Experiments with a un SQUID based integrated magnetometer.*

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Abstract

The unshunted (un) SQUID is a novel device, whose Josephson junctions are locally damped at high frequencies only. At low frequencies damping is provided by the readout circuitry. We have constructed a LTS device in which a un SQUID chip is flip-chip bonded to thin film pick-up loops in magnetometer and gradiometer configurations. The device shows a noise level below $10^{-6}\ \Phi_0\sqrt{\mathrm{Hz}}$. The device characteristics appear to follow the previously published theory. This device is the first practical implementation of the un SQUID.

1 Introduction

We have designed and manufactured magnetic field sensors based on unshunted (un) SQUIDs. The damping of the Josephson junctions in the un SQUID is provided at high frequencies (Josephson oscillation) by resistors close to the junctions and at low frequencies (measurement band) by the readout electronics. This arrangement behaves as if we were measuring the current flowing through the shunt resistors of a traditional dc SQUID. According to simple analytic analysis and also according to numerical simulations, the un SQUID has lower noise than the dc SQUID. To provide damping for the SQUID at low frequencies another SQUID is recommended to be used as readout electronics. In principle any other high speed current amplifier can be used.

The sensors consist of a 2×2 mm SQUID chip (Fig. 1) flip-chip bonded to a 20×20 mm pickup coil chip (Fig. 2). The pickup coil chip contains a thin-film magnetometer and two orthogonal first-order gradiometers. The SQUID chip contains three un SQUIDs and three dc SQUIDs used for readout, plus one

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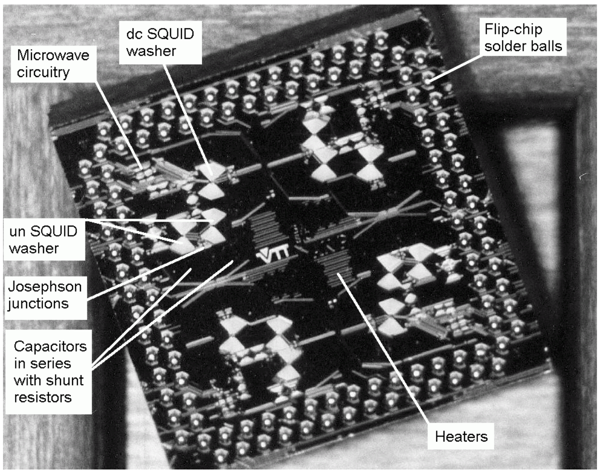

Figure 1: The 4-channel SQUID chip, each channel consisting of a un SQUID and a dc SQUID for readout.

redundant un/dc SQUID pair. The current-voltage (IV-) characteristics exhibit the predicted negative-resistance region and the noise level attained indicates that the device is stable.

The novel construction of the un SQUID consists of a 15 pH doubly-octagonal two-hole washer, 4 μm diameter Nb-AlO$_x$-Nb Josephson junctions, a 14-turn signal coil and circuitry to handle LC resonances and terminate microwave signals. The device parameters are $\beta_c = 0.7$, $\beta_l = 2.5$, $c = 0.005$ and $q_b = 2.8$ (for definitions of c and q_b see [2]). Our recent simulations verify that these parameters ensure low noise and smooth IV characteristics. The junctions are located at the lowermost layer where the underlying surface quality is best, with the purpose of reducing the critical current fluctuation. Because un SQUID requires voltage bias, a traditionally shunted on-chip dc SQUID is used for current readout (Fig.3). On each SQUID chip there are 112 Sn-Pb-Bi solder balls of 50 μm diameter for flip-chip bonding.

Because flip-chip bonding allows low-inductance superconducting chip-to-chip connections, there is no need for an intermediate transformer. Instead, the input coil is directly coupled to the fractional-turn pick-up coil comprising several parallel loops. Flip-chip bonding allows fabrication of the area-consuming pick-up coils with a simpler process.

