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# Low Noise Radio Frequency Amplifiers Based on Niobium dc SQUIDS with Microstrip Input Coupling

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*Certain applications, such as axion detectors, require radio frequency (rf) amplifiers with noise temperatures well below 1 K. This need cannot be met with current semiconductor amplifiers, which have minimum noise temperatures of 2 or 3 K, even when cooled to liquid helium temperatures or below. Lower noise temperatures can be obtained by using a dc SQUID as an rf amplifier. We have carried out experiments using a dc SQUID to amplify rf signals that were coupled to one end of the microstrip which is formed by the input coil of the SQUID and the SQUID washer. We achieved gains of up to 20 dB in the frequency range of 100 MHz to 900 MHz. With a bath temperature of 4.2 K and a room temperature post-amplifier, the system noise temperature ranged from 0.5 K  $\pm$  0.3K at 80 MHz to 3.0 K  $\pm$  0.7 K at 500 MHz. Particularly at frequencies above 350 MHz, however, the measured noise temperature was determined by the noise of the semiconductor post-amplifier ( $T_n \approx 80K$ ) rather than the SQUID. When we cooled the SQUID down to 1.8 K and used a cooled post-amplifier consisting of a hetero-field effect transistor (HFET) with a noise temperature of 12 K, we measured a system noise temperature of 0.3 K  $\pm$  0.15 K at 250 MHz and 0.25 K  $\pm$  0.15 K at 365 MHz.*

## 1. Introduction

Experiments in fundamental physics, such as axion detectors [1] or gravitational wave detectors, require pre-amplifiers with ever-increasing sensitivity. DC Superconducting Quantum Interference Devices (SQUIDs) are promising as sensors to meet these requirements. While conventional SQUIDs can readily be used for gravitational wave detectors, this is not the case for an axion detector, because of the high operating frequency, typically 0.5 - 1 GHz.

Up to now, rf amplifiers have virtually always involved semiconductors as active elements. Recently their noise temperatures have been substantially reduced by the use of hetero-field effect transistors (HFETs, sometimes also called high electron mobility transistors or HEMTs). Noise temperatures of about 2 K can be achieved with these devices in the 100 MHz region [2], when the amplifier is cooled to liquid helium temperatures. Cooling the amplifier to still lower temperatures does not reduce the noise temperature further because of intrinsic noise sources in the HFET. Generally speaking, the minimum noise temperature is achieved with the amplifier at about 10 K. It is also questionable whether the channel of the HFET can be cooled to, say, 4 K because of the relatively large power dissipation. Although it seems possible to achieve lower noise temperatures by using pseudomorphic HFETs with even smaller gate lengths than currently employed, there may be problems of electrical instability. It turns out that because of the high transit frequency of these HFETs, several tens to hundreds of GHz, coupling the input of the HFET to a lower frequency matching circuit can cause self-oscillations at very high frequencies. These oscillations usually increase the noise temperature of the amplifier without affecting the gain very much, so that in

normal operation it is difficult to determine whether the increased noise is caused by the signal source or by the amplifier itself.

At least at frequencies of several hundred MHz, better results can be obtained by using a dc SQUID as an rf amplifier. For this device, the noise temperature continues to decrease linearly with the bath temperature as it is lowered to about 0.1 K [3]. This is because the power dissipation in the SQUID is orders of magnitude lower than for a HFET, and because the only intrinsic noise source at frequencies above a few hertz is Nyquist noise in the shunts of the junctions.

