Investigation on readout coil design for fluxed locked loop control of HTS rf-SQUID

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Abstract. We investigated the readout coil, electro-magnetically coupled with a HTS rf-SQUID for the flux-locked loop control. The design and size of the readout coil affected the SQUID performances. Among the tested combinations of different readout coils with the rf-SQUID, the rectangular coil, which just surrounded the slit in the rf-SQUID, was advantageous for the better performance. We also demonstrated the rf-SQUID operation with the rectangular coils made of the thin flexible print circuit board, which could be put on the rf-SQUID stably.

1. Introduction
Superconducting quantum interference devices (SQUIDs) are well known as highly sensitive magnetic sensor for various applications. We have developed HTS rf-SQUIDs for the application of SQUID microscopy [1]–[3]. An rf-SQUID measures the extremely weak magnetic field by detecting its resonance change caused by the external quasi-static magnetic field. The SQUID performance depends on the designs of not only the rf-SQUID itself, especially the slit inside it [3], but also the readout coil combined with it for fluxed locked loop (FLL) control. In this study, we focused on the readout coil to improve the SQUID performance. Figure 1 shows the schematic illustration of the total system for the HTS rf-SQUID magnetometer. In this system, one readout coil can serve as three functions: the transmission coil for the rf-magnetic field to excite the rf-SQUID at the resonant frequency, the reception coil for the rf-magnetic field returned back from the resonated rf-SQUID, and the feedback coil for FLL control to measure the intensity of the external magnetic field quantitatively. For the transmission and receipt of the rf-magnetic field, the readout coil should be coupled to the rf-SQUID in the proper coupling condition. In contrast, for the FLL feedback, the weak coupling should

Figure 1. Total measurement system of an rf-SQUID magnetometer.
be better for the sensor sensitivity as long as the noise is not increased. It was supposed that the coil design should affect the SQUID performance. We investigated the coil influences to the conventional rf-SQUID operated with a substrate resonator [4], and to our modified rf-SQUID having a meandered slit, which can be operated without a resonator [3]. The SQUID performances were investigated by changing the combinations of the rf-SQUIDs with various coils with the different sizes and designs.

2. Setup for measurements of the rf-SQUIDs
The rf-SQUIDs and the substrate resonator were made of the YBCO thin films on bi-crystal and mono-crystal SrTiO$_3$ (STO) substrates, respectively. Figures 2(a) and (b) respectively show our conventional rf-SQUID and the substrate resonator fabricated in reference to a commercially available rf-SQUID set (Jülicher SQUID GmbH). On the other hand, figure 3(a) shows our modified rf-SQUID having a meandered slit, which plays the resonator role to adjust the resonant frequency. Each outer diameter of both rf-SQUIDs was set at 3.5 mm.

Readout coils having different designs were also made with the printed circuit boards (PCBs) having a 35 µm copper layer by a CNC milling machine. We firstly prepared two types of the coils: square and circular coils as shown in figures 4 and 5, respectively. Based on the results of two type coils, we also prepared the rectangular type coils as shown in figure 6. Each wire width of the readout coils was set at 0.5 mm in the PCB drawing, but the actual width was 0.5±0.2 mm due to the machining accuracy of the milling machine. For the square type (figure 4), we fabricated four coils having the different inner side length: L (L=5, 4, 3 and 2 mm). For the circular type (figure 5), we made three coils having the different inner diameter: R (R=5, 4 and 3 mm). For the rectangular type (figure 6), we made two coils having the different inner side width: W (W=0.8 and 0.4 mm), keeping the inner side length L=1.8 mm, in which the coil wire just surrounded the slit and hole in the rf-SQUID.

The rf-SQUID was operated using the commercially available FLL electronics (HTSL-RF-SQUID-ELEKTRONIK ver.5, Jülicher SQUID GmbH) [5]. The V-Φ characteristics and the noise density spectra were obtained by the open-loop (FLL off) and the closed-loop (FLL on), respectively. For the measurements of the rf-SQUID, the rf-SQUID was mounted with the PCB coils using the

![Figure 2](image1.png)

**Figure 2.** Optical microscope images of (a) our conventional rf-SQUID and (b) substrate resonator. Inset shows the magnified image around the center. The square bright region corresponds to the SQUID hole, and arrows indicate the grain boundary. (c) Assembly of the rf-SQUID and resonator inside the holder. The rf-SQUID was combined with the substrate resonator in a flip-chip configuration.

