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Development of Small-sized SQUID and Direct-coupled Electronics for High-T_c Scanning SQUID Microscope

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소형 SQUID, 직접 되먹임 방식 전자회로, 고온초전도 SQUID 주사현미경의 개량

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Abstract

The spatial resolution of high-T_c scanning SQUID microscope is limited by the washer size of SQUID and the gap distance between SQUID sensor and the sample. In this work, we tried to improve the spatial resolution of scanning SQUID microscope by reducing the size of SQUID sensor fabricated with $YBa_2Cu_3O_7$ thin film. Outer dimensions of the SQUIDs we tested are 24 μm × 28 μm, 12 μm × 16 μm, 12 μm × 12 μm, 10 μm × 10 μm each. To operate them in the flux-locked loop scheme, we used a direct-coupled electronics instead of using conventional electronics involving a modulation scheme. Since the direct-coupled feedback scheme does not require modulation current adjustment that poses as a practical difficulty in the SQUID operation in modulation-scheme, the direct feedback operation is rather simpler than the conventional modulation method. The resulting noise features were dominated by the noise of preamp in FLL electronics except that of the largest SQUID. The noise levels of SQUIDs are expected below $1 \times 10^{-5}\ \Phi_0/Hz^{1/2}$ (at 300 Hz), that is a typical noise level for SQUID made of $YBa_2Cu_3O_7$ thin film. The data acquisition and motion-controlling parts were also improved, resulting in faster data acquisition rate and less vibration of the system

Keywords : SQUID, Scanning SQUID Microscope, Flux-Locked Loop

I. Introduction

As the interest on the magnetic property in a small scale device grows up, many instruments using various sensors have been developed and improved. Scanning SQUID microscope uses SQUID sensor which is either self-sensing [1], [2], [3] or equipped with small pick-up loop [4]. The major limitation of the scanning SQUID microscope is the moderate spatial resolution due to the size of pick-up loop or SQUID sensor, reaching at best 4 μm for the low-T_c niobium SQUID sensor [5]. For the case of high-T_c's, the difficulty in the fabrication of the multiplayer structure [6] prevents patterning a pick-up loop

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structure or small junctions. We tried fabricating small SQUIDs from $YBa_2Cu_3O_7$ thin film, and operated it with home-made direct-coupled feedback electronics which has advantages when operating a small SQUID for the scanning SQUID microscope.

Other than those, efforts were made to increase the scanning speed using a motor controller equipped with digital signal processor and data acquisition board. Reduction of data traffics between peripherals and CPU of control PC can increase scanning speed.

II. SQUIDs

The material for the SQUID is $YBa_2Cu_3O_7$ thin film evaporated by the pulsed laser deposition method. The substrate used in this work is a bicrystal $SrTiO_3$ whose misorientation angle is 30°.

Sizes of fabricated SQUIDs are 24 μm × 28 μm, 12 μm × 16 μm, 12 μm × 12 μm, 10 μm × 10 μm, respectively (Fig. 1).

The electronics for the SQUIDs has the flux-locked loop scheme without an ac modulation. Its detail is shown in the next section. Measured parameters at optimal working states are presented in Table 1. We had difficulty in locking SQUID4 and did not obtain the noise spectrum. The most important among those is the peak-to-peak voltage modulation when we use the direct-coupled readout electronics, for it sees larger noise than that of the flux-modulation scheme. The SQUID we fabricated showed large voltage modulations.

The noise characteristics of various size SQUIDs are shown in Fig. 2. In addition to the external noise, $1/f$ noise with a level typical of high-T_c SQUID is also observed. It is known that bias reversal can reduce this noise [7]. Bias reversal would be very effective because the frequency band involved in the operation of the scanning SQUID microscope is from about 1 mHz to a few 100 Hz at present. The external noise is less prominent for two smaller SQUIDs. We can estimate the detectable level of external noise to be 100 $pT/Hz^{1/2}$ for a small SQUID of which effective area is about 10 μm x 10 μm and flux sensitivity $10^{-5}\ \Phi_0/Hz^{1/2}$

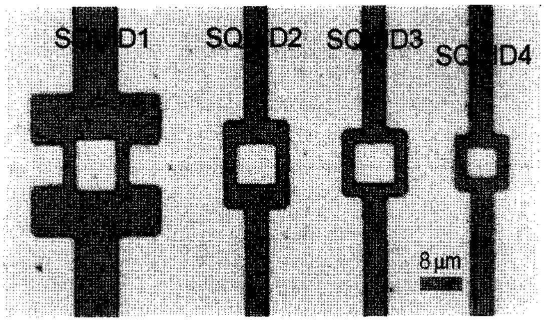


Fig. 1. Photographs of 4 SQUIDs.

