Magnetocardiography with GMR-based sensors

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Abstract. We have developed a sensor based on the Giant Magneto-Resistive (GMR) effect, associated to a superconducting flux-to-field transformer, which allows femtotesla field detection in a wide range of frequencies [1]. Such sensors are good candidates for measurements of biomagnetic signals generated by the brain or the heart. Here we present Magneto-Cardiographic (MCG) recordings over the chest of healthy volunteers at 4K and 77K with these sensors in a magnetically shielded room. The sensitivity is now limited by the 1/f noise of the GMR element which appears below few kHz. We present a technique based on supercurrent switching which reduces this low frequency noise.

1. Introduction

Biomagnetic signals are generated either by ferromagnetic particles in the body either by the electrical activity of cells. In particular, the heart electrical activity generates magnetic signal with amplitude in the picotesla range (1pT=10^{-12} T) at the chest surface. Electrical activity of bunches of neurons in the brain generates signals even weaker, typically of tens or hundreds of femtotesla (1fT=10^{-15} T). These signals can be measured non-invasively and without electrodes by extremely sensitive magnetometers. Most of the MCG recordings so far have been acquired with Superconducting Interference Devices (SQUIDs), mainly low-Tc SQUIDS for brain imaging.

New proposals for alternative detection have been proposed [1], [2]. Here we present first detection of biomagnetic signals using a spin-electronics based sensor.

In the first part of this paper, we give an example of MCG recordings made with a mixed sensor and in the second part we present a supercurrent modulation technique to repel the 1/f noise out from the low frequency measurement range.
2. Experimental set-up

2.1. Mixed sensor

A mixed sensor associates one or several magnetoresistive elements (Fig. 1), here a GMR spin valve, whose sensitivity at room temperature is of the order of 0.5nT/√Hz, with an efficient flux-to-field transformer realized with a superconducting loop containing a constriction at the position of the GMR element. When a field is applied perpendicularly to the loop in its superconducting state, a supercurrent is generated to prevent the entrance of the flux. The current density in the loop constriction becomes high enough to be detected by the spin valve element. Sensitivity in the femtotesla range can be reached in the thermal noise [3]. The typical GMR stack composition is Ta(2)/NiFe(3)/CoFe(1)/Cu(2)/CoFe(2.5)/MnIr(6)/Ta(5), thicknesses given in nm, and the superconducting loop is either made of Nb or YBCO. Limitation to performances of this device at low frequencies is due to the small magnetic volume of the GMR element, which leads to a 1/f noise contribution which is dominant below typically few hundred Hertz. Nevertheless, a 1cm² surface sensor exhibit field equivalent noise of about 1pT/√Hz at 1Hz [1], which is sensitive enough to record biomagnetic signals as those produced by the heart electrical activity. A mixed sensor resistance varies linearly on a field range of about 1μT which is far larger than the detected signals.

![Figure 1. Schematic (left) and micrograph (right) picture of a hybrid sensor with YBCO superconducting loop with two constrictions in parallel and four GMR sensing elements mounted in Wheatstone bridge configuration. The length of each GMR element is 250 μm, its width 5μm.](image)

2.2. Experimental setup

To realize the MCG recording, the sensor is cooled in a home-made fiberglass dewar allowing a distance of 2.5cm between the sensor and the outer surface of the cryostat. The sensor is in a magnetometer configuration and the experiment is carried out in a magnetically shielded room to reduce the contribution of the environmental noise. The volunteer is laying under the measurement system, the sensor being located over his/her chest. The measurement system can be translated along the x-y plane. Electrocardiographic (ECG) recordings are performed at the same time with three electrodes, located on the volunteer’s wrists and shoulder to avoid magnetic contamination from the electrodes on the MCG.

The output voltage of the GMR elements is amplified by a first stage low noise INA 103 with a gain of 500, followed by a SR560 with an adjustable gain, and filtering between 0.3Hz and 1 kHz. The acquisition is realized on one channel of a commercial Elekta 306- channel MEG system. Real time signals are acquired. The signal is also averaged during 1mn.

In the present experiment, the acquisition has been done with a Nb based sensor of 15x15mm the field equivalent noise level of the sensor was of 2pT/√Hz at 1Hz and 100fT/√Hz above 300Hz.
3. MCG recordings

MCG recordings have been successfully realized (see Figure 2) on a healthy male volunteer. In these recordings, the T-wave and the QRS-complex of the cardiac cycle were clearly visible with few averages.

![MCG and ECG signals](image)

Figure 2: MCG (top) and ECG (bottom) signals averaged during 30s. QRS complex and T-wave are clearly visible. The differences in shape are expected since the ECG records the sum of the electrical signal while the MCG depends on the sensor position with respect to the electrical source in the heart.

4. 1/f noise reduction

In order to improve the sensitivity of the sensor for biomagnetic signal measurements, 1/f noise reduction techniques have been developed. In the case of non linear sensors, like SQUIDs, modulation techniques can be successfully used by an external modulator [4]. In our device, as the response is linear, another strategy should be applied to allow modulation of the signal in the kHz range, where the sensitivity is given by the thermal noise level. The technique proposed here is based on a modulation of the supercurrent passing through two constrictions in parallel of the loop by a local Joule heating (Fig.3).

Without heating, the supercurrent is split equally in the two constrictions, inducing the same resistance change on both GMRs. When one branch is heated, all the supercurrent is running in the other branch and the GMR experiences a change due to this current, whereas the other GMR experiences only the environmental noise. By switching the heating to the other branch, the effect is reversed from the first GMR to the other. This modulation can be achieved in the kHz range, and the relevant signal can be extracted from the demodulated signal.
Figure 3: Parallel mixed –sensor designed for Joule effect heating modulation. Left: schematic of an antiparallel mixed sensor. In response to the applied field $H_a$, a supercurrent runs into the superconducting loop (arrows). Field measured in nT by four GMRs mounted in bridge configuration on a parallel mixed sensor that toggles at 2kHz, while a 200nT sinusoidal magnetic field at 30 Hz is applied perpendicularly to the loop.

If one considers the field-equivalent noise power spectrum $S_B$ with and without toggling (Figure 4), it appears that the low frequency noise is shifted towards the 2kHz modulation peak, and that the signal-to-noise ratio of a 1nT test signal at 30Hz is enhanced by a factor of 8. During the modulation, a low pass filter effect is also observed, due to the loss in flux during the switching.

Figure 4: Detection limit of a parallel mixed sensor in bridge configuration with (plain squares) and without (open dots) toggle at 2 kHz. The signal with toggle has been demodulated and exhibits a noise level 8 times lower than without toggle. Hence the 1/noise of the GMR sensor appears around 2kHz.

This high pass filtering effect limits at present the use of this technique for very low frequency applications. It is due to the quantity of flux which enters the loop when a toggling is done. This flux is roughly proportional to the length of the constriction divided by the perimeter of the sensor. For our present sensor, each toggle leads to a 5% loss of supercurrent. It can be demonstrated that this effect is formally equivalent to a first order high pass filtering of the signal with a cut-off frequency equal to 5% of the toggle frequency [5]. We are presently working on new designs to improve this effect by reducing the length of the GMR elements.
5. Conclusion

MCG recordings have been successfully acquired with GMR superconducting mixed sensors. This opens the possibility of developing that technique with rather cheap, nitrogen cooled sensors. The limitation given by the intrinsic $1/f$ noise of GMR elements can be partially overcome with a toggle technique based on supercurrent switching.

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