Superconducting quantum interference device as a near-quantum-limited amplifier at 0.5 GHz

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A dc superconducting quantum interference device (SQUID) with a resonant microstrip input is operated as an amplifier at temperatures down to 20 mK. A second SQUID is used as a postamplifier. Below about 100 mK, the noise temperature is 52 ± 20 mK at 538 MHz, estimated from measurements of signal-to-noise ratio, and 47 ± 10 mK at 519 MHz, estimated from the noise generated by a resonant circuit coupled to the input. The quantum-limited noise temperatures are 26 and 25 mK, respectively. The measured noise temperature is limited by hot electrons generated by the bias current. *© 2001 American Institute of Physics.* [DOI: 10.1063/1.1347384]

At submillimeter or shorter wavelengths, a wide variety of detectors of electromagnetic radiation are quantum limited, that is, able to detect a single photon.[1] There have recently been advances in this technology using, for example, superconducting transition-edge sensors for infrared, optical, and ultraviolet wavelengths,[2] and a single-electron transistor involving a semiconductor quantum dot for far infrared wavelengths.[3] Quantum-limited performance has been achieved at frequencies as low as 20 GHz, with a Josephson-parametric amplifier.[4] At still lower frequencies, it becomes increasingly difficult to approach the quantum limit. For example, at frequencies f around 1 GHz, the lowest noise is achieved with a cooled heterostructure field effect transistor[5] (HFET), which can attain a noise temperature T_N of about 2 K. At 0.5 GHz, this value is about a factor of 80 above the quantum noise temperature, $T_Q = hf/k_B \approx 25$ mK.

The recent development of an amplifier based on a microstrip coupled to a dc superconducting quantum interference device (SQUID)[6–8] has resulted in noise temperatures that are substantially lower than those achievable with cooled semiconductors. A microstrip SQUID amplifier cooled to about 0.5 K achieved a *system* noise temperature of 0.50 ± 0.07 K at 438 MHz. This noise temperature was dominated by the noise of the postamplifier—a cooled HFET—coupled to the SQUID, which contributed an estimated 0.38 ± 0.07 K to the system noise temperature. In this letter we describe an amplifier cooled to 20 mK in which the postamplifier is a second microstrip SQUID.[7] The noise temperature of the first stage microstrip SQUID is about 50 mK; by comparison, the quantum-limited noise temperature is about 25 mK. The noise temperature is limited by hot electrons in the resistive shunts of the SQUID, which cause the effective temperature of the shunts to saturate at about 100 mK.

The SQUID is in the conventional square washer configuration[9] shown in Fig. 2. The inner and outer dimensions of the Nb washer are $0.2\times0.2\,\mathrm{mm}^2$ and $1\times1\,\mathrm{mm}^2$, giving an estimated inductance $L\approx450$ pH (including the slit). The 11-turn niobium coil has a width of 5 μm, an estimated self-inductance $L_i \approx n^2 L \approx 55$ nH, and a mutual inductance to the washer $M_i \approx nL \approx 5$ nH. Each of the Nb–Al$_x$O$_y$–Nb tunnel junctions has a critical current $I_0 \approx 3.5\,\mu$A, so that $\beta_L \equiv 2LI_0/\Phi_0 \approx 2.5$; here $\Phi_0 \equiv h/2e \approx 2.07\times10^{-15}$ Wb is the flux quantum. Each shunt has a resistance $R\approx22\,\Omega$, and the hysteresis parameter $\beta_c \equiv 2\pi I_0 R^2 C/\Phi_0$ is estimated to be about 0.8. At 4.2 K and at frequencies of a few kilohertz, the flux-to-voltage transfer coefficient $V_\Phi = |\partial V/\partial\Phi| \gtrsim 90\,\mu\mathrm{V}/\Phi_0$, and the flux noise is about $3\,\mu\Phi_0\,\mathrm{Hz}^{1/2}$.

