Integrated $YBa_2Cu_3O_7$Magnetometers for Biomagnetic Applications

S. Krey, K.-O. Subke, D. Reimer and M. Schilling
Universität Hamburg, Institut für Angewandte Physik und Zentrum für Mikrostrukturforschung,
Jungiusstraße 11, D-20355 Hamburg, Germany

R. Scharnweber
Oxford Instruments, Scientific Research Division, Cambridge CB4 4WZ, England

***Abstract*—Two concepts of integrated magnetometers intended for multichannel systems are investigated. The multiloop magnetometer and the magnetometer with integrated multiloop pick-up coil (IMPUC) are compared regarding their specific advantages in shielded and unshielded environment. In these magnetometers, step-edge grain-boundary Josephson junctions as well as ramp-edge junctions with $PrBa_2Cu_3O_7$ barriers are employed. At 77 K we achieve a magnetic flux density noise down to $\sqrt{S_B} = 60\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ at 1 Hz and of $17\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ in the white noise regime for the multiloop device and $\sqrt{S_B}(1\,\mathrm{Hz}) = 100\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ and $\sqrt{S_B}(1\,\mathrm{kHz}) = 44\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ for the IMPUC device, respectively. By analysis of the local epitaxy with micro-Raman spectroscopy the low-frequency flux-noise can be related to the epitaxial quality of the top $YBa_2Cu_3O_7$ layer in the integrated magnetometers. The noise performance is also analyzed with respect to the influence of static magnetic fields.**

I. INTRODUCTION

Magnetometers employing direct current superconducting quantum interference devices (dc SQUIDs) are used for the highly sensitive measurement of magnetic flux and magnetic flux density. To benefit from the high temperature superconductors (HTS), concerning the ease of handling and cost reduction by the use of liquid nitrogen, the complete magnetometer has to be prepared from HTS materials. To operate these devices at a temperature of 77 K, the inductance of a dc SQUID has to be less than about 200 pH. Since a SQUID of small inductance implies a small flux-collecting area, the sensitivity to external flux is increased by the use of large area flux-collecting antennas coupled to the dc SQUID. On the other hand, multichannel applications require a dense array of magnetometers and therefore a small sensor size. Due to the lack of a superconducting interconnect technology, integrated thin-film magnetometers are employed.

In the following, we focus on two different approaches for highly sensitive integrated magnetometers. The first type is the multiloop dc SQUID, which has been originally developed in niobium technology for 4.2 K [1] and has been redesigned for HTS by Drung *et al.* [2]. In this concept 16 pick-up loops are used directly as the SQUID inductance. They are connected in parallel to obtain a sufficiently small inductance. With this type of magnetometer very low-noise operation has been demonstrated [3]. The second is the magnetometer with an integrated multiloop pick-up coil (IMPUC), which is inductively coupled to a dc SQUID of square washer type [4]. The latter is a combination of the multiloop approach with the Ketchen-type layout, where only one single pick-up loop is inductively coupled to the SQUID [5]. The following comparisons are restricted to the commonly used chip area of $10 \times 10\,\mathrm{mm}^2$.

II. MAGNETOMETER PROPERTIES

A. Inductance and Effective Area

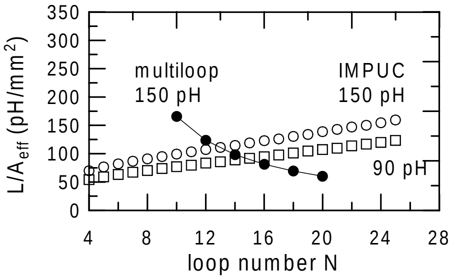

Fig. 1. The ratio L/A_{eff} in dependence on the number of loops for IMPUC and multiloop magnetometers of given inductances.

