Signal enhancement techniques for rf SQUID based magnetic imaging systems

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Abstract
We have investigated the rf SQUID (radio-frequency superconducting quantum interference device) and its coupling to tank circuit configurations to achieve an optimal front-end assembly for sensitive and high spatial resolution magnetic imaging systems. The investigation of the YBCO rf SQUID coupling to the conventional LC tank circuits revealed that coupling from the back of the SQUID substrate enhances the SQUID signal while facilitating the front-end assembly configuration. The optimal thickness of the substrate material between the SQUID and the tank circuit is 0.4 mm for $LaAlO_3$ resulting in an increase of the SQUID flux–voltage transfer function signal, V_{spp}, of 1.5 times, and 0.5 mm for $SrTiO_3$ with an increase of V_{spp} of 1.62 times compared to that for direct face to face couplings. For rf coupling with a coplanar resonator, it has been found that the best configuration, in which a resonator is sandwiched between the SQUID substrate and the resonator substrate, provides a V_{spp} about 3.4 times higher than that for the worse case where the resonator and the SQUID are coupled back to back. The use of a resonator leads to a limitation of the achievable spatial resolution due to its flux focusing characteristics. This resulted in a favouring of the use of the conventional tank circuits when considering the desired high spatial resolution. The effect of the YBCO flip chip magnetic shielding of the SQUIDs in the back-coupling with the LC tank circuit configuration has also been investigated, with a view to reducing the SQUID effective area to increase the spatial resolution and also for studying the effect of the coupling of various kinds of transformers to the SQUIDs. It is revealed that there is no very considerable change in the flux–voltage transfer function signal level with respect to the effective shield area, while the lowest working temperature of the SQUIDs was slightly shifted higher by a couple of degrees, depending on the shield area.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

For sensitive applications of rf SQUID based magnetic imaging systems, where high magnetic field sensitivity with high spatial resolution is required, two important issues to be considered are the front-end assembly of the rf SQUID based system and the rf SQUID flux to voltage transfer function signal level, V_{spp} [1, 2]. With respect to the system design, use of high T_c SQUIDs is superior compared to that of low T_c devices,

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mainly due to the lift-off distance (LOD), the distance between the SQUID and the sample, which plays a vital role for front-end assembly. LOD is inevitably widened for helium based systems, whereas it can be decreased to a few tens of microns in nitrogen based systems by using a thin window. Designing such a system offers serious challenges especially when it is required to work for samples at room temperature, which furthermore requires a precise separation adjustment system. Bottlenecks allied to such applications of the rf SQUID based systems are highlighted and investigated in this work. In this study we have probed some of these limiting factors, which not only provides insight for improving the sensitivity and field resolution, but also helps in the development of new configurations for the front-end assembly of high resolution magnetic field imaging systems [3–5].

2. Sample preparation and the experimental set-up

The rf SQUID magnetometers and gradiometers were made using YBaCuO film deposited on $LaAlO_3$(100) and $SrTiO_3$ (100) substrates. The YBaCuO films were deposited by pulsed laser deposition techniques using a KrF excimer laser and were patterned using either wet chemical etching in 0.25% dilute phosphoric acid or a low energy argon IBE process. The rf washer SQUIDs were made either using step edge junctions or bicrystal grain boundary junctions. The magnetometers were made using a layout with a 3.5 mm diameter washer and a loop size of 150×150 μm^2. The gradiometers were made using layouts with washer areas with 1.5 mm diameter, loop areas of 75×75 cm^2 and a baseline of 1.5 mm [6].

During our study, a coplanar resonator and flux concentrator was fabricated on a standard STO substrate coated with a 200 nm layer of YBCO film. An rf SQUID is placed on the $10 \times 10 \times 1$ mm^3 substrate to form a flip chip package [7].

3. Analytical coupling techniques and improving techniques

3.1. Coupling techniques advantages and disadvantages

Both field sensitivity and spatial resolution for SQUID microscopes are highly dependent on the distance between the sensor and the sample. Hence, we have investigated various approaches for coupling the rf SQUID sensor and the samples to find the optimal configuration. The high field sensitivity of high T_c rf SQUIDs is associated with their large area layout; this area inherently hinders achieving high spatial resolution. The washer area of the rf SQUIDs must be optimized for the minimum area needed for efficient coupling to the rf coupling circuit [5].

