Superconductor Science and Technology

Improving the sensitivity of a high-T_c SQUID at MHz frequency using a normal metal transformer

To cite this article: D F He *et al* 2006 *Supercond. Sci. Technol.* **19** S231

Supercond. Sci. Technol. **19** (2006) S231–S234 doi:10.1088/0953-2048/19/5/S14

Improving the sensitivity of a high-T_c SQUID at MHz frequency using a normal metal transformer

D F He[1,3], H Itozaki[1,2] and M Tachiki[1]

[1] Superconducting Materials Center, National Institute for Materials Science, Tsukuba 305-0047, Japan
[2] Graduate School of Science Engineering, Osaka University, 1-3 Machikaneyama, Toyonaka, Osaka 560-8531, Japan

E-mail: he.dongfeng@nims.go.jp

Received 25 August 2005, in final form 12 October 2005
Published 27 February 2006
Online at stacks.iop.org/SUST/19/S231

Abstract
Superconducting quantum interference devices (SQUIDs) can be used to detect the signals of nuclear quadrupole resonance (NQR). The NQR frequencies of some interesting materials are in the order of MHz. However, the sensitivity of a high-T_c SQUID is normally not enough to detect the weak NQR signals. To improve the sensitivity of a high-T_c SQUID at MHz frequency, we used a transformer made of normal copper wire. The transformer was composed of a pickup coil, an input coil and a capacitor. The pickup coil was used to detect the magnetic field; the input coil was used to couple the field to the SQUID; and the capacitor was used to create a resonant frequency. By using the normal metal transformer, the magnetic field resolution of the high-T_c dc SQUID was improved by about 38.8 times (from 220 to 5.67 fT Hz$^{-1/2}$) at 954 kHz.

1. Introduction

The frequencies of NQR (nuclear quadrupole resonance) signals range from tens of kHz to MHz. A SQUID (superconducting quantum interference device) can be used to detect the NQR signals. Low-T_c SQUIDs have been used for NQR detections [1–3]. Compared with a low-T_c SQUID, a high-T_c SQUID has much worse magnetic field resolution. To detect the NQR signals using a high-T_c SQUID, the magnetic field resolution of the high-T_c SQUID must be improved.

It has been proved that transformers made of normal conducting wires could be used to improve the sensitivity of a SQUID at several kHz [4–6]; and they have been used for SQUID-based low-frequency applications, such as I-MCG (impedance-magnetocardiogram), and NDE (nondestructive evaluation). Since the normal metal coil usually has better sensitivity at higher frequency, it is also possible to improve the sensitivity of a SQUID at higher frequency by using a normal metal transformer.

[3] Address for correspondence: SQUID group, Superconducting Materials Center, National Institute for Materials Science, 1-2-1 Sengen, Tsukuba, Ibaraki 305-0047, Japan.

In this paper, we will report our research on improving the sensitivity of a high-T_c dc SQUID at MHz frequencies by using a transformer made of copper wire. The transformer was composed of a pickup coil, an input coil and a capacitor. Using the same pickup coil, the same input coil and different capacitors, we measured the magnetic field resolutions at various resonant frequencies.

2. SQUID with normal metal transformer

Figure 1 shows the schematic diagram of the high-T_c dc SQUID setup with the normal metal transformer. The transformer was composed of a pickup coil, an input coil and a capacitor. The coils were made of copper wire. The wire between the pickup coil and the input coil was twisted to avoid getting environmental noise. The input coil and the SQUID were put in liquid nitrogen and were shielded magnetically.

Figure 2 shows the equivalent circuit of the SQUID with the normal metal transformer. L_p and R_p are the inductance and the equivalent resistance of the pickup coil; L_i, and R_i are the inductances and the equivalent resistances of the input coil.

0953-2048/06/050231+04$30.00

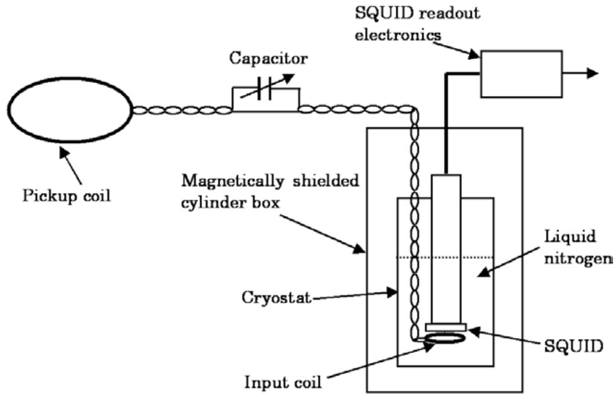

Figure 1. A schematic diagram of the SQUID with the normal metal transformer.

