Thin-Film Planar Gradiometer with Long Baseline

Robin Cantor¹, Ad Hall¹ and Andrei Matlachov²

¹ STAR Cryoelectronics, 25-A Bisbee Court, Santa Fe, NM 87508 USA
² Los Alamos National Laboratory, Biological and Quantum Physics Group P-21, MS-D454, Los Alamos, NM 87545 USA

Email: rcantor@starcryo.com

Abstract. Gradiometers are attractive for magnetic field measurements in noisy environments. Thin-film planar gradiometers are in particular attractive for measurements of the off-diagonal components of the magnetic field gradient tensor, and they can be fabricated with high intrinsic balance owing to the precision photolithographic techniques used to fabricate these devices. We have developed a low-\(T_c\) first-order planar gradiometer with a long baseline of 4 cm. The pickup loops are series configured and connected to the input circuit of a dual washer gradiometric dc SQUID. The white rms flux noise measured in a shielded environment is 1.6 \(\mu\Phi_0/\text{Hz}^{1/2}\). The magnetic field sensitivity referred to one pickup loop is 2 nT/\(\Phi_0\), resulting in an rms magnetic field noise referred to one pickup loop of 3.2 \(\text{fT/Hz}^{1/2}\) and an rms gradient noise of 0.8 \(\text{fT/cm-Hz}^{1/2}\). Based on the lithographic methods used to fabricate the gradiometers, the expected balance level is 1 part in 24,000 or 0.004%. The gradiometer is operable without shielding in typical laboratory environments without losing lock, with an rms white noise at 10 kHz of 3.5 \(\mu\Phi_0/\text{Hz}^{1/2}\).

1. Introduction

The first thin-film planar gradiometers were demonstrated in 1976 by Ketchen et al.¹ These first designs consisted of parallel- or series-configured pickup loops directly coupled to the SQUID inductance. The overall dimensions of these devices were 1.5 cm \(\times\) 5 cm, and the best gradient noise performance exhibited by a parallel-loop gradiometer was 20 \(\text{fT/cm-Hz}^{1/2}\). The development of efficient planar coupling schemes² for dc SQUIDs in 1981 led to the development of improved thin-film planar gradiometers with an intrinsic balance of better than 1 part in 10,000 and a projected factor of 100 improvement of the magnetic field gradient noise sensitivity for a planar gradiometer with 4 cm baseline. For applications requiring sensitivity to deep-lying sources (e.g., magnetocardiography), a long baseline design is desirable. Several other planar gradiometers were described in the 1980’s³,⁴,⁵ and early 1990’s⁶ but all of these designs were much smaller with baselines of less than 2 cm.

More recently, Stolz et al.⁷ reported a planar gradiometer design with long, 4-cm baseline. These devices were designed using two 2 cm \(\times\) 2 cm series-configured pickup loops transformer coupled to a thin-film SQUID. The magnetic field gradient noise ranged from 0.36 to 0.72 \(\text{fT/cm-Hz}^{1/2}\) with an intrinsic balance in the range from 10⁻² to 10⁻¹.

We describe here a similar long-baseline planar gradiometer that features contact pad placement at the ends of the chip rather than in the middle along the longer edge of the chip, which simplifies installation for practical applications. The gradiometers are packaged in a fiberglass epoxy assembly that improves handling. The gradiometer design, fabrication, package and test results are described in the following sections.
2. Planar Gradiometer Design

The gradiometer design consists of two 7.0 mm × 11.75 mm OD pickup loops configured in series and inductively coupled to a parallel-configured dual-washer, dc SQUID. The SQUID and pickup loop parameters are summarized in table 1. The nominal chip size is 12 mm × 48 mm, and the baseline is 40.75 mm.

To symmetrize the biasing of the SQUID with parallel-configured washers, the bias current is injected through two resistors that also serve as damping resistors across the SQUID inductance. In this way, there is very little coupling between the bias circuit and the SQUID.

The contact pads for the SQUID bias and voltage out (one pair) and for the feedback coils (two each symmetrically located in each pickup loop) are located at the end of the chip. A dummy SQUID, feedback loops, and contact pads are located symmetrically at the opposite end of the chip in order to improve symmetry and balance.

