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A highly sensitive YBCO serial SQUID magnetometer with a flux focuser

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Abstract

We have designed and fabricated a low noise, high T_c superconducting quantum interference device (SQUID) magnetometer with an improved yield. In order to reduce the field noise level of the magnetometer, we increased the voltage modulation depth with a series SQUID array and enhanced the effective area with a flux focuser. Ten washer-type SQUIDs were connected in series, thereby increasing the voltage flux transfer function by a factor of 10. An enhancement in effective area by a factor of 5 was achieved by coupling the 10-SQUID array to a single-layered flux focuser. For the directly coupled SQUID array magnetometer, the yield was improved by selecting the best SQUIDs to have in series in order to reduce the flux noise. The magnetic field sensitivity of $40 \text{ fT Hz}^{-1/2}$ in the white regime and $100 \text{ fT Hz}^{-1/2}$ at 1 Hz is demonstrated by using a single layer of high T_c film. The proposed high yield magnetometers would be suitable for building low noise multi-channel magnetocardiographs.

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

1. Introduction

The superconducting quantum interference device (SQUID) is the most sensitive device for detecting a weak magnetic flux. SQUID magnetometers have unsurpassed energy sensitivity and have been used to provide images of the magnetic field distributions associated with nerve and muscle currents, currents in integrated circuits, trapped flux in superconductors and defects in metals, and Johnson noise [1]. Active research in the development of high T_c SQUIDs is being conducted worldwide and commercialization is expected soon. The lower flux noise and large output voltage are very important for the above applications. According to the sensitivity relation $S_B^{1/2}(f) = S_\Phi^{1/2}(f)/A_{\text{eff}}$, it is crucial to reduce the flux noise and have a large effective area for HTS sensitive SQUIDs [1–3]. Many studies have so far been made for

the development of highly sensitive SQUID magnetometers operating at 77 K. With low T_c technology, it is shown that by using serially connected SQUID arrays the flux-to-voltage transfer function can be improved and the flux noise reduced [4]. Low flux noise is attractive for magnetometer applications. However, for a serial SQUID magnetometer the reduction in flux noise would be accompanied by a reduction in effective area. Moreover, the non-negligible spread of junction parameters and non-uniformity of magnetic flux density in the array may further degrade the field noise level. Owing to trouble with the SQUID array, high sensitivity, low T_c SQUID magnetometers with multiple turns reported to date were realized by enhancing the effective area rather than reducing the flux noise with a SQUID array. With high T_c technology, a single-layered device is preferred owing to the difficulty in engineering multi-layered high T_c film. For a single-layered directly coupled magnetometer [5, 6], the effective area is typically 0.2 mm^2 and the typical field noise level is about

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100 fT Hz^{-1/2} on a 10 × 10 mm² chip [7]. It seems possible to further reduce the field noise by using a high T_c serial SQUID array. However, for the works reported to date [8–10] the performances of magnetometers in serial arrays are limited by the small effective area and the spread of the junction parameters. Briefly, some other techniques must be applied to exploit the advantages of the serial SQUID array for low noise magnetometers.

In this work, we investigate a magnetometer consisting of a washer-type SQUID array to obtain a large effective area and reduce the white flux noise. The serial SQUID array increases the voltage modulation depth while the washer-type loop with a flip-chip flux focuser enhances the effective area [11–14]. The optimal performance achievable with the high T_c serial SQUID array with a flip-chip flux focuser is discussed.