For layout optimizations, the ratio of the inductance and the effective area L/A_{eff} measures the efficiency of flux coupling into the magnetometer. In Fig. 1, this ratio is shown in dependence on the number of loops connected in parallel for the flux antenna. One finds, that for the IMPUC magnetometer of a given inductance low loop numbers are preferable, whereas for a multiloop device with an inductance of 150 pH high loop numbers are required. Since the transfer function $dV/d\Phi$ and therewith the white noise of the dc SQUID depends on the inductance of the SQUID, small inductances should be chosen, especially for operation in unshielded environment where a high slew-rate is needed.

This work was supported by the Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie, Federal Republic of Germany under Contract No. 13N6734-0
email: `krey@physnet.uni-hamburg.de`

Our multiloop dc SQUID is optimized for the maximum effective area at an inductance of 145 pH. It is an enlarged version of the WH1 layout described in [2]. For an outer diameter of 8.5 mm, we had to adjust the pick-up coil width and the spoke width to keep the inductance at 145 pH, resulting in an effective area of 2.3 mm^2 [6]. The geometry of the IMPUC magnetometer has been optimized for a lower SQUID inductance of 90 pH by which it achieves an effective area of 1.4 mm^2 [7]. The input coil of only 5 windings of 3 μm linewidth is integrated on top of the SQUID washer. One important difference between both magnetometer types is, that in the multiloop layout the effective area is determined by a single loop, and open loops result in an increase of the inductance of the magnetometer. In contrast, for the IMPUC magnetometer the number of loops connected in parallel determines the inductance matching of the flux-transformer to the SQUID and therefore also influences the effective area [7]. The inductance of the SQUID is not significantly affected by a change in the number of loops. The temperature dependence of the effective area of both magnetometer types is very similiar and caused by the temperature dependence of the London penetration depth. An increase in the temperature results in an increase of the spoke inductance and also in an increase of the stray flux coupled into the slits, which reduces the effective area. In the multiloop dc SQUID the first effect reduces the transfer function, whereas for the IMPUC magnetometer the inductance matching changes due to the increased inductance. However, for both types these effects are small.

B. *Noise Properties*

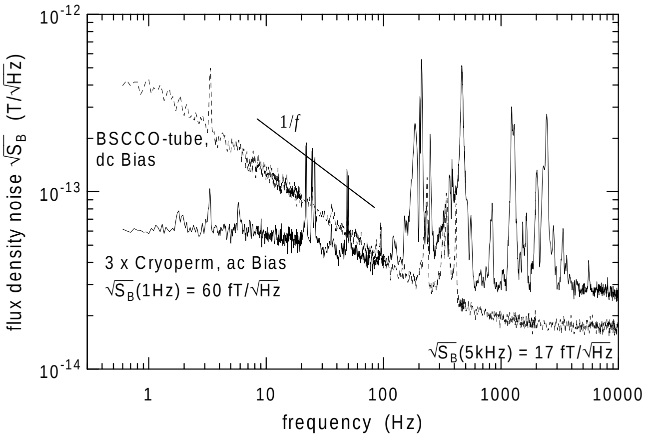

Fig. 2. Noise spectra of a multiloop magnetometer, measured with different shieldings: A superconducting BSCCO shield and a triple Cryoperm shield. The superconducting shield strongly induces $1/f$-noise, whereas the metallic shield produces frequency independent Nyquist noise.

Due to its higher inductance, a multiloop magnetometer is expected to have a slightly higher white noise level, compared to an IMPUC-magnetometer. However, for biomagnetic applications the $1/f$-noise is of far more importance, since the signals to be measured have low frequencies. From the analysis of the local epitaxy by scanning micro-Raman spectroscopy with a spatial resolution of 2 μm we find, that regions where $YBa_2Cu_3O_7$ grows on top of a $YBa_2Cu_3O_7$-$SrTiO_3$ bilayer are most sensitive to degradation of epitaxy. In these regions flux is more weakly pinned, due to the occurence of grain boundaries between adjacent a- and c-axis oriented grains where thermally activated hopping of vortices can take place [8].

