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High T_c superconducting second-order gradiometer

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A planar, second-order gradiometer was fabricated from single-layer $YBa_2Cu_3O_{7-x}$ films. The gradiometer consists of a symmetric flux transformer with an overall length of 80 mm inductively coupled to a directly coupled magnetometer, and has a baseline of 31 mm. The mutual inductance between the flux transformer and the magnetometer is adjusted mechanically to reduce the response to a uniform magnetic field applied perpendicularly to the plane of the gradiometer to typically 50 ppm. From an independent measurement, the residual first-order gradient response was determined to be at most 1.4% relative to the second-order gradient response. © *1998 American Institute of Physics.* [S0003-6951(98)03641-9]

A major application of superconducting quantum interference devices (SQUIDs) is the detection of weak magnetic signals from the human brain or heart.[1] Such measurements are rendered difficult by the presence of background noise, which one attempts to mitigate by means of either a magnetically shielded room or flux transformers configured as spatial gradiometers,[2] or often both. In the case of low T_c SQUIDs, one uses either wire-wound axial gradiometers or thin-film planar gradiometers; in the case of high T_c SQUIDs, for which wire is not currently a viable option, only planar gradiometers have been realized.[3] An alternative approach to measuring either diagonal or off-diagonal gradient components is to subtract the output from two or more magnetometers.[4] Because the background noise generally originates in relatively distant sources, the magnitude of the noise relative to the signal from a nearby source is progressively reduced as one implements higher order gradiometers.

In an earlier publication[5] we described an asymmetric, planar gradiometer fabricated from a thin film of $YBa_2Cu_3O_{7-x}$ (YBCO) that measures the off-diagonal gradient $\partial B_z/\partial x$ (B_z is the z component of the magnetic field). The gradiometric flux transformer is inductively coupled to a magnetometer and its action is to cancel any uniform magnetic field applied to the magnetometer; however a gradient $\partial B_z/\partial x$ produces a response from the magnetometer. In this letter we describe a gradiometer involving a symmetric flux transformer with an overall length of 80 mm that measures $\partial^2 B_z/\partial x^2$.

The principle of the second-derivative gradiometer is shown in Fig. 1(a). Two pickup loops (1 and 2) of areas A_{p1} and A_{p2} and inductances L_{p1} and L_{p2} are connected in series with an input loop of area A_i and inductance L_i. The input loop is inductively coupled via a mutual inductance $M_i = \alpha(L_m L_i)^{1/2}$ to the pickup loop of a directly coupled magnetometer which has area A_m and inductance L_m. We neglect the inductance and area of the stripline. Assume that we apply a uniform magnetic field B_z with a superimposed gradient $\partial B_z/\partial x$ such that the magnetic fields applied to the two outer loops of the flux transformer are $B_z - l_1\partial B_z/\partial x$ and $B_z + l_2\partial B_z/\partial x$, respectively. Here, l_1 and l_2 are the distances from the midpoint of the central loop to the midpoints of the pickup loops 1 and 2. Conserving magnetic flux in the pickup loop of the magnetometer and in the transformer, we find:

$$B_z A_m - L_m J_m - M_i J_t = 0, \quad (1)$$

$$(B_z - l_1\partial B_z/\partial x)A_{p1} + (B_z + l_2\partial B_z/\partial x)A_{p2} + B_z A_i - J_t(L_{p1} + L_{p2} + L_i) - M_i J_m = 0. \quad (2)$$

Here, J_m and J_t are the screening supercurrents in the magnetometer and transformer. It is evident from Eq. (2) that the current in the flux transformer J_t is insensitive to $\partial B_z/\partial x$ provided $l_1 A_{p1} = l_2 A_{p2}$. For a symmetric flux transformer we set $l_1 = l_2 = l$ and $A_{p1} = A_{p2} = A_p$, and solve Eqs. (1) and (2) to find the condition for zero response ($J_m = 0$) to uniform fields:

$$\alpha = [A_m/(2A_p + A_i)](2L_p + L_i)/(L_i L_m)^{1/2}. \quad (3)$$

Clearly, one must choose parameters so that $\alpha \leqslant 1$.

