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We fabricated directly coupled gradiometers made of $YBa_2Cu_3O_y$ thin films on bicrystal substrates. The parasitic effective area of the gradiometric pickup coil was found to be comparable with that of the superconducting quantum interference devices (SQUIDs) in each gradiometer. A gradiometer balance of below 10^{-3} was achieved by selecting the coupling direction of the SQUID so as to cancel the parasitic effective area of the pickup coil by the effective area of the SQUID itself. The noise of the gradiometers measured in an unshielded environment decreased in proportion to the improvement in the gradiometer balance; however, the noise of the gradiometer with a balance of 0.03% was limited by the gradient-field component of the environmental noise. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1429291]

In order to measure a faint magnetic field, like that of biomagnetic signals, in the presence of a much higher background field, it is necessary not only to improve the sensitivity of a superconducting quantum interference device (SQUID) but also to cancel out environmental noise. A gradiometer, which detects the spatial gradient of the magnetic field, can reduce sensitivity to the background field from distant noise sources. There are two basic approaches for constructing a gradiometer system using high-T_C superconductor SQUID. The first is the electronic gradiometer, in which the output signals from two or more separate magnetometers are electrically subtracted.[1–4] The electronic gradiometer allows a long baseline and a high degree of balance but requires complex electrical and/or mechanical adjustments of individual channels. The other approach is the directly coupled, planar-type gradiometer, in which the two symmetric superconducting loops are coupled to a SQUID directly.[5–8] Such a directly coupled gradiometer can be made simply of a single-layer superconducting thin film. Although this gradiometer is less sensitive than the electronic gradiometer because of its short baseline limited by the substrate dimensions, mechanical adjustment and additional electronics are not necessary. The ease of handling is convenient for a multichannel system.

Only the gradiometric response of the gradiometer is the output signal that should be measured. This means that the effective area, which represents the sensitivity to the uniform field, should be infinitely small. In the case of the directly coupled gradiometer, the SQUID itself, which acts as a magnetic sensor with an effective area of A_{SQ} and limits the gradiometer balance, has a magnetometric response. In addition, the pickup coil of the actual gradiometer probably has a small magnetometric response due to the asymmetry of the field sensitivity between two superconducting loops.

In this study, in order to estimate the effective area of the SQUID (A_{SQ}) and the effective area of the gradiometric pickup coil (A_{PK}), we fabricated gradiometers in which two SQUIDs are coupled with the same pickup coil in a different coupling direction to each other. We found that A_{PK} is comparable with A_{SQ}, and can be partly cancelled by selecting the coupling direction of the pickup coil and the SQUID, thus improving the gradiometer balance. The noise properties in an unshielded environment were also measured by using the gradiometers with a variety of gradiometer balance.

The directly coupled gradiometers were fabricated by using 150-nm-thick c-axis-oriented $YBa_2Cu_3O_y$ thin films deposited on $SrTiO_3(100)$ bicrystal substrates ($15 \times 15\,mm^2$) with a misorientation angle of 30°. Patterning was done using electron-beam lithography and an ion beam etching. The detailed fabrication process is described in Ref. 9. Figure 1(a) shows a schematic drawing of a directly coupled gradiometer consisting of two SQUIDs, Q1 and Q2, and two symmetrical pickup loops. Q1 is arranged in the opposite direction to Q2 (i.e., in the opposite "coupling direction") as shown in Fig. 1(b). Hereafter, "SQUID" denotes the SQUID itself and "gradiometer" denotes the SQUID coupled with the gradiometric pickup coil. Both SQUIDs have the same dimensions. The width of the bicrystal junction is 1.5 μm. The linewidth of the SQUID loop is 3 μm, and the slit hole length and width are 74 μm and 2 μm, corresponding to an estimated SQUID inductance of 100 pH. The linewidth of the SQUID is restricted to 3 μm to prevent flux trapping during cooling in an unshielded environment and to minimize A_{SQ}. The dimensions of the pickup coil are shown in Fig. 1. The baseline, defined as a half of the outer dimension, is 6.75 mm. Note that when one of the two SQUIDs is biased by a flux-locked loop (FLL) electronics, the other SQUID is not biased and acts as a part of the pickup coil.

