FERMILAB-POSTER-21-109-STUDENT

Qubit Signal Processing and the Search for Dark Matter

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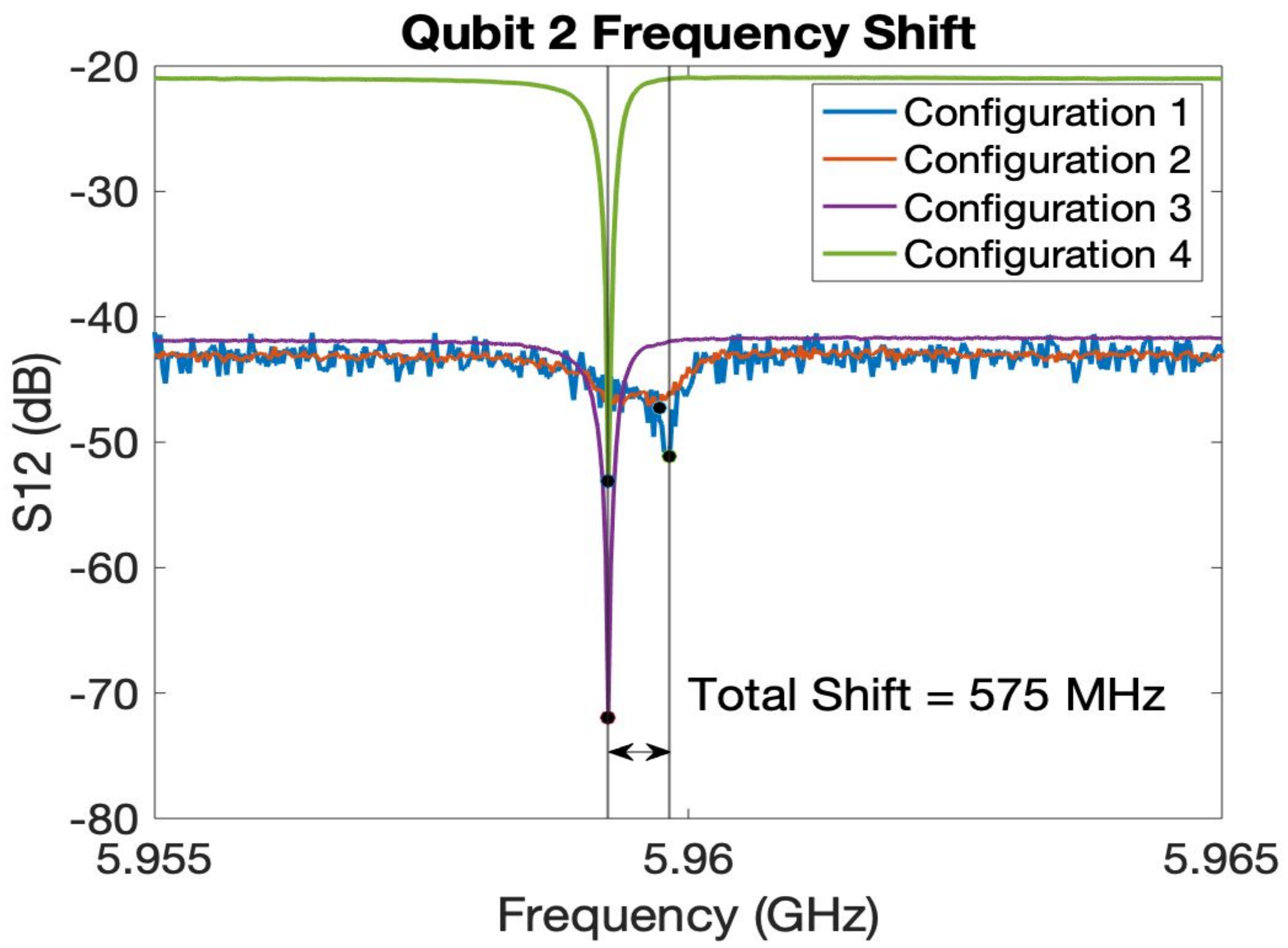
Introduction and Motivation

While first theorized to solve the strong CP problem in quantum chromodynamics, axion particles are also a popular cold dark matter candidate. Superconducting qubits may be beneficial in future searches for this elusive particle. However, qubits are susceptible to state decoherence due to ionizing radiation[1]. The goal of this experiment is to further study the decoherence errors in qubits. My work focused on designing the warm electronics used to read out the qubits.



