Optimized SQUID sensors for low frequency measurements

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Abstract. We have fabricated and measured optimized SQUID sensors (superconducting quantum interference device) for low frequency measurements of magnetic field. We have also investigated the dependence of flux trapping field on the position of Josephson junctions with respect to the Ketchen-type washer. The sensors are measured using direct room temperature readout utilizing noise cancellation techniques based on negative and positive feedback. A superconducting magnesium diboride can is used to shield the sample in pulse-tube cryocooler measurements.

1. Introduction

Superconducting quantum interference devices (SQUID) are widely used to detect magnetic flux in geo- and biomagnetic applications. In many cases, only niobium-based low critical temperature (low-$T_c$) SQUIDs are capable of measuring tiny low frequency magnetic signals under study. Recently, so-called atomic magnetometers have yielded sub-fT noise level even without cryogenic environment \cite{1}. Due to this challenge, noise performance and general behaviour of SQUIDs should be improved especially in cryocooler operation. Recent advances \cite{2} in SQUID-based low field magnetic resonance imaging (MRI) have lead many groups to work on combining MRI with magnetoencephalography (MEG) \cite{3, 4}. If successful, this combination could enable both functional and structural image of human brain which in turn has positive impact on both scientific brain studies and also commercial applications of superconductors.

In this work we have studied shielding of low-$T_c$ SQUIDs in cryocooler environment. We have also performed measurements in liquid helium with SQUIDs coupled to large magnetometer pickup coils in order to study noise and trapping of flux to Josephson junctions. This ability to tolerate large fields is especially important in MRI applications.

2. Design

The SQUID is equipped with a flux transformer circuit to provide good coupling to reasonably sized pickup coil and to minimize parasitic capacitance and control resonances at frequencies less than Josephson frequency. Figure 1a shows the schematic layout of the circuit.

In basic optimization the parameters $\beta_c = 2\pi R_s^2 I_c C_J / \Phi_0$ and $\beta_L = 2L_s I_c / \Phi_0$ are kept below unity. Using conservatively-sized junctions with diameter of 6 $\mu$m, critical current $I_c = 50$ $\mu$A and shunt resistance $R_s = 1.3$ $\Omega$ yields $\beta_c = 0.5$. The junction capacitance $C_J \sim 2$ pF takes into account parasitic capacitance arising from the contact via of the junction. Figure 2 shows CAD...
Figure 1. a) Schematics of the SQUID and the intermediate transformer. b) Schematic view of the voltage bias readout with negative flux feedback via FET.

The layout of the SQUID washer with 16-turn input coil. Josephson junctions (JJ’s) are situated either near the centre of the washer or outside the input coil. The inductance of the SQUID loop is $L_s \approx 7 \text{ pH}$. The design is reviewed more closely in [5]. The flux noise of the autonomous SQUID at 4.2K, $\Phi_n = (24 k_B T L_s \sqrt{L_s C_J})^{0.5} \approx 0.1 \mu\Phi_0/\sqrt{\text{Hz}}$.

Figure 2. CAD layout of the SQUID. Two circular Josephson junctions are visible in the centre of (left panel) / outside (right panel) the input coil. The shunts are on the outer edge.

To account for the input coil $L_{in}$ on top of the washer we have made numerical simulations with distributed inductor-capacitor model. Using this model a suitable resistor - capacitor shunt $R_{in} - C_{in}$ is chosen to terminate the lowest-order input coil resonance at 3.3 GHz. Similar simulations for larger intermediate transformer reveal several resonances starting well below one GHz. These resonances are somewhat damped using $R_{sec} - C_{sec}$ shunt in parallel with the secondary coil $L_{sec}$. We have also utilized a low-Q filter (labelled LP in figure 1a) to separate washer and input coil from the resonance-plagued intermediate transformer. It is advantageous to have large termination impedance for transformer coils since, at high frequencies, they transform into a small resistor ($\sim 500 \text{ m}\Omega$) parallel to the input coil. In worst case, it corresponds to $\sim 1.2 \mu\Phi_0/\sqrt{\text{Hz}}$ noise in the SQUID. However, the noise current is partially screened by $L_{pri}$ and is only effective as mixed-down noise.

In practical applications, the SQUID is read out by room temperature amplifier. Noise matching requires increase of SQUID output impedance by local feedback [6]. The case of negative feedback (noise cancellation) is shown schematically in figure 1b. In practise the amplifier voltage noise is eliminated and the dominant noise is due to thermal noise of the FET channel:

$$\Phi_{n,FET} = \sqrt{\frac{4k_B T M_{fb}}{\partial U/\partial \Phi}},$$  \hspace{1cm}(1)$$

where $M_{fb}$ is the mutual inductance of the feedback coil and $\partial U/\partial \Phi \sim 100 \mu V/\Phi_0$. In our sensors the feedback can be connected to either of the two feedback coil inputs (labelled as FB in figure 1a). In the high mutual inductance input, $\Phi_{n,FET} \approx 0.7 \mu\Phi_0/\sqrt{\text{Hz}}$.

Irreversible flux trapping in Josephson junctions can be a serious problem in multi-SQUID applications. To experiment this, we have designed sensors where the JJ area is shifted from
the centre of the washer towards the edge (see right panel of figure 2). In edge junction SQUIDs the parasitic capacitance of the slit cover must be added to junction capacitance. Also loop and mutual inductances are increased.

