Integrated rf Amplifier Based on dc SQUID

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***Abstract*—Integrated radio-frequency amplifiers comprising 4-loop dc SQUID, seriesly connected input coil turns, resonant capacitor parallel to the input coil, series capacitors at the input and output ports and bias resistors have been designed, fabricated and experimentally studied. Multiloop dc SQUID with parallel loops and seriesly connected single-turn input coils placed inside each loop and integration with the input resonant matching circuit elements and with elements of dc bias circuit allows to increase signal frequency and reduce the influence of external noise. The amplifiers with three different capacitors have resonant frequencies 560, 656, 758 MHz and bandwidth about 50 MHz. The noise temperature of such amplifiers below 1.5 K has been measured using cold attenuator and room-temperature noise source. The layout comprising three pairs of such amplifiers placed on the same 15x24 mm substrate was designed to increase the bandwidth over the bandwidth of individual amplifier.**

I. INTRODUCTION

The dc SQUID radio-frequency amplifier (SQA) is one of the promising devices to be used as IF amplifier together with SIS quasiparticle or Josephson mixer and Josephson-type oscillator in the integrated superconducting receiver. The main problems in design of such amplifier are to reduce SQUID loop inductance and capacitances in the input circuit and between input circuit and the loop. In traditional Ketchen-Jaycox type planar SQUIDs the best noise temperature about 1 K has been achieved at frequency 140 MHz [1]. In multiloop SQUID with parallel loops and series connected input turns placed inside each loop the operation frequency can be increased up to 400 MHz with the noise temperature about 0.5 K [2]. Further increase of resonant frequency was limited by series stray inductances and losses in external nonintegrated capacitors and wiring. The obvious way to improve the performance of such amplifier is to integrate it with the input resonant matching circuit and also with elements of dc bias circuit to reduce the influence of external noise.

A. Background

1) SQUID-amplifier signal parameters: The dc SQUID amplifiers can be viewed as a magnetic flux controlled device, which amplifies signal at frequencies much below the Josephson frequency at bias point. According to [3] one can obtain the voltage gain $K_v \approx \alpha^2 r/M\omega$, where r - the SQUID resistance, L - the loop inductance, $M=\alpha(LL_i)$ - the mutual inductance of loop and input coil L_i. For approximate estimations one can take the current gain as $K_i \approx ML$ and the power gain $G=K_v K_i \approx \alpha^2 r/L\omega$. Important feature of dc SQUID contrary to rf SQUID is that former is nonreciprocal device and $t_{12}= d\Phi_i/dI \approx 0$, here Φ_i is the input flux defined through the relation $V_i=j\omega\Phi_i$, V_i is the voltage across the input coil, I - output current. Input impedance can be presented by $t_{11}=L_i[1-\alpha^2/(1-4jR_d/\omega L)] \approx L_i-j\alpha^2\omega LL_i/4R_d$, where R_d - dynamic resistance. The forward transfer impedance $t_{21}=Z_f=M_i V_\phi$, while the output impedance $t_{22}=dV/dI=R_d=R/2$ for frequencies much less than Josephson oscillation's frequency f_j.

As mentioned in [4] the SQA may be viewed as a peculiar type of parametric amplifier in that amplification of the signal of power P_i at frequency f_i is realised by up conversion to frequency $\omega_i+\omega_j$ (where ω_j is the Josephson oscillations frequency) and detection (down conversion) takes place in the same device. According to Manley-Rowe relationships for a parametric up-converter, $P_i/\omega_i+P_0/(\omega_j+\omega_i)=0$, which means that the power gain $G=P_0/P_i=(\omega_j+\omega_i)/\omega_i \approx \omega_j/\omega_i$ equals pump-to-signal frequency ratio.

The pump frequency in dc SQUID with dc bias is the Josephson oscillation and the above mentioned expression $G=\alpha^2 r/L\omega$ can be explained as the ratio of frequency r/L limiting the Josephson current in the loop to the signal frequency. In the case of high 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 inductance and stray capacitance of SQUID loop and to place the bias current point at the dynamic resistance maximum close to the voltage step corresponding the resonant frequency. If we use the limiting value of Josephson oscillations frequency

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corresponding to the energy gap of Nb which is ≈750 GHz than, in principle, it may be possible to achieve ~20 dB gain for the signal frequency ~10 GHz.

