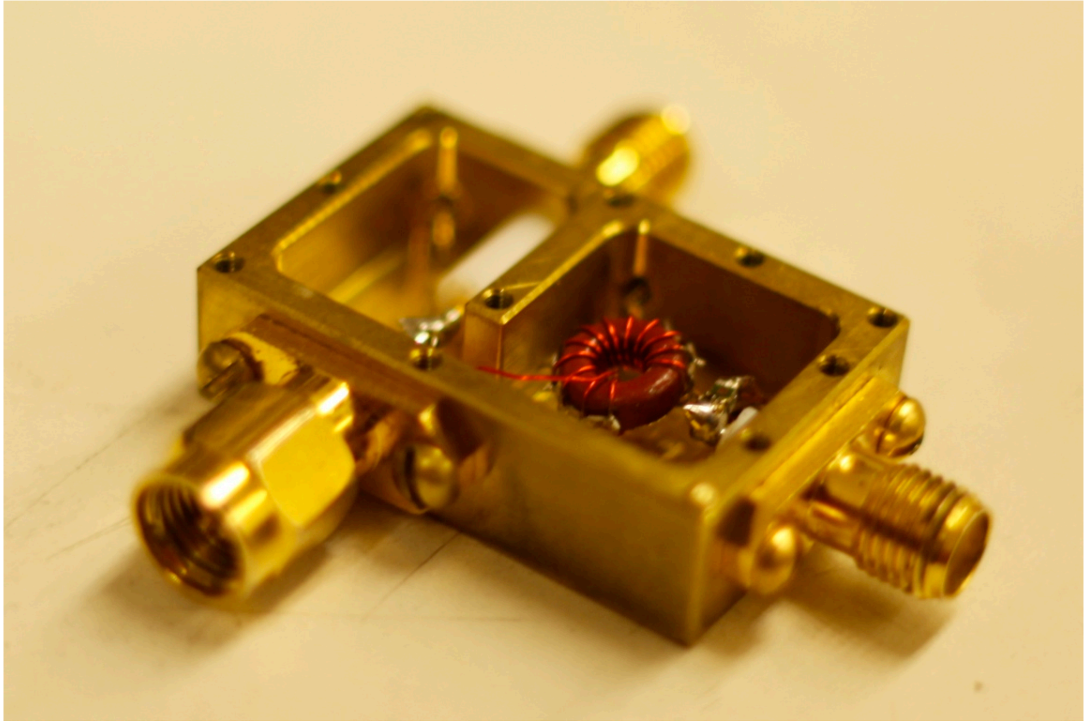
BIAS TEE 2.0

Reducing the Size of the Filtering Hardware for Josephson Junction Qubit Experiments Using Iron Powder Inductor Cores.

Daniel Staudigel



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Quantum Computer Basics

The purpose of quantum computing is to leverage the fundamentally parallel nature of quantum mechanics to solve problems that would be much more time consuming using conventional computers. The name is somewhat confusing given that the fundamental building block of modern computers, the transistor, can only be understood in terms of quantum mechanics. The reason why conventional machines, based on transistors, do not fully harness quantum mechanics is that they deal with large numbers of electrons, and do not pay attention to the fundamental quantities. In large part, deeper quantum mechanics is lost because transistors usually operate at such high temperatures that the vast majority of quantum effects are no longer visible on top of the thermal and other environmental noise sources.

For this reason quantum computers must be set in a “quiet” environment, with highly sensitive measurement and addressing electronics. “Quiet” can mean a variety of factors; temperature and electromagnetic noise must be isolated from the quantum computer in some way. Without this isolation, energy from the environment will leak into the experiment or computation and disturb the outcome. Like conventional computers, it is convenient to work in terms of two-level, binary states. Conventional bits turn into quantum bits (qubits) in a quantum computer. Aside from a carefully prepared, quiet environment, and a focus on two-level systems, quantum computers come in a variety of shapes and sizes. Single-atom qubits use individual atoms whose electrons are excited into higher states to convey information. Quantum dot qubits are a silicon wafer equivalent of single-atom qubits. Spin 1/2 systems like polarized light or bare electrons are also used in many experiments. Josephson junction qubits are based on an potential well generated in a superconducting LC oscillator with a Josephson junction providing an anharmonic component.

