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Development of 1.3GHz high-T_c rf SQUID*

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A new high-T_c (HT_c) rf SQUID working at around 1.3GHz has been developed to avoid electromagnetic interference such as growing mobile communication jamming. This new system works in a frequency range from 1.23 to 1.42GHz (centred at 1.3GHz), which is not occupied by commercial communication. The sensor used in the 1.3GHz rf SQUID is made of a HT_c coplanar superconducting resonator and a large-area HT_c superconducting film concentrator. We have achieved in the 1.3GHz HT_c rf SQUID system a minimal flux noise of $2.5\times10^{-5}\,\Phi_0/\sqrt{\text{Hz}}$ and a magnetic field sensitivity of $38\text{fT}/\sqrt{\text{Hz}}$ in white noise range, respectively. The effective area of the concentrator fabricated on a $15\times15\text{mm}^2$ substrate is 1.35mm^2. It is shown that the 1.3GHz rf SQUID system has a high field sensitivity. Design and implementation of 1.3GHz HT_c rf SQUID offers a promising direction of rf SQUID development for higher working frequency ranges.

Keywords: 1.3GHz HT_c rf SQUID, new structure sensor, large effective
PACC: 7400, 7430C, 7450, 7490

1. Introduction

It is one of the most important aspects in high-T_c (HT_c) superconductor study to design and develop the rf superconducting quantum interference device (SQUID). Much progress has been made in recent years.[1–4] The central issue of the SQUID design is to improve its field resolution: $S_B^{1/2} = \dfrac{\partial B}{\partial \Phi} \times S_\Phi^{1/2}$. Such a field resolution $S_B^{1/2}$ of a magnetometer is determined by two factors: $\dfrac{\partial B}{\partial \Phi}$ and $S_\Phi^{1/2}$,where $S_\Phi^{1/2}$ is the flux noise of the SQUID and $\dfrac{\partial B}{\partial \Phi}$ is the flux-to-field conversion coefficient which is the reciprocal of the effective area of the SQUID washer. In order to achieve a high field resolution we need reduce the white noise and increase the effective area of the sensor.

The flux noise of the rf SQUID magnetometer has close relations with the tank circuit. According to theories and experiments, the higher the rf-bias frequency f_0 and the unloaded quality factor Q_0, the lower the system flux noise becomes. It is generally not very difficult to fabricate tank circuit with high rf-bias frequency and high unloaded quality factor Q_0 using a HT_c superconducting film. Zhang and Mueck [5] developed an S-shaped $\lambda/2$ resonator with a superconducting film, reaching a resonant frequency of about 3GHz. Their SQUID was placed in the centre of the resonator system. Such a structural design did not have a large effective area, therefore it could not obtain higher field resolution. Attempts have been made to place a flux concentrator made of superconducting nubby (or block) material tightly next to the SQUID to obtain a larger effective area, and thus a higher field resolution. Zhang [6] developed a flux concentrator using a YBCO superconducting block of 3.5mm thick and 22mm in diameter, which improved its effective area by 2.4 times for a $6\times6\text{mm}^2$ sized rf SQUID. However, the flux white noise was quite high ($2.13\times10^{-4}\,\Phi_0/\sqrt{\text{Hz}}$) because it adopted the tank circuits made of inductor and capacitor, and the resonator frequency was 100MHz. It could not achieve a very high field resolution. Later, Zhang [7,8] developed a type of YBCO coplanar superconducting resonator containing a flux concentra-

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tor (Fig.1). It is composed of three microstrip slit openings. The middle one is a half wavelength ($\lambda/2$) microstrip, the inner and the outer microstrips are grounds. In order to achieve large effective area, the inner microstrip was expanded into a wider ring, which acted as a flux concentrator with the inner hole of 1.5mm in diameter. The SQUID was positioned (centred) on top of the concentrator, as shown in Fig.2. The structure mentioned above adopted the flip-chip configuration as standard, and was able to fabricate on a substrate, multiply small SQUID of 3.5mm in diameter. Its HT_c coplanar superconducting resonator working at 800MHz was fabricated on a $10\times10mm^2$ $LaAlO_3$ substrate. The central length D was 8mm, the SQUID was 3.5mm in diameter. Such a design can obtain a $0.81mm^2$ effective area when $\partial B/\partial\Phi$ was $2.56nT/\Phi_0$. One can easily achieve the flux white noise of $2\times10^{-5}\Phi_0/\sqrt{Hz}$ and the corresponding field sensitivity $S_B^{1/2}$ of $50fT/\sqrt{Hz}$, The best possible white noise was as good as $8.5\times10^{-6}\Phi_0/\sqrt{Hz}$, with the optimal field sensitivity reaching $23fT/\sqrt{Hz}$.[7,8]

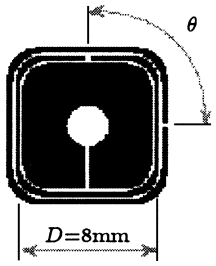


Fig.1. Schematic of flux concentrator/coplanar resonator layout.