3. Fabrication
The fabrication is based on a Nb/Al-AlOx/Nb Josephson junction process utilizing optical lithography with minimum line width of 3 \( \mu \text{m} \) [7]. The junctions are patterned using anodization. The critical current density of 200 A/cm\(^2\) can be monitored during the process using automatic wafer-scale prober to measure the resistance of test JJs around the wafer [9]. The first SiO\(_2\) insulating layer is planarized using chemical-mechanical polishing. An external pickup coil can be contacted to Pb-alloy bonding pads by superconducting wires.

4. Measurements
Various shielding arrangements are studied in cryocooler setup (Optistat AC-V, Oxford Instruments, UK). MgB\(_2\) shield, supplied by EDISON SpA, Milan, Italy [8], yielded better results compared to Pb partially due to easier thermal anchoring of higher \( T_c \) material. In these measurements SQUID was current biased and the voltage was read out by INA163 instrumentation amplifier. A local positive feedback (APF) was used to obtain noise matching. Figure 3 shows flux modulation as function of current in feedback coil with different current bias values ranging from 0 to 150 \( \mu \text{A} \). The effect of shielding is illustrated in figure 4, which shows flux modulation curves (no APF) with different shielding arrangements. Without shielding the modulation curve is spoiled by magnetic disturbances.

![Figure 3](image1.png)

**Figure 3.** Flux modulation curves with positive feedback off (left panel) and with optimal feedback (right panel) measured with Pb shield.

![Figure 4](image2.png)

**Figure 4.** Flux modulation curves with different shielding materials in cryocooler environment.

Noise characterization was carried out in shielded liquid-\(^4\)He dewar with voltage bias readout utilizing noise cancellation. In these measurements, a pickup coil was connected to the input. The following table 1 shows the white flux noise at 88 Hz measured from several sensors. The effect of slightly different transmission-line terminations is negligible, i.e. within the typical scatter of data. Smaller mutual inductance of feedback coil \( M_{fb} \) has barely notable effect as
verified also by equation 1. The dominant excess noise mechanism is probably instability of local feedback at high frequencies above the amplifier bandwidth.

Flux trapping was studied by applying slow \((f = 5 \text{ Hz})\) magnetic field sweep from a 18 mm-diameter copper coil attached on top of the magnetometer pickup. The amount of flux quanta \(\Phi_0\) penetrating the SQUID loop was counted and the amplitude of flux modulation curve i.e. SQUID current was monitored. At some field the amplitude dropped by 20 - 30 percent and did not recover even in zero field unless an on-chip heater was used. We interpret that the drop of modulation amplitude is due to flux trapping in the JJ’s which decrease the critical current \(I_c\) permanently. The flux density in the washer hole approaches the critical field of Nb (200 mT) making the center junctions vulnerable to trapping. The following table 1 shows the amount of \(\Phi_0\)’s needed to decrease \(I_c\) for SQUIDs with different junction positions. The edge junction SQUID (D1) did not show any decrease even with maximum flux sweep corresponding to average magnetic field of \(\sim 15 \text{ µT}\) at the pickup or a field of order of the critical field of Nb in the SQUID loop.

| Table 1. Flux noise in \(\mu\Phi_0/\sqrt{\text{Hz}}\) and trapping flux in number of \(\Phi_0\)’s of several types of SQUID sensors. A1: center JJ’s, conservative transmission-line terminations. A2: As A1, but smaller \((\sim 1/3)\) mutual inductance \(M_{fb}\). B1: As A1, but three times larger \(R_{sec}\). C1: As A1, but junctions between turns 2 and 3 of the input coil (starting from center). D1: As A1, but junctions outside the input coil (see figure 2). |          |
|-------------------------------------------------|--------|
| SQUID type                                      | A1     | A2     | B1     | C1     | D1     |
| minimum noise                                   | 1.0    | 1.1    | 1.3    | 1.2    | 1.1    |
| average noise                                   | 1.4    | 1.3    | 1.5    | 1.4    | 1.5    |
| flux quanta                                     | 350    | -      | -      | 1300   | larger than 7300 |

5. Conclusions
We have fabricated low noise SQUID sensors and operated them in MgB2-shielded cryocooler environment. By placing Josephson junctions outside input coil the SQUID sensor tolerates magnetic fields of several tens of \(\mu\text{T}\) which makes possible to use them in low field MRI.

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References
[1] Komins I K, Kornack T W, Allred J C and Romalis M V 2003 Nature 422 596
[2] McDermott R, Trabesinger A H, Mück M, Hahn E L, Pines A and Clarke J 2002 Science 295 2247
[3] Volegov P, Matlachov A N, Espy M A, George J S and Kraus Jr. R H 2004 Mag. Reson. Med 52 467
[4] http://megmri.tkk.fi
[5] Seppä H, Kiviranta M, Satrapinski A, Grönberg L, Salmi J and Suni I 1993, IEEE Trans. Appl. Supercond. 3 1816
[6] Kiviranta M and Seppä H 1995, IEEE Trans. Appl. Supercond. 5 2146
[7] Grönberg L, Seppä H, Cantor R, Kiviranta M, Ryhänen T, Salmi J and Suni I 1991, Proc. 4th Int. Conf. SQUID’91, Berlin, p. 281
[8] Giunchi G, Ripamonti G, Cavallin T and Bassani E 2006, Cryogenics 46 237
[9] Grönberg L, Hassel J, Helistö P and Yilammi M 2007 IEEE Trans. Appl. Supercond. 17 952