Progress Towards Large Locally Linearized SQUID Arrays

Mikko Kiviranta and Leif Grönberg

VTT, Tietotie 3, 02150 Espoo, Finland

Abstract. We have fabricated 200-SQUID and 480-SQUID arrays, intended for uppers stages of a 2-stage locally linearized amplifier chain to read out frequency-domain multiplexed X-ray transition edge sensors. The SQUIDs are of narrowline construction which allows their use without superconductive shielding. We discuss the design criteria and present preliminary device characteristics. The work is still in progress.

Keywords: SQUID arrays, low noise amplifiers, frequency domain multiplexing.
PACS: 85.25Dq, 84.30Le

INTRODUCTION

The demand for highly linear SQUID amplifiers, needed in both Time Domain (TD) and Frequency Domain (FD) multiplexers, has recently driven attempts to contain the whole negative feedback path within the cryogenic stage [1 - 4]. The resulting small feedback delay would imply a large signal bandwidth, which is a necessity in multiplexing schemes where information content of several detector signals must be packed into a single amplification chain. The last cryogenic stage should deliver the signal power which is by factor D^2 larger than the noise floor of the first room-temperature amplifier (LNA), where D is the desired amplitude dynamic range at a prescribed linearity level. Due to the relatively large required signal power the first attempts [1,2] used a semiconductor based output stage. Recently Drung et. al. [5] have demonstrated that the narrowline SQUID construction, originally intended for shield-less operation in the ambient magnetic field [6], also makes it possible to build very large SQUID arrays still retaining the coherent operation of the constituent SQUIDs. Using this approach, we have fabricated 4-parallel 50-series SQUID arrays and 6-parallel 80-series SQUID arrays for the output stage. Additionally we have fabricated smaller first-stage arrays, aiming to a two-stage approach in which both stages are separately linearized by local feedback. The design parameters are compatible with the Transition Edge Sensor (TES) -based X-ray calorimeters for the XEUS/IXO mission [7]. This is still work in progress.

DESIGN CONSIDERATIONS

Power Gain

The TES detector delivering the current I_D to the SQUID input at the maximum frequency ω_{BW} must simultaneously provide the voltage $\omega_{BW}\, L_{IN}\, I_D$ across the SQUID input inductance. This implies power delivering capability required from the TES although most of the power is reactive rather than real. One may take ½ $(I_D\, M_{IN}\, \partial I/\partial \Phi)^2\, R_D$ as the SQUID output power, expressed in terms of the input mutual inductance, the flux-to-current gain and SQUID dynamic resistance. Well-known SQUID relations then lead to the order-of magnitude SQUID power gain as

$$\frac{dP_{OUT}}{dP_{IN}} = \frac{\varsigma_D}{2\,\omega_{BW}\sqrt{L_{SQ} C_J}} \qquad (1)$$

in terms of the SQUID loop inductance and the Josephson junction capacitance. ς_D is the ratio of the dynamic resistance to the shunt resistance. From analytically solvable overdamped SQUID characteristics it is possible to compute $\varsigma_D \approx 0.7$ in the current-biased, $\varsigma_D \approx 1.5$ in match-biased and $\varsigma_D \approx 3$ in the voltage-biased case at a typical setpoint.

Constructing an array merely constitutes an impedance transformation, and does not change the power gain from its single-SQUID value. Negative or positive feedback can be used to trade power gain for linearity or vice versa [3], but not to attain both simultaneously. Considering now that noise power at the output of a 100 mK TES is in the order of 10^{-24}

W/Hz, whereas Johnson noise in the cryostat wiring and the typical room-temperature low noise amplifier (LNA) imply noise power in the order of 10^{-21} W/Hz. One can estimate that, given losses and non-idealities, a single-stage SQUID with reasonable design parameters is hard pressed to provide the required power gain at 10 MHz or higher. Linearization by negative feedback unavoidably reduces the power gain further, so that a two-stage amplifier is necessary.

Linearizing Feedback

The local negative feedback can be voltage sampling (V-FB), current sampling (I-FB), or a combination of the two [3]. V-FB decreases dynamic resistance R_D of the array and linearizes voltage response $\partial V/\Phi$ but leaves $\partial I/\Phi$ unaffected. V-FB can only occur if the LNA allows voltage changes across the SQUIDs, i.e. circuitry must be of current biased or match biased type. Analogously I-FB increases R_D, linearizes current response, and must be accompanied with an LNA allowing SQUID current changes.

In addition to effects at the output, feedback also affects the input properties. In the shunt-summing configuration negative feedback screens the SQUID input inductance L_{IN}. A side effect is that the SQUID energy resolution appears to improve, when expressed as $\varepsilon = ½\, L_{IN}.\, i_N^2$ in terms of the input-referred current noise i_N.