So for low noise operation of the magnetometers the total area of these regions should be minimized, as long as a perfect multilayer epitaxy is not achieved in every layer of the chip. The multiloop magnetometer with 16 loops requires at least 16 equivalent via contacts between the top and bottom $YBa_2Cu_3O_7$ electrodes and a central overlap region. In contrast, the 4-loop IMPUC magnetometer contains only 5 via contacts. Independent of the kind of Josephson junctions used, both magnetometer types can be prepared in the same process, because of the same number and order of the required layers.

We measured the lowest noise levels with a multiloop magnetometer employing step-edge junctions, which was fabricated at Philips, Hamburg. With a voltage swing of $\Delta V = 11.5\,\mu\mathrm{V}$, we measured $\sqrt{S_B}(1\,\mathrm{Hz}) = 60\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ for the low frequency noise and $17\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ in the white noise regime. Noise spectra of this device are depicted in Fig. 2. Because metallic Cryoperm shields generate Nyquist noise and our superconducting BSCCO-tube produces $1/f$-noise, we had to characterize this device with both shields. For the IMPUC magnetometer with ramp-edge junctions, we measured the low frequency noise of $\sqrt{S_B}(1\,\mathrm{Hz}) = 100\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ and $\sqrt{S_B}(1\,\mathrm{kHz}) = 44\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ for the white noise with $\Delta V = 2.8\,\mu\mathrm{V}$ [4]. All noise measurements were done at 77 K.

C. *Biomagnetic Measurements*

The magnetic field noise of both magnetometers is low enough to allow the recording of high quality magnetocardiograms. Unaveraged magnetocardiograms, taken with a measuring bandwidth of 200 Hz inside a magnetically shielded room, are depicted in Fig. 3. No additional filtering was applied. For the multiloop device we measured a peak-to-peak field noise level of about $6\,\mathrm{pT_{pp}}$, while it is $8\,\mathrm{pT_{pp}}$ for the IMPUC device, due to its higher low frequency noise.

D. *Operation in Unshielded Environment and in Static Magnetic Fields*

So far, only the multiloop magnetometer has been extensively tested in unshielded environment. Fig. 4 shows the magnetic field noise in a typical laboratory environment, measured unshielded with this magnetometer. The magnetometer remained stable in the flux locked loop (FLL) during the whole measuring time of about an hour.

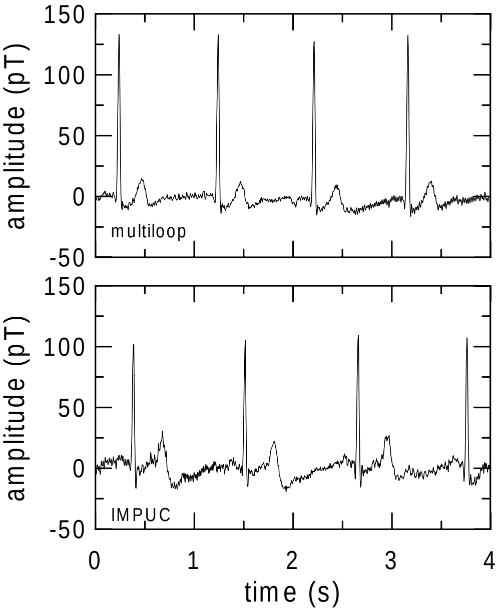

Fig. 3. Real time magnetocardiograms taken with two different types of magnetometers inside of a shielded room.