Theory and Electronics of Josephson Junction Qubits

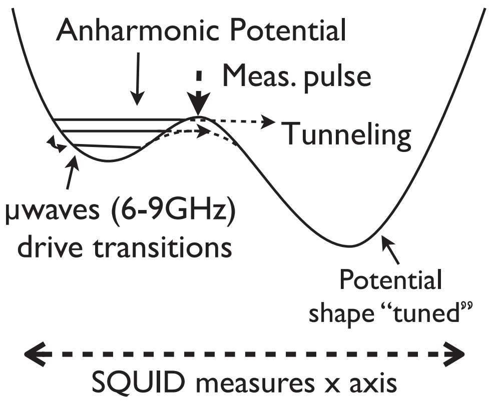

Fig. 1: Tuned Josephson Potential. Flux bias controls shape of potential well. Microwaves drive transitions between states in well. Measure pulse allows tunneling of higher states, so they can be read along the x-axis of the potential.

Josephson qubits work based on the potential created by a nonlinear superconducting oscillator. The operation of the qubit is controlled by a few external inputs. The first is the flux bias, which tunes the depth and relationship of the potential wells in the system. Microwaves excite higher energy states, and are tuned to specific transitions. In a harmonic oscillator, all transitions between states have the same energy gap. In the nonlinear potential of the Josephson qubit, every transition has slightly different frequency, allowing them to be individually excited. Once the qubit is excited into a higher state, a measure pulse is applied, which depresses the potential barrier for a brief time. During this time, higher states have a much greater probability of tunneling through the barrier, leaving them in the right well. Using a SQUID, the x position of a state can be easily measured (see figure 1).

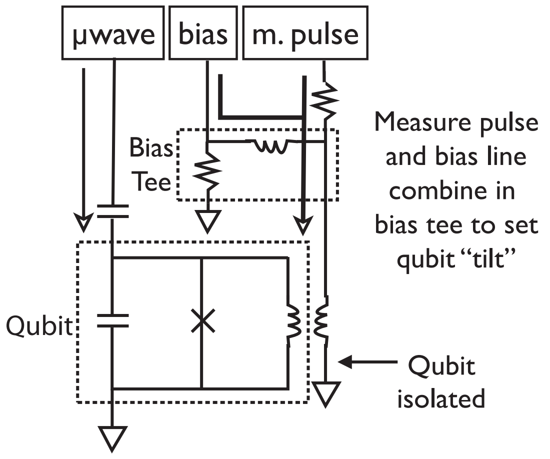

Fig. 2: Electronics of Josephson Qubit. The qubit is physically isolated to reduce noise. The bias line is added to the measure pulse before going into the qubit.

Purpose of the Bias Tee

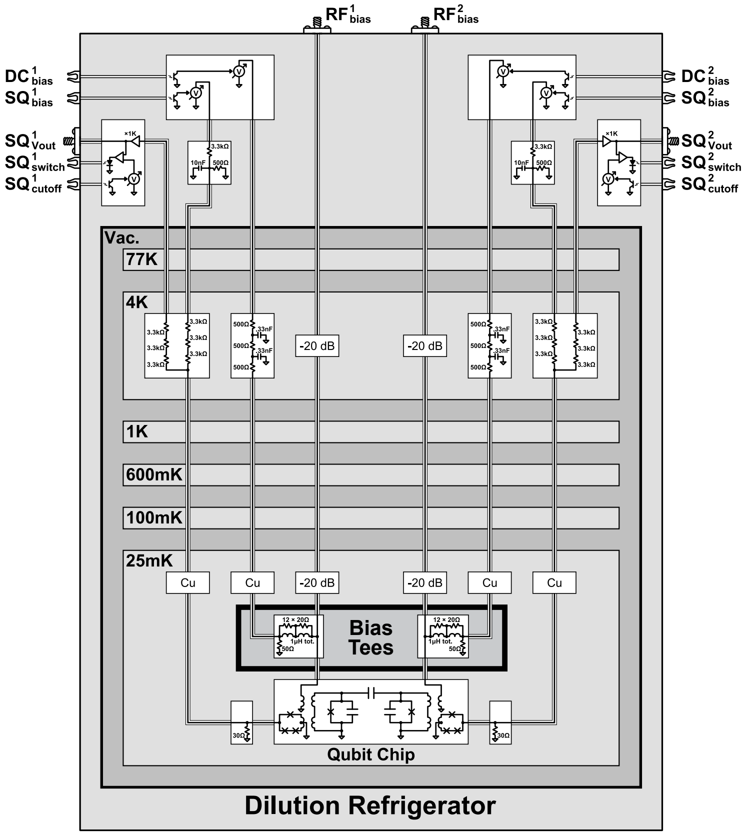

Fig. 3: Location of the bias tee in the wiring setup of the dilution refrigerator

