DC SQUID RF Amplifiers

Michael A. Tarasov, Victor Yu. Belitsky, and George V. Prokopenko

Abstract—**The noise and signal parameters of several types of RF amplifiers based on different SQUID's with integrated and hybrid input coils were studied. We designed a new type of multiloop dc SQUID with an integrated input coil and extremely low stray capacitances. The inductance of a 4-loop SQUID was 100 pH, the input coil inductance 1.3 nH, and mutual inductance 300 pH. The tuned integrated 4-loop amplifier at 420 MHz had a noise temperature lower 0.5 K and power gain nearly 20 dB in a 60-MHz bandwidth. For the noise calibration of such amplifiers we used SIS junctions as a shot noise source, or a cooled attenuator and a room temperature semiconductor noise source.**

I. Introduction

The nearest competitor of dc SQUID RF amplifiers (SQA's) is cooled HEMT amplifiers which have $T_N \sim (1-3)$ K at $f \sim (1-3)$ GHz, but have rather high power dissipation of tens milliwatts and have nearly achieved their asymptotic parameters. On the other hand, SQA has more than one-order reserve in the margins of gain, noise temperature, and signal frequency even on the basis of the present technology. The advantages of SQA are extremely low power dissipation of several picowatts, a small size of ~ 1 mm^2, and full electrical and temperature compatibility with the superconducting sensitive devices such as Josephson and SIS mixers.

The SQA's are the most sensitive type of amplifiers in 10^2-MHz band. The gain of an untuned amplifier [1] operating at 100 MHz and 4.2 K is 16.5 dB with a noise temperature of 3.8 ± 0.9 K. A tuned amplifier operating at 93 MHz and 4.2 K has a gain 18.6 dB and a noise temperature of 1.7 ± 0.5 K. The measured gain and noise temperature of SQA in [2] at 150 MHz are 20 dB and 0.7 K, respectively.

The dc SQUID amplifier may be viewed as a magnetic flux controlled device, which amplifies signals at frequencies much lower than the Josephson frequency at the bias point. According to [3], the SQA voltage gain $K_u \simeq \alpha^2 r/M\omega$, where $M = \alpha(LL_i)^{1/2}$ is the mutual inductance of the loop inductance L and input coil L_i, r—the SQUID resistance. For approximate estimations if the current gain $K_i \simeq M/L$, it is possible to obtain a simple expression for the power gain $G = K_u K_i \simeq \alpha^2 r/L\omega$.

As mentioned in [4], the SQA may be viewed as a peculiar type of parametric amplifier, in that amplification of the signal with power P_i at frequency f_i is realized by up conversion to the frequency $\omega_i + \omega_j$ (where ω_j is Josephson frequency) and detection (down conversion) take place in the same device. According to Manley–Rowe relations for a parametric up converter $P_i/\omega_i + P_0/(\omega_i + \omega_j) = 0$, which means that power gain $G = P_0/P_i = (\omega_j + \omega_i)/\omega_i \simeq \omega_j/\omega_i$ equals the pump to signal frequencies ratio. The pump frequency in a dc SQUID with dc bias is the Josephson oscillation frequency, and the above mentioned expression $G = \alpha^2 r/L\omega$ may be explained as the ratio of frequency r/L limiting the Josephson current in the loop to the signal frequency. In the case of sufficient capacitance in the loop the limiting resonant frequency will be $(LC)^{-1/2}$. From this point of view it is useful for gain increase to reduce both the inductance and stray capacitance of the SQUID loop and to place the bias current point close to the voltage step corresponding to the resonant frequency. If we use the limiting value of the Josephson current frequency corresponding to the energy gap of Nb which is ~ 750 GHz then, in principle, for a SQUID with loop inductance of 2 pH it may be possible to achieve $\sim$20-dB gain for a signal frequency of ~ 10 GHz.