We are constructing an amplification chain with separate stages at 50mK and 4K (Fig. 1). The goal is to distribute the unavoidable SQUID power dissipation as much as possible to the higher temperature stage. Both stages are linearized separately. This is unlike the approach [5] where a long feedback crosses both stages of a 2-stage cascade.

We have used the loop gain 4 - 5 as the design parameter, which should leave sufficient power gain to drive the LNA when TESes are providing the input signal . The lower stage uses pure I-FB, because of the natural presence of voltage bias. Voltage bias also leads to lower dissipation, i.e. voltage times current at the setpoint, as one can see by studying the load lines jotted in Fig. 2. The number of parallel v.s. series coupled SQUIDs has been chosen so that the I-FB enhanced R_D is able to drive the inductive load of cabling and upper stage SQUID input at the highest design frequency of 20 MHz.

The flux ratio between lower and upper stage has been designed as ~1, so that both stages contribute equally to the total non-linearity when operated at the same loop gain. The upper SQUID array should be impedance-matched with the cryostat cable, otherwise the source impedance seen by the LNA rotates in the Smith chart as a function of frequency and does not provide the correct noise matching impedance for the LNA. To meet the impedance match it is possible to arrange an array with many SQUIDs in parallel and use I-FB to enhance R_D, or couple many SQUIDs in series and use V-FB to suppress R_D. We have chosen the array aspect ratio so that R_D is close to 50 Ω without feedback, and intend to use simultaneous I-FB and V-FB to keep the R_D approximately unchanged as a function of loop gain. The fabricated SQUID arrays are equipped with appropriate feedback coils.

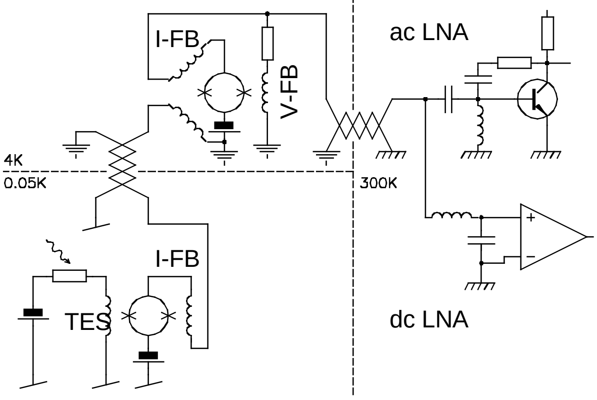

FIGURE 1. The envisaged amplification chain.

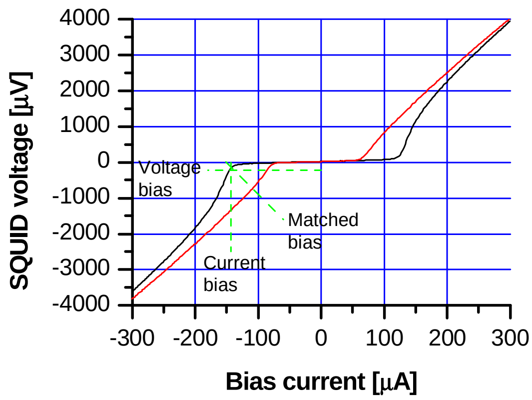

FIGURE 2. Voltage-current characteristics of the 4 x 50 SQUID array at integer flux quanta and half-integer flux quanta. Also drawn are load lines corresponding to different bias conditions. Power dissipation can be calculated to be approximately $R_S\, I_C$ for current bias at half-point of the load line, but almost arbitrarily small for voltage bias.

Stability

The large washer-coil capacitance of the long input coils and the high voltage response ∂V/Φ of SQUID series arrays makes the devices sensitive to capacitively mediated instabilities. The most easily invoked is the lumped-model feedback where SQUID output voltage couples as flux to SQUID input [8]. The long chain of input coils and the distributed coil-to-washer capacitance also makes possible transmission line modes, which however couple more weakly because currents do not remain in phase over the whole array.

In our previous design [9] we tried to avoid the instability by a layout where capacitively coupled currents cancel out (Fig. 3b), so that the output mode does not couple to the mode in SQUID dynamics in which Josephson junctions oscillate out-of-phase (flux mode). Unintentionally, we created coupling between output mode and the mode in which Josephson junctions oscillate in-phase (voltage mode). Previously we remedied the resulting enhanced McCumber parameter by reducing the critical current. In the design at hand we have added circuitry in the output side of the array, which cuts the high-frequency currents between C_{1b} and C_{2a}, between C_{2b} and C_{3a} and so on. To make this feasible, we have since the design [9] rotated the SQUID loops so that the junctions can be accessed from the side of the array.

