Operation of a $YBa_2Cu_3O_7$ dc SQUID magnetometer with integrated multiloop pick-up coil in unshielded environment and in static magnetic fields

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ABSTRACT: We investigate the behavior of a dc SQUID magnetometer with integrated multiloop pick-up coil (IMPUC) in unshielded environment and in static magnetic flux densities of up to $220\,\mu$T. The magnetometer is based on the high-temperature superconductor $YBa_2Cu_3O_7$ with bicrystal Josephson junctions. With shielding we obtain a low frequency flux density noise of $\sqrt{S_B}(3\,\text{Hz}) = 50\,\text{fT}/\sqrt{\text{Hz}}$ at 77 K in zero magnetic field. The noise level at 3 Hz exhibits a moderate linear increase with the static magnetic field of $4.7\,\text{fT}/(\sqrt{\text{Hz}}\mu\text{T})$, confirming the high epitaxial quality of our optimized $YBa_2Cu_3O_7$ films.

1 INTRODUCTION

Integrated dc SQUID magnetometers based on the high-temperature superconductor $YBa_2Cu_3O_7$ achieve sufficiently low flux density noise levels for biomagnetic applications. Drung et al reach $53\,\text{fT}/\sqrt{\text{Hz}}$ at 1 Hz with an integrated flux-transformer coupled magnetometer operated at 77 K (1996). However, these results can only be obtained inside heavily shielded rooms. Without shielding the magnetometers are subjected to external noise sources interfering with the SQUID operation and the earth's magnetic field of $50\,\mu$T. The latter leads to vortices pinned in the superconducting films. Their motion causes excess low-frequency noise contributions as described by Ferrari et al (1994) and Miklich et al (1994). Dantsker et al (1997) demonstrated that patterning SQUIDs with slits or holes helps to maintain the noise levels obtained in zero field up to a threshold field determined by the maximum superconducting linewidth. This concept was used by Krey et al (1999) to investigate the influence of patterning on a directly coupled magnetometer. Investigations of integrated flux-transformer coupled magnetometers and multiloop SQUIDs by Krey et al (1998) show that a high epitaxial quality of the superconducting films leads to an only moderate linear increase in excess noise of the magnetometers operated in static magnetic flux densities of up to $110\,\mu$T. In this work we investigate the behavior of a dc SQUID integrated multiloop pick-up coil

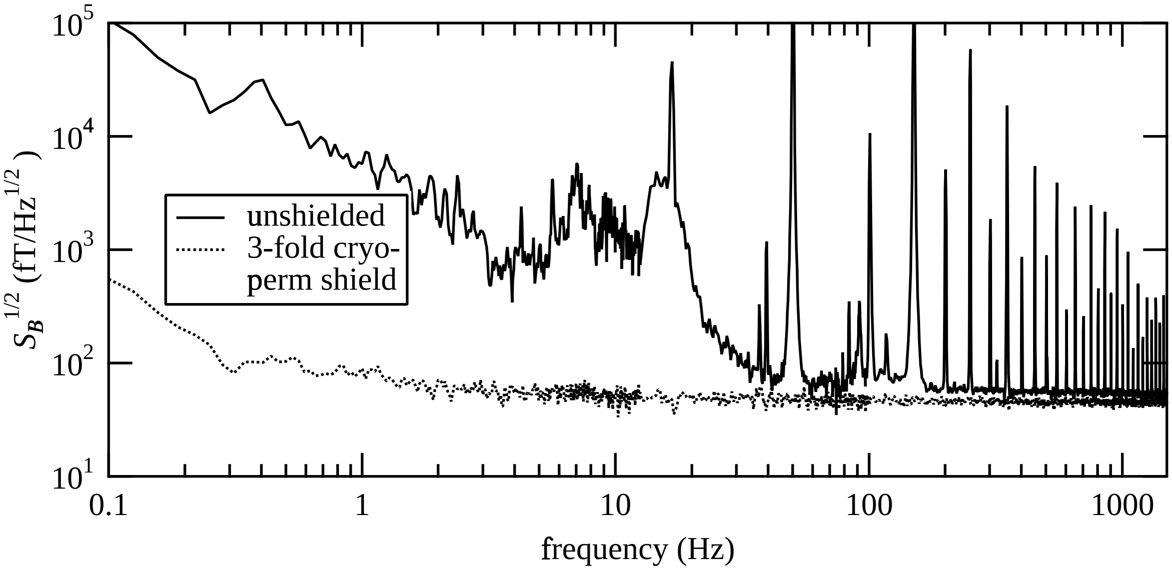

Figure 1: Flux density noise of the IMPUC magnetometer with a threefold cryoperm shield and without shielding in a rural environment at 77 K.

