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High-T_c SQUID magnetometers for biomagnetic measurements

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Abstract. We have designed and fabricated three types of high-T_c SQUID (superconducting quantum interference device) magnetometers based on step-edge Josephson junctions using three different concepts of coupling magnetic flux into the SQUID: (i) a single pickup loop galvanically coupled to the SQUID, (ii) a flux transformer inductively coupled to the SQUID and (iii) a multiloop pickup loop used directly as the SQUID inductance. On a 10×10 mm^2 substrate we achieved an effective flux capture area of 1.70 mm^2 and 1.67 mm^2 for the inductively coupled and multiloop devices, respectively. Due to the low white noise levels of 44 fT Hz$^{-1/2}$ for the inductively coupled magnetometer and 30 fT Hz$^{-1/2}$ for the multiloop device high quality magnetocardiograms were recorded inside a magnetically shielded room without signal averaging.

1. Introduction

Typical peak-to-peak signals in magnetocardiography (MCG) are in the range of several 10 pT. However, physicians are more interested in the smaller signals, e.g. the onset of an extrasystole, where the mean signal amplitude is on the order of 2 pT. The measurement bandwidth must be at least 1 to 100 Hz. For adequate source localization a signal to noise ratio of 5 is necessary. With this data in mind, the desired magnetic field noise $\sqrt{S_B}$ of future MCG systems can be determined to less than 50 fT Hz$^{-1/2}$. High-T_c SQUID magnetometers made of YBa2Cu3O7 (YBCO) are now able to reach this noise level in a shielded environment.

For a magnetometer, the relevant figure of merit is the magnetic field noise $\sqrt{S_B}(f) = \sqrt{S_\Phi}(f)/A_{eff}$. Here, $\sqrt{S_\Phi}(f)$ is the rms flux noise and A_{eff} is the effective flux capture area of the magnetometer, which may also be expressed in terms of the field-to-flux conversion efficiency $B_\Phi = \Phi_0/A_{eff}$. Thus, the magnetic field noise of a magnetometer can be optimized by minimizing the flux noise and maximizing the effective area.

Due to their low effective flux capture area A_s, bare SQUIDs have an insufficient magnetic field resolution. To enhance the sensitivity of a SQUID, one has to increase its effective area whilst keeping its inductance low to ensure low noise operation. This has been accomplished in a variety of ways. For example, Zhang *et al* [1] increased the area of their rf SQUID by taking into account the flux focusing effect of their large size square washer or by coupling a single-layer thin-film flip-chip flux transformer to the SQUID. Another approach was introduced by Koelle *et al* [2] who galvanically coupled a dc SQUID to a loop patterned in the same YBCO film to realize a directly coupled magnetometer. Lee *et al* [3] reported an improved directly coupled magnetometer. A more efficient way to enhance the field sensitivity of a SQUID is to inductively couple it to a multi-turn flux transformer [4] either by flip-chip (Grundler *et al* [5] and Ludwig *et al* [6]) or monolithically integrated (Kromann *et al* [7] and David *et al* [8]) techniques. An alternative approach is the multiloop magnetometer, successfully demonstrated by Drung and co-workers in low-T_c devices [9], and recently made by Ludwig *et al* [10] from the high-T_c material YBCO.

Here we report on the design, fabrication and characterization of three different types of magnetometers all based on the same step-edge junction process: (i) directly coupled magnetometer, (ii) inductively coupled (Ketchen type) magnetometer and (iii) multiloop (Drung type) magnetometer. We compare the effective area A_{eff} and the field resolution $\sqrt{S_B}$ of these magnetometers fabricated on 10×10 mm^2 substrates and demonstrate their suitability for magnetocardiography.

2. Experiment

The inductively coupled and multiloop magnetometers are both fabricated from a YBCO–STO–YBCO multilayer on 10×10 mm^2 $SrTiO_3$ (STO) substrates. The multilayer fabrication process is described in detail elsewhere [11]. In summary; we deposit the YBCO and STO films by