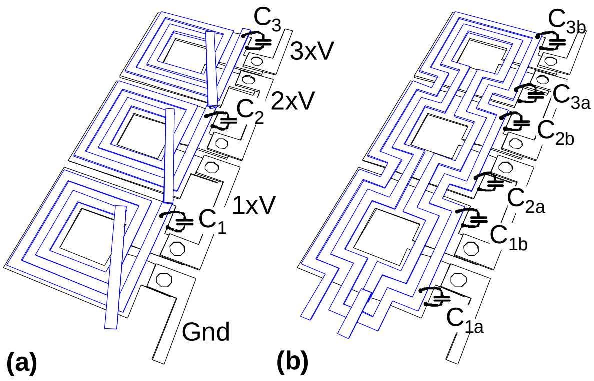

FIGURE 3. (a) In the traditional first-turns-then-washers input coil arrangement capacitive feedback currents generate flux and lead to Enpuku-style instability. (b) In the first-washers-then-turns arrangement capacitive feedback currents flow symmetrically and do not generate flux.

LNA

The LNA is built using the Infineon BFP650 SiGe heterojunction transistor whose low voltage noise (Fig. 4) makes it attractive for low source impedances. The LNA contains an ac coupled section for FD-multiplexed TES signals. A separate dc-accurate amplifier based on Texas Instruments INA163 tracks the SQUID setpoint. The LNA utilizes active feedback [10] to obtain sufficient impedance for matched bias and cable termination .

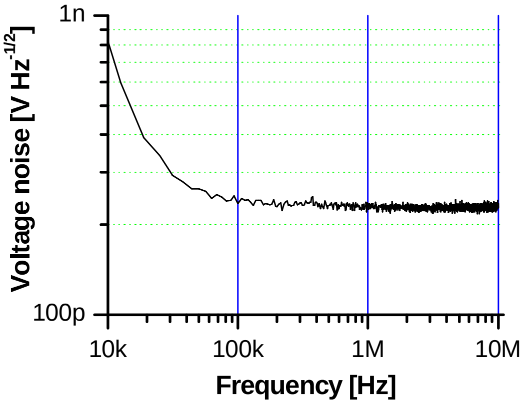

FIGURE 4. Voltage noise of a BFP650 SiGe transistor at 11 mA collector current, base grounded.

FABRICATION

The SQUIDs were fabricated in the Micronova cleanroom [11], using a process with three superconducting Nb layers. The lowermost layer also contains Pd resistors. The middle metallization is formed of a Nb-Al/AlOx-Nb trilayer, design value of whose critical current density is 500 A/cm^2 . Insulation layers are PECVD SiO_2, with the lower layer CMP polished to provide a smooth surface for the trilayer deposition. All contact vias are plasma etched, and a protective layer is used on top of the trilayer to prevent plasma induced damage during via etching.

Contact lithography with Süss MA-6 mask aligner allowed us to keep all superconducting structures below 6 µm linewidth, which should prevent spontaneous flux trapping at earth field [6]. These structures include the 3µm diameter (nominal) anodization defined Josephson junctions, and the 2µm - 1.5µm - 2µm two-turn input coil aligned underneath the 6 µm wide SQUID loop. The loops are gradiometric, with 40 pH nominal inductance.

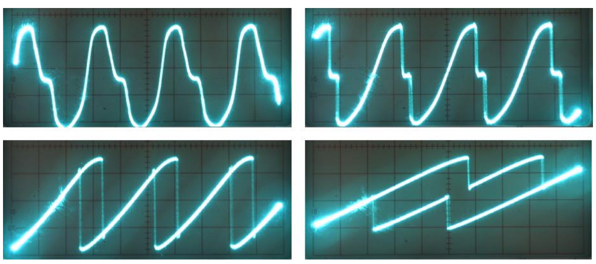

FIGURE 5. The flux response of an array at approximate voltage-sampling loop gains of 0, 0.7, 1.5 and 3. The loop gain selection takes place through a cryogenic CMOS switch. The plateau in the falling slope is caused by SQUID array interaction with the SiGe amplifier.

EXPERIMENTAL STATUS

Currently we are concentrating on the large output arrays to understand their behaviour. Unfortunately the Pd shunts in the current wafer appear to have significantly lower resistance than designed, which reduces the obtainable voltage response $\partial V/\Phi$. Another problem is interaction of the fast SiGe transistor stage with the on-chip I-FB circuitry, which leads to an instability and has so far prevented I-FB related tests. The plateau indicating this appears when the SiGe transistor is biased, and can be seen in Fig. 5. The figure demonstrates the V-FB operation, however. Work to improve stability is in progress.