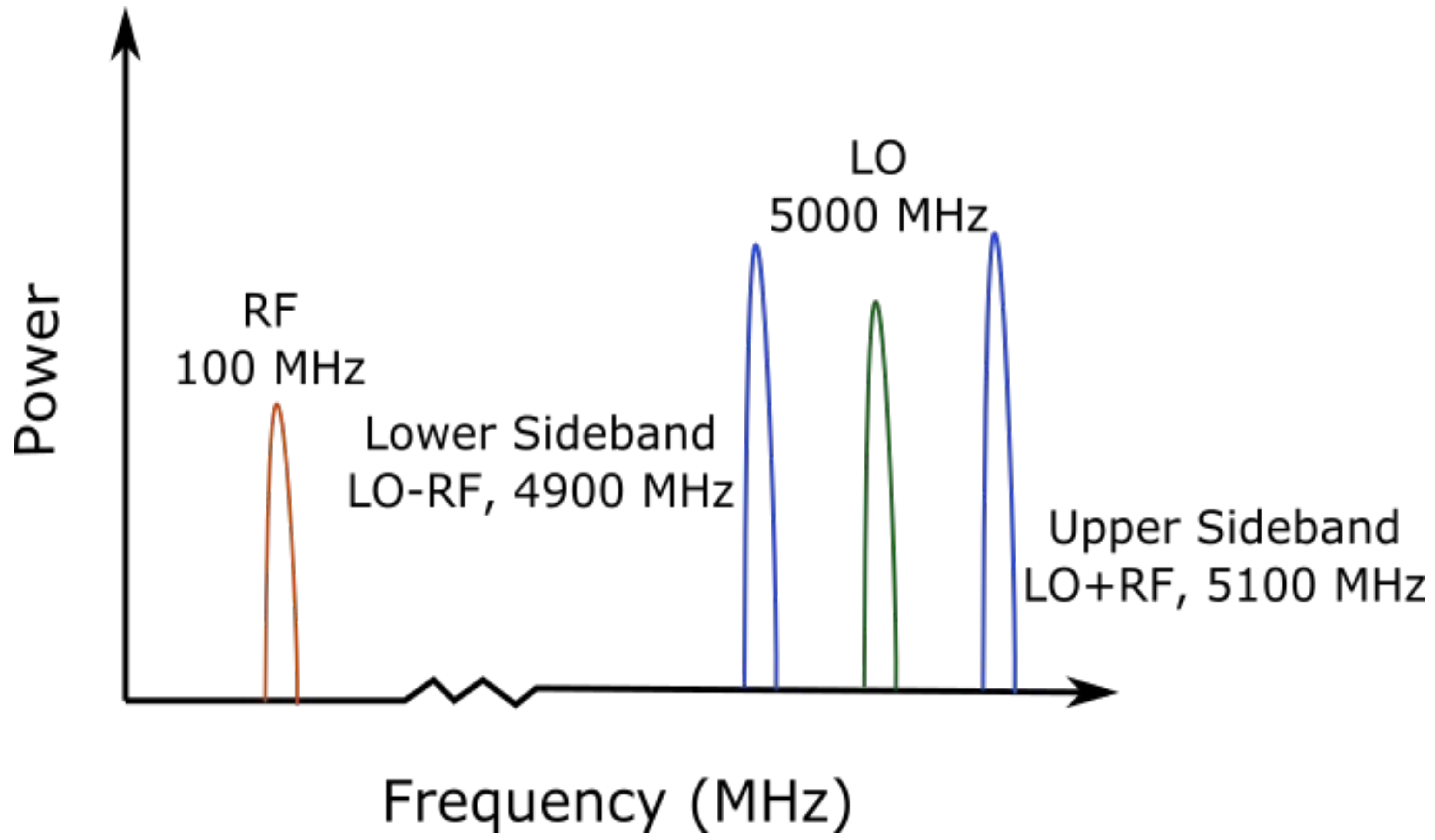
Observed Stark shift on qubit 2. Configuration 1 has the lowest input signal power and Configuration 4 has the highest signal power.

Experimental Setup

This experiment has a resonant cavity coupled to a package of 4 qubits situated inside a helium dilution refrigerator. Qubit readout includes sending a signal to the cavity and observing the reflected signal power. This is described by the hamiltonian shown below[2]. A shift in the cavity's resonant frequency, ω_r, indicates a change in the qubit's occupancy, σ_z.

$$H = \hbar\omega_r(a^\dagger a + 1/2) + \hbar\omega_q\sigma_z/2 + \frac{\hbar g^2}{\Delta}(a^\dagger a + 1/2)\sigma_z$$

$$\omega_r \to \omega_r \pm \frac{g^2\sigma_z}{\Delta}$$



Frequency modulation example. RF and LO are inputs, and the lower and upper sidebands are the outputs from the mixer. The upper sideband is selected to send to the qubit using a filter.

Qubit Measurement Methodology

Our qubits' resonant frequencies are between 5 and 7 GHz. To produce signals at this frequency, I sourced the relevant electronic equipment and designed an I/Q mixing scheme. A low-frequency signal from an arbitrary waveform generator (called the reference frequency, or RF) is input into an I/Q mixer along with a high-frequency tone (called the local oscillator, or LO). The mixer then outputs two tones, at LO + RF and LO - RF. The tone at LO + RF is sent to the qubits. The output signal from the qubit is similarly mixed down to a lower frequency before digitization.

