Dc-SQUID Readout with High Dynamic Range and Intrinsic MHz Frequency-Division Multiplexing Capability

Daniel Richter*, Andreas Fleischmann*, Christian Enss*, and Sebastian Kempf*
* Kirchhoff-Institute for Physics
Heidelberg University
Heidelberg, Germany
Email: sebastian.kempf@kip.uni-heidelberg.de

***Abstract*—We present a novel dc-SQUID readout scheme that provides linearization of the relation between the input and output signal without using a conventional flux-locked loop circuit. It relies on applying a periodic, sawtooth-shaped magnetic flux signal to the modulation coil of the SQUID to continuously measure the flux-to-voltage SQUID characteristic within each period of the flux ramp. In case that the amplitude and repetition rate of the ramp are chosen such that multiple flux quanta are induced in the SQUID and that the input signal is quasi-static within one period of the flux ramp, the input signal adds a constant magnetic flux offset to the SQUID that leads to a phase shift of the SQUID characteristic being proportional to the input signal. We show that this scheme allows for significantly increasing the dynamic range and that it intrinsically allows for MHz frequency-division SQUID multiplexing.**

***Index Terms*—SQUIDs, linearization techniques, dynamic range, frequency division multiplexing**

I. Introduction

Direct-current superconducting quantum interference devices (dc-SQUIDs) are among the most sensitive wideband devices for measuring any physical quantity that can be naturally converted into magnetic flux. They are used for a variety of applications including the measurement of biomagnetic signals [1], the readout of energy-dispersive low-temperature particle detectors [2], magnetic sensing at the nanoscale level [3] or the geophysical explorations of mineral deposits [4]. But due to their periodic flux-to-voltage characteristic, dc-SQUIDs are intrinsically non-linear devices and possess only a small linear flux range. For this reason, additional circuits are often employed to linearize the relation between the input and output signal. However, these circuits often impose stringent performance requirements on different system components, e.g. the digitizer sampling the output signal or the SQUID readout electronics. The limited voltage range and the finite voltage resolution of the digitizer, for example, limit the overall dynamic range of an flux-locked loop (FLL) based SQUID readout [5]. In addition, FLL circuits require to route feedback wires to the SQUID which might set a practical limit to the implementation of massive multi-channel SQUID systems. Therefore, alternative readout techniques are developed to allow for simultaneously having a linearized relation between the input and output signal as well as a large dynamic range. In addition, SQUID based frequency-division multiplexers are strongy required to equip, for example, next generation experiments relying on large cryogenic microcalorimeter arrays (see, for example, [6]).

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II. Principle of dc-SQUID readout scheme

Fig. 1 summarizes the concept of our readout scheme which can be applied to any kind of current-sensing dc-SQUID being equipped with an input coil for signal coupling and a modulation coil that allows for flux biasing the SQUID. Our scheme relies on applying a periodic, sawtooth-shaped current flux signal I_{ramp} to the modulation coil of the SQUID to continuously measure the flux-to-voltage SQUID characteristic within each period of the flux ramp (see lower right inset of Fig. 1). The amplitude and repetition rate of the flux ramp are chosen such that multiple flux quanta are induced in the SQUID and that the input signal is quasi-static within each period of the flux ramp. Consequently, the input signal is transduced into a constant magnetic flux offset within the SQUID loop which results in a phase shift of the flux-to-voltage SQUID characteristics that is proportional to the input signal (see Fig. 1). The amplitude of the input signal can hence be inferred by determining the phase shift of the flux-to-voltage SQUID characteristic with respect to the SQUID characteristic in the absence of an input signal. Since the input signal is transduced into a phase shift of the SQUID characteristic, the dynamic range of the analog-to-digital (ADC) converter is not a limiting factor anymore. Theoretically, this scheme therefore allows for an infinitely large dynamic range.

III. Demonstration of dynamic range enhancement

For proving the concept of our readout scheme, we used an integrated two-stage current-sensing dc-SQUID (C6X116W,

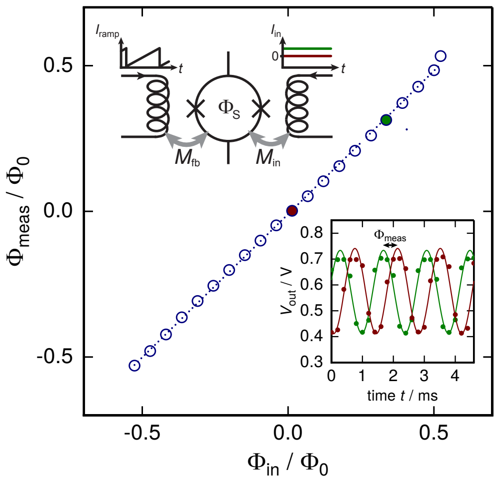

Fig. 1. Reconstructed magnetic flux change $\Phi_{\rm meas}$ versus the applied magnetic flux change $\Phi_{\rm in}$ using the dc-SQUID readout scheme discussed within this paper. The upper left inset depicts the used readout configuration and the lower right inset displays the measured flux-to-voltage SQUID characteristic for $\Phi_{\rm in} = 0\,\Phi_0$ (red line and dots) as well as $\Phi_{\rm in} = 0.35\,\Phi_0$.