(IMPUC) magnetometer with bicrystal Josephson junctions operated without shielding and in static magnetic fields.

2 PREPARATION

The IMPUC magnetometer, introduced by Scharnweber and Schilling (1996), is prepared on a 10 mm × 10 mm × 1 mm, 24° bicrystal $SrTiO_3$ (100) substrate. We employ a pulsed KrF Excimer laser for the deposition of the superconducting $YBa_2Cu_3O_7$ and insulating $SrTiO_3$ films. Heinsohn et al (1998) describe the optimization of the $YBa_2Cu_3O_7$ films. First a 100 nm $YBa_2Cu_3O_7$ film with a protective $SrTiO_3$ cap layer for good overgrowth conditions of 25 nm is deposited in situ. It is patterned by conventional photolithography and Argon-ion etching in a parallel-plate reactor, thus defining the washer SQUID with the Josephson junctions and the four pick-up loops. A 50 nm $SrTiO_3$ film is deposited to insulate the $YBa_2Cu_3O_7$ ramp edges from crossovers, and windows for via contacts are etched. The four-turn input coil is structured from a 200 nm $YBa_2Cu_3O_7$ film, with the washer serving as the back contact to the pick-up loops.

With the magnetometer size of 8 mm × 8 mm and a SQUID inductance of 80 pH an effective area of 1.4 mm^2 is achieved. The bicrystal Josephson junctions of the magnetometer exhibited a maturing behavior over the first six month after the preparation, presumably due to oxygen loss at the grain boundary. As a consequence, the modulation swing was almost doubled to 17 μV and the flux density noise was reduced accordingly.

3 NOISE PROPERTIES

3.1 Unshielded operation

Figure 1 depicts the noise spectra of the IMPUC magnetometer measured in a rural environment at 77 K. For all the measurements the magnetometer was operated with a bias reversal scheme, thus eleminating noise contributions from critical current fluctuations

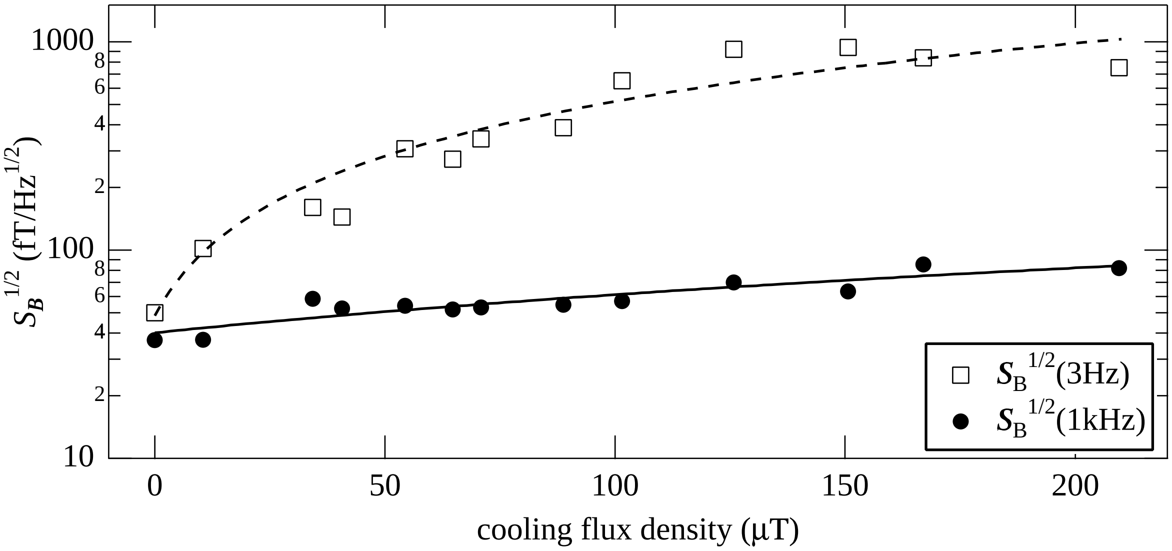

Figure 2: Flux density noise levels at 3 Hz and 1 kHz in dependence of the static magnetic flux density in which the IMPUC magnetometer was cooled and operated at 77 K. The lines are linear fits to the data.

in the Josephson junctions (Dössel 1991). The spectrum obtained inside a threefold cryoperm shield is almost frequency independent down to 3 Hz, below which the shielding admits external noise. For this reason all the spectra are evaluated at 3 Hz for the low-frequency noise levels. In the unshielded measurement a $1/f$ excess noise contribution appears due to the vortex motion in the films. Additionally, a broad structure appears around 10 Hz due to wind moving the magnetometer in the earth's magnetic field. The peak at $16\frac{2}{3}$ Hz origins in the railway operation frequency, while the dc/ac converter feeding the SQUID electronics operated close to the magnetometer causes the sharp 50 Hz harmonics. Despite these unfavorable conditions the magnetometer remained in the flux-locked loop operation during all the measurements for more than 30 minutes.

