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Superconducting thin-film gradiometer[a)]

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We describe the design, fabrication, and performance of planar thin-film dc SQUID's and planar gradiometers in which a dc SQUID is incorporated as a null detector. Each gradiometer was fabricated on a planar substrate and measured an off-diagonal component of changes in the magnetic field gradient. The gradiometer with the highest sensitivity had 127×33-mm loops that could be connected in parallel or in series: The sensitivities were 2.1×10^{-13} and 3.7×10^{-13} $\mathrm{T\,m^{-1}\,Hz^{-1/2}}$, respectively. The intrinsic balance of the gradiometers was about 100 ppm for fields parallel to their plane, and a balance of about 1 ppm could be achieved for fields perpendicular to their plane. When the series-loop gradiometer was rotated through 360° in the earth's field, the output returned to its initial value to within an amount corresponding to a balance of 1 ppm. Possible improvements in sensitivity are discussed.

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I. INTRODUCTION

A superconducting gradiometer[1] that measures time-varying spatial derivatives of magnetic fields consists of a superconducting flux transformer coupled to a dc or rf SQUID. A first-derivative gradiometer has two pickup loops that are balanced so that a change in a uniform magnetic field induces no supercurrent in the transformer, whereas a change in the gradient of the field generates a supercurrent that is proportional to the change. The supercurrent produces a flux that is measured by the SQUID. The highest gradient sensitivity quoted in the literature was achieved by Wynn *et al.*,[2] about 3×10^{-14} T m^{-1} Hz$^{-1/2}$ at frequencies above a few Hz. The best gradiometers can be mechanically balanced against uniform magnetic field fluctuations and translational and angular variations in the position of the gradiometer to a few parts in 10^7 by adjusting the position of nearby pieces of superconductor. Alternatively, a comparable balance can be achieved by adaptive balancing,[3] in which a three-axis magnetometer is mounted near the gradiometer, and the appropriate fraction of each of the three outputs is added to the gradiometer output. The contributions of the magnetometers can be adjusted to minimize the response of the system to a uniform field.

In all gradiometers described previously the flux transformers have consisted of wire loops. In this paper, we describe two prototype gradiometers in which the pickup loops and the SQUID are made of thin films deposited on a single planar substrate. The gradiometer incorporates a tunnel-junction dc SQUID and measures off-diagonal gradients of the form $\partial B_z/\partial x$. Our best gradiometer is not as sensitive as the best wire-loop gradiometers, but we make suggestions for improving the sensitivity to a comparable value. The thin-film device offers several advantages. It has an intrinsic balance against fields parallel to the plane of the loop of about 100 ppm; its intrinsic balance is unaffected by thermal cycling; and it has the potential for relatively large-scale manufacture.

Section II describes two planar dc SQUID configurations, one a magnetometer suitable for adaptively balancing a gradiometer, and the other a galvanometer that was used to measure the current induced in the gradiometer by a change in the magnetic field gradient. Section III describes the fabrication of 48- and 254-mm-long gradiometers. Section IV contains our conclusions and suggestions for further work. The Appendix describes the use of a cooled transformer to match the dc SQUID to the room-temperature electronics. The transformer gives a substantial improvement in the frequency response and slewing rate compared with a cooled-tank circuit. Brief accounts of this work have appeared elsewhere.[4]

II. PLANAR dc SQUID's

In Sec. II we describe two planar dc SQUID's: one to be used as a magnetometer and the other to be used as a galvanometer in the gradiometers. We chose the configuration of the galvanometer to make the device relatively insensitive to changes in uniform magnetic fields, and to minimize its effect on the balance of the gradiometer. Figures 1(a) and 1(b) show the configurations of the dc SQUID magnetometer and of the dc SQUID galvanometer. We made the magnetometer [Fig. 1(a)] by first evaporating onto a glass substrate two disks (5 nm of Cr followed by 10 nm of Au) to form the resistive shunts and four contact pads (5 nm of Cr followed by 100 nm of Au). Next, we transferred the substrate to a sputtering system and sputtered a U-shaped Nb strip 125 μm wide and 300 nm thick. The substrate was removed from the sputtering chamber and the Nb was thermally oxidized for 12 min at 130 °C in a closed oven containing air at atmospheric pressure. The substrate was returned to the evaporator and a Pb/In strip 125 μm wide and 300 nm thick was evaporated to form the tunnel junctions. The fabrication of the galvanometer [Fig. 1(b)] was similar [two contact pads at the ends of

