Reduction of Radio Frequency Interference to HTS-dc-SQUID by Adding a Cooled Transformer

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SUMMARY Effect of an addition of a cooled step-up transformer to a flux locked loop (FLL) circuit was studied to reduce indirect rf interference to HTS-dc-SQUID. First, we demonstrated that a noise level of an HTS-dc-SQUID system using the FLL circuit with single room-temperature transformer could be easily degraded by radiation of rf electromagnetic wave to cables in the FLL circuit. It is thought that the rf radiation induced rf current in the circuit, and was transmitted to the SQUID to modulate the bias current, resulting in the increase of the noise level. To avoid the degradation due to such indirect rf interference, the cooled set-up transformer was added to the FLL circuit since it was expected that the additional transformer would work as a “step-down” transformer against the induced rf current. It was shown that the noise level of a HTS-SQUID system (SQUITEM system) operated in an electromagnetically unshielded environment could be improved to the same level as that measured in a magnetically shielded room by the additional cooled transformer and appropriate impedance matching.

key words: rf interference, HTS-dc-SQUID, noise reduction, cooled transformer

1. Introduction

High temperature superconductor (HTS) dc superconducting quantum interference devices (dc-SQUIDs) are the magnetic sensors with extremely high field sensitivity in low-frequency range and easy handling thanks to cooling with liquid nitrogen or compact cryocoolers [1]–[4]. Taking these advantages, several applications using HTS-dc-SQUIDs have been proposed for e.g. geophysical exploration, nondestructive evaluation of materials and structures, and so on [5]–[10]. In such applications, the SQUID systems are often used in unshielded environments, whereas the other SQUID applications usually use magnetically shielded rooms (MSRs) and/or electromagnetically shielded rooms (EMSRs), to reduce magnetic and electromagnetic (EM) interference from the environments [11]–[14]. In particular, due to widespread use of cellular phones and satellite networks, intensity and diversification of used frequencies of rf EM radiation may continue to grow. It is well-known that direct and indirect interference due to the rf radiation to a SQUID system degrade its sensitivity [3], [4], [15], [16], especially in the unshielded environments. The rf radiation directly coupled to a HTS-SQUID can be cancelled by use of gradiometer for instance. However, the indirect rf interference can be a serious problem to cause degradation of the sensitivity of the HTS-SQUID operated in a usual flux-locked loop (FLL) circuit with a single room-temperature (RT) transformer because the rf radiation coupled to cables between the HTS-SQUID and the FLL circuit induces rf current, and it is transmitted to the SQUID in the configuration. To avoid the degradation of the sensitivity due to the indirect rf interference, we studied the effect of an addition of a cooled transformer to the FLL circuit. The cooled transformers have been used for low temperature superconductor (LTS) dc-SQUIDs [17], but rarely used for HTS-dc-SQUIDs in the unshielded environments since simpler systems are preferable for HTS system.

2. Indirect rf Interference to Single Step-Up Transformer in FLL Circuit

First, we examined the effect of the indirect rf interference to a commercial FLL electronics, which employs a room-temperature (RT) step-up transformer, dc bias and flux modulation schemes. A directly-coupled HTS-dc-SQUID magnetometer “DCX014C” made by Sumitomo Electric Hightechs Co., Ltd. was employed. The magnetometer is based on a 10 mm-square bicrystal SrTiO3 (STO) substrate. HoBa2Cu3O7−x thin film with the thickness of 160 nm was deposited on the substrate. The effective area of the SQUID is 0.25 mm2. The modulation depth Vpp of the SQUID was about 10 μV. The experimental setup is schematically depicted in Fig. 1. To study the indirect rf interference coupled to the cables between the SQUID and the electronics, the SQUID, which was mounted on the probe, was set in a tri-layer magnetically shielded (MS) case in a moderate MSR with a shielding factor of about 40 dB, and was cooled in liquid nitrogen. A field coil was employed to radiate an rf EM wave at 10 MHz to the FLL circuit. The rf EM wave was applied at the twisted-pair lines in the probe with poor EM shield (only aluminum foil on each twisted-pair line) indicated as “A” in Fig. 1, and at the cable between the probe and the head amplifier with proper EM shield (aluminum foil on each twisted-pair line, and all the lines were surrounded in wound aluminum flat tape) indicated as “B”, and at the metal connector on the probe indicated as “C”. The noise spectra...
of the field sensitivity of the SQUID were measured with the rf radiation at the respective positions. The measurement results are shown in Fig. 2. When the rf wave was applied at the probe (position “A”), the FLL circuit could not become the lock mode. When the rf wave was applied at the cable (position “B”), the white noise level of the SQUID increased slightly from that of about 180 fT/Hz$^{1/2}$ at 100 Hz without the rf wave. In the case of “C”, the noise of the SQUID increased to about 360 fT/Hz$^{1/2}$ at 100 Hz, while rounding appeared around 1 kHz. It is estimated that the rounding (i.e. down shift of cut-off frequency) was due to reduction of flux-to-voltage transfer coefficient $V_{\Phi}$ by the rf wave as explained later in Sect. 3.1. Figure 3 shows the relationship between the amplitude of the rf wave and the white noise level of the SQUID at 100 Hz when the rf wave was applied at “C”. The noise level increased linearly with the amplitude. These results suggest that rf radiation can easily couple to the lines in the FLL circuit with the single RT step-up transformer to degrade the sensitivity of the system, especially to the lines with poor EM shield.

