INVITED PAPER *Special Section on Superconducting Signal Processing Technologies*

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

Yoshimi HATSUKADE[†a)], **Yoshihiro KITAMURA**[†], ***Nonmembers***, **Saburo TANAKA**[†], **Keiichi TANABE**[††], ***Members***, **Eiichi ARAI**[†††], ***and*** **Hiroyuki KATAYAMA**[†††], ***Nonmembers***

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 $SrTiO_3$ (STO) substrate. $HoBa_2Cu_3O_{7-x}$ thin film with the thickness of 160 nm was deposited on the substrate. The effective area of the SQUID is 0.25 mm^2. The modulation depth V_{pp} 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

Manuscript received July 20, 2010.
Manuscript revised October 29, 2010.
[†]The authors are with Toyohashi University of Technology, Toyohashi-shi, 441-8580 Japan.
[††]The author is with International Superconductivity Technology/Superconductivity Research Laboratory (ISTEC/SRL), Tokyo, 105-0011 Japan.
[†††]The authors are with Japan Oil, Gas and Metals National Corporation (JOGMEC), Kawasaki-shi, 212-8554 Japan.
a) E-mail: hatukade@ens.tut.ac.jp
DOI: 10.1587/transele.E94.C.266

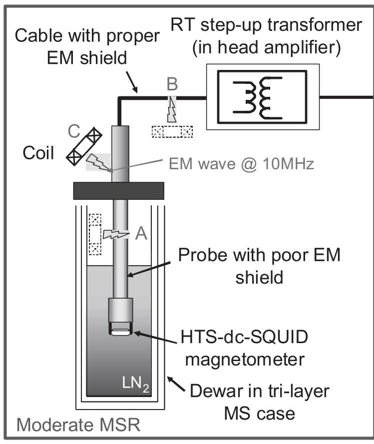


Fig. 1 Experimental setup with single RT transformer in FLL circuit.

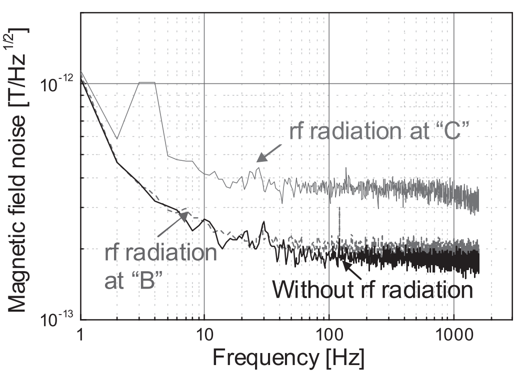


Fig. 2 Magnetic field noise spectra of HTS-dc-SQUID with and without rf radiation on the lines or cable of FLL circuit.

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_Φ 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 system 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.

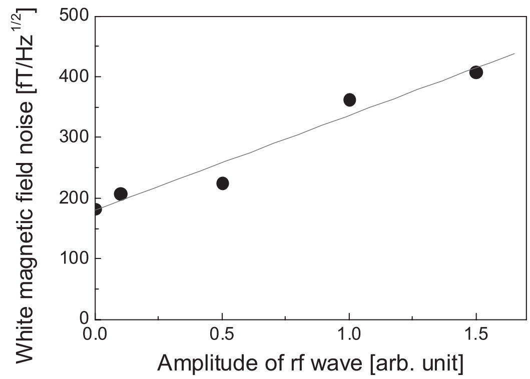


Fig. 3 White magnetic field noise level as the function of amplitude of rf wave applied at the location "C" in Fig. 1.

