A SQUID gradiometer module with large junction shunt resistors*

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A dual-washer superconducting quantum interference device (SQUID) with a loop inductance of 350 pH and two on-washer integrated input coils is designed according to conventional niobium technology. In order to obtain a large SQUID flux-to-voltage transfer coefficient, the junction shunt resistance is selected to be 33 Ω. A vertical SQUID gradiometer module with a baseline of 100 mm is constructed by utilizing such a SQUID and a first-order niobium wire-wound antenna. The sensitivity of this module reaches about 0.2 fT/(cm·Hz$^{1/2}$) in the white noise range using a direct readout scheme, i.e., the SQUID is directly connected to an operational amplifier, in a magnetically shielded room. Some magnetocardiography (MCG) measurements with a sufficiently high signal-to-noise ratio (SNR) are demonstrated.

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1. Introduction

Magnetocardiography (MCG) is a useful diagnostic technique measuring the magnetic field signals generated from myocardial current.[1] In order to suppress the environmental noise and detect the human heart magnetic field, superconducting quantum interference device (SQUID) gradiometer modules are widely used.[2] Usually, a vertical gradiometric configuration can be set up either by electronic gradiometers composed of planar SQUID magnetometers,[3] or by axial gradient antenna wound from niobium wire.[4]

Recently, we have reported that a voltage-biased SQUID with a large junction shunt resistor R_J can reach a low system noise level even when it is directly connected to a room temperature operational amplifier.[5] The amplifier has two noise sources, i.e., the voltage noise V_n and the current noise I_n, and the latter is always ignored. Consequently, the preamplifier noise contribution is $\delta\Phi_{\rm preamp} = V_n/(\partial V/\partial\Phi)$, where $\partial V/\partial\Phi$ is the flux-to-voltage transfer coefficient. Our study has shown that the large R_J, or say, large Steward–McCumber parameter β_c, leads to a large $\partial V/\partial\Phi$.[5] As a result, $\delta\Phi_{\rm preamp}$ could be suppressed with no need of additional feedback electronics, such as additional positive feedback (APF),[6] noise cancellation (NC),[7] and SQUID bootstrap circuit (SBC).[8]

In this work, we report a simple SQUID gradiometer module. It consists of a weakly damped SQUID and a wire-wound first-order gradient antenna L_p, which couples to the SQUID loop L_s via a mutual inductance M_{in} between the integrated input coils L_{in} and L_s. Using this module, MCG measurements with high signal-to-noise ration (SNR) are demonstrated.

2. Experimental setup

2.1. SQUID chip design

In our experiment, SQUIDs each with a designed loop inductance $L_s = 350$ pH are employed. The complete layout of our SQUID on a chip of 5 mm × 3 mm in size is shown in Fig. 1(a). In this layout, we use the dual-washer SQUID on the one hand to increase the coupling between L_s and L_{in} and on the other hand to reduce the disturbance from the ambient magnetic field. A flux feedback coil L_{FLL} for the flux locked loop (FLL) operation, a heating resistor R_h for removing trapped flux and two opposite input coils L_{in} (≈ 300 nH) with 32.5 turns, each integrated on SQUID-washer, are also included in the design. L_{in} is shunted by C_x and R_x to damp the high frequency resonances caused by parasitic capacitance between the multi-turn input coils and the SQUID washer.[9] Two large pads each with a size of 2.2 mm × 1.45 mm are designed to realize conveniently the superconducting connection between L_{in} and L_p by soldering lead–indium (PbIn) alloy. The equivalent circuit of the layout is shown in Fig. 1(b).

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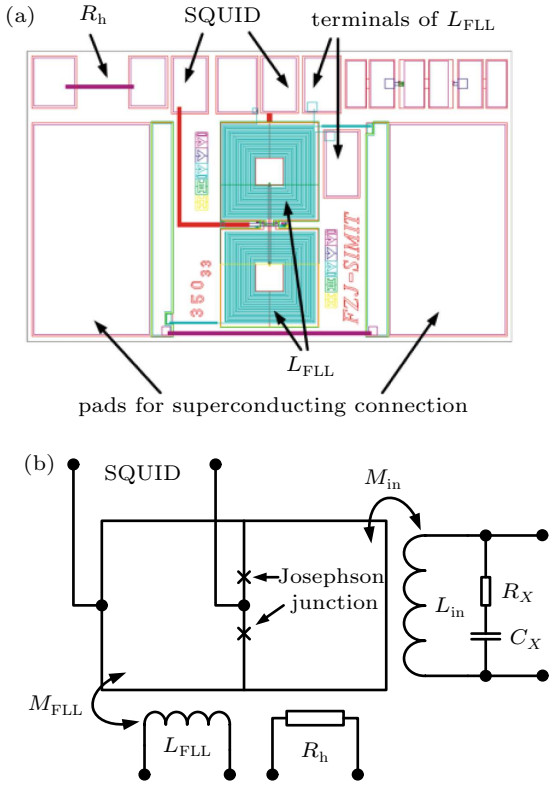


Fig. 1. (color online) (a) Layout of the SQUID chip with a size of 5 mm × 3 mm and (b) equivalent circuit of the SQUID layout.

