Multichannel Heart Scanner based on High-T_c SQUIDS

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Abstract—A 7-channel magnetometer for magneto-cardiography based on high-T_c SQUIDS has been realized. This magnetometer is used for test experiments in the development of a multichannel high-T_c SQUID based heart-scanner for clinical applications. The intrinsic noise level of the channels in the 7-channel system is typically 120 fT/√Hz down to 1 Hz. Magnetocardiograms were recorded inside a magnetically shielded room. Introductory experiments were performed on the suppression of noise by combining magnetometers to form planar gradiometers. The noise suppression that can be established appeared to be limited by the imbalance of the gradiometric configuration, which is roughly 2 %. This relatively poor balance of the system is caused by inaccuracies in the transfer functions of the individual SQUID magnetometers, and by deviations from the planar geometry.

I. INTRODUCTION

A multichannel heart scanner equipped with high-T_c SQUIDS is under development. The heart scanner is to be used in standard clinical environments. It should be transportable and inexpensive compared to low-T_c systems that typically cost 1.5 million US dollars. As a result, a magnetically shielded room cannot be applied and the suppression of the environmental noise is a major challenge. Besides noise suppression, sensor development and cooling are the main research topics in the heart scanner project. In this paper attention is paid to the former two topics. We describe a 7-channel heart scanner demonstrator, with which 7-channel magnetocardiograms were recorded inside a magnetically shielded room. Introductory experiments were performed on the suppression of noise by combining magnetometers into gradiometric configurations. Results are presented and discussed. The cooling aspect of the heart scanner is considered in a recent publication elsewhere [1].

II. 7-CHANNEL HEART-SCANNER DEMONSTRATOR

A. SQUIDS

In the magnetometer single-layer inductively shunted SQUIDS based on 24° SrTiO₃ bicrystal grain boundary junctions are used [2]. The SQUIDS are structured in laser-deposited YBaCuO layers of 100 nm thickness. The SQUID inductance consists of a 4 μm wide and 83 μm long slit and its calculated inductance is 80 pH. The pick-up loop measures 10 mm x 10 mm on the outside and has a line width of 3.3 mm. The inductance of this loop is calculated to be 5.3 nH. The SQUIDS were characterized in a magnetically shielded flow cryostat using battery powered flux-locked loop electronics for noise measurements. The $I_c R_n$ product is quite homogeneous, yielding an average value over the seven devices of 0.17 mV. The voltage modulation is perfectly periodic for all SQUIDS showing a modulation depth at 77 K ranging from 11 μV to 35 μV. The effective areas at 77 K were experimentally determined resulting in an average over the seven devices of 0.3 mm², which corresponds to a mean magnetic field noise of 120 fT/√Hz.

To protect the high-T_c SQUIDS from moisture the SQUIDS were placed in non-magnetic leadless chip carriers [3]. The housing material is a mixture of alumina powder and an organic resin. The metal conductors consist of tungsten with gold plating. No nickel is used. The outside dimensions of the carrier are 16.5 mm x 16.5 mm x 2.5 mm, without the cover. The inside measures 10.8 mm x 10.8 mm x 1.8 mm, big enough for a substrate of 10 mm x 10 mm. Before the SQUIDS were glued in the chip carriers, the carriers were soldered on small printed circuit boards to make the connections to the electronics. Due to differences in thermal expansion, stress can occur in the SrTiO₃ bicrystal while cooling down. Therefore, a dummy SrTiO₃ substrate (10 mm x 10 mm x 0.5 mm) was first glued in the carrier, and on top of that the bicrystal with the SQUID was glued. We use an epoxy resin glue that remains 'flexible' at low temperatures [4] and thus the stress in the bicrystal is reduced. The glue was allowed to cure for about 48 hours at room temperature under a flow of dry nitrogen gas. The connections between the contact pads on the SQUID and the pads inside the carrier were made by ultrasonic bonding. The alumina

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covers were glued on the carriers using the same epoxy. After mounting the SQUIDs in the carriers, some of the devices were again characterized on critical temperature, $I_c R_n$ product, voltage modulation and noise. None of these parameters changed significantly for any of the SQUIDs. Even after at least 25 thermal cycles, during which the packages became wet on the outside, the properties did not change. The noise of one of the SQUIDs was re-examined in the flow cryostat after half a year, and again we observed no change in properties. We, therefore, conclude that the packaging process is very reliable.

B. Cryostat and Insert

The 7-channel magnetometer consists of 7 separate sticks placed in a cryostat insert (Fig. 1). Basically, each stick comprises a copper-nickel tube with a connector at the top end and a textile reinforced epoxy holder for the SQUID package at the bottom end. The position of each stick inside the insert is fixed via thin-walled guiding tubes. In the insert 19 positions are available for the 7 sticks: a center position, 6 positions on a circle with a radius of 36 mm and 12 on a circle with a radius of 70 mm. The insert, as depicted in Fig. 1, can be placed inside a glass-fiber reinforced epoxy cryostat. Further details on the cryostat and the insert were presented elsewhere [5].

The average noise of the 7 channels is 120 fT/ $\sqrt{\text{Hz}}$ measured down to 1 Hz (best 80 fT/ $\sqrt{\text{Hz}}$, worst 160 fT/ $\sqrt{\text{Hz}}$); 7-channel magnetocardiograms were successfully recorded inside a magnetically shielded room [5].

