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A 300-mK Test Bed for Rapid Characterization of Microwave SQUID Multiplexing Circuits

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Abstract

Microwave SQUID multiplexing is a promising technique for multiplexing large arrays of transition edge sensors. A major bottleneck in the development and distribution of microwave SQUID multiplexer chips occurs in the time-intensive design testing and quality assurance stages. To obtain useful RF measurements, these devices must be cooled to temperatures below 500 mK. The need for a more efficient system to screen microwave multiplexer chips has grown as the number of chips requested by collaborators per year reaches into the hundreds. We have therefore assembled a test bed for microwave SQUID circuits, which decreases screening time for four 32-channel chips from 24 h in an adiabatic demagnetization refrigerator to approximately 5 h in a helium dip probe containing a closed cycle ^{3}He sorption refrigerator. We discuss defining characteristics of these microwave circuits and the challenges of establishing an efficient testing setup for them.

Keywords Microwave multiplexing · Screening · Transition edge sensor

1 Introduction

In recent years, success in the use of transition edge sensors (TESs) for both bolometry [1] and calorimetry [2] has heightened demand for larger and faster arrays of these devices. The pixel count and pixel speed of TES arrays are limited by the need for multiplexed readout [3]. One multiplexing scheme, which provides the bandwidth necessary

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for future arrays, is microwave SQUID multiplexing [4,5]. In this readout technique, changes in current through the TES circuit are sensed by an RF-SQUID, which inductively loads a superconducting microwave resonator. When the TES absorbs a photon, the resonator experiences a change in its resonance frequency. The shift can be detected as a change in the amplitude and phase of a transmitted probe tone at the resonance frequency. With multiple resonators coupled to a common microwave feedline, many sensors can be read out simultaneously using a superposition of tones. This allows hundreds of pixels to be read out on a single pair of coaxial cables.

These microwave SQUID multiplexer chips contain lithographically patterned niobium resonators which become superconducting around 9 K. However, microwave loss remains significant in these devices down to much lower temperatures [6,7], in accordance with the exponential suppression of the quasiparticle population which goes as $e^{-T_c/T}$, only becoming acceptable below approximately 500 mK (see Fig. 1). Cooling chips to such temperatures for screening and research purposes is time- consuming and requires specialized cryogenics. To minimize the time and resources devoted to screening, a helium dip probe with an enclosed ^{3}He sorption refrigerator, originally built at Princeton University for DC testing [8], was modified for efficient testing of microwave circuits.

The rise in demand for microwave SQUID multiplexing chips has resulted in a need for screening large numbers of chips and pursuing new chip designs. The need to screen 1000 multiplexer chips in the next two years for the Simons Observatory [9] is one example of a project that will require a new testing infrastructure. The probe described here can perform high-throughput screening and prevent this process from monopolizing other cryostats. Beyond quality assurance, this probe can help to shorten the design cycle for these chips, which typically consists of a week of design, a week of fabrication and at least 2 weeks of testing. Testing for design flaws directly after fabrication can significantly shorten this cycle and expedite the development process.

2 Characterizing Microwave Circuits

It is beneficial to screen multiplexer chips before sending them to collaborators [10] or integrating them into an instrument. Additionally, it is important to test chips for design errors when developing chips for new applications. Testing chips involves checking for working resonators and SQUIDs as well as measuring important circuit characteristics. These characteristics include the frequency spacing of the resonances, internal quality factor (Q_i), coupling quality factor (Q_c) and resonator response to flux through the SQUID.

Variations or inaccuracies in resonance frequency spacing can lead to elevated cross talk between channels on the multiplexer response chip. Cross talk due to coupling through resonators' Lorentzian tails scales as $\frac{1}{16n^2}$ for n bandwidths between resonators. Resonators are typically spaced by 10 times their bandwidth to keep this type of cross talk to less than 1 part in 1000. Discrepancies between the assumed and actual electrical lengths of resonators on the chip can lead to nonuniformities in frequency spacing and greater cross talk between resonators.