For the internal Johnson noise source in the SQUID with spectral densities, $S_v(f) = 4\gamma_v kTr$, $S_i(f) = 4\gamma_i kT/r$, and $S_{vi} = 4\gamma_{vi}kT$, where k is Boltzmann's constant, T is the physical temperature, γ are the constants and not too high frequencies, according to [3] the noise temperature of SQA $T_N \simeq T\omega(\gamma_v\gamma_i)^{1/2}/V_\Phi$. Taking into account $\gamma_v = 8$, $\gamma_i = 5.5$, $\gamma_{vi} = 6$ [5] one can obtain $T_N = 6.5T\omega L/r\alpha^2$, i.e., for $\omega = 10^9$, $L = 10^{-10}$ H one can obtain $T_N = 0.04$ T and $R_i^{\text{opt}} = \alpha^2\omega L_i(\gamma_i/\gamma_v - \gamma_{vi}^2/\gamma_v^2)^{1/2} \simeq 0.3\alpha^2\omega L_i$. It should be mentioned that in real SQUID's the values of γ_v, γ_i, γ_{vi}, and T_N may be 2–3 times higher.

In the theoretical work [6] it was shown that the noise characteristics of the single broadband SQA is approximately an order of magnitude worse compared to an array of narrow-band SQA connected in parallel and covering the same frequency band.

The extremely low noise temperatures $T_N = 6.5T\omega L/r\alpha^2$ mentioned previously may be realized only for relatively low frequencies. At higher frequencies, the SQA is quantum noise limited. Taking into account coupling coefficient $\alpha^2 = M^2/LL_i$ and noise parameters of practical SQUID's Tesche in [7], calculated SQA quantum limited noise temperature

$$T_n = (S_E\omega/k)\cdot\left[(1-\alpha^2)/\alpha^2\right]$$

$$\cdot\left(1 + 2\alpha^2 LV_\phi S_{VJ}/S_V + \alpha^2L^2V_\phi^2S_JS_V\right)^{1/2}$$

where S_E is energy resolution. For energy resolution of practical coupled SQUID $S_E \simeq 5$ h and coupling $\alpha^2 \simeq 0.5$ one can obtain $T_n \simeq 0.2$ K at $f = 0.5$ GHz.

The main task of our SQA studies were to understand the mechanisms of signal amplification and noise in such a type

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of amplifiers and to increase signal frequency of SQA in order to use it in future as an IF amplifier with a SIS mixer.

II. Planar Integrated and Hybrid Single-Loop DC SQA Studies

At the beginning of our studies of SQA we tried to use three types of SQA. The first one was similar to [8], the second one to [9], and the third to [10]. The first and the second contain shunted tunnel junctions and the third has the junctions with semiconductor interlayer. We studied SQUID's with junctions situated both inside and outside the square inductive loop and used both integrated and hybrid input spiral coils. For preliminary gain and noise measurements a cooled attenuator and a room temperature signal and noise sources were used.

The output noise and voltage gain have some interesting features. Fig. 1 shows the I-V curve (1), noise (2), and amplified signal (3, 4, 5) for three levels of input signal in a hybrid dc SQUID with clamped wire wound flat input coil. The important feature of the I-V curve is the presence of very broad current steps at voltages corresponding to resonant frequencies of the SQUID. If the bias point is placed at the maximum of dynamic resistance nearby one of these steps, the amplifier gain and noise temperature may be not worse than for a bias point near the Josephson critical current. It is possible to explain this, according to [11], by the presence of broadband Josephson oscillations which give rise to the noise at the signal frequency for the bias voltage nearby the Josephson critical current. This noise will be sufficiently lower for a bias voltage $V > 100$ μV.

As it was mentioned previously, an efficient method to increase the gain and reduce the noise is to locate the bias point near the resonant step where the dynamic resistance is larger and Josephson frequency exceeds the values nearby the critical current. The amplified signal maxima (Fig. 1) at voltages far from critical current confirms this conclusion. The lower output signal amplitudes at far from I_c maxima may be explained by the impedance mismatch at the signal output. The best results for a hybrid SQA with Cu spiral wire wound coil were $G > 20$ dB, $T_N = 1.2 \pm 1$ K at 100 MHz.

