Low field MRI with magneto resistive mixed sensors

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Abstract. Low-field magnetic resonance imaging (MRI) requires very sensitive magnetometers for detection of weak magnetic signals in femtoTesla range. Magneto resistive mixed sensors could be used as the sensitive magnetometers [1]. These sensors are the combination of a Giant Magneto resistive (GMR) field sensor and a superconducting loop used as a flux-to-field transformer. A MRI set-up based on mixed sensor has been mounted. This system operates in static field up to 10mT without shielded room. We will present the LF-MRI setup with the implementation of mixed sensors and the first MRI images obtained at low field without prepolarization.

1. Introduction

Low-field magnetic resonance imaging is a very promising imaging method for biological tissue study. This technique is less expensive and operates in lower frequencies than conventional clinical MRI systems. Nevertheless, as the working frequency is lower the magnetic signals from tissues are very weak requiring femtotesla range very sensitive magnetometers to detect them. Superconducting Quantum Interference Devices (SQUID) [2] are mostly used as detection devices for low-field MRI applications. New devices have been proposed such as atomic magnetometers [3] and mixed sensors [1].

In this paper we present mixed sensors which combine a field GMR sensor and a superconducting flux-to-field transformer. This sensor is sensitive in the femtotesla range and is broadband. This gives the possibility to detect the low-field Nuclear Magnetic Resonance (NMR) signals and to perform MRI imaging.

2. Mixed sensors

Thin film technology is applied to fabricate mixed sensors. This device is a combination of the GMR element and of a superconducting loop which acts as a flux-to-field transformer. Mixed sensors could be fabricated either with a low Tc superconducting loop (Nb) or with a high Tc loop (YBaCuO-YBCO) combined with GMR element. First one operates at liquid helium temperature (4K) whereas the second one needs to be cooled to liquid nitrogen temperature (77K). GMR element is a spin valve which consists of a hard magnetic layer which magnetization orientation is fixed, a copper spacer and a free magnetic layer whose magnetization orientation could be changed under small magnetic fields. This GMR element has a form of yoke to reduce the magnetic noise (figure1).
Figure 1. Schematic (left) and micrograph (right) picture of a hybrid sensor with YBCO superconducting loop with two constrictions in parallel and GMR sensing elements. The length of each GMR element is 250 µm.

The typical response of a mixed sensor to magnetic field applied perpendicular to the superconducting loop is shown in figure 2. The applied field generates the supercurrent to prevent the entrance of the flux. As the loop has a constriction, supercurrent flowing in the constriction creates locally high field lines which could be detected by GMR sensors located on top or under the constriction.

Mixed sensor performance could be estimated from its gain and its noise characteristics. Sensor gain is the ratio between the slope of magnetoresistance when the superconducting loop is acting (magnetic field is applied perpendicular to the loop) and the slope of GMR elements (magnetic field is applied on the GMR element sensitive axis with a non acting superconducting loop).

The detectivity of a mixed sensor (figure 3) gives information about the signal-to-noise ratio as a function of frequency. It is clearly seen from the detectivity characteristics that the 1/f noise is dominant below kHz range, leading to a loss of sensitivity at low frequency. This contribution to noise is given by the GMR element of small volume. To reduce this contribution, a modulation technique is proposed in [4] which consists of the local heating of the constriction. At higher frequencies the thermal noise is dominant, which is very important for MRI measurements.

3. Experimental setup

The experimental setup [5] shown in figure 4 consists on double pair of coils generating main static magnetic field of 8mT (corresponding to 340 kHz). The RF pulses are applied by a coil situated around the sample perpendicularly to the main field. The mixed sensor is placed on a liquid nitrogen dewar on top of room temperature sample. The distance between the sensor and the sample is about 30 mm. The experimental setup is an open system without shielding.