3. Reduction of rf Interference by Additional Cooled Transformer

3.1 Two-Stage Step-Up Transformer with Cooled Transformer

The degradation of the SQUID sensitivity described in chapter 2 can be explained as following [3], [4]; the rf current induced in the lines between the HTS-SQUID and the RT transformer by the rf wave was transmitted to the SQUID, and the rf current modulated the dc bias current to reduce the flux-to-voltage transfer coefficient $V_{\Phi}$, leading the increase of the noise level of the SQUID (see Fig. 4(a)). In the FLL circuit, the total flux noise density $S_{\phi,FLL}^{1/2}$ is generally given by

$$S_{\phi,FLL}^{1/2} = S_{\phi}^{1/2} + S_{V_{\text{amp}}}^{1/2}/V_{\Phi}$$

(1)

where $S_{\phi}^{1/2}$ is the intrinsic flux noise density of the SQUID, and $S_{V_{\text{amp}}}^{1/2}$ is the preamplifier voltage noise density. Here, we neglect the noise contribution from the bias current source for simplicity. The intrinsic flux noise of the SQUID $S_{\phi}^{1/2}$ can be derived as Eq. (2) with the conditions such as inductance parameter $\beta_L = 1$ and noise parameter $\Gamma \ll 1$,

$$S_{\phi}^{1/2} \approx \frac{\sqrt{16K_BTR}}{V_{\Phi}}$$

(2)

where $K_B$, $T$ and $R$ are the Boltzmann constant, temperature, and resistance of the SQUID, respectively [3]. Since the indirect rf interference reduces $V_{\Phi}$, both $S_{\phi}^{1/2}$ and the noise contribution from the preamplifier ($S_{V_{\text{amp}}}^{1/2}/V_{\Phi}$) should increase. To suppress the indirect rf interference transmitted to the SQUID from the cable, we examined the addition of the cooled step-up transformer in liquid nitrogen. It was expected that the cooled transformer should work as “step-down” transformer against the rf current in the FLL circuit.

3.2 Experimental Setup

In the FLL circuit with the cooled transformer shown in
Fig. 4  FLL circuits (a) with single RT transformer and (b) with additional cooled transformer to form two-stage step-up transformer.

Fig. 5  Cooled transformer. As a core, “Amobeads®” made from amorphous cobalt-based alloy was used [18].

Fig. 6  SQUITEM system. (a) Appearance. The left photo shows the controller with note PC. The right photo shows the probe with FLL circuit on its top. The inset photo shows the configuration of cooled transformer and HTS-SQUID. (b) Schematic diagram of the experimental setup using SQUITEM system.

Fig. 4(b), the SQUID and the primary coil of the cooled transformer form a closed circuit, while the secondary coil of the cooled transformer and the primary coil of the RT transformer form a closed circuit, also. Thus, we thought that the impedance matching in each circuit should be considered to optimize the system in order to obtain the lowest noise level. Therefore, we prepared various sets of the cooled and RT transformers, to find the optimum combination of the cooled and RT transformers for the impedance matching.

We employed amorphous cobalt-based alloy beads “Amobeads” with magnetic permeability that changes little in liquid nitrogen (See Fig. 5). For the RT transformer, normal toroidal ferrite cores were used.

In this experiment, we employed the SQUITEM system, which has been developed for geophysical exploration by Sumitomo Electric Hightechs Co., Ltd. as shown in Fig. 6. The detail of the system and its application are detailed in elsewhere [7]. The whole system was set not in the MSR but in an open space in our laboratory, in order that the cables of the FLL circuit were exposed to the environmental EM interference, whereas only the MS case was used to reduce the influence of the direct rf interference coupled to the SQUID. This system was basically optimized with the single RT transformer, which is set in the FLL circuit including the head amplifier. A flux modulation and dc bias schemes are used. The turns of the primary and secondary coils of the original single RT transformer had been optimized to be 7 and 140, i.e. a gain of 20. Thus, we combined the cooled transformers with a gain 5 and RT transformers with a gain 4, and those with 10 and 2, in order to match the original gain 20. The turn numbers of the cooled transformers with the gain 5 and RT transformers with the gain 4 are summarized in Table 1. Table 2 shows the turn numbers of those with 10 and 2. Copper wire with a diameter of 127 μm with specific coating for use in low temperature was used for the cooled transformers. Each cooled transformer was set above the SQUID on the bottom of the probe as shown in Fig. 6(a). The directly-coupled HTS-dc-SQUID magnetometer “DCX014C” was used to measure the system noise. The white field noise level of the magnetometer measured in the MSR using the tri-layer MS case was about 180 fT/Hz^{1/2} as shown in Fig. 2.