![Figure 3](image2.png)

**Figure 3.** Optical microscope images of (a) our modified rf-SQUID. Inset shows the magnified image around the slit. Arrows indicate the grain boundary. (b) Assembly of the rf-SQUID inside the holder. The substrate resonator was omitted differently from figure 2(c).
holder of the FLL electronics accessory, as shown in figure 2(c) or 3(b). The rf-SQUID measurements were carried out in the liquid nitrogen Dewar flask, around which a Helmholtz coil was wound (diameter: 13 cm, 5 turns in each side), inside a μ-metal magnetic and a copper EM shields. The V-Φ curve and the flux conversion coefficient, defined as α, for the FLL-output voltage signal were measured by sweeping the static magnetic field from the readout coil, and by applying the external magnetic field from the Helmholtz coil, respectively.

3. Experimental results
For the comparison among the combinations of the different readout coils, we extracted characteristic features from the measurement results, related with the transmission, the feedback and the output signal. In the transmission measurement, the frequency and the power of the rf-source must be optimized to get the largest amplitude appearing in the V-Φ curve, as shown in the example in figure 4.

Figure 4. Square type of readout coils. Schematics of the coil shapes with (a) L=5 mm and (b) L=2 mm. Outlines of our conventional rf-SQUID and resonator were superimposed. (c) Photograph of a fabricated coil.

Figure 5. Circular type of readout coils. Schematics of the coil shapes with (a) R=5 mm and (b) R=3 mm. Outlines of our conventional rf-SQUID and resonator were superimposed. (c) Photograph of a fabricated coil.

Figure 6. Rectangular type of readout coils. Schematics of the coil shapes with (a) W=0.8 mm and (b) W=0.4 mm, while keeping the side length L=1.8 mm. Outlines of our conventional rf-SQUID and resonator were superimposed. (c) Photograph of a fabricated coil.

Figure 7. Example of (a) V-Φ characteristic and (b) noise density spectrum in combination of our conventional rf-SQUID with the square coil (the case of L=5 mm).
7(a). These optimized values can make the rf-SQUID resonated. From the optimized condition, the period and the maximum slope values of the V-Φ curve were obtained, as shown in figure 7(a). Note that every V-Φ curve’s horizontal axis in this paper means the current fed to the readout coil, related with magnetic flux for the modulation or FLL feedback. The period, defined as Δ$I_{\Phi0}$, means the application current for generating 1 $\Phi_0$ flux quanta of the magnetic flux from the readout coil to the rf-SQUID, corresponding to the magnetic coupling efficiency between the rf-SQUID and the coil. The smaller Δ$I_{\Phi0}$, the bigger coupling efficiency. The slope mainly affects the slew rate and the bandwidth of the FLL control. In the feedback measurement, the effective area and the flux conversion coefficients, defined as $A_{\text{eff}}$ and $\alpha$, respectively, were obtained by using the Helmholtz coil. In the output measurement, the white noise levels were obtained from the noise density spectra, in which the noise level was settled to be constant at the high frequency range, as shown in figure 7(b).

### 3.1. Coil combinations with our conventional rf-SQUID

We firstly measured the combinations of the square and circular coils, as shown in figures 4 and 5, with our conventional rf-SQUID as shown in figure 2. As described in the following section 3.1.2, we assumed that it would be preferable for the readout coil to surround the slit in the rf-SQUID. Then, we prepared the rectangular coils as shown in figure 6, and also measured their combinations.

#### 3.1.1. Result Comparison

The total measurement results are listed up in this section. The transmission frequencies and $A_{\text{eff}}$ values for the combinations with the different readout coils were almost constant at 620±2 MHz and 0.42±0.04 mm$^2$, respectively. Figures 8, 9, 10, 11 and 12 respectively show dependence of the transmission power, Δ$I_{\Phi0}$ value of each V-Φ curve, slope of each V-Φ curve, coefficient $\alpha$, and white noise level, on the coil feature size (L, R and W).