The electrical interface to the qubit in use in the Martinis Lab falls into one of several categories. The bias tee adds two of these inputs in the fridge, right before the signal enters the qubit. The two lines in question are a high frequency (up to about 300-500MHz, $\mathrm{RF}_{\mathrm{bias}}$ in Fig. 3) line, and a low-frequency (bias, $\mathrm{DC}_{\mathrm{bias}}$, in Fig 3) line. The bias tee must isolate the RF signal from the bias line, so that the pulse shapes have higher fidelity. The low-frequency line is also high-power, whereas the microwave line is low-power. Tuning the bias voltages must swing multiple qubits (on the same chip) between 200-500MHz, to bring multi-qubit experiments into and out of resonance with each other. Once on or off resonance, the voltages must be stable. This means that at best, the bias tee must be clean, quiet, and predictable enough to keep voltage pulses stable to about 1 part in 500. Without this stability, the two qubits in a multi-qubit experiment might drift into and out of resonance, causing unpredictable results. Performance must be predictable enough to reliably bring pulses from their sources to the cold-plate unchanged.

Previous Design of the "Handwound" Bias Tee

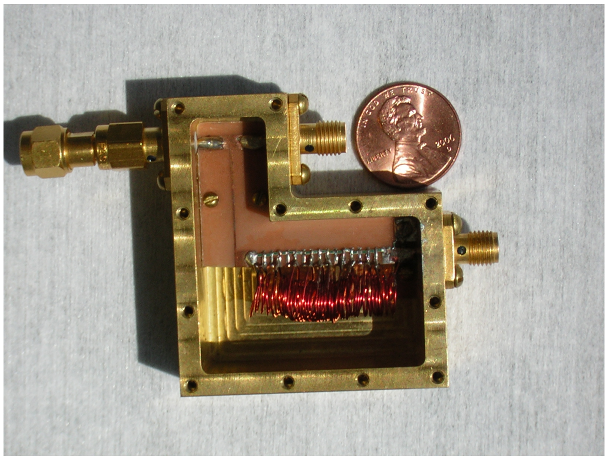

Fig 4: External Dimensions of current Bias Tee

The previous design of the bias tee was constructed using a resistor-damped air-core 4.5μH inductor, terminated at one end to 50Ω. The schematic is visible in Fig. 2, and the external dimensions are illustrated in figure 4. A simple air-core inductor of this geometry has significant parasitic capacitance between each of the loops. Inter-winding parasitic capacitance is in series with the inductor and causes LC oscillators which cause resonance peaks that "poison" the pure-inductance curve of the inductor. Resonance peaks allow certain frequencies to pass through the filter with no damping at all (0 dB attenuation). Pass-through means that the filter doesn't cleanly attenuate high frequencies, allowing some to get through and make the filter less effective as a circuit protector, and gives oscillations to the pulses at the qubit. To help reduce resonance peaks, in-line resistors form an RLC circuit, damping out the resonance peaks. The difference between these two systems are illustrated in Figure 5. The effect of the resistors is dramatic in the air-core inductor system. They are critical for good performance anywhere greater than about 80MHz.