Table 1 shows the design parameters of the SQUID chip. The junction shunt resistance $R_J = 33\ \Omega$ is designed to provide a large $\beta_c \approx 5$, thus increasing the $\partial V/\partial \Phi$.[5] Because L_{in} is closed by L_p, the effective SQUID loop inductance $L_{s,eff}$ decreases from 350 pH to below 200 pH. In this case, the SQUID screening parameter will decrease to $\beta_L = 2I_0L_{s,eff}/\Phi_0$, which is helpful to enlarge the critical current modulation depth[10] and furthermore to increase $\partial V/\partial \Phi$.

Table 1. Design parameters of the SQUID chip.

Parameter	Value	Unit
One junction size	3×3	μm^2
Junction resistance R_J	33	Ω
Junction critical current I_0	4	μA
Junction capacitance C	40[a]	fF/μm^2
One SQUID hole size	280×280	μm^2
L_s	350	pH
Turns of L_{FLL}	1	
M_{FLL}	0.2[b]	nH
Turns of L_{in}	32.5×2	
M_{in}	26[b]	nH
R_h	131[b]	Ω

[a] Estimated value. [b] Measured value.

2.2. SQUID gradiometer module

We use an axial first-order gradient pickup antenna (L_p) wound on a ceramic support to connect the input coils L_{in} to construct a SQUID gradiometer module (see Fig. 2). The niobium wire with a diameter of 0.076 mm is employed for the antenna which consists of two opposite single coils connected in series. The coil diameter is 18 mm and the baseline of the antenna is 100 mm. The antenna inductance L_p is calculated to be 250 nH, which matches $L_{in} = 300$-nH well. We do not use a superconductive tube to shield the SQUID, which will otherwise introduce a field distortion due to the small distance (40 mm) between the SQUID and the antenna. Furthermore, such a small distance increases the available liquid helium height, or in other words, it increases the duration of the liquid helium refill.

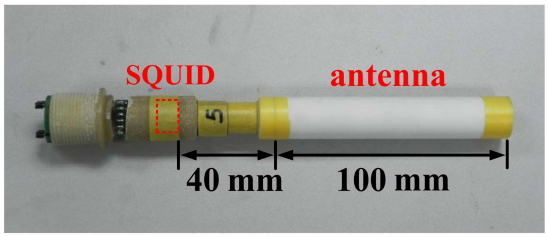


Fig. 2. (color online) SQUID gradiometer module. The SQUID is located inside the epoxy tube. The superconducting connection between the SQUID input coils and the antenna is realized by soldering lead–indium (PbIn) alloy.

3. Experimental results

3.1. Noise measurements of SQUID gradiometer module

A commercial operational amplifier (OP) with a voltage noise V_n of 1 nV/Hz$^{1/2}$ is used to directly connect the SQUID (see Fig. 3(a)). Here the SQUID is voltage-biased and the OP acts as a current-to-voltage convertor with a gain of R_g.

Figure 3(b) shows the noise spectrum measurements of the SQUID gradiometer module mounted in a non-magnetic liquid helium cryostat inside a magnetically shielded room (MSR). The gradiometer module can work stably in MSR with the noise suppression of about 54 dB $= 20 \times \log_{10}(100/0.2)$ (the imbalance of the gradiometer is about 0.2%). Due to the large β_c, the SQUID exhibits a large $\partial V/\partial \Phi = (\partial i/\partial \Phi) \times R_d = (14.1\ \mu A/\Phi_0) \times (35\ \Omega) \approx 490\ \mu V/\Phi_0$, thus leading to the preamplifier noise contribution, $\delta\Phi_{preamp} = V_n/(\partial V/\partial \Phi) = 2\ \mu\Phi_0/Hz^{1/2}$. Here, $\partial i/\partial \Phi$ is the flux-to-current transfer coefficient measured from the I–Φ curve (see the inset) and R_d is the SQUID dynamic resistance measured from the I–V curve (not shown here). In this case, the measured SQUID system noise $\delta\Phi \approx 7\ \mu\Phi_0/Hz^{1/2}$ (> 10 Hz) is almost dominated by its intrinsic noise $\delta\Phi_s = (\delta\Phi^2 - \delta\Phi^2_{preamp})^{1/2} \approx 6.7\ \mu\Phi_0/Hz^{1/2}$. A large β_c leads to a large $\delta\Phi_s$, which is already discussed in Ref. [11]. The field sensitivity δB, which is a product of the flux-to-field transfer coefficient $(\partial B/\partial \Phi)$ and $\delta\Phi$, i.e., $\delta B = (\partial B/\partial \Phi) \times \delta\Phi$ reaches about 2 fT/Hz$^{1/2}$ shown by the noise spectrum in Fig. 3(b). It corresponds to a gradient field sensitivity of 0.2 fT/(cm·Hz$^{1/2}$), which is better than 0.8 fT/(cm·Hz$^{1/2}$) reported in Ref. [12].

