Design And Characterization Of A YBa$_2$Cu$_3$O$_{7-\delta}$ dc-Superconducting Quantum Interference Device For Magnetic Microscopy

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Abstract. A dc-SQUID (Superconducting Quantum Interference Device) based magnetometer for magnetic microscopy applications has been designed and tested. A square loop has been chosen as pick-up coil and a direct coupling configuration with the SQUID has been realized. On this scale dimension, the strips connecting SQUID and pick-up coil induce a non-negligible effect on the device performances. In particular, a reduction of the effective area is predicted. A SQUID device has been fabricated on symmetric 30° [001]-tilt YBa$_2$Cu$_3$O$_{7-x}$ bicrystal and its behavior has been tested. Characterization results in terms of current-voltage characteristics and magnetic field response are reported. They will agree with expected behaviors. Moreover, magnetometer response to a localized magnetic field has also been investigated.

1. Introduction
Superconducting Quantum Interference Device (SQUID) based magnetometers have been widely proved as a powerful tool in both fundamental and applied physics. A SQUID essentially acts as a magnetic flux-to-voltage transducer and the sensed magnetic flux $\Phi$ is linked to the magnetic field $B$, which is to be measured, by the expression

$$\Phi = A_{\text{eff}} B$$

where $A_{\text{eff}}$ is the device effective area. This parameter also affects the magnetometer spatial resolution $\delta$ [1] that is one of the most relevant parameter in determining magnetometer performances in applications fields such as Scanning Magnetic Microscopy (SMM) [2]. Beside the high temperature operation, the interest in using High Temperature Superconductors (HTS) SQUID magnetometer in SMM arises from the less stringent requirements in the thermal isolation of the sensor and the cooling system. This allows to reduce operating costs and minimize the distance between the sensor and the sample in case the latter is at room temperature.

Considering the sensor design, many constraints on SQUID parameters have to be observed. The device inductance $L_s$ cannot overcome an upper limit in order to avoid that thermal noise compromises SQUID performance. Indeed, the flux noise $\delta \Phi_n = \sqrt{k_B T L_s}$ (where $k_B$ is the Boltzmann constant) has to be kept smaller than the flux quantum $\Phi_0 (\approx 2 \cdot 10^{-15}$ Wb) [3]. In general, to keep small the inductance of a superconducting loop, small geometric dimensions are required. This implies a

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reduced effective area. In order to overcome this limitation, it is commonplace to produce SQUID based magnetometers by coupling the bare SQUID to a superconducting loop (pickup coil).

In the case of direct coupling between SQUID and pickup coil, typical of HTS SQUIDs, the current \( i_p = \Phi / L_p \), which is induced in the pickup coil of inductance \( L_p \) by the applied magnetic flux \( \Phi \), also flows in a part of the SQUID (e.g. see [4] and references therein). In this case the sensor effective area to be considered is given by [4]

\[
A_{\text{eff}} = A_s + k A_p \frac{L_s}{L_p}
\]  

(2)

where \( A_p \) and \( A_s \) are the pickup loop and bare SQUID effective area, respectively. \( k \) is a coupling coefficient and it is given by the \( L' / L_s \) ratio, where \( L' \) represents the inductance of the SQUID portion in which \( i_p \) flows.

Here, we propose a possible layout for HTS directly coupled SQUID based magnetometers when a small pickup loop is required. However, because of small dimensions, the actual design introduces a reduction of the sensor total effective area. This effect was experimentally verified by the magnetic characterization of a YBa\(_2\)Cu\(_3\)O\(_{7-\delta}\) (YBCO) dc-SQUID. Moreover, the designed and fabricated magnetometer was tested by applying to the device the magnetic field in two different ways: one of them is uniform over the entire device, while the other one is applied only over a portion of the pickup loop. As a result, a different sensor magnetic response depending on the way to apply the magnetic field was observed. This confirmed the dependence of the effective area, and hence of the spatial resolution, not only on the device layout, but also on the relative extension of the magnetic field to be revealed.