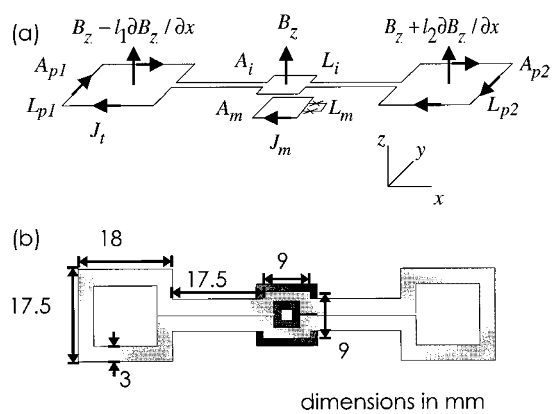

FIG. 1. (a) Schematic of the second-order gradiometer, consisting of a single-layer flux transformer inductively coupled to a directly coupled magnetometer. (b) Configuration of practical flux transformer placed symmetrically over a magnetometer; for clarity, the width of the slit is shown enlarged by a factor of 5.

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To assess the sensitivity of the device, consider a magnetic field δB_z applied to one pickup loop of the flux transformer. The current induced in the magnetometer loop is $\delta J_m = \eta \delta B_z A_m / L_m$, where

$$\eta = (A_p / A_m) \alpha (L_m L_i)^{1/2} / [2L_p + L_i(1-\alpha^2)] \quad (4)$$

represents the reduction in the current compared with the value $\delta B_z A_m / L_m$ for the bare magnetometer.

We fabricated a gradiometer with dimensions shown in Fig. 1(b). The directly coupled magnetometer was patterned in a YBCO film on a 10×10 mm^2 $SrTiO_3$ bicrystal.[5] The pickup loop has inner and outer dimensions of 2 and 10 mm, and we estimate $A_m = 20$ mm^2 and $L_p = 4$ nH. The flux transformer was patterned in a 260 nm thick YBCO film that had been coevaporated onto a 100 mm diam sapphire wafer. The separation of the centers of the two pickup loops is 62 mm; thus the baseline of the second-order gradiometer l is 31 mm. We estimate $A_p \approx 218$ mm^2, $L_p \approx 23$ nH, $A_i \approx 49$ mm^2, and $L_i \approx 9$ nH. These parameters lead to the estimated values $\alpha \approx 0.38$ and $\eta \approx 0.47$.

We mounted our gradiometer on a probe that allowed us to change the separation between the magnetometer and the flux transformer by means of a wedge that we could adjust from outside the Dewar. This arrangement enabled us to vary α while maintaining the symmetry required to reject first-order gradients. The gradiometer was immersed in liquid nitrogen and the SQUID, flux modulated at 256 kHz, was operated in a flux-locked loop. There was no magnetic shielding. To balance the gradiometer, we placed it at the center of a 1.1 m diam Helmholtz pair with the axis of the coils perpendicular to the plane of the gradiometer. Even if the gradiometer had been misaligned by as much as 5 mm in any direction, the values of $2l\partial B_z / B_z \partial x$ and $l^2 \partial^2 B_z / B_z \partial x^2$ produced by the coils were below 10^{-5}. We applied a 100 Hz current to the coils and measured the output of the flux-locked loop using a lock-in detector with a noise bandwidth of 26 mHz.

Figure 2(a) shows the magnitude $|S|$ of the in-phase and out-of-phase rms signals versus the relative separation of the magnetometer and gradiometer in response to an applied 100 Hz field of constant amplitude. The magnitude of the field (as would be measured by the bare magnetometer) is shown for each case. At the separation corresponding to the optimum value of α given by Eq. (3), the in-phase signal is reduced by a factor of about 10^5. The out-of-phase signal, which is presumably generated by eddy currents induced in nearby conductors (such as the steel frame of the building), exhibits a minimum at a different separation than the in-phase signal, with a reduction of only about 400. This result suggests that the out-of-phase signal has higher-order gradient components that are partly cancelled by choosing a different value of α. Figure 2(b) shows the signal S from the same measurements. The out-of-phase component varies nonlinearly with the separation, implying that it has higher-order gradient components. On the other hand, the in-phase component varies linearly with the separation, with a slope of 46 pT/μm; thus, the observed cancellation corresponds to an error of about 0.04 μm in the separation. However, we emphasize that such a high degree of cancellation is obtained only rarely; a more typical value that we can obtain routinely is 50 ppm.