The microstrip SQUID is operated as an amplifier with the counterelectrode grounded (inset, Fig. 2). The signal source is connected between the innermost turn of the coil and ground, and the amplified signal is measured between the washer and ground. In this configuration, positive feedback from the output to the input via the capacitance between the coil and the washer increases the frequency at which the maximum gain occurs.[6] We measured the noise temperature of a microstrip SQUID amplifier in a dilution refrigerator, using a second nominally identical device as a postamplifier (Fig. 1). A low pass filter network prevented the two SQUIDs from interacting with each other. The SQUID chips were attached with vacuum grease to a printed circuit board which was bonded to the cold stage of the refrigerator. All leads connected directly to the SQUIDs were very heavily filtered over a wide frequency range using a combination of lumped circuit and copper powder filters, and a superconducting shield surrounding the SQUIDs eliminated ambient magnetic field fluctuations. With its current and flux biases adjusted to maximize V_Φ at low frequencies, the gain of the first SQUID peaked at 538 MHz. The current and flux biases of the second SQUID were adjusted slightly

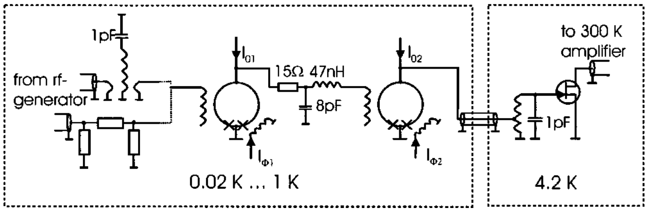

FIG. 1. Schematic of cascaded microstrip SQUIDs and HFET. The input circuit consists of either a resistive network (lower) or a resonant circuit (upper).

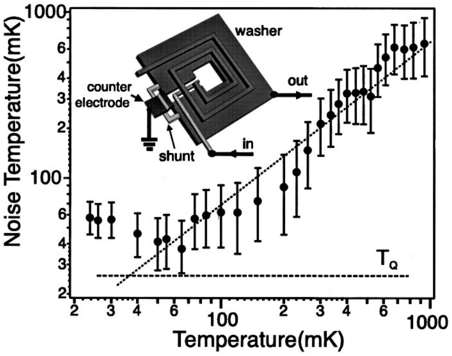

FIG. 2. Noise temperature of input microstrip SQUID at 538 MHz vs temperature measured with a resistive source. The dashed line through the data corresponds to $T_N \propto T$, and the horizontal dashed line indicates $T_Q = hf/k_B \approx 26\,\text{mK}$. Inset shows configuration of microstrip SQUID with grounded counter electrode.

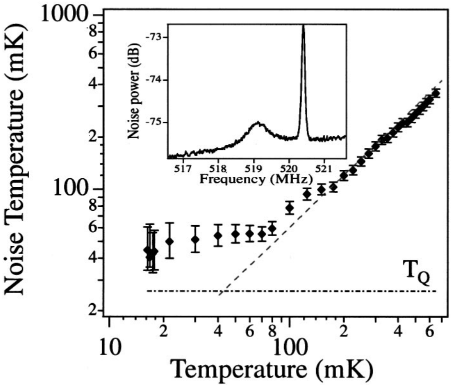

FIG. 3. Noise temperature of input microstrip SQUID at 519 MHz vs temperature measured with a resonant source. The dashed line through the data corresponds to $T_N \propto T$, and the dot-dashed line indicates $T_Q = hf/k_B \approx 25\,\text{mK}$. Inset is noise peak produced by LC-tuned circuit at 20 mK. The upward trend of the baseline reflects the fact that the peak in the amplifier gain is at a higher frequency. The peak at 520.4 MHz is a calibrating signal.

to maximize its gain at the same frequency. The overall gain of the two SQUIDs was 30 ± 1 dB and 32 ± 1 dB at 4.2 K and 100 mK, respectively. A third stage of amplification was provided by an HFET (Fujitsu FXH 13 LG) with a resonant input circuit, cooled to 4.2 K and connected to the SQUID postamplifier via a cryogenic cable with a loss of 6 dB. At 550 MHz, the gain of the HFET was 22 ± 1 dB, and its noise temperature T_p about 6 K. At the lowest temperatures, the cable loss reduced the effective gain G of the two SQUIDs to 26 ± 1 dB so that the HFET contributed a noise temperature $T_p/G \approx 15\,\text{mK}$ referred to the input of the first SQUID.

We measured the noise temperature of the input microstrip SQUID amplifier in two different ways. In the first method (Fig. 1, lower input circuit) the input was coupled to a calibrated attenuator. In a separate experiment, to calibrate the system excluding the two SQUIDs, we disconnected them and measured the gain of the system with the attenuator coupled to the input of the cryogenic cable. By remeasuring the system gain with the SQUIDs restored, we determined their gain to ± 1 dB. To determine the noise temperature, we applied a -134 dBm, 538 MHz signal to the input of the attenuator, and used a spectrum analyzer to measure the ratio of the signal power delivered to the attenuator to $[2hf \coth(hf/2k_BT) + 4k_BT_N + 4k_BT_p/G]$. The inferred values of T_N are plotted in Fig. 2. The ± 1 dB error bars are largely due to systematic errors in measuring the losses in the input coaxial cable and attenuator and in calibrating the spectrum analyzer. To within the scatter of the data, T_N scales as T for $T \lesssim 150\,\text{mK}$ and flattens out at lower temperatures to a value (averaged over $T < 100\,\text{mK}$) of $52 \pm 20\,\text{mK}$. The quantum-limited noise temperature is $T_Q = hf/k_B \approx 26\,\text{mK}$.