The conventional dc SQUID amplifier [4,5] consists of two resistively shunted Josephson junctions incorporated into a square washer of inductance  $L$  over which is deposited an  $n$ -turn superconducting input coil with inductance  $L_i \approx n^2 L$  [6]. The SQUID is current- and flux-biased so that the flux to voltage transfer function  $V_\Phi = \partial V / \partial \Phi$  is close to a maximum. A signal current  $I_i$  in the input coil generates a flux  $M_i I_i$  in the SQUID and an output voltage  $V_o \approx M_i I_i V_\Phi$  across it;  $M_i$  is the mutual inductance between the input coil and the SQUID. Unfortunately, the conventional flux locked loop operation of the SQUID, which is used to linearize its transfer function, cannot be realized for the required high frequency operation. This means that the amplitude of the input signal is limited to currents which produce flux changes in the SQUID of less than about  $\Phi_0/4$ . Fortunately, in most high frequency applications the integrated input signal amplitude is much less than  $\Phi_0/4$ . If a SQUID with a flux noise of  $10^{-6} \Phi_0/\sqrt{\text{Hz}}$  is used, one can still achieve a dynamic range of nearly 120 dB/ $\sqrt{\text{Hz}}$ . Larger flux changes, caused, for example, by 50 or 60 Hz fields, can easily be compensated by operating the SQUID in a slow flux locked loop, which maintains the flux bias at odd multiples of  $\Phi_0/4$ .

Using a SQUID amplifier with an input circuit tuned to 93 MHz, Hilbert and Clarke [4] achieved a gain of about 18 dB and a noise temperature of about 1.5 K for a bath temperature of 4.2 K. Above 100 MHz however, parasitic capacitance  $C_p$  between the input coil of inductance  $L_i$  and the SQUID produced self-resonances [7] and severely reduced the gain. The  $L_i C_p$ -parallel resonance can be moved to higher frequencies by reducing the number of turns, reducing their width or increasing the thickness of the insulating layer separating the coil from the SQUID. However, reducing the number of turns may reduce the mutual inductance between the coil and the SQUID to a value that is too small to produce a satisfactory gain. For the same reason the size of the SQUID hole should be made as large as possible (for example, 200 mm  $\times$  200 mm).

Takami *et al.* [8] have described a SQUID amplifier in which the input circuit was tuned to the desired resonant frequency by adjusting the thickness of the insulating layer between the SQUID and coil, thus varying the parasitic capacitance. To match the high resistance of the parallel  $L_i C_p$  circuit to the 50  $\Omega$  signal source, the signal was coupled to the coil by a small (3 pF) capacitor. This scheme leads to a relatively high quality factor  $Q$  of the  $L_i C_p$  circuit, a high input current at the resonant frequency and thus a high gain. They measured gains of up to 23 dB at 150 MHz, and a noise temperature of about 0.7 K for a bath temperature of 4.2 K. Unfortunately, the high  $Q$  of the resonant circuit decreases the bandwidth to about 1 % of the operating frequency, which for most applications is much too small. Increasing the bandwidth by decreasing the  $Q$  decreases the gain. Nevertheless, for narrow band applications such as NMR, this coupling scheme provides a high gain, low noise amplifier for frequencies of up to 200 MHz.

If operation at higher frequencies is required, the parasitic capacitance either has to be reduced or its influence removed with a resonance technique. Reducing the capacitance can be achieved by placing the input coil inside the SQUID hole. Because of the decreased coupling between coil and SQUID, however, the gain is quite small. Tarasov *et al.* [9] have made a SQUID amplifier in this way, and reported gains of 8 dB at 700 MHz and a noise temperature of about 1.5 K. In an alternative design, Prokopenko *et al.* [10] used a SQUID amplifier with a series resonant input circuit to achieve a gain of 10 dB at 3.8 GHz and a noise temperature of 5 K.

## 2. A SQUID amplifier with microstrip input coupling

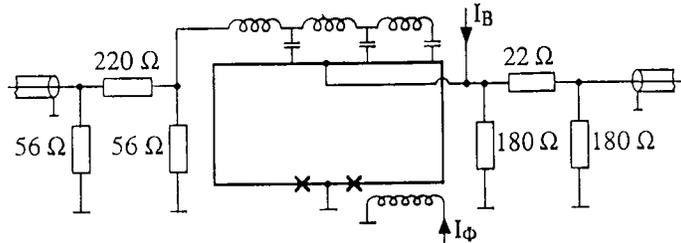
An alternative way of achieving high gains and low noise temperatures at high frequencies is to take advantage of the parasitic capacitance, rather than to reduce it. We have developed a new configuration in which the input coil is used as a microstrip resonator. The input signal is no longer coupled to the two ends of the input coil, but rather between one end of the coil and the SQUID loop, which acts as a ground plane for the coil. The microstrip resonator is thus formed by the inductance of the input coil and its ground plane and the capacitance between them. In this configuration, the parasitic capacitance no longer prevents currents from flowing through the coil.