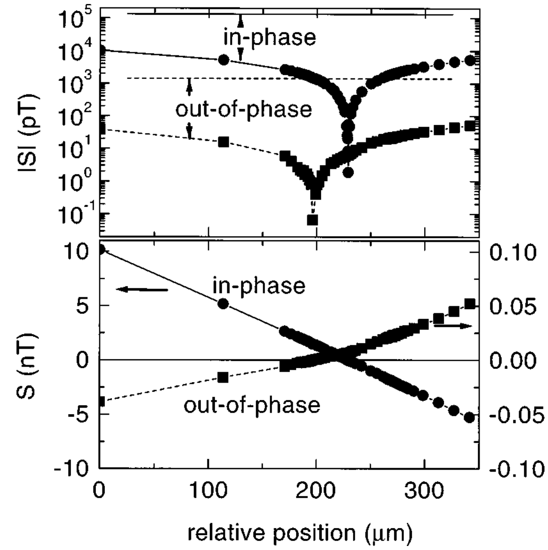

FIG. 2. (a) Magnitude of the signal $|S|$ and (b) the signal S from the magnetometer vs its position from the flux transformer (arbitrary zero) in the presence of a 100 Hz perpendicular magnetic field of constant amplitude. In (a) horizontal lines represent the response of the bare magnetometer.

To determine the accuracy with which our gradiometer responds only to $\partial^2 B_z / \partial x^2$, we arranged two parallel wires below the Dewar, one 10 mm above the other in the plane of the gradiometer. We passed a 100 Hz current through one wire and back through the other to produce a gradient $\partial^2 B_z / \partial x^2$ that falls off as $1/X^4$, where X is the distance between the center line of the two wires and the center line of the gradiometer. Figure 3 shows the output of the flux-locked loop versus X. A least squares fit yields a slope of -3.900 ± 0.028, compared with the expected value of -4. The systematic deviation arises from a small response to either a uniform field or $\partial B_z / \partial x$, or both. To characterize the balance of the gradiometer, we write the magnetometer response in the form $R = c_0 B_z + 2c_1 l \partial B_z / \partial x + c_2 l^2 \partial^2 B_z / \partial x^2$, where c_0 / c_2 and c_1 / c_2 define the balance of the second-order gradiometer with respect to B_z and $\partial B_z / \partial x$, respectively. Imposing a response to $\partial^2 B_z / \partial x^2$ that scales as $1/X^4$, we can fit the data in Fig. 3 with $c_0 / c_2 = 1.7\times 10^{-3}$, assuming the deviation is due solely to a uniform field, or with $c_1 / c_2 = 1.4$

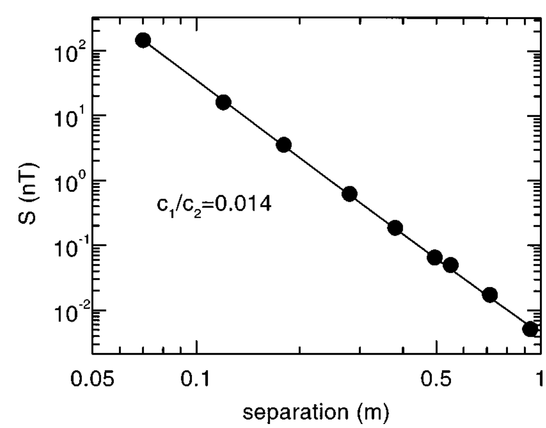

FIG. 3. Signal S from the magnetometer vs separation from two parallel wires. The line, fitted with $c_1 / c_2 = 0.014$, assumes that the deviation from a slope -4 arises solely from a residual response to $\partial B_z / \partial x$.