3.3 Results and Discussion

At first, the field noise spectrum of the system using the original single RT transformer with the gain 20 was measured. Because the environmental rf interference always changed, the white noise level of the SQUID changed slightly time
Table 1  Combination of cooled transformer with gain 5 and RT transformer with gain 4. White noise levels at 100 Hz are shown on the right column.

<table>
<thead>
<tr>
<th>Cooled transformer with gain 5</th>
<th>RT transformer with gain 4</th>
<th>$S_{10}^{1/2}$ [fT/Hz]</th>
<th>@ 100 Hz</th>
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<tbody>
<tr>
<td>Primary coil turns</td>
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<tr>
<td>10</td>
<td>50</td>
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<td>15</td>
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<td>40</td>
<td>160</td>
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Table 2  Combination of cooled transformer with gain 10 and RT transformer with gain 2. White noise levels at 100 Hz are shown on the right column.

<table>
<thead>
<tr>
<th>Cooled transformer with gain 10</th>
<th>RT transformer with gain 2</th>
<th>$S_{10}^{1/2}$ [fT/Hz]</th>
<th>@ 100 Hz</th>
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<tr>
<td>Primary coil turns</td>
<td>Secondary coil turns</td>
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by time. Among the several measurements, the lowest noise levels of $230 \text{fT/Hz}^{1/2}$ at 100 Hz were obtained with the setup shown in Fig. 6(b). This noise level was higher than that without the rf radiation measured in the MSR shown in Fig. 2. While the white noise region continued over 1 kHz in the MSR, the down shift of the cut-off frequency was observed in the measurement using only the MS case. Therefore, it is supposed that the indirect rf interference should cause the decrease of $V_\Phi$, and the resultant increase in the noise level.

Next, the system noise with the cooled and RT transformers were measured. Preliminarily, we found that even though the magnetic cores were set near the SQUID, their magnetism did not affect to the characteristics of the SQUID. It must be due to the closed shape of the core beads. The noise spectra with the combinations in Table 1 are shown in Figs. 7(a) to (c). For comparison, each result includes the noise spectrum measured with the single RT transformer.

As shown in Fig. 7(a), the noise levels with the RT transformers of 20 and 80 turns were higher than that with the single RT transformer. While the noise levels with the RT transformer of 30 and 120 turns were almost identical with the single RT transformer, those with the RT transformer of 40 and 160 turns were a bit lower than that the
The noise spectra with the combinations in Table 2 are shown in Figs. 8(a) to (c). As well as the results in Fig. 7, the white noise levels decreased with the increase of the turns of the secondary coils of the RT transformers. The noise level obtained with the RT transformer of 100 and 200 turns shown in Fig. 8(c) became almost identical with those shown in Fig. 7(c). The down shift of the cut-off frequency was also observed, while some large noise peaks at 40 Hz and its harmonic frequencies were observed in these measurements.

From the measurement results, it can be said that the noise of the SQUITEM system set in the electromagnetically unshielded environment could be improved by the application of the two-stage step-up transformer configuration. It is supposed that the indirect rf interference from the environment was well suppressed by the configuration. Since it is indicated that the impedance matching between the secondary coil of the RT transformer and the head amplifier is the strong factor to obtain the same noise level as that in the MSR without rf radiation, the RT transformers with the appropriate turns must be selected. Further study will be done to fully understand the mechanism of the noise reduction by the two-step transformer configuration to optimize the configuration.

4. Conclusion

The effect of the addition of the cooled transformer to the FLL circuit with the RT transformer was studied to reduce the indirect rf interference. We demonstrated that the noise of the SQUID system could be easily degraded by the indirect rf interference, while the addition of the cooled transformer to the SQUITEM system, which used only the MS case and was set in the electromagnetically unshielded environment, well suppressed the indirect rf interference from the environment. It was possible to achieve the same noise level as that in the MSR without rf radiation by applying the combination of the cooled transformer and the RT transformer with the appropriate impedance matching in the FLL circuit. It is thought that the two-stage step-up transformer configuration must be effective when any HTS-SQUIDs system would be used in an electromagnetically unshielded environment.
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References

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Hiroyuki Katayama graduated from Kyoto University in 1994 and received master degree in 1996 on exploration geophysics. He had been working in Metal Mining Agency of Japan (MMAJ) since 1996 to 2004 as an exploration geophysicist, and then has been working in Japan Oil, Gas and Metals National Corporation (JOGMEC) since its establishment in February, 2004. He was also dispatched to University of Utah from January 2002 to December 2003 to study exploration geophysics, especially numerical analysis techniques for an electromagnetic method. Since January 2004, he has been involved non-ferrous mineral exploration projects in North America and technical assessments of resource evaluation for mining projects. He is a member of the Society of Exploration Geophysicists of Japan, the Society of Exploration Geophysicists and Society of Resource Geology.