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High-sensitivity microwave RF SQUID operating at 77 K

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Abstract. High-T_c RF SQUIDS with bias frequencies in the microwave range exhibit low noise and high energy resolution compared with conventional 20 MHz RF SQUIDS. Especially interesting for applications is the absence of any low-frequency excess noise above about 1 Hz. Due to a relatively low flux focusing factor of the SQUID body, the field sensitivity of bare SQUIDS is only of the order of 1 pT $Hz^{-1/2}$. In this work, several modifications of the SQUID geometry were studied in some detail to decrease the flux noise further and to enhance the field sensitivity.

1. Introduction

The integration of conventional washer-type RF SQUIDs into a superconducting half-wavelength microstrip resonator which serves as a tank circuit [1], leads to compact planar sensors, which can be operated at high bias frequencies. In a previous paper [2] we demonstrated the feasibility of this concept for SQUIDs made of $YBa_2Cu_3O_7$. An interesting feature of the devices presented here is the low flux noise of about 10 $\mu\Phi_0$ $Hz^{-1/2}$ (for a 50 pH SQUID) and the absence of any low-frequency excess noise at frequencies about 1 Hz. However, despite the low flux noise, the field sensitivity of these SQUIDs is relatively low, compared with 150 MHz for washer-type RF SQUIDs [3]. This is due to the small flux focusing factor of the 400 μm wide microstrip resonator, which is of the order of 8, compared with 60 for a 8 × 8 mm^2 SQUID washer. To improve the field sensitivity, we have investigated several modifications in the sensor geometry to decrease its flux noise and increase the flux focusing factor.

2. Investigations of λ/2 microwave SQUIDs

A first modification or our original geometry [2, 4] is shown in figure 1. The square- or rectangular-hole SQUID is removed from the s-shaped resonator and attached parallel to its edge, where a higher current density can be expected, thus improving the coupling between SQUID and tank circuit (microstrip resonator). Two side wings, separated from the resonator by a 10 μm wide slit, were added to improve the flux focusing. The critical current of the step-edge junction used as a weak link was adjusted by a trimming process to obtain a $\beta_L \simeq 1$. Figure 2 shows an example of flux–voltage transfer functions of a 140 pH SQUID, for five different RF bias powers. In this case, a maximum value of the flux–voltage transfer function of about 200 $\mu V/\Phi_0$ could be obtained. Table 1 summarizes some important parameters of SQUIDs with the above-mentioned geometry and various inductances. Only an approximate value for the transfer function value $\partial V/\partial\Phi$ is given, since neither the input impedance of the preamplifier nor the (frequency-dependent) gain of the electronics could be determined accurately. All these data were obtained with a copper ground plane.

The inductance values at 77 K were determined using a three-dimensional calculation procedure, which accounts for the temperature dependence of the penetration depth $\lambda_L(T)$ in YBCO, with $\lambda_L(0) = 0.16$ μm [5]. In all cases, the noise was white to below 1 Hz, except at 25 pH, where the crossover to a $1/f$ noise occurred at 5 Hz. The spectral density of the white noise in most cases was proportional to L_s^2, in agreement with Kurkijärvi's theory of the white noise in RF SQUIDs [6]. It is believed that, at least for the low inductance SQUIDs, the measured noise is the intrinsic noise of the SQUID, since with the measured values of the SQUID signal voltage, an equivalent flux noise of the preamplifier of about 3 $\mu\Phi_0$ is calculated, which is lower than the intrinsic noise. The measured Q-value of the tank circuit of about 1000 results in a tank circuit noise of 2–3 $\mu\Phi_0$, which is also small compared with the intrinsic SQUID noise.

An estimation of the critical frequency of the SQUID $\omega_c = R_{wl}/L_s$, where R_{wl} is the normal resistance of the weak link, results in ω_c values of a few hundred MHz for the large inductance ($L_s > 400$ pH) SQUIDs if a weak-link resistance of the order of 1 Ω is assumed. In this

