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UCRL-TR-226752

Development of a Quantum-Limited Microwave Amplifier using a dc Superconducting Quantum Interference Device (dc-SQUID)

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December 12, 2006

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This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

FY05 LDRD Final Report
Development of a Quantum-Limited Microwave
Amplifier using a dc Superconducting Quantum
Interference Device (dc-SQUID)
LDRD Project Tracking Code: 02-ERD-071
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Abstract

This report summarizes the research performed on the LDRD project 02-ERD-071 to develop a quantum-limited microwave amplifier based on a dc Superconducting Quantum Interference Device (dc-SQUID). This project began in June 2002 and concluded in May 2005.

Introduction/Background

Experiments in many scientific fields rely on ultra-low noise microwave amplifiers. The noise temperatures of traditional transistor-based amplifiers remain an order-of-magnitude higher than the limit imposed by the Uncertainty Principle of Quantum Mechanics (50 mK at 1 GHz). Reaching the Standard Quantum Limit (SQL) would be a major scientific and technological achievement in its own right, and lead to rapid progress in many areas, including radio astronomy, particle astrophysics, spin measurement and quantum information processing.

A promising device for reaching the SQL is the dc SQUID [1] which consists of two Josephson junctions (thin insulating barriers) in a superconducting loop. They are by far the most sensitive magnetic flux detectors presently available. When properly biased, they act as very low-noise amplifiers at frequencies from a few kHz to ~10 GHz. A schematic of a typical square-washer SQUID amplifier is shown in Figure 1. The SQUID loop is formed by the washer and counter-electrode separated by two Josephson junctions with external shunt resistors. The input signal is applied to the input coil which acts as a microstrip resonator, and the output signal is the voltage between the counter-electrode and the washer. Present devices are an order of magnitude quieter than the best transistor-based amplifiers.

Figure 1: Schematic of the microstrip SQUID amplifier.

Since early results had shown the potential of microstrip amplifiers, a number of groups have become interested in using them. One of the first applications will be as a read-out for the radio-frequency Single Electron Transistor (rf-SET). One of the biggest challenges in the field of Quantum Information Processing is the measurement of a single electron or nuclear spin faster than the decoherence time which is typically microseconds in a solid-state system. Perhaps the most promising device for single spin detection is the Single-Electron Transistor (SET)[2]. SETs exploit the Coulomb blockade phenomenon to control and measure single electrons inside a solid-state circuit, essentially acting as a charge amplifier. Individual electrons tunnel through two small capacitance junctions that define the island of the SET. When the SET is appropriately biased, the conductance is extremely sensitive to the charge configuration in the vicinity of the island. A new type of SET, the radio frequency SET[3] (rf-SET), has been designed to operate at frequencies well over 100 MHz. In this device, the SET is placed in a tuned circuit and the conductance is determined by measuring the damping of the circuit (see Figure 2). The charge sensitivity of the rf-SET with a conventional amplifier read-out is about a factor of 50 above the quantum limit. Theoretical studies indicate that a microstrip SQUID amplifier with a noise temperature less than about twice the SQL would give the rf-SET quantum-limited charge sensitivity.

Figure 2: Schematic diagram of the apparatus used to measure the rf-conductance of an SET. Changes in the conductance of the SET affect the reflected power from the tuned circuit containing the device. This signal is measured very accurately by the microstrip SQUID.

A second important application is the Axion Dark-Matter Experiment (ADMX) located at LLNL [4]. This experiment searches for a hypothetical particle called the axion by searching for photons resulting from axion-to-photon decay. The photons are detected using a resonant cavity which sits in an 8 T magnetic field. The mass of the axion is unknown, so the resonant frequency of the cavity must be tuned in a narrowband search. The scan rate scales inversely as the square of the system noise temperature (physical temperature + amplifier noise temperature), so a low-noise microwave amplifier would be extremely useful.

Research Activities/Technical Plan

The technical plan for this project was developed to improve upon an earlier experiment to measure the noise temperature of a SQUID amplifier at mK temperatures [5]. This experiment showed the potential of microstrip SQUID amplifiers to reach the SQL, coming within a factor of 2 of this limit. By addressing limitations of the SQUID amplifiers as well as the measurement technique, this plan provides a path to reaching the lowest noise temperatures ever measured.

This plan started from the very beginning, the first step was to develop a reliable process for niobium (Nb) tunnel junctions to be used in new SQUID amplifiers. The process involves a tri-layer of Nb-AlO_x-Nb, where AlO_x is a thermal oxide layer grown on top of a few nm thick aluminum (Al) layer. Since the dc SQUID requires non-hysteretic junctions, resistive shunts are placed in parallel with the tunnel junction. These shunts were typically made from thin films of palladium (Pd) or a gold-copper alloy (AuCu). Since low temperature (mK) operation is necessary, the junctions must be tested at 300 mK and 4.2 K. Al becomes superconducting at 1 K, so areas of unoxidized Al could become shorts below this temperature and the device would no longer operate as a dc SQUID.