2) The noise temperature of SQA: For Johnson noise source in SQUID with spectral density $S_v(f)=4\gamma_v kTr$, $S_i(f)=4\gamma_i kT/r$, $S_{vi}=4\gamma_{vi}kT$ where k -Boltsman's constant, T - physical temperature, γ - constants and for not too high frequencies, according to [3] the noise temperature of SQA $T_n \approx T\omega(\gamma\gamma)^{1/2}/V_\phi$. Taking into account $\gamma_v=8$, $\gamma_i=5.5$, $\gamma_{vi}=6$ [5] one can obtain $T_n \approx 6.5T\omega L/r\alpha^2$, i.e. for $\omega=10^9$, $L=10^{-10}$ H one can obtain $T_n=0.04T$ in the case of optimal input load $R_i^{opt}=\alpha^2\omega L_i(\gamma_i/\gamma_v \; -\gamma^2_{vi}/\gamma^2_v)^{1/2} \approx 0.3\alpha^2\omega L_i$. It should be mentioned that in real SQUIDs the values of γ_v , γ_i , γ_{vi} and T_n can be 2-3 times as much.

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

The quantum noise limit of SQA at T=0, according to [7], can be calculated by replacing the Johnson noise by zero fluctuations in the expression for the tuned SQA noise. The obtained value $T_n \approx hf/k\ln 2$ is just the same as for any amplifier in the quantum limit. Taking into account coupling coefficient $\alpha^2=M^2/LL_i$ and noise parameters of practical SQUID's C. Tesche in [8] calculated SQA quantum limited noise temperature at nonzero temperature:

$$T_n=(S_E\omega/k)[(1-\alpha^2)/\alpha^2](1+2\alpha^2 LV_\phi S_{vi}/S_v+\alpha^2L^2V_\phi^{\,2}S_iS_v)^{1/2}$$

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

II. EXPERIMENTAL

A. Planar integrated and hybrid single-loop dc SQA studies

At the beginning of our studies of SQA we measured parameters of three types of SQA, the first one was similar to [1], 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 SQUIDs with junctions placed 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 have been used.

The output noise and voltage gain have some specific features. Fig. 1 shows IV curve (1), noise (2) and amplified signal (3,4,5) for three levels of input signal. The important feature of the IV curve is the presence of current steps at voltages corresponding to resonant frequencies of SQUID. If the bias point is placed at the maximum of dynamic resistance nearby one of these steps the amplifier gain and noise temperature can be not worth than for bias point nearby the Josephson critical current. It is possible to explain this fact, according to [11], by the presence of broad-band Josephson oscillations which give rise to the noise at signal frequency for the bias voltage nearby the voltage step. This noise is lower for the bias voltage V>100mV.

The possible method to rise the gain and reduce the noise is to locate the bias point near the resonant step where the dynamic resistance exceeds the normal one (this brings better matching) and the 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 can be explained by the impedance mismatch at the signal output. The best results for hybrid SQA with Cu spiral wire-wound coil were G>20 dB, $T_n=1.2\pm1$ K at 100 MHz .

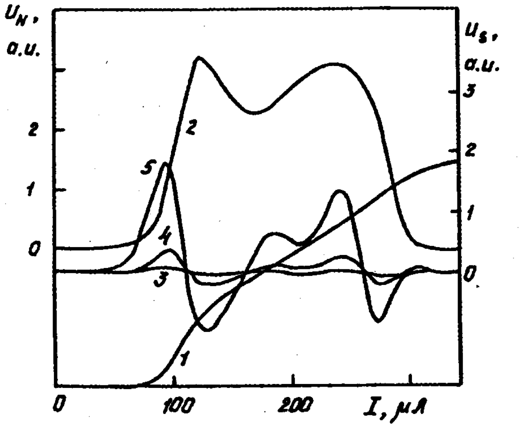

Fig. 1 For SQUID with clamp input coil, (1) - dc SQUID IV curve, (2) - output noise in 1-1000 MHz band, (3,4,5) - amplified signal at 100 MHz for three input signal levels differing by 10 dB versus bias voltage.

B. 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 [12] connected the input coil of SQUID amplifier to 50 Ω resistor which was enclosed in a vacuum can. The temperature of this resistor can be varied by means of a heater and controlled by a thermometer. In our measurements we use as the noise source a tunnel SIS junction with the bias point placed above the gap voltage. The noise voltage in this case, according to [13],

$U_n^2=2eIR^2\Delta f$ is the accurate value. Between the SIS noise source and the SQUID amplifier has been placed a filter-attenuator. The noise temperature at the amplifier input can be varied between 1 and 20 K. The advantages of SIS noise generator in comparison with variable temperature load noise generator are full compatibility with SQUID amplifier, the possibility of noise modulation, wide noise temperature range, small sizes.

C. 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. For the signal frequency increase with preservation of 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 [1] the stray capacitance in the loop exceeds 10 pF. The capacitance between the evaporated above the loop input coil and the 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 each loop (see Fig. 2).

The SQUID loop inductance consists of the four connected in parallel square loops of 200x200 μm^2 area. The input coil consists of four connected in series square turns with Nb film widths 10 μm. Parallel connection of the loops allows to reduce inductance of the loop and increase the resonant frequency. Series connection of the input turns allows to increase the input coil inductance and make easier the impedance matching with the input 50 Ω line. The position of input turns inside the loops was chosen to reduce stray input-output capacitance.

