Progress in Superconductivity Vol.2 No.1 pp1-5 1 October 2000

INVITED PAPER

An Ultra Low-noise Radio Frequency Amplifier Based on a DC SQUID

Michael Mück[*,a], Marc-Olivier André[+,a], Darin Kinion[b] and John Clarke[a]
[a] *Department of Physics, University of California, Berkeley, CA 94720*
[b] *Lawrence Livermore National Laboratory, 7000 East Ave., Livermore, CA 94550*

Received 21 July 2000

Abstract

We have developed an extremely sensitive radio frequency amplifier based on the dc superconducting quantum interference device (dc SQUID). Unlike a conventional semiconductor amplifier, a SQUID can be cooled to ultra-low temperatures (100 mK or less) and thus potentially achieve a much lower noise temperature. In a conventional SQUID amplifier, where the integrated input coil is operated as a lumped element, parasitic capacitance between the coil and the SQUID washer limits the frequency up to which a substantial gain can be achieved to a few hundred MHz. This problem can be circumvented by operating the input coil of the SQUID as a microstrip resonator: instead of connecting the input signal between the two ends of the coil, it is connected between the SQUID washer and one end of the coil; the other end is left open. Such amplifiers have gains of 15 dB or more at frequencies up to 3 GHz. If required, the resonant frequency of the microstrip can be tuned by means of a varactor diode connected across the otherwise open end of the resonator. The noise temperature of microstrip SQUID amplifiers was measured to be between 0.5 K ± 0.3 K at a frequency of 80 MHz and 1.5 K ± 1.2 K at 1.7 GHz, when the SQUID was cooled to 4.2 K. An even lower noise temperature can be achieved by cooling the SQUID to about 0.4 K. In this case, a noise temperature of 100 mK ± 20 mK was achieved at 90 MHz, and of about 120 ± 100 mK at 440 MHz.

Keywords: SQUID, rf amplifier, microstrip, low noise

I. Introduction

Traditionally, most dc Superconducting QUantum interference Devices (SQUIDs) are used as utrasensitive detectors of magnetic flux at low frequencies, that is, below a few kilohertz, most notably for biomagnetic applications. In these applications, one operates the SQUID in a flux-locked loop to linearize the response of the SQUID, which is periodic in the applied flux with a period of one flux quantum, $\Phi_0 \equiv h/2e \approx 2.07\ W_b$. For some applications — an example is low-frequency nuclear magnetic resonance (NMR) and nuclear quadruple resonance (NQR) — one requires higher bandwidth, a need that can be met with a flux-locked loop at frequencies up to about 5 MHz. DC SQUIDs have been used at much higher signal frequencies, however, in an open loop configuration in which the input signal is required to be less than $\Phi_0/2$. Amplifiers with gains approaching 20 dB and noise temperatures of about 1 K have been operated successfully at frequencies of around 100 MHz [1] and used as sensitive detectors of NMR and NQR [2]. At still higher frequencies, parasitic capacitance between the superconducting input coil and the body of the SQUID causes the gain to drop substantially [1]. As a result, SQUIDs have not been competitive as

---

[1] * Corresponding author. Fax: +1 510 642 1304
email: mueck@uclink4.berkeley.edu

+ Current address: Moving Magnet Technology, Besancon, France cooled high electron mobility transistors [HEMTs] offer substantial gain and noise temperatures of a few kelvin [3].

However, further improvement of the recently developed axion detector [4] depends critically on the existence of amplifiers in the 1 GHz frequency range with noise temperatures at least one order of magnitude lower than can nowadays be achieved with semiconductors. This need spurred the development of a new approach to SQUID amplifiers in which the input coil deposited on the SQUID body is used as a resonant microstrip, thus making a virtue of the parasitic capacitance [5]. With this approach, gains of well over 20 dB at a frequency of 1.6 MHz and about 12 dB at 3 GHz and noise temperatures as low as 0.1 K have been achieved [6]. Furthermore, by using a cooled GaAs capacitance diode, the resonant frequency can be readily tuned over a range of nearly two [7].

II. The dc SQUID and the conventional SQUID amplifier

The dc SQUID consists of two Josephson junctions which are connected in parallel on a superconducting loop of inductance L. Each junction is in parallel with a resistance R, usually an external shunt, and a capacitance C. According to the resistively-shunted-junction model [8,9], the current-voltage (I-V) characteristics will be nonhysteretic provided $\beta_c = 2 I_0R^2C/\Phi_o \leq 1$, where I_0 is the critical current of each junction. When the SQUID is biased with a constant current (> 2 I_0), the voltage across the SQUID oscillates with period Φ_o as Φ is steadily increased. The bias current is adjusted to give the maximum voltage change, and the SQUID is operated on the steep part of the V-Φ curve where the flux-to-voltage transfer coefficient, $V_\Phi \equiv |(\partial V/\partial\Phi)_I|$, is a maximum. Thus, the SQUID produces an output voltage in response to a small input flux $\delta\Phi(<<\Phi_0)$, and is effectively a flux-to-voltage transducer.