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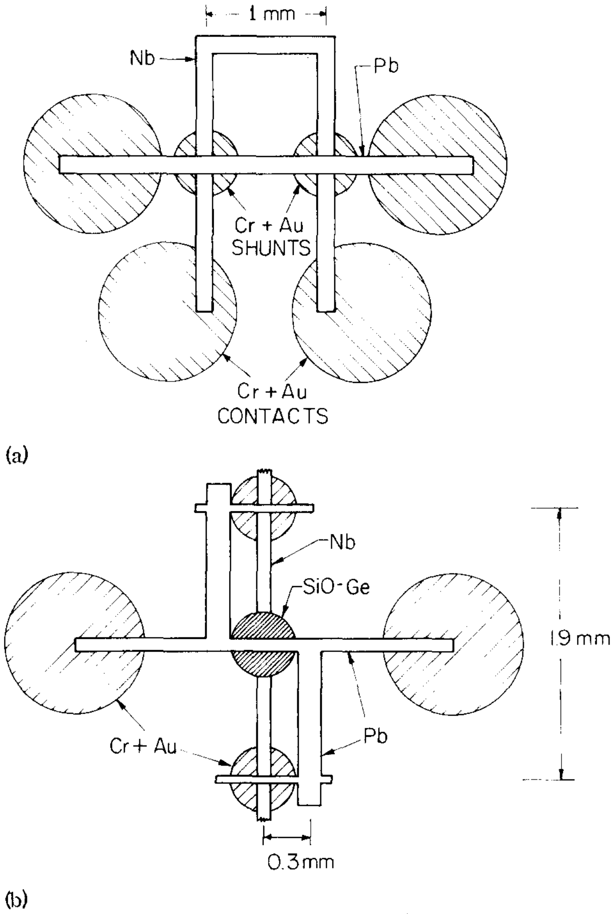

FIG. 1. Configuration of (a) planar dc SQUID magnetometer and (b) planar dc SQUID galvanometer.

the Nb strip are not shown in Fig. 1(b)]. We evaporated a disk consisting of 100 nm of SiO followed by 50 nm of Ge onto the Nb strip midway between the junctions to insulate the Nb from the Pb/In cross strip. The capacitance of the disk, about 1 pF, gave rise to an impedance of about 300Ω at the Josephson frequency corresponding to the operating voltage (~1 μV), and had a negligible effect on the behavior of the SQUID. We protected both devices with a thin layer of Duco cement applied by immersing them in a solution of 1 part Duco cement in 10 parts acetone. We used pressed In contacts to attach two Cu wires to the SQUID, one to a contact pad on the Nb strip, and the other to a contact pad on the Pb strip. (The remaining two contact pads were spare and were used only if the others were accidentally damaged.) A 10- or 20-turn coil wound from No. 40 Cu wire was attached to the substrate with In near the SQUID as a modulation and feedback coil. For each junction the shunt resistance R was typically 0.6 Ω, the critical current I_c was typically 2 μA, and the junction capacitance C was estimated to be about 400 pF. The hysteresis parameter,[5] $\beta_c = 2\pi I_c R^2 C/\phi_0$ (ϕ_0 is the flux quantum), was less than unity, and the current-voltage characteristics were therefore nonhysteretic.

We operated both types of SQUID in a flux-locked loop with the same circuitry as we used with the cylindrical dc SQUID's.[6] The SQUID was biased at ~1 μV with a dc current I_0, and a 100-kHz ac flux with a peak-to-peak amplitude of $\sim \frac{1}{2}\phi_0$ was applied by means of a current in the modulation coil. The 100-kHz voltage across the SQUID magnetometer was amplified by a factor of ~300 with either a cooled resonant circuit or a cooled transformer (see the Appendix). The SQUID galvanometer used a tank circuit with a 0.25-mH coil wound from Cu rather than Nb to avoid distortion of the applied fields. The resistance of the coil was about 1 Ω. The signal was further amplified by room-temperature electronics and lock-in detected. The smoothed output from the lock-in was fed back into the modulation-feedback coil to flux lock the SQUID.

