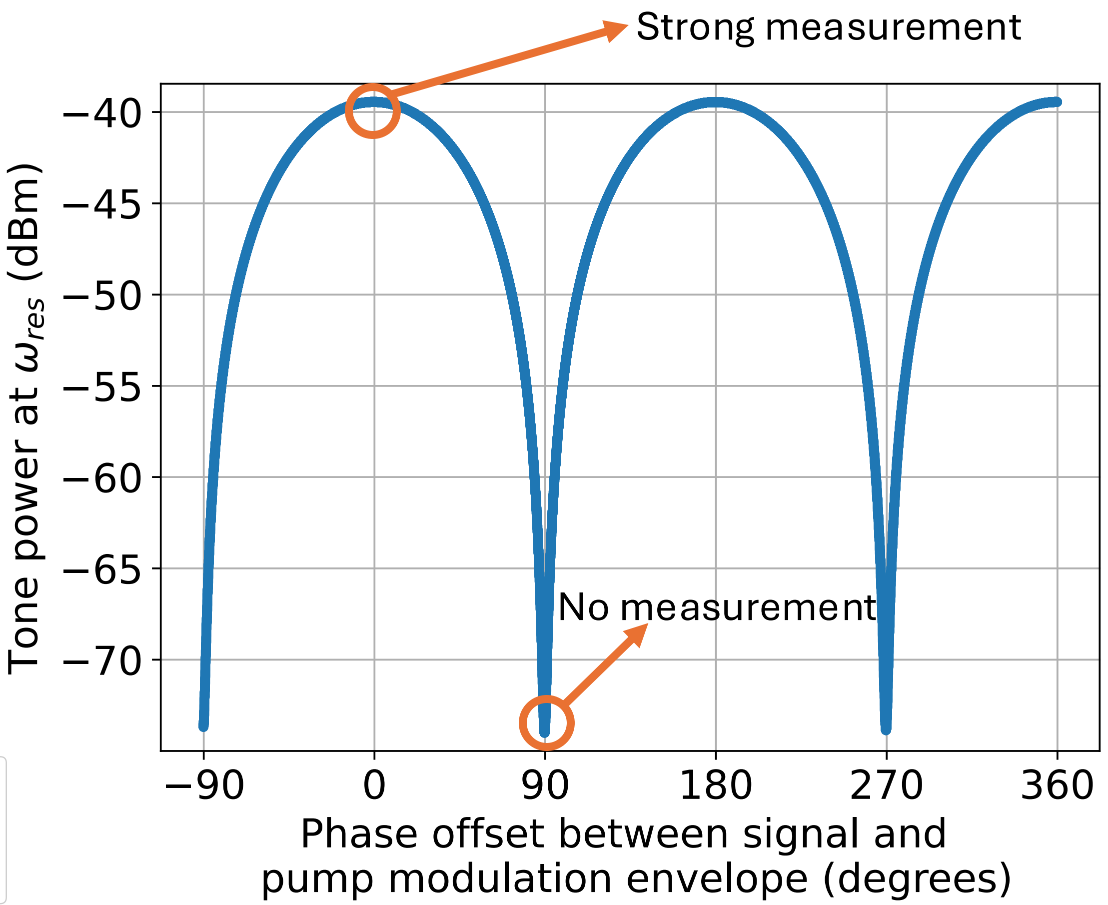


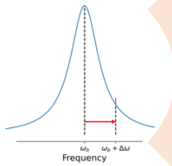
Demonstration of phase-sensitive gain

- An amplitude-modulated readout with an envelope that matches the MHz flux signal selectively amplifies one quadrature.

