3-Channel Double Relaxation Oscillation SQUID Magnetometer System with Simple Readout Electronics

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Abstract- Recently several approaches have been made to simplify the readout scheme of the standard dc SQUID. A Double Relaxation Oscillation SQUID(DROS) consisting of a hysteretic dc SQUID and a reference junction in series shunted by an inductor and a resistor can provide a very large flux-to-voltage transfer coefficient. Thus, a DROS with direct readout with room temperature dc amplifier can be a good candidate for the next-generation SQUID magnetometer. We report on the development of a 3-channel magnetometer system based on DROS. The DROS is based on Nb/AIO_x/Nb Josephson junctions and the main feature of the system is its simple readout electronics.

I. INTRODUCTION

Magnetometers based on SQUIDs are the most sensitive magnetic flux sensors available. The noise performance of the presently used dc SQUID made from low temperature superconductors is well enough for many applications like biomagnetism. But because of its low flux-to-voltage transfer, a relatively complex readout scheme is needed to detect the SQUID output voltage without a significant reduction of the sensitivity of the SQUID[1].

Several approaches have been made to simplify the readout electronics of the present dc SQUID, such as, SQUID with additional positive feedback[2], series array of dc SQUIDs[3], two stages SQUID with the second SQUID as an amplifier of the first one[4], digital SQUID[5], (Double) Relaxation Oscillation SQUID[6], [7], etc.

In addition to simplifying the readout scheme, these *second generation SQUIDs* will improve the dynamic properties, such as available bandwidth and slew rate of the system. For use in relatively quiet environment, high dynamic performance is not necessary. But in noisy environment, a fast SQUID is necessary for stable flux-locked loop operation.[8]

In this paper, we describe the development of a magnetometer system based on DROS. The DROS is based on a hysteretic dc SQUID with Nb/AIO_x/Nb Josephson junctions and provides a very high flux-to-voltage transfer coefficient. The main features of the system are simple readout electronics.

II. LAYOUT AND FABRICATION OF THE DROS

Schematic drawings of DROSs are shown in Fig. 1. A DROS consists of a hysteretic dc SQUID, a signal SQUID and a reference SQUID(Fig. 1(a)) or a reference junction(Fig. 1(b)) in series, shunted by a relaxation circuit consisting of an inductor and a resistor.

If a constant bias current larger than one or both of the two critical currents is applied to the DROS, relaxation oscillations occur at appropriate values of the critical currents, shunt inductance and shunt resistance[9],[10]. In fact, the DROS acts as a comparator of the two critical currents. This means that, if $I_{c1} < I_{c2}$, there is no output voltage, while if $I_{c1} > I_{c2}$, a finite time-averaged voltage can be measured. So, if I_{c2} is somewhat smaller than the maximum critical current of the signal SQUID, the average voltage can be varied between 0 and a finite value by changing the flux applied to the signal SQUID. The transition between the two states will be very abrupt at $I_{c1}(\Phi_{\text{signal}}) = I_{c2}$, resulting in a very large flux-to-voltage transfer coefficient.

A possible disadvantage of the DROS with reference SQUID is that it consists of two SQUID loops, which makes it more sensitive to external flux trapping than the SQUID with single loop. Moreover, compared with standard dc SQUIDs, additional two wires and

Fig. 1. Schematic drawings of DROSs with a reference SQUID (a) and a reference junction (b).

adjustment are necessary for the reference flux.

Since the reference SQUID is needed only for its critical current, this SQUID can be replaced by a single junction with a constant critical current somewhat below the maximum critical current of the signal SQUID. In this way, the number of wires between the DROS and room temperature electronics can be reduced, which is very advantageous in multichannel systems.

