Study of Cu-wound Flux transformer for High-Tc SQUID Ultra-Low Field MRI

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Abstract. We constructed a ultra-low field (ULF) nuclear magnetic resonance (NMR) / magnetic resonance imaging (MRI) system employing a high-temperature superconductor (High Tc) SQUID with a separated Cu-wound flux transformer. The pickup coil consisted of two single solenoid coils and each coil was differentially connected each other. The flux transformer consisted of a pickup coil at room temperature and an input coil, which was put in liquid nitrogen and was magnetically coupled with a high-Tc SQUID. The ratio of the transformer was considered and optimized. A water phantom of 10 mL was located in the one side of pickup coil. In the system, we applied polarizing field \( B_p \) perpendicular to the measurement field \( B_m \) before measurements. \( B_p \) was 0.8 T and permanent magnet was used. By using this system, free induction decay (FID) signals of \(^1\)H were measured at \( B_m \) of 30 \( \mu \)T to evaluate the system. The longitudinal relaxation times \( T_1 \) of water were also estimated by changing the polarizing time of \( B_p \).

1. Introduction
The ultra low field (ULF) magnetic resonance imaging (MRI) systems using high sensitive and frequency independent low-Tc SQUID sensors, which feature small-sized system, lower cost, higher frequency-resolution and shorter measurement time due to less averaging number with narrow bandwidth, have attracted attention in recent years [1-3]. The use of high-Tc (HTS) SQUIDs for ULF MRI may enhance these advantages further due to much easier handling with cryoliquid or cryocooler. It is not the easy way while in present technology of high-temperature superconductor (HTS) a possibility to fabricate and to use superconducting HTS transformer with the aim to obtain high magnetic field sensitivity comparable with one for low-Tc SQUID sensors is still the open question. Nevertheless a few attempts have been done to employ HTS SQUIDs for nuclear magnetic resonance (NMR) detection and approaching to MRI [4-7]. In this study we constructed and studied an ultra low-field (ULF) nuclear magnetic resonance (NMR) imaging system using a HTS rf SQUID with a room-temperature (RT) flux transformer. By using this system, free induction decay (FID) signals of \(^1\)H were measured to evaluate the system.

2. ULF MRI System Using HTS rf SQUID

2.1. System Configuration

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The ULF-SQUID-MRI system was constructed in an electromagnetic shield room of 2.2D×2.2W×2.2H m³. The system consists of a polarizing magnet, HTS rf SQUID, SQUID driving electronics, input coil, Helmholtz-type measurement field coil, pick up coil, Maxwell gradient coil, two Golay gradient coils [6], delay pulse generator, function generators, power suppliers, mixer with filters, digital multi channel oscilloscope, and spectrum analyzer. The schematic diagram of the system is shown in figure 1. The rf SQUID and driving electronics used in the experiment are made by Jülicher SQUID GmbH in Germany. The rf SQUID is a washer-type YBa$_2$Cu$_3$O$_{7-x}$ (YBCO) SQUID ring with an outer diameter of 3.5 mm and with one step-edge Josephson junction deposited on a SrTiO$_3$ (STO) substrate [6]. The rf SQUID completed with a YBCO flux focuser of 10 mm x 10 mm size on a STO substrate, which works as a substrate resonator, and an LC tank circuit in liquid nitrogen in the cryostat, is operated by the SQUID electronics. The white noise level of the SQUID in the MSR is approximately 80 fT/Hz$^{1/2}$.

The SQUID is placed at the center of the copper wound input coil. The SQUID and input coil are then cooled by liquid nitrogen in an aluminum Dewar (30 L), which was surrounded by a three-layer mu-metal cylinder with a 2-mm thickness. The measured mutual inductance between the input coil and the SQUID is 16 nH. The pickup coil consists of two single solenoid coils and each coil is differentially connected each other. The pickup coil is connected to the input coil in the LN$_2$ in series so that these coils make a flux transformer as shown in figure 2. All of the coils used in the system except for the input coil are the room temperature coils.

2.2. Optimization of the Flux Transformer

We estimated optimal condition of numbers of turns of input coil and pickup coil by calculation. Figure 3 shows an equivalent circuit of the flux transformer. The voltage $V$ across the pickup coil generated by the motion of flux $\Phi_{ex}$ is written by eq. (1), which is known as Faraday’s electromagnetic law. The current in the transformer is expressed by eq. (2). As a result, the flux $\Phi_s$ detected by the rf-SQUID is obtained as eq. (3). The calculated results are shown in figure 4. The results indicate that there is the best number of turns of an input coil for each pickup coil. The combination of the pickup coil with $N_p = 500$ and the input coil with $N_i = 500$ gives the maximum but it is too sharp and unstable. The combination of $N_p = 2000$ and $N_i = 800$ to 1000 seems to give the stable and better results.