For the case in which the impedance  $Z_s$  of the source coupled to one end of the microstrip is larger than its characteristic impedance  $Z_0$  and the other end of the input coil is left open, the fundamental resonance occurs when the length  $\ell$  of the microstrip is equal to one-half the wavelength of the rf signal. In this mode, the microstrip resonator is analogous to a parallel tuned circuit and, neglecting losses in the microstrip and the SQUID, one calculates a quality factor  $Q = \pi Z_s / 2Z_0$  [11]. At the resonant frequency the current fed into the resonator is amplified by  $Q$ , producing a magnetic flux that is coupled into the SQUID via a mutual inductance  $M_s = \alpha(LL_s)^{1/2}$ , where we assume  $L_s$  to be the microstrip inductance and  $\alpha$  the coupling coefficient. One selects the resonant frequency by choosing the length of the coil appropriately. The quality factor  $Q$ , which determines the bandwidth of the amplifier, can be varied by selecting the characteristic impedance of the microstrip, that is by choosing an appropriate width of the turns of the coil and thickness and dielectric constant of the insulating layer between the coil and SQUID. One has to keep in mind, however, that reducing  $Q$  will increase the bandwidth and lower the gain, since the resonant current amplification is proportional to  $Q$ .

We estimate the parameters for the microstrip using formulas for the linear case [12], although we note that crosstalk between turns and the presence of the SQUID hole may have a substantial influence. With this proviso, we estimate the inductance  $L_0$  and capacitance  $C_0$  per unit length for typical SQUID geometries and materials to be  $L_0 = \mu_0(d+2\lambda)/w \approx 200$  nH/m and  $C_0 = \epsilon\epsilon_0 w/d \approx 1$  nF/m; here  $\lambda \approx 150$  nm is the penetration depth for sputtered niobium films and  $\epsilon \approx 9$  is the dielectric constant for Si films. Thus the characteristic impedance for a typical input coil is  $Z_0 = (L_0/C_0)^{1/2} \approx 15 \Omega$  and the propagation velocity  $c = (L_0C_0)^{-1/2} \approx 0.25 c_0$ , where  $c_0 = 3 \times 10^8$  m/s. In this simplistic model, the fundamental resonance of the microstrip resonator occurs at a frequency  $c/2\ell$ , which is approximately 500 MHz for a typical SQUID having an input coil with about 40 turns. When the microstrip resonator is coupled to a 50  $\Omega$  signal source, the corresponding  $Q$  of the resonator is expected to be  $Q = \pi Z_s / 2Z_0 \approx 5$ , so that the -3 dB bandwidth is about 20 % of the operating frequency.

### 3. Measurement configuration

We have fabricated and operated a number of such SQUID amplifiers. We used conventional square-washer SQUIDs in our experiments, with inner and outer dimensions of  $0.2 \text{ mm} \times 0.2 \text{ mm}$  and  $1 \text{ mm} \times 1 \text{ mm}$ ; the 31-turn input coil had a width of 5 mm and a length  $\ell = 71 \text{ mm}$ . The SQUID loop and input coil were fabricated from niobium films and separated by a silicon film with a thickness  $d = 400 \text{ nm}$ . The estimated inductance of the SQUID was 320 pH, leading to the estimated values  $L_i = 300 \text{ nH}$  and  $M_i = 10 \text{ nH}$ . The critical current and shunt resistance per junction were typically  $5 \mu\text{A}$  and  $10 \Omega$ , and the maximum value of  $V_\Phi$  was about  $60 \text{ mV}/\Phi_0$ . At 4.2 K the white flux noise at low frequencies (10 Hz) was typically  $2.5 \times 10^{-6} \Phi_0/\sqrt{\text{Hz}}$ . We note that in this (conventional) SQUID configuration virtually the entire length of the input coil overlays the washer, which is at a uniform rf potential.



