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SQUID Current Sensor With Differential Output

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***Abstract*—We have developed a superconducting quantum interference device with differential output (diffSQUID). The device concept aims at improving the operability of SQUID current sensors in the presence of large common-mode signals. The diffSQUID is based on a series connection of two identical SQUID sensors. The biasing and input signal coupling provides for the differential output signal. The diffSQUID is read out by a fully differential amplifier. A compact, low-power and low-noise differential amplifier has been developed for this purpose. This amplifier is partially powered via the diffSQUID's combined bias and output signal leads and can be operated at temperatures between 77 K and 300 K.**

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I. INTRODUCTION

Superconducting quantum interference devices (SQUIDs) [1] are sensitive detectors of magnetic flux. They are used for precision measurements of physical quantities, for example magnetic flux density, mechanical displacement, or temperature. Another prominent application of SQUIDs is current sensing, in particular the readout of low-impedance detectors operated at low (<4.2 K) temperatures, such as superconducting transition-edge sensor (TES) bolometers and micro-calorimeters [2]. Transforming the TES current to be measured into magnetic flux threading the SQUID is done by means of an input coil which inductively couples to the SQUID loop. State-of-the-art SQUID current sensors for TES readout have integrated, photo-lithographically defined input coils that realize a well defined input signal coupling. Also, the concepts of SQUID series arrays [3], parallel arrays, or combinations thereof [4] are applied in order to benefit from the increased dynamic range that SQUID arrays offer in comparison to single SQUID current sensors. Moreover, using highly gradiometric, narrow-line design, SQUID array current sensors can realized that are "single-SQUID-like" in their ease-of-use as well as to a high degree insensitive to parasitic signals from background magnetic fields [5].

The use of SQUID sensors can be severely complicated in measurement setups where large common-mode (CM) interference, also called "structure noise" [6], is present. Such CM interference is associated with a significant potential difference along the SQUID output leads. It manifests itself as a CM voltage superimposed onto the SQUID output signal. This CM voltage is present at both output leads and can be non-negligible compared to the small output signal levels of SQUIDs. For Niobium-based, single SQUIDs tens of μV and for SQUID arrays of moderate lengths hundreds of μV are typical output signals.

CM interference is likely to occur in measurement setups that involve nearby sources of electromagnetic interference (EMI), for instance in nowadays widely used cryocooler setups. Furthermore, physically remote system grounds due to long wiring between the SQUID sensor and its readout can be detrimental in the effort to avoid CM interference. In order to comply with cooling power conditions, long and comparably high-resistance wiring may be necessary for low-temperature refrigerator setups. An example for an instrument configuration that sets particularly stringent requirements with respect to immunity to CM interference is the SpicA FAR-infrared Instrument (SAFARI) currently under development [7]. The SAFARI detector system will employ TES bolometers with unprecedented sensitivity read out by SQUID current sensors. The preliminary design of the SAFARI detector system [8] foresees an ≈7 m long wiring (≈60 Ω per lead) between the output of SQUID sensors at temperatures <1.7 K and a low-noise amplifier at 136 K. The amplifier will be used to overcome losses in the cabling to the warm electronics, ≈7 m in length as well.

In order to make its operation more robust against large CM signals we have developed a SQUID current sensor with a differential output (diffSQUID). In the following we describe the diffSQUID concept, results of proof-of-principle experiments and a fully differential low-noise amplifier (LNA) developed to read out the diffSQUID.

II. DIFFSQUID CURRENT SENSOR

Figure 1 depicts the basic principle of a diffSQUID current sensor. Single dc SQUIDs are shown (circles with two crosses indicating the Josephson junctions), but any type of SQUID or SQUID series/parallel arrays may be used. In Figure 1(a), a conventional SQUID configuration is shown. The SQUID is biased at a working point W by sending a bias current $I_{B,SQ}$ through the device and applying a bias flux Φ_B via a separate bias/feedback coil. The input current is sent through an input coil which is coupled to the SQUID via a mutual inductance M_{In} to create the input flux Φ_{In}. Commonly, the SQUID voltage V is transferred to the preamplifier via a long cable. This cable may pick up EMI, which is directly superposed to the signal or affects the signal by mixing. In any case, the output of the amplifier might show a severe distortion caused by EMI.