Low noise preamplifier is used for the signal amplification. Acquisitions are done with homemade NMR spectrometer. First the 1H NMR signal detection with mixed sensor has been performed to verify the robustness of the sensor.
Figure 3. Field equivalent noise as a function of frequency for a YBCO-based mixed sensor. Indication of thermal noise is given with straight line.

The mixed sensor used for NMR measurements is high-$T_c$ sensor with a gain of 716 and critical temperature of $T_c=80K$. The sensitivity of the sensor is about 20 fT/sqrt(Hz).

Figure 4. Schematics of experimental setup. A main field (B) is generated by 2 pairs of coils. An RF pulse is applied at corresponding frequency by coil wounded around the sample. The signal is detected by the mixed sensor placed into liquid nitrogen cooled dewar.
4. Results

4.1. NMR measurements

Mixed sensor is used for the $^1$H NMR signal detection. The NMR resonance line for a single acquisition is given in figure 5. The linewidth is 3Hz which corresponds to 10ppm of homogeneity. To give a scale, this corresponds only to 70nT of inhomogeneity. If we perform a 100 averaging of the signal in time, the linewidth is doubled. This effect is due to the 50Hz and magnetic fluctuations present in the laboratory which creates a low frequency random field of about 100nT.

![Figure 5](image.png)

**Figure 5.** $^1$H NMR signal measured on doped water at 340kHz with a mixed sensor. The black curve is a single acquisition on 5ml of water

4.2. MRI measurements

For MRI experiments, we have added to the setup a set of three gradients made of a Helmholtz inverted pair for the z gradient and two X and Y figure-of-eight square coils. The linearity of the gradients is better than 1% on the detection volume. First a classical MRI with tuned detection coil has been performed to optimize imaging sequence. This detection coil is placed around the sample perpendicular to the RF coil. The first gradient is applied to perform the slice selection, the second one for the phase encoding and the third gradient is applied during the acquisition. Once the slice is selected, the covering of 2D reciprocal space is performed and then 2D Fast Fourier transform is applied to reconstruct the image. The size of coils is 8cm and the homogeneity zone is 6x6x6cm$^3$.
The MRI image of a phantom is performed using a gradient echo sequence as shown in figure 6. The selective excitation pulse has a bandwidth of 160 Hz. The phantom is a plastic holder with holes of different diameter (from 7mm to 2 mm) filled with doped water (NiCl$_2$) with different doping concentrations (figure 7) varying from 0 to 80 nM. The five 4mm holes (2nd line on the left) have been filled with concentrations varying from 5nM to 20nM. The brightest holes are filled with 80nM NiCl$_2$ concentration. We used a fast T2 (20ms),T1 (200ms) acquisition scheme so the rapid relaxation times correspond to brighter holes. Exact quantization of the link between brightness and precise relaxation times will be published elsewhere [6].

Figure 6. 3D imaging gradient echo-sequence. $G_z$ – slice selection, $G_y$ – phase encoding, $G_x$- reading gradient.

Figure 7. Photo (left) and MRI image (right) of phantom. The size of the phantom is 5cm with holes varying from 2 to 7 mm.
From Figure 7, one can see the good spatial resolution obtained 1mm³. 128 kʻ values along y (phase encoding) have been used. This corresponds to a pitch of 0.4mm. 20 averages on each k value have been done. The slice thickness, determined by the Gz gradient, is about 2.5mm.

5. Conclusions

Mixed sensors composed of superconductor with a magnetoresistive element are very promising devices for ultra-low signal detection. Main advantages of these sensors are their robustness and wideband operation. These properties allow us performing NMR and MRI sequences without prepolarization as these sensors could operate in mT range static magnetic field and do not require a magnetic shielding room. The effective surface of the sensor and the distance to sample play an important role in MRI performance. It could be enhanced by using of flux transformer with a large pick-up loop [7]. Mixed sensors are also good candidates for MEG; however the 1/f noise cancellation technique should be applied. The combination of simultaneous MEG and MRI acquisition are targeted using mixed sensor for simultaneous anatomic and functional information of human brains.

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