The current required in the U-shaped Nb strip of Fig. 1(a) to produce a flux change Φ_0 in the SQUID was $\Delta I = 1.25$ μA; thus, we estimate the inductance of the SQUID magnetometer to be $\frac{4}{3}\phi_0/\Delta I \approx 2.2$ nH. The current required in the Nb strip of Fig. 1(b) to generate a flux change ϕ_0 was 2.2 μA; the mutual inductance M_i between the Nb strip and the SQUID galvanometer was thus 0.94 nH, a value that leads us to estimate a total SQUID inductance of (5.0/1.9)0.94 nH ≈ 2.5 nH. Figure 2 shows the spectral density of the flux noise of a typical SQUID galvanometer operated in a Pb can in liquid He^4 at a nominal temperature of 4.2 K, and with a Cu tank coil. An essentially identical power spectrum was obtained when the Pb can was replaced with three μ-metal cans outside the cryostat. The noise was white with an rms value of about $8\times10^{-5}\phi_0$ $Hz^{-1/2}$ from the high-frequency rolloff of the electronics (~100 Hz in this case) down to $\sim 5\times10^{-2}$ Hz, where $1/f$ noise became significant. The current resolution in the white-noise region was approximately 1.7×10^{-10} A $Hz^{-1/2}$. Comparable flux noise power spectra were obtained with the SQUID magnetometers. The inductances of the SQUID magnetometer and galvanometer were higher than the inductance of the cylindrical dc SQUID by more than a factor of 2. The measured rms noise of the planar SQUID's, which is expected to be proportional to the inductance,[6] exceeded the rms noise of the cylindrical SQUID's (typically $4\times10^{-5}\phi_0$ $Hz^{-1/2}$) by a comparable factor. Both types of SQUID could be operated unshielded in a laboratory environment. To whatever direction the SQUID was rotated, the change in critical current was sufficiently small that no readjustment of I_0 was necessary.

The field sensitivity of the magnetometer was about 2×10^{-13} T $Hz^{-1/2}$ in the white-noise region. This sensitivity was a factor of about 16 poorer than that of the cylindrical dc SQUID, as expected from the ratio of the

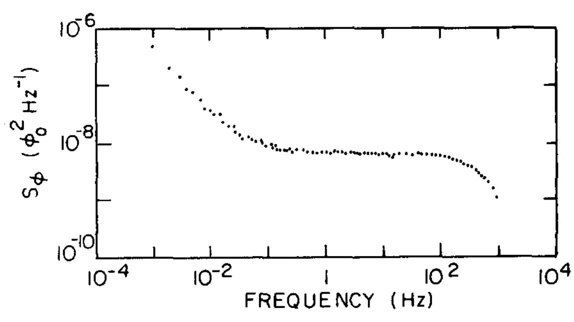

FIG. 2. Flux noise power spectrum of dc SQUID galvanometer.

inductances of the planar and cylindrical SQUID's, about 2.5, divided by the ratio of their areas, about $\frac{1}{7}$. However, a sensitivity of 2×10^{-13} T $\mathrm{Hz}^{-1/2}$ is quite adequate for adaptively balancing a gradiometer or for most geophysical applications.[3] The magnetometer is particularly simple to fabricate and three of them could readily be mounted in an orthogonal array.

The use of the galvanometer in gradiometers is described in Sec. III.