In the second method, we measured the noise generated by an inductor–capacitor (LC)-resonant circuit consisting of a 1 pF capacitor and a four-turn Cu coil, about 4 mm in diameter, inductively coupled to the input of the microstrip via a loop of wire (Fig. 1, upper input circuit). In separate experiments at 4.2 K, we connected the loop to a 50 Ω cable, and adjusted the distance between the coil and the loop to produce a 3.5 dB coupling loss: this reduces the Q of the LC circuit by a factor of about two. A second loop, with a coupling loss of about 15 dB to the tuned circuit, was connected to a signal generator via a cold 30 dB attenuator and a stainless steel coaxial cable with a loss of 26 dB to enable us to determine the gain and Q of the system. The loaded Q of the LC circuit was about 510 at 4.2 K, and did not change noticeably with temperature. During the measurement, we applied a small (about -140 dBm) signal to the LC circuit, via the coupling loop, at a frequency about 2 MHz above its 519 MHz resonant frequency. We used this signal to optimize the bias currents and fluxes of the two SQUIDs first for maximum gain and subsequently for optimum signal-to-noise ratio. We also monitored the peak throughout the measurements to verify that the gain did not drift. We measured the height of the noise peak produced by the LC circuit; an example is shown inset in Fig. 3. This peak contains contributions from the Nyquist noise of the resonant circuit and from the system noise of the amplifier. On resonance, since the input impedance Z_0 of the microstrip SQUID amplifier reduces the Q of the resonant circuit to approximately one half of its unloaded value, the source impedance presented to the microstrip is roughly equal to Z_0. In separate experiments, we found that the noise power of the SQUID was essentially unchanged when we varied the source impedance from 20 to 330 Ω, so that to a first approximation we can neglect the variation in noise power with source impedance. Thus, we can characterize the effective temperature on resonance as $[(hf/2k_B)\coth(hf/2k_BT) + T_N + T_p/G]$ and off resonance as $T_N + T_p/G$. We infer T_N from the measured height of the peak and the values of T and T_p/G. In Fig. 3 we plot T_N vs T. The error bars are determined solely by the uncertainty in the spectrum analyzer measurement, and are therefore smaller than in Fig. 2. We see that T_N scales as T above about 150 mK, and flattens off at temperatures below about 70 mK to $47 \pm 10\,\text{mK}$; by comparison, $T_Q \approx 25\,\text{mK}$.

A potential source of the low-temperature saturation of T_N is hot electrons produced in the resistive shunts by bias current heating. Wellstood *et al.*[10] obtained remarkably similar results for noise measured at frequencies below about 50 kHz in SQUIDs cooled to around 20 mK, and found good agreement with a model in which the temperature of the electrons is determined by their coupling to the phonons. To investigate whether hot electrons were indeed responsible for the saturation in Figs. 2 and 3, we remeasured the noise of

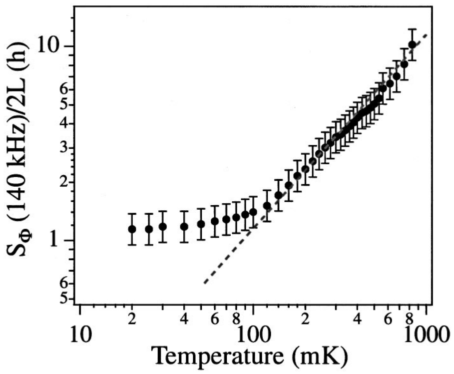

FIG. 4. Noise energy $S_\Phi(140\,\mathrm{kHz})/2L$ of input microstrip SQUID vs temperature. The dashed line through the data corresponds to $S_\Phi/2L \propto T$.