A. Cryogenic Noise Source

One of the problems of the low noise amplifier parameters measurements is the noise calibration. To measure the noise temperature Hilbert and Clarke [1] connected the input coil of the SQUID amplifier to a 50-Ω resistor which was enclosed in a vacuum can. The temperature of this resistor could be regulated by means of a heater and controlled using a thermometer. In our measurements we used as the noise source a tunnel SIS junction (see Fig. 2) with the bias point placed higher than the gap voltage. The voltage noise power in this case, according to [12], is $U_N = (4kTR + 2eIR^2)\Delta f$. A filter-attentuator was placed between the SIS noise source and the SQUID amplifier. The noise temperature at the amplifier input may be varied between 4 and 20 K. The advantages of an SIS noise generator in comparison with a variable temperature load noise generator are full compatibility with SQUID amplifier, the possibility of noise modulation, wide noise temperature range, and small size [13].

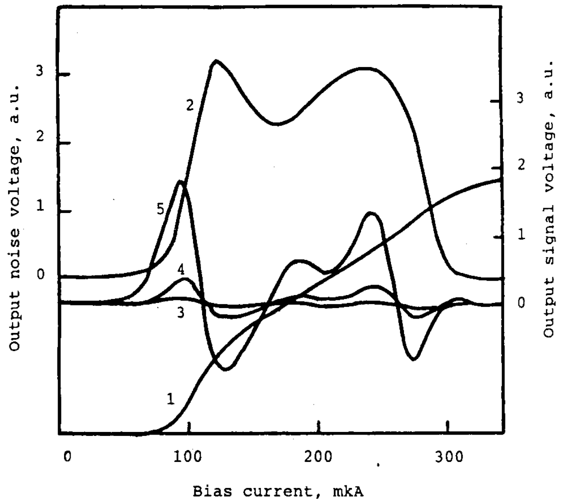

Fig. 1. Hybrid SQUID with clamped wire wound flat input coil, 1: dc SQUID I-V curve, 2: output noise in 1-1000-MHz band, 3, 4, 5: amplified signal at 100 MHz for three input signal levels differing by 10 dB versus bias current.

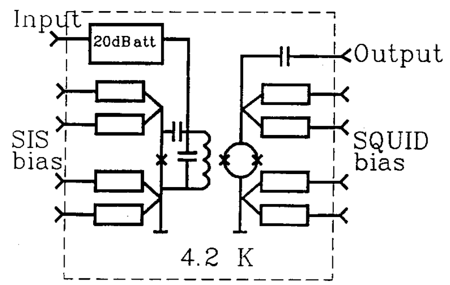

Fig. 2. Schematic layout for gain and noise temperature of SQUID amplifier measurements with SIS noise source and with room temperature semiconducting noise source and precise RF oscillator.

B. Four-Loop DC SQUID Amplifier Studies

The main disadvantages of the previous studied SQA are relatively low amplified frequency and a high influence of external magnetic fields on SQA parameters. To increase the signal frequency while preserving the low noise temperature and high gain, the Josephson frequency in the SQUID loop should be increased and it means that the loop inductance and capacitance should be decreased. In the common integrated SQUID structure [8] the stray capacitance in the loop exceeds 10 pF. The capacitance between the loop and evaporated above the loop input coil is even more, and this capacitance leads to the significant stray input-output feedback.

To eliminate these disadvantages and increase the input signal frequency and bandwidth we designed a four-loop dc SQUID with an integrated input coil in the form of rectangular turns inside the loops (see Fig. 3).

The SQUID loop inductance consists of the four parallel connected partial square loops of 200 μm by 200 μm size. The input coil consists of four series connected square turns