In Figure 1(b), a second, identical SQUID setup is added. The second SQUID B is biased at the same working point $I_{B,SQ}$ and Φ_B as the first SQUID A, but the input current is sent through the input coil with reversed polarity. Therefore, the polarity of the input flux and of the resulting output signal V_{Out} is reversed. In contrast, EMI creates the same output as before if both cables pick up the same interference (common-mode distortion). Finally, as shown in Figure 1(c), if both SQUIDs A and B are combined and connected to a difference amplifier, the effect of EMI is suppressed at the amplifier output while the signal passes without distortion.

To achieve maximum EMI suppression, the diffSQUID setup should exhibit a high degree of symmetry. As the outputs of both SQUIDs A and B have the same impedance, a twisted pair can be driven with a high common-mode rejection ratio (CMRR) up to high frequencies. Note that the effects of background magnetic fields and of temperature fluctuations are also suppressed by the diffSQUID configuration.

A differential structure similar to the diffSQUID has been suggested recently to increase the linearity of high-frequency amplifiers based on the superconducting quantum interference filter (SQIF) [9]. In this scheme, the input flux is applied to all SQUIDs with the same polarity, but the devices are flux biased at different slopes of the V-Φ_{In} characteristic in order to obtain transfer coefficients $V_\Phi \equiv \partial V/\partial\Phi_{In}$ with opposite polarity. This way, even harmonics are removed if the SQUIDs are symmetric. In the diffSQUID scheme, these harmonics are suppressed even if the individual SQUIDs exhibit a systematic asymmetry because all devices are operated at the same working point.

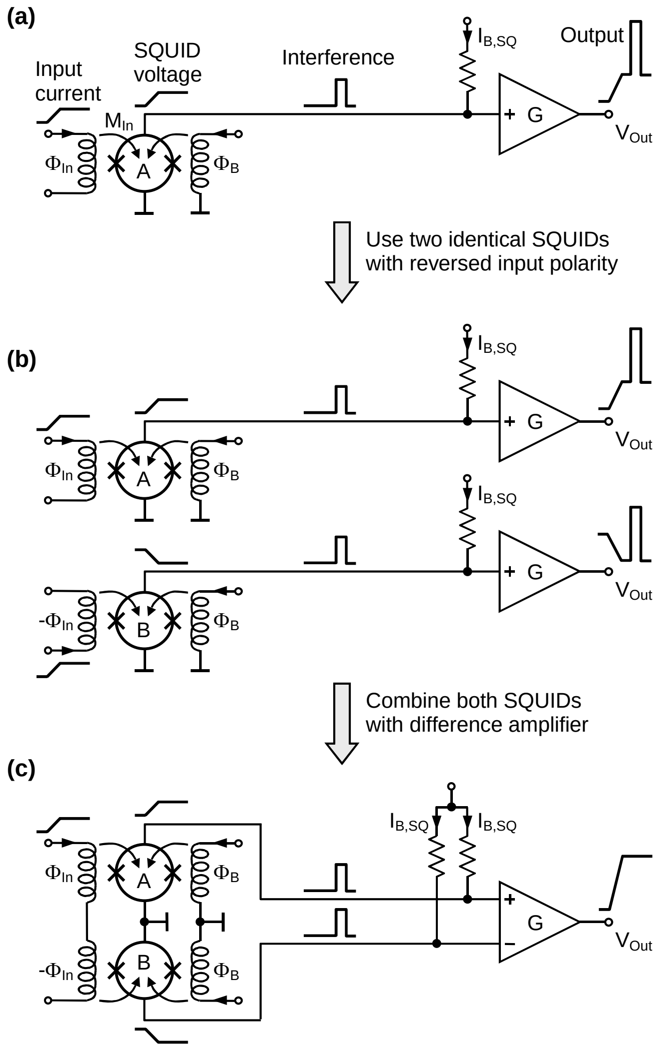

Fig 1. Basic principle of a diffSQUID current sensor. The merging of conventional dc SQUID setups into a diffSQUID configuration is shown from (a) to (c). The SQUIDs are drawn as circles with two crosses indicating the Josephson junctions. Both devices A and B are identical, and are operated at the same bias current $I_{B,SQ}$ and bias flux Φ_B. Details are omitted for clarity.

A proof-of-principle was performed by wiring two identical 16-SQUID series arrays according to Figure 1(c). The arrays were integrated into a common chip which results in a good parameter matching [5]. The readout was done with a Magnicon XXF-1 electronics switched into the “AMP mode” [10] thus acting as a low-noise difference amplifier with a voltage gain G = 2000. With this setup, correct diffSQUID function was obtained both when the SQUIDs were operated in liquid helium (T = 4.2 K) and in a dilution refrigerator ($T \approx$ 10 mK). The resulting V-Φ_{In} characteristics (Fig. 2) were in good agreement with expectation.