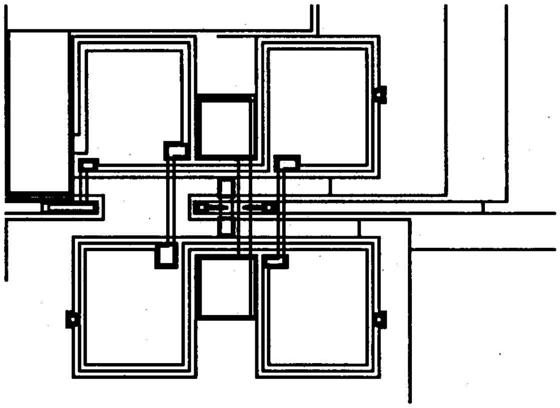

Fig. 2 Four-loop planar dc SQUID with integrated input coil. Four equal squares each 200x200 μm serve as inductive SQUID loops, inside each of them single turns are arranged and connected in series to form an input coil.

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 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 have been used as Josephson junctions. The input coil resonant frequency is estimated to be 8 GHz and the loop resonant frequency 10 GHz.

To match small reactive impedance of input coil of about 2.5 Ω at 300 MHz to the input 50 Ω we used the resonant matching circuit similar to [14]. In the design of the matching circuit the important 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 can obtain the equivalent capacitance $C_T \approx C_1+C_0$, where C_1 and C_0 are series and parallel capacitance's, and resistance $R_T \approx R(C_1/C_0)^2$. According to [4] the optimal Q-factor is $Q \approx (1+L_s/L_i)/\alpha^2$ which in our case gives $Q_{opt} \approx 10$ and taking into account $Q \approx \omega L_s/R_T$ one can obtain $C_1 \approx 0.2C_0$.

D. Four-loop dc SQUID with integrated matching circuit.

From the above consideration it is clear that to increase the signal frequency and bandwidth one should reduce series inductance and stray capacitance of input matching circuit. This was achieved by integrated input circuit comprising series and parallel capacitors places close to the input coil leads (Fig. 3). At the same substrate three different chips with central frequencies 560, 656 and 758 MHz were placed. The layout comprising three pairs of such amplifiers placed on the same 15x24 mm substrate has been designed to increase the bandwidth over the bandwidth of individual SQA. The measured bandwidth of such amplifiers was about 50 MHz. The noise temperature below 1.5 K has been measured using cold attenuator and room-temperature noise source. Measured amplified signal and noise are presented in Fig. 4.

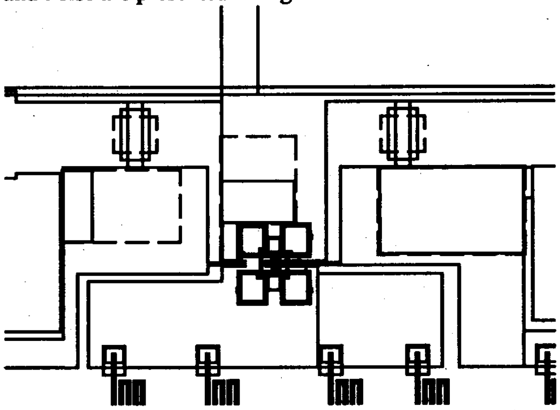

Figure 3. Layout of 4-loop SQA with integrated matching circuit, including series and parallel input capacitors and output capacitor, shown as dashed squares.

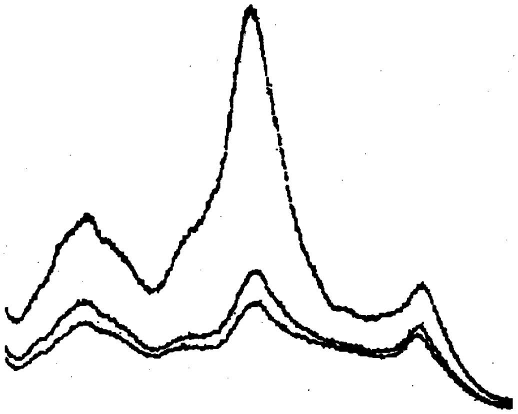

Fig. 4. Spectrum of integrated SQA output signal with resonance at 758 MHz at different levels of input signal. The halfwigth of maximum is 60 MHz. The lower curve corresponds to zero input signal, the signal amplitude difference for upper and middle curves is 10 dB.

III. CONCLUSION

The important advantages of SQA are extremely low power dissipation of several picowatt, small size ~1 mm^2 and full electrical and temperature compatibility with the superconducting sensitive devices such as Josephson and SIS mixers. The multiloop SQA with integrated input circuit allows to increase the signal frequency to 670 MHz. Further improvement of amplifiers parameters can be achieved by combination of single amplifiers with slightly different frequencies in parallel to increase the bandwidth that is important for application of SQA as IF amplifier in SIS mixer.

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