2. Experimental details

In figure 1(a), we show the layout of our SQUID magnetometer with a flip-chip flux transformer. The width of the junction is 3 μm. The area of the SQUID hole was 30 × 30 μm². The calculated geometrical inductance of the SQUID loop is 38 pH. Ten SQUIDs in series were aligned along a bi-crystal line 5 mm long, shown in figure 1(b). The serial SQUIDs were fabricated onto 5 mm × 5 mm SrTiO₃ bi-crystal substrates with 36.8° misorientation angle. The film thickness is 150 nm. The superconducting YBa₂Cu₃O₇ (YBCO) films were grown with high oxygen pressure off-axis pulsed laser ablation [15–17]. High T_c YBCO serial SQUIDs were fabricated using the standard techniques of photolithography and Ar⁺ ion milling. Gold contacts are evaporated at about 300 nm thickness from the SQUID to the back of the substrate. In the flip-chip configuration, the SQUID is fabricated on one substrate and the flux focuser is fabricated on another substrate. The input coil of the transformer is aligned with the SQUID loop. In the design of the thin film flux focuser, 20 × 20 mm², shown in figure 1(a), the flux over a larger area is concentrated on the small hole of 5 × 3 mm² at the centre. Thus, a much larger flux is coupled to the SQUID, leading to an enhancement in the magnetic field sensitivity of the SQUID. The voltage versus current ($V-I$) and voltage versus flux ($V-\Phi$) characteristics of magnetometers were measured using NKT's DC SQUID Catcher™ system. The flux noise spectra of the magnetometers were measured by using Conductus's multi-channel PC interface, PC-1000, with programmable feedback loops, PFL-100.

3. Results and discussion

The SQUID is generally operated on the steep part of the $V-\Phi$ curve where the transfer coefficient, V_Φ , is a maximum. Thus, the SQUID produces an output voltage in response to a small input flux $\delta\Phi$, and is effectively a flux-to-voltage transducer. The relatively small voltage signal of a single SQUID can be enlarged considerably by connecting many identical SQUIDs in series. Provided that all have the same working point and that the same flux Φ is coupled into each of the SQUIDs, the array behaves like a single SQUID with an enhanced voltage swing. The flux noise spectral density $S_\Phi(f)$ in a high T_c series SQUID array can be derived from known formulae for voltage

Figure 1. (a) Schematic diagram of the flip-chip high T_c SQUID magnetometer. (b) A 10-SQUID serial array was aligned along a bi-crystal line. (c) The junction width is 3 μm. The distance between two SQUIDs was 15 μm. The hole area of the SQUID was 30 μm².

noise and voltage swing of a single SQUID. Given the voltage noise power spectral density of a SQUID being $S_V(f)$, the flux noise power spectral density, $S_\Phi(f)$, for a single SQUID is given by

$$S_\Phi(f) = \frac{S_V(f)}{\left(\frac{\partial V}{\partial \Phi}\right)^2}. \quad (1)$$

Enpuku *et al* [18] concludes empirical formulae for the voltage modulation depth ΔV and flux-to-voltage transfer function V_Φ of a single SQUID to be

$$\Delta V = \frac{7}{\pi^2} \frac{I_c R_n}{(1 + \beta_L)} \left(1 - 3.57 \frac{\sqrt{k_B T L}}{\Phi_0}\right),$$

$$\text{with } V_\Phi = \frac{\partial V}{\partial \Phi} \cong \pi \frac{\Delta V}{\Phi_0} \quad (2)$$

where I_c and R are the critical current and normal resistance of a Josephson junction, L is the SQUID loop inductance, T is the SQUID operating temperature, k_B is Boltzmann's constant, and Φ_0 is the fluxon. If N SQUIDs are connected serially in an array and when all SQUID output voltages add coherently, the total array voltage modulation depth is

$$(\Delta V)_{\text{array}} = N \cdot (\Delta V)_{\text{SQUID}}, \quad (V_\Phi)_{\text{array}} = N \cdot (V_\Phi),$$

$$S_V(f)_{\text{array}} = N \cdot S_V(f). \quad (3)$$

Figure 2. I – V characteristics of a single SQUID and 10 SQUIDs connected in series at 77 K.

By using equations (1)–(3) we see that the flux noise spectral density is $S_{\Phi}(f)_{\text{array}} = S_{\Phi}(f)/N$, decreasing with $1/\sqrt{N}$ where N is the number of SQUIDs [1, 19]. For ten SQUIDs connected in series with all the SQUID output voltages added coherently, the white flux noise should decrease to $1/\sqrt{10}$ the noise of a single SQUID.