III. GRADIOMETERS

A. Configuration and fabrication

The configurations of the small and large gradiometers are shown in Figs. 3(a) and 3(b). For the small gradiometer we first evaporated a Pb/In strip 150 μm wide and 0.5 μm thick as a 48×16-mm rectangle on the surface of an 89×21×12-mm Pyrex substrate. We used thick substrates to minimize their warping when they were cooled down. The remaining depositions followed the sequence of the SQUID fabrication discussed in Sec. II. The Nb strip of the SQUID made a superconducting contact with the Pb/In rectangle. A uniform magnetic field B_z at right angles to the plane of the gradiometer induced a persistent current in each of the pickup loops. If the loops were perfectly symmetric, these currents cancelled in the Nb strip and there was no response from the SQUID. The application of a gradient $\partial B_z/\partial x$ produced a current in the Nb strip that was detected by the SQUID. We balanced the gradiometer along the x axis by adjusting the position of two Pyrex blocks on each of which was sputtered a 20-mm×3-mm×300-nm Nb film. The blocks were mounted in a carriage with the Nb films pressed against the substrate (from which the Duco cement had been removed) by springs. The position of the carriage in the x direction was adjusted by means of a differential screw that was operated from outside the cryostat. The total travel of the carriage was limited to about 6 mm so that the glass blocks could not overlap and thereby possibly damage the Pb/In films of the gradiometer. We found that the Nb balance films did not appear to be damaged by sliding over the substrate, even after their position had been adjusted 50 or more times. The gradiometer was mounted vertically in a 5-liter fiberglass cryostat, with the insert spring loaded against the bottom of the Dewar to minimize vibration. All solder joints immersed in the helium were made with In to avoid the presence of pieces of superconductor near the gradiometer.

The fabrication of the large gradiometer [Fig. 3(b)] followed the same general procedure. The substrates were either Pyrex (285×38×31 mm) or quartz (295×38×38 mm); the quartz substrates were optically polished on one surface, while the Pyrex substrates were not. Each pickup loop was 127×33 mm. An additional diagonal Pb/In strip was evaporated as shown, electrically insulated from the Nb strip with a SiO-Ge disk. When the films were cut at locations A, we obtained the parallel-loop configuration of the small gradiometer, whereas when they were instead cut at B, the loops were in series. Two SQUID's, one a spare, were fabricated on the Nb strip. We used a single Nb balance film, mounted and adjusted as for the small gradiometer.

B. Performance

The gradiometers were initially balanced along the z axis by mounting them at the center of a 1.1-m-diam Helmholtz pair of single-turn coils. The coils were driven with an ac current at 0.1 Hz to produce a peak-to-peak field of about 0.5 μT at right angles to the plane of the gradiometer. With the SQUID flux locked, we adjusted the balance films to minimize the response to the field. We were able to balance the small gradiometer to 10 ppm with respect to the field produced by the Helmholtz coils. This limit was set by mechanical hysteresis in the balance mechanism. In the case of the large gradiometer, it was first necessary to adjust the length of one of the pickup loops to compensate for the asymmetry introduced by the use of a single balance film. The appropriate Pb/In film was removed and a new one evaporated in a slightly different position. The best z balance that we achieved with the series-loop configuration using the Helmholtz coils was 3 ppm. This balance was limited by ambient noise rather than mechanical hysteresis in the balancing mechanism. We determined the intrinsic balance with respect to fields in the plane of the gradiometer by applying the same ac field in the y direction. We define the y balance as the response to a field in the y direction divided by the response that would be produced by the same field applied in the z direction to *one* of the pickup loops. The y balance for both small and large gradiometers was about 100 ppm. The fact that we achieved the same y balance for the large gradiometers on substrates that were optically polished and on those that were not, strongly suggests that the x and y balances were limited by the distortion of the magnetic fields in the vicinity of the SQUID, rather than by lack of flatness of the substrate.

It is clear that one must balance the gradiometer in the x and y directions to obtain a useful device. We im-