Acknowledgements

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

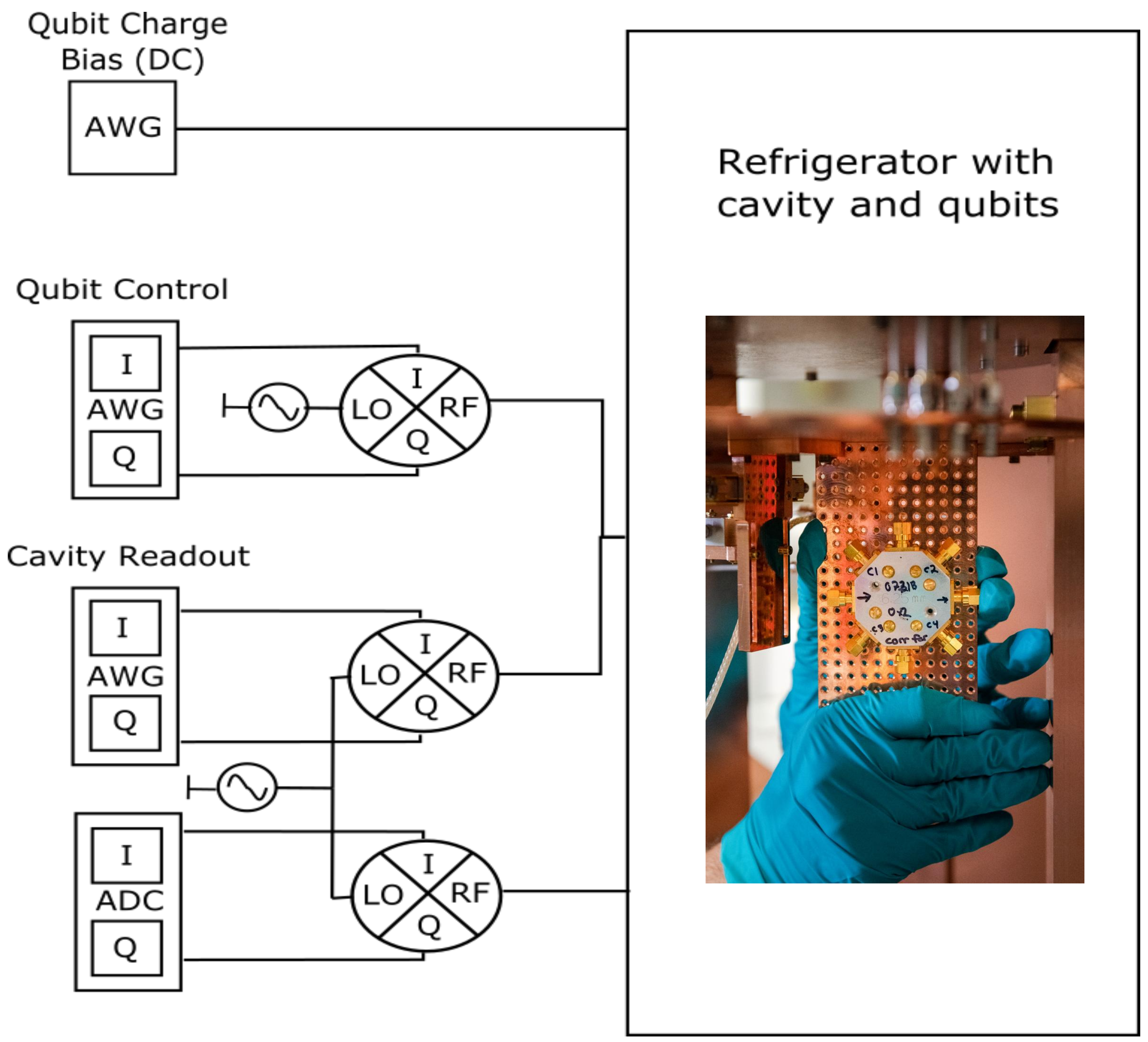
References

[1] Wilen, C.D., Abdullah, S., Kurinsky, N.A. *et al.* Correlated charge noise and relaxation errors in superconducting qubits. *Nature* **594,** 369–373 (2021). https://doi.org/10.1038/s41586-021-03557-5

[2] Krantz, P.,Kjaergaard M., Yan F. *et al.* A Quantum Engineer's Guide to Superconducting Qubits. *Applied Physics Reviews* **6**, 021318 (2019). http://dx.doi.org/10.1063/1.5089550

Qubit Readout System

I developed a series of measurements and wrote scripts to automate their execution. This qubit readout system will be used for future tests of qubit decoherence from ionizing radiation.



Block diagram of the signal processing system[1]. Various attenuators and amplifiers on refrigerator input and output lines are not shown. Photo of qubit package, designed by UW Madison team.

Conclusions and Future Research

The signal processing procedure is integral to testing the correlated errors seen in qubit measurements. The resulting data will be compared to past aboveground tests to better understand the systemic decoherence effects. Understanding qubit errors is necessary for further development of quantum computers and qubit-based dark matter searches.