

# High- $T_c$ superconducting gradiometer with a long baseline asymmetric flux transformer

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The planar gradiometer consists of a directly coupled magnetometer inductively coupled to the smaller loop of an asymmetric, two-loop flux transformer patterned in a single film of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ . The coupling is adjusted mechanically to balance the gradiometer to about 1 part in 3000 with respect to fields perpendicular to its plane. The baseline is 48 mm and the intrinsic balance with respect to in-plane fields about 1 part in 1400. When a magnetic field is applied solely to the magnetometer, its sensitivity is reduced by only 5% by the presence of the flux transformer. © 1997 American Institute of Physics. [S0003-6951(97)04138-7]

In many applications of superconducting quantum interference devices (SQUIDs), notably magnetoencephalography and magnetocardiography, one needs to measure relatively weak magnetic signals from a nearby source in the presence of a much higher background noise. One addresses this problem by using a magnetically shielded enclosure or spatial gradiometers,<sup>1</sup> or often a combination of both. In the case of low- $T_c$  SQUIDs, axial gradiometers consisting of two pickup loops wound in opposition from niobium wire are commonly used, usually measuring either the first- or second-order diagonal derivatives  $\partial B_z/\partial z$  or  $\partial^2 B_z/\partial z^2$  ( $B_z$  is the component of magnetic field in the  $z$  direction).<sup>2</sup> The baseline is, typically, 50–100 mm. Planar thin-film gradiometers measuring an off-diagonal gradient such as  $\partial B_z/\partial x$  are also used.<sup>3</sup> An alternative approach is to subtract the signals from two or more magnetometers to form diagonal or off-diagonal derivatives.<sup>4,5</sup> In the case of high- $T_c$  SQUIDs, the use of wire is currently not a viable option. Thin-film, planar gradiometers, albeit with rather short baselines, have been successfully demonstrated,<sup>6</sup> as have gradiometers formed by electronic subtraction.<sup>5,7,8</sup> To our knowledge, however, there has not yet been a demonstration of a high- $T_c$  gradiometer involving a flux transformer with a baseline that is sufficiently long for biomagnetic measurements.

In this letter, we describe an asymmetric, planar gradiometer measuring  $\partial B_z/\partial x$  fabricated from a thin film of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  (YBCO) with a baseline of 48 mm. We have achieved a balance in the  $z$  direction of about 1 part in 3000. The gradiometer evolved from a design by Zimmerman<sup>1</sup> for a wire-wound, axial gradiometer coupled to a fractional-turn SQUID machined from niobium; a thin-film version was demonstrated by Matlashov *et al.*<sup>9</sup> The device, shown schematically in Fig. 1, consists of a directly coupled SQUID magnetometer with a pickup loop of inductance  $L_m$  and area  $A_m$ , and a superconducting flux transformer with an input

loop of inductance  $L_i$  and area  $A_i$  coupled to a pickup loop of inductance  $L_p$  and area  $A_p$ . The mutual inductance between the magnetometer and input loop is  $M_i = \alpha(L_m L_i)^{1/2}$ .

We first find the condition for the gradiometer to be balanced, that is, for the directly coupled magnetometer to produce zero output in response to a uniform magnetic field  $B_z$  [Fig. 1(a)]. Using flux conservation, we find

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

and

$$B_z (A_p + A_i) - (L_p + L_i) J_i - M_i J_m = 0, \quad (2)$$

where  $J_m$  and  $J_i$  are the screening supercurrents in the magnetometer loop and transformer, respectively. To achieve the balance condition  $J_m = 0$ , we solve Eqs. (1) and (2) to find

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

Obviously, one must choose parameters so that  $\alpha \leq 1$ . To find the response to a gradient  $\partial B_z/\partial x$ , we apply a field  $\delta B_z$

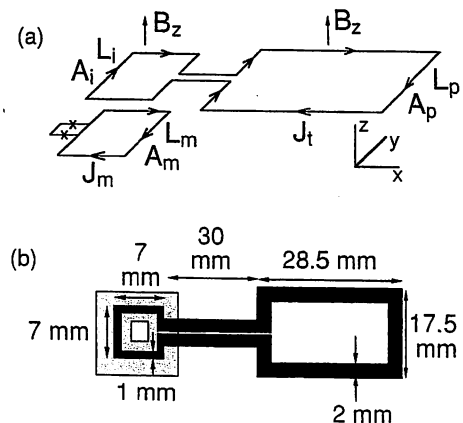


FIG. 1. (a) Schematic of the gradiometer, consisting of an asymmetric flux transformer coupled to a directly coupled magnetometer; and (b) configuration of the flux transformer inductively coupled to the magnetometer (shaded square).

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to the magnetometer loop and input loop only. The current induced in the pickup loop of the magnetometer is  $\delta J_m = \eta \delta B_z A_m / L_m$ , where

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

represents the screening effect of the flux transformer. As we shall see, with appropriate design  $\eta$  is only slightly less than unity so that the sensitivity of the magnetometer itself is not significantly reduced by the presence of the flux transformer.