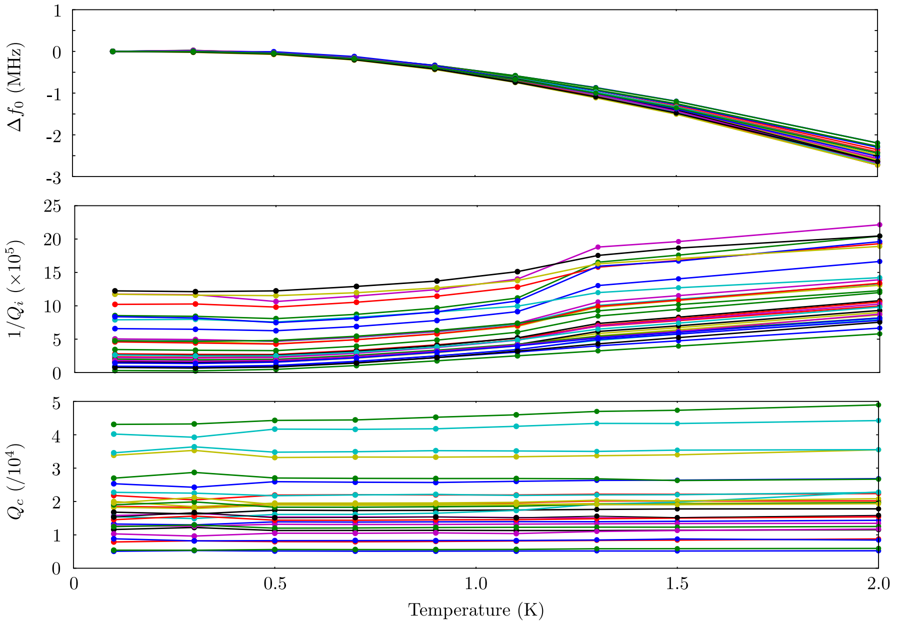

Fig. 1 Resonance frequency shift, internal Q and coupling Q of several different resonators (each a different curve) as a function of temperature. These data were measured in an ADR and indicate that these important parameters can be measured at temperatures up to 500 mK without changing dramatically from their values at the lower temperatures used for readout scenarios (Color figure online)

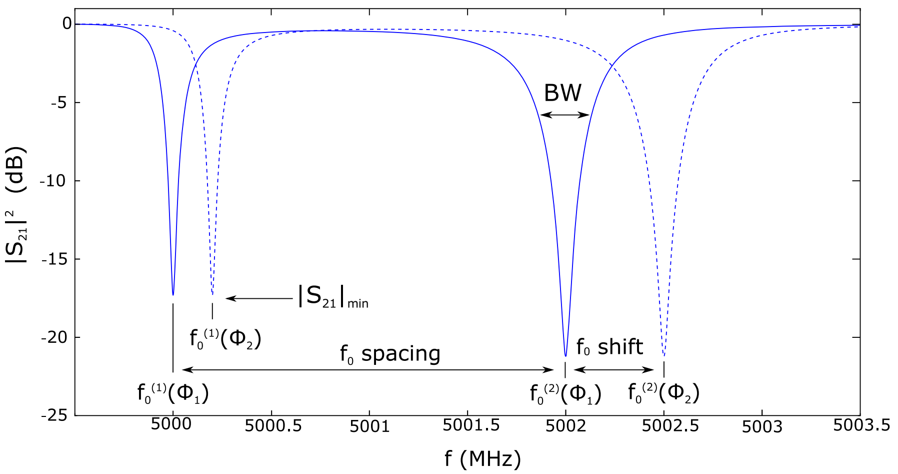

Fig. 2 Model of an $|S_{21}|$ measurement. The dashed line represents a measurement of the same two resonators with a different amount of flux (Φ) through the SQUIDs. Measurements are taken at approximately 20 different values of flux per resonator. This will provide the maximum f_0 shift, and other parameters can be averaged over all of the flux points (Color figure online)

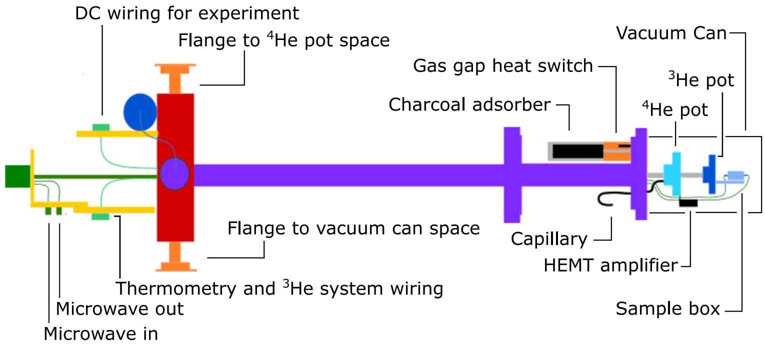

Fig. 3 Diagram of the super rapid dip probe. A vacuum can enclose the ^{4}He (1 K) pot, the ^{3}He (300 mK) pot and the sample boxes, and the probe is submerged in liquid helium to a level somewhere above the capillary (Color figure online)