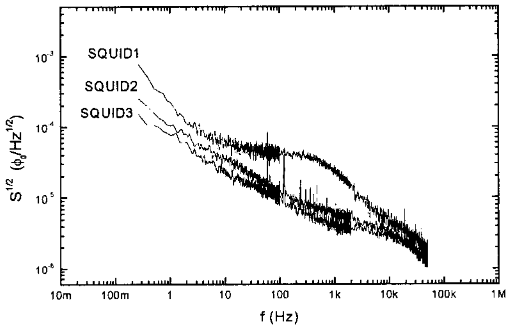


Fig. 2. Noise spectra of 3 SQUIDs.

Table 1. Working parameters.

	Outer size (μm x μm)	Inner size (μm x μm)	Bias current (μA)	Voltage modulation (μV)	FLL output (V/Φ_0)
SQUID1	28 × 24	8 × 10	43	63	25
SQUID2	12 × 16	8 × 8	44	78	54
SQUID3	12 × 12	8 × 8	78	78	59
SQUID4	10 × 10	8 × 8	84	92	(93)

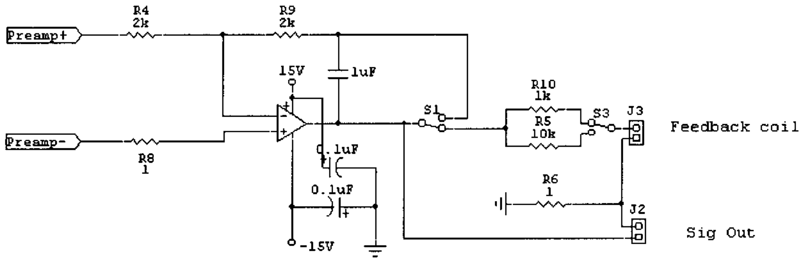


Fig. 3. Integrator part of direct-coupled feedback circuit.

III. Electronics

To operate SQUID with conventional electronics with an ac modulation, we have to apply a modulational ac magnetic flux of 1/2 Φ_0 p-p. In case of a small SQUID, the magnitude of the modulation field is quite large, e.g. 0.1 gauss p-p for effective area of 10 μm x 10 μm. Unlike other applications of SQUID, SQUID and sample are very closely located and the modulating field can perturb the magnetic property of sample.

If we use direct feedback scheme, the situation is somewhat different. The feedback maintains the amount of the flux through SQUID at $(n+1/4)\Phi_0$ or $(n-1/4)\Phi_0$. The large modulation flux is replaced by a dc-bias flux, which is also large but static. The working point is more shifted for smaller SQUID, which is the reason we could not deal with SQUID4 properly. Fig. 3 and 4 illustrate our design.

Preamp design follows D. Drung's [8]. Its major advantage is the minimization of the thermal drift. Temperature sensing Zener diode controls the collector current of the transistor pairs to cancel the drift of the transistors.

There's additional 2nd stage amplifier and integrator involved. The amplified signal gets in an integrator giving a nulling current through R5 or R10. A switch S1 selects preamp output mode or feedback mode. SQUID bias reversal feature is not designed in it yet.

The bandwidth of the feedback loop is wider than 10 kHz as shown in Fig. 2. The noise characteristics of the preamp is shown in Fig. 5. At high frequencies, the noise level is 1 nV/Hz$^{1/2}$. White noise and 1/*f* noise cross at about 100 Hz which is rather higher than we expected. A little high collector current may have increased the 1/*f* noise.