Figure 2(a) illustrates how the transfer characteristic of the diffSQUID results from the characteristics of the two arrays A and B. To characterize these arrays separately, the bias current of the respective other array was set to zero. For this measurement, two XXF-1 channels were used according to Fig. 1(b) in order to enable separate biasing of array A and B.

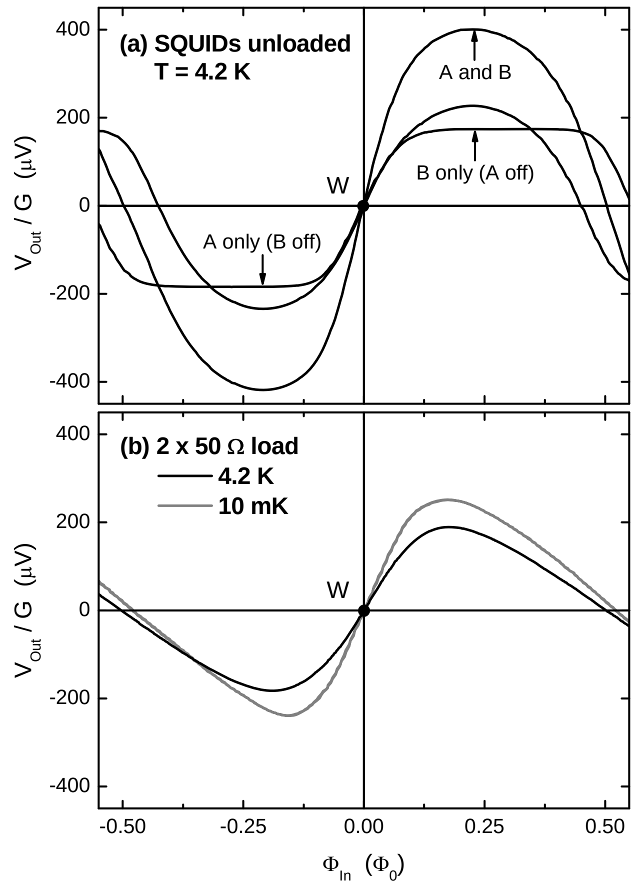

Fig 2. Transfer characteristics of a diffSQUID consisting of two 16-SQUID series arrays (a) without load and (b) with a ≈50 Ω load at each output. The devices were operated in liquid helium (black lines) or in a dilution refrigerator at $T \approx 10$ mK (gray line). For comparison, the unloaded, individual characteristics of the diffSQUID halves A and B are also shown (cf. Fig. 1(c)).

Figure 2(b) depicts the "loaded" transfer characteristics of the diffSQUID, i.e., with a ≈50 Ω load resistor at each array output. With load, the peak-to-peak voltage swing at 4.2 K is reduced from 820 μV to 370 μV. Note that the asymmetry in the loaded transfer characteristic is intended. It is realized by implementing asymmetric bias current feed in our SQUID design, which steepens the loaded transfer characteristic at one slope while flattening it at the other slope [11]. As a result, the transfer coefficient of the loaded characteristic is increased compared to the symmetric case, and the amplifier noise contribution is reduced.

An effective diffSQUID configuration requires nearly identical V-Φ_{In} characteristics of its two halves, i.e, all single SQUIDs should feature the same junction parameters and uniform input coupling. These requirements are met by niobium-based state-of-the-art SQUID series arrays with single-SQUID-like behavior [5].

III. LOW-POWER LNA

To read out the diffSQUID, we have developed a compact, low-power LNA with fully differential inputs and outputs (Figure 3). The amplifier can be operated between 77 K and room temperature. It is implemented on a single-sided printed-circuit board and occupies 11 mm × 18 mm board space per channel. The SQUID bias current $I_{B,SQ}$ is passed through the LNA in order to minimize the wire count. An extra control unit placed at room temperature generates an amplifier bias current $I_{B,Amp}$. This current is divided into two equal parts and superposed to $I_{B,SQ}$ to adjust the quiescent current of the bipolar transistors in the LNA. Only one bias line is required per LNA channel, thus making the amplifier well suited for multi-channel applications.