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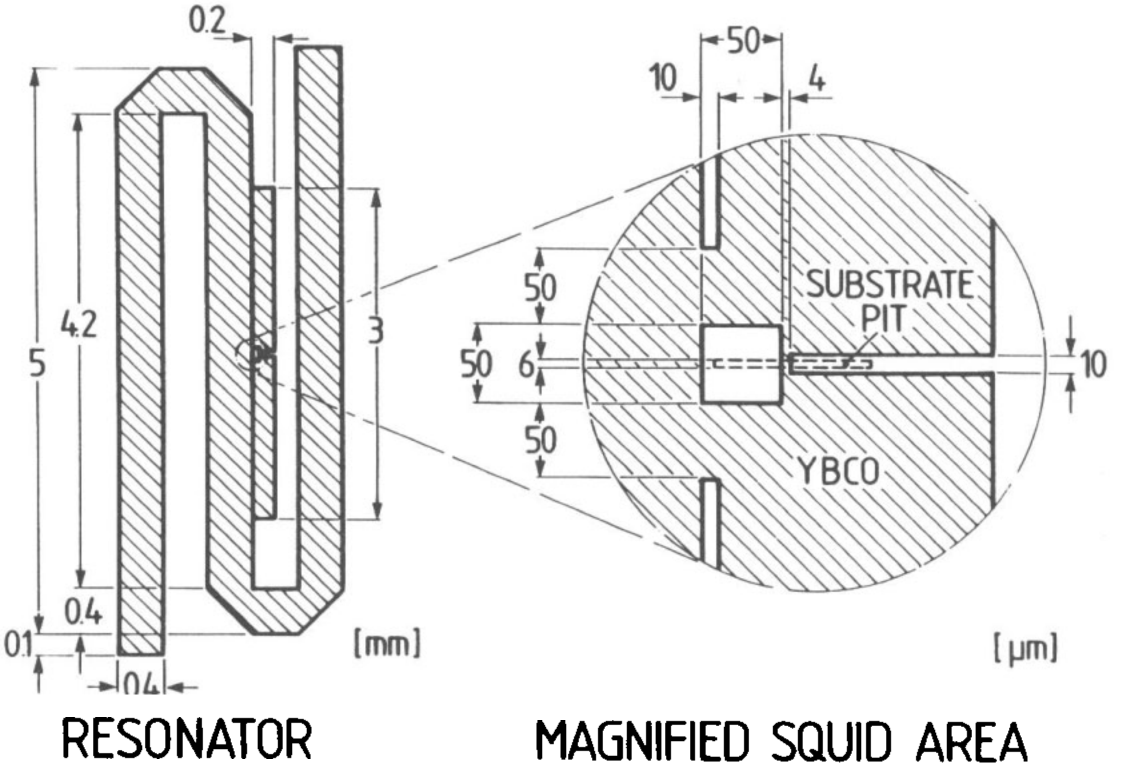

Figure 1. Design of a microwave SQUID integrated into a $\lambda/2$ microstrip resonator. The right-hand side is a magnified detail of the encircled part of the left-hand side.