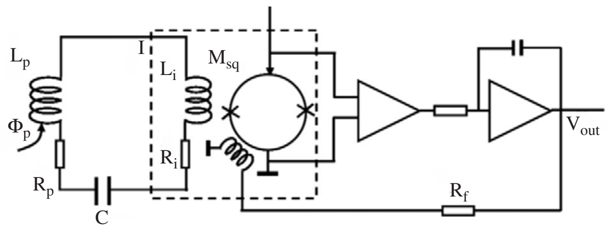

Figure 2. The equivalent circuit of the SQUID with the normal metal transformer. The part in the dashed line is in liquid nitrogen.

C is the capacitor. The resonant frequency can be adjusted by changing the value of the capacitor. The mutual inductance between the SQUID and the input coil is M_{sq}. The part in the dashed line in figure 1 is in liquid nitrogen. The SQUID can operate in FLL (flux locked loop) mode or in open-loop mode.

The resonant frequency f_r of the transformer is determined by L_p, L_i and C. At resonant frequency f_r, the largest flux can be coupled to the SQUID [5, 6]. The magnetic field resolution $S_B^{1/2}$ of a dc SQUID with a normal metal transformer can be expressed as

$$S_B^{1/2} = \frac{1}{2\pi f_r n\pi r^2}\sqrt{4k_B(T_pR_p + T_iR_i) + \left(\frac{R_p + R_i}{M_{sq}}S_{\Phi,sq}^{1/2}\right)^2}$$
$$\approx \frac{R_p}{2\pi f_r n\pi r^2}\sqrt{\frac{4k_BT_p}{R_p} + \left(\frac{S_{\Phi,sq}^{1/2}}{M_{sq}}\right)^2} \qquad (\text{if } R_p \gg R_i) \tag{1}$$

where f_r is the resonant frequency; n is the number of turns of the pickup coil, and r is the radius of the pickup coil; $S_{\Phi,sq}^{1/2}$ is the flux noise spectrum of the dc SQUID; T_p is the temperature of the pickup coil and T_i is the temperature of the input coil. In our experiment, the pickup coil is at room temperature and the input coil is at liquid nitrogen temperature. From formula (1), if we would like to achieve high resolution for a SQUID with a normal metal transformer, we should choose a large pickup coil, small resistances of the coils, and large mutual inductance between the input coil and the SQUID. The actual values of these parameters will also limited by the applications.

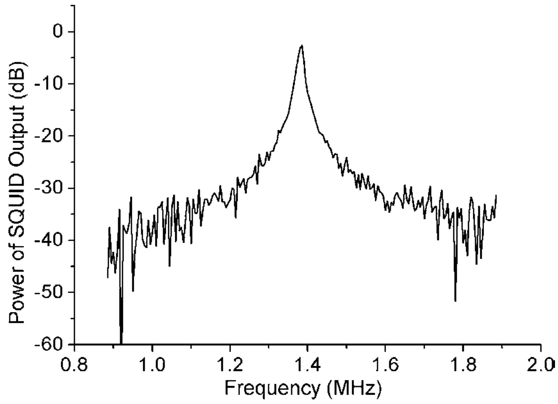

Figure 3. The frequency response of the SQUID with the normal metal transformer, which was measured by a network analyser.

3. Experiments and results

3.1. SQUID and normal metal transformer

A high-T_c dc SQUID was used in our experiments. The washer size of the SQUID chip was 2 cm × 2 cm and the effective area was about 0.46 mm^2. Without the transformer, the white flux noise level was about 50 $\mu\Phi_0$ Hz$^{-1/2}$ until 4 MHz, and magnetic field resolution was about 220 fT Hz$^{-1/2}$. The Dewar holding the liquid nitrogen was put into a magnetic shielding. The SQUID readout electronics could operate in FLL mode or in open-loop mode. With the transformer, the SQUID could not lock well sometimes, so we operated it in open-loop mode and the SQUID acted as a low noise amplifier.

We used copper wire with a diameter of 1 mm to make the pickup coil and the input coil. The pickup coil was 4 turns with a diameter of 9 cm and the input coil was 10 turns with a diameter of 3.8 cm. The pickup coil was at room temperature and the input coil was put in liquid nitrogen. The inductance of the pickup coil was about 3.13 μH; the inductance of the input coil was about 8.4 μH; the mutual inductance between the input coil and the SQUID was about 150 pH. At room temperature, the resistances of the pickup coil and the input coil were both about 0.07 Ω. The resistance of the input coil was reduced to about 0.01 Ω when it was at liquid nitrogen temperature. The above resistances were measured by applying a dc current to the coils. Due to the skin effect and the influence of the parasitic capacitance between the turns of the coils, the equivalent resistances of the pickup coil and the input coil might increase with frequency.

