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Wolfgang M. Goubreau, and John Clarke

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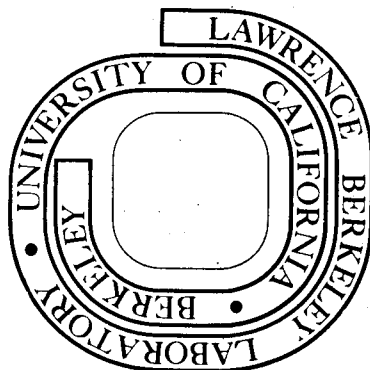
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A THIN-FILM DC SQUID GRADIOMETER

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## THIN-FILM DC SQUID GRADIOMETER

Mark B. Ketchen\*, Wolfgang M. Goubau\*, John Clarke\*,  
and Gordon B. Donaldson\*\*

## ABSTRACT

A thin-film dc SQUID gradiometer has been fabricated on a single planar substrate. The superconducting pick-up loops consist of a lead strip in the form of a  $48 \times 16$  mm rectangle with a niobium strip bisecting the rectangle. A tunnel junction dc SQUID is symmetrically located on the niobium strip. If there is a spatial gradient in the magnetic field applied to the gradiometer so that the magnetic fluxes threading the two pick-up loops differ, a supercurrent is induced in the niobium strip that is detected by the SQUID. The noise power spectrum of the SQUID is white down to a frequency of about  $5 \times 10^{-2}$  Hz with a rms flux noise of  $8 \times 10^{-5} \phi_0 \text{ Hz}^{-1/2}$ , corresponding to a gradient sensitivity of  $2 \times 10^{-10} \text{ G cm}^{-1} \text{ Hz}^{-1/2}$ .

## I. INTRODUCTION

Superconducting gradiometers<sup>1</sup> that measure time varying spatial derivatives of magnetic fields have been used for a number of years. The gradiometer consists of a superconducting flux transformer coupled to a SQUID. The flux transformer has two pick-up loops that are (in principle) balanced so that a change in a uniform magnetic field induces no supercurrent in the transformer, whereas a gradient change generates a proportional supercurrent. This supercurrent in turn produces a flux that is detected by a flux-locked SQUID. The highest sensitivity quoted in the literature appears to be that achieved by Wynn *et al.*<sup>2</sup>, about  $3 \times 10^{-12} \text{ G cm}^{-1} \text{ Hz}^{-1/2}$ , although a much higher noise level at low frequencies was observed. A balance against uniform field fluctuations and angular variation in the position of the gradiometer of 1 part in  $10^7$  was achieved by adjusting the positions of small pieces of superconductor.

Possible disadvantages of this type of gradiometer include microphonic noise, and loss of balance with thermal cycling of the device. In an attempt to overcome those problems, we have constructed and tested a prototype integrated thin-film gradiometer in which the pick-up loops and SQUID are deposited on a single substrate. The device is sensitive to off-diagonal gradient changes of the form  $\partial H_z / \partial x$ . In principle, this device should be insensitive to magnetic field changes in the plane of the pick-up loops, and should require balancing only in one dimension. Our prototype gradiometer has a length of 48 mm, and a sensitivity of about  $2 \times 10^{-10} \text{ G cm}^{-1} \text{ Hz}^{-1/2}$ . We achieve a balance of 1 part in  $10^5$  or better against uniform fields applied at right angles to the plane of the pick-up loops. The intrinsic balance (i.e. with no adjustment) against fields applied in the plane of the loops is better than 1 part in  $10^4$ . Although this preliminary design of the gradiometer clearly does not compete with state-of-the-art devices in either sensitivity or balance, we feel that larger versions based on the same principles may well do so.

In this paper, we briefly describe the fabrication and testing of the gradiometer, and give projections for the expected sensitivity and balance of a larger version.