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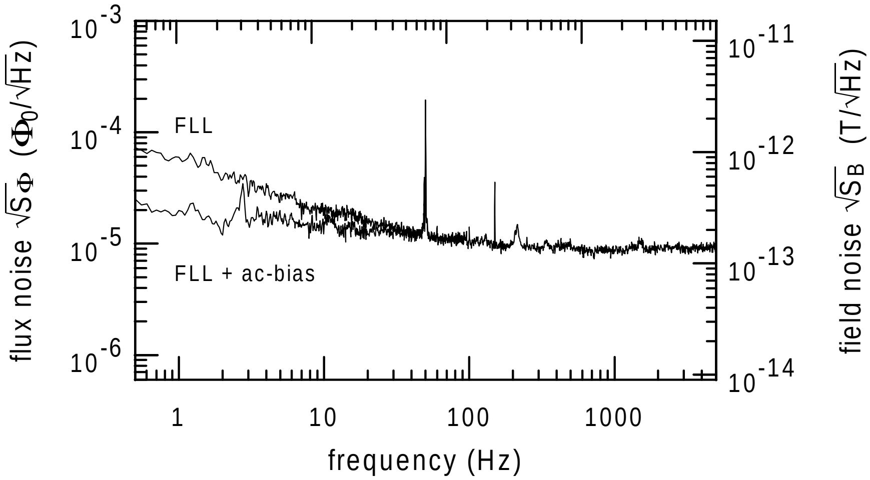

Figure 1. Noise spectra of a directly coupled magnetometer measured at 77 K inside a superconducting BSCCO tube using standard FLL electronics. Additional ac-bias modulation assists the reduction of $1/f$-noise effectively.

rf magnetron sputtering and pattern them by standard photolithography and Ar-ion beam etching. To obtain bevelled edges on the lower YBCO film and STO insulating layer we bake the photoresist after development and mill the films at a 60° angle of incidence to the rotating substrate. The steep slope required for the step-edge junctions, however, is milled at normal incidence into the STO insulating layer. The two junctions with a nominal width of 3 μm are patterned from the top YBCO film. The thickness of the lower YBCO and STO layers are 150 nm and 200 nm, respectively. The thickness of the upper YBCO layers which form the junctions, equals the step height of about 200 nm. The contact pads are covered by a 30 nm Ag layer which is sputter deposited through a shadow mask.

The fabrication process for our directly coupled magnetometer is less complicated and starts with the patterning of a steep step in the STO substrate and the deposition of a single YBCO film. Finally, the pickup loop and the SQUID loop are patterned by the same process described above.

The electrical characterization of the devices is performed either: (a) inside a superconducting BSCCO tube (MCP-BSCCO 2212 tube, Hoechst AG, Frankfurt) immersed in liquid nitrogen, (b) a double μ-metal shield inside a He-flow-type cryostat or (c) inside a low noise biomagnetic dewar filled with liquid nitrogen inside the Berlin magnetically shielded room (BMSR). To compare the different measurement environments, we investigated the multiloop device for each of these procedures. We found different values for the field-to-flux conversion efficiency B_Φ when we compared procedure (a) and (b) with procedure (c). This is attributed to the distortion of the magnetic field lines in our small copper coils generating the magnetic field inside the narrow BSCCO tube or μ-metal tube. We therefore multiplied our results of B_Φ measurement for procedures (a) and (b) by a factor of 1.22 using the measured data of the multiloop device inside the BMSR where the magnetic field is applied by a calibrated Helmholtz coil.

3. Results

3.1. Directly coupled magnetometer

The effective flux capture area of the directly coupled magnetometer is given by

$$A_{\mathrm{eff}} = A_{\mathrm{s}} + \left(\frac{L_{\mathrm{s}}}{L_{\mathrm{s}} + L_{\mathrm{p}}}\right) A_{\mathrm{p}} \approx \left(L_{\mathrm{s}}/L_{\mathrm{p}}\right) A_{\mathrm{p}} \qquad (1)$$

where A_s is the effective area of the SQUID loop with inductance L_s and A_p is the effective area of the pickup loop with inductance L_p. In the course of our experiments we fabricated magnetometers which differed in the shape of the pickup loop and the size and inductance of the SQUID loop. For one device with a pickup loop area of 50 mm^2 and a pickup loop inductance of 15 nH coupled to a 55 pH SQUID inductance, we measured a field-to-flux conversion efficiency B_Φ of 15.1 nT Φ_0^{-1}, corresponding to an effective area A_{eff} of 0.14 mm^2.

The discrepancy between calculated and measured effective areas is due to the uncertainties in the SQUID and pickup loop inductances. The rms flux noise of this particular device is 8.5 $\mu\Phi_0$ Hz$^{-1/2}$ at 1 kHz and 18.7 $\mu\Phi_0$ Hz$^{-1/2}$ at 1 Hz measured in a superconducting BSCCO tube using flux-locked loop (FLL) electronics with additional ac-bias current modulation. The resulting magnetic field noise of the magnetometer, depicted in figure 1, is 128 fT Hz$^{-1/2}$ at 1 kHz and 280 fT Hz$^{-1/2}$ at 1 Hz.