the same SQUID at 140 kHz, where $T_Q < 10\,\mu\mathrm{K}$. For this experiment, we coupled the output of the first SQUID to the two ends of the input coil of a second SQUID, via a superconducting transformer with a current gain of about 3. The output of the second SQUID was coupled to a room-temperature amplifier with a noise temperature of about 3 K. We applied a small 140 kHz signal to a coil beneath the first SQUID and adjusted the current and flux biases of both SQUIDs for optimum signal-to-noise ratio. Figure 4 shows the noise energy of the input SQUID, $S_\Phi(140\,\mathrm{kHz})/2L$ vs T. This noise energy scales with temperature above about 150 mK, and levels off to a constant value of $1.2 \pm 0.2\,\mathrm{h}$ at lower temperatures. The similarity of this behavior to that shown in Figs. 2 and 3 provides strong evidence that the low-temperature saturation of T_N arises from hot electrons.

In conclusion, we have used two methods to obtain an average noise temperature for a microstrip SQUID amplifier of $50 \pm 10\,\mathrm{mK}$ at about 0.5 GHz; by comparison, $T_Q \approx 25\,\mathrm{mK}$. This noise temperature is about 40 times lower than that achievable by cooled semiconductor amplifiers. Below about 100 mK the noise temperature was limited by hot electrons. Since Wellstood *et al.*[10] were able to reduce the temperature of the electrons in the shunts of their SQUIDs by a factor of 2–3 at a bath temperature of 20 mK by adding a thin-film cooling fin, a similar modification of the microstrip SQUID will likely reduce the noise temperature significantly. Development of the microstrip SQUID amplifier was spurred by the need for a much quieter amplifier on the cavity axion detector installed at Lawrence Livermole National Laboratory.[11] Implementing this amplifier on an upgraded detector may increase the rate at which one can scan a given energy range by two orders of magnitude. Another application of the microstrip SQUID amplifier is as a postamplifier for the rf single electron transistor,[12] potentially enabling it to attain quantum-limited performance. Finally, a very low-noise amplifier in the gigahertz frequency range may be useful in reading out circuits exhibiting macroscopic quantum coherence of flux.[13,14]

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[1] For a general review, see G. H. Rieke, *Detection of Light from the Ultraviolet to the Submillimeter* (University Press, Cambridge, 1994).
[2] B. Cabrera, R. M. Clarke, P. Colling, A. J. Miller, S. Nam, and R. W. Romani, Appl. Phys. Lett. **73**, 735 (1998).
[3] S. Komiyama, O. Astaflev, V. Antonov, T. Kutsuwa, and H. Hirai, Nature (London) **403**, 405 (2000).
[4] R. Movshovich, B. Yurke, P. G. Kaminsky, A. D. Smith, A. H. Silver, R. W. Simon, and M. V. Schneider, Phys. Rev. Lett. **65**, 1419 (1990).
[5] R. F. Bradley, Nucl. Phys. B (Proc. Suppl.) **72**, 137 (1999).
[6] M. Mück, M-O. André, J. Clarke, J. Gail, and C. Heiden, Appl. Phys. Lett. **72**, 2885 (1998).
[7] M-O. André, M. Mück, J. Clarke, J. Gail, and C. Heiden, Appl. Phys. Lett. **75**, 698 (1999).
[8] M. Mück, M-O. André, J. Clarke, J. Gail, and C. Heiden, Appl. Phys. Lett. **75**, 3545 (1999).
[9] M. B. Ketchen and J. M. Jaycox, Appl. Phys. Lett. **40**, 736 (1982).
[10] F. C. Wellstood, C. Urbina, and J. Clarke, Phys. Rev. B **49**, 5942 (1994).
[11] C. Hagmann, D. Kinion, W. Stoeffl, K. Van Bibber, E. Daw, H. Peng, L. J. Rosenberg, J. La Veigne, P. Sikivie, N. S. Sullivan, D. B. Tanner, F. Nezrick, M. S. Turner, D. M. Moltz, J. Powell, and N. A. Golubev, Phys. Rev. Lett. **80**, 2043 (1998).
[12] R. J. Schoelkopf, P. Wahlgren, A. A. Kozhevnikov, P. Delsing, and D. E. Prober, Science **280**, 1238 (1998).
[13] J. R. Friedman, V. Patel, W. Chen, S. K. Tolpygo, and J. E. Lukens, Nature (London) **406**, 43 (2000).
[14] C. H. van der Wal, A. C. J. ter Haar, F. K. Wilhelm, R. N. Schouten, C. J. P. M. Harmans, T. P. Orlando, S. Lloyd, and J. E. Mooij, Science **290**, 773 (2000).