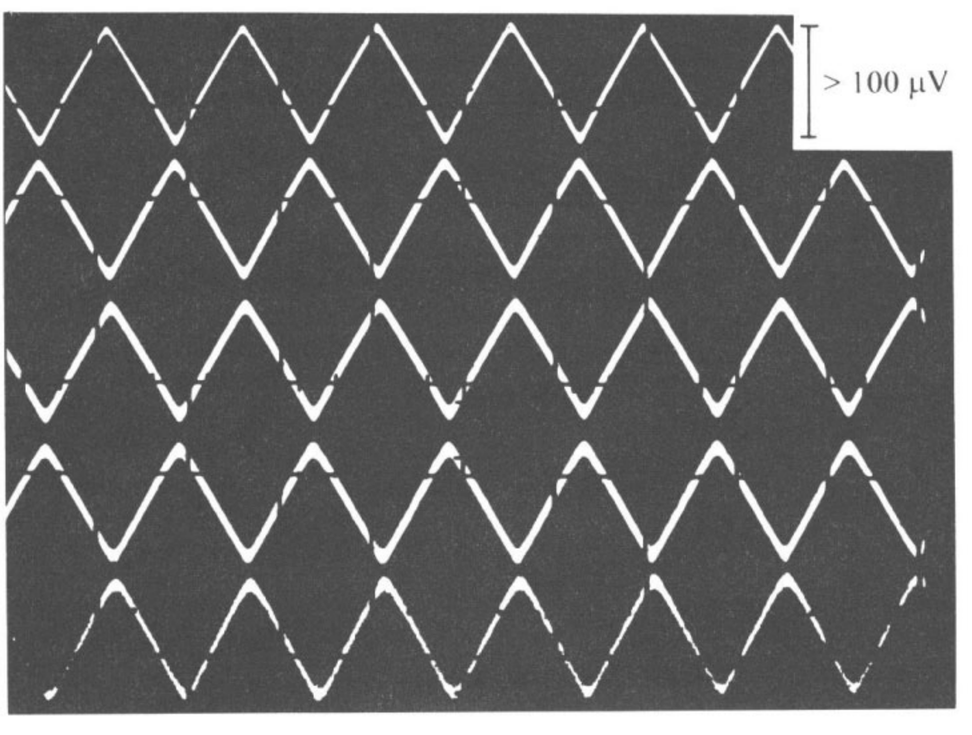

Figure 2. Flux–voltage transfer function of a 140 pH SQUID biased at five different power levels (first five steps of the tank circuit *I–V* curve).

Table 1. $\lambda/2$ microwave SQUID characteristics at various inductances.

Hole area	$a \times b$	μm^2	20×20	30×30	50×50	100×60	400×60
Inductance	L_s	pH	25	42	78	140	440
Transfer function	$\partial V/\partial\Phi$	$\mu V\ \Phi_0^{-1}$	300	300	300	200	80
Flux noise	$S_\Phi^{1/2}$	$\mu\Phi_0\ Hz^{-1/2}$	8.5	12	18	33	110
Energy resolution	ϵ	10^{-30} J Hz^{-1}	5.8	6.8	8.3	16	55
Field-flux coeff.	$\partial B/\partial\Phi$	nT Φ_0^{-1}	250	170	90	45	15
Field resolution	B_N	pT $Hz^{-1/2}$	2.1	2.0	1.6	1.5	1.5

Table 2. Effect of a bulk YBCO flux focuser used as groundplane for $\lambda/2$ microwave SQUIDs. The S_Φ, $\partial V/\partial\Phi$ and B_N data are for copper (upper lines) and superconducting ground plane (lower lines).

Hole area	$a \times b$	μm^2	100×10	100×60	400×60
Flux noise	$S_\Phi^{1/2}$	$\mu\Phi_0\ Hz^{-1/2}$	16	33	95
(with focuser)			10	26	50
Field-flux coeff.	$\partial B/\partial\Phi$	nT Φ_0^{-1}	105	45	15
(with focuser)			56	28	11
Field resolution	B_N	pT $Hz^{-1/2}$	1.7	1.5	1.4
(with focuser)			0.56	0.65	0.75
Gain in B_N	—	—	3	2.3	1.9

Table 3. λ-resonator microwave SQUID characteristics at various SQUID hole geometries.

Hole area	$a \times b$	μm^2	100×10	300×10	100^2+150×10
Inductance	L_s	pH	63	150	240
Transfer function	$\partial V/\partial\Phi$	$\mu V\ \Phi_0^{-1}$	100	100	80
Flux noise	$S_\Phi^{1/2}$	$\mu\Phi_0\ Hz^{-1/2}$	28	31	50
Energy resolution	ϵ	10^{-30} Hz^{-1}	25	12.8	21
Field-flux coefficient	$\partial B/\partial\Phi$	nT Φ_0^{-1}	27	10.4	4.7
Field resolution	B_N	pT $Hz^{-1/2}$	0.75	0.32	0.23

case, it is questionable whether a high bias frequency of 3 GHz will result in a lower noise value than in conventional 150 MHz washer SQUIDs [3], or not.

In order to improve the field-flux coefficient, the normal conducting copper ground plane of the microstrip resonator was replaced by a bulk YBCO disc. The disc, 29 mm in diameter, serves as a flux focuser. It was split in half and then glued together, to provide an insulating slit. The slit and a 1 mm diameter hole in the centre of the disc allow flux to penetrate the focuser. With a relatively large separation between SQUID and focuser, which was imposed by the 0.5 mm thick $LaAlO_3$ substrate, a modest increase in the field resolution by a factor of 2 to 3 was obtained (see table 2). This increase was mainly due to a reduction of the flux noise by a factor of 1.5 to 2. The origin of this noise reduction is attributed to a possibly high field noise of the normal conducting copper groundplane and a slight reduction of the SQUID inductance by the presence of the superconducting ground plane.