The total quality factor Q and its components Q_c and Q_i can be extracted from microwave transmission (S_{21}) versus frequency data. The internal quality factor, Q_i, is inversely proportional to the amount of power dissipated in the resonator, $P_{diss} \approx P_{in}\frac{Q_{tot}}{Q_i}$, with P_{in} being the power incident on the resonator. This can be extracted from the minimum S_{21} value (see Fig. 2) with knowledge of the coupling quality factor, Q_c. $Q_i > 3Q_c$ is considered satisfactory because the effective size of the signal used for readout goes as $1 - \frac{Q_c}{Q_i}$. The coupling Q (Q_c) depends on the resonator's capacitative coupling to the microwave feedline and is typically the limiting Q in the system and therefore the factor which defines resonator bandwidth.

The system's response to flux through each SQUID needs to be characterized to determine functionality of the resonators in a readout scenario. Each chip has a common flux bias line which allows the user to change the magnetic flux through the SQUIDs, yielding a periodic response from the resonators. The SQUID response is measured as the peak-to-peak shift of the resonator's resonance frequency. Ideally, this value should match the resonator bandwidth, to maximize SQUID response without saturation.

Measurements of these critical quantities were taken to determine their temperature dependence. Figure 1 shows the results of these measurements. As expected, Q_c had very little dependence on temperature. Frequency shift and internal loss both exhibit changes down to about 500 mK. The results of Fig. 1 show that although these chips must still be cooled below 500 mK, they can be tested in a less specialized system with a higher base temperature than the large adiabatic demagnetization refrigerators (ADRs) used for testing TESs and the complete readout system.

3 Measurement Setup

To perform the necessary measurements efficiently and without using a lower base temperature system already dedicated to another purpose, a helium dip probe containing a ^{3}He sorption refrigerator was selected. With a base temperature of 300 mK, it meets the criteria discussed above for measurement temperature. The system can achieve base temperature in 2–3 h, making it an excellent platform for rapid chip testing.

The apparatus consists of a ^{3}He sorption refrigerator, backed by a pumped ^{4}He stage, in a compact liquid helium dip probe (see Fig. 3). A vacuum can encloses the ^{4}He (1 K) and ^{3}He (300 mK) stages and contains approximately one torr of helium exchange gas to help cool the inner stages to 4 K. The cooldown process begins with a precooling step in which the probe is vapor-cooled at the top of a liquid ^{4}He dewar for at least 45 min. This is followed by submersion of the probe in liquid ^{4}He. A small capillary connecting the bath to the ^{4}He pot allows a small flow of ^{4}He into the pot, and after the pot reaches 4 K a room-temperature roughing pump attached to the pot's vacuum space pumps on this helium to bring the stage to its base temperature of approximately 1.4 K.

The closed ^{3}He system consists of a pot connected to a small space containing a charcoal adsorber via a tube which runs through the ^{4}He pot. The charcoal can be thermally connected to the ^{4}He bath via a gas-gap heat switch. To begin a ^{3}He cooldown cycle, this charcoal is heated to about 30 K, causing desorption of ^{3}He and releasing a significant amount of gas into the closed ^{3}He system. The 1.4 K temperature of the ^{4}He pot then begins to condense ^{3}He into the ^{3}He pot. After the charcoal has released most or all of its helium, the gas-gap heat switch is closed and the charcoal's temperature begins to drop. The charcoal then becomes a ^{3}He pump which sequesters any gaseous ^{3}He atoms that come in contact with its large surface area. This pumping action drives the ^{3}He pot down to its base temperature of 300 mK via evaporative cooling. The current base temperature of this stage with the HEMT amplifier on is 400 mK, and the hold time at this temperature is about 3 h with the HEMT amplifier on.