The optimum value of the reference critical current is determined by the screening parameter $\beta (=LI_{c1}^{\max}/\Phi_0)$ of the signal SQUID. Since the critical current modulation depth of the signal SQUID is given by $I_{c1}^{\max}/(1+\beta)$, the critical current of the reference junction should be between $I_{c1}^{\max}$ and $\{I_{c1}^{\max} - I_{c1}^{\max}/(1+\beta)\}$. The size of reference junction is designed to have three different values; 23, 26 and 28 μm^2 , such that its critical current is 72, 81 and 88 % of the maximum critical current of the signal SQUID. Therefore, depending on the magnitude of β , a reference junction with a suitable critical current can be chosen.

The fabrication process of the sensors is based on Nb/AlO_x/Nb junctions and multilayer wiring technology. The Josephson junctions, sized 4 x 4 μm^2 , were defined by standard photo-lithography and reactive ion etching using SF₆ gas[11]. All other layers were patterned by lift-off process using monochlorobenzene soaking to make photoresist overhang. The insulation between metal layers is made by rf-sputtered SiO₂ film and each SiO₂ film is deposited in two separate steps using two different masks for better insulation.

Fig. 2 shows the overall structure of the fabricated DROS. The signal SQUID is of the washer-type with a tightly coupled input coil, according to the scheme introduced by Jaycox and Ketchen[12]. The signal SQUID loop has an inner diameter of 38 μm , resulting in calculated loop inductance of 60 pH. A 50-turns input coil is integrated on the SQUID loop. At the outside of the SQUID washer, a 3-turns feedback coil is integrated. The Josephson junctions are in the center of the loop to avoid the large parasitic inductance resulting from the long slit structure. The thin film shunt inductor is formed by a planar, double-layer, low capacitance multiturn Nb coil. The shunt inductance is designed to have 35 nH. The shunt resistor is a sputtered thin film of Pd and its resistance is about 6 Ω . Therefore the time constant of the shunt circuit is about 5.8 ns, resulting in relaxation frequency around 170 MHz. The wiring of the shunt circuit is made symmetrically around the SQUID loop.

Fabricated DROSs usually showed irregular flux-voltage curves and the flux-to-voltage transfer coefficient is rather small. This is due to resonances

Fig. 2. Photograph of DROS.

between the input coil and the SQUID, caused by large parasitic capacitance. We damped the resonances by a series circuit of a 100 Ω resistor and a 1.5 nF capacitor between the input coil pads. This RC circuit also provides an effective rf filter with its pass band below about 1 MHz, otherwise substantial amount of interference from the pickup coil will easily degrade SQUID operation in the presence of spurious fields.

III. DROS CHARACTERISTICS

Fig. 3(a) shows a flux modulated current-voltage curve of a DROS. Here the area of reference junction is 23 μm^2 ; its critical current is 72 % of the maximum critical current of the signal SQUID. The flux-voltage curve traces for four different bias currents; 11 μA , 17 μA , 24 μA and 32 μA , are shown in Fig. 3(b). Here the flux is applied through the feedback coil. The output voltage is almost a step function of applied field. The curves are quite regular and we could not see any resonance effects, which means that the RC-shunt circuit is very effective for the damping of the resonances. The width of voltage state and zero state depends on the magnitude of the critical current in the reference junction; with increasing reference critical current the width of zero state increases. The maximum transfer coefficient is obtained at around half of the step height and its value is about 5 mV/ Φ_0 , which is large enough for direct readout with a room-temperature preamplifier.

Fig. 3. Flux-modulated current-voltage characteristics (a) and flux-voltage modulation curves (b).

The calculated inductance of input coil is 0.15 μ H and the measured mutual inductance between SQUID loop and input coil is 2.1 nH. Based on the theoretical SQUID loop inductance, the coupling coefficient is estimated to be 0.73. While the feedback coil has a mutual inductance of 128 pH to the SQUID loop.