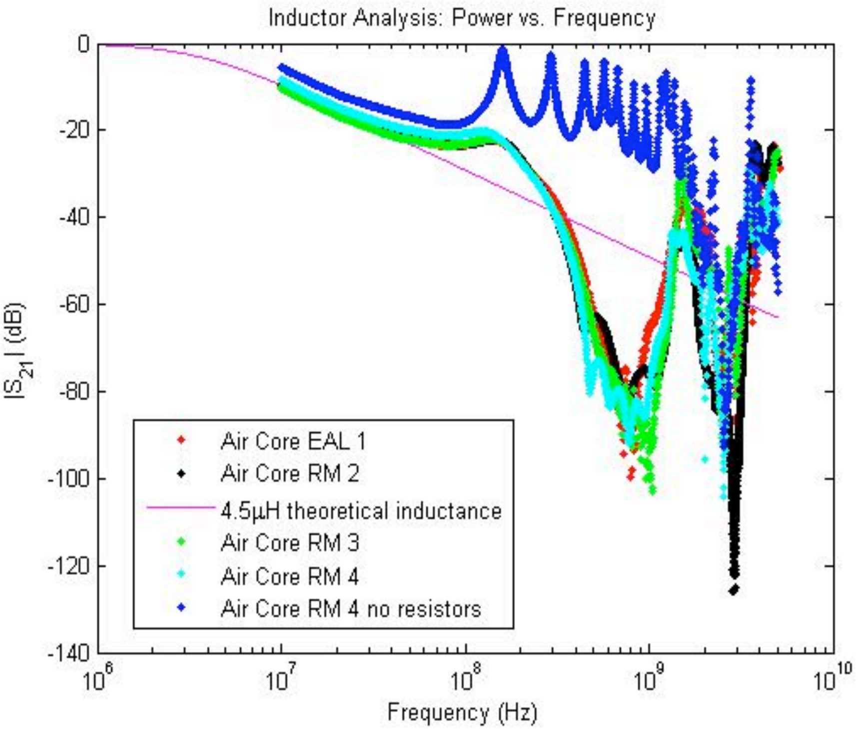

Fig.5: Effect of in-line resistors on filter performance. The blue line is without these in-line resistors, other lines are various models with in-line resistors. Notice the high resonance peaks that are a result of undamped parasitic capacitance in the "handwound" inductor.

The resonance peaks are clearly visible in the blue line, where several peaks come up to 0dB, and several more are closer to -5dB. Since ideally -30dB is required for frequencies greater than 100MHz, the resonance peaks must be eliminated. This is done by using resistors in-between groups of coils. The inter-coil resistors foil much of the inter-coil parasitic capacitance, reducing the parasitic LC oscillations.

Problems with Hand-wound Design

The primary concern with the hand-wound bias tee design is physical size. There is limited size on the cold-plate of the fridge. The limiting factor in the number of qubits that can be simultaneously run in a single fridge is the footprint of auxiliary devices like the bias tee. Reducing the external dimensions of the bias tee while keeping its electrical properties the same will save a lot of space on the cold-plate, allowing more qubits to be run simultaneously.

Initially, an air-core was chosen because it is guaranteed to have no temperature dependence. With this guarantee, it is easy to design the bias tee at room temperature, requiring very little low-temperature testing before the design is finalized. Vacuum-cores (the refrigerator is evacuated during cool-down) behave perfectly linearly with temperature, and thus make this geometry easy to "debug". The problem with vacuum cores is that, while linear in many respects, it takes far more turns to get a desired inductance. With more turns comes more parasitic capacitance, so while the design is easier from a temperature perspective, it is much more difficult to get a nicely linear inductor at high frequencies.

Design Considerations and Research for Updated Design

Reduction of the physical size of the vacuum-core cylindrical inductor was the primary goal in the design process of the new bias tee. A reduction in size of an order of magnitude is about all that is mechanically reasonable. 3 SMA connectors determine the external dimensions of the bias tee, and further shrinking of the inductor core will not reduce the external size of the bias tee. Also, smaller cores will be difficult to construct and smaller resistors do not exist. Reducing the size of the magnetics will require a different geometry and a magnetic material with a relative permeability of about 10 or so, to reduce the size by a similar factor. In choosing a magnetic material, temperature independence is a crucial variable. Many magnetic materials do not retain their magnetic properties to low temperatures (especially those with high relative permeabilities). The other primary concern will be minimizing the LC resonance peaks, in the same way that it was for the previous design.