![Figure 8](image1)

**Figure 8.** Transmission powers for the combinations with (a) square, (b) circular and (c) rectangular coils as functions of the inner side length: L, diameter: R and side width: W, respectively.

![Figure 9](image2)

**Figure 9.** Δ$I_{\Phi0}$ values of each V-Φ curve for the combinations with (a) square, (b) circular and (c) rectangular coils as functions of the inner side length: L, diameter: R and side width: W, respectively.
3.1.2. **Discussion.** From the measurement results, the characteristic features except the transmission frequency and $A_{\text{eff}}$ value depended on the readout coil. The reason why the transmission frequency and $A_{\text{eff}}$ value showed the independence of the coil design or size is because the resonant frequency and the effective area are little influenced by the coil, but strongly depend on the rf-SQUID and the resonator, themselves. In contrast, the reason why the other features depended on the coil must be because magnetic coupling between the rf-SQUID set and the coil played an important role for the operation. In figure 8, the transmission power is slightly decreased with decreasing the coil size. It indicates that the magnetic coupling for the rf-magnetic field to excite the rf-SQUID set was mildly improved due to reduction of the energy required to reach the same resonant condition. Figure 13 shows the simulation result of the rf-magnetic field over the rf-SQUID, excited in resonance. The field is mainly distributed around the slit and hole. As the result, it is advantageous for the coil to surround the slit of the rf-

![Figure 10](image1.png)  
**Figure 10.** Slopes of each V-Φ curve for the combinations with (a) square, (b) circular and (c) rectangular coils as functions of the inner side length: L, diameter: R and side width: W.

![Figure 11](image2.png)  
**Figure 11.** Coefficients $\alpha$ for the combinations with (a) square, (b) circular and (c) rectangular coils as functions of the inner side length: L, diameter: R and side width: W, respectively.

![Figure 12](image3.png)  
**Figure 12.** White noise levels for the combinations with (a) square, (b) circular and (c) rectangular coils as functions of the inner side length: L, diameter: R and side width: W, respectively.
SQUID for receipt of the rf-magnetic field. This was why we reached concept of the rectangular type and prepared the rectangular coils. Conversely, in figure 9, $\Delta I_{\Phi 0}$ values seems to be increased with decreasing the coil size. In contrast to the rf-magnetic coupling, it is supposed that the static magnetic coupling between the rf-SQUID set and the coil became weaker due to increase of the application voltage required to cause the same flux change against the rf-SQUID. These results suggest that the magnetic coupling behaved differently between the rf-range for transmission/receipt and the low frequency range for the feedback. In figure 10, the slopes of each V-\Phi curve are somewhat fluctuated, but the reason is unclear at present. In addition, in figure 11, the coefficient $\alpha$ is also increased with decreasing the coil size. The $\alpha$ is related with mutual inductance, or the static magnetic coupling between the rf-SQUID and the coil for the FLL feedback control. It is consistent with $\Delta I_{\Phi 0}$. If the voltage noise from the FLL electronics is dominant, the larger $\alpha$ is desirable to reduce the flux noise density. Consequently, the flux noise density was successfully reduced with decreasing the coil size, especially in the rectangular coils, as shown in figure 12. For the comparison, we specially pick up the V-\Phi characteristic and noise density spectrum in combination with the rectangular coil ($W=0.4$ mm), as shown in figure 14, which showed the lowest white noise level among the tested combinations. The V-\Phi curve shape is largely changed, and the white noise level is greatly reduced from figure 7.

![Figure 13. Simulation result of rf-magnetic field distribution in the resonated rf-SQUID.](image1)

![Figure 14. (a) V-\Phi characteristic and (b) noise density spectrum in combination of our conventional rf-SQUID with the rectangular coil (W=0.4 mm).](image2)