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_Φ, leading the increase of the noise level of the SQUID (see Fig. 4(a)). In the FLL circuit, the total flux noise density $S^{1/2}_{\Phi,FLL}$ is generally given by

$$S^{1/2}_{\Phi,FLL} = S^{1/2}_{\Phi} + S^{1/2}_{V,amp}/V_\Phi \tag{1}$$

where $S^{1/2}_{\Phi}$ is the intrinsic flux noise density of the SQUID, and $S^{1/2}_{V,amp}$ 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 $S^{1/2}_{\Phi}$ can be derived as Eq. (2) with the conditions such as inductance parameter $\beta_L = 1$ and noise parameter $\Gamma \ll 1$,

$$S^{1/2}_{\Phi} \approx \frac{\sqrt{16K_B TR}}{V_\Phi} \tag{2}$$

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_Φ, both $S^{1/2}_{\Phi}$ and the noise contribution from the preamplifier ($S^{1/2}_{V,amp}/V_\Phi$) 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 as shown in Fig. 4(b) [17]. The additional transformer was set near the SQUID 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

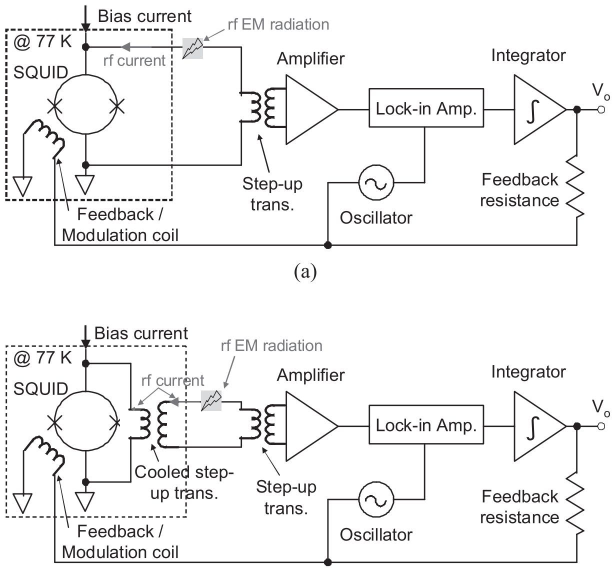


Fig. 4 FLL circuits (a) with single RT transformer and (b) with additional cooled transformer to form two-stage step-up transformer.

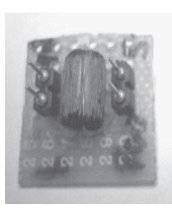


Fig. 5 Cooled transformer. As a core, “Amobeads®” made from amorphous cobalt-based alloy was used [18].

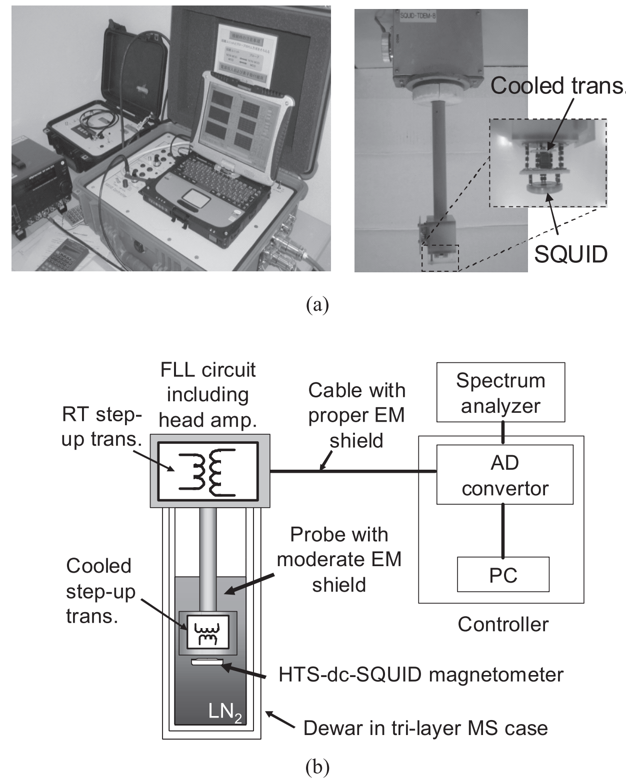


Fig. 6 SQUITEM system. (a) Appearance. The left photo shows the controller with note PC. The right photo shows the probe with FLL circuit on its top. The inset photo shows the configuration of cooled transformer and HTS-SQUID. (b) Schematic diagram of the experimental setup using SQUITEM system.