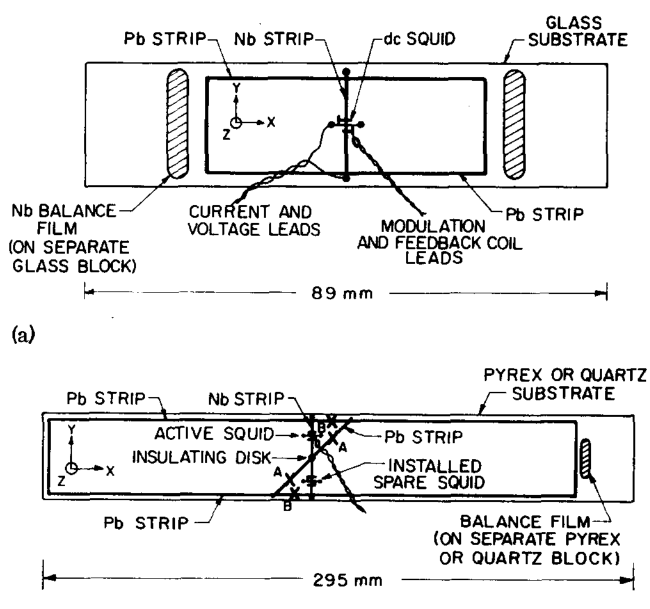

FIG. 3. Configuration of (a) small gradiometer and (b) large gradiometer.

proved the y balance of a small gradiometer by evaporating a Pb film on the appropriate edge of the substrate (perpendicular to the surface on which the gradiometer was deposited) along the length of one pickup loop. The film was 350 μm wide, 1 μm thick, and its center was approximately 1 mm from the surface on which the gradiometer was deposited. This superconducting film distorted the magnetic field in the vicinity of the nearby pickup loop. We found that the y balance was again about 100 ppm, but that its polarity was reversed. The effect of the balance film was reduced by scraping away part of it near the center of the substrate. After two such reductions, the length of the film was about 14 mm and the y balance was improved to better than 10 ppm, a factor of 10 improvement over the original balance. With care, we believe it should be possible to achieve a balance of 1 ppm by this procedure. To achieve this precision, the length would have to be adjusted to 0.1 mm. A similar balance film could be used to improve the x balance.

We also balanced the large series-loop gradiometer at a remote site where the earth's field could be assumed to be reasonably uniform. In order to eliminate rf interference in this experiment, we enclosed the cryostat in a copper screen. We balanced the gradiometer by rotating the cryostat about the vertical x axis and adjusting the balance film for minimum response.[1] The best z balance achieved was 1 ppm. The balance was limited by ambient magnetic noise picked up in the x and y directions. In addition, after the cryostat had been rotated about the x axis through 60° in either direction and returned to its original position, the SQUID output returned to its initial value to within an amount corresponding to a balance of 1 ppm. The same result was obtained when the cryostat was rotated through 360°.

We obtained the gradient sensitivity of the balanced gradiometer by measuring its response to a known flux imbalance between the pickup loops. For a SQUID resolution of $8\times10^{-5}\phi_0\ \mathrm{Hz}^{-1/2}$, the small gradiometer had a sensitivity of $2\times10^{-12}\ \mathrm{T\,m^{-1}\,Hz^{-1/2}}$, while the large series-loop and parallel-loop gradiometers had sensitivities of 3.7×10^{-13} and $2.1\times10^{-13}\ \mathrm{T\,m^{-1}\,Hz^{-1/2}}$, respectively.

C. Analysis of characteristics

A field B_z applied to one loop of a parallel-loop gradiometer generates a current $B_z ab/(L_l+M_l)$ in the Nb strip, where a and b are the x and y dimensions and L_l is the inductance of each loop and M_l is the mutual inductance between the loops. If we neglect the gradient sensitivity of the SQUID ($<\frac{1}{2}\%$ of that of the small gradiometer), the rms gradient resolution per $(\mathrm{Hz})^{1/2}$ is

$$\Delta\left(\frac{\partial B_z}{\partial x}\right)=\frac{S_\Phi^{1/2}(L_l+M_l)}{M_l a^2 b}\ . \tag{1}$$

The measured value of M_i is 0.94 nH. From the measured flux imbalance between the loops required to produce a change ϕ_0 in the SQUID, we obtain (L_l+M_l). Using the approximation $M_l/L_l\approx b/2(a+b)$, we estimate the values of L_l and M_l for the parallel-loop gradiometers given in Table I.