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## II. CONFIGURATION AND FABRICATION

The configuration of the thin-film gradiometer is shown in Fig. 1. A uniform magnetic field  $H_z$  applied at right-angles to the plane of the rectangular pick-up loops produces zero current in the Nb cross-strip provided the loops are balanced. On the other hand, the application of a gradient  $\partial H_z / \partial x$  produces a proportional supercurrent in the Nb strip that is detected by the planar dc SQUID. Details of the SQUID are shown in Fig. 2.

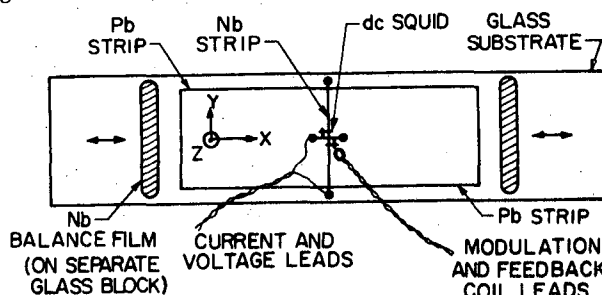


Fig. 1. Configuration of thin-film gradiometer.

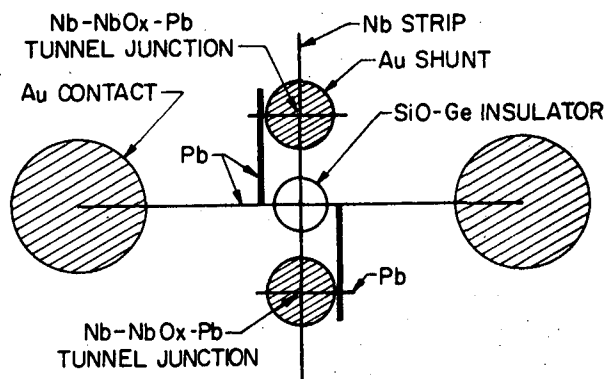


Fig. 2. Configuration of planar dc SQUID.

The gradiometer is constructed as follows. A Pb/In (5% wt. In) strip 150  $\mu\text{m}$  wide and 0.5  $\mu\text{m}$  thick is evaporated as a  $48 \times 16$  mm rectangle on an  $89 \times 21 \times 12$  mm pyrex substrate. Next, 0.01  $\mu\text{m}$  thick Au shunts (for the tunnel junctions) and contacts are evaporated. A niobium strip 100  $\mu\text{m}$  wide and 0.3  $\mu\text{m}$  thick is then sputtered; the Nb makes superconducting contacts with the Pb/In strips. The niobium is thermally oxidized. Two tunnel junctions are formed by evaporating two 50  $\mu\text{m}$  wide Pb/In cross strips 1.9 mm apart over the Nb film and the Au shunts. An insulating disk, consisting of a 0.1  $\mu\text{m}$  thick film of SiO with a 0.05  $\mu\text{m}$  thick overlay of Ge is evaporated over the mid-point of the Nb strip. The SQUID is completed by evaporating the remaining Pb/In strips as shown in Fig. 2. The finished gradiometer is coated with a thin layer of Duco cement to protect the metal films from moisture.

The gradiometer is balanced along the x-axis by moving two pyrex blocks onto each of which has been sputtered a 0.3  $\mu\text{m}$  thick Nb film. The Nb films are pressed against the substrate on which the gradiometer is fabricated, so that the gradiometer and balancing films are as co-planar as possible. The gradiometer substrate is mounted vertically on a fiberglass dewar insert, and the balancing blocks are assembled on a

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carriage that can be moved by a differential screw arrangement operated from outside the cryostat. The insert is mounted in a fiberglass cryostat, with the gradiometer directly immersed in liquid helium.