As a replacement for the conventional LC tank circuit, which not only provides less V_{spp} but also takes more space, thus hindering the front-end assembly, thin film superconducting coplanar resonators were used and investigated in the flip chip configuration [7, 8]. In the case of the coplanar resonator, we used either an 8 mm rectangular (SR8) or a 13.4 mm circular (SR13) layout design with integrated flux concentrators [7]. The difference between the performances of the rf SQUIDs using these couplings was investigated. As shown in figure 1, the V_{spp} is an order of
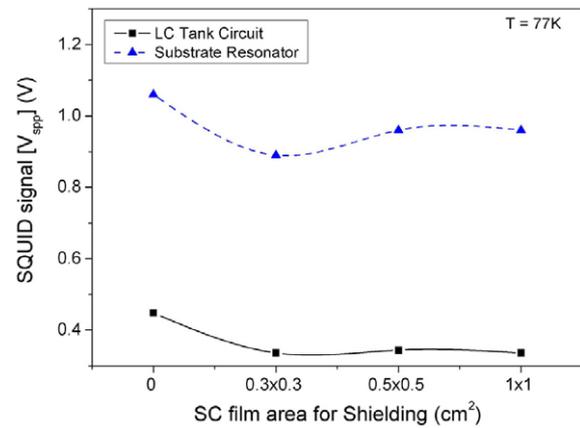
Figure 1. Comparison between the tank circuit and resonator for the rf SQUID signal level under different shielding conditions. A shielding SC film has been applied in the flip chip configuration.
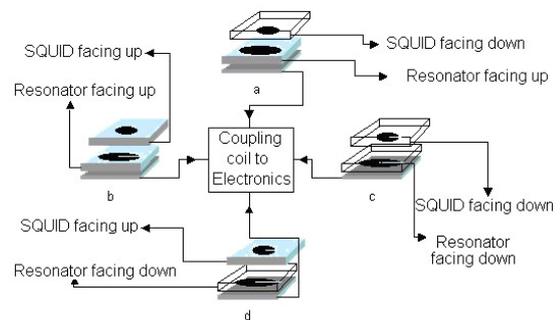

Figure 2. Basic possible configurations for the resonator to rf SQUID coupling.

magnitude higher in the case of coplanar resonator compared to a LC tank circuit. The noise level of the rf SQUIDs has been found to be almost independent of the type of rf coupling technique [9], favouring the use of the tank circuit when considering the desired high spatial resolution. It is to be noted that the use of coplanar resonators with integrated flux concentrators introduces serious limitations in the spatial resolution. The possibilities for coupling with the coplanar resonator that were investigated are shown in figure 2.

3.2. Signal improvement techniques

Results obtained from our systematic study of the techniques of coupling for the resonator, rf SQUID and pick-up coil of the electronics are listed in table 1. In the type 'B' configuration of figure 2, where there is a substrate between the rf SQUID and the resonator and a substrate between the resonator and the pick-up coil, it has been observed that both higher SQUID signal level and noise reduction can be achieved. The improvement in the signal level compared to the worse case, D, is about 3.4 times. These results provide insight into two important facts:

(a) a distance between the resonator and the coupling coil provides better signal coupling with the electronics;
(b) dielectric material between the SQUID and the resonator improves the rf SQUID signal level, V_{spp}.
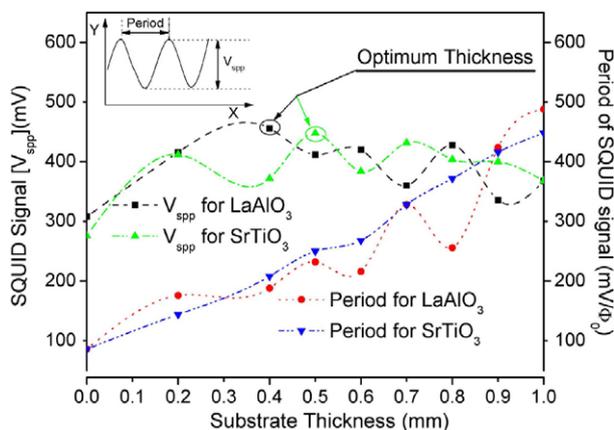
Figure 3. Effect of substrate (LaAlO$_3$ and SrTiO$_3$) thickness between rf SQUID and LC tank circuit. The inset explains the terms period and V_{spp}, from the x–y graph where the x-axis represents the input applied modulation flux and the y-axis represents the output of the rf SQUID electronics.