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.

Cooled transformer with gain 5		RT transformer with gain 4		$S_B^{1/2}$ [fT/Hz$^{1/2}$] @ 100 Hz
Primary coil turns	Secondary coil turns	Primary coil turns	Secondary coil turns	
5	25	20	80	330
10	50	20	80	330
15	75	20	80	300
5	25	30	120	230
10	50	30	120	230
15	75	30	120	230
5	25	40	160	180
10	50	40	160	180
15	75	40	160	180

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.

Cooled transformer with gain 10		RT transformer with gain 2		$S_B^{1/2}$ [fT/Hz$^{1/2}$] @ 100 Hz
Primary coil turns	Secondary coil turns	Primary coil turns	Secondary coil turns	
5	50	60	120	230
7	70	60	120	250
10	100	60	120	230
5	50	80	160	200
7	70	80	160	210
10	100	80	160	200
5	50	100	200	180
7	70	100	200	190
10	100	100	200	180

by time. Among the several measurements, the lowest noise levels of 230 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_Φ, 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

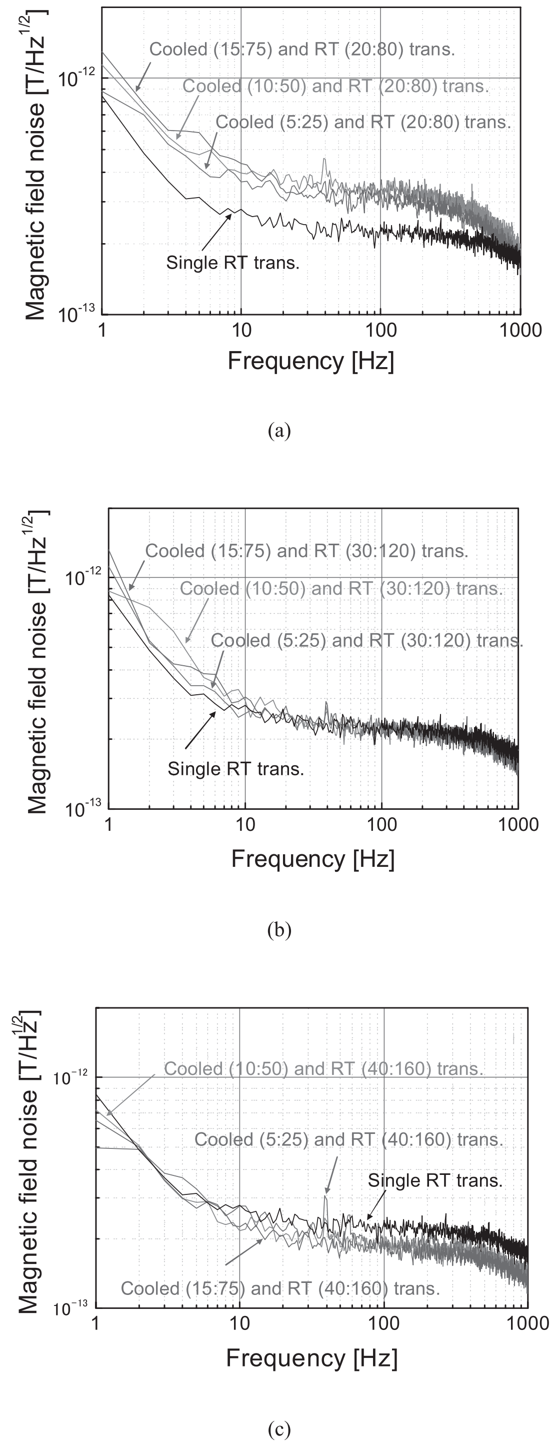
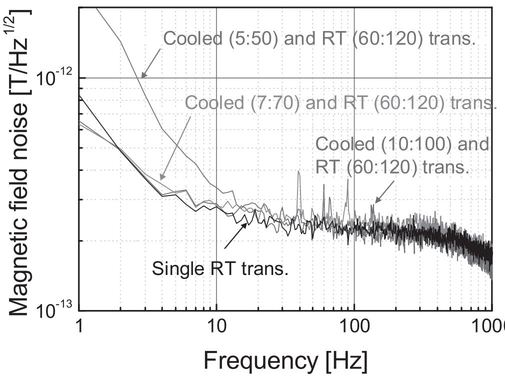
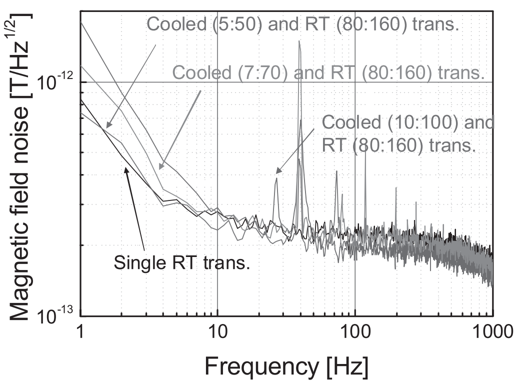