### III. SQUID OPERATION AND PERFORMANCE

The configuration of the planar SQUID is such that ideally it does not respond to uniform magnetic fields. The critical current,  $I_c$ , of both junctions is typically 2 to 5  $\mu$ A, and the resistance of the two shunted junctions is typically 0.3  $\Omega$ . The hysteresis parameter  $\beta_c$  is not greater than 0.25, so that the current-voltage characteristics are non-hysteretic. The mutual inductance,  $M_1$ , between the Nb strip and the SQUID is measured to be approximately 1 nH, while the SQUID inductance,  $L$ , is estimated to be 2.5 nH.

Copper leads are attached to the SQUID by means of indium contacts, as shown in Fig. 1. A 10-turn copper coil attached to the substrate near one of the SQUID loops is used to apply the ac-modulation and feedback fluxes. The SQUID is operated as a null-detector in a feedback circuit using the same electronics as is used with cylindrical dc SQUIDs<sup>4</sup>. The SQUID is current-biased at a voltage of  $\sim 1$   $\mu$ V. A 100 kHz modulation flux of peak-to-peak amplitude  $\approx \phi_0/2$  is applied to the SQUID via the copper coil. Any 100 kHz voltage developed across the SQUID is amplified by a cooled resonant circuit. (The tank coil is wound of copper wire rather than of superconducting wire, which would distort low-frequency magnetic fields applied to the gradiometer.) The 100 kHz signal from the tank circuit is amplified, lock-in detected, integrated, and fed back as a current into the 10-turn coil to cancel changes in the applied flux.

We have measured the flux noise power spectrum of planar SQUIDs with the gradiometer loops removed. A typical power spectrum,  $S_\phi$ , is shown in Fig. 3. The spectrum was obtained with the SQUID mounted inside a

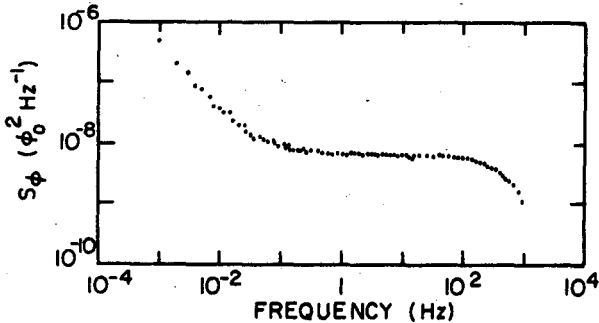


Fig. 3. Noise power spectrum of a planar dc SQUID.

superconducting Pb shield. An identical spectrum was obtained without the Pb shield but with three concentric  $\mu$ -metal cans around the cryostat. In both cases, the SQUID was immersed directly in liquid helium at 4.2 K with no temperature regulation. The noise power spectrum closely resembles that obtained from cylindrical dc SQUIDs<sup>4</sup>. The spectrum is nearly white from the high-frequency roll-off of the electronics ( $\sim 100$  Hz in this case) down to  $5 \times 10^{-2}$  Hz, where  $1/f$  noise becomes significant. The rms flux noise in the white noise region is about  $8 \times 10^{-5} \phi_0 \text{ Hz}^{-1/2}$ . (Theoretically, the rms flux noise scales as  $L$ : It is interesting to note that the inductance and the rms noise of the planar dc SQUID are both approximately 2.5 times greater than the inductance and rms noise of the cylindrical dc SQUID<sup>4</sup>.)

The planar SQUID can be operated in the earth's magnetic field without shielding. If the SQUID is rotated in any direction, it continues to function without adjustment of the bias current, although changes in critical current ( $\approx 10\%$ ) may occur.