*Fig. 1 Circuit used to determine the gain of the microstrip SQUID, which is shown with counter-electrode grounded.  $I_B$  is the current bias and  $I_\Phi$  provides the flux bias.*

We used the circuit shown in Fig. 1 to measure the gain of our microstrip SQUID amplifier. The current and flux biases were supplied by batteries that could be floated relative to the system ground. The flux was generated by a copper coil. It was necessary to use a cold attenuator of about 20 dB to prevent noise produced by the room temperature signal generator from saturating the SQUID. The attenuator also presented an impedance of  $50 \Omega$  to both the input coaxial line and the microstrip. This impedance matching largely eliminated standing waves on the coaxial line. It also helped to minimize errors in the measured gain due to impedance mismatch. For the same reasons, a cold 5 dB attenuator coupled the output of the SQUID to a low noise (80 K) preamplifier at room temperature. The gain of the system excluding the SQUID was calibrated by disconnecting the SQUID and connecting together the input and output attenuators. All measurements of the gain of the SQUID amplifier were referred to the baseline so obtained.

### 4. Gain Measurements

Since the conventional washer SQUID is an asymmetric device (the two Josephson junctions are situated close together rather than on opposite sides of the SQUID loop), one can either ground the washer or ground the counter electrode close to the Josephson junctions. Using the washer as ground plane for the input coil suggests one should ground the washer. However, it is also possible

to ground the counter electrode and have the washer at output potential. In this case, depending on the sign of  $V_{\Phi}$ , one can obtain either a negative or positive feedback from the output to the input. This is shown in Fig. 2, where we plot the measured gain of a SQUID amplifier with a 6-turn input coil as a function of frequency. The input signal was connected between the innermost turn of the coil and ground. When we grounded the washer, we measured a gain of about 14 dB at 635 MHz, with a Q of about 10. On the other hand, when we grounded the counter electrode of the junctions and allowed the square washer to float at output potential, for the sign of the transfer function which we denote as  $V_{\Phi}^+$  the gain increased to 18 dB at 620 MHz and the Q increased to about 31. Conversely, for the other sign of the transfer function,  $V_{\Phi}^-$ , the gain is greatly diminished with no evidence of a resonance.

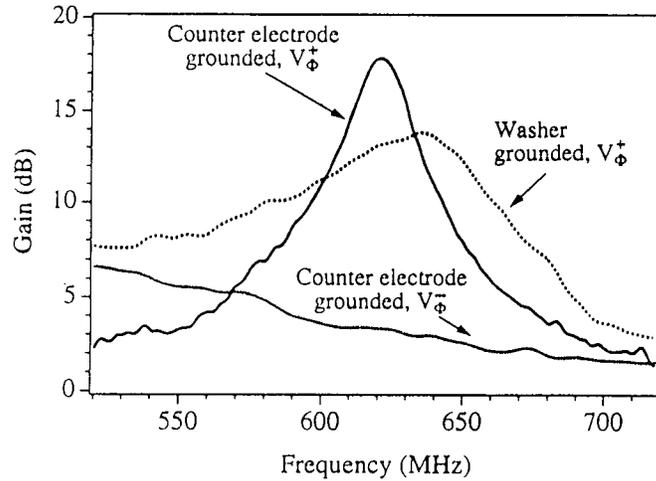


Fig. 2 Gain vs. frequency for microstrip SQUID with a 6-turn input coil, and signal applied to innermost turn. Data are for  $V_{\Phi}^+$  and  $V_{\Phi}^-$  with counter electrode grounded, and for  $V_{\Phi}^+$  with washer grounded.

To achieve the maximum possible gain, we mostly operated our SQUID amplifiers with the counter electrode grounded and the washer at output potential. When we measured the gain as a function of frequency, for SQUIDs with 31-turn coils with a total length of 71 mm we obtained a resonant frequency of about 200 MHz (see Fig. 3). The signal was connected between the innermost turn of the input coil and ground, and the outermost turn was left open. To achieve higher resonant frequencies, and thus higher gains at higher frequencies, we progressively shortened the length of the coil.