3.2. Measuring the resonant frequency and the equivalent resistance of the transformer

We used a network analyser to measure the resonant frequency of the normal metal transformer. A large transmission coil with a diameter of 50 cm was used to produce the magnetic field by connecting it to the output of the network analyser. The pickup coil was put in the centre of the transmission coil. The SQUID output signal was sent to the input of the network analyser.

Figure 3 shows the frequency response of the SQUID with the normal metal transformer when the capacitor of the transformer was 1 nF. From that, we could easily know that the resonance frequency of the transformer was 1.384 MHz and

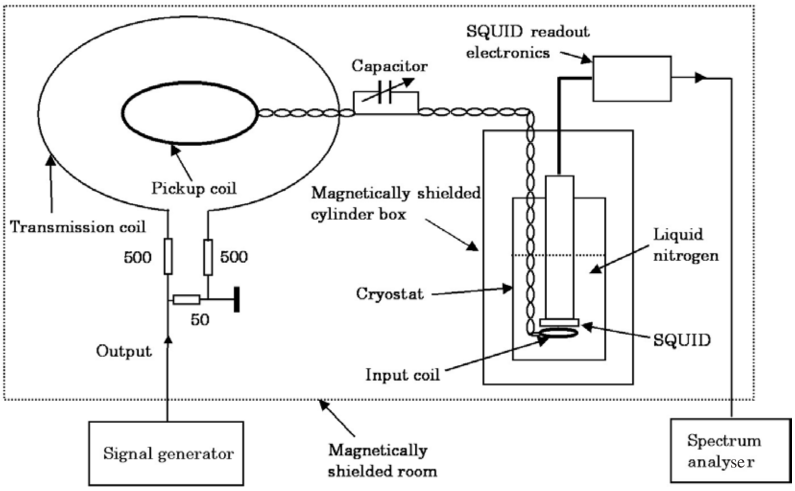

Figure 4. The experimental setup for measuring the field resolution of the SQUID with the normal metal transformer.

the quality factor was about 104. The equivalent resistance of the transformer could also be calculated from the quality factor of the transformer. If the resonance frequency of the transformer is f_r, the quality factor Q and the capacitance of the transformer C, then the total equivalent resistance of the transformer could be estimated as $R = 1/(2\pi f_r C Q)$.

For example, if C is 1 nF, f_r is 1.384 MHz, and Q is 104, the total equivalent resistance of the transformer R becomes about 1.12 Ω at a frequency of 1.384 MHz. The resistance of the input coil was about 1/8 of the total resistance, so it was about 0.14 Ω; and the resistance of the pickup coil was about 7/8 of the total resistance, so it was about 0.98 Ω.

Using the same method and changing the value of the capacitor, we could measure the equivalent resistances of the pickup coil and the input coil for other frequencies. Due to the skin effect, the resistances increased with frequency. It was about 0.28 Ω at about 200 kHz, 0.32 Ω at 300 kHz, 0.6 Ω at 600 kHz, 0.83 Ω at 1 MHz, 1.12 Ω at 1.38 MHz, 1.6 Ω at 2 MHz, 3 Ω at 2.8 MHz, and increased to 5 Ω at 3.8 MHz.

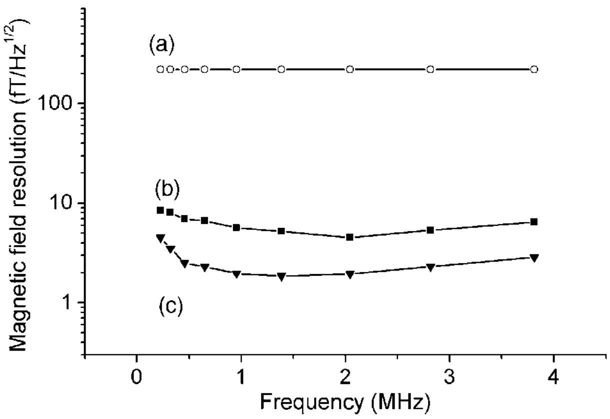

Figure 5. (a) The magnetic field resolution of the high-T_c dc SQUID. (b) The measured magnetic field resolution of the SQUID with the normal metal transformer. (c) The calculated magnetic field noise of the SQUID with the normal metal transformer.

3.3. Measuring the field resolution of the SQUID with the normal metal transformer.

Figure 4 shows the experimental setup to measure the field resolution of the SQUID with the normal metal transformer. The transmission coil was connected to a signal generator to produce magnetic field. The pickup coil was put in the centre of the transmission coil. The SQUID output was connected to a spectrum analyser. The experiment was done in a magnetically shielded room.