2 Experiments

We have measured behaviour of the complete sensor with the readout (dc-) SQUID operated in flux locked loop. The un SQUID connected to the pickup coil was outside of the feedback loop. No bias modulation was utilized in this experiment. We found the white noise level below 10^{-6} $\Phi_0/\sqrt{\mathrm{Hz}}$ at frequencies down to a few tens of Hz. This figure corresponds to the gradiometer sensitivity of 3.4 fT/(cm$\sqrt{\mathrm{Hz}}$) and the magnetometer sensitivity of 2.0 fT/$\sqrt{\mathrm{Hz}}$. It should be emphasized here that the inductance of the magnetometer was purposely

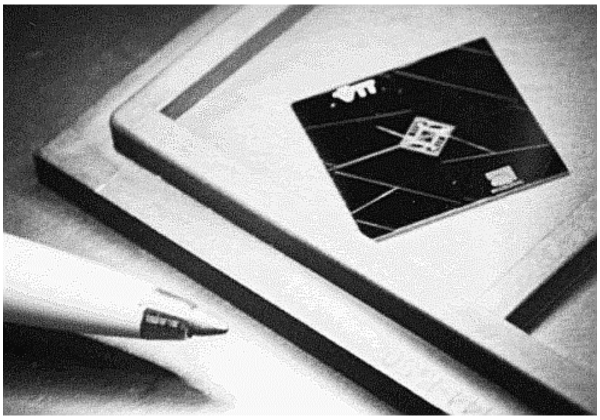

Figure 2: The pickup coil chip, containing a magnetometer and two planar orthogonal gradiometers.

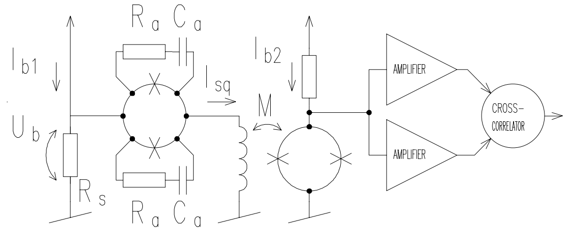

Figure 3: Biasing and preamplifier arrangement for the cross-correlation experiment.

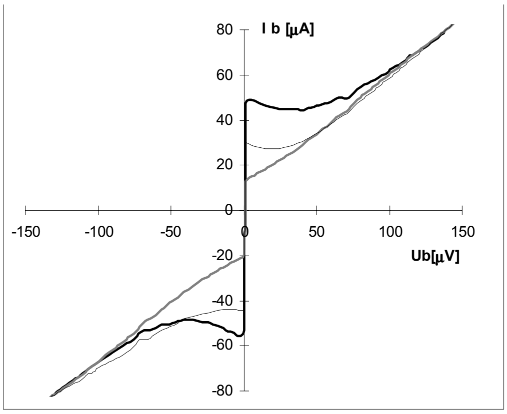

Figure 4: IV curves of the un SQUID sensor, read using a dc SQUID in flux locked loop.

unmatched to the inductance of the signal coil and thus the field sensitivity remained much below the value allowed by the pick-up loop area.

Since the readout SQUID had a gain of $\partial V/\partial\Phi \approx 120\ \mu\mathrm{V}/\Phi_0$ and the flux conversion gain from un SQUID input to the readout SQUID input was measured to be about 8, the noise is dominated by the op amp voltage noise, specified at $\sim 1\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$.

We also measured the noise of the un SQUID with the signal coil present but not connected to the pick-up loop. To get rid of the amplifier noise two independent LT1028 op amps were used to detect the dc SQUID output signal and outputs of the amplifiers were correlated (Fig. 3). Since the dynamic output resistance of the dc SQUID is low, the correlated part of the output signals of the amplifiers is due to the dc SQUID. The correlation method enabled us to to eliminate the noise contributions of the room temperature amplifiers but the contribution of the dc SQUID remains. The dc SQUID noise was measured when the un SQUID was biased to the zero voltage stage, and subtracted to obtain the plain un SQUID noise. We were able to conclude that the white noise of this particular un SQUID is $(3.5 \pm 0.5)\ \times 10^{-7}\ \Phi_0/\sqrt{\mathrm{Hz}}$. This means that the limitation for the gradient field sensitivity set by the un SQUID would be about 1 fT/cm and for the the magnetic field sensitivity about 0.7 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$ if our 2 cm x 2 cm pick-up was used.