The properties of the gradiometers were measured at the boiling point of liquid nitrogen in a magnetically shielded

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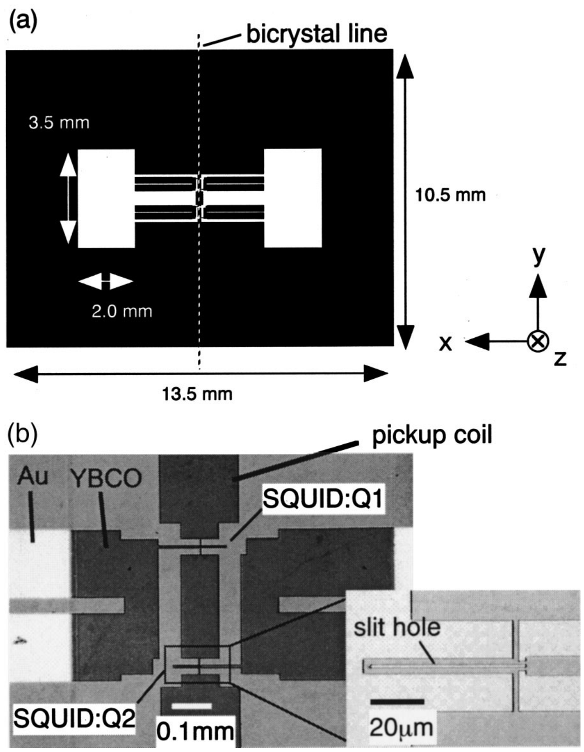

FIG. 1. Schematic drawing of (a) the directly coupled gradiometer and (b) optical microscope image of SQUIDs.

room. Field sensitivity, i.e., effective area, was measured by using a large solenoid (0.3 m in diameter and 1 m in length) to apply a uniform field. Gradient field sensitivity was measured by using a planar coil ($1.8\times0.9\,\mathrm{m}^2$), which can produce a field with a uniform gradient (dB_z/dx). The planar coil is similar to that used by Zhang *et al.*[6]

We fabricated two identical SQUIDs coupled with the same pickup coil but in the opposite directions to each other to evaluate A_{PK} and A_{SQ}. When the SQUID itself has an effective area of A_{SQ} and the gradiometric pickup coil has a effective area of A_{PK}, the following equation holds

$$A_{eff}=A_{PK}\pm A_{SQ}, \tag{1}$$

where A_{eff} is the total effective area of the gradiometer. The sign of A_{SQ} depends on the coupling direction of the pickup coil to the SQUID. The coupling direction can be determined after measurement. Here, A_{PK} was found to be in the order of the $10^{-4}\,\mathrm{mm}^2$, the same order of magnitude as A_{SQ}. When the same measurement was performed at about the 2-cm-off position in the $x-y$ plane from the center axis (z) of the solenoid, the measured effective area was unchanged. This confirms the homogeneity of the applied field B_z. Table I summarizes the results and measured properties of the best balanced gradiometers. It is clear that a gradiometer with better balance is obtained when Q2 is biased. However, in some gradiometers fabricated on different substrates, better balance is obtained when the Q1 is biased. Note that A_{PK} and A_{SQ} are the same order of magnitude. Therefore, the total effective area of the gradiometer becomes small when the pickup coil is coupled with the SQUID in the direction in which the sign of A_{SQ} in Eq. (1) becomes minus.