The conventional dc SQUID amplifier consists of a dc SQUID with a square washer of inductance L over which is deposited an n-turn superconducting input coil with inductance $Li \approx n^2L$ — see Fig. 1 (a).

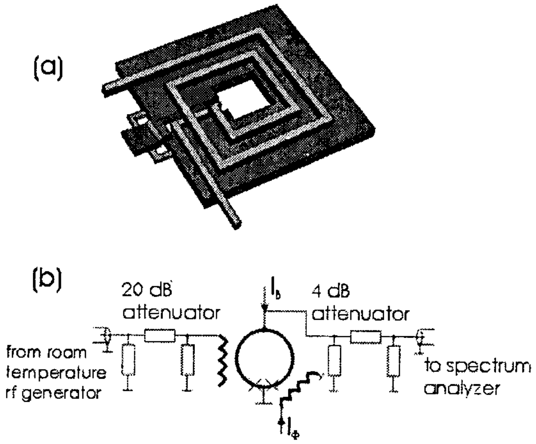

Fig.1 (a) Configuration a square washer SQUID, with overlaying spiral input coil. (b) Schematic diagram of configuration used to measure the gain of the microstrip SQUID.

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_iI_i in the SQUID and an output voltage $V_o \approx M_iI_iV_\Phi$ across it; M_i is the mutual inductance between the input coil and the SQUID. We note that in this kind of operation, the amplitude of the input signal is limited to currents which produce flux changes in the SQUID of less than $\Phi_o/4$.

Using a SQUID amplifier with an input circuit tuned to 93 MHz, Hilbert and Clarke [1] 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 and severely reduced the gain.

The L_iC_p-parallel resonance can be shifted to higher frequencies by reducing the number of turns, decreasing 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.

III. A SQUID amplifier with microstrip input coupling

Recently, we described a new configuration in which the input coil is used as a microstrip resonator [5]. 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. The microstrip resonator is analogous to a parallel tuned circuit and, neglecting losses in the microstrip and the SQUID, one calculates a quality factor $Q = \pi Z_{in}/2Z_0$. Here, Z_{in} and Z_0 are the impedance of the source and stripline, respectively. At the resonant frequency the current fed into the resonator is amplified by Q. One selects the resonant frequency by choosing the length of the coil appropriately.

We have fabricated and tested a number of such SQUID amplifiers. We used conventional square-washer SQUIDs in our experiments, with inner and outer dimensions of 0.2 mm x 0.2 mm and 1 mm x 1 mm; the individual turns of the input coil had a width of 5 μm. The SQUID loop and input coil were fabricated from niobium films and separated by a SiOx film with a thickness $d \approx 400$ nm. The estimated inductance of the SQUID was 320 pH. The critical current and shunt resistance per junction were typically 5 μA and 10 Ω, and the maximum value of V_Φ was about 60 $\mu V/\Phi_0$.

We used the circuit shown in Fig. 1(b) to measure the gain of our microstrip amplifier. The current and the flux biases were supplied by batteries that could be floated relative to the system ground. The flux was generated by a small copper coil. The Hewlett-Packard 8620C sweep oscillator was coupled to the microstrip via a 20 dB attenuator that prevented noise produced by the generator from saturating the SQUID. The attenuator also presented an impedance of 50 Ω 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, for most of our measurements a cold 4 dB attenuator coupled the output of the SQUID to a room-temperature postamplifier (MITEQ JS2-00100200-10-5P), which has a measured noise temperature of about 80 K. 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.