2. Effective area reduction

Here the layout of our directly coupled SQUID based magnetometer is reported. In figure 1(a) the total sensor layout is depicted. A square-shaped pickup coil was chosen because of the simplicity of determining both its inductance and effective area. In fact, if \( d \) and \( D \) are the inner and outer dimension of the superconducting square loop, respectively (figure 1(a)), \( A_p \approx dD \) [5] and \( L_p \approx 1.25 \mu_0 d \) [6]. In our case \( d = 100 \) \( \mu \)m and \( D = 400 \) \( \mu \)m, and hence \( A_p \approx 4 \times 10^{-8} \) m\(^2\) and \( L_p \approx 1.57 \times 10^{-10} \) H. In order to maximize the direct coupling, a rectangular shaped SQUID has been chosen. In figure 1(b) the used bare SQUID and the coupling region are shown and relative dimensions are reported too. The inductance of the SQUID was evaluated by adding the geometric and the kinetic term: the former was evaluated by using the formula valid for coplanar strips [7], and the latter was obtained by following [8]. To determine the coupling coefficient \( k \), the inductance of the part of the SQUID containing the Josephson junctions, \( L_j \), and the one of the part interested by the direct coupling, \( L' \), were determined separately. In this way we obtained: \( L_j \approx 4.5 \) pH and \( L' \approx 33.5 \) pH, \( L_s \approx 38 \) pH and finally \( k = L' / L_s \approx 0.88 \). The bare SQUID effective area \( A_s \) was roughly evaluated by considering the inner half of the device as the area over which the magnetic field actually contributes to the magnetic flux, as shown by the dashed line in figure 1(b). In our case \( A_s \approx 7.6 \times 10^{-10} \) m\(^2\).

In our sensor the connection between the bare SQUID and the pickup coil is realized by using two strips parallel to the SQUID body for the most of their length, as shown in figure 1. In this configuration the current \( i_p = B_{\text{app}} A_p / L_p \) (where \( B_{\text{app}} \) is the applied magnetic field) couples an additional magnetic field to the bare SQUID by flowing in these strips. This contribution can be seen as an extra magnetic flux that adds to the applied magnetic flux and to the one generated by the flowing of \( i_p \) in the portion of the SQUID. Because in the strips \( i_p \) flows in opposite directions in respect of the SQUID body, this extra flux has to be subtracted. The magnetic field has been estimated as generated by a straight wire laying in the middle of the strips. The flux has been obtained integrating such a field in the interval \([r_1, r_2]\) along the SQUID eight \( l \) (see figure 1(b)). The total magnetometer effective area can be expressed as [9]:

2
Figure 1. (a) Final magnetometer layout and pickup loop dimensions; (b) The bare SQUID layout and coupling region with geometric dimensions \((w_j=4\mu m, t=4\mu m, w_s=8\mu m, l_j=6\mu m, l_{sl}=55\mu m)\); the dashed closed line in the SQUID body represents the edges of the SQUID effective area; the bicrystal line is also shown.

\[
A_{\text{eff}}^{\text{int}} = A_s + k \frac{A_p}{l_p}L_s + 2 \frac{\mu_B A_p}{2\pi} \log \frac{r_2}{r_1}
\]  

(3)

It is worth to notice that the contribution is doubled because of the presence of two connecting strips. The values obtained for the total effective area by using this latter expression are quite different as compared to the results obtainable by applying expression (2). For the device reported here we obtained: \(A_{\text{eff}}^{\text{int}} \approx 9.3 \cdot 10^{-9} \text{ m}^2\) and \(A_{\text{eff}}^{\text{tot}} \approx 4.5 \cdot 10^{-9} \text{ m}^2\) with a total reduction of the effective area of about 50%.

Let us consider a square superconducting loop of inner and outer dimensions \(d\) and \(D\) respectively, as the pickup coil used in our device. As long as the applied magnetic field is uniform over the entire loop the effective area introduced in previous sections still holds, i.e. \(A_p \approx dD\). But if the magnetic field is present only in a reduced region of the pick-up loop, let say in a circular region of radius \(r_m\), the \(A_p\) expression has to be reconsidered. In particular, if

\[
r_m < (D+d)/4
\]  

(4)

i.e. if the magnetic field is present in a region less than the inner half of the pickup loop, the effective area to be considered is now \(A_p = \pi r_m^2\). As a consequence this reflects in a variation of the total effective area via the redefinition of \(A_p\).