For the microwave transmission line, 0.86-mm-diameter CuNi coaxial cable is run from room temperature to the ^{4}He pot, where it is heat sunk with a 20-dB attenuator. A 10-cm section of CuNi coaxial cabling connects this stage to a sample box on the ^{3}He stage, and a 10-cm section of NbTi cabling connects the output of the box to a HEMT amplifier heat sunk at the ^{4}He pot. Another CuNi coaxial cable carries the output signal to room temperature. The sample box consists of a microwave launch board and microwave multiplexing chip, with a low-frequency circuit board for routing flux ramp wiring and miscellaneous other inputs to the chip. The CuNi coaxial cable has low thermal conductivity, making it a good choice for connecting room-temperature microwave elements to those thermally connected to the ^{4}He pot at 1 K. The NbTi cable has about half of the thermal conductivity of the CuNi, and very low loss when it is superconducting, making it the optimal choice for connecting the amplifier on the ^{4}He pot to the low noise signal coming out of the box on the ^{3}He pot. The HEMT amplifier used here provides about 30 dB of gain to the signal coming out of the box and has a noise temperature of around 3 K, which helps to reduce measurement time.

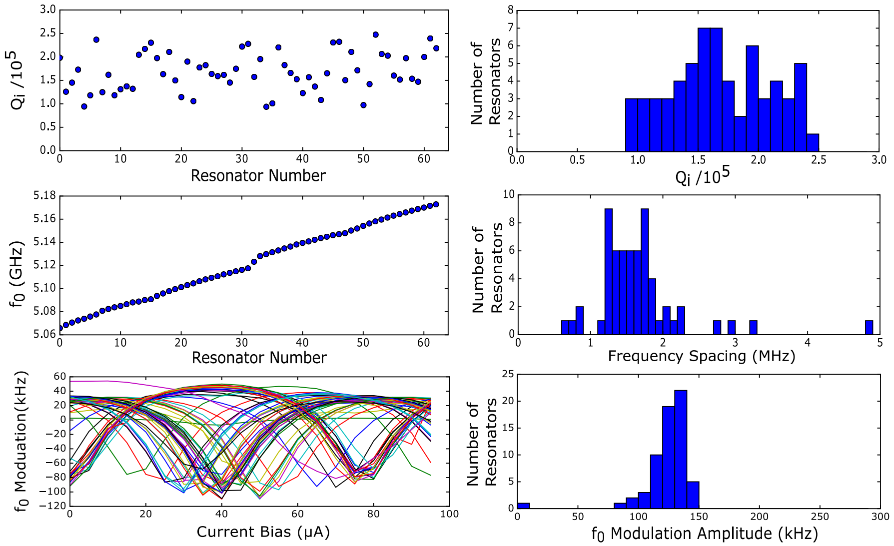

Fig. 4 Data obtained from screening a 64-channel multiplexer chip. All data were obtained at 400 mK. One channel did not respond to flux through the SQUID, and one channel was not included in this survey because it was too close in frequency to another resonator (Color figure online)

4 Results and Future Work

We have determined that temperatures below 500 mK are adequate for screening microwave multiplexer chips and developed a ^{3}He sorption refrigerator-backed testing platform to rapidly perform microwave measurements in that regime. The probe has been successfully used to measure the important parameters discussed above on several different types of microwave multiplexer chips. To gather the necessary information, S_{21} versus frequency data is obtained for each resonator at approximately 20 values of flux through the SQUIDs, spanning at least one period of the response. This provides information about the amplitude of the resonance frequency shift and the changes in the quality factors of the resonators as a function of applied flux. The measurement process takes about a minute per resonator depending on how finely the vector network analyzer is sampling in frequency. Each chip contains either 32 or 64 resonators, and up to four chips can be cooled at once in the probe. Given the hold time of the lowest temperature stage, the ^{3}He system would need to be recycled after screening about 180 channels, which adds another half hour to the total screening time.

Figure 4 shows an example of results from a chip design with 64 channels, having twice the physical packing density and closer frequency spacing than the previous 32-channel chips. These results came after the first 64-channel design was tested in the probe and found to have nonuniform resonance spacing. A new model for the electrical length of the resonators was proposed based on the results of this test, and measurements like the one above suggest that it was effective. More in-depth studies on the accuracy of this model are planned.

Goals for the future with this probe include achieving a lower base temperature for measurement and decreasing the total time per cooldown. If the heat load on the lowest stage produced by the HEMT can be minimized, it will both ensure that we are well below 500 mK for measurement and increase the hold time of this stage. Increasing the hold time should help decrease total cooldown time and allow us to realistically push for two measurement cycles per day.

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