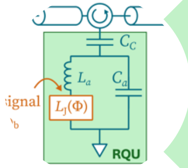




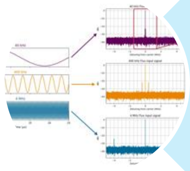




Intro to SQL



RF Quantum Upconverters

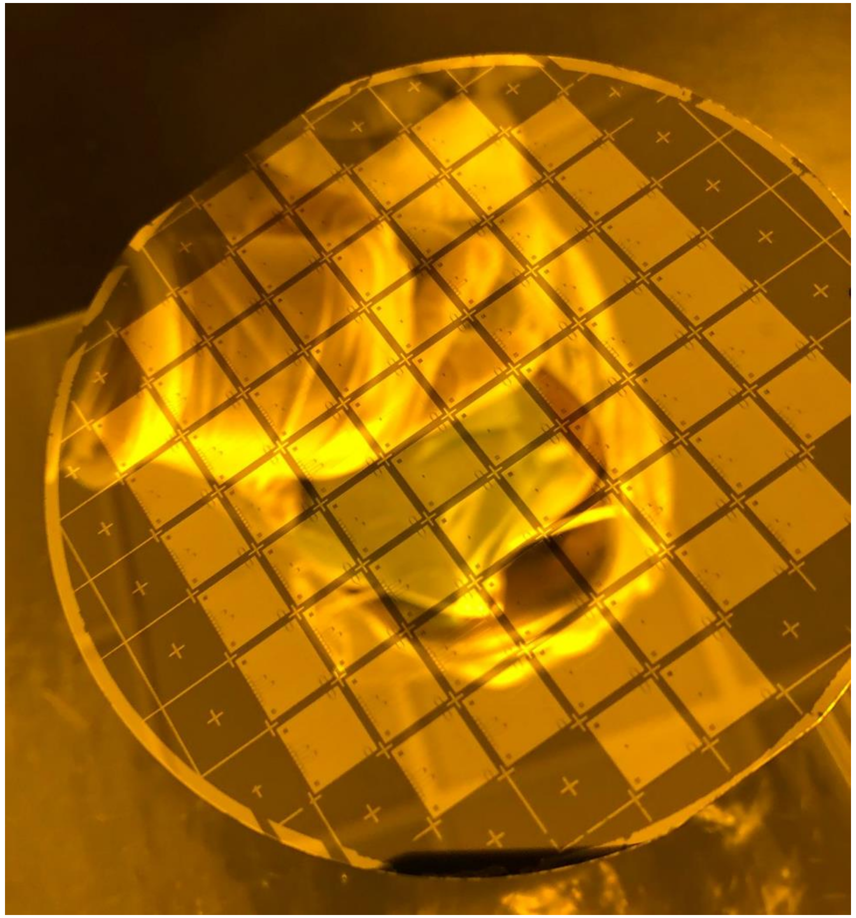


RQU Design and Testing

Outlook and Next Steps

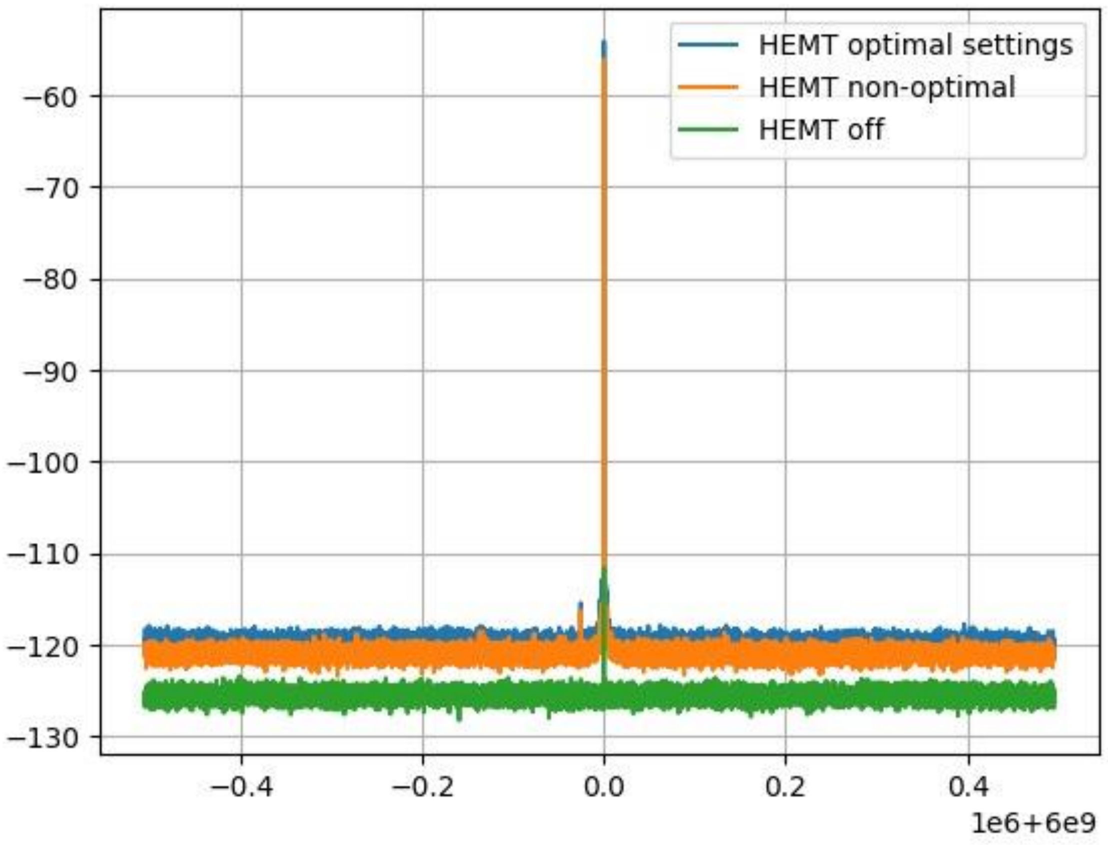
Device design and fab are iterative processes

- Fast turnaround and testing means we can dial in processes and make changes to the designs.
- Varying number of junctions, relative sizes, flux loop geometry, etc.
- Working on improvements to grounding, ability to inject flux from off-chip, and more.



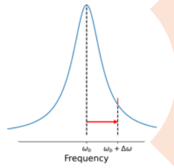
Characterizing and improving readout chain

- Currently working on full-readout-chain noise analysis to determine sensitivity and limits of the current devices.
- Additional microwave hardware (8.5 GHz Lock-in) adds flexibility and expands measurement capabilities.

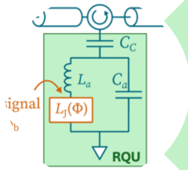


Adding resonator to input

- Next testing steps include adding a MHz test resonator to the RQU input.



Intro to SQL



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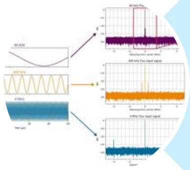
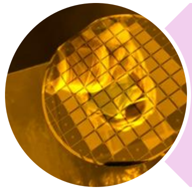


RQU Design and Testing



Outlook and Next Steps

That’s all! Thank you to the RQU team!