| Parameter                      | Value                                      |
|--------------------------------|--------------------------------------------|
| Chip Size                      | 12 mm × 48 mm (nom.)                       |
| Wire bond pads                 |                                            |
|       Bias/Voltage, Mod./Feedback (2 sets) | Six pads, 200 µm × 200 µm each            |
| Pickup coil OD                | 7.0 mm × 11.75 mm                         |
| Pickup coil inductance \( L_p \), configuration | 58.5 nH, series-configured                |
| Pickup coil effective area \( A_p \) | 73.9 mm²                                 |
| Baseline                      | 40.75 mm                                   |
| SQUID type                     | First-order gradiometric, parallel-configured |
| SQUID inductance \( L \)       | 62.8 pH                                    |
| Input inductance \( L_i \)     | 105 nH                                     |
| SQUID critical current \( 2I_c \) | 77 µA                                     |
| SQUID resistance \( R/2 \)     | 0.5 Ω                                      |
| Damping Resistor \( R/2 \)     | 1 Ω                                        |
| \( \beta = 2LI/\Phi_0 \)      | 2.3                                        |
| \( \beta_c = 2\pi I R^2 C/\Phi_0 \) | 0.5                                      |
| Modulation/Feedback coil coupling \( 1/M_f \) | 18 µA/\(\Phi_0\)                      |
| Voltage swing \( \Delta V \)   | 45 µV                                      |
| Transfer coefficient \( \partial V/\partial \Phi \) | 250 µV/\(\Phi_0\)                   |
| Field sensitivity \( B_\Phi = \Phi_0/A_{eff} \) | 2 nT/\(\Phi_0\)                         |
| Flux noise \( S_\Phi^{1/2} (f), f > 10 \text{ Hz} \) | 1.6 µΦ/Hz²                                 |
| Field noise \( S_B^{1/2} (f), f > 10 \text{ Hz} \) | 3.2 fT/Hz²                                 |

3. Fabrication

The gradiometers are fabricated using a six-layer Nb/Al-AlO/Nb trilayer Josephson junction process described elsewhere. To improve handling and reduce sensitivity to damage caused by electrostatic discharge (ESD), the final process step is the deposition of a doped Si layer that is conductive at room temperature but completely insulating at typical operating temperatures (e.g., 4 K). The gradiometers are currently fabricated on 100-mm Si wafers; to increase device yield per wafer, this process is being transitioned to 150-mm wafers, which will enable 20 gradiometers to be fabricated per wafer.

4. Results

The dc characteristics of the gradiometer are shown in figures 1 and 2. The current-voltage \((I-V)\) characteristics exhibit a linear portion for bias currents below the SQUID critical current owing to the two symmetric resistors in the bias circuit. The voltage-flux characteristic \((V-\Phi)\) at the nominal
working point is very smooth and free of resonances, which simplifies tuning and improves gradiometer performance.

The gradiometers are mounted on standard FR-4 printed circuit boards and are protected with a fiberglass epoxy cover that is glued to the board. Contact pads for electrical connections are located at the end of the package assembly. A photograph of the gradiometer chip and package assembly is shown in figure 3.

The gradiometers were operated in locked-loop mode using standard PC-based readout electronics. The intrinsic noise was measured with the gradiometers shielded inside a Cryoperm10 can with a Pb foil can insert. All measurements were carried out at 4 K in liquid helium. The rms white flux noise at 1 kHz was measured to be 1.6 \( \mu \Phi_0/\text{Hz}^{1/2} \). A plot of the rms flux noise is shown in figure 4. The field sensitivity with respect to one pickup loop was measured by coupling a test signal to the gradiometer using a small co-planar coil that could be placed axially at three locations below the gradiometer outside the dewar. The measured field sensitivity was 1.2 \( \text{nT}/\Phi_0 \) referred to a single pickup loop; based on the gradiometer geometry and calculated SQUID parameters, which were confirmed through separate experiments, however, the projected field sensitivity is 2 \( \text{nT}/\Phi_0 \). The reason for this discrepancy is not clear, and further tests are underway to more accurately measure and confirm the field sensitivity. Using the calculated field sensitivity, the rms magnetic field noise is 3.2 \( \text{fT/Hz}^{1/2} \). The long, 4.075 cm baseline then gives a magnetic field gradient sensitivity of 0.8 \( \text{fT/cm-Hz}^{1/2} \).

The gradiometer could easily be operated without magnetic shielding in a typical laboratory environment without losing lock. For these measurements, Mylar film with a thin Au coating was used for rf shielding only. At 10 kHz, the rms white flux noise was 3.5 \( \mu \Phi_0/\text{Hz}^{1/2} \), only a factor of two higher than measured inside a well-shielded environment.

A rough determination of the gradiometer balance was made by measuring the magnitude of the 60 Hz power line signal present in the laboratory with the gradiometer and comparing this with the magnitude of this signal measured separately using a magnetometer. These measurements suggest that the balance level is better than 1 part in 1000. Based on the accuracy of the photolithographic processes used to fabricate the gradiometers, however, the intrinsic balance is projected to be better than 1 part in 24,000 or 0.004%.

Figure 1. Current-voltage characteristic (100 \( \mu \text{A}/\text{div vertical}, 100 \mu \text{V}/\text{div horizontal} \)). The linear part of the trace for bias current below the SQUID critical current is due to the matched resistors in the bias circuit.

Figure 2. Voltage flux characteristic at the nominal SQUID working point (10 \( \mu \text{A}/\text{div vertical}, 10 \mu \text{V}/\text{div horizontal} \)).
Summary
We have developed a thin-film planar dc SQUID gradiometer with 4 cm baseline. The gradiometer features smooth dc characteristics, low-noise performance and can be operated without shielding in typical laboratory environments without losing lock. Gradiometers of this type are attractive for biomedical imaging and other applications requiring low-noise measurements in noisy environments.

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