Multiplexed readout of MMC detector arrays using non-hysteretic rf-SQUIDs

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Abstract  Metallic magnetic calorimeters (MMCs) are widely used for various experiments in fields ranging from atomic and nuclear physics to x-ray spectroscopy, laboratory astrophysics or material science. Whereas in previous experiments single pixel detectors or small arrays have been used, for future applications large arrays are needed. Therefore, suitable multiplexing techniques for MMC arrays are currently under development. A promising approach for the readout of large arrays is the microwave SQUID multiplexer that operates in the frequency domain and that employs non-hysteretic rf-SQUIDs to transduce the detector signals into a frequency shift of high Q resonators which can be monitored by using standard microwave measurement techniques. In this paper we discuss the design and the expected performance of a recently developed and fabricated 64 pixel detector array with integrated microwave SQUID multiplexer. First experimental data were obtained characterizing dc-SQUIDs with virtually identical washer design.

Keywords  microwave SQUID multiplexer, metallic magnetic calorimeters, integrated array readout

1 Introduction

The very high energy resolution, the intrinsically dissipationless nature of operation, the inherent fast pulse rise time and the excellent linearity are only a few out of many properties that make metallic magnetic calorimeters (MMCs) particularly attractive candidates for a variety of applications requiring energy dispersive particle detectors with high time resolution. State-of-the-art MMCs, for example, being optimized for soft x-ray spectroscopy have shown an energy resolution of $\Delta E_{\text{FWHM}} = 2 \text{eV}$ at a photon energy of $6 \text{keV}$ and a rise formation time of $90 \text{ns}$.

S. Kempf · M. Wegner · L. Gastaldo · A. Fleischmann · C. Enss
Kirchhoff-Institute for Physics, Heidelberg University, Im Neuenheimer Feld 227, 69120 Heidelberg, Germany
E-mail: sebastian.kempf@kip.uni-heidelberg.de
Due to the consequent use of microfabrication techniques for device fabrication, detector arrays consisting of tens or hundreds of virtually identical MMCs can be routinely produced. However, at present, only small detector arrays are used since multiplexing of MMCs without significant degradation of the single pixel performance such as the energy resolution or the rise time has not yet been established.

Very recently, time domain SQUID multiplexing (TDM) of small arrays was successfully demonstrated. The obtained results are promising and show that small arrays can be read out without a significant degradation of the energy resolution. However, TDM of arrays consisting of several hundred or thousand detectors is difficult to imagine since the apparent energy sensitivity $\varepsilon_s$ of the SQUIDs increases with the number of detectors due to wideband SQUID noise aliasing that results from the required large open-loop bandwidth of the SQUIDs combined with the less often sampling of the detector signal. In addition, the bandwidth of each detector has to be limited in order to avoid detector noise aliasing. This prevents the use of TDM for applications requiring a short response time. In contrast, a microwave SQUID multiplexer is well suited for the readout of large arrays since $\varepsilon_s$ is independent of the number of detectors and the bandwidth per pixel needs not to be limited to avoid detector noise aliasing.

In this paper we discuss the design of a recently developed and fabricated 64 pixel detector array with integrated microwave SQUID multiplexer. This array was produced to test the suitability of this readout technique and will be used in a first small-scale ECHO experiment.

2 Principle of the microwave SQUID multiplexer

Figure 1 shows a schematic of a detector array read out using a microwave SQUID multiplexer that is based on dissipationless, non-hysteretic rf-SQUIDs. Each detector is inductively coupled to an unshunted single-junction SQUID with loop inductance $L_s$ and critical current $I_c$. For $\beta_L \equiv 2\pi L_s I_c / \Phi_0 < 1$ with $\Phi_0$ denoting the magnetic flux quantum, the SQUID is non-hysteretic, i.e. it behaves purely re-
active, and can be modelled as a non-linear inductor $L(\Phi)$ whose value depends on the magnetic flux $\Phi$ threading the SQUID. In order to read out the change of $L(\Phi)$ that is caused by a magnetic flux change $\Phi$ associated with a detector signal, the SQUID is inductively coupled to the load inductor $L_A$ terminating the associated high $Q$ superconducting transmission line resonator with unique resonance frequency in the GHz range that is defined by the resonator length. Due to the mutual interaction with the SQUID, the actual value $L_A(\Phi)$ of the load inductor is also flux dependent and therefore the circuit’s resonance frequency gets shifted as the magnetic flux $\Phi$ changes. Assuming the circuit is excited with a fixed microwave signal, this frequency shift can be monitored as a change of amplitude or phase by using a homodyne detection technique. Furthermore, by capacitively coupling many of those circuits to a common transmission line, injecting a microwave frequency comb driving each circuit at resonance and monitoring the amplitude or phase of each resonator, it is possible to measure the signals of a quite large number of detectors simultaneously. In particular, just one HEMT amplifier and two coaxial cables are required for the readout of some hundreds of detectors.