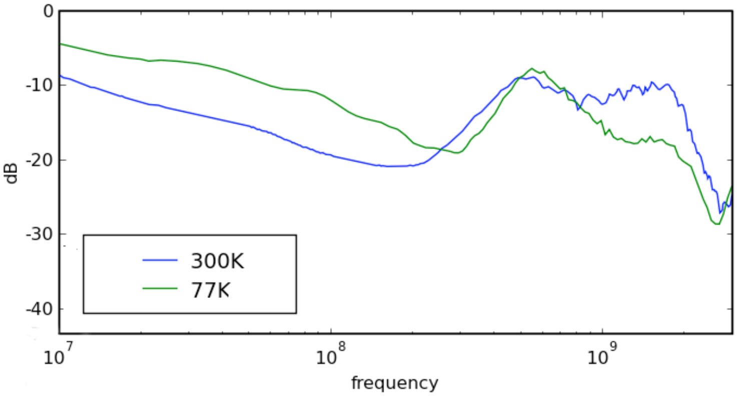

Fig. 6: Poor temperature independence. Inductance drops markedly at 77K, compared to 300K. This is not an ideal sample.

The most important part of the research that went into the design of the updated bias tee is the temperature dependence work. A wide variety of materials are available commercially for toroidal inductor cores. They vary greatly in relative permeability, and one with suitable temperature stability is critical to a working bias tee. Since no data exists in the specifications for the inductor cores about 4K performance, let alone 25mK performance, we must perform these experiments ourselves.

To do so, a properly terminated experiment mount was constructed and tested at room temperature, in liquid helium (77K), and in liquid helium (4K). If temperature stability was good at 77K, and at 4K, the cores were tested in a different mount at approximately 100mK in a adiabatic demagnetization refrigerator. Once tested successfully in this fridge, they were mounted in the final brass housing, and placed in the dilution refrigerator as bias tees, where their true performance was verified.

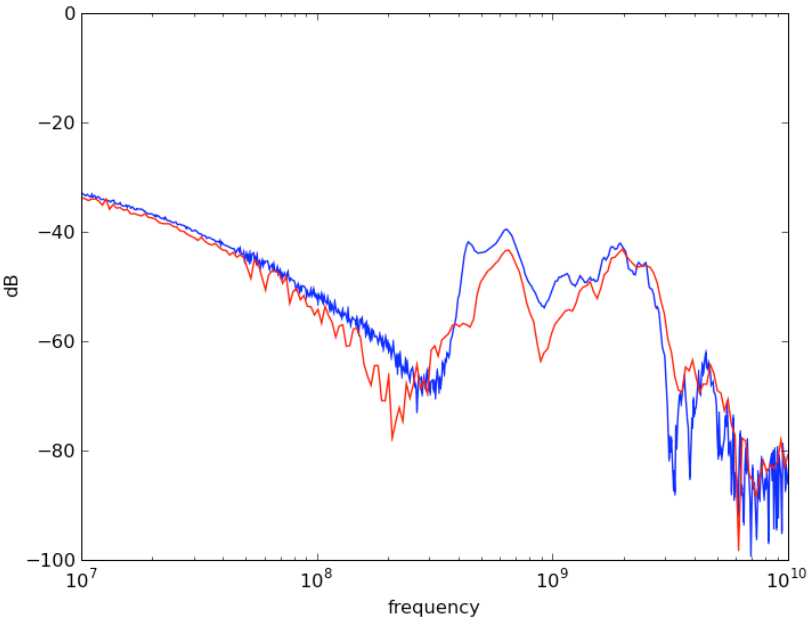

Fig. 7: Good Temperature Independence in T25-2 model Amidon™ iron powder toroid. Inductance does not change measurably between 300K (red) and 100mK (blue).

Several models were found to have good temperature stability as well as sufficient relative permeability to deliver sufficient inductance to be useful (Amidon™ Corporation models T25-2, T25-6, and T25-10). In figure 7, temperature independence is clearly visible, as well as fairly high LC resonance peaks. This test was done without any damping resistors.

Damping resistors were added to remove resonances, as well as to reduce parasitic capacitance. Many different resistor configurations were tested, from sparse configurations (far fewer resistors than turns) to dense configurations (1 less resistor than turns). In the dense configuration, there is a resistor bridge between each of the turns, making a resistive path entirely bypassing the inductor.