3.2. Inductively coupled (Ketchen type) magnetometer

The effective flux capture area of an inductively coupled magnetometer is given by

$$A_{\mathrm{eff}} = A_{\mathrm{s}} + \tfrac{1}{2} k \sqrt{\frac{L_{\mathrm{s}}}{L_{\mathrm{p}}}} A_{\mathrm{p}} \qquad (2)$$

assuming the inductance L_i of the input coil of the flux transformer to be equal to the inductance L_p of the pickup loop. Our magnetometer chip contains two $10\frac{1}{2}$ turn input

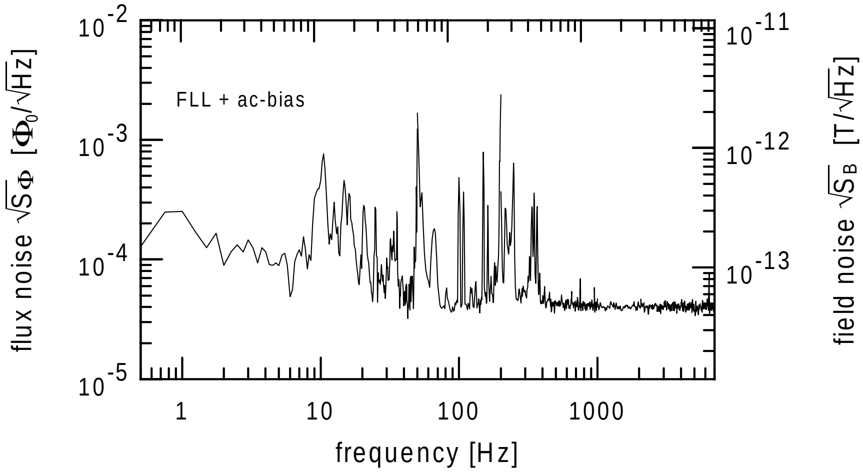

Figure 2. Noise spectrum of an inductively coupled (Ketchen type) magnetometer using FLL electronics. The spectrum, measured at 77 K in a He-flow-type cryostat includes a lot of environmental noise which affected the SQUID inside the double μ-metal shield.

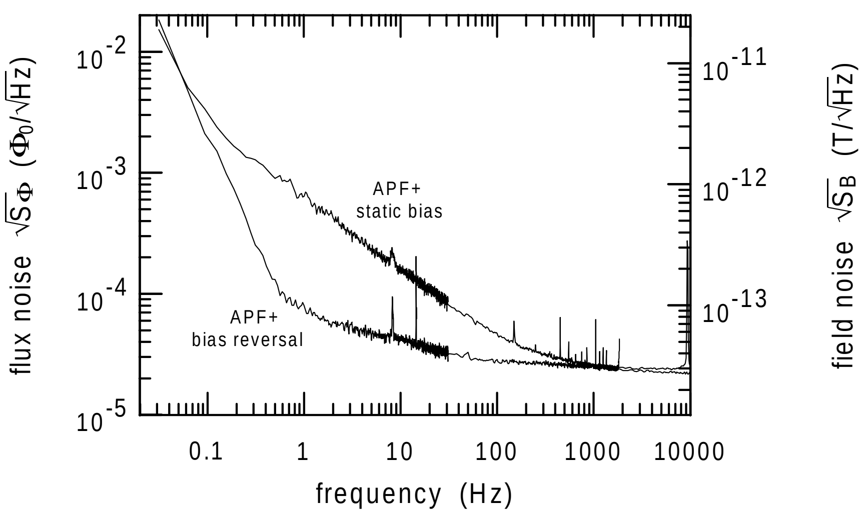

Figure 3. Noise spectra of a multiloop (Drung type) magnetometer at 77 K, measured in the Berlin magnetically shielded room using additional positive feedback (APF) electronics with static bias and bias reversal.

coils and SQUIDs which are shunted and connected to the same square pickup loop. The better SQUID is activated by scribing the respective shunt. The pickup loop has an outer diameter of 8.8 mm and a width of 0.6 mm with two indentations for the SQUIDs and the bond pads, giving a practical pickup area of $A_p \approx 54$ mm^2. Using $L_p = 15$ nH and a SQUID inductance L_s of 85 pH we estimate an effective flux capture area of 1.71 mm^2, taking into account a coupling coefficient k of 0.84 derived from the measurement of the mutual inductance (at 4.2 K) between the input coil and the SQUID washer. The measured field-to-flux conversion efficiency B_Φ is 1.22 nT Φ_0^{-1}, corresponding to an effective area $A_{eff} \approx 1.70$ mm^2. This is a surprisingly close conformity between the estimated and measured effective flux capture areas.