3. Experimental results

In order to verify the studied effective area reduction effects, a HTS SQUID magnetometer was realized following the design of section 2 and its response to an applied magnetic field was studied. The sensor was fabricated in a 180 nm thick YBCO thin film deposited on a symmetric [001] oriented SrTiO\(_3\) (STO) bicrystal substrate with an in plane misorientation angle of 30°. Low-resistance electric contacts were obtained by the deposition of a 100 nm thick gold layer. The characterization was carried out in a shielded environment assured by three μ-metal cylinders surrounding a liquid nitrogen Dewar. Moreover, a 1 cm thick aluminum box encloses all the system. The device was characterized in terms of current-voltage (IV) curves and magnetic response, i.e. voltage vs. applied magnetic field (VB). All the characterizations have been carried out at \(T = 77\text{K}\).
The transport measurements were performed with low noise home-made electronics. The $IV$ curve shown in figure 2 was carried out by a classical four-probe technique. The magnetometer exhibited a critical current $2I_c \approx 70 \mu$A, where $I_c$ is the critical current of a single junction. This corresponds to a critical current density $J_c \approx 4.9 \cdot 10^3$ A/cm$^2$. Moreover, the devices showed a normal resistance $R_n \approx 4.8 \Omega$. All the data are in good agreement with results reported in literature [10].

The sensor magnetic response, and hence the information about the effective area, was obtained by applying a magnetic field by means of a long solenoid surrounding the chip containing the sample. In this way field uniformity over the device was ensured. The output voltage was recorded as a function of the applied magnetic field for different bias currents. The obtained results are reported in figure 3, where the typical periodic behavior of the voltage as a function of the magnetic field may be observed. The characteristics present a non symmetric behavior as a function of the applied magnetic field, that may be explained by considering intrinsic asymmetries typically affecting HTS devices, such as critical current and normal resistance asymmetric values. Additionally, asymmetric current feed also induces shift of the VB curves. The magnetic field needed to couple a single quantum flux $\Phi_0$ to the magnetometer has been evaluated. For our device we obtained $B_T \approx 3.7$ mG, which implied $A_{\text{eff}} \approx 5.4 \cdot 10^{-9}$ m$^2$. By comparing this value with the results obtained in section 2 for the two different derivations of the effective area of our device, the reduction effect due to the proposed layout was confirmed.

### Figure 2. IV curve of the tested magnetometer

### Figure 3. Magnetic response in uniform magnetic field for different bias currents

In order to experimentally verify the variation of the effective area as a function of the geometric features of the applied magnetic field, a home-made micro-solenoid was used. It was realized by rounding in ten coils a copper wire of about 120 $\mu$m of diameter. The internal diameter of this solenoid was 120 $\mu$m and its eight was about 1.3 mm. The magnetic field generated by the solenoid was tested by means of a square washer SQUID with an inner hole dimension of 8 $\mu$m and an outer one of 12 $\mu$m.

Successively, the micro-solenoid was placed on the pickup coil of our magnetometer. The applied magnetic field was geometrically limited to a circular region of radius $r_m = 60 \mu$m, in agreement with relation (4). So expression (3) was adapted to the new configuration, i.e. $A_p$ was now evaluated as $A_p = \pi r_m^2 \approx 1.13 \cdot 10^{-8}$ m$^2$. This time $A_s = 0$ because the localized magnetic field was not applied to the bare SQUID. It is worth observing that this situation ($A_s \approx 0$) is common in SMM applications, where magnetometers usually are operated with the SQUID shielded by a superconducting layer. Following equation (2), the final effective area of our device resulted $A_{\text{eff}}^{\text{tot,l}} \approx 1 \cdot 10^{-9}$ m$^2$. The magnetometer was then characterized again in terms of the magnetic response to both the uniform and the localized magnetic field. Both the results are reported and compared in figure 4. The measurements were both carried out by biasing the magnetometer by the same current, namely $I_{b} \approx 82 \mu$A.
As expected the period of the voltage oscillations as a function of the applied magnetic field resulted quite different in the two cases. In particular $B_T^u \approx 3.6 \text{ mG}$ and $B_T^l \approx 17 \text{ mG}$, where $u$ and $l$ stand for uniform and localized applied field respectively. These values correspond respectively, to $A_{eff}^u \approx 5.5 \cdot 10^{-9} \text{ m}^2$ and $A_{eff}^l \approx 1.2 \cdot 10^{-9} \text{ m}^2$, which are in very good agreement with the expected values.

![Graph](image)

**Figure 4.** Comparison between the magnetic responses obtained by applying an uniform (dotted line) and a localized (continuous line) magnetic field

4. Conclusions
An HTS SQUID based directly coupled magnetometer was designed and characterized. The proposed layout introduces an effective area reduction effect that was theoretically studied and experimentally verified on an YBCO bicrystal device. This effect has to be taken into account when in specific applications a small pick-up loop is directly coupled to the SQUID. Moreover, the response of the sensor to magnetic fields applied over different extensions was studied. A reduction of the magnetometer total effective area, as a consequence of the variation of the pickup coil effective area, was experimentally confirmed.

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