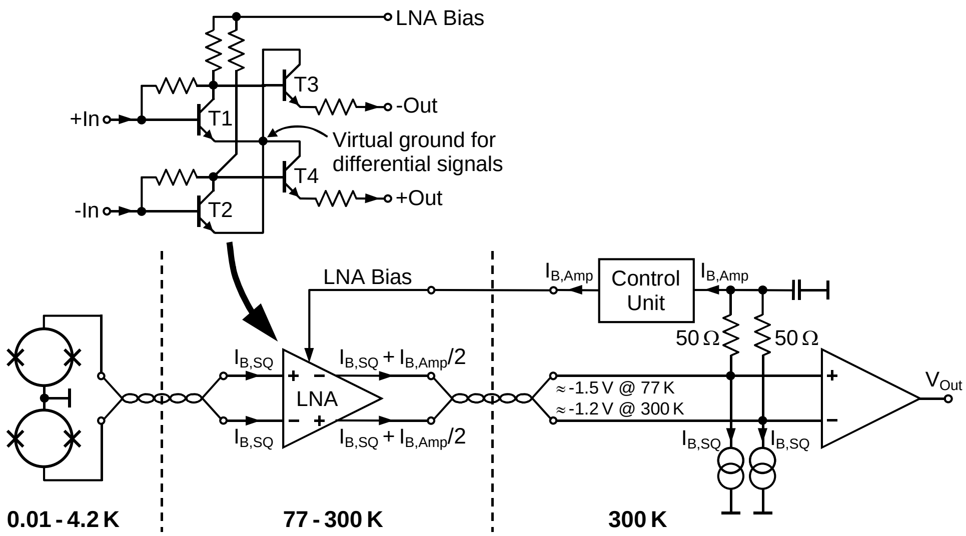

Fig 3. Basic schematic diagram of the low-power LNA. The diffSQUID is indicated by two single SQUID loops. The bias current $I_{B,SQ}$ is passed through the LNA. One bias line per LNA is required to adjust the quiescent current of the tansistors T1-T4 for minimum temperature dependence of the amplifier gain. The quoted currents and voltages apply for zero SQUID output. Circuit details (e.g., SQUID input/feedback coils or extra rf filters) are omitted for clarity.

In order to meet the stringent power limits of the SAFARI detector system (2 mW per LNA at 136 K) a special amplifier design was developed. A two-stage setup was implemented to obtain sufficiently high voltage gain and low output resistance. Basically, the amplifier consists of a differential, common-emitter transistor pair T1, T2 providing a voltage gain of about 17, followed by emitter followers T3, T4 acting as buffers (cf. Fig. 3). In contrast to a conventional design, the collectors of the emitter followers are not connected to a positive power supply, but to the emitters of the differential input stage. This point has a low impedance for differential input signals, i.e., it represents a virtual ground. Due to this connection, the quiescent current of the input differential stage T1, T2 is passed through the buffer transistors T3, T4. In other words, the buffer transistors are used as a current source for the differential stage.

Due to the special amplifier design, the bipolar transistors are biased at collector-emitter voltages V_{CE} of about half the base-emitter voltage V_{BE}, i.e., not as far away from the saturation region as commonly. However, for collector currents below about 1 mA considered here, operation of low-noise bipolar transistors at $V_{CE} \approx V_{BE}/2$ is possible without significant loss in performance. On the other hand, the low collector-emitter voltages combined with the "collector current sharing" described above leads to the minimum possible power dissipation for a bipolar two-stage amplifier. Typically, the LNA power was kept below 1 mW at 77 K or 3 mW at 300 K, respectively. Note that the temperature dependence of the power dissipation is intended. It is realized by a proper adjustment of the LNA bias current $I_{B,Amp}$ and results in a minimum temperature dependence of the amplifier voltage gain. We adjusted the bias current to obtain equal gains at 77 K and room temperature. During cycling, the gain changed by a few % only.

To pass the SQUID bias current $I_{B,SQ}$ through the LNA, resistors are required between collector and base of the input transistors T1, T2. These resistors have to be selected such that $I_{B,SQ}$ creates a voltage drop of about half the base-voltage of the employed transistors. We used a resistance of 3 kΩ for a projected $I_{B,SQ} \approx 150$ μA. Due to these resistors and the negative gain of the input stage, the differential input resistance is lowered to about 2×160 Ω, which helps to damp cable resonances. Series resistors are connected to the emitters of the output buffers T3, T4 to obtain an output impedance of 2×65 Ω compatible with the characteristic impedance of a twisted pair.