Fig. 1. Cryostat insert with a separate magnetometer stick

III. NOISE SUPPRESSION

Because large-baseline hardware gradiometers cannot yet be realized in high- T_c technology, we combine separate SQUID magnetometers into gradiometers. In this so-called electronic noise cancellation, a first-order gradiometer is for instance configured by subtracting the output of one SQUID magnetometer from that of another. This method has been applied to low- T_c SQUIDs, e.g. by Drung[6]. We performed noise suppression experiments incorporating 3 of the 7 available high- T_c SQUID magnetometers: the center channel and two opposite neighbours. By electronically combining the outputs of these channels various planar gradiometers can be realized. With the SQUIDs placed in the center position of the insert and on the inner ring, two first-order gradiometers can be configured with a baseline of 3.6 cm, and also a first-order gradiometer with a baseline of 7.2 cm and a second-order gradiometer with a baseline of 3.6 cm. If the SQUIDs are placed in the center and on the outer ring of the insert the baselines become 7 cm and 14 cm. The second-order gradiometer is obtained by doubling the output of the center magnetometer and subtracting the outputs of the two neighbouring magnetometers.

An experiment was performed inside the magnetically shielded room of the Biomagnetic Centre Twente [7] with the SQUIDs on the inner insert ring and in the center. A subject was placed under the cryostat for measuring the heart signal. Noise was generated by means of a small 5 mm diameter coil positioned 37 cm under the plane of the SQUIDs, with its magnetic moment parallel to that plane. The coil was fed with a 30 Hz current. Furthermore, the door of the room was open so as to introduce extra noise arising from the environment. The results are depicted in Fig. 2 and show that the 30 Hz contribution in the first-order gradiometer is 7 % of that in the magnetometer. Because the larger-baseline first-order gradiometer (7.2 cm instead of 3.6 cm) yielded 14 % of the magnetometer signal, we conclude that the imbalance for these first-order gradiometers is roughly 2 %. The relatively poor balance of the system is caused by two effects: firstly, inaccuracies in the transfer functions of the individual SQUID magnetometers (the error in the calibration factors is roughly 1 %) and secondly, deviations from the planar geometry (out-of-plane angles were measured ranging from 0.6° to 1.5°).

In the spectra depicted in Fig. 2 also the 50 Hz noise is significantly suppressed. In this case, the imbalance contribution is below the intrinsic SQUID noise level.

Fig. 2. Noise suppression experiment in magnetocardiography: Noise generated by 30 Hz coil and door of shielded room open; upper curves: magnetometer, center curves: first-order gradiometer, lower curves: second-order gradiometer (both gradiometers 3.6 cm baseline).

The time plots in fig. 2 are self-evident; The first-order gradiometer gives a large improvement and the magnetocardiogram can clearly be distinguished. The second-order gradiometer configuration is worse because the noise contribution due to the imbalance overrules the second-order gradient contribution of the heart magnetic field.

The noise suppression was also tested with 3 SQUID magnetometers that were operated outside the magnetically shielded room. In this experiment the earth's magnetic field was compensated by 40 dB by means of a single coil having a diameter of 55 cm and 200 turns (1 layer of 0.2 mm diameter copper wire). This coil was placed 13.7 cm above the SQUIDs. The earth's field compensation was installed to reduce various noise contributions among which thermally activated flux motion of flux vortices [8,9]. In order to verify this noise reduction, in the near future experiments will be performed inside the shielded room

with a DC field applied to the SQUIDs. In the present experiment outside the shielded room a subject was placed under the cryostat, and the 3 SQUID magnetometers were positioned in line: one in the center and two on the outer ring allowing for baselines of 7 cm and 14 cm for the first-order gradiometers. The resulting spectra are depicted in Fig. 3. The first-order gradiometer reduces the noise by roughly one order of magnitude. Because the imbalance resulting from the previous experiments is roughly 2 %, the remaining noise in the gradiometer is determined by the contribution of the gradient in the noise field and not by the imbalance. In the higher-frequency range several peaks are present that are not sufficiently suppressed by the first-order radiometric configuration. Although the 50 Hz contribution is reduced by a factor 130, other dominant peaks are reduced far less: 60 Hz only by a factor of 3, 70 Hz by 7 and 87 Hz by 6. These factors are determined by the gradient in the noise field, but

also by the sign of the imbalance contribution with respect to that of the field gradient. We assume that the 50 Hz imbalance contribution in this particular experiment was opposite to the gradient contribution, and for that reason the suppression factor was relatively high.

Fig.3. Spectra recorded outside the shielded room (subject under cryostat): upper curve: magnetometer; lower curve: first-order gradiometer (baseline 7 cm).

V. CONCLUSIONS

A 7-channel magnetometer equipped with packaged high- T_c SQUIDs was realized with a noise level of typically 120 fT/ $\sqrt{\text{Hz}}$. With this heart-scanner demonstrator introductory experiments were performed on electronic noise cancellation. The noise suppression that can be established is limited by the imbalance of the gradiometric configuration, which is roughly 2 %.

For applications in standard clinical environments this balance has to be improved by at least one order. To arrive at this point, future research will focus on the stabilization of the signal transfer of individual SQUID magnetometers, on accurate calibration methods, and on the reduction of tilt effects.

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