To test this concept, we fabricated a gradiometer in the configuration of Fig. 1(b). The single-layer, directly coupled magnetometer was patterned by photolithography and Ar ion milling in a 150 nm thick film of YBCO laser deposited on a  $10 \times 10 \text{ mm}^2$  SrTiO<sub>3</sub> bicrystal. The outer and inner dimensions of the magnetometer loop are 10 and 2 mm, respectively, yielding an estimated inductance  $L_m$  of 4 nH and an estimated area  $A_m$  of  $20 \text{ mm}^2$ .<sup>10,11</sup> We estimate the SQUID inductance to be 50 pH, including contributions from the two  $1 \mu\text{m}$  wide junctions. The critical current and resistance per junction are  $200 \mu\text{A}$  and  $1.2 \Omega$ , respectively. The flux transformer was fabricated from a 260 nm thick YBCO film co-evaporated at Conductus on a 100 mm *r*-plane sapphire wafer, buffered with CeO<sub>2</sub>, and patterned by photolithography and etching in a 0.05% aqueous solution of HNO<sub>3</sub>. We estimate the inductance and area of the input coil to be  $L_i \approx 10 \text{ nH}$  and  $A_i \approx 36 \text{ mm}^2$ , and of the pickup loop to be  $L_p \approx 50 \pm 5 \text{ nH}$ , including a 13 nH contribution from the strip-line, and  $A_p \approx 411 \text{ mm}^2$ . From Eq. (3), these estimated values lead to  $\alpha = 0.43 \pm 0.04$ , and from Eq. (4) to  $\eta = 0.95$ ; thus, the presence of the flux transformer reduces the intrinsic sensitivity of the magnetometer by only 5%. The gradiometer base line, given by the separation of the midpoints of the input and pickup loops, is approximately 48 mm.

We mounted the magnetometer and flux transformer face to face, separated by a  $2.5 \mu\text{m}$  thick mylar sheet and (after some experimentation) several layers of  $50 \mu\text{m}$  thick Teflon tape. The magnetometer was attached to a fiberglass mount while the flux transformer was attached to a delrin mount, the position of which we could adjust in the *x* direction from outside the cryostat by means of a screw. In this way, we could vary  $\alpha$  *in situ* to obtain the balance condition of Eq. (3); the position of the flux transformer could be adjusted to about  $2.5 \mu\text{m}$ . The gradiometer was immersed in liquid nitrogen with the *x* axis vertical and the magnetometer at the lower end. There was no magnetic shielding. The SQUID was flux modulated at 100 kHz and operated in a flux-locked loop. To assess the balance of the gradiometer, we placed it at the center of a 1.2 m diam Helmholtz pair, with the axis of the coils perpendicular to the plane of the gradiometer. We injected a 100 Hz current into the coils and averaged the output from the flux-locked loop 200–400 times, using a spectrum analyzer.

The output of the magnetometer at a fixed 100 Hz magnetic field versus the position of the flux transformer is plotted in Fig. 2; at  $x=0$ , the position of the input loop is entirely outside the central hole of the magnetometer pickup loop, and the coupling between them is small. As we slide the input loop towards the opening in the magnetometer loop, the output from the flux-locked loop progressively decreases, dipping sharply near  $x=4.3 \text{ mm}$ , and then increases again.

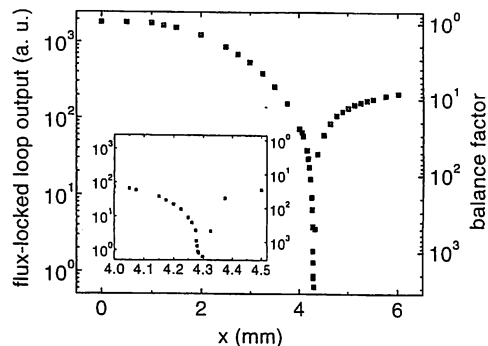


FIG. 2. Amplitude of the signal from the flux-locked loop for a uniform 100 Hz magnetic field applied at right angles to the gradiometer vs the position *x* of the input loop relative to the magnetometer. Right-hand ordinate is the balance factor. Inset shows expanded *x* axis.

Observations on an oscilloscope show that the phase of the output signal relative to the driving field changed sign across the minimum. The minimum represents the optimum balance point of the gradiometer, and corresponds to a reduction in the response to the applied magnetic field of approximately 2930. This value may or may not represent the intrinsic balance limit; it is entirely possible that gradients introduced into the 100 Hz magnetic field by nearby steel objects were the limiting factor. The balance remains stable at 77 K, but requires readjustment after the gradiometer has been thermally cycled.