Table 1. Possible rf SQUID and the coplanar resonator coupling configurations with their relative signal and signal locking states (S: SQUID, R: resonator, sub: substrate, C: pick-up coil).

| Type	Description	V_{spp} level	Quality
A	S–R–sub–C	900 mV	Lockable
B	S–sub–R–sub–C	1.18 V	Lockable and less noisy
C	S–sub–R–C	400 mV	Lockable and noisy
D	S–sub–sub–R–C	350 mV	Barely lockable and noisy

3.3. The effect of the substrate thickness on the rf SQUID signal

As theoretically expected [10] and seen in table 1, the SQUID signal improves on introducing dielectric material in the gap between the coupling circuit and the rf SQUID for both cases of coplanar resonators and the LC tank circuit. This effect has been investigated by introducing substrate materials with various thicknesses, between the rf SQUID and the LC tank circuit, for the two kinds of substrate materials used, namely LaAlO$_3$ and SrTiO$_3$. The effect of the substrate thickness on the SQUID signal, V_{spp}, for both LaAlO$_3$ and SrTiO$_3$ materials is shown in figure 3. As shown in the figure, the optimum substrate thickness was found to be about 0.4 mm for LaAlO$_3$ and 0.5 mm for SrTiO$_3$ substrate materials. To reach the optimal substrate thicknesses one should thin the substrates either prior to the SQUID fabrication or after. Both techniques gave satisfactory results [11, 12]. Devices with various substrate thicknesses were made, and characterized and presented elsewhere [12].

4. Shielding characteristics

4.1. The effect of shielding and the temperature effect

It has been observed that noise coupling from the resonator circuit is very influential in most of the applications. This is especially the case when pick-up transformers are being used to increase the spatial resolution [11]. In such cases, field sensing is not only due to the SQUID but also due to the resonator and the transformer legs which serve as sensing
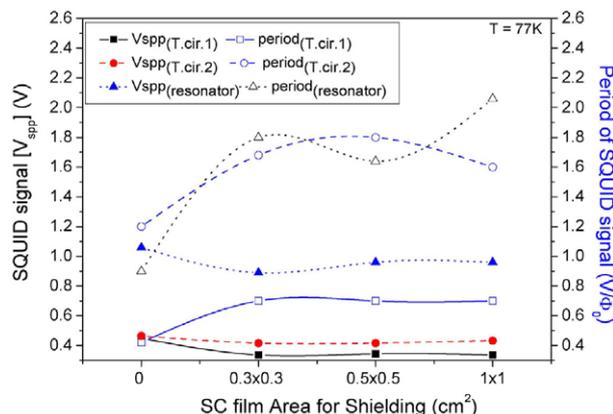

Figure 4. Effect of the applied shield area (a). Tank circuits 1 and 2 are conventional LC tank circuits but the loop diameter of the inductor for tank circuit 1 is $\sim$0.5 mm and for 2 it is $\sim$1 mm. The resonator circuit of the conventional superconducting circular washer type.

devices, and add to the noise. To overcome this hurdle, the solution of shielding the unwanted areas has been investigated in detail. In order to determine the shielding factor, rf SQUIDs were covered with a 1 cm^2 YBaCuO thick film acting as a magnetic shield. The theoretical expectation for the shielding factor of a 1 $\times$ 1 cm^2 shield applied to a rf SQUID through a substrate of about 1 mm thickness is about 10 [10], whereas from experimentally obtained data show a best result of 8.67 for a small washer area rf SQUID [4, 11]. The measured shielding factor shows an inverse dependence on the SQUID's washer area and it shows linear behaviour with respect to the applied field. This leads to the observation that proper shielding of the SQUID can be achieved by having a smaller washer area for the case when a transformer is used to pick the signal up. The possibility of suppressing the SQUID signal by applying a shield in different coupling techniques has been investigated by covering the rf SQUID washer area with 200 nm thick YBaCuO film. The measured unlocked signal of the test SQUID is shown in figure 4.