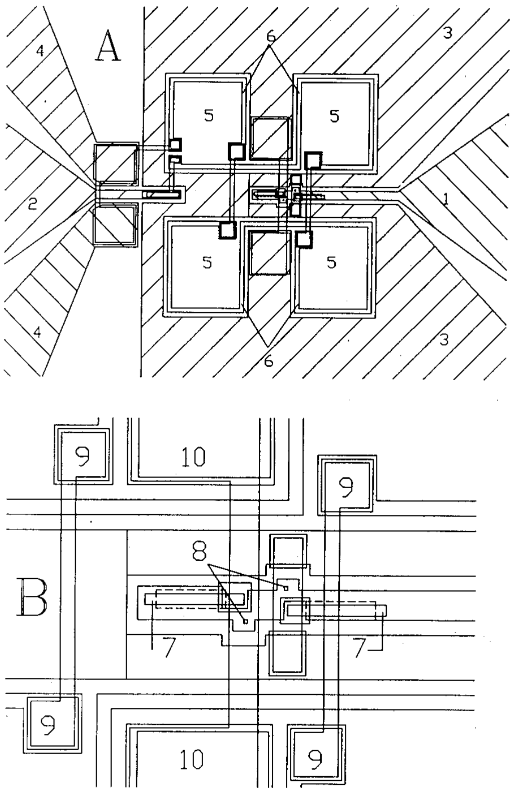

Fig. 3. *A*: Four-loop planar dc SQUID with integrated input coil point. 1,3 and 2,4: output and input coplanar lines. 5: parallel connected inductive SQUID loops each 200 μm by 200 μm, inside each of them single turns, 6, are arranged and connected in series to form an input coil. *B*: The central part of the four-loop SQA in details, 7: shunt resistors, 8: SIS junctions, 9: input coil turns interconnections, 10: SQUID loop counter interconnections electrode.

with Nb film widths of 10 μm. Parallel connection of the loops reduces the inductance of the loop and increases the resonant frequency. Series connection of the input turns increases the input coil inductance and makes impedance matching with the input 50-Ω line easier. The position of input turns inside the loops was chosen to reduce stray input-output capacitance.

The SQUID loop inductance in this construction is 100 pH, the input coil is 1.3 nH, and mutual inductance is 300 pH. The stray capacitance in the SQUID loop is 1.8 pF, the sum junctions capacitance 0.8 pF, input coil capacitance 0.3 pF, and the loop coil capacitance 2.2 pF. The Nb-AlO$_x$-Nb shunted tunnel junctions of 2.5 μm by 2.5 μm area were used as Josephson junctions. The input coil resonant frequency is estimated to be 8 GHz and the loop resonant frequency is 10 GHz.

Since at 300 MHz the input coil inductive impedance is $\sim 2.5\ \Omega$, then to match the input 50-Ω line and the input coil we used resonant circuit matching [2]. In the design of the matching circuit the sufficient element is series additional inductance L_s, which was in the range of 5-15 nH and depends on the size of connecting leads. Scaling the input circuit elements to the input resonant circuit one may obtain the equivalent capacitance $C_r \simeq C_1 + C_0$, where C_1 and C_0 are series and parallel capacitances, and resistance $R_r \simeq R(C_1/C_0)^2$. According to [1], the optimal Q-factor is $Q \simeq (1 + L_s/L_i)/\alpha^2$ which in our case gives $Q_{\text{opt}} \simeq 10$ and taking into account $Q \simeq \omega L_s/R_r$ one could obtain $C_1 \simeq 0.2C_0$.

For the Fig. 2 matching circuit, the dependence of the amplified noise signal on frequency is shown in Fig. 4. Using the SIS noise source (Fig. 4(a)) enables us to make frequency dependencies more smooth and achieve good input matching by applying the SIS junction with normal resistance equal to the SQA optimal input impedance. For comparison, in Fig. 4(b), the same dependencies are shown, obtained with a semiconducting noise source. In these figures the lowest noise temperature 0.4 K is only twice higher the calculated quantum limit, and the power gain was $G \simeq 20$ dB in the 60-MHz band.

To confirm the assumption about the frequency dependence of the gain and the noise we measured the spectral density of the voltage noise at bare SQUID output (Fig. 5). The dependence is of $1/f$ type and corresponds to amplified Johnson noise according to mentioned gain dependence $G = \alpha^2 r/L\omega$.

