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DC SQUID RF amplifier with external mm-wave pumping and its testing by SIS junction noise

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Abstract. The power gain and the noise temperature of a DC SQUID RF amplifier at a signal frequency 400 MHz were measured in the presence of external microwave radiation at 2 cm, 8 mm and 4 mm wavelengths. We used a four-loop planar DC SQUID with an integrated input coil and very low values of inductances and stray capacitances. In our noise measurements we used an SIS junction as a precise source of input noise at high DC bias voltage $V_b > V_{2\Delta}$. In such a configuration the studied system is the same as an SIS mm-wave mixer with a SQUID IF amplifier.

1. Introduction

According to one of the SQUID amplifier models (Zimmerman and Sullivan 1977) such an amplifier 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 realized by up-conversion to the frequency $\omega_i + \omega_j$ (where ω_j is the Josephson 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 $G = P_0/P_i = (\omega_j + \omega_i)/\omega_i \simeq \omega_j/\omega_i$ equals the pump-to-signal frequency ratio.

The well known relation for power gain $G = \alpha^2 r/L\omega$ 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 the gain increase to reduce both the inductance and stray capacitance of the SQUID loop and to place the bias current point at the dynamic resistance maximum close to the voltage step corresponding to the resonant frequency or to the Shapiro step due to external microwave radiation. Near the resonant or the Shapiro step the dynamic resistance is higher than the normal one and the Josephson frequency is higher than near the critical current. 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 it would be possible to achieve 20 dB gain for the signal frequency up to 10 GHz.

The SQUID amplifier noise temperature for the Johnson noise source in a 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 is the Boltzmann constant, T is the physical temperature, γ are constants and not too high frequencies, according to Clarke and Tesche (1979), is $T_n \simeq T\omega(\gamma_v \gamma_i)^{1/2}/V_\Phi$. Taking into account $\gamma_v = 8$, $\gamma_i = 5.5$, $\gamma_{vi} = 6$ and $V_\Phi \simeq r/L$ one can obtain $T_N = 6.5 T\omega L/r\alpha^2$, i.e. for $\omega = 10^9$, $L = 10^{-10}$ H one can obtain $T_N = 0.04T$ and $R_i^{\rm opt} = \alpha^2 \omega L_i(\gamma_i/\gamma_v - \gamma_{vi}^2/\gamma_v^2)^{1/2} \simeq 0.3\alpha^2\omega L_i$.

Such low values of the noise temperature may be realized only for relatively low frequencies. At higher frequencies the SQUID amplifier is quantum noise limited (Tesche 1982) and the noise temperature is constrained by the uncertainty principle, which leads to $T_n \geqslant hf/k \times \ln 3$, where h is Planck's constant. Taking into account the coupling coefficient $\alpha^2 = M^2/LL_i$ of SQUID inductance L to the input coil L_i and the noise parameters of practical SQUIDs, Tesche calculated the SQUID amplifier quantum limited noise temperature

$$T_n = (S_E\,\omega/k)[(1-\alpha^2)/\alpha^2](1 + 2\alpha^2 L V_\Phi S_{VJ}/S_V + \alpha^4 L^2 V_\Phi^2 S_j/S_V)^{1/2}$$

where S_E is the energy resolution. For the energy resolution of practical coupled SQUID $S_E \simeq 5h$ and coupling $\alpha^2 \simeq 0.5$ one can get $T_n \simeq 10hf/k$, which leads to $T_n \simeq 0.2$ K at $f = 0.5$ GHz.

2. External RF pump influence on DC SQUID I–V curve

We studied experimentally the influence of external microwave irradiation at frequencies of 16, 36 and 75 GHz on I–V curves of integrated four-loop DC SQUIDs (Tarasov *et al* 1991). Figure 1 shows typical curves for different values of magnetic flux caused by input coil current bias.

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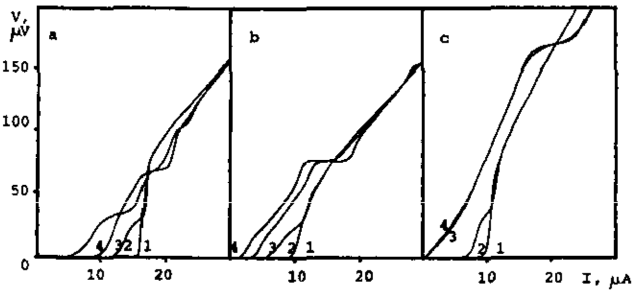

Figure 1. *I–V* curves of DC SQUID with external irradiation at 16 GHz (*a*), 36 GHz (*b*) and 75 GHz (*c*). Curves 1, 2, without and 3, 4 with RF pumping.

At 16 GHz the Shapiro steps on the *I–V* curve are not separated, and between them the dynamic resistance is significantly higher than the normal one. This effect may be used for better impedance matching of SQUID output. In figure 1(*a*) the *I–V* curve near the steps is efficiently changed by magnetic flux and the critical current modulation depth is even better than without irradiation. For more than twice the higher radiation frequency in figure 1(*b*) the current steps are practically separated one from another, the dynamic resistance between the steps nearly achieves the normal curve and the modulation depth is lower than the previous case. The preference of such a mode is a practically parallel shift of the *I–V* curve between the steps under magnetic flux changes, i.e. dynamic resistance does not change, output coupling is preserved and dynamic range is wider. At 75 GHz irradiation in figure 1(*c*) the efficiency of current drive by magnetic flux is significantly reduced and such a mode is inefficient for the SQUID amplifier.