For a capacitor, such as 2.2 nF, the transformer had a typical resonant frequency of 954 kHz. We sent a signal to the transmission coil with a frequency of 954 kHz and amplitude of 10 mV. A peak appeared at a frequency of 954 kHz with a value of about 1.67 mV Hz$^{-1/2}$. We could also put the SQUID in the centre of the transmission coil to measure the magnetic field directly, and the value at 954 kHz was about 43 μV Hz$^{-1/2}$. Therefore, the signal at 954 kHz was increased about 38.8 times by the transformer. If the field resolution of the SQUID without the transformer was 220 fT Hz$^{-1/2}$, the field resolution of the SQUID with the normal metal transformer at the resonant frequency of 954 kHz could be calculated: $220/38.8 = 5.67$ fT Hz$^{-1/2}$.

Using the same method and different value of the capacitor, we could also measure the field resolution for various frequencies; the results are shown in figure 5(b). We could see that the field resolution had no large difference for different frequency, and the best magnetic field resolution of 4.5 fT Hz$^{-1/2}$ was obtained at about 2 MHz. Curve (a) in figure 5 shows the magnetic field resolution of the SQUID. It was 220 fT Hz$^{-1/2}$. We can see that the magnetic field resolution is significantly improved by using the normal metal transformer.

To compare with the measured results, we also calculated the magnetic field noise according to formula (1). According to the calculation, we found that the thermal noise of the transformer had less contribution to the total noise. Curve (c) in figure 5 shows the calculated magnetic field noise at several frequencies, which had the same order as the measured values. Both the experimental results and the calculation results show that the field resolution has no great difference in the frequency range from 200 kHz to 4 MHz. We can give a simple explanation. The voltage induced by the pickup coil and the resistance of the transformer both increase with the frequency, so the induced current flow in the transformer has no great difference for different frequencies.

4. Conclusion and discussion

Using a normal metal transformer, we improved the magnetic field resolution of a high-T_c dc SQUID from 220 fT Hz$^{-1/2}$ to several fT Hz$^{-1/2}$. If we use a better SQUID, such as 20 fT Hz$^{-1/2}$, and better coupling between the input coil and the SQUID, field resolution below 1 fT Hz$^{-1/2}$ is possible in the frequency range 200 kHz–4 MHz.

To compare a SQUID and a normal transistor, we now calculate the magnetic field resolution of using a capacitor in parallel with the same pickup coil and connecting with a transistor at room temperature.

For the same pickup coil (4 turns, 9 cm diameter made of 1 mm copper wire), the voltage induced by the pickup coil is about 3.2×10^5 V T^{-1} at 2 MHz. Tuning the coil by connecting a capacitor in parallel with the coil and assuming a Q value of 100, the induced voltage increased to 3.2×10^7 V T^{-1}. The resistance of the coil at 2 MHz is about 1.6 Ω. For a Q value of 100, the impedance of the tuned circuit is about 16 kΩ, producing a voltage noise of about 16 nV Hz$^{-1/2}$. Thus, the obtainable field resolution at 2 MHz is about 16/32 fT Hz$^{-1/2}$ = 0.5 fT Hz$^{-1/2}$. Using the same method, we can also estimate the field resolution at other frequencies. It is about 0.8 fT Hz$^{-1/2}$ at 1 MHz and 2 fT at 200 kHz.

Therefore, we can conclude that, for the same pickup coil, if a better SQUID is used, a high-T_c SQUID may have advantages over a transistor at a frequency below 1 MHz.

Acknowledgments

This study was performed through Special Coordination Funds for Promoting Science and Technology from the MEXT, Japan, and it was partly supported by Japan Science and Technology Corporation. We are grateful for the help from Ms N Iwamoto.

References

[1] TonThat D M and Clarke J 1996 Direct current superconducting quantum interference device spectrometer for pulsed nuclear magnetic resonance and nuclear quadrupole resonance at frequencies up to 5 MHz *Rev. Sci. Instrum.* **67** 2890–3

[2] Connor C, Chang J and Pines A 1990 Magnetic resonance spectrometer with a DC SQUID detector *Rev. Sci. Instrum.* **61** 1059–63

[3] Jach T 1976 Detection of nuclear quadrupole resonance via induced longitudinal magnetization *Appl. Phys. Lett.* **28** 49–51

[4] Kandori A, Suzuki D, Yokosawa K, Tsukamoto A, Miyashita T, Tsukada K and Takagi K 2002 A superconducting quantum interference device magnetometer with a room-temperature pickup coil for measuring impedance magnetocardiograms *Japan. J. Appl. Phys.* **41** 596–9

[5] Yang T Q and Enpuku K 2002 High T_c superconducting quantum interference device magnetometer utilizing cooled copper pickup coil and resonant coupling circuit *Japan. J. Appl. Phys.* **41** L1221–3

[6] Kondo T and Itozaki H 2004 Normal conducting transfer coil for SQUID NDE *Supercond. Sci. Technol.* **17** 459–62