After a reliable, reproducible junction technology was developed it was used to make prototype SQUIDs to test the dc and rf performance. In particular, it was necessary to determine the temperature dependence of the junction parameters (critical current and normal resistance). A SQUID that was optimized for 4.2 K operation would no longer be optimized at 30 mK.

These prototypes were useful to optimize the design of the microstrip amplifier as well. In the past twenty years, a tremendous amount of work had gone into understanding the operation of a SQUID, and this is incorporated into the design of both the washer and the junctions. On the other hand, few of the microstrip properties were well understood at the start of this project. Many of the parameters such as coil width and spacing, number of turns, and dielectric spacing were chosen more for ease of fabrication than microwave properties. A model relating the physical geometry and junction parameters of the microstrip SQUID to amplifier performance would be a tremendous help in optimizing the design. We made significant strides addressing this problem.

The most significant improvement to the earlier experiment was the addition of large area cooling fins to the shunt resistors. The limiting noise temperature in the early experiment was due primarily to hot electrons in shunt resistors. There was insufficient thermal coupling between the tiny shunt resistors and the substrate. Adding large area cooling fins (see Figure 3) improves the thermal coupling substantially, reducing the hot-electron problem [6]. The second issue to be

addressed was the low frequency of operation (< 500 MHz) of the original experiment. This was primarily due to the need to cascade two SQUIDs to overcome the post-amplifier noise from the homemade HFET post-amp (> 6 K). Cascading SQUIDs is a very tedious task since they are resonant devices, and the resulting cascaded amplifier always operates at a lower frequency than the individual devices. With the goal of reaching the SQL, lower frequencies mean lower ultimate noise temperature with increasing systematics. The plan to overcome this problem was two-fold, improve the post-amplifier noise (~ 1 K) and improve the SQUID design to achieve higher gain (> 25 dB) with only a single stage at frequencies between 750 and 1000 MHz.

Figure 3: Photograph of the junction area of a microstrip SQUID amplifier showing the AuCu cooling fin.

With the improved SQUIDs allowing single stage operation, the next step was to use a dilution refrigerator to measure the noise temperature as a function of physical temperature down to 25 mK. An NRAO-built GaAs HFET amplifier with noise temperature below 1.2 K at 750 MHz was installed to replace the previous post-amplifier. Further improvements were made by replacing the old coaxial cable between the SQUID and post-amp with a lower-loss version. A significant improvement was the refinement of a different technique to measure the noise temperature. The early experiment used Nyquist noise from a tank circuit at the input of the SQUID amplifier as a noise source. This required delicate matching of the tank circuit to the SQUID amplifier and only allowed measurements at a single frequency. An improved method using the signal-to-noise ratio from a carefully calibrated input signal was developed. This had the advantage that once a calibration was performed, the measurement could be done at any frequency. The biggest potential drawback was that this was an absolute measurement which was very sensitive to systematics from the calibration. The tank-circuit method was a ratio measurement, more immune to systematic effects. Nonetheless, the flexibility of the SNR method was very desirable as long as great care was exercised in calibrating the system.

With the measurement system in place, the plan was simple: fabricate SQUIDs and iterate the design until the ultimate noise temperature was achieved, hopefully corresponding to the SQL.

Both applications require effort to improve the packaging and matching. In the measurement system at UCB, years of SQUID experience has led to cryostats specially designed for magnetic and electric shielding. Few other groups have this built-in to the cryostat, so the amplifier packaging must be more robust for real-

world applications. The first steps have been taken in this direction, allowing the first applications of microstrip amplifiers in actual experiments.

Results/Technical Outcome

The first Josephson junction was successfully fabricated in FY02 and tested both at 4.2 K and 300 mK. The 300 mK test was successful and ruled out problems with un-oxidized Al below 1.1 K. Towards the end of FY02, this junction process was used to make prototype SQUIDs that were tested at 4.2 K. Figure 3 shows the gain versus frequency for one of the microstrip SQUID amplifiers. These devices performed reasonably well as amplifiers, but were most useful for developing a low-loss transmission line model for the microstrip amplifier. This model was developed using the first-ever input impedance measurements of an actual microstrip amplifier and led to improvements of the SQUID design. Figure 3 shows the results of a measurement of the input impedance along with the resulting fit from the transmission line model. The agreement is excellent, allowing an extraction of the transmission line parameters.

Figure 4: Gain of a prototype microstrip SQUID at 4.2 K.

Figure 5: Measured (dots) and fit (solid) input impedance for a 19-turn microstrip.

The prototype SQUIDs were then tested at 300 mK and 30 mK to determine the change in critical current and shunt resistance as a function of temperature. Testing the SQUIDs below 300 mK is a difficult, time-consuming process since it requires a dilution refrigerator. Calibrating the temperature dependence allowed us to establish the expected critical current and shunt resistance values at 4.2 K for devices optimized for 30 mK operation. Since the shift in critical current is approximately 30%, this was a significant step. Figure 4 shows a measured current-voltage (I-V) curve at 30 mK, the critical current (10 μ A) and normal resistance (10 Ω) match the design target. Figure 5 shows the measured voltage-flux relation for the same SQUID, the smooth sinusoidal curve shows that the two junctions are very similar and that the device is indeed a SQUID.