Figure 2 shows the typical I – V characteristics of a single-SQUID magnetometer at 77 K. The current–voltage curves fit well with the resistively shunted junction (RSJ) model under thermally activated phase slippage [20]. According to the fitting with the RSJ model under thermal noise, the SQUID has the normal resistance of $1.1 \, \Omega$ and critical current of $37 \, \mu\text{A}$, giving the characteristic voltage of $I_c R_n = 41 \, \mu\text{V}$ at 77 K. Figure 2 also shows I – V characteristics for 10 SQUIDs connected in series. The normal state resistance was found to increase when the number of SQUIDs was increased. By adapting the same single-junction RSJ model with thermal noise to the SQUID array, the normal state resistance is found to be $9.8 \, \Omega$ and the critical current to be $33 \, \mu\text{A}$. The resistance does scale with the number of the SQUIDs in series. This implies that the spread in normal resistance of the SQUID is small. In comparison with the critical current of a single SQUID, the slight reduction in the critical current of the array suggests that the spread in critical currents may be small for this sample. In figure 3(a), we show the voltage flux characteristic curve, V – I_{mod} , of the single SQUID and the 10-SQUID array at 77 K. The peak-to-peak voltage swing is about $3.2 \, \mu\text{V}$ for a single SQUID. The small flux-to-voltage transfer function resulted in a small slew rate and made it difficult to lock the SQUID with the flux modulation scheme by using the commercially available programmable feedback loop PFL-100.

Although the voltage swing of one SQUID is small on this chip, the voltage swing is enhanced effectively with the 10-SQUID series array as shown in figure 3(a). With the uniform flux focusing of the washer, the voltage flux curves of the SQUIDs in the array were superimposed coherently. The voltage modulation depth is increased from $3.2 \, \mu\text{V}$ for one SQUID to $30 \, \mu\text{V}$ for the 10-SQUID array. The peak-to-peak voltage swing of the 10-SQUID magnetometer is roughly tenfold compared with that of the one-SQUID magnetometer. In figure 3(b), the voltage flux curves for the 10-SQUID array

Figure 3. (a) Modulation current–voltage curve of a single SQUID and 10 serial SQUIDs. (b) I_{mod} – V curve of 10 serial SQUIDs with a flux focuser and without it.

with and without a flux focuser are shown. The smaller period for the case with the flux focuser corresponds to a larger effective area. The effective area without the flux focuser is $0.037 \, \text{mm}^2$ while that with the flux focuser is $0.185 \, \text{mm}^2$. The increase in effective area reveals the effectiveness of the flux focuser. As the beating phenomenon is not obvious in the voltage flux curve with the flux focuser, the magnetic flux density at the flux focuser is quite uniform. Hence, by using the washer SQUID with the flux focuser, the effective area can be enhanced effectively by a factor of about 5.

Figure 4 shows the corresponding magnetic field sensitivity for 10 SQUIDs without and with a flux focuser. Without a flux focuser, the 10-SQUID magnetometer showed the magnetic field sensitivity of about $600 \, \text{fT Hz}^{-1/2}$ at 1 kHz and $1.5 \, \text{pT Hz}^{-1/2}$ at 1 Hz in a shielded environment. With the flux focuser, the magnetic field noise level of the 10-SQUID flip-chip magnetometer was improved to $150 \, \text{fT Hz}^{-1/2}$ at 1 kHz and $400 \, \text{fT Hz}^{-1/2}$ at 1 Hz. The reduction in field noise level was caused by the increase in effective area with the flux focuser. However, we note that the field noise is reduced by a factor of 4 rather than 5 as expected from the enhancement in effective area. The slight discrepancy was not caused by the flux motion in flux focuser since there was no strong increase in low frequency flux noise. By investigating the voltage flux curves carefully, we found that the presence of the flux focuser

Figure 4. The magnetic field sensitivity of (a) the serial SQUID magnetometer, (b) SQUIDs with flux focuser.

Figure 5. (a) Schematic diagram of a directly coupled SQUID with a flux focuser. (b) A six-SQUID array was aligned along a bi-crystal line. (c) The junction width is $3 \mu\text{m}$. The distance between two SQUIDs was $15 \mu\text{m}$. The SQUID inductance is 65 pH .

altered the ‘shape’ of the voltage flux characteristic curves. Namely, the deviation from the sinusoidal approximation in (2) differs for the voltage flux curves with and without a flux focuser.