Comparison of the presented curves shows that there is no reason to increase the external RF pumping frequency higher than the self-resonant frequency of a SQUID loop. In our case the self-resonant step corresponds to 17 GHz. The characteristic frequency of the rL circuit of the SQUID is 20 GHz. The most effective RF pumping influence for improvement of SQUID parameters was observed in the 16 GHz band, which is close to both of these frequencies. It should be mentioned that the characteristic frequency of our Josephson junctions $V_0 = I_c R_N \simeq 200$ μV corresponds to Josephson frequencies of 100 GHz, and for such junctions it is reasonable to lower inductance and stray capacitances to achieve resonant frequencies of the same order.

3. Application of the SIS junction as a cryogenic noise source

In our measurements of SQUID amplifier noise temperature we used a tunnel SIS junction with the bias point placed higher than the gap voltage as the noise source (figure 2). The noise voltage in this case, according to Vystavkin *et al* (1983), $U_N^2 = (4kTR + 2eIR^2)\,\Delta f$, is the accurate value. A filter–attenuator was placed between the SIS noise source and the SQUID amplifier. The noise temperature at the amplifier input may be varied between 1 and 20 K by changing the SIS junction bias current. The advantages of an SIS noise generator in comparison with a variable temperature load noise generator are: full compatibility with the SQUID amplifier, the possibility of noise modulation, wide noise temperature range and exclusion of the feeder cable Johnson noise. This rather easy method may be used for IF amplifier calibration in an SIS heterodyne receiver and in such a case an SIS mixer would function as the noise source (Belitsky *et al* 1990)

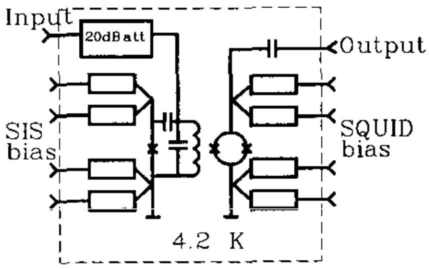

Figure 2. Schematic layout to measure gain and noise temperature of a SQUID amplifier with an SIS noise source.

4. SQUID amplifier noise measurements

Signal and noise characteristics were measured with a precise RF oscillator of Schlumberger 4009 type up to 550 MHz, a semiconducting noise source up to 1.3 GHz and an SIS junction as a low-level noise source. Figure 3(*a*) shows the *I–V* curve, with the amplified signal at 426 MHz and the noise at the output of the next stage amplifier in the presence of external irradiation at 16 GHz. One can see that under these particular conditions the noise temperature is halved and the gain doubled when the bias point is changed from the first to the second current step. Figures 3(*b*) and 3(*c*) show the same dependences for the pump frequency 36 GHz and without RF pumping.

Using an SIS noise source (figure 4(*a*)) enables one to make frequency dependences smoother and achieve a good input matching by applying SIS junctions with normal resistance equal to the SQUID amplifier optimal

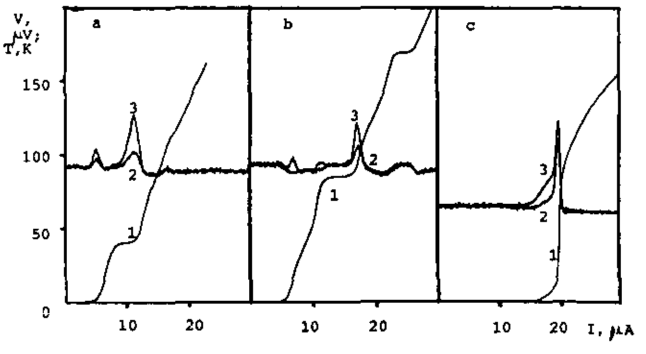

Figure 3. *I–V* curves (1), noise (2) and amplified signal (3) under external irradiation at 16 GHz (*a*), 36 GHz (*b*) and without external pumping (*c*).

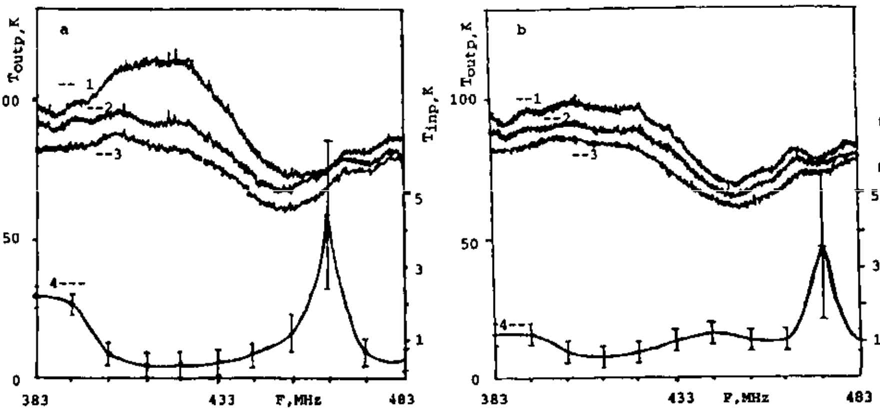

Figure 4. Output noise frequency dependences with (1) and without (2) input signal and at zero SQUID bias (3). Curve (4) is the noise temperature of a SQUID amplifier obtained with semiconducting (*a*) and SIS (*b*) noise sources.

input impedance. For comparison, in figure 4(*b*) are shown the same dependences obtained with a semiconducting noise source. In these figures the noise temperature reduces to 0.4 K, which is only twice the calculated quantum limit.

5. Conclusion

Application of external RF pumping to a DC SQUID amplifier is effective only for pump frequencies not higher than the characteristic frequency of a SQUID loop, which is determined by SQUID inductance. It is shown that a SQUID amplifier may be effectively used with an SIS mixer. Optimization of SQUID parameters allows one to achieve the SQUID amplifier noise temperature of 0.4 K, which is only twice the quantum limit for this SQUID amplifier at 400 MHz.

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