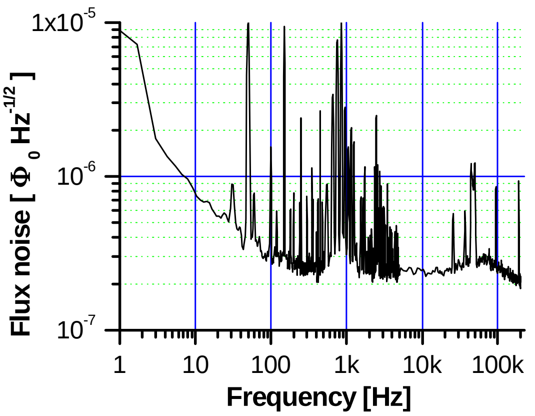

FIGURE 6. Flux noise of the unshielded 6 x 80 array in the laboratory environment measured through the INA channel.

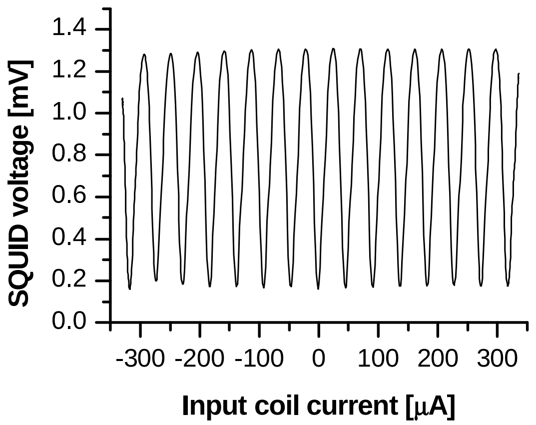

FIGURE 7. Flux response of the 4 x 50 array at 135 μA bias current. Coil current scale is not reliable as the values of the cryogenic resistors have not been calibrated.

The fabricated arrays tolerate the ambient earth field and EMI present in the laboratory environment. Cooling the devices in the ambient field and operating them without any superconducting or mu-metal shield has no noticeable effect in the device characteristics, except appearence of a 50 Hz flux signal with approximately 0.05 $\Phi_{0\ p\text{-}p}$ amplitude. Fig. 6 shows the measured flux spectrum, limited by the INA163 amplifier noise.

We have so far not observed evidence of any constituent SQUID to lose coherence, as would be evidenced by distorted charcteristics or flux jumps. This encourages speculation about of multichannel systems where SQUIDs would share a common flux adjustment line.

ACKNOWLEDGMENTS

Thanks are due to: Dr. Juha Hassel for fruitful discussions in the fabrication development and error checking the mask drawings; Mr. Hannu Sipola for help in LNA design; Ms. Paula Holmlund has helped in electronics preparation and Mr. Tuomas Haggren in selecting the devices for closer scrutiny. Parts of this work has received support from the ESA contract TRP5417 and parts from the Centre of Excellence of the Academy of Finland.

REFERENCES

1. M. Kiviranta, "Use of SiGe bipolar transistors for cryogenic readout of SQUIDs", *SuST* **19**, 1297-1302 (2006).
2. D. Drung et al, "Highly Sensitive and Easy-to-Use SQUID Sensors", *IEEE Tran. Appl. Supercond.,* **17**, 699-704 (2007).
3 M. Kiviranta, "SQUID linearization by current-sampling feedback", *SuST* **21**, 045009 (2008).
4. T. M. Lanting et al, "Linearized SQUID Array (LISA) for High Bandwidth Frequency-Domain Readout Multiplexing", *arXiv:*0901.1919v1 (2009).
5. D. Drung et al, "Novel SQUID Sensors with High Linearity at High Frequencies", to appear in *IEEE Tran. Appl. Supercond.* (2009).
6. G. Stan, S.B. Field and J.M. Martinis, "Critical Field for Complete Flux Expulsion in Narrow Superconducting Strips", *PRL* **92**, 097003 (2004).
7 http://sci.esa.int/xeus/
8. T. Minotani, K. Enpuku and Y. Kuroki, "Effect of capacitive feedback on the characteristics of direct current superconducting quantum interferometers", *J. Appl. Phys.* **82**, 457-463 (1997).
9. M. Kiviranta, "High Dynamic Range SQUID Readout for Frequency Domain Multiplexers", *J. Low. Temp. Phys.* **151**, 952-957 (2008).
10. W. S. Percival, "An Electrically 'Cold' Resistance", *Wireless Engineer* **16**, 237 (1939).
11. http://www.micronova.fi/facilities/