The measured current-voltage characteristics (Fig. 4) showing a negative recistance region resemble those of the hg SQUID rather than those of the un SQUID. In the un SQUID the negative resistance region should extend to all bias voltages. We suspect that this inconsistency is due to the parasitic flux leakage described below.

3 Discussion

3.1 Flux leakage

Using a simple model the output current of the un SQUID, including the parasitic flux leakage from the input bias current to the next SQUID amplifier stage, can be given as

$$i_{sq} = \sqrt{u_b^2 + \cos^2 \varphi_a} - (1 - r_m) u_b \tag{1}$$

where $u_b = U_b / R_a I_c$, $i_{sq} = I_{sq}/2I_c$, $r_m = M_{ext} R_a / (2 R_s M)$ and $\varphi = \pi \Phi_a / \Phi_0$. Here R_a is a shunt resistance of the Josephson junction at high frequencies, R_s is the shunt resistor providing the voltage bias for the un SQUID, M is the mutual inductance between the signal coil and the SQUID loop of the preamplifier SQUID, M_{ext} is the parasitic magnetic coupling from the bias current I_{b1} to the input of the preamplifier SQUID, I_c is the critical current of the Josephson junction and I_{sq} is the output current of the un SQUID.

We have named the SQUID with an additional resistance R_d across the un SQUID output a *hg SQUID* [1]. Unfortunately, any magnetic coupling from the bias current for the voltage source to the input of the readout SQUID converts the un SQUID to the hg SQUID.

Using the model given in Eq. 1 $r_m = 0.5$. Since R_s is 0.2 Ω, R is 2 Ω, and $M = 200$ pH, we get $M_{ext} = 20$ pH, which is close to the inductance of the SQUID loop. We are unware of the detailed mechanism that couples the bias current for the un SQUID to the preamplifier SQUID.

The measured IV characteristics are closely similar to the theoretical characteristics of a hg SQUID with $r = 0.5$. The result indicates that we were able to eliminate signal coil resonances and also to terminate the microwave transmission lines, i.e, a coupled SQUID behaves like an autonomus device.

3.2 Noise

Since this particular un SQUID behaves as a hg SQUID we estimate its theoretical flux noise based from the data obtained for the hg SQUID. Due to the magnetic coupling discussed above, not only the IV characteristics but also the noise characteristics of the un SQUID are modified. Consequently, we estimate $S_\Phi^{hg} = 16 k_B T L^2 / R_a$, which when applying to this particular case leads to the flux noise of the order of 1.5×10^{-7} $\Phi_0/\sqrt{\mathrm{Hz}}$. To eliminate a possible excess noise, the transmission lines formed by the signal coil and the rest of the flux sensing coil are terminated for microwave signals. Because of the load resistance at high frequency we also have a high frequency current fluctuations in the pick-up loop. Easiest way to estimate the noise related to the termination is to transform the microwave load to the SQUID loop. The spectral density of the high frequency current noise can be now given as $S_i^{hf} \approx 4 k_B T n^2 / R_{mic}$. Taking into account the mixing between the Josephson oscillation and the current noise we get $S_\Phi^{mic} \approx k_B T L^2 n^2 / R_{mic}$. Now we may write the prediction for the flux noise in the form

$$S_\Phi = \frac{16 k_B T L^2}{R_{ac}} \left(1 + \left(\frac{n}{4} \right)^2 \frac{R_{ac}}{R_{mic}} \right) \tag{2}$$

This result can be considered principally as a lower limit, because the mixing between the current noise and the higher harmonics of the Josephson oscillation