The coplanar resonator with the flux concentrator mentioned above has increased the effective area of the SQUID, and thus the field resolution. This high-performance HT_c rf SQUID operates in the frequency range from 600 to 1000MHz. This frequency band happens to be the peak frequency bandwidth of the mobile communication signals. The electromagnetic interference (EMI) will not only bring much noise, but sometimes also prevent a SQUID from working practically. The radio frequency allocation protocol issued by the Ministry of Information Industry of People's Republic of China has allocated the frequency band of 600 to 1000MHz to the 800MHz CDMA, GSM (global system of mobile) 900MHz/1800MHz mobile stations, base stations, repeat stations, and TV transmission stations. Even the frequency band of 1–2GHz has been occupied by higher frequency GSM mobile stations, base stations, and repeat stations, etc. However, in the frequency range of 1–2GHz there is currently an unoccupied slot from 1.2276 to 1.427GHz. If we suggest our new SQUID system operate in the frequency range from 1.23 to 1.42GHz (centred at 1.3GHz), the SQUID will suffer as little EMI as possible. This is the reason why we developed our new 1.3GHz rf SQUID system. The SQUID adopts both a high Q superconducting coplanar resonator and a large-area superconducting flux concentrator, so that we can obtain not only low white flux noise but also high field sensitivity.

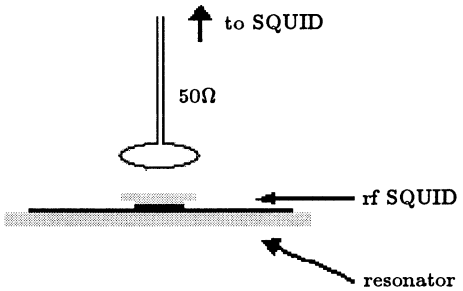


Fig.2. Schematic structure of 800MHz HT_c rf SQUID. The dark lines represent superconducting films.

2. 1.3GHz HT_c SQUID radio frequency circuit

The 1.3GHz rf SQUID circuit operates at low noise and very low rf-bias power level. The circuit is a kind of feedback lock model as usual. The block diagram for the 1.3GHz rf circuits is shown in Fig.3.

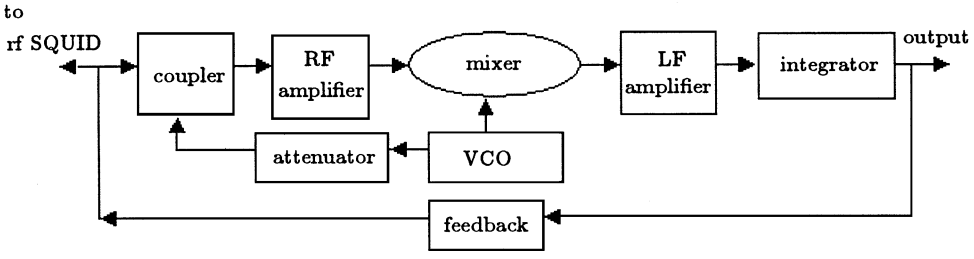


Fig.3. Block diagram for the 1.3GHz radio frequency circuit.

The characteristics of our circuit design are summarized below:

(1) The rf-bias current fed out of the 1.3GHz HT_c rf SQUID circuit is separated from the rf voltage signals detected in the external magnetic field transmitted through the directional coupler in different directions. Only one cable connects the tank circuit at 77K and the RF (radio frequency) amplifier at room temperature, which allows easier fabrication for the measuring tube.

(2) A high performance mixer is used as the detector. It produces a higher degree of isolation between RF and LF (local frequency), RF and IF (intermediate frequency), LF and IF.

(3) By tuning the DC voltage to change the local frequency, the SQUID system can be adjusted easily to reach optimal working conditions.

(4) The 1.3GHz rf circuit consists of eight independent modules of different functions. Among them, the two important modules, the voltage control oscillator (VCO) and the attenuator are easily connected to the computer by digital interfaces without affecting other modules.

The 1.3GHz rf circuit works properly in the frequency range from 1.23 to 1.42GHz. Different SQUID sensors require different rf-bias powers, ranging from -97 to -72dBm, via a SMA (Subminiature Version A) connector.