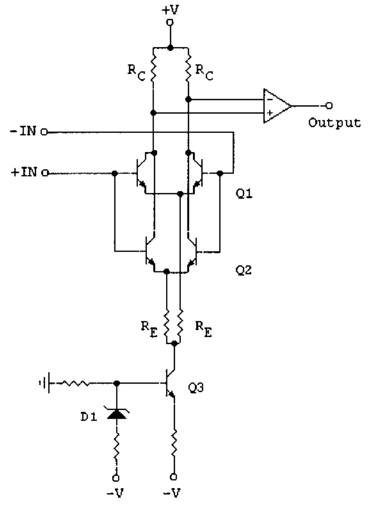


Fig. 4. Preamp design. Q1 and Q2 (SSM2210) make a differential amplifier, of which thermal drift is reduced by D1 (LM335)

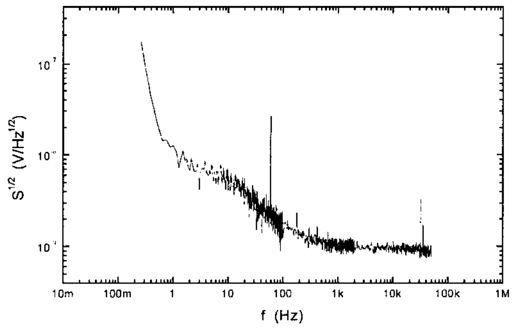


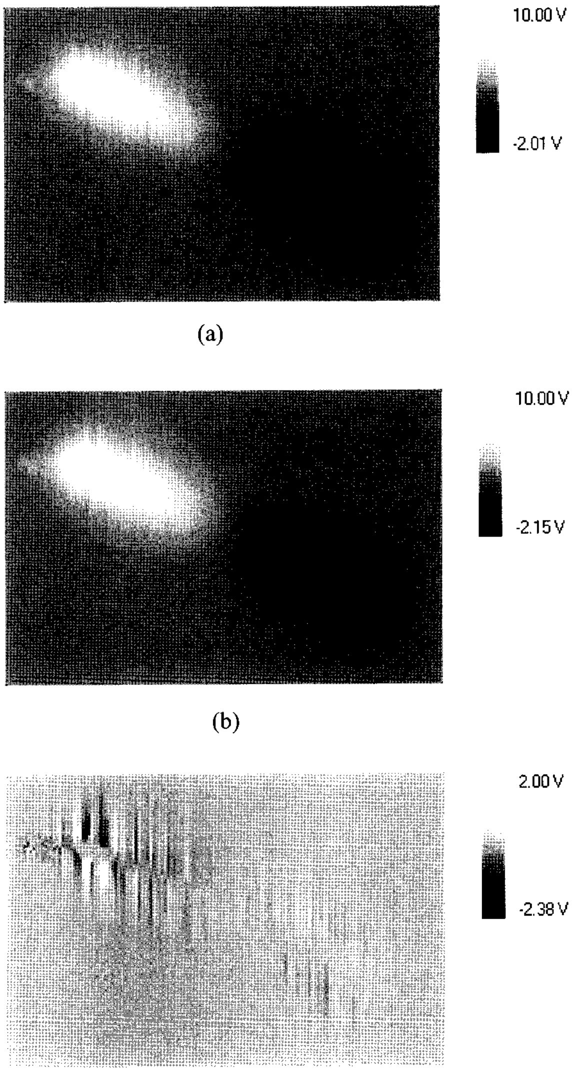
Fig. 5. Noise spectrum of preamp.

IV. Scanning

The noise of scanned data largely depends on the elapsed time of the scanning due to a characteristic $1/f$ noise feature. Moreover, a drift in the dc-feedback scheme affects the stability of the feedback itself.

We tested two modes of the scanning method. One sequence is that the motor rotates, stops, and then ADC reads values, and motor rotates again. The other is that the controller generates ADC-triggering pulses while the motor rotates continuously to the end of the scanning line. We used commercial ones for the controller, step motors, and xy stages. The scanning system moves 2.75 μm per each step of the motor, and 8 cm × 8 cm maximally. The sensor used for the scanning test is a magnetoresistance (MR) sensor. Data acquisition board (National Instruments) acquires the output of the MR-sensor controller.