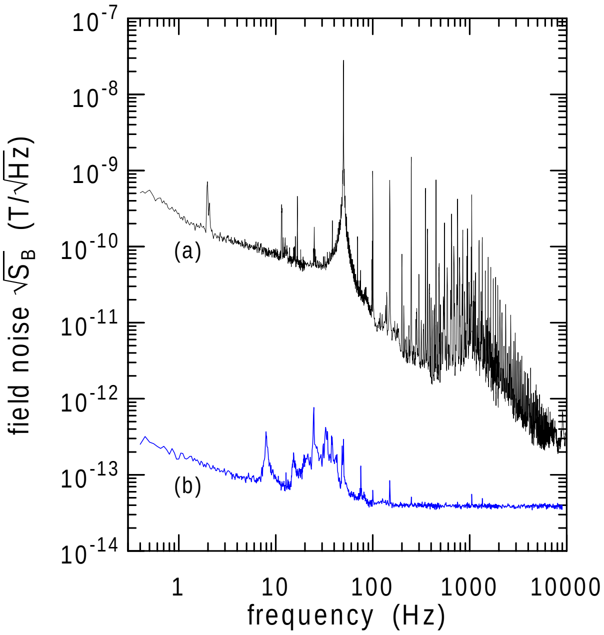

Fig. 4. Unshielded measurement of the environmental noise in our laboratory (a) in comparison with the intrinsic noise (b) of a multiloop magnetometer.

The flux noise of a multiloop magnetometer and an integrated inductively coupled magnetometer (Ketchen type) was measured in dependence on the applied field during cooling. As shown in Fig. 5, in both samples only a moderate increase of the low frequeny flux noise is found in fields up to 110 μT, which is attributed to the high epitaxial quality of the involved HTS multilayer films [6].

In a changing magnetic field the screening currents can induce vortices into the film that generate extra low frequency noise. The multiloop layout includes an intrinsic flux dam [9] because the screening currents are forced across the Josephson junctions, whereas for the IMPUC magnetometer the via contact between washer and input-coil can act as a flux dam.

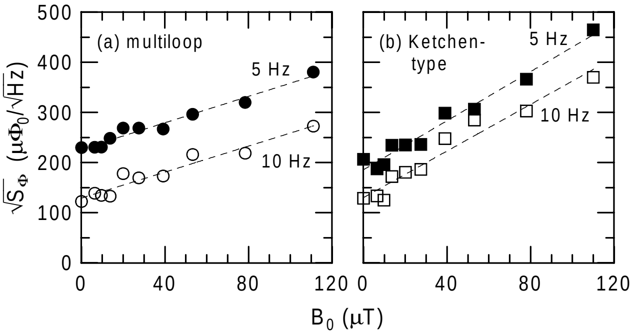

Fig. 5. Flux noise of a multiloop and an inductively coupled magnetometer in dependence on the cooling field B_0. The dashed lines are least squares fits to the data. Measured in FLL mode with ac bias at 5 Hz (filled symbols) and 10 Hz (open symbols).

III. Conclusions

The inductance, effective area, and noise properties of the multiloop magnetometer are compared to the properties of the IMPUC magnetometer. We have demonstrated that both types can be fabricated in the same multilayer process, that is capable of producing low noise HTS magnetometers. We also have demonstrated the stable operation of a multiloop magnetometer in unshielded environment and the low noise operation in static magnetic fields higher than the earth's field of about 50 μT. This is a prerequisite for future applications in a moderately or unshielded environment. However, a crucial task for the future will be the development of highly effective noise suppression methods to obtain the same sensitivity as in magnetically shielded rooms.

References

[1] D. Drung, IEEE Trans. Appl. Supercond. **5**, 2112 (1995)

[2] D. Drung, S. Knappe, and H. Koch, J. Appl. Phys. **77**, 4088 (1995)

[3] D. Drung, E. Dantsker, F. Ludwig, H. Koch, R. Kleiner, J. Clarke, S. Krey, D. Reimer, B. David, and O. Dössel, Appl. Phys. Lett. **68**, 1856 (1996)

[4] R. Scharnweber and M. Schilling, Appl. Phys. Lett. **69**, 1303 (1996)

[5] J.M. Jaycox and M.B. Ketchen, IEEE Trans. Magn. **17**, 400 (1981)

[6] S. Krey, B. David, R. Eckart, and O. Dössel, unpublished

[7] R. Scharnweber and M. Schilling, IEEE Trans. Appl. Supercond. (1997), in press

[8] R. Scharnweber, N. Dieckmann and M. Schilling, Appl. Phys. Lett. **70**, 2189 (1997)

[9] R.H. Koch, J.Z. Sun, V. Foglietta, and W.J. Gallagher, Appl. Phys. Lett. **67**, 709 (1995)