3 Design of the 64 pixel detector array with integrated SQUID readout

The detector array being discussed within this paper consists of 32 two-pixel detectors that are depicted in figure 2a) and that are arranged in a linear $2 \times 16$ configuration. Every detector features two electroplated Au absorbers, each having an area of $170 \mu m \times 170 \mu m$ and a thickness of $2 \times 5 \mu m$. In between the two $5 \mu m$ thick Au layers, $^{163}$Ho can be deposited within a slightly reduced area, e.g. by means of ion implantation, resulting in a $4\pi$ geometry with a quantum efficiency of more than 99.9% for particles emitted during the decay of $^{163}$Ho. Each absorber is connected via 5 stems with a diameter of $10 \mu m$ to an underlying planar Au:Er$_{300ppm}$ temperature sensor having an area of $170 \mu m \times 170 \mu m$ and a thickness of $1.35 \mu m$. Since the effective contact area between sensor and absorber is only about 1.4%, a loss of athermal phonons to the solid substrate is greatly re-

Fig. 2 (Color online) (a) Schematic of the developed two-pixel detector. The sensor, the stems as well as the metallic link to the heat bath of the second pixel are not shown for clarity. (b) Schematic of the developed rf-SQUID. The upper part of the load inductor is connected to the microwave resonator while the other ends are connected to ground. The Josephson junction (JJ) is located in the middle of the SQUID.
duced. Underneath both sensors, superconducting meander-shaped pickup coils with a linewidth of 3 µm and a pitch of 6 µm are placed. They are gradiometrically connected in parallel with the input coil of the current-sensing rf-SQUID reading out the detector. This circuitry allows to store a persistent current to create the bias magnetic field being required to magnetize the sensor and to read out two pixels using a single SQUID. To adjust the signal decay time to 1 ms, each sensor is connected via a Au link with a low temperature resistance of about 1 Ω to an on-chip heat bath made of electroplated Au.

The inductance $L_i$ of the input coil of the SQUID reading out the detector has a value of 1.3 nH and is matched to the inductance $L_m$ of the meander-shaped pickup coils, thus ensuring maximum flux coupling between detector and SQUID. Due to the resistor $R_F = 2 \Omega$ (see figure 1), that is placed in parallel to the input coil, the frequency response of the superconducting flux transformer formed by $L_i$ and $L_m$ has a low-pass characteristic with a cutoff frequency of about 500 MHz. This prevents microwave power to leak into the detector.

The rf-SQUID that is depicted in figure 2b) is a second order parallel gradiometer. It is formed by four slotted octagonal washers, each of it having a nominal inductance of 200 pH, that are connected in parallel, hence resulting in a total SQUID inductance of $L_s = 50$ pH. The critical current of the Josephson junction is designed to be 5 µA translating into a hysteresis parameter of $\beta_s = 0.76$. The slotted washer design is chosen to reduce parasitic capacitive coupling effects between the SQUID and the input coil. The SQUID is furthermore equipped with a common flux modulation coil that runs through all SQUIDs to allow for a simultaneous flux biasing or flux ramp modulation of all SQUIDs.

The coplanar transmission line resonators have a resonance frequency $f_r$ between 4 GHz and 6 GHz which is set by their geometrical length. The coupling capacitance $C_c$ (see figure 1) is in each case chosen to achieve a loaded quality factor $Q_l = 5000$ and is implemented by running a part of each resonator in parallel to the common transmission line having a characteristic impedance of 50 Ω. The bandwidth of each resonator is large enough to resolve the expected fast signal rise time of a detector which is expected to be in the order of 500 ns. The mutual inductance between the SQUID and the load inductance $L_A$ is about 3 pH which leads to a peak-to-peak resonance frequency shift that equals twice the bandwidth of the resonator. This ensures high SQUID gain and stable resonator operation without the occurrence of bifurcations at relatively high microwave powers that are required to strongly drive the SQUID.

Taking into account all design parameters and assuming that the SQUID is driven hard, i.e. the antinode current $I_A$ that oscillate the magnetic flux inside the SQUID is set to $I_A = \Phi_0 / 2 \pi M_T$, the expected energy sensitivity of the SQUIDs is around 600 nJ depending on the actual resonance frequency of the related resonator. This translates into an expected energy resolution of about 5 eV of the detectors.