For the transistors T1-T4, we selected the BFP650 from Infineon [12]. This type has been successfully used for cryogenic amplifiers operated at 4.2 K [5], [13]. We tested the LNA with two 60 Ω resistors at the inputs to simulate the diffSQUID's output impedance. A high bandwidth of about 40 MHz was found. A CMRR of >70 dB was observed in the frequency range of 30 kHz to 3 MHz with the LNA operated at room temperature.

The amplifier noise was measured both at room temperature and with the LNA immersed in liquid nitrogen (Figure 4). We first tested the circuit with transistors from an "old" batch (date code 71, production year 2007). At 300 K, a white noise level of 1 nV/√Hz and a 1/*f* corner well below 100 Hz were obtained at a power of 1.9 mW. When cooling the amplifier to 77 K, the white noise dropped to ≈0.5 nV/√Hz and the power to 0.6 mW; the 1/*f* noise remained practically unchanged.

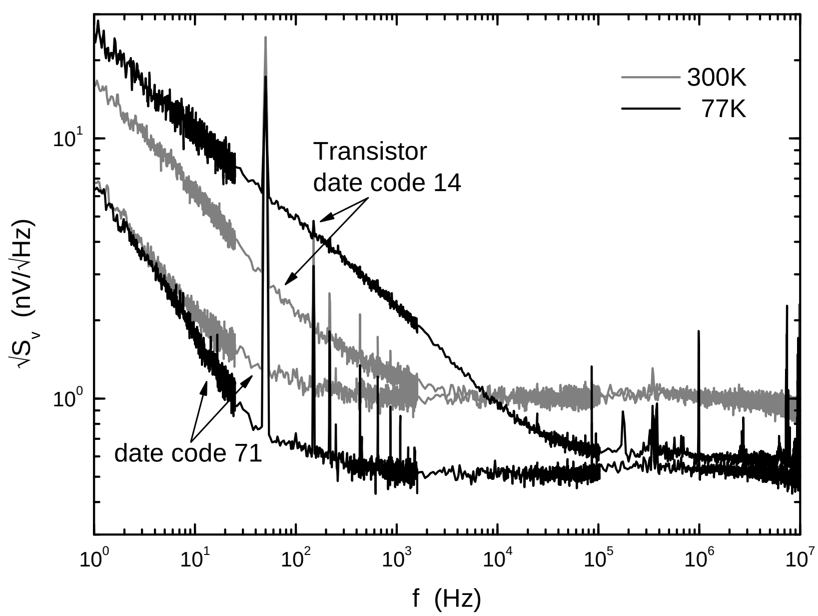

Fig 4. Total noise of the LNA operated at 77 K (black lines) or 300 K (gray lines) measured with BFP650 transistors produced in 2007 (date code 71) or 2011 (date code 14), respectively. The amplifier inputs were shunted by 60 Ω resistors to simulate a diffSQUID consisting of 2×320 SQUIDs. The spectra are corrected for Nyquist noise in the source resistors.

When switching to transistors from a "new" batch (date code 14, production year 2011), we observed a slight reduction in the gain accompanied by a corresponding increase in the white noise level. At low frequencies, however, the noise increased strongly compared to the "old" batch, in particular at 77 K (cf. Fig. 4). To keep the gain and the white noise at a similar level as before, we had to increase the collector current, resulting in power levels of 1 mW at 77 K and 2.7 mW at 300 K, respectively. We performed room temperature tests on a series of BFP650 transistors ordered from different distributors over the past years. Samples produced in 2007 exhibited a low 1/*f* noise, whereas those from 2010-2011 showed a degraded noise performance. Nevertheless, for high-frequency applications above about 100 kHz the BFP650 is a good choice due to its low voltage noise and high bandwidth.

IV. CONCLUSION

We have proposed a SQUID with differential output to improve the EMI hardness of current sensors in harsh cryogenic environments. The diffSQUID is well suited for the output stage of two-stage SQUID setups. Proof-of-principle experiments were performed by wiring two separate 16-SQUID series arrays as a diffSQUID. As a next step, we plan to realize a fully integrated diffSQUID line driver consisting of 2×320 SQUIDs. The design will be adapted from the 640-SQUID output stage of our two-stage current sensor with output current feedback [4]. A peak-to-peak output drive of ≈3 mV into a 2×50 Ω load is projected. If necessary, our low-power LNA can be used at a low-temperature stage to further boost the signal. This way, the SQUID output can be transmitted over very long distances with minimal signal distortion. The combination of the diffSQUID line driver at <1.7 K with the LNA at 136 K is compatible with the SAFARI system design.

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