The series-loop gradiometer is nearly a factor of 2 less sensitive than the parallel-loop gradiometer, as expected. However, for most applications the series-loop configuration is preferable. A major disadvantage of the parallel-loop configuration is that currents induced in the rectangular loop when it is rotated in the earth's magnetic field can be large enough to drive the loop normal momentarily. Thus, gradiometers of this configuration are suitable only for operation in a fixed position.

IV. DISCUSSION

The large parallel-loop gradiometer has a resolution of about $2\times10^{-13}\ \mathrm{T\,m^{-1}\,Hz^{-1/2}}$, about a factor of 7 poorer than the device of Wynn *et al.*[2] The lower sensitivity of the thin-film gradiometer is due to the mismatch between the SQUID inductance L and the inductance of the parallel pickup loops, approximately $\frac{1}{2}L_l$. The optimum flux transfer occurs when $M_i\approx(\frac{1}{2}LL_l)^{1/2}$. If $L\approx2.5$ nH and $L_l\approx675$ nH, the optimum value of M_i is about 30 nH, compared with the value of ~1 nH for our planar SQUID's. This mismatch reduces the sensitivity of the gradiometer by about a factor of 15 over the optimum value for the given pickup loops and SQUID sensitivity. The value of M_i could possibly be enhanced by the use of a planar spiral coil. However, it appears to be difficult to couple efficiently to the SQUID with this arrangement, and such a coil would not be easy to fabricate. An alternative means of improving the sensitivity would be to reduce the area of the junctions. If the area of the junctions were reduced to 1 $\mu\mathrm{m}^2$, an order-of-magnitude improvement in the SQUID sensitivity would be expected.[6]

A balance of 1 ppm in the z direction was readily achieved mechanically; this limit was probably set by fluctuations in the earth's field picked up in the x and y directions, which were intrinsically balanced to 100 ppm. The x and y imbalance probably arise from the distortion of the magnetic field by the overlapping films in the SQUID. An x and y imbalance of 100 ppm is consistent with our estimates of this distortion. In the case of the small gradiometer, we were able to improve the y balance to 10 ppm by means of a balance film evaporated on the edge of the substrate, with the plane of the film perpendicular to the plane of the gradiometer. It should be possible to balance the gradiometer to 1 ppm in both the x and y directions by this technique. A similar technique could also be used in the z direction, so that the gradiometer would be very stably balanced. Needless to say, this balancing procedure is tedious, as one is required to remove the gradiometer from the crystat for each adjustment. An alternative, less tedious but less stable scheme would be to adjust all

TABLE I. Parameters for small and large parallel-loop gradiometers.

	a (mm)	b (mm)	Number of ϕ_0's in one loop to produce ϕ_0 in SQUID	L_l (nH)	M_l (nH)
Small	24	16	110	86	17
Large	127	33	675	575	59

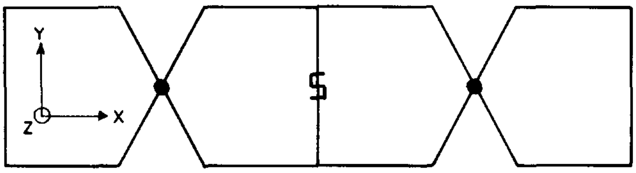

FIG. 4. Proposed second-derivative gradiometer to measure $\partial^2 B_z/\partial x^2$. The black dots indicate insulated crossovers.

three axes by means of movable films. With photolithographic masking, it should be straightforward to achieve an intrinsic balance of 100 ppm in the z direction, so that the as-made gradiometer would be balanced in all directions to about 100 ppm. The gradiometer could then be balanced adaptively, with three planar magnetometers evaporated on the same substrate, without the need for mechanical balancing.