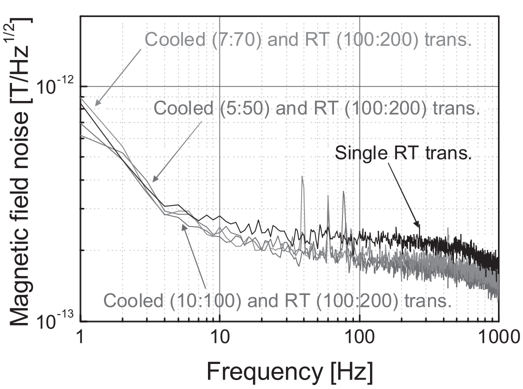
Fig. 7 System noise spectra with cooled transformers of gain 5 and RT transformers of gain 4 with various turns. (a) Cooled transformers (5:25, 10:50, and 15:75) and RT transformer (20:80). (b) Cooled transformers (5:25, 10:50, and 15:75) and RT transformer (30:120). (c) Cooled transformers (5:25, 10:50, and 15:75) and RT transformer (40:160). For comparison, the noise with single RT transformer (7:140) is shown together.



(a)



(b)



(c)

Fig. 8 System noise spectra with cooled transformers of gain 10 and RT transformers of gain 2 with various turns. (a) Cooled transformers (5:50, 7:70, and 10:100) and RT transformer (60:120). (b) Cooled transformers (5:50, 7:70, and 10:100) and RT transformer (80:160). (c) Cooled transformer (5:50, 7:70, and 10:100) and RT transformer (100:200). For comparison, the noise with single RT transformer (7:140) is shown together.

single RT transformer. The noise level obtained with the last combination using the RT transformer of 40 and 160 turns became almost identical with the noise level without rf radiation in the MSR shown in Fig. 2, although the down shift of the cut-off frequency was observed in every result. This may be due to the entry and hopping of the flux vortices during the cooling in the MS case, or the direct rf interference, which only the MS case could not perfectly shield. The both can reduce V_Φ of the SQUID. On the other hand, the turns of the cooled transformers were hardly related to all the noise profiles. This indicates that the before-mentioned impedance matching in the two closed circuits shown in the left part in Fig. 4(b), which includes the SQUID, the cooled transformer, and the primary coil of the RT transformer, may less related to the noise profiles than the impedance matching between the secondary coil of the RT transformer and the amplifier in the FLL circuit.