III. DISCUSSION

Achieved SQA gain and noise parameters at 4.2 K and rapid progress of high T_c thin films technology allows for

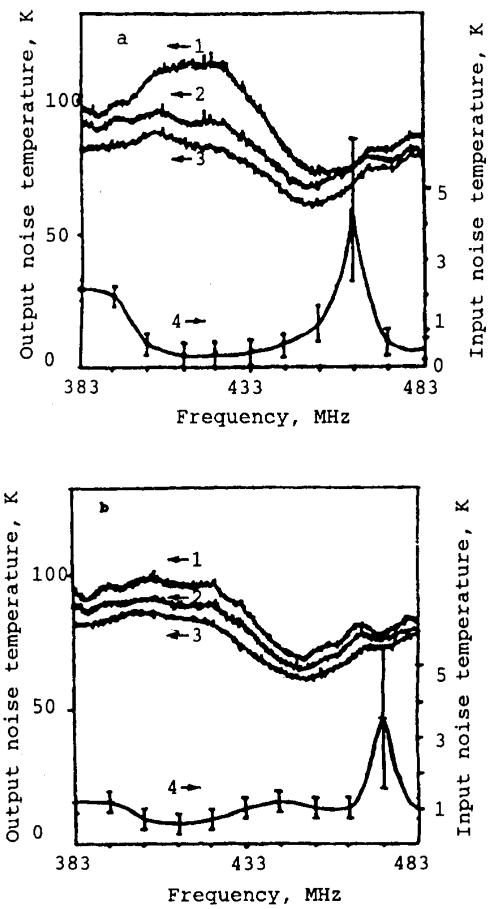

Fig. 4. Integrated 4-loop dc SQUID amplifier output noise frequency dependencies, with 1 and without 2 input signal, output noise at zero SQUID bias 3, noise temperature of SQA 4 obtained with semiconducting, (a) and SIS noise (b) sources.

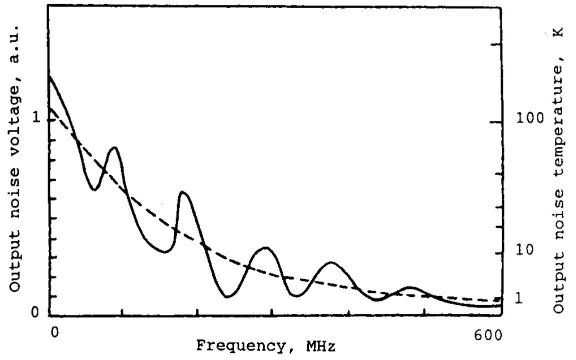

Fig. 5. Internal SQUID output noise frequency dependence. The solid line oscillation is connected with the SQUID output and 50-Ω cable mismatch; dashed line is extrapolation for the case without cable.

study of the possibility of the HTSC SQA design and its asymptotic margins. According to the mentioned relation for noise temperature, the HTSC SQA at 77 K should have a noise temperature lower than 10 K at $f \sim 10^2$ MHz. In contrast to the SQUID magnetometer, the SQA does not need superconductivity in the input coil, and HTSC SQA may be realized on the basis of the present thin HTSC films and Josephson tunnel junctions technologies.

Concerning HTSC SQA asymptotic margins, they are even better than low temperature SQA because of the energy gap voltage of YBaCuO $V_\Delta \simeq 25$ mV, whereas that of Nb is only 2.8 mV; so at the same temperatures the gain may be nearly an order higher and noise temperature lower in HTSC SQA. If we compare LTSC SQA at $T_1 = 4.2$ K and HTSC SQA at $T_2 = 77$ K, the noise temperature ratio will be $T_L^N / T_H^N = (T_1 / T_2) \cdot (\Delta_H / \Delta_L) \simeq 0.5$ which means that the noise temperature of HTSC SQA at 77 K may be only twice higher than the LTSC SQA noise temperature at 4.2 K. However, realization of such values will be possible only when submicrometer HTSC structures become available.

IV. CONCLUSION

The review of theoretical works and experimental results show that asymptotic parameters of SQA may be obtained from a very clear and simple model of parametric up conversion with down conversion in the same device. Estimations give the noise temperature values several times lower than the physical temperature at hundreds of megahertz for different types of SQUID's, including HTSC.

The presented gain and noise dependencies obtained in multiloop SQA at 430 MHz confirms the conclusion that to improve the SQA parameters the loop inductance and capacitance should be lowered. The measured noise temperature of SQA $T_n \simeq 0.4$ K at 430 MHz is only twice higher the quantum noise limit estimations.

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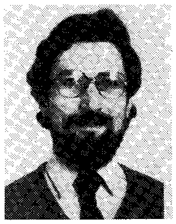

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