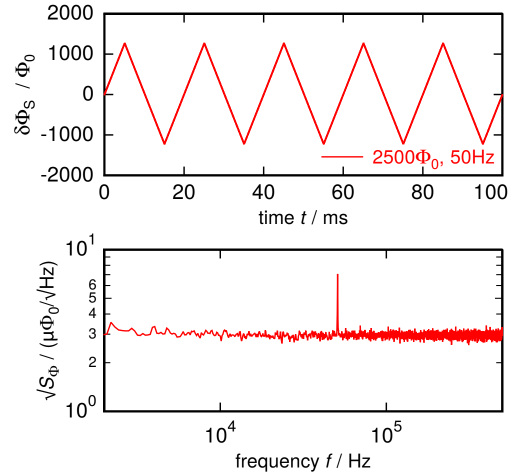

Fig. 2. **a)** Reconstructed magnetic flux amplitude $\delta\Phi_{\rm S}$ versus time t for a $2500\,\Phi_0$ (peak-peak) triangular signal with a repetition rate of $50\,$Hz and **b)** measured flux noise spectrum of the SQUID setup read out using our readout approach in the absence of any input signal. For the measurement, a flux ramp with an amplitude and repetition rate of $4.2\,\Phi_0$ and $1\,$MHz were used.

PTB Berlin) that was current-biased and read out open-loop using a commercial SQUID electronics (XXF-1, Magnicon GmbH). We connected an arbitrary function generator (HMF2550, Rhode&Schwarz GmbH & Co. KG) as well as a $10\,\mathrm{k}\Omega$ resistor in series to the feedback coil of the first-stage-SQUID and connected a test signal generator to the input coil of the first-stage SQUID. The amplitude and repetition rate of the flux ramp were $4.2\,\Phi_0$ and $1\,$MHz, respectively. Both, the flux ramp as well as the SQUID output signal were digitized using a $14\,$bit ADC with a sampling rate of $50\,$MSPS. For determining the phase shift, two periods of the SQUID characteristic within each flux ramp were used in order to allow transients to settle. The range of the input signal was limited by the used signal generator as well as the resistor connected in series and could be varied between $100\,\mathrm{m}\Phi_0$ and $2500\,\Phi_0$. Noise measurements were performed without applying an input signal.

Fig. 2 shows exemplarily the reconstructed signal of a $2500\,\Phi_0$ (peak-peak) triangular signal with a repetition rate of $50\,$Hz as well as the measured noise spectrum in the absence of an input signal. We observe a linear relation between the input and the reconstructed signal over the full input signal range, clearly demonstrating the linearization capability of our readout scheme. The measured noise level is about a factor 3 larger as compared to the noise level using a conventional FLL based SQUID readout. A part of this noise degradation (factor of about 2) can be explained by the fact that the SQUID characteristic is sampled at magnetic flux insensitive parts of the SQUID characteristics (see, for example, [7]). The reason for the remaining degradation is not yet fully understood and presently under investigation.

Taking into account the measured noise level as well as the maximal amplitude of the input signal (limited by the input circuitry, see above), the dynamic range is $105\,$dB assuming the use of the full ADC bandwidth or $152\,$dB assuming a bandwidth of $10\,$Hz as used, for example, for geophysical explorations. Comparing these values to the dynamic range of the $14\,$bit ADC of $84\,$dB clearly shows that the dynamic range is significantly enhanced when using our readout scheme.

IV. MHz FREQUENCY-DIVISION SQUID MULTIPLEXER

Transducing the input signal into a phase shift of the voltage-to-flux SQUID characteristic that is continuously measured allows to implement an easy-to-use MHz frequency-division SQUID multiplexer. Fig. 3 shows a schematic circuit diagram of a four-channel MHz SQUID multiplexer that is based on this readout approach. The individual dc-SQUIDs are connected in series for simultaneously biasing them using a constant-current source and for measuring the output voltage drop of the whole series connection. The latter is the sum of the individual flux-to-voltage SQUID characteristics. The input coil (red coils in Fig. 3) is identical for each SQUID and is connected via the mutual inductance $M_{\rm in}$ to the associated SQUID. In contrast, the different modulation coils (blue coils in Fig. 3) are coupled with different strengths $M_{{\rm fb,SQ}i}$ $(i = 1, \dots, 4)$ to the associated SQUIDs and are connected in series. This allows for applying a common flux ramp to all SQUIDs that induces a different number of flux quanta in each SQUID due to the different values $M_{{\rm fb,SQ}i}$. This results in a different period of the flux-to-voltage characteristic for each SQUID within a frame of the flux ramp. Since all SQUID characteristics are combined into a single voltage signal, the summed voltage signal contains different carrier signals those frequencies are defined by the period of the related SQUID characteristic. When simultaneously monitoring the phase of each carrier signal, e.g. by using software defined radio as used for reading out microwave kinetic inductance detectors