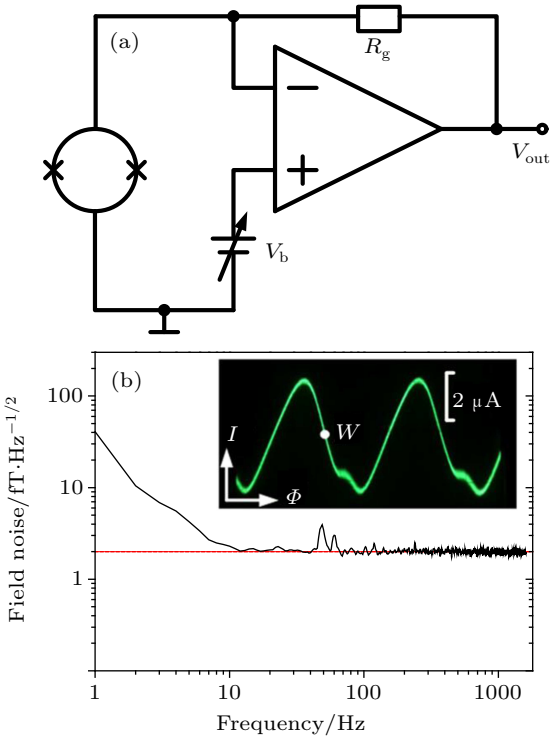


Fig. 3. (color online) (a) Schematic diagram of voltage-biased SQUID connecting to a current-to-voltage convertor. Here V_b is the bias voltage. (b) The noise measurements of the SQUID gradiometer module, whose $\partial B/\partial \Phi$ is measured to be 0.3 nT/Φ_0. The inset shows the recorded I–Φ curve and W denotes the working point.

3.2. MCG measurement

Based on the gradiometer module, the MCG signal detection of an adult is demonstrated inside the MSR. The SQUID gradiometer module is mounted at the inner bottom of a non-magnetic liquid helium cryostat. The distance between the lower pickup coil of the antenna and the outer bottom of the cryostat is about 16 mm. The SQUID gradiometer module is connected to the readout electronics with the flux-locked-loop (FLL) at room temperature via a cryogenic cable. The output of the FLL circuit is sampled with a 24-bit A/D card (NI PCI-4472) at a sampling rate of 1 kHz. In order to remove the disturbance from the ambient, such as the power line interference, a low-pass FIR filter with a cut-off frequency of 150 Hz and a notch filter of 50 Hz are employed for the data processing. Other noise suppression methods, such as a three-axis reference magnetometer, are not adopted.

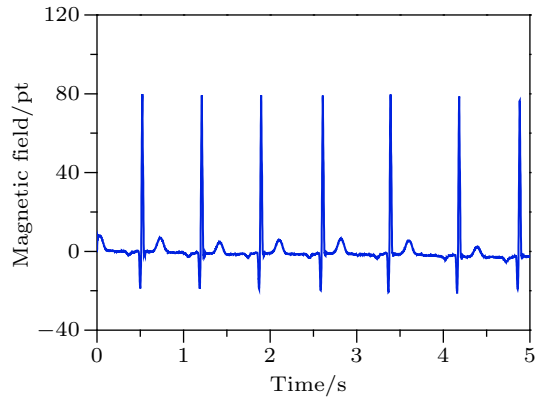


Fig. 4. (color online) Measured MCG signal of an adult 28-years old.

Figure 4 shows one of the recorded MCG signals of an adult of 28 years. The peak-to-peak value of the QRS-complex is about 100 pT and the noise is in a range from −0.2 pT to +0.2 pT, which leads to a high SNR of 48.0 dB.

4. Conclusion

We construct a SQUID gradiometer module, which consists of a first-order gradient pickup antenna and a SQUID with a large shunt resistor. The superconducting connection between the wire-wound antenna and the SQUID is realized by soldering lead–indium (PbIn) alloy. Due to the large flux-to-voltage transfer coefficient ($\partial V/\partial \Phi$) of about 490 μV/Φ_0 of SQUID, it can be directly connected to a commercial operational amplifier (AD797) and exhibits an acceptable low system noise of about 7 $\mu\Phi_0/\mathrm{Hz}^{1/2}$. Indeed, the gradient resolution of our gradiometer module reaches about 0.2 fT/(cm·Hz$^{1/2}$).

Finally, the SQUID gradiometer module is successfully employed for MCG signal detection. The recorded MCG signal displays a high enough SNR of 48 dB, which meets the requirements of most heart-related researches.

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