We performed a demonstration for the second scanning method. The sample is μ-metal strip and only the scanning speeds are different from each other. Fig. 6 shows the results and the differences of the two. Let's estimate the differences. ADC reading rate is 200 kHz, and this means it take only 5 μs to acquire one datum. Then the traveled distance during the data acquisition is estimated to be 0.14 μm and 0.035 μm each. The tolerable limit of the distance is about the spatial resolution, ~1 μm for the case of SQUID. If we estimate reversely, the speed as high as 20 cm/s has no significant effect on the resolution. For 1 mm × 1 mm area and 256 lines, this speed gives total scanning time ~13 seconds. The major difficulty to achieve this fast scanning would be the limit of motor acceleration.



(a)

(b)

(c)

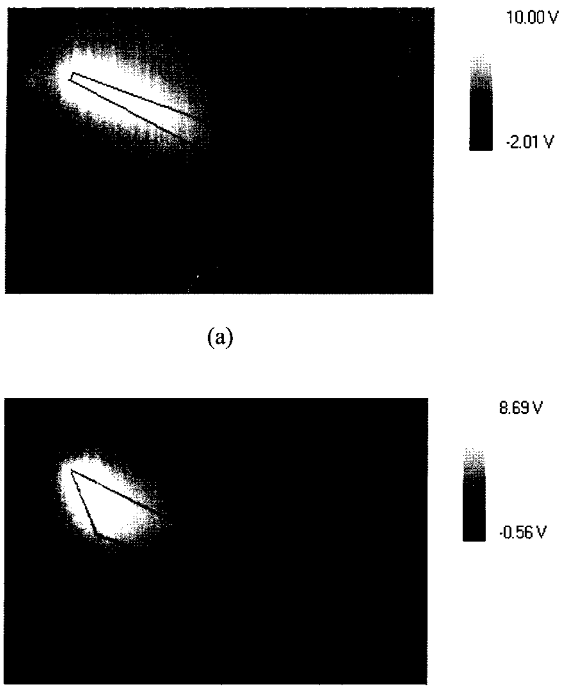
Fig. 6. MR-scanning images of μ-metal strip. Scan area and speed are (a) 41 mm × 28 mm and 27.5 mm/s, (b) the same as (a) and 6.9 mm/s respectively. (c) the difference of (a) and (b).

V. Soft Magnetic Strip

We tested a μ-metal strip sample. The material can be utilized as a field guide of SQUID and suggests another way to improve the spatial resolution. In this case, we expect the dimension of field guide's edge determines the resolution. Distributed magnetic particles of which diameters were under 1 μm were observed in a previous work by P. Pitzius *et al.* [9]

We used the earth magnetic field as external static field and obtained scanned data for two opposite orientations of the sample. The feature on the soft magnetic material is obvious, that is, the magnetization direction follows the direction of external field.

But as you see, the magnetization gets smaller by about 23 % on the second scan. It is hysteretic behavior and means coercivity is not negligible. The coercivity of μ-metal is 0.05 Oe, and the horizontal component of earth magnetic field – we aligned the



(a)

(b)

Fig. 7. MR-scanning data. (a) and (b) are at the same condition except for the opposite orientations of the sample, μ-metal strip.

direction of sample to this field - is about 0.3 gauss in Korea.

The ratio is 17:100, which might be thought to explain naively the amount of the loss of magnetization. But considering the fact that this sample did not go through a saturation state with the external field of 6500 gauss, the loss is larger than we expected. This means the shape anisotropy as a long strip played a significant role to widen the hysteresis loop.

This hysteresis would be reflected on the scanned image undesirably if we use this material as field focuser of SQUID.

VI. Conclusions

Progresses in scanning SQUID microscope have been made. The spatial resolution can be improved by using a small SQUID. The smallest size of SQUID we could fabricate and operate stably was 12 μm × 12 μm in the washer size and it showed voltage modulations large enough to be operated by direct-coupled feedback electronics and white noise levels as low as state-of-the-art high-T_c SQUIDs. But the increase of dc-bias flux prevented a stable feedback for the SQUID of 10 μm × 10 μm with our home-made dc feedback electronics.

To reduce interference on the magnetic state of the sample due to a large modulation field required for such a small SQUID sensor, we operated SQUID with a direct-coupled feedback electronics. The shortcoming of the dc feedback scheme is, however, the appearance of a significant effect of drift or $1/f$ noise. To reduce the influence of drift or $1/f$ noise, we tried to increase scanning speed.

Another way to improve spatial resolution, field-guiding structure has been studied. We found hysteresis may be problematic in employing the field-guiding structure.

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