3.2 Operation in static magnetic fields

The investigations of the behavior in static magnetic fields are carried out in a threefold cryoperm shield in liquid nitrogen at 77 K. As described by Krey et al (1999), a pair of Helmholtz coils provide the magnetic field in which the magnetometer is cooled and operated. These measurements were obtained after the end of the maturing process mentioned in Section 2. At zero field, a low-frequency noise level of $\sqrt{S_B}(3\,\mathrm{Hz}) = 50\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ is reached, a further improvement even compared with the shielded measurement in a rural environment two month after the magnetometer fabrication, as depicted in Fig. 1.

Figure 2 descibes the dependence of the low-frequency noise at 3 Hz and the white noise at 1 kHz on the applied flux density B_0 between zero and $210\,\mu$T. For the low-frequency noise we obtain a linear increase of $\frac{\partial\sqrt{S_B}}{\partial B_0}(3\,\mathrm{Hz}) = 4.7\,\mathrm{fT}/(\sqrt{\mathrm{Hz}}\mu\mathrm{T})$ due to the $1/f$ excess noise from the motion of vortices. In the white noise regime the noise levels are only weakly affected with a slope of $\frac{\partial\sqrt{S_B}}{\partial B_0}(3\,\mathrm{Hz}) = 0.2\,\mathrm{fT}/(\sqrt{\mathrm{Hz}}\mu\mathrm{T})$. The increased white noise levels can partly be attributed to the observed linear reduction of the effective magnetometer area. This is obviously caused by higher slit inductances between the pick-up loop spokes, resulting in a reduced inductance adaption between the pick-up loops and the SQUID. This parallels the findings of Scharnweber and Schilling (1997) about the temperature dependence of the effective area in this magnetometer type. The deviations from the linear behavior in the low-frequency noise are attributed to measurement errors caused by external noise sources of unidentified origin from the laboratory environment, penetrating the shielding at frequencies below 20 Hz. The moderate linear increase of the low-frequency noise is comparable to the findings of Krey et al (1998). From the linear behavior we conclude that the excess noise contribution is entirely due to the motion of vortices. Their density is approximately linearly dependent on B_0, while the quality of the films determines the extend to which they can contribute to the magnetometer noise.

4 CONCLUSION

We have fabricated a $YBa_2Cu_3O_7$ dc SQUID magnetometer with integrated multiloop pick-up coil based on bicrystal Josephson junctions. In shielded environment a flux density noise of $\sqrt{S_B}(3\,\mathrm{Hz}) = 50\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ at 77 K is achieved. The magnetometer remains stable in unshielded operation. Investigations of the excess noise caused by static magnetic fields in which the magnetometer is cooled and operated yield a linear slope of $4.7\,\mathrm{fT}/(\sqrt{\mathrm{Hz}}\mu\mathrm{T})$ at 3 Hz due to the motion of vortices trapped in the superconducting films. We attribute this moderate increase to the high epitaxial quality of our optimized $YBa_2Cu_3O_7$ film deposition and multilayer process.

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REFERENCES

Dantsker E, Tanaka S and Clarke J 1997 Appl. Phys. Lett. **70**, 2037

Dössel O, David B, Fuchs M, Kullmann W H and Lüdeke K-M 1991 IEEE Trans. Magn. **27**, 2797

Drung D, Ludwig F, Müller W, Steinhoff U, Trahms L, Koch H, Shen Y Q, Jensen M B, Vase P, Holst T, Freltoft and Curio G 1996 Appl. Phys. Lett. **68**, 1421

Ferrari M J, Johnson M, Wellstood F C, Kingston J J, Shaw T J and Clarke J 1994 J. Low Temp. Phys. **94**, 15

Heinsohn J-K, Reimer D, Richter A, Subke K-O and Schilling M 1998 Physica C **299**, 99

Krey S, David B, Eckart R and Dössel O 1998 Appl. Phys. Lett. **72**, 3205

Krey S, Barthelmeß H and Schilling M 1999 accepted for publication in J. Appl. Phys.

Miklich A H, Koelle D, Shaw T J, Ludwig F, Nemeth D T, Dantsker E, Clarke J, Alford N McN, Button T W and Colclough M S 1994 Appl. Phys. Lett **64**, 3494

Scharnweber R and Schilling M 1996 Appl. Phys. Lett. **69**, 1303

Scharnweber R and Schilling M 1997 IEEE Trans. Supercond. **7**, 3485