3.2. **Coil combinations with our modified rf-SQUID**

We also investigated combinations of our modified rf-SQUID, as shown in figure 3(a), with the square, circular and rectangular coils, as shown in figures 4, 5 and 6. In each combination, the transmission frequency and effective area were $543 \pm 2$ MHz and $0.31 \pm 0.02$ mm$^2$, respectively. In this frequency range, the rf-SQUID could be operated without a resonator by our electronics. The coil combinations of our modified rf-SQUID showed the similar dependence to our conventional rf-SQUID results, as mentioned previous section. The smaller coil size, especially in the rectangular coils, the lower white noise level the combination showed. Here, we specially pick up the V-\Phi characteristics and noise density spectra for the combinations of the square coil ($L=5$ mm) and two rectangular coil ($W=0.8$ and 0.4 mm), as shown in figures 15 and 16, respectively. Compare to the conventional rf-SQUID, the V-\Phi characteristics were deformed probably because the optimum rf-power was out of the minimum power limit of the FLL electronics (the limit: $-82.2$ dBm); nevertheless, we measured the noise spectra as far as we could adjust the transmission condition to get the largest amplitude within the limit in each V-\Phi curve (the optimized transmission power: $\sim -82$ dBm). Among the coil combinations, the rectangular coil with $W=0.8$ mm showed the lowest white noise density. Our modified rf-SQUID had the meandered slit with the meander-width of 0.8 mm, as shown in figure 3(a). In contrast, for the combination of the conventional rf-SQUID having the straight slit, the rectangular coil with the narrowest width of $W=0.4$ mm showed the best performance. It suggests that it should be more advantageous for the readout coil width to just fit into the slit width of the rf-SQUID.
4. Rectangular coil on flexible PCB

One of the applications of our rf-SQUID is for an STM SQUID microscope, in which the rf-SQUID is combined with STM microscopy [1]. In this microscope, the high-permeability probe transfers the magnetic flux from the sample surface to the rf-SQUID. It is important to make the gap distance between the probe end and the rf-SQUID as short as possible, so as not to be brought in contact for the thermal insulation. The rf-SQUID should be mounted on the sapphire rod cooled by liquid N$_2$. The readout coil must be put on the surface of the rf-SQUID. However, it is necessary for the readout coil not to interfere this gap. Therefore, we applied thin flexible PCBs to the readout coils. The flexible PCB coils were made of a 35 µm thick copper layer on a polyimide substrate, of which total thickness was 90 µm including a polyimide cover and glue layers. For our conventional and modified rf-SQUIDs, the same rectangular designs with W=0.4 mm and W=0.8 mm as figures 6(a) and (b) were employed to the flexible PCB coils, as shown in figures 17(a) and (b), respectively.

Figure 15. V-Φ characteristics in combinations of our modified rf-SQUID with (a) the square coil (L=5 mm), (b) the rectangular coil (W=0.8 mm) and (c) the rectangular coil (W=0.4 mm).  

Figure 16. Noise density spectra in combinations of our modified rf-SQUID with (a) the square coil (L=5 mm), (b) the rectangular coil (W=0.8 mm) and (c) the rectangular coil (W=0.4 mm).  

Figure 17. Flexible PCB coils for (a) our conventional and (b) modified rf-SQUIDs. (c) Photograph of example in combination of the conventional rf-SQUID with the flexible PCB coil.
The flexible PCB coils were fixed on the top surface of the rf-SQUIDs by using the vacuum grease, and were connected to the FLL electronics from its contact pads, soldered to a coaxial cable. Figure 18 shows the measurement results in combinations of our conventional and modified rf-SQUIDs with each flexible PCB coil. The results were almost the same as results in the rigid PCB coils, as mentioned in the previous section (figures 14, 15(b) and 16(b)). The flexible PCB coils improved the SQUID performance, similarly to the rigid PCB coils. Thus, these flexible PCB coils can be also applicable to the STM-SQUID microscope to improve its performance.

5. Summary
The SQUID performances were compared by combining the different readout coils with the rf-SQUIDs. The coil significantly affected the white noise level of the rf-SQUID. When the rectangular coil, which just surrounded the slit and hole of the rf-SQUID, was employed, the rf-SQUID showed the lowest white noise level among the tested coils. The results suggested that the performance could be affected by the magnetic coupling between the rf-SQUID and the coil. In addition, the flexible PCB coils were very useful for stable operation. Thus, it is important to optimize the readout coil as well as the rf-SQUID itself for improvement of the SQUID performance.

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