4 Characterization dc-SQUIDs with virtually identical washer design

The characterization of the rf-SQUIDs that are present in the microwave SQUID multiplexer can not be directly done. In order to quantify important paramaters such as the critical current $I_0$ or the capacitance $C_J$ of the Josephson junction or the SQUID inductance $L_s$, we also produced dc-SQUIDs with virtually identical
washer design that allows to survey some important parameters at 4.2 K. Both junctions of the dc-SQUIDs were shunted with \( R_N = 4 \Omega \) and their critical current \( I_0 \) were tripled compared to the rf-SQUIDs. But, due to a design flaw which was recognized not before the characterization, the SQUID is a first order gradiometer with \( L_s = 200 \text{pH} \) instead of a second order gradiometer with \( L_s = 50 \text{pH} \). This makes the dc-SQUIDs slightly hysteretic since \( \beta \equiv 2L_s I_0 / \Phi_0 > 1 \). However, a partial SQUID characterization could still be performed.

Figure 3a), b) and c) show representative \( V-I \), \( V-\Phi \) and \( I_c-\Phi \) characteristics of one of our dc-SQUIDs which were measured at 4.2 K. A linear fit to the resistive branch of the \( V-I \) characteristic reveals a normal state resistance of \( R_N = 6.4 \Omega \) which is about 60% larger than our design value and is most likely caused by an insufficient parameter control during lithography. However, this affects the performance of the SQUID multiplexer just marginally since the junctions are un-shunted. Solely the cutoff frequency of the low-pass filter within the input circuit is increased to about 1 GHz which is however still sufficient to prevent microwave power to leak into the detectors. The \( I_c-\Phi \) characteristic shows a \( I_c \) modulation of \( \Delta I_{c_{\text{max}}} / I_{c_{\text{max}}} = 0.27 \) with \( I_{c_{\text{max}}} = 27.8 \mu \text{A} \) and is slightly asymmetric which we attribute to an asymmetry in the shunt resistors, again most likely due to an insufficient parameter control. According to Tesche and Clarke\(^{11}\) we get a SQUID inductance of \( L_s = 186 \text{pH} \) taking into account \( \beta \) as determined from the measured value of \( \Delta I_{c_{\text{max}}} / I_{c_{\text{max}}} \). Both, the junction critical current \( I_0 \) and the inductance \( L_s = 186 \text{pH} \) of a single slotted washer, hence agree within 10% with our design values and anticipate a successful operation of the microwave SQUID multiplexer.

Since the washers are not resistively damped, the fundamental SQUID resonance appears at a voltage of 37 \( \mu \text{V} \). This value reveals a junction capacitance of \( C_j = 0.85 \text{pF} \) which is about 70% smaller than the calculated value taking into
accout the critical current density of $j_c = 40 \text{A/cm}^2$ and the junction area $A$. The reason for this is not yet clear, but will be investigated more in detail in near future.

Figure 3d) shows the measured magnetic flux noise of one of our SQUIDs. The white noise level of this device is $\sqrt{S_{\Phi, w}} = 2.1 \mu\Phi_0/\sqrt{\text{Hz}}$ and includes a contribution of $\sqrt{S_{\Phi, \text{el}}} = 0.9 \mu\Phi_0/\sqrt{\text{Hz}}$ of the direct readout electronics. The intrinsic flux noise is $\sqrt{S_{\Phi, \text{int}}} = 1.9 \mu\Phi_0/\sqrt{\text{Hz}}$ and is about 35% larger than the calculated value assuming that $\sqrt{S_{\Phi, \text{int}}}$ is solely determined by the current noise of the shunt resistors. But, since $\beta > 1$ and $\beta_c \equiv 2\pi C J R / N I_0 > 1$, resonances are very likely to occur that might not be observed in the SQUID characteristics but appear as an increased white noise level. At low frequencies a $1/f$ like noise contribution with a corner frequency of about 3Hz is observed. It can be attributed rather to external pertubations due to the magnetically unshielded SQUID operation than to critical current fluctuations or magnetic impurities in the vicinity of the SQUID.

5 Conclusions

We have summarized the design and the expected performance of a recently developed and fabricated 64 pixel detector array with integrated microwave SQUID multiplexer that was produced to test the suitability of this readout technique and that will be used in a first small-scale ECHo experiment. The characterization of dc-SQUIDs with virtually identical washer design revealed that the crucial SQUID parameters such as the critical current of the Josephson junctions or the washer inductance are close to the design values and anticipates a successful operation of the SQUID multiplexer which will be tested in near future.

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