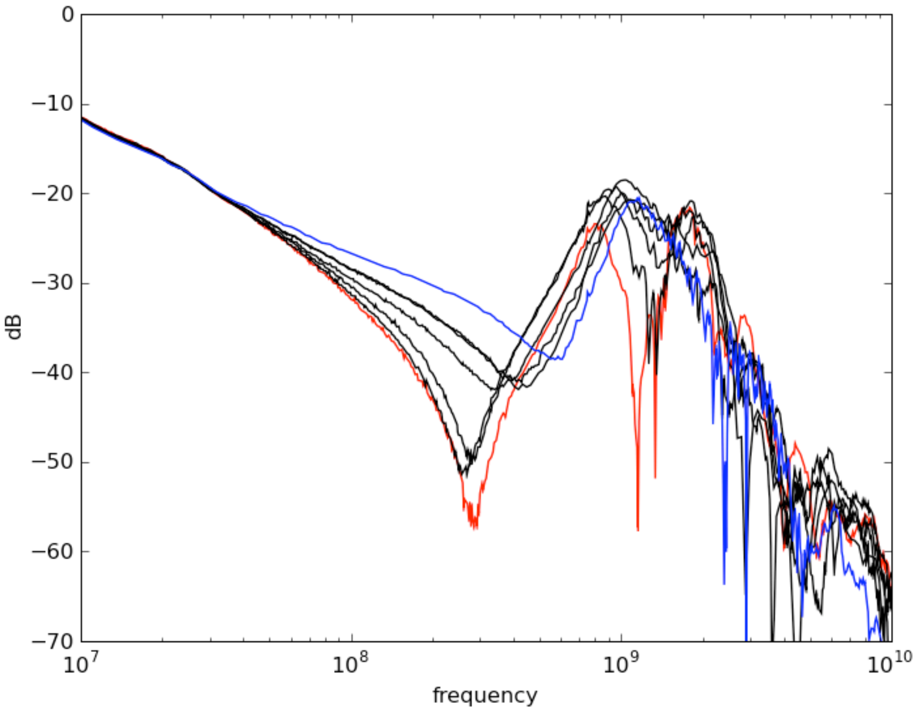

Fig. 8: Effects of Resistors. The curve without resistors (red) transitioning (black) to the dense configuration of resistors (blue) shows the effects of resistors.

In figure 8 the damping effect of the resistors is illustrated. In this experiment, the LC resonant peak is not moved much by the addition of resistors, but this will be addressed in the final design. Choice of resistor value affects the height of this peak.

Physics of "Iron Powder" Inductor Cores

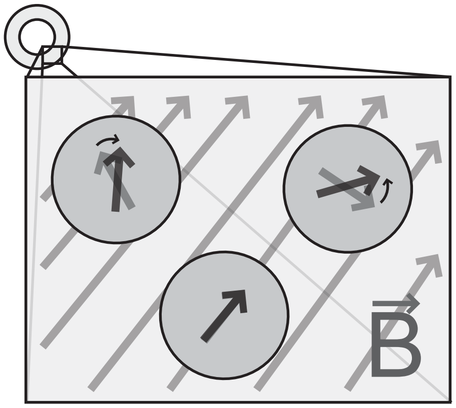

Fig. 9: External B field applies small torque on each magnetic cell, causing slight deflection and a corresponding increase in magnetic field.

Based on some of the the papers that were consulted about the design of the toroidal "carbonyl iron powder" inductor cores, the makeup of these cores appears to be relatively straightforward. Iron powders of various compositions (depending on the make and model of the core) are ground into spheres of approximately one cell of magnetism. The spheres are pressed with an inert binder into the desired shape (for us, 0.25in outer diameter toruses). Each sphere is approximately one magnetic cell, which has a given magnetic moment. In the presence of an external magnetic field, all of the magnetic moments deflect slightly and increase the overall field by an order of magnitude, giving them a relative permeability of 10. This mechanism gives this design relatively good temperature independence and linearity, both qualities that are important to us.

Toroidal Design Outline and Performance

The toroidal design is centered around a 0.25 inch (outer diameter) toroidal iron powder inductor. It is wound with 12 winds of 28AWG copper magnet wire, stripped at the ends, and around the perimeter of the torus. Eleven 10Ω resistors are soldered around the perimeter, between each of the stripped turns. These damp out parasitic capacitance that would otherwise cause LC oscillations.

The final torus is housed in a small brass enclosure on which the 3 SMA connectors are mounted.