As is shown in Fig. 3, a coil length of 33 mm results in a resonant frequency of 310 MHz, and a 7 mm long coil yields a maximum gain at 620 MHz. The measured resonant frequencies are significantly lower than we expect from our *a priori* predictions. In Fig. 4 we plot the resonant frequencies vs. the coil length together with the fitted curve  $[1.49 \times 10^4 / (\ell + 16)]$  MHz, where  $\ell$  is in millimeters. There are two reasons for the deviation from the predicted behavior: First there is a non-negligible parasitic inductance from the wiring between the cold attenuator and the coil, which consists of five 4-mm long wires in parallel bonded to a 3-mm long niobium line on the SQUID.

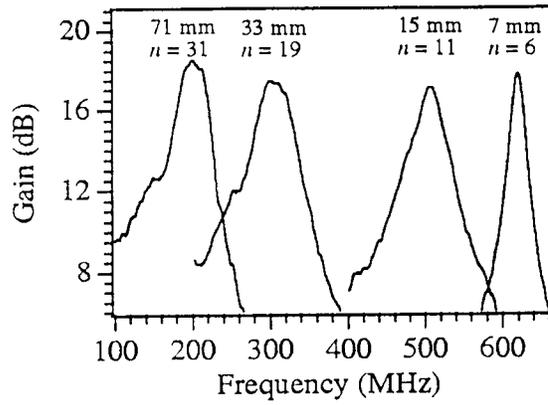


Fig. 3 Gain vs. frequency for four coils on the same SQUID, with signal applied to the innermost turn. Data are for counter electrode grounded and  $V_{\phi}^+$ .

This wiring increases the electrical length of the microstrip resonator and thus decreases its resonant frequency. In addition, both the SQUID hole and crosstalk between turns influence the inductance per unit length of the coil. To investigate these mechanisms we made a 195:1 scale model of the SQUID with a 31-turn input coil patterned on one side of a printed circuit board and a square washer containing a slit on the reverse side. With the hole in the washer and the slit covered with a copper sheet, the resonant frequencies of the coil, and of cut segments of the coil, were in good agreement with our estimates. When we removed the copper sheet, however, the resonant frequency for the fundamental  $\lambda/2$  mode dropped by a factor of about 3. The scale model also exhibited dispersion, since the higher order resonances were not affected by the presence or absence of the copper sheet.

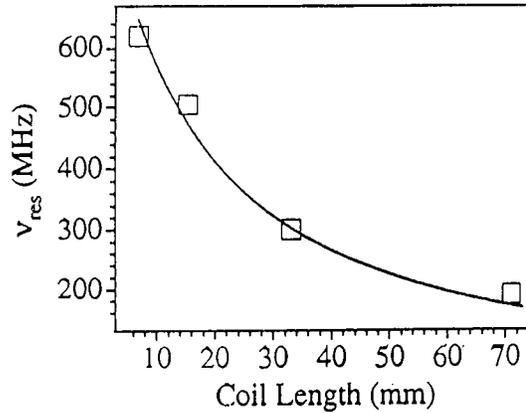


Fig. 4 Resonant frequencies for the four lengths of microstrip shown in Fig. 3; fitted curve is  $[1.49 \times 10^4 / (\ell + 16)]$  MHz, where  $\ell$  is in millimeters.

The observed reduction of the resonant frequency by a factor of three in the presence of the model SQUID hole and slit is in good agreement with our observation on the actual SQUID, where the resonant frequency is three times lower than our prediction for a linear microstrip. The SQUID hole and slit thus significantly slow the wave on the input coil. This mechanism also has a non-negligible effect on the characteristic impedance of the microstrip, which is now close to  $50 \Omega$  rather than the predicted  $15 \Omega$ .