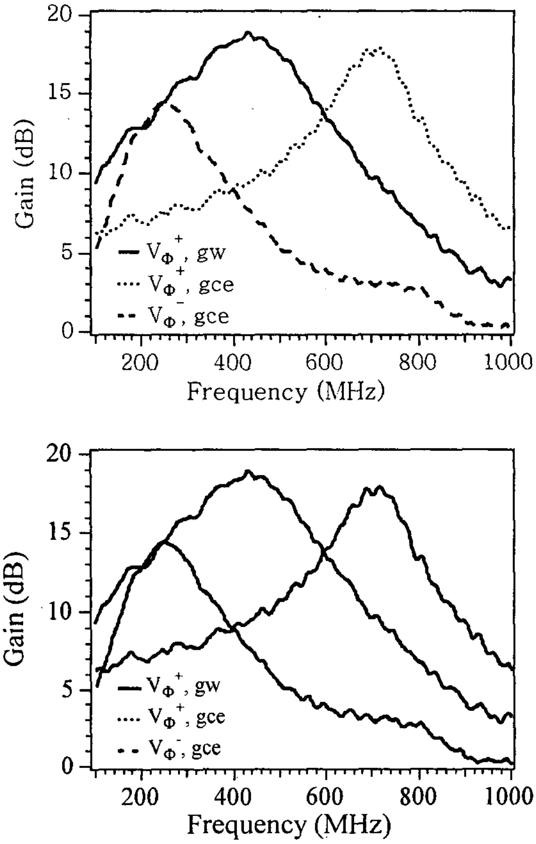

Fig. 2 Gain vs. frequency of a microstrip amplifier for grounded washer (solid: V_Φ^+) and grounded counter-electrode (dotted: V_Φ^+, dashed: V_Φ^-).

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, one achieves feedback from the output voltage generated on the washer to the input coil, via the capacitance between them. If the sign of V_Φ is such that the output voltage has the same sign as the input voltage, the feedback is positive; if the signs are opposite, the feedback is negative. We designate the flux-to-voltage transfer coefficients as V_Φ^+ and V_Φ^-, respectively.

The differences between the two cases, that is, for grounded washer or grounded counter electrode, are shown in Fig. 2, where we plot the measured gain as a function of frequency for a SQUID with a 11-turn input coil. The signal was connected between the innermost turn of the coil and ground. When we grounded the washer, we measured a gain of about 19 dB at 430 MHz, with a Q of about 1.7. On the other hand, when we grounded the counter electrode of the junctions and allowed the square washer to float at output potential, for V_Φ^+ the gain remained unchanged, but the frequency of maximum gain increased to 700 MHz and the Q increased to about 5. Conversely, for the other sign of the transfer function, V_Φ^-, the maximum gain occurred at about 300 MHz and the Q was about 4. We attribute these effects to feedback from the output voltage of the SQUID to the input via the distributed capacitance between the coil and the washer.

IV. Noise temperature measurements

We measured the noise temperature of several amplifiers. As a noise source, we used a 64 Ω resistor (51 Ω at room temperature) connected to the input of the microstrip via a length of stainless steel coaxial cable. The resistor was in thermal contact with a thermometer, an Allen-Bradley resistor, and 100 turns of manganin wire were wound around the combination. By passing a current through the manganin wire, we could increase the temperature of the 63 Ω resistor to a measured value T. Thus, the resistor provides a well-defined source of Nyquist noise power. To determine the noise temperature TN, we measured the output power of the SQUID with a spectrum analyzer, generally with the resistor at the bath temperature and at about 10 K.

Figure 3 shows the gain and noise temperature vs. frequency for a 31-turn SQUID; in this case there was no attenuator between the SQUID and the postamplifier. At the resonant frequency of 240 MHz, the gain is about 23 dB ≈ 200 and the system noise temperature 0.8 ± 0.3 K. The contribution of the postamplifier is about 80 K/200 ≈ 0.4 K, so that the intrinsic noise temperature of the SQUID microstrip amplifier is approximately 0.4 K. As the frequency moves away from resonance, the gain falls and the system noise temperature, which becomes dominated by the postamplifier, rises correspondingly. In the frequency range between 80 MHz and 1.7 GHz, the noise temperatures of such amplifiers ranged from 0.5 ± 0.3 K at 80 MHz to 1.6 ± 1.2 K at 1.7 GHz; in the latter case, a postamplifier contribution of 2.5 K has been subtracted.

While it is clear that the microstrip SQUID amplifier has a very low intrinsic noise temperature, it is also evident that the room temperature postamplifier makes a substantial contribution to the overall noise temperature. In order to reduce this contribution, we built a single-stage cryogenic amplifier using a heterostructure field effect transistor (HFET). The noise temperature of these HFET postamplifiers was about 4 K at 90 MHz and 7 K at 640 MHz. When we cooled our SQUID amplifiers to 1.8 K and used the HFET postamplifier, we achieved a system noise temperature of 0.30 ± 0.05 K for a SQUID amplifier at 250 MHz, and 0.28 ± 0.06 K for another at 365 MHz.