Although the serial SQUID array demonstrated above shows a reduction in flux noise, the yield of the 10-SQUID array is not high since the on-chip critical spread of bi-crystal Josephson junctions is usually not small at 77 K [21, 22]. To improve the yield of a SQUID array magnetometer with bi-crystal Josephson junctions, the best way would be to fabricate many SQUIDs and choose the best ones for being connected in series. To do this, we designed and fabricated the directly coupled SQUID magnetometer for series array operation shown in figure 5. The SQUID magnetometer

Figure 6. $I_{\text{mod}}-V$ curve of a single SQUID, two serial SQUIDs and two SQUIDs with a flux focuser.

Figure 7. The magnetic field sensitivity of (a) a one-SQUID magnetometer, (b) two SQUIDs with a flux focuser.

was fabricated onto a $10 \text{ mm} \times 10 \text{ mm}$ SrTiO_3 bi-crystal substrate with a 24° misorientation angle. The junction width is $3 \mu\text{m}$ and the SQUID inductance is 65 pH . The bare SQUIDs share a common pick-up loop to form the directly coupled SQUID magnetometer. To further reduce the flux noise with the SQUID array, any two out of the six bare SQUIDs can be connected in series for the directly coupled magnetometer. Figure 6 shows the $V-\Phi$ curve of the directly coupled magnetometer. The voltage swing was $19 \mu\text{V}$ for the single-SQUID magnetometer and $37 \mu\text{V}$ for the two-SQUID series array magnetometer. The amplification in voltage swing by a factor of 2 would lead to a reduction in white flux noise by a factor of 1.4 according to equation (3). By measuring the periods of the voltage flux curves in figure 6, the effective areas were determined as 0.2 mm^2 for both the single-SQUID and two-SQUID array magnetometers without the flux focuser. When the flip-chip flux focuser was applied, the effective areas were boosted by a factor of 1.6 to 0.32 mm^2 . Therefore, by using the two-SQUID array with a flip-chip flux focuser, the field sensitivity can be improved by a factor of $1.4 \times 1.6 = 2.24$. Figure 7 shows the corresponding magnetic field noise spectral densities respectively for the single-SQUID magnetometer without a flux focuser and the

two-SQUID-array magnetometer with a flux focuser. For the conventional single-SQUID magnetometer without a flux focuser, the magnetic field noise level was $90 \text{ fT Hz}^{-1/2}$ at 1 kHz and $350 \text{ fT Hz}^{-1/2}$ at 1 Hz in a shielded environment. For the two-SQUID-array magnetometer with flux focuser, the magnetic field noise level was reduced to $40 \text{ fT Hz}^{-1/2}$ at 1 kHz and $120 \text{ fT Hz}^{-1/2}$ at 1 Hz. The observed reduction in white field noise level by a factor of 2.25 was in agreement with the observed amplifications in voltage swing and effect area. Since the flux focuser and SQUID array are made from single-layered high T_c thin films on separate chips, the yield of our low noise magnetometer should be much higher than that of high T_c SQUID magnetometers with multi-layered flux transformers [23].

4. Conclusion

We have characterized a high T_c YBCO dc SQUID array magnetometer fabricated on a bi-crystal STO substrate. The improvement in magnetic field sensitivity $S_B^{1/2}$ was achieved by reducing the flux noise $S_\Phi^{1/2}$ with a SQUID array and enhancing the effective area A_{eff} with a flip-chip flux focuser. For the washer-type 10-SQUID array, the enhancement in the effective area by a factor of 5 was achieved with a single-layered flux focuser. By using single-layered YBCO thin films, a high T_c directly coupled SQUID magnetometer with a flux focuser exhibiting a magnetic field sensitivity of $40 \text{ fT Hz}^{-1/2}$ in the white regime and $100 \text{ fT Hz}^{-1/2}$ at 1 Hz was achieved. Our design can improve the yield and reduce the flux noise by selecting the best SQUIDs for operation in a serial array. From the standpoint of application, it is quite practicable to build a high sensitivity multi-channel SQUID system for magnetocardiograms by using the proposed magnetometers.

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