## 5. Noise measurements

We measured the noise temperature of a number of SQUID amplifiers. As a noise source we used a  $64 \Omega$  surface mounted device (smd) resistor embedded in epoxy and connected via a piece of stainless-steel coaxial cable to the input of the SQUID amplifier. We could raise the temperature of the resistor by passing a current through a length of manganin wire wound tightly around it. This resistor acts as a white noise source of well-defined noise power. Results of noise measurements performed using this linear noise source should be more accurate than those using an avalanche diode or a SIS tunnel junction. Since we expect our amplifiers to have low noise temperatures, it is sufficient for all measurements to raise the resistor temperature to about 10 K. By changing the temperature of the  $64 \Omega$  resistor between 4.2 K and 10 K and noting the corresponding change in the system noise with a spectrum analyzer, we calculated the noise temperature of the SQUID amplifier.

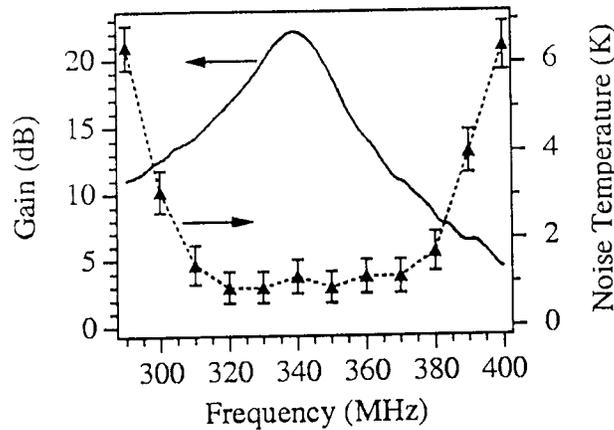


Fig. 5 Gain and noise temperature vs. frequency for 11-turn SQUID.

Figure 5 shows the gain and noise temperature for a 11-turn SQUID. On resonance, the gain is 22 dB and the noise temperature  $T_N = 0.9 \text{ K} \pm 0.3 \text{ K}$ . We note that this is the overall system noise temperature, which includes a 0.4 K contribution of the room temperature post-amplifier. As the frequency moves away from resonance, the gain falls and the noise temperature increases, presumably due to the contribution from the post-amplifier.

For a device with a resonant frequency of 500 MHz and a gain of 17 dB, we measured a noise temperature of  $3.0 \text{ K} \pm 0.7 \text{ K}$ , including a contribution of about 1.5 K from the post-amplifier. In order to reduce the noise contribution of the post-amplifier, we have built a single-stage amplifier using a HFET (Fujitsu FHX 13LG), which we operated at 4.2 K. The lowest noise temperature we achieved with this amplifier was about 12 K. Unfortunately, because of a high-Q resonant input matching network, the bandwidth over which we obtained the low noise temperature was only a few MHz. We have measured two SQUID amplifiers using this post-amplifier, one with a resonant frequency of 250 MHz and a second with 365 MHz. When we cooled the SQUIDs to about 1.8 K, the gain increased slightly, and we achieved a system noise temperature of about  $0.3 \text{ K} \pm 0.1 \text{ K}$  and  $0.25 \text{ K} \pm 0.1 \text{ K}$ , respectively. To our knowledge, these are the lowest noise temperatures achieved in this frequency range.

## 6. Conclusion

We have demonstrated a novel SQUID amplifier in which the signal is coupled via a microstrip resonator. For a bath temperature of 4.2 K and a room temperature post-amplifier, we achieved gains of about 20 dB and amplifier noise temperatures of between 0.5 K and 1.5 K for resonant frequencies of 100 MHz to 600 MHz. For a bath temperature of 1.8 K and a cooled post-amplifier, the noise temperature was reduced to about 0.3 K. Several questions remain, however, about this mode of operation, including the exact nature of the coupling between the microstrip and the SQUID, the way in which the SQUID inductance lowers the resonant frequency of the microstrip, and the details of the feedback mechanism when the counter electrode is grounded. Finally, we anticipate that these SQUID amplifiers operated at dilution refrigerator temperatures with a second SQUID as a post-amplifier will be quantum limited.

## 7. Acknowledgments

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