MULTILOOP INTEGRATED DC SQUID LOW NOISE RF AMPLIFIER

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A new type of multiloop dc SQUID in the form of a second order gradiometer with integrated input coil and extremely low stray capacitances was designed to improve SQUID amplifier parameters. For decreasing the loop inductance four partial loops were connected in parallel. Single input turns placed inside each loop were connected in series to increase the input coil inductance for better impedance matching. The amplifier noise temperature lower than 0.5 K and power gain nearly 20 dB were measured at 430 MHz for 60 MHz bandwidth in the case of tuned amplifier.

INTRODUCTION

The dc SQUID RF amplifiers are the most sensitive type of amplifiers in 10^2 MHz frequency band. The gain of untuned amplifier [1] operated at 100 MHz and 4.2 K was 16.5 dB with noise temperature 3.8±0.9 K. A tuned amplifier operated at 93 MHz and 4.2 K has gain 18.6 dB and noise temperature 1.7±0.5 K. The measured gain and noise temperature of SQUID amplifier in [2] at 150 MHz were 20 dB and 0.7 K, respectively.

The dc SQUID amplifier (SQA) 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 SQUID amplifier 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. 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.

For the internal Johnson noise source in the SQUID with spectral densities $S_v(f)=4\gamma_v kTr$, $S_i(f)=4\gamma_i kT/r$, $S_{vi}=4\gamma_{vi} kT$, where k is Boltsman's constant, T is the physical temperature, γ – 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 $T_N=0.04T$ and $R_i^{opt}=\alpha^2\omega L_i(\gamma_i/\gamma_v-\gamma_{vi}^{\ 2}/\gamma_v^{\ 2})^{1/2}\simeq 0.3\alpha^2\omega L_i$. It should be mentioned that in real SQUIDs the values of γ_v, γ_i, γ_{vi} and T_N may be 2–3 times higher.

In [6] it was shown tnat 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.

Extremely low noise temperatures $T_N=6.5T\omega L/r\alpha^2$ mentioned above 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 SQUIDs Tesche [7] calculated SQA quantum limited noise temperature

$$T_n=(S_E\omega/k)\bullet[(1-\alpha^2)/\alpha^2]\bullet(1+2\alpha^2 LV_\phi S_{VJ}/S_V+\alpha^2L^2V_\phi^{\ 2}S_JS_V)^{1/2},$$

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

PLANAR INTEGRATED MULTI–LOOP DC SQUID AMPLIFIER STUDIES

The main disadvantages of the previous studied SQUID amplifiers 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 to 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.1).

The SQUID loop inductance consists of the four parallel connected partial square loops of 200x200 μm^2 size. The input coil consists of four series connected square turns with Nb film widths 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 Ohm 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, input coil 1.3 nH, mutual inductance 300 pH. The stray capacitance in SQUID loop is 1.8 pF, the sum junctions capacitance 0.8 pF, input coil capacitance 0.3 pF, loop–coil capacitance 2.2 pF. The Nb–AlO_x–Nb shunted tunnel junctions of 2.5x2.5 μm^2 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 ~2.5 Ohm, then to match the input 50 Ohm 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 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 $Q_{opt} \simeq 10$ and taking into account $Q \simeq \omega L_s/R_r$ one could obtain $C_1 \simeq 0.2C_0$.

For described matching circuit the dependence of the amplified noise signal on frequency is shown in Fig.2. Using of SIS junction as noise source enables to make frequency dependencies more smooth and to achieve good input matching applying SIS junction with normal resistance equal to the SQA optimal input impedance. One can see that the lowest achieved noise temperature 0.4 K is only twice higher the calculated quantum limit, and the power gain was $G \simeq 20$ dB in 60 MHz band.

DISCUSSION

The resonant circuit used in our experiments is necessary part of dc SQUID RF amplifier. Without such circuit when signal source (for example SIS junction) is connected directly to the input coil of SQUID the power gain dramatically decreases and noise temperature sharply increases. This experimental result confirms the conclusion of theory [6] that noise characteristics of a wide bandwidth amplifier are ten times worse the noise characteristics of a set of narrow bandwidth amplifiers with similar SQUIDs operated in parallel in the same bandwidth. It is easy to explain the well known fact that direct connection in series two dc SQUIDs without resonant circuit between them leads not to increase but to decrease the gain and increase the noise temperature.

CONCLUSION

The asymptotic parameters of SQA may be obtained from very clear and simple model of parametric up–conversion with down conversion in the same device. 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. This result was obtained in the case of tuned amplifier with optimized resonant circuit at the input. To increase the bandwidth of SQUID amplifier without decreasing the noise temperature and gain a parallel connection of several amplifiers with shifted resonant frequencies should be used.

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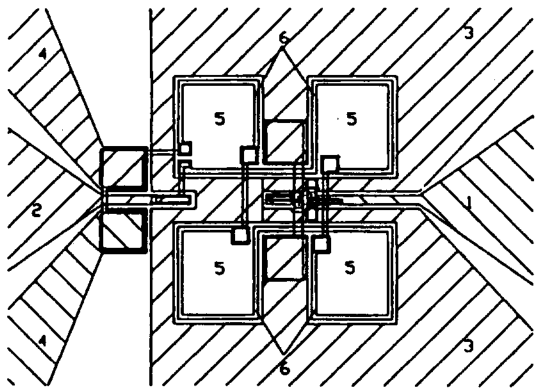

Figure 1 Multiloop planar integrated dc SQUID with integrated input coil, where 1,3 and 2,4 – output and input coplanar lines, 5 – connected in parallel four inductive SQUID loops each 200 μm by 200 μm, inside each of them four single turns (6) are connected in series to form an input coil.

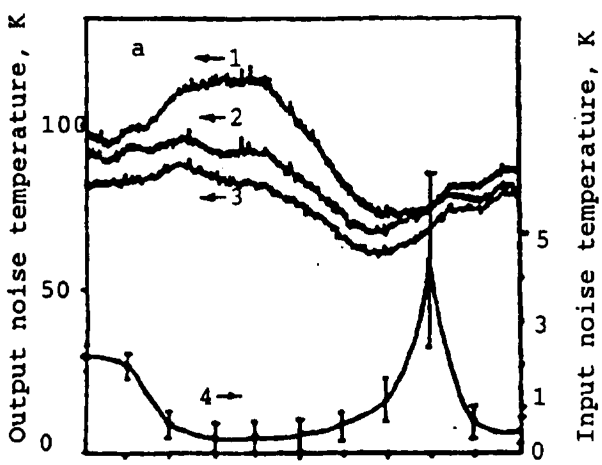

Figure 2 SQUID amplifier output noise frequency dependencies with (1) and without (2) input signal, zero SQUID bias (3) and SQUID amplifier noise temperature (4).