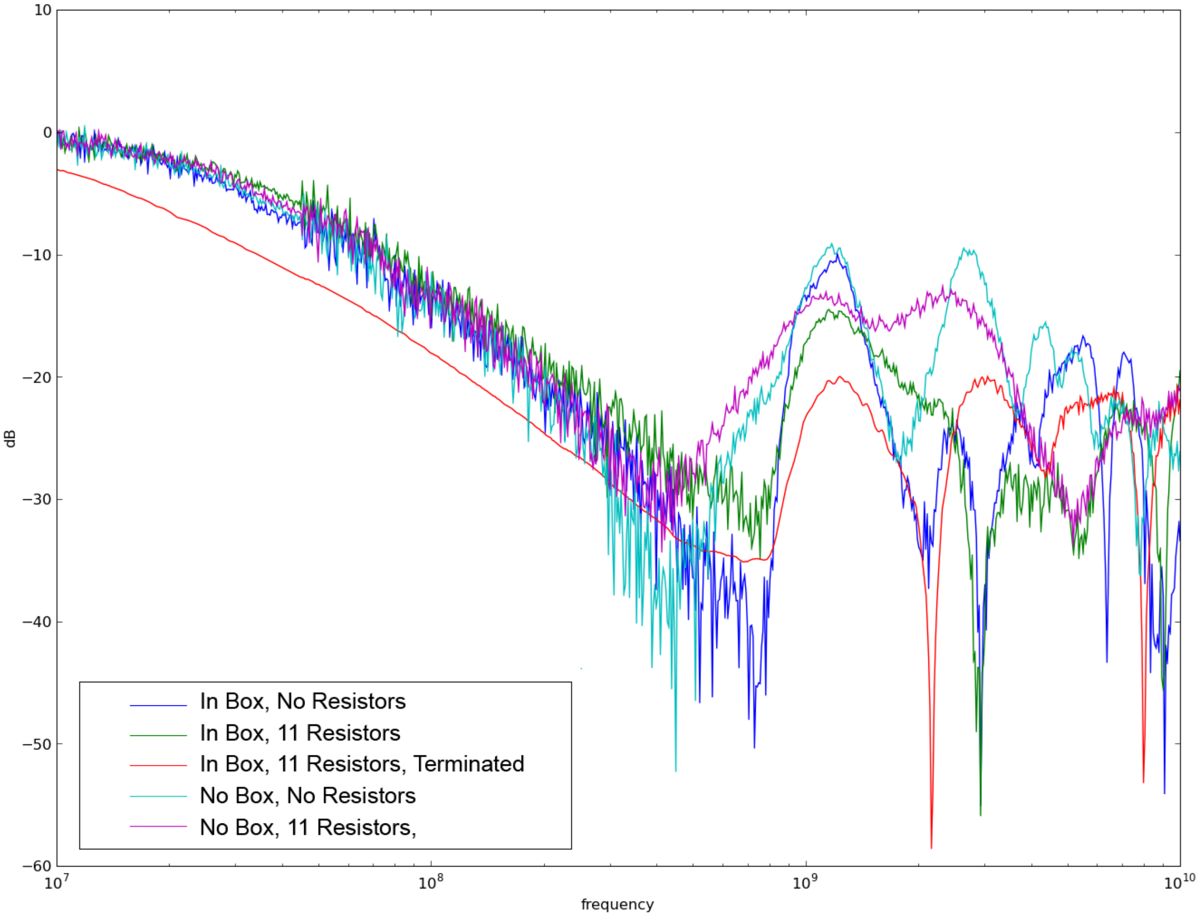

Fig. 10: Final Performance Criteria. Enclosed, terminated, and damped (red) shows best performance. Enclosed and damped (green) shows better linearity and less LC resonance than enclosed and undamped (blue). The same pattern can be seen in the unenclosed version (purple/teal).

The copper box is closed and mounted to the cold-plate.

The toroidal design performs very well. It has good temperature stability, linear inductance, and no significant resonance peaks. It compares favorably with the vacuum-core design, especially given its far smaller package dimensions. In figure 10, the effects of damping resistors are shown in the brass enclosure. The reduction of LC resonances is much better illustrated in Fig. 10 than in Fig. 9, due to the choice of the resistors.