An important criterion for a useful gradiometer is that the response to fields applied in the plane of the gradiometer should also be low. To evaluate the response in the *y* direction, we first rotated the dewar by approximately  $90^\circ$  with the gradiometer unbalanced ( $x=0$ ) to locate the precise angle  $\theta_m$ , at which the minimum response to the 100 Hz occurred. We restored the dewar to its original position, balanced the gradiometer, and then rotated the dewar back to  $\theta_m$ . This procedure yielded an average rejection in the *y* direction of about 1400. As before, we were unable to determine whether this residual response was intrinsic to the gradiometer or a measure of the nonuniformity of the 100 Hz field.

As a demonstration of the reduction in ambient noise, in Fig. 3 we show the output of the magnetometer for the unbalanced ( $x=0$ ) and optimally balanced cases, with the signal from the Helmholtz pair switched off. The 60 Hz peak is reduced by a factor of 1600. This reduction is consistent with the balance we have been able to achieve, but it is possible that the residual signal arose from a gradient in the 60 Hz field. The peaks at 40 and 80 Hz are of unknown origin; peaks at lower frequencies are due to microphonics.

Finally, we measured the response of the balanced gradiometer to a gradient field  $\partial B_z / \partial x$  by passing a 100 Hz current through a long wire in the *y* direction placed vertically below the gradiometer, parallel to its plane. The separation of the wire from the midpoint of the baseline was changed progressively from  $r=0.5\text{--}0.75 \text{ m}$ , distances substantially greater than the base line. The gradiometer response versus distance is shown in the inset in Fig. 3. The least-squares-fitted slope on this log-log plot,  $-1.90 \pm 0.05$ , is close to the expected value of  $-2$ . We note that

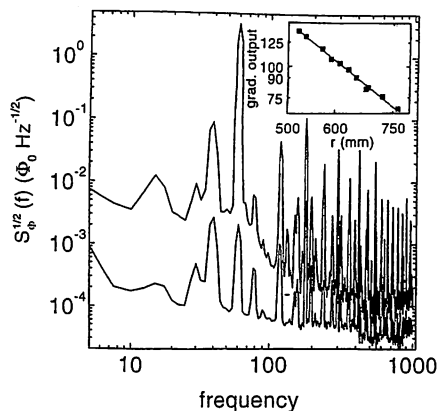


FIG. 3. Output of the flux-locked loop for the unshielded gradiometer at optimal balance (lower trace) and with flux transformer at  $x=0$ . Inset shows the signal from the flux-locked loop for the optimally balanced gradiometer vs the distance  $r$  of a wire carrying 100 Hz current below the centerline of the gradiometer.

distortions in the applied gradient due to nearby conducting objects and, particularly, a slight residual response to a uniform magnetic field, will cause deviations from the ideal  $1/r^2$  behavior.

This approach to planar gradiometers has several advantages. The flux transformer involves only a single layer of YBCO, and its length could readily be extended, to, say, 100 mm, thereby increasing its baseline. Furthermore, it should not be necessary to use particularly high quality films: we have shown previously<sup>12</sup> that relatively high levels of intrinsic  $1/f$  noise due to the motion of flux vortices in a flux transformer with a relatively large area and inductance do not contribute significantly to the overall  $1/f$  magnetic-field noise. Thus, it may be possible to use sintered YBCO films on inexpensive polycrystalline substrates.<sup>13</sup> The fact that the intrinsic magnetic-field sensitivity of the magnetometer is reduced by only a few percent by the presence of the transformer is particularly appealing for high- $T_c$  devices, in which resolution is at a premium. Needless to say, one could use high- $T_c$  magnetometers that are more sensitive than the directly coupled magnetometer used in this demonstration, for example, a multilayer, multiturn flux transformer coupled to a SQUID. The asymmetric flux transformer could be used equally well with rf SQUIDS, and its simplicity makes it worthy of consideration for low- $T_c$  gradiometers. The general principle could be extended to other derivatives. For example, the addition of a second, identical pickup loop to the transformer on the opposite side of the input loop would produce a second derivative gradiometer measuring  $\partial^2 B_z / \partial x^2$ . In principle, axial gradiometers are also possible, for example, using YBCO sintered on a tube,<sup>13</sup> but it may be difficult to achieve a high rejection of fields perpendicular to the axis.

Our asymmetric gradiometer has a base line of 48 mm and has achieved a measured balance of about 1 part in 3000

with respect to magnetic fields perpendicular to its plane. Direct measurements and the observed reduction in the ambient 60 Hz noise indicate an in-plane rejection of better than 1 part in 1000. This combination of balance and relatively long base line, together with the minimal reduction in the sensitivity of the magnetometer, make this high- $T_c$  gradiometer eminently suitable for multichannel arrays for biomagnetic measurements. One could subtract signals among the gradiometers to achieve higher-order gradients and use magnetometers measuring  $B_x$  and  $B_y$  to reduce the pickup of the in-plane noise. However, in such arrays, it would be impracticable to balance the gradiometers mechanically in the way we have described, not least because of the need to repeat the procedure after thermal cycling. A more practicable approach might be to couple the flux transformer permanently to the magnetometer in a flip-chip arrangement and to achieve the final balance by laser trimming a specially designed region of the transformer.

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