3. The structure of the 1.3GHz HT_c rf SQUID sensor

The coplanar resonator operating at 800MHz rf SQUID is a half wavelength superconducting resonator. To increase the resonator frequency, say, to the range of 1.23 to 1.42GHz (out of the mobile communication jamming frequency band), the size of coplanar resonator should be decreased. Therefore, the effective area will also be decreased, causing the field sensitivity $S_B^{1/2}$ to drop significantly.

A new type of HT_c superconducting coplanar resonator without flux concentrator has been developed by our group [9] (Fig.4). In the design, the coplanar resonator is structurally separated from the larger area flux concentrator. The coplanar resonator has a central void. The original flux concentrator shown in Fig.1 has been changed into a thin ring, which no longer acts as a concentrator. The length D shown in Fig.4 is 7.8mm long for 800MHz frequency. A large SQUID washer is placed below the resonator, as shown in Fig.5. It has been proved that such a design not only can work stably, but also can achieve an effective area larger than what the original resonator with flux concentrator does.

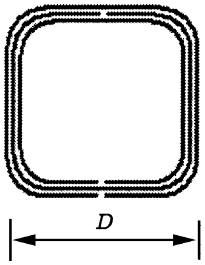


Fig.4. Schematic of coplanar resonator layout.

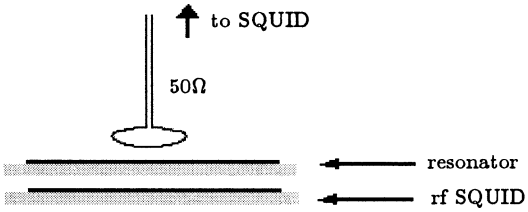


Fig.5. Schematic structure of HT_c rf SQUID. The dark lines represent superconducting films.

Based on the previous development on HT_c rf SQUID described above, we have developed a new type of HT_c rf SQUID with a three-layer structure. A larger area flux concentrator is also separated from the coplanar resonator. The coplanar resonator shown in Fig.6(a) has also void in the centre. The flux concentrator is fabricated with a large area superconducting film so that it can obtain a much larger effective area. The rf SQUID sensor of 3.5mm in diameter is located immediately on the top of the flux concentrator and below the resonator. The superconducting resonator is below the microwave coupling ring. Materials like $LaAlO_3$ with a certain thickness can be placed between the SQUID and the resonator for adjusting the coupling coefficients.

The superconducting coplanar resonator has a 300nm thick patterned epitaxial $YBa_2Cu_3O_7$ (YBCO) film on a 10×10mm^2 $LaAlO_3$ substrate, as shown in Fig.6(a). The resonator having a length D of 4.4mm can operate at 1.3GHz. The width of each of the three microstrip lines is 200μm, the radial spacing between neighbouring microstrip lines is 100μm, the angle between the outer and the middle microstrips is 180°. The resonator frequency f_0 is 1.24GHz and the unloaded quality factor Q_0 is about 1850, as measured by HP8590L spectrum analyser.

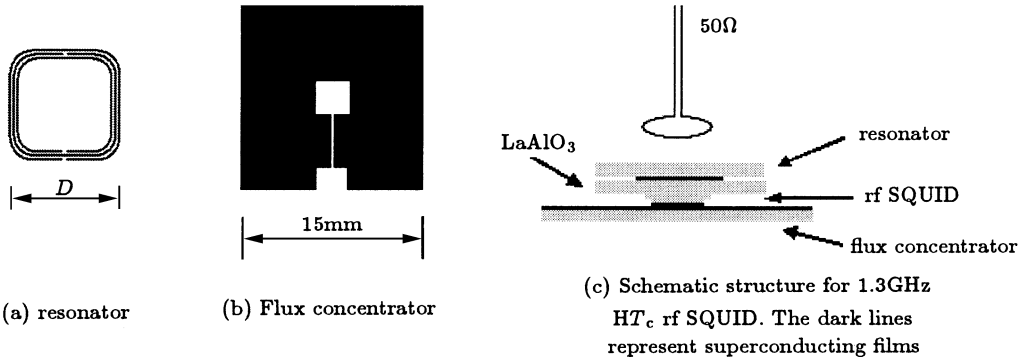


Fig.6. Schematics of resonator, concentrator and HT_c SQUID.

The superconducting concentrator is also patterned from 300nm thick epitaxial $YBa_2Cu_3O_7$ film, on $15\times15mm^2$ large $LaAlO_3$ substrate (Fig.6(b)), and the film is stretched to the edge of the substrate. The size of the inner hole of the concentrator is $1.2\times1.2mm^2$. There is a square opening to avoid closing of the split at the end.