To achieve an even lower noise temperature, we cooled the SQUIDs to 0.4 - 0.5 K using a closed-

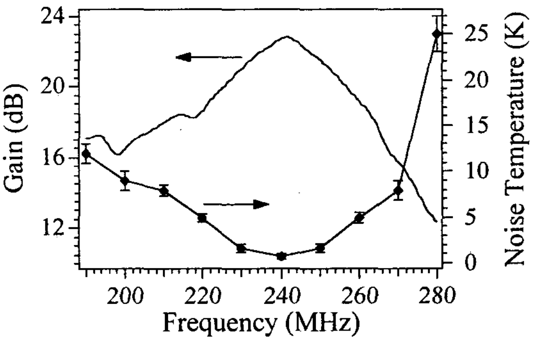

Fig. 3 Gain and noise temperature of a microstrip amplifier at 4.2 K

mounted on the 1 K pot of the system and kept to about 1.8 K during the measurements.

The measured noise temperature of 0.10 ± 0.02 K measured at 90 MHz contained a noise contribution from the HFET postamplifier of about 0.04 K. In the case of a 438 MHz SQUID, the contribution of the postamplifier (0.38 ± 0.07 K) was subtracted from the measured system noise (0.50 ± 0.07 K) to obtain an intrinsic noise temperature for the SQUID of 0.12 ± 0.10 K.

V. Increasing the bandwidth of a SQUID amplifier by varactor tuning

The high gain and low noise temperature make the SQUID amplifier attractive for a number of applications. However, the limited bandwidth of the device may be somewhat disadvantageous. Although for a given device the bandwidth over which the gain exceeds a certain value, say 15 dB, is typically 50 MHz to 100 MHz, the gain falls off rapidly outside this range.

The resonant frequency of a transmission line resonator can be changed by terminating the normally open end by a reactive load, for example a capacitor. By making the capacitance variable, in principle, one can reduce the resonant frequency with zero capacitance to one-half its value (infinite capacitance). It is convenient to use a varactor or capacitance diode as the variable capacitor. Since the diode has to be close to the SQUID and thus at its operating temperature, one has to use a GaAs, rather than a Si device. In a microstrip amplifier with a resonant frequency of 205 MHz, by connecting a varactor to the open end of the coil the frequency at which the amplifier had maximum gain could be tuned from 195 MHz down to 117 MHz. Over this tuning range, the gain varied by no more than 1 dB.

VI. Conclusion

We have described a new approach to the operation of the dc SQUID in which the input signal is coupled between one end of the input coil and the square washer that forms the body of the SQUID.

On resonance, a power gain of typically 20 dB is achieved over a frequency range of 0.1 - 1.6 GHz, and 12 dB at a frequency of 3 GHz. The intrinsic noise temperature of the amplifier is typically 1/4 of the bath temperature T and, within the measurement errors, scales with T. Thus, noise temperatures of around 0.1 K have been achieved for a bath temperature of about 0.5 K.

Acknowledgments

The authors are indebted to L. Rosenberg and K. van Bibber for their ongoing encouragement, and to X. Meng for technical support. This work was supported by the National Science Foundation under grant number FD96-00014.

References

[1] Hilbert, C. and Clarke, J. (1985) J. Low Temp. Phys. 61, 263-280.

[2] Hilbert, C., Clarke, J., Sleator, T. and Hahn, E. L. (1985) Appl. Phys. Lett. 47, 637-639. (See references therein for earlier work on NMR with SQUIDS).

[3] Bradley, R. F. (1999) Nucl. Phys. B (Proc. Suppl.) 71, 137.

[4] Hagmann, C., Kinion, D., Stoeffl, W., van Bibber, K., Daw, E., Peng, H., Rosenberg, L. J., La Veigne, J., Sikivie, P., Sullivan, N. S., Tanner, D. B., Nezrick, F. Turner, M. S., Moltz, D. M., Powell, J. and Golubev, N. A. (1998), Phys. Rev. Lett. 80, 2043.

[5] Mück, M. André, M-O., Clarke, J., Gail, J. and Heiden, C. (1998) Appl. Phys. Lett. 72, 2885.

[6] André, M-O., Mück, M. Clarke, J., Gail, J. and Heiden, C. (1999) Appl. Phys. Lett. 75, 698.

[7] Mück, M. André, M-O., Clarke, J., Gail, J. and Heiden, C. (1999) Appl. Phys. Lett. 75, 3545.

[8] Stewart, W.C. (1968) Appl. Phys. Lett. 12, 277.

[9] McCumber, D.E. (1968) J. Appl. Phys. 39, 3113.