Figure 2 shows the effects of the coupling direction on the gradiometer balance of four gradiometers formed on different substrates. The measured balance values are plotted against the sign of A_{SQ} in Eq. (1). The balance was defined as A_{eff}/A_{mag}, where A_{mag} is the effective area of a hypothetical magnetometer where only one pickup loop ($10.5\times6.75\,\mathrm{mm}^2$) is coupled with a SQUID. A_{mag} was estimated from the gradient field sensitivity measured by using a planar coil. Each set of symbols in Fig. 2 represents the data for each gradiometer. It is clear that the balance of the gradiometers depends on the sign of A_{SQ}; that is, the coupling direction of the pickup coil and the SQUID. The best device, shown by circles in Fig. 2, has a balance of one part in 3000 (0.03%). Note that the fabricated gradiometers have almost the same gradient field sensitivity in spite of the wide spread of gradiometer balance.

TABLE I. Properties of the directly coupled gradiometer.

	Q1	Q2	
Gradient sensitivity ($dB_z/dx/\Phi$)	1.5	1.5	μT/(m Φ_0)
Effective volume[a] (V_{eff})	1.4	1.4	mm^3
Effective area of hypothetical magnetometer[b] (A_{mag})	0.21	0.21	mm^2
Field sensitivity (B/Φ)	3.8	36	μT/Φ_0
Effective area of gradiometer (A_{eff})	5.4	0.6	$\times10^{-4}\,\mathrm{mm}^2$
Effective area of gradiometric pickup coil (A_{PK})	3.0	3.0	mm^3
Effective area of SQUID (A_{SQ})	2.4	2.4	mm^3
Balance[c]	0.29	0.03	%

[a]Effective volume is defined as the inverse of gradient sensitivity.
[b]$A_{mag}=V_{eff}$/baseline (6.75 mm).
[c]Balance is defined as A_{eff}/A_{mag}.

There are two causes of the imbalance of the pickup coil. One is the variation of the pickup-coil dimensions. The estimated effective area of the pickup coil corresponds to a geometric imbalance of more than 10 μm, which is larger than the error in our fabrication process. The inhomogeneity of the film quality is another reason; it affects the distribution of the superconducting circulating current in the pickup coil. Distribution of substrate temperature and variation of film thickness will cause such inhomogeneity.

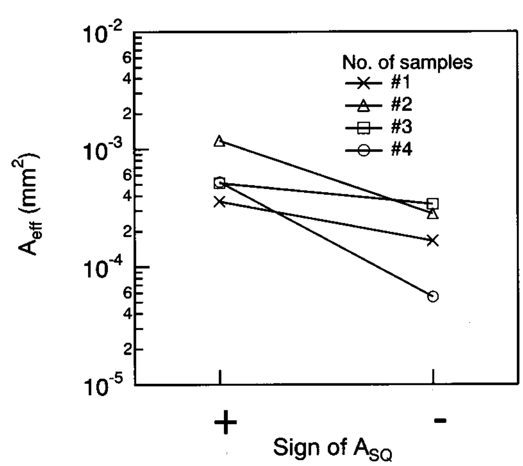

FIG. 2. Effect of the coupling direction of the SQUID to the pickup coil. The balance values of four gradiometers are plotted against the sign of A_{SQ} in Eq. (1). The different symbols correspond to the gradiometers fabricated on the different substrates. The circles correspond to the best balanced gradiometer listed in Table I.

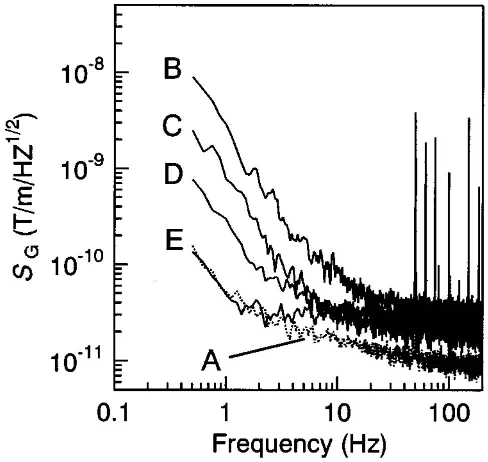

FIG. 3. Gradient-field noise spectra of directly coupled gradiometers. Curve A is the intrinsic noise measured in a magnetically shielded space. Curves B, C, and D are the noise of the gradiometers with balances of 0.36%, 0.16% and 0.03%, respectively, measured in the magnetic field of the Earth. The *x* axis of the gradiometers are positioned parallel to the direction of the magnetic field of the Earth. Curve E is the noise of the gradiometer with 0.03% balance measured in the magnetic field of the Earth, where the *x* axis of the gradiometer is positioned perpendicular to the magnetic field of the Earth.