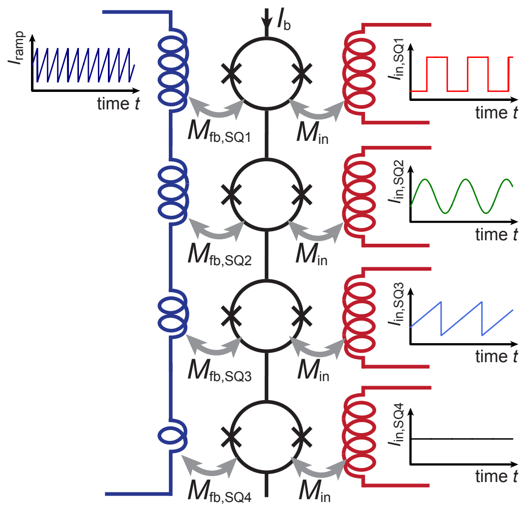

Fig. 3. Schematic circuit diagram of a four-channel MHz frequency-division SQUID multiplexer based on the dc-SQUID readout scheme introduced within this work. The $I_{\mathrm{in,SQ}i}$-vs.-t-plots close to the input coils (red) of the SQUIDs illustrate the test signals used for generating the data shown in Fig. 4.

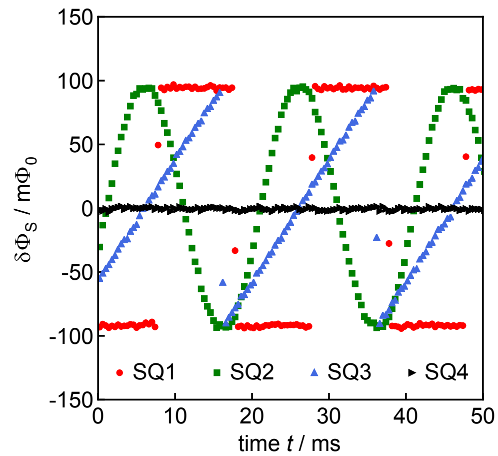

Fig. 4. Measured magnetic flux change $\delta\Phi_{\mathrm{S}}$ versus time t in channels SQ1 to SQ4 of the four-channel MHz frequency-division SQUID multiplexer introduced within this work. The test signals that were applied to the input coils of the different channels are illustrated in Fig. 3.

or microwave SQUID multiplexers (see, for example, [8]), the input signals of all SQUIDs can be inferred using only two single readout lines routed from room-temperature to the SQUID.

For demonstrating the multiplexing capability of our readout approach we fabricated a MHz frequency-division SQUID multiplexer with four channels. The SQUIDs are parallel gradiometers formed by four planar washers that are connected in parallel. Each of the washers has two washer holes, one is used for the input and the other is used for the modulation coil. Both coils are therefore inductively isolated from each other to prevent the flux ramp to parasitically couple into the input circuit. The mutual inductances $M_{\mathrm{fb,SQ}i}$ are varied by changing the overlap between the modulation coil and the corresponding washer hole, i.e. for the largest value $M_{\mathrm{fb,SQ1}}$ the modulation coil is routed directly on top of the SQUID washer while for the smallest value $M_{\mathrm{fb,SQ4}}$ the modulation coil is lying within the washer hole.

Similarly to the measurements described in the previous section, the multiplexer was current-biased and read out open-loop using a commercial SQUID electronics (XXF-1, Magnicon GmbH). An arbitrary function generator (HMF2550, Rhode&Schwarz GmbH & Co. KG) as well as a $2\,\mathrm{k}\Omega$ resistor connected in series to the common modulation coil were used for creating the flux ramp signal and individual test signal generators were connected to the input coils of the different SQUIDs.

Fig. 4 shows the reconstructed output signals of all multiplexer channels versus time while simultaneously applying test signals to the multiplexer channels SQ1, SQ2, and SQ3. To test for possible cross-talk, the output signal of the fourth multiplexer channel was recorded without the application of a test signal. Clearly, all test signal can be reconstructed and cross-talk in channel SQ4 is not observed. Moreover, a dedicated cross-talk measurement by applying a sinusoidal test signal in the second channel and measuring the intensity of the power spectrum at the frequency of the applied signal in all other channel indicated a cross-talk level below about $0.3\,\%$ for this not-yet optimated device.

V. Summary

We have presented a novel dc-SQUID readout scheme that relies on applying a periodic, sawtooth-shaped magnetic flux signal to the modulation coil of a dc-SQUID and continuously measuring the phase shift of the flux-to-voltage SQUID characteristic as caused by an input flux signal. We have shown that this scheme allows for significantly increasing the dynamic range of a SQUID system (a dynamic range enhancement of more than $70\,\mathrm{dB}$ has already been demonstrated using a non-optimized experimental setup) and that it intrinsically allows for MHz frequency-division SQUID multiplexing.

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