$$V = j \cdot \omega \cdot N_p \cdot \Phi_{ex} \cdot \frac{1}{2}$$  (1)

$$|I| = \Phi_{ex} \cdot \frac{1}{\sqrt{R_p + R_i}^2 + \omega^2(L_p + L_i)^2}$$  (2)

$$\Phi_s = |I| \cdot M = \frac{1}{2} \cdot \Phi_{ex} \cdot \omega \cdot N_p \cdot L_i \cdot k \sqrt{L_p L_s}$$  (3)

Here, $k$ is coefficient of coupling between the input coil and rf-SQUID.
3. Experiment and Discussion

3.1. Performance of the Flux Transformer
A flux transformer was made and examined. It consisted of a pickup coil with \( N_p = 1000 \times 2 \) and an input coil with different \( N_i \). The \( N_i \) was 470, 800, 1000, 1200 and 1800. The experimental system is shown in figure 2. An ac sinusoidal magnetic field of 390 nT p-p with frequency of 1270 Hz was applied to one side of differential pickup coil. Then the signal for an input coil with different \( N_i \) was detected by the rf-SQUID. The peak-to-peak values were plotted as a function of the \( N_i \). The results were shown in figure 5. There is a maximum value at around \( N_i \) of 800-1000, which is almost consistent with the calculation as shown in figure 4. The reason for the moderate reduction over \( N_i \) of 1000 is due to the lower real inductance than the expectation in the calculation. Therefore the combination of the pickup coil with \( N_p = 2000 \) and the input coil with \( N_i = 800 \) was employed in the following experiments. The inductances of the pickup coil and the input coil were 23 mH and 18 mH, respectively. These values are close and almost the same.

3.2. Measurement of NMR Spectra of Water Phantom
First we measured the NMR spectrum of a water phantom, which was placed in the pickup coil; 10 mL of tap water was filled in the phantom. The measurement field coil generated a measurement field \( \mathbf{B}_m \) in the \( z \)-direction, whose field amplitude was about 30 \( \mu \text{T} \) including an ambient earth magnetic field in this work. The diameter of the measurement coil was 611 mm. The magnetization \( \mathbf{M} \) of the sample (tap water in this study, i.e., \(^1\text{H}\)) in \( \mathbf{B}_m \) precesses around the \( z \)-axis at a Larmor frequency \( \nu = \gamma \mathbf{B}_m \) where \( \gamma \) is a gyromagnetic ratio (42.6 MHz/T). The permanent magnet (0.8 T) is located at about 2 m away from the pickup coil. In NMR measurements, a water phantom, which is pre-polarized in the permanent magnet for 5 s, is transferred into the one side of the pickup coil, and then exposed in a measurement field \( \mathbf{B}_m \) from the measurement coil in the \( z \)-direction. Subsequently, by applying a 90° pulse field \( \mathbf{B}_{AC} \) in the \( y \) direction from the AC pulse coil, which flips the magnetized vector \( \mathbf{M} \) from the \( z \)-axis to the \( x \)-axis, \(^1\text{H}\) precesses about the \( z \)-axis with the magnetized vector \( \mathbf{M} \) at the Larmor frequency of \( \nu \) while undergoing spin-lattice \( T_1 \) and spin-spin \( T_2 \) relaxations. During the precession, \(^1\text{H}\) radiates a NMR signal, which is called a free induction decay (FID) signal, to be measured by the pickup coil. The FID signal is magnetically transferred to the SQUID by the flux transformer and converted to a NMR spectrum by fast Fourier transform (FFT) and recorded by the spectrum analyzer. The gradient coils generate \( \partial \mathbf{B}_x / \partial z \) and \( \partial \mathbf{B}_y / \partial y \) gradients of the order of 2-10 \( \mu \text{T/m} \) to compensate an environmental noise. In the measurements, we compensated for the homogeneity of \( \mathbf{B}_m \) so as to make the \(^1\text{H}\)-NMR signal larger and sharper by using the gradient coils as compensation coils.
Figure 6 shows the measured $^1$H-NMR spectra. The harmonics of appliance frequency 60Hz was hidden for clarification. The peak value is 18 pT/Hz$^{1/2}$. Since the Larmor frequency correspond to the applied field $B_m$ of 30 $\mu$T is 1278 Hz, the spectra is reasonable. The $^1$H-NMR spectrum without the field gradient was not shown but it was much smaller and one third of this peak.

3.3. Measurement of $T_1$ relaxation

Next, we measured the NMR spectra for water, while changing the polarizing time of $B_p$ from 0 to 10 s to estimate the respective $T_1$ values. In the measurements, we also compensated for the homogeneity of $B_m$ by the gradient coils [6]. The amplitude of the $^1$H-NMR signal for the water saturated with a polarization was measured. From this result, we estimated that $T_1$ of water was 2.8 s. This result becomes the base of $T_1$-weighted contrast imaging in the near future by using this system.

4. Summary

In this study, we constructed a ULF NMR/MRI system using an HTS-rf-SQUID and a Cu flux transformer. It was found that the combination of the pickup coil with $N_p = 2000$ and the input coil with $N_i = 800$ is the best by experiments and calculations. Using this system, the $^1$H-NMR spectrum was measured under $B_m$ of 30 $\mu$T and $T_1$ value of 2.8 s was experimentally estimated.

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