From figure 4, for tank circuit 1, it is clear that an increase of the shield area from 0 to 1 cm^2 causes about a 16.2% decrease in V_{spp}, while the period (inset of figure 3) of the SQUID signal is increased by 82%. Therefore, for applications, where V_{spp} is being used for measurement, shielding does not very considerably affect the overall measurement. It has also been observed that application of the rf coupling technique not only affects the SQUID signal level, but also causes suppression in the signal level when applying a shield. It is clear from figure 4 that a coplanar resonator provides a 2.28 times better signal level compared to that obtained by the LC tank circuit. But on the other hand, shielding adversely affects the resonator coupling by decreasing the signal level by 10–20%, whereas in an optimized LC tank circuit, it is just about 7%, depending on the applied shield area.

4.2. The effect of the shielding on different coupling techniques

In order to investigate the reason for the reduction in the signal of the SQUID produced by the use of the shield, the
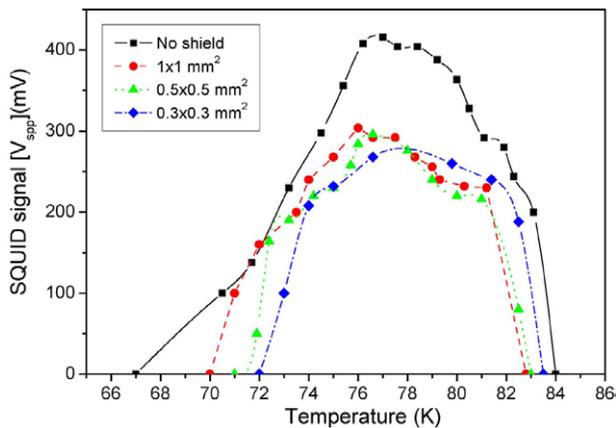
Figure 5. Effect of the temperature on the V_{spp} of the shielded rf SQUID.

temperature sensitivity versus shielding effect on V_{spp} for the devices has been measured and is shown in figure 5. Theoretically, the inductance of the SQUID is changed by applying a shield, and this inductance change of the SQUID loop causes a change in the bias point. In such a situation, by increasing the temperature we return the SQUID signal back to same value, which relates to the need of a SQUID with higher J_c than that calculated for an unshielded SQUID. In this way the inductance and current product will remain the same under shielding for the optimum temperature, which in our case is 77 K. From figure 5, it is clear that such an intersection point can be found by increasing the temperature, where the signal with the shield is equal to that without the shielding. This leads to the need for further optimization of an rf SQUID design with the desired J_c for optimum operation under shielding conditions, which is under investigation.

5. Summary and conclusions

The bottlenecks related to the applications of the rf SQUID for high spatial and high field sensitivity resolutions have been systematically investigated. In this study, liquid nitrogen based systems were used since they provide a better solution than liquid helium based systems due to the possibility of just using the thin window concept to reduce the lift-off distance. Both the coplanar resonator and the conventional LC tank circuit based configurations were investigated. Use of coplanar resonators has been found to provide better signal levels compared to conventional LC tank circuits for bare rf SQUIDs without an YBCO film shield. However for the usage under shielding, a conventional LC tank circuit with appropriate optimization is advantageous, based on lower suppression of the rf SQUID signal and lower unwanted pick-up which cannot be avoided in the case of a coplanar resonator due to its large flux focusing area. The LC tank circuit also provides a lower percentage suppression under shielding compared to

the coplanar resonators. The shielding effect on coupling techniques and with respect to temperature on the V_{spp} has also been investigated. This investigation can be concluded as follows:

(a) according to our speculation, film used for shielding should be as thick as possible ($\sim$400–500 nm), so that a better shielding factor can be achieved,

(b) SQUIDs with relatively high J_c are required, as under shielding the reduction in the inductance caused by the shield is compensated.

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