In figure 2 the noise spectrum of an integrated inductively coupled magnetometer is shown, measured at 77 K inside a double μ-metal shield. The field noise of 44 fT Hz$^{-1/2}$ at 1 kHz and 260 fT Hz$^{-1/2}$ at 1 Hz measured in FLL with ac-bias current modulation is one of the lowest yet reported for this type of high-T_c device.

3.3. Multiloop (Drung-type) magnetometer

The effective area of a multiloop magnetometer is given by [12]

$$A_{eff} = \frac{A_p}{N} - A_{sp} \qquad (3)$$

where A_p is the total effective area of the large outer loop, A_{sp} the parasitic effective area of one spoke, and N is the number of loops. Our device (type WH1 in [12]) consists of 16 equal loops forming a cartwheel-like device with an outer diameter of 7 mm. The effective flux capture area is estimated to be 1.77 mm^2, the measured value is 1.67 mm^2. Noise measurements were performed in the Berlin magnetically shielded room using the additional positive feedback (APF) electronics with bias reversal [13]. The noise spectra of the multiloop magnetometer, measured

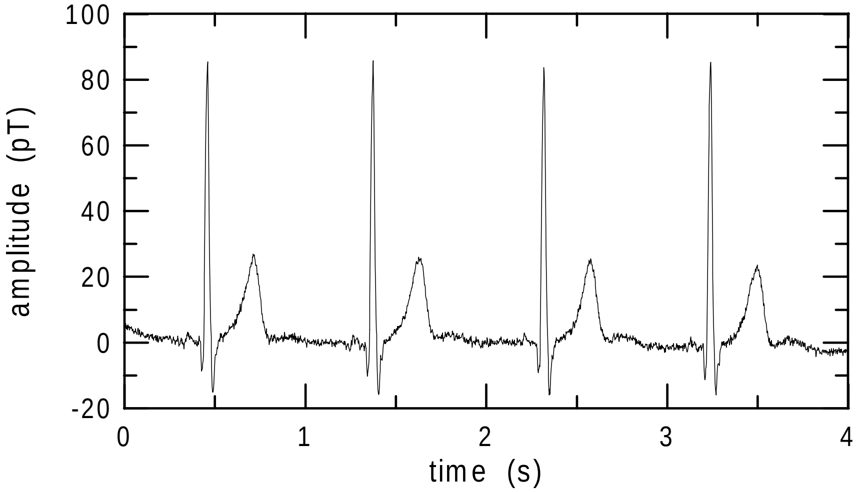

Figure 4. Real-time trace of a magnetocardiogram recorded with the multiloop magnetometer inside the Berlin magnetically shielded room. The measurement bandwidth is 0.016–200 Hz.

with static bias current and with bias reversal, are depicted in figure 3. A very low white noise level of 30 fT $Hz^{-1/2}$ was obtained. With bias reversal, the low frequency noise is greatly reduced to 95 fT $Hz^{-1/2}$ at 1 Hz.

4. Discussion

We have fabricated three types of magnetometers. Although there is substantial inductance mismatch, a reasonable enhancement of the effective area can be achieved using the directly coupled magnetometer. The real advantage, as compared with an integrated magnetometer, is that the complete device can be fabricated from a single layer of YBCO. However, the effective flux capture area of the inductively coupled and multiloop magnetometer is about one order of magnitude larger compared to the directly coupled magnetometer, if fabricated on a substrate of 10×10 mm^2. This gain in field-to-flux conversion efficiency B_Φ is at the expense of a more complicated fabrication technology. The inductively coupled magnetometer can be scaled up to larger substrates by increasing the number of turns of the input coil. The realized multiloop magnetometer is a compromise between the largest acceptable SQUID inductance of about 145 pH and a significant enhancement of the effective area. Our results demonstrate that the various coupling schemes are well understood and effectively enhance the field-to-flux conversion efficiency. An even better noise performance can be expected by further improving the flux noise of the SQUID. Nevertheless, the magnetic field noise of all three types of magnetometers is already low enough to record MCGs. As an example, a magnetocardiogram is shown in figure 4, recorded with a multiloop magnetometer inside the Berlin magnetically shielded room. Due to the low SQUID noise level ($\cong$ 3 pT peak-to-peak in 200 Hz bandwidth) a good signal to noise ratio was obtained even without signal averaging. A crucial task for the future will be the development of magnetometers working in an unshielded environment.

Acknowledgments

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