### IV. GRADIOMETER PERFORMANCE

Each gradiometer is tested by placing it at the center of a 1.1 m diameter, single-turn Helmholtz pair of coils. A magnetic field at a few Hz with a peak-to-peak amplitude of  $\sim 5$  mG is applied to the gradiometer. The gradiometer is first mounted so that this field is in the z-direction, perpendicular to the plane of the pick-up loops. The ac-signal from the flux-locked gradiometer is lock-in detected. The position of the Nb balance films is adjusted to balance the gradiometer in the x-direction. A balance of 1 part in  $10^5$  is readily obtainable. The Helmholtz coils are then rotated through approximately  $90^\circ$ . In this position, we determine the "parallel rejection", defined as the change in the SQUID signal produced by the application of a field parallel to the plane of the gradiometer divided by the change in signal produced by the same field applied in the z-direction to one of the pick-up loops. The parallel rejection is a measure of the departure of the gradiometer from a planar structure. We find that the parallel rejection is  $\approx 10^{-4}$ . This limit is thought to be set by distortion introduced by overlapping films in the SQUID, by irregularities in the surface of the substrate (which was not optically polished), or by spatial inhomogeneities in the applied magnetic field.

We calibrated the balanced gradiometer by applying a known gradient that was produced by a current in a long straight wire parallel to the y-axis, co-planar with the gradiometer, and 0.5 m from it. The measured response of the gradiometer together with the flux resolution of the planar SQUID implies a gradient sensitivity of  $2 \times 10^{-10} \text{ G cm}^{-1} \text{ Hz}^{-1/2}$ . We also determined that a flux change of  $109 \phi_0$  in one of the pick-up loops is required to produce a flux change of  $\phi_0$  in the SQUID.

### V. DISCUSSION

It can be shown that the rms gradient resolution per  $\text{Hz}^{1/2}$  for uniform gradient changes in the x-direction is given by

$$\Delta(\partial H_z / \partial x) \approx S_\phi^{1/2} (L_\ell + M_\ell) / M_1 a^2 b \quad (1)$$

In Eq. (1),  $L_\ell$  is the inductance of one pick-up loop,  $M_\ell$  is the mutual inductance between the pick-up loops, and  $a$  and  $b$  are, respectively, the x- and y-dimensions of one of the pick-up loops. If we assume that  $M_\ell / L_\ell \approx b / 2(a + b)$ , the fact that  $109 \phi_0$  in one pick-up loop generates a flux  $\phi_0$  in the SQUID leads us to estimate  $L_\ell \approx 86$  nH and  $M_\ell \approx 17$  nH. Thus, the gradient resolution scales very roughly as  $L_\ell / a^2 b$  for constant  $S_\phi / M_1$ .

We are now constructing a larger thin-film gradiometer that is about five times longer and twice as wide as the present version. We anticipate a gradient sensitivity of  $2 \times 10^{-11} \text{ G cm}^{-1} \text{ Hz}^{-1/2}$  or better. This gradiometer is deposited on an optically polished quartz substrate and should have a significantly better parallel rejection. Closer dimensional tolerances will reduce the dynamic range required of the balancing mechanism, and should improve the balance achieved. Ultimately, it may be possible to obtain a permanent high degree of balance and parallel rejection by the careful trimming of small strips of superconducting film deposited on the substrate.

It should be noted that the planar SQUID is not optimally matched to the pick-up loops. A further increase in sensitivity may be possible by coupling the SQUID to the pick-up loops using a planar coil of several turns. The flux sensitivity may also be improved by increasing the resolution of the dc SQUID. The rms flux resolution in the white noise region is limited by Johnson noise in the resistive shunts, and scales<sup>4</sup> as  $R^{-1/2}$ . The upper limit on  $R$  is set by the requirement<sup>3</sup>  $4\pi I_c R^2 C / \phi_0 \ll 1$ , where  $C$  is the capaci-

tance of one of the tunnel junctions. If  $C$  can be reduced by reducing the area of the tunnel junctions,  $R$  can be correspondingly increased. If the junction dimensions were reduced to  $10\text{ }\mu\text{m}$  square, we estimate that the resolution of the SQUID would be increased by a factor of 3.

In our measurements on the small-scale gradiometer, we have not observed any additional noise that can be ascribed to the pinning of flux in the thin films and its subsequent motion. However, it is possible that flux motion could limit the ultimate sensitivity of the thin film gradiometer, and a careful study of this effect will be made.

#### ACKNOWLEDGEMENTS

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