Figure 6: Measured current-voltage relation at 30 mK. The critical current is 10 μ A and the normal state resistance is 10 Ω .

Figure 7: Measured voltage-flux relation at 30 mK. The peak-to-peak voltage is 60 μ V.

The next step in the project was to equip a dilution refrigerator for precise noise temperature measurements. Significant improvements were made over previous attempts to measure the amplifier noise temperature at 30 mK. First, the SQUID design was improved using the circuit model, resulting in higher gains than previously achieved. These high gains combined with the new lower-noise GaAs HFET post-amplifier eliminated the need to cascade two SQUIDs as hoped. Thus, the experiment was able to be performed at a higher frequency where the SQL was correspondingly higher. Second, the calibrated signal-to-noise ratio measurement

was developed. This was much simpler to perform, and allowed the first measurement of the frequency dependence of the noise temperature.

One of the keys to continued refinement of the measurement was a better understanding of the input impedance of the microstrip amplifier, and applying this knowledge to improving the matching. Of particular importance was the recognition that a small capacitor at the input could adjust the strength of the coupling to the microstrip, and that this coupling could be optimized. The required value of the capacitor can be predicted using the measured input impedance. Achieving this so-called critical coupling was very important to achieving high gain with a single stage amplifier. Figure 6 shows three gain measurements with different coupling capacitors and demonstrates overcoupling, undercoupling and critical coupling.

Figure 8: Gain measurement with different coupling capacitors. The three curves show overcoupling (blue) undercoupling (black) and critical coupling (red).

After achieving sufficient gain, several devices were measured at temperatures between 4.2 K and 30 mK. The results are shown in Figure 6. As seen before, there is a temperature below which the noise temperature of the amplifier no longer decreases. The ultimate noise temperature measured was roughly 50 mK, same as the previous experiment, except now the SQL was 40 mK instead of 25 mK. This represents the closest approach ever to the SQL. As mentioned earlier, the SNR technique allows a straightforward measurement of the frequency dependence of the noise temperature. The lowest noise temperature is not achieved on resonance, but actually slightly below. Figure 7 shows a measurement of the noise temperature and gain versus frequency for a SQUID amplifier at 30 mK. The lowest noise temperature is 47.1 ± 5 mK, representing the closest approach to the SQL.

Figure 9: Noise temperature as a function of physical temperature for two different microstrip amplifiers. The dashed line represents the SQL.

Figure 10: Frequency dependence of the noise temperature showing the closest approach to the SQL.

Since the lowest noise temperature is above the SQL, a follow-up measurement will be required to determine if the limit is still hot electrons in the shunt, or a fundamental limit of the amplifier itself. This measurement consists of measuring the flux noise at kHz frequencies and looking for a similar flattening at low temperatures. Since the SQL at kHz frequencies is essentially 0, any flattening would have to be due to an effect which is not related to the quantum limit such as hot electrons.

Exit Plan

The exit plan of this LDRD project involves funding for projects in desperate need for ultra-low-noise microwave amplifiers in narrow-band measurements. The primary application will be in a planned upgrade to the Axion Dark-Matter Experiment

(ADMX) situated at LLNL. The primary technical hurdle for the upgrade was the demonstration of working SQUID amplifiers. This LDRD produced a demonstration of working amplifiers which was pivotal for the decision by the DOE Office of Science to fund the upgrade proposal in FY04.

A second application of these amplifiers was developed during the course of this project. One of the most promising avenues for demonstrating a Quantum Computer is the readout of charge qubits using a Single Electron Transistor. A fast method for reading out charge qubits has been developed which requires a low-noise microwave amplifier. This so-called rf-SET is an almost ideal application of the microstrip SQUID amplifier. This LDRD project spawned a number of university collaborations with the goal of improving the charge sensitivity of the rf-SET using a microstrip SQUID amplifier. Most of these collaborations (Yale, U. New South Wales, Maryland, Chalmers...) are working on projects with national security applications, opening the door for NSA funding to continue in this direction. The first ever measurement of the rf-SET using a microstrip SQUID as a post-amplifier is shown in Figure 11. The amplifier and tank circuit were not well-matched, but the charge sensitivity was still improved by more than a factor of 2.

Figure 11: First measurement of charge sensitivity using a microstrip SQUID as a postamplifier. The charge sensitivity is determined by the SNR of the two sideband peaks.

Summary

This project produced the lowest noise temperature amplifiers ever produced, both in absolute terms and in relation to the Standard Quantum Limit. Being an order of magnitude lower in noise than the best HFET devices available, they are of great interest to a number of groups. Potential applications are numerous, from dark-matter searches to national security applications in Quantum Information Processing. Collaborations started during this project are continuing with the goal of single-spin detection using the rf-SET.

Publications are forthcoming covering both the experimental results and the theoretical modeling. The most important publication with the noise temperature results will appear after the low frequency follow-up experiment. The other

publications in production cover the input impedance measurements and the resulting transmission line models.

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