$\times 10^{-2}$, assuming the deviation is due solely to $\partial B_z/\partial x$. Since the uniform field response c_0/c_2 measured in the Helmholtz pair was no more than 5×10^{-5}, we conclude that the deviation from $1/X^4$ arises from a residual sensitivity to $\partial B_z/\partial x$. This response implies that the flux transformer either has an asymmetry or is misaligned relative to the magnetometer. In the latter case, it can be shown that $c_1/c_2 \approx \delta x/l$, where δx is the distance between the centers of the magnetometer pickup loop and the input loop of the flux transformer. Given our technique of assembling the SQUID and the flux transformer, a misalignment of 0.5 mm is entirely possible.

In conclusion, we briefly consider whether a balance of 0.1% in both B_z and $\partial B_z/\partial x$—which should be very adequate for systems with software subtraction—could be realized with a permanently assembled flip-chip arrangement. The data in Fig. 2 imply that a second derivative accurate to 0.1% requires a separation accuracy of about 5 μm, which should be achievable with a parallel-sided shim. A first-order gradient balance of 0.1% requires that a flux transformer be placed over the magnetometer with an accuracy of 30 μm, which should be possible with the aid of small alignment marks on the flux transformer. As a final remark, we note that the sensitivity of the second-order gradiometer in terms of a magnetic field applied to one pickup loop (represented by $\eta = 0.47$) is about one half that for the first-order, asymmetric gradiometer ($\eta = 0.95$). However, the subtraction of the outputs of two first-order gradiometers to obtain a second-order gradient would increase the noise by $\sqrt{2}$. Thus, for magnetometers of given sensitivity, the second-derivative gradiometer has a noise level only $\sqrt{2}$ higher, while requiring only a single transformer, magnetometer, and flux-locked loop.

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[1] For reviews, see M. Hämäläinen, R. Hari, R. J. Ilmoniemi, J. Knuutila, and O. Lounasmaa, Rev. Mod. Phys. **68**, 413 (1993); J. Vrba, in *SQUID Sensors: Fundamentals, Fabrication and Applications*, NATO ASI series, edited by H. Weinstock (Kluwer Academic, Dordrecht, 1996), p. 117.

[2] J. Zimmermann, J. Appl. Phys. **48**, 702 (1977).

[3] See, for example, W. Eidelloth, B. Oh, R. P. Robertazzi, W. J. Gallagher, and R. H. Koch, Appl. Phys. Lett. **59**, 3473 (1991); V. Zakosarenko, F. Schmidl, H. Schneidewind, L. Dorrer, and P. Seidel, *ibid.* **65**, 770 (1994); V. Schultze, R. Stolz, R. Ijsselsteijn, V. Zakosarenko, L. Fritzsch, F. Thurm, E. Il'chev, and H.-G. Meyer, IEEE Trans. Appl. Supercond. **7**, 3473 (1997); M. I. Faley, U. Poppe, K. Uran, H.-J. Krause, H. Soltner, R. Hohmann, D. Lomparski, R. Kutzner, R. Wordenweber, H. Bousack, A. I. Braginski, V. Y. Slobodchikov, A. V. Gapelyuk, V. V. Khanin, and Y. V. Maslennikov, *ibid.* **7**, 3702 (1997); G. M. Daalmans, Appl. Supercond. **3**, 399 (1995).

[4] See, for example, D. Drung, IEEE Trans. Appl. Supercond. **5**, 2112 (1995); R. H. Koch, J. R. Rozen, J. Z. Sun, and W. J. Gallagher, Appl. Phys. Lett. **63**, 403 (1993); Y. Tarvin, Y. Zhang, M. Mück, A. I. Braginski, and C. Heiden, *ibid.* **62**, 1824 (1993); H. J. M. ter Brake, W. A. M. Aarnink, P. J. van den Bosch, H. J. Holland, J. Flokstra, O. Dössel, and H. Rogalla, Proceedings of the 2nd Workshop on HTS Application and New Material, University of Twente, Enshede, The Netherlands, May 8–10, 1995, p. 154; B. O. David, O. Dössel, V. Doorman, R. Eckhart, W. Hoppe, J. Kruger, H. Landau, and G. Rabe, IEEE Trans. Appl. Supercond. **7**, 3267 (1997).

[5] E. Dantsker, O. M. Fröhlich, S. Tanaka, K. Kouznetsov, J. Clarke, Z. Lu, V. Matijasevic, and K. Char, Appl. Phys. Lett. **71**, 1712 (1997).