A schematic of the structure for 1.3GHz HT_c rf SQUID sensor is shown in Fig.6(c). The rf SQUID sensor of 3.5mm in diameter uses a step-edge junction. The inner hole of $10\times500\mu m^2$ is fabricated on the $5\times5mm^2$ $SrTiO_3$ substrate. The coupling coefficient κ and its loaded quality factor Q_L can be adjusted by the spacing between the resonator and the microwave coupling ring. The resonator frequency f_0 and the loaded quality factor Q_L of the HT_c rf SQUID sensor are 1.27GHz and 240, respectively, as measured by HP8590L Spectrum Analyser.

4. Experimental result of the 1.3GHz HT_c rf SQUID

We have tested the 1.3GHz HT_c rf SQUID system consisting of the rf circuit and the new type of rf SQUID sensor. The flux noise was measured by HP 35665 dynamic signal analyser while the SQUID sensor was shielded by a μ alloy (a kind of Ni-based alloy) cylinder. A typical result is shown in Fig.7, which shows the flux white noise of $2.8\times10^{-5}\,\Phi_0/\sqrt{\text{Hz}}$ when a 2mm thick $LaAlO_3$ substrate is placed between the resonator and rf SQUID. The flux-to-field conversion coefficient$(\partial B/\partial\Phi)$ is $1.52\text{nT}/\Phi_0$. Effective area of the concentrator on a $15\times15mm^2$ substrate is $1.35mm^2$. We have obtained the magnetic field sensitivity of $43\text{fT}/\sqrt{\text{Hz}}$ in the white noise range.

The best 1.3GHz rf SQUID we fabricated has the flux noise of $2.5\times10^{-5}\,\Phi_0/\sqrt{\text{Hz}}$, and its corresponding magnetic field sensitivity is $38\text{fT}/\sqrt{\text{Hz}}$ in the white noise range when $\partial B/\partial\Phi$ is $1.52\text{nT}/\Phi_0$.

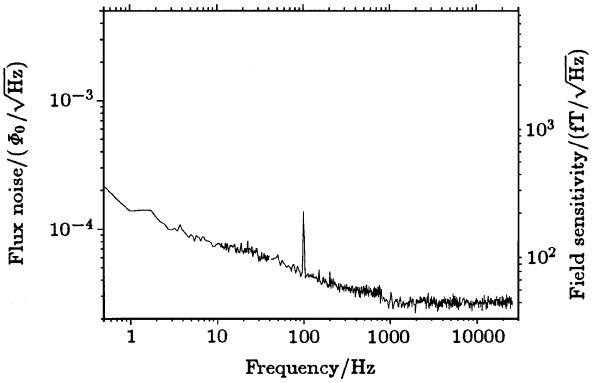


Fig.7. Flux noise spectrum of 1.3GHz HT_c rf SQUID.

5. Conclusion

Table 1 lists the comparison in performance between the 1.3GHz rf SQUID and the 800MHz rf SQUID developed by our group. It indicates clearly that we can achieve the flux white noise to as good as $2.5\times10^{-5}\,\Phi_0/\sqrt{\text{Hz}}$ by adopting a washer SQUID of 3.5mm in diameter with the inner hole $10\times500\mu m^2$. When the flux-to-field conversion coefficient $(\partial B/\partial\Phi)$ is $1.52\text{nT}/\Phi_0$, the effective area of the concentrator fabricated on a $15\times15mm^2$ substrate is $1.35mm^2$. Thus, we have obtained a better magnetic field sensitivity of $38\text{fT}/\sqrt{\text{Hz}}$ in the white noise range.

Table 1. Performance for 800MHz HT_c rf SQUID and 1.3GHz HT_c rf SQUID fabricated by our group.

	800MHz rf SQUID	1.3GHz rf SQUID
$(\partial B/\partial\Phi)/(\text{nT}/\Phi_0)$	2.56	1.52
$A_{\text{eff}}/\text{mm}^2$	0.81	1.35
$S_\Phi^{1/2}/(\Phi_0/\sqrt{\text{Hz}})$	2×10^{-5}	2.5×10^{-5}
$S_B^{1/2}/(\text{fT}/\sqrt{\text{Hz}})$	50	38

Our new design of the HT_c rf SQUID has been systematically improved in both the white flux noise and the effective area of the concentrator—and thus the magnetic field resolution—from the previous work at 800MHz by our group (Figs.4 and 5). More importantly, our new 1.3GHz HT_c rf SQUID works in an optimal frequency range because it is kept away from the mobile commercial communication jamming bandwidth. Such an improvement in the SQUID design will help greatly in high-temperature superconductor study.

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