A major concern in the design of thin-film magnetometers and gradiometers is the possible penetration of the earth's field in a direction perpendicular to the plane of the film. When the device is translated or rotated in the earth's field and returned to its original position, a slight movement of this flux may give rise to hysteresis in the output. For most applications it is essential that this hysteresis be negligible. Ideally, flux will not penetrate for fields less than a critical field of order $(t/w)B_{c1}$ for type II materials, where B_{c1} is the lower bulk critical field and t and w are the thickness and width of the film.[7] For the Pb/In films used in our devices $B_{c1} \sim 3\times10^{-2}$ T and $t/w \gtrsim \frac{1}{300}$, so that the critical field was $\lesssim 10^{-4}$ T. The critical field of the Nb film was comparable. Thus, it is probable that flux penetration occurred in both Pb/In and Nb films, especially at inhomogeneities near the edges, where the flux may penetrate at appreciably lower applied fields. There is no doubt that flux penetrated the Nb balance films, for which $t/w \sim 10^{-4}$. Despite the presence of flux penetration, there appeared to be no hystersis in the large series-loop gradiometer at the level of 1 ppm when it was rotated in the earth's field. Nevertheless, if the balance of the gradiometer were improved, it is possible that hysteresis would become apparent. The use of much narrower linewidths ($t/w \sim \frac{1}{10}$, for example) would be expected to reduce any observed hysteresis.

Our fabrication technique, which used machined masks, proved quite satisfactory in our prototype gradiometers. Nevertheless, the photolithographic masking technique would be particularly appropriate for these planar structures. Linewidths of a few μm and a high degree of symmetry should be possible. Gradiometers made in this way should have improved sensitivity, reduced flux-trapping problems, and a good initial z balance. Further, the smaller quantities of material used in the SQUID may well substantially improve the intrinsic x and y balance. The gradiometers would be almost completely resistant to damage through handling and from water vapor if they were made entirely from Nb, rather than with substantial lengths of Pb/In films. Nb-Nb tunnel junctions are particularly stable.[8]

Finally, we note that the planar geometry is adaptable to second-derivative gradiometers, as indicated in Fig. 4. This device might be very suitable for magnetocardiology and magnetoencephalography. With photolithographic masking one should be able to achieve a high degree of balance in the first derivatives, so that it should be necessary to balance only against the response to uniform field changes.

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We are grateful to Professor M. R. Beasley for a helpful discussion on flux entry in thin films, and to Dr. R. H. Clark and Dr. J. Titus for information on their gradiometers. G. B. Donaldson was supported in part by a Fulbright-Hays Fellowship during his visit to Berkeley.

APPENDIX

For certain applications, it is desirable for the SQUID to have the highest possible slewing rate. The cooled-tank circuit used to optimally match the cylindrical dc SQUID to the FET preamplifier[6] had a relatively narrow bandwidth that restricted the slewing rate to about $2\times10^4\phi_0\ \mathrm{s}^{-1}$. We have increased the slewing rate by replacing the tank circuit with a cooled resonant transformer. The transformer was made by first winding 3350 turns of 50-μm-diam insulated Nb wire on a coil former 9 mm long and 3.8 mm in diameter. This secondary coil was covered with a layer of Teflon tape. The primary consisted of 11 turns of Pb foil 75 μm thick and 1.5 mm wide in two layers, with Teflon tape separating them and protecting the final layer. The measured gain of the transformer (at 4.2 K) was 270, and the measured inductance of the secondary was 16 mH. The primary was coupled in series with the SQUID and a resistance of 0.2 Ω. The dc bias current applied to the SQUID thus divided between the SQUID and the primary coil. The leads connecting the secondary coil to the top of the cryostat had a capacitance of about 100 pF. The secondary was tuned to 100 kHz by means of a 60-pF trimmer capacitor at room temperature. The resistance of the SQUID and series resistor transformed into the secondary was typically 50 kΩ, giving a Q of about 5.

Using this transformer with a cylindrical SQUID, we obtained a 3-dB rolloff frequency of 40 kHz and a flux slewing rate of about $2.5\times10^5\phi_0\ \mathrm{s}^{-1}$ at 1 kHz. The planar SQUID's had an inductance that was a factor of 2.5 greater than that of the cylindrical SQUID's and a signal that was correspondingly smaller. The frequency response and flux slewing rate were therefore reduced by a similar factor. However, because the area of the planar magnetometer was seven times smaller than that of the cylindrical SQUID, the magnetic field slewing rate of the planar magnetometer, about $2\times10^{-4}\ \mathrm{T\,s}^{-1}$, was about three times higher.

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