IV. ELECTRONICS

Because of the large flux-to-voltage transfer, the electronic circuit for flux-locked loop (FLL) operation can be relatively simple. The preamplifier section consists of LT1028 op-amps in a differential input mode to have high input impedance and the input voltage noise of the amplifier chain is 1.8 nV/ $\sqrt{\text{Hz}}$ in the white region. With a typical flux-to-voltage transfer of 5 mV/ Φ_0 , the amplifier contributes an equivalent flux noise of 0.36 $\mu\Phi_0/\sqrt{\text{Hz}}$. The gain of the amplifier is 10^4 and its bandwidth is about 1 MHz. Ordinary one-pole integrator is used and its time

constant is 10^{-4} s.

The main feature of the electronics system is its simplicity and small size, which is very important in a multichannel system. The electronics for each SQUID consists of two parts: the head, mounted directly on top of the probe inside an aluminum box, where the amplifier, integrator and feedback circuit are enclosed, the detector and control unit, where all the circuits for the control of SQUID bias point and feedback operation are enclosed. In contrast to the conventional flux modulation scheme, where the head box has several compartments to avoid interference between circuits, we used only one compartment.

Special care has been taken to prevent high frequency noise to enter the DROS via the leads connecting DROS to the electronics, because this high frequency noise could mix down with the relaxation frequency. Therefore, all leads to the DROS are twisted and low-pass filtered with a cut-off frequency of about 1 MHz, which is the bandwidth of the amplifier.

V. PICKUP COIL

Second-order gradiometers are used as the pickup coils with 10 mm coil diameter and 40 mm baseline. The coil diameter is rather small such that 3 pickup coils could be distributed over the bottom of the cryostat (CTF model B-10) which has 32 mm diameter at the bottom of the tail. Niobium wire of 0.1 mm diameter is wound on Macor ceramic support and the self-inductance of the gradiometer is 0.5 μ H. The gradiometer wires are connected to the SQUID input coil pad via Nb blocks with screws.

Reliable superconductive contact between Nb input coil pad and Nb wire is achieved by ultrasonic bonding of 50 μ m Nb wire to a Nb thin film pad [12]. In order to make the Nb wire ductile enough for bonding, it is annealed in a vacuum chamber at a dc current of 0.5 A for 5 minutes. The thin Pd layer of about 5 nm that protects the Nb thin film pads from oxidation has a positive influence on the quality of the bonding. The critical current of the superconductive contacts is measured to be more than 50 mA.

Each probe consisting of pickup coil and SQUID is a single cryogenic probe and is mechanically independent with respect to the others. This modular construction makes it possible to replace each channel for maintenance without warming up the whole insert, even during operation.

VI. SYSTEM PERFORMANCE

The SQUID noise has been measured in the FLL mode with the SQUID inside a lead tube without magnetically shielded room. Fig. 4 shows the flux

Fig. 4. Flux noise spectrum of DROS in FLL operation.

noise of a DROS. The white noise level is about $9 \mu\Phi_0/\sqrt{\text{Hz}}$. This noise level is rather high compared with the present dc SQUIDs. The main source of noise in DROS is thermal fluctuations of the critical currents in the signal SQUID and reference junction and this can be decreased by increasing the relaxation frequency, since the relaxation frequency determines the sampling rate of critical currents[14].

On the basis of the measured flux noise level, the white field noise at the pickup coil is calculated to be $36 \text{ fT}/\sqrt{\text{Hz}}$. Here field noise is given by $\Phi_n(L_p + L_i)/M_{12}A_{\text{eff}}$, where Φ_n is SQUID flux noise, L_p and L_i are inductance of pickup coil and input coil, respectively, M_{12} is mutual inductance between input coil and SQUID loop and A_{eff} is effective pickup area of pickup coil.

VII. CONCLUSIONS

We fabricated a magnetometer system based on DROSs with a reference junction. Our sensors need neither special fabrication process nor additional implementation after SQUID characterization, which are necessary in, for example, series array of dc SQUIDs and SQUID with additional positive feedback. Noise performance of the DROS system with modest readout preamplifier, however, is yet to be improved by about one order of magnitude to compete the present dc SQUIDs, which is thought to be achieved mainly by increasing the relaxation oscillation frequency.

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