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 frequency and 60 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.

Acknowledgment

We would like to acknowledge Prof. Oleg Snigirev of Moscow State University for the helpful discussion.

References

[1] A. Barone, Principles and Applications of Superconducting Quantum Interference Devices, World Scientific, Singapore, New Jersey, London, Hong Kong, 1992.

[2] T. Kobayashi, H. Hayakawa, and M. Tonouchi, Vortex Electronics and SQUIDs, Springer-Verlag, Berlin Heidelberg, 2003.

[3] J. Clarke and A.I. Braginski, The SQUID Handbook, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, 2004.

[4] J. Clarke and A.I. Braginski, The SQUID Handbook II, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, 2006.

[5] A. Chwala, R. Stolz, J. Ramos, V. Shultze, H.G. Meyer, and D. Kretzschmar, "An HTS Dc SQUID system for geomagnetic prospection," Supercond. Sci. Technol., vol.12, pp.1036–1038, 1999.

[6] C.P. Foley, D.L. Tilbrook, K.E. Leslie, R.A. Binks, G.B. Donaldson, J. Du, S.K. Lam, P.W. Schmit, and D.A. Clarke, "Geophysical exploration using magnetic gradiometry based on HTS SQUIDs," IEEE Trans. Appl. Supercond., vol.11, pp.1375–1378, 2001.

[7] H. Ota, T. Nagaishi, and E. Arai, "Development of TDEM data acquisition system based on high Tc SQUIDs for mineral exploration," IEICE Trans. Electron., vol.E88-C, no.2, pp.192–197, Feb. 2005.

[8] C. Carr, E.J. Romans, J.C. Macfarlane, C.M. Pegrum, and G.B. Donaldson, "HTS dc SQUIDs for eddy current NDE in an unshielded environment," IEEE Trans. Appl. Supercond., vol.5, pp.373–378, 1998.

[9] Y. Hatsukade, K. Yotsugi, and S. Tanaka, "Mobile HTS-SQUID NDE system with robot arm and active shielding using fluxgate," Physica C, vol.468, pp.1932–1935, 2008.

[10] Y. Hatsukade, K. Yotsugi, S. Kanai, K. Hayashi, H. Wakana, Y. Tarutani, K. Tanabe, and S. Tanaka, "Robot-based NDE system using 3D-mobile HTS-SQUID," IEEE Trans. Appl. Supercond., vol.19, no.3, pp.796–800, 2009.

[11] K. Enpuku, T. Minotani, M. Hotta, and A. Makahodo, "Application of high Tc SQUID magnetometer to biological immunoassays," IEEE Trans. Appl. Supercond., vol.11, pp.661–664, 2001.

[12] K. Nikawa, "Laser-SQUID microscopy as a novel tool for inspection, monitoring and analysis of LSI-chip-defects," IEICE Trans. Electron., vol.E85-C, no.3, pp.746–751, March 2002.

[13] D. Suzuki, A. Tsukamoto, A. Kandori, K. Ogata, et al., "Development of multichannel compact HTS MCG system using transversal magnetically shielded cylinder," Proc. 14th Internat. Conf. Biomagnetism, Biomag2004, p.662, Boston MA, 2004.

[14] S. Tanaka, H. Fujita, Y. Hatsukade, T. Otani, S. Suzuki, and T. Nagaishi, "High-Tc SQUID micro-detector using high performance magnetic shield for industrial products," Supercond. Sci. Technol., vol.20, pp.S385–S388, 2007.

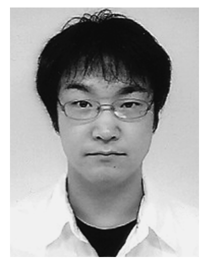
[15] N. Ishikawa, K. Nagata, H. Sato, N. Kasai, and S. Kiryu, "Effect of rf interference on characteristics of dc SQUID system," IEEE Trans. Appl. Supercond., vol.3, no.1, pp.1910–1913, 1993.