3. λ-resonator SQUIDs

Another method for obtaining a higher field resolution is the addition of a current-coupled pick-up loop to the SQUID (see figure 3). An elegant realization of this pick-up loop is the integration of the SQUID into a λ ring resonator [7] (see figure 4), where part of the DC screening current in the ring resonator flows through the SQUID, thus increasing the field resolution. A rough estimation of the maximum field gain, which can be expected in this geometry, leads to a gain of r_{rr}/r_{SQ}, where r_{rr} is the radius of the ring resonator and r_{SQ} that of the SQUID. For a bias frequency of 3 GHz and an $LaAlO_3$ substrate with $\epsilon \simeq 25$ ($\epsilon_{eff} \simeq 16$), an overall length of 30 mm is needed for the λ-resonator (see figure 4). To place the SQUID loop near the centre of the substrate, where the film quality is expected to be optimum, the ring resonator was given a kind of constriction. Table 3 summarizes some important parameters of λ SQUIDs, for various SQUID hole geometries.

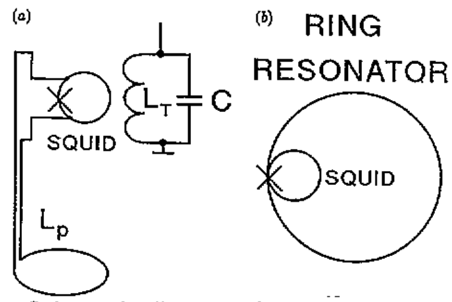

Figure 3. Schematic diagram of a SQUID with a current-coupled loop to improve field resolution. (*a*) lumped element tank circuit, (*b*) ring resonator serving as a current-coupled pick-up loop.

Despite the higher flux noise at the same SQUID inductance level, a seven-fold improvement in field sensitivity over that of the $\lambda/2$ SQUIDs is obtained. The field gain of the pick-up loop is of the order of 40 to

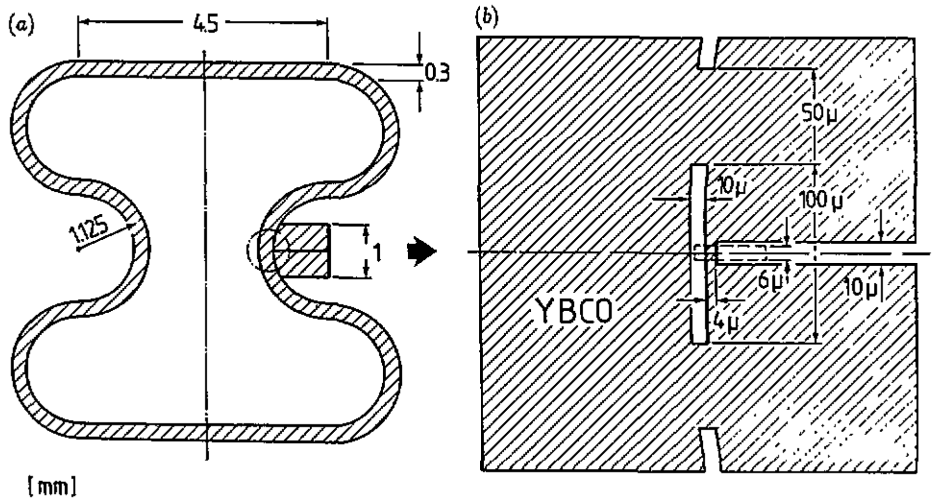

Figure 4. Design of a microwave SQUID integrated into a λ ring resonator. (*b*) is the magnified detail of the encircled part of the resonator (*a*).

80, and corresponds roughly to the ratio of the radii of SQUID hole and pick-up loop. The reason for the somewhat lower transfer function and higher flux noise is not clear yet. It is believed that the coupling between SQUID and resonator as well as the quality factor of the resonator are comparable to those of the λ/2 SQUIDs. Investigations to clarify this point are under way.

4. Conclusion

Low flux noise values and a low crossover frequency to $1/f$ noise could be achieved in microwave biased RF SQUIDs. Here λ-ring resonator SQUIDs exhibit the maximum field sensitivity, whereas the lowest value of energy resolution is obtained when using low-inductance λ/2 SQUIDs. A further increase in field sensitivity is realized by the use of a superconducting ground plane, which, however, if fabricated from bulk material, can give rise to additional low-frequency excess noise. The geometry of the SQUID should allow for the integration of superconducting input coils, which, in combination with low inductance λ/2 SQUIDs, should lead to even higher field sensitivities.

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