Concerns With New Design & Future Changes

The main concern with the first toroidal design is that the microwave performance is somewhat degraded on the thru-line. Because of the initial design of the box, the high frequency line is not matched perfectly to 50Ω. The non-matched microwave line means that high-frequency throughput is suboptimal. To match this line better will require more careful microwave engineering of the box. While not important for the current application of the bias tee, improvements of the microwave performance would allow the microwave pulses as well as the measure pulses to be added to the flux bias line before all entering the qubit in the same inductor.

Conclusions

The new bias tee box was a success, performance was improved over the previous model in the low frequency linearity, with some sacrifices in the higher frequency attenuation. The box is significantly smaller than the previous iteration (see figure 11). With some more work, the performance can be improved even more, but the desired characteristics have all been borne out in the final design.

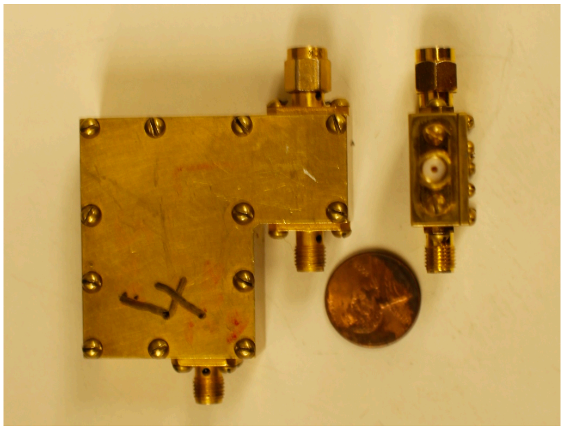

Fig. 11: Bias Tees. New design on the right.

Appendix 1 - Construction Instructions

Materials Required

1. Bias tee enclosure (see appendix 2) and lid
2. Amidon™ T25-2 iron powder toroid inductor core
3. 28AWG magnet wire
4. 11 10Ω NiCr 0402 resistors
5. 2 female SMA connectors
6. 1 male (screw-on) SMA connector
7. 6 2-56UNC and 13 0-80 UNC brass screws
8. 1 50Ω NiCr resistor (or 2 100Ω) and brass strapping

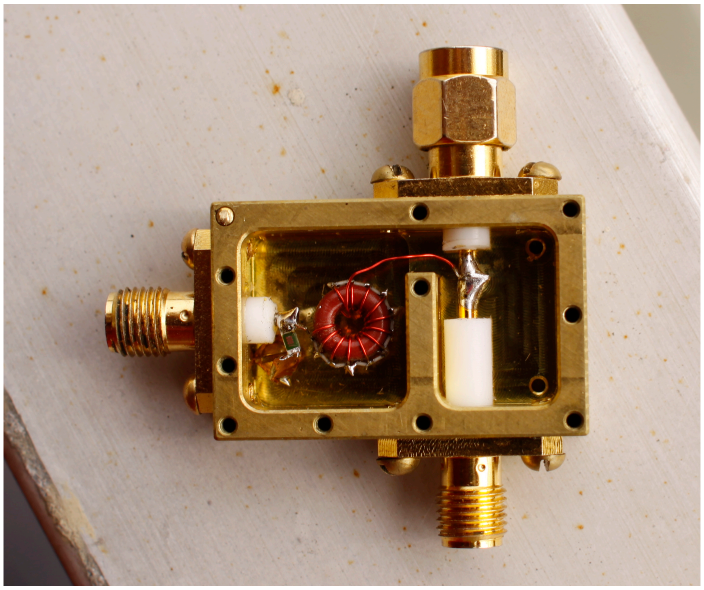

Fig A1: Final Construction

Steps

1. Wrap the inductor core with 12 turns of 28AWG magnet wire. Windings should be evenly spaced.
2. Strip the ends and around the perimeter of each of the turns, making sure to strip on all three sides of the wire (excluding the side touching the toroid).
3. Solder resistors in between each turn (where the wire has been stripped).
4. Mount SMA connectors to brass box with 2-56UNC screws
5. Solder inductor to appropriate SMA connectors.
6. Solder 50Ω to brass strapping and connect flux input line via 50Ω to the grounding 0-80 screw in the lower right corner of the inductor box.
7. Solder through-line together
8. Close box with 0-80UNC screws.

Appendix 2 - Enclosure Fabrication Drawing