[16] R.H. Koch, V. Foglietti, J.R. Rozen, K.G. Stawiasz, M.B. Ketchen, D.K. Lathrop, J.Z. Sun, and W.J. Gallagher, "Effects of radio frequency radiation on the dc SQUID," Appl. Phys. Lett., vol.65, no.1, pp.100–102, 1994.

[17] F. Wellstood, C. Heiden, and J. Clarke, "Integrated dc SQUID magnetometer with a high slew rate," Rev. Sci. Instrum., vol.55, no.6, pp.952–957, 1984.

[18] http://www.toshiba-tmat.co.jp/eng/list/am_am.htm

Yoshimi Hatsukade received the B.S. and M.S. degrees from Waseda University in 1998 and 2000, respectively. He received his Doctoral degree in engineering from Waseda University in 2003. Since 1998, he has been engaged in the research of application of superconductive electronics, mainly HTS-SQUID. Currently he is associate professor in Toyohashi University of Technology. He is a member of the Japan Society of Applied Physics, the Cryogenic Association of Japan, and Japan Biomagnetism and Bioelectromagnetics Society.



Yoshihiro Kitamura was born in Miyagi Japan, on July 14, 1987. He received his B.E. from Toyohashi University of Technology in 2010. At present, he is studying toward M.E. degree at the graduate school. His research interest is magnetic metallic contaminant detector using High-Tc SQUID magnetometer. He is a member of the Japan Society of Applied Physics and Cryogenic Society of Japan.

Saburo Tanaka received his B.E. and M.E. from Toyohashi University of Technology in 1981, and 1983, respectively. He received his Doctoral Degree in engineering from Osaka University in 1991. Since 1987 he has been involved in the research of high-temperature superconductors at Sumitomo Electric Itami Research Lab. He was engaged in the development of multi-channel high-Tc SQUID systems at the Superconducting Sensor Laboratory from 1991 to 1995. He was a visiting research associate at the Department of Physics, University of California at Berkeley from 1996 to 1997. Currently, he is a professor and a presidential advisor at Toyohashi University of Technology. He is a member of the Japan Society of Applied Physics, the Institute of Electrical Engineers of Japan, the Institute of Electrostatics Japan and IEEE.

Keiichi Tanabe received his B.E., M.E., and Ph.D. degrees in applied physics from the University of Tokyo in 1977, 1979, and 1988, respectively. In 1979, he joined the Electrical Communication Laboratories of Nippon Telegraph and Telephone Corporation, Ibaraki, Japan, where he worked on the research of superconducting thin films and Josephson junctions for electronic applications. From 1987 to 1988, he was with the School of Applied and Engineering Physics, Cornell University, as a visiting scientist. In 1995, he joined the SRL-ISTEC, Tokyo, Japan, where he has been working on the research and development of high-temperature oxide superconducting materials, thin films, electronic devices, coated conductors, and new superconducting materials. He is currently Deputy Director General and concurrent Division Director of Electronic Devices Division and Advanced Materials & Physics Division. Dr. Tanabe is a member of the Japan Society of Applied Physics, the Physical Society of Japan, and the American Physical Society. He has also been a Board Member in Electronics of Applied Superconductivity Conference since 2006.

Eiichi Arai received his B.S. and M.S. degrees in Earth Resources Engineering from Kyoto University in 1991 and 1993, respectively. He started his career in 1993 at the former MMAJ (Metal Mining Agency of Japan, the present Japan Oil, Gas and Metals National Corporation). From 1997 to 1999 he furthered his studies at the Colorado School of Mines (CSM), and received his professional degree in 1999. After graduation from CSM, he returned to MMAJ and has worked in mineral exploration projects and R&D projects on mineral exploration technology. During this period, he completed the requirements for his doctorate in engineering which he received from Kyoto University in 2004.

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.