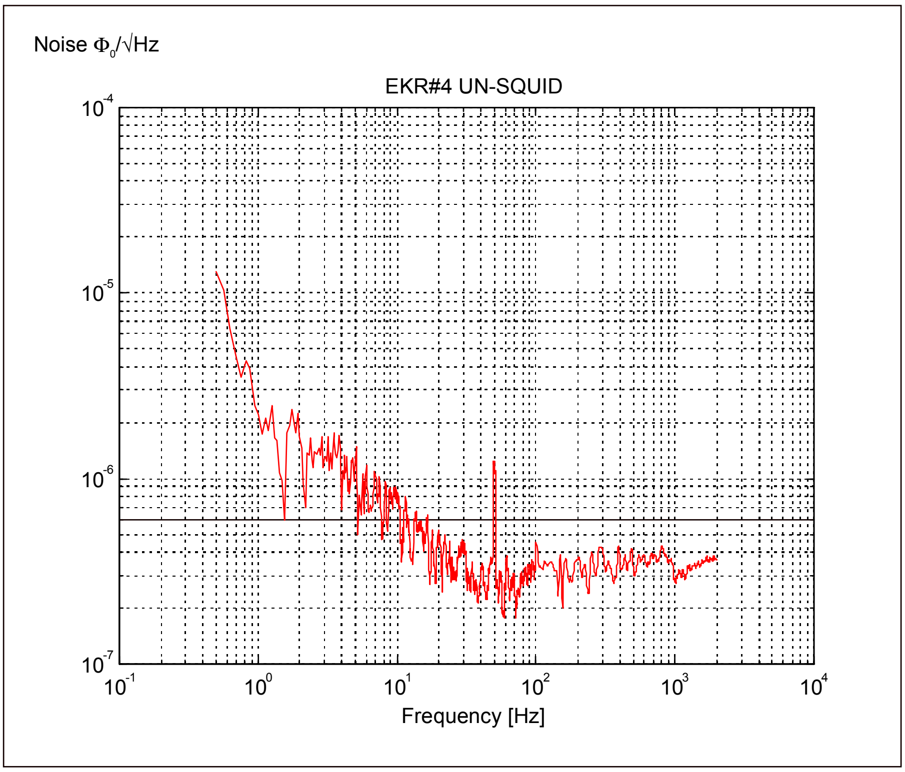

Figure 5: Flux noise of a un SQUID measured with the cross-correlation technique.

are neglected. We can now estimate that in this device $S_\Phi^{un} \approx 1.5 \times 10^{-7}$ $\Phi_0/\sqrt{\mathrm{Hz}}$. Taking into account the intrincic noise of the SQUID and noise from the pick-up loop we get $S_\Phi \approx 3 \times 10^{-7} \Phi_0/\sqrt{\mathrm{Hz}}$. This analysis suggests that we are unable to obtain lower flux noise from the SQUID following this design. The noise could be sligtly lower if the addiotional magnetic coupling could be eliminated but the noise from the pick-up loop is difficult to overcome.

4 Conclusion

We have constructed a magnetic field detector characterized by a small size and a low noise. It detects both magnetic field and two of its gradients in a very compact way. The SQUID based on the unshunted Josephson junctions were used but the flux leakage modified its IV characteristics so that they now resemble more those of the hg SQUID. The noise of the SQUID was very close to the predicted values. The calculations and experiments indicate that the noise of the system is limited not only by the SQUID noise but also by the noise originating in the microwave termination in the pick-up loop. Noise from the room temperature electronics limited the measured gradient noise to 3.4 fT/(cm$\sqrt{\mathrm{Hz}}$) and field noise to 2.0 fT/$\sqrt{\mathrm{Hz}}$.

References

[1] H. Seppä, M. Kiviranta and L. Grönberg, "Dc SQUID based on unshunted Josephson junctions: experimental results," *IEEE Tran. Appl. Supercond.*, vol. 5, no. 2, p. 3248, 1995.

[2] M. Kiviranta and H. Seppä, "Noise simulation of the un SQUID", these abstracts.