Figure 3 shows the noise spectra of the gradiometers with various balance measured using a FLL circuit with a 128-kHz ac bias current. Curve A (dotted line) shows the intrinsic gradient field noise measured in a highly magnetically shielded space. The intrinsic noise level is about $10\,\mathrm{pT}/(\mathrm{m}\,\Phi_0)$ above 100 Hz and about $40\,\mathrm{pT}/(\mathrm{m}\,\Phi_0)$ at 1 Hz. These values are extremely low for a directly coupled gradiometer with a baseline below 10 mm,[10] although Eulenburg *et al.*[8] reported a directly coupled gradiometer fabricated on a long bicrystal substrate with a gradient field noise of $5\,\mathrm{pT}/(\mathrm{m}\,\Phi_0)$ at 1 kHz.

When the gradiometer is operated outside the magnetic shield, the gradient field noise increased because of the environmental noise. Curves B, C, and D in Fig. 3 show the noise data cooled and measured in an unshielded environment. The *x* axis of the gradiometer (see Fig. 1) was positioned parallel to the direction of the magnetic field of the Earth. In proportion to the improvement of the gradiometer balance, the low-frequency noise decreases although the white noise above 100 Hz is similar, about $30\,\mathrm{pT}/(\mathrm{m\,Hz}^{1/2})$. The low-frequency noise at 1 Hz of the gradiometer with a balance of 0.03% (curve D) is approximately 300 $\mathrm{pT}/(\mathrm{m\,Hz}^{1/2})$. These results mean that the uniform field noise is dominant in the low balance gradiometer, and it can be reduced in the highly balanced gradiometer. It is notable that, when the *x* axis of the gradiometer was positioned perpendicular to the magnetic field of the Earth, the low-frequency noise measured by the highly balanced gradiometer was further decreased to close to the intrinsic noise level, as shown by curve E. These results suggest that the gradient-field component of the environmental noise is dominant in the low-frequency noise of the highly balanced gradiometer. To reduce such low-frequency noise, the second-order gradiometry or a magnetic shield is necessary, because the gradient-field component of the environmental noise can not be reduced by further improvement of the gradiometer balance.

It was also found that the gradiometers are stable in an unshielded environment even though the pickup coil does not have a narrow line structure.[11] The low noise level was maintained for at least half an hour after the gradiometer was cooled in an unshielded environment with field fluctuations of several μT. The low-frequency noise increased in the directly coupled magnetometer with a wide pickup coil,[11] like our gradiometer, when it was cooled in a magnetic field. The fluctuation of the environmental field causes a circulating current to flow in the pickup coil and SQUID loop, and this current produces flux trapping. Therefore, a narrow line structure[11] to prevent from the flux trapping and/or a flux dam[12] to limit the circulating current have been used. The flux trapping by the circulating current should occur in our gradiometer during cooling in the magnetic field of the Earth and may cause additional noise due to the motion of the trapped flux. In the case of the gradiometer, however, a very small circulating current flows in the SQUID loop. Therefore, the effect of the trapped flux in the pickup coil seems to be small compared with that in the magnetometer.

In summary, by selecting the coupling direction of the pickup coil and SQUID, we have obtained a first-order, directly coupled gradiometer with a gradiometric balance below 0.1% without a balance adjustment procedure. Stable and low-noise operation of the gradiometer in the magnetic field of the Earth was also demonstrated, even though the pickup coil did not have a narrow line structure. The easy handling without a balance adjustment procedure and stable operation in unshielded environment make it suitable for a multichannel system like a biomagnetometer.

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