Two-Stage SQUID Amplifier With Bias Current Re-Use

Mikko Kiviranta and Leif Grönberg

Abstract—Biasing arrangements in multi-channel multi-stage SQUID amplifier systems, such as Transition Edge Sensor matrices for astronomical observation (Barrett et al., 2023) or quantum science (Hummatov et al., 2023), typically require a large number of wires. This is due to the need for two or more cascaded SQUID stages to obtain sufficiently large power gain over a sufficient bandwidth, and to moderate obtainable multiplexing factors, which forces implementation of many parallel readout chains to serve all the sensor pixels. We suggest an arrangement where one bias line and one flux setpoint line are shared by two cascaded SQUID stages on a single chip, halving the number of lines two cascaded stages would ordinarily require. The stages are connected in series, sharing a single supply current, dual to ordinary integrated transistor circuits in which many transistor stages are connected in parallel and share a single supply voltage. We show experimental results at $T = 4.2$ K for a proof-of-concept amplifier chip, fabricated in the VTT Micronova foundry, using SWAPS Josephson junctions (Grönberg et al., 2017) at $J_C = 20 \mu A/(\mu m)^2$ critical current density. The device shows larger than 3 k$\Omega$ transresistance, when operating from $L_{IN} = 29 nH$ input inductance to $R_D < 150 \Omega$ output dynamic resistance.

Index Terms—Multiplexing, SQUID designs and applications, Josephson device noise, superconducting microcalorimeters.

I. INTRODUCTION

MULTIPLEXED readouts for Transition Edge Sensors (TESs) [4], [5] rely typically on 3 cascaded stages [6] or more commonly 2 stages [7], [8] of SQUID amplifiers between the TES matrix and the Low Noise Amplifier (LNA) located at room temperature. Reduction in the number of stages simplifies system design, as less bias and flux setpoint lines are needed, but the reduction may jeopardize the total power gain and bandwidth required from the amplifier cascade.

Such a trade-off may become a discussion topic at some point of development of the X-IFU instrument for the ATHENA space observatory [1], planned to contain 1 536 X-ray TES microcalorimeters [9] at $T = 50$ mK followed by a Time Domain Multiplexing (TDM) readout chain. The chain consists of a 50 mK TDM SQUID [8] also providing the first gain stage, followed by a SQUID booster stage at $T = 2$ K. At current planning the booster will resemble our N2-type SQUID array [7].

In the pre-2022 X-IFU system design [10], the flight cryostat interface to the spacecraft was to take place at $T = 300$ K temperature, and the Warm Front-End Electronics (WFEE) box containing the LNA was to reside at the $T = 300$ K cryostat surface, a moderate distance from the cryogenic stages. In the 2022 re-configuration, passive V-groove cooling was planned, so that cryostat interface to the spacecraft would take place at $T = 50$ K [11] and the WFEE box would be located somewhat farther from the cryostat in the 300 K compartment of the spacecraft. Re-configuration triggered us to consider options for increasing signal power generated by the AMP SQUID, to compensate against the possible increase in resistive losses, EMI pickup and parasitic cable capacitance of the lengthened 2 K – 300 K cable, even if the impact on the cable length was not known at the time. Some of the cable non-idealities have been addressed in [12], [13]. A further driving heuristic was the assumed sensitivity of TDM to dispersion in the 2 K – 300 K cable, relative to Frequency Domain Multiplexing (FDM).

Because changes in system architecture, such as the number of bias lines in the wiring harness, would cause major repercussions in a complex instrument such as the X-IFU, any new SQUID booster should preferably be drop-in compatible with the old one. The proof-of-concept demonstration of the two-stage SQUID booster presented here is a result of those considerations. The full readout chain would in this case consist of a TDM SQUID at $T = 50$ mK and a two-stage booster on a single chip at $T = 2$ K, i.e., a total of 3 cascaded SQUID stages. The two-stage booster however is not in the official development plan of X-IFU, which as a baseline relies on a single-stage booster driving $l = 2.5$ m cable.

II. SIGNAL POWER GENERATION IN A SQUID ARRAY

Output signal power of a booster SQUID array is proportional to its voltage swing $\Delta V$. The maximum SQUID voltage should be sufficiently much above the voltage noise floor of the LNA to provide enough dynamic range for the net signal that occurs when an X-ray detection event takes place in a detector pixel. In negative feedback systems such as Flux Locked Loop [14], Baseband Feedback [15] or the TDM frame-delayed feedback [16], error signals of the feedback loop should fit within the sufficiently linear part of the booster dynamic range. If no detector pixel signal is changing value, i.e., not slewing, the error signal

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is zero. The dynamic range headroom provided by the booster, together with the cable delay, determines how fast detector pixels can slew, and how many pixels can slew simultaneously. The situation is different in feed-forward linearizing systems such as the ramp modulation [17], where full signal from all pixels is present in the cable-driving booster at all times.

In addition to $\Delta V$, the current swing $\Delta I$ of the booster SQUID array is important. In case of a high-impedance LNA the $\Delta I$ determines how rapidly the cable capacitance can be charged at signal transitions, thereby affecting the interstage bandwidth. In the case where the LNA resistively terminates the cable, the booster dynamic resistance $R_D \sim \Delta V/\Delta I$ must not be too far from characteristic impedance $Z_0$ of the cable.

Local positive feedback is used in some cases [18], [19], [20] to increase the transresistance $R_{TR} = dV_O/dI_{IN}$ of the booster. Feedback however only affects the small-signal $R_{TR}$ but does not change the large-signal $\Delta V$ or $\Delta I$ which are important in determining the slew rate capability of the detector system. Additionally, local feedback affects input and output impedances of the booster, in a way that partially counteracts the advantage of the feedback (Fig. 1). Some SQUID arrays comparable to our devices are discussed in [22], [23], [24].

III. ONE-STAGE AND TWO-STAGE BOOSTERS

The starting point for our 2-stage proof-of-concept amplifier chip is a 44-series 8-parallel SQUID array, Fig. 2(a), designated as the type O11 at VTT. It is constructed on a $3 \times 3$ mm chip, using a simplified version [25] of our fabrication process [7], which provides two independent superconductive wiring layers and SWAPS [3] Josephson junctions at 20 $\mu$A/$\mu$m$^2$ critical current density. The O11 shows $\Delta V \geq 7$ mV voltage swing (Fig. 3(b)) and $R_{D,REF} = 96 \Omega$ reference dynamic resistance.

1U-FB coil of the XN1-type SQUID array contains 2 turns, rather than 1 turn as erroneously stated in [21].

Dynamic resistance $R_D$ of a SQUID is setpoint dependent, however based on simulations [14], [21], [26], [27] $R_D$ tends to be close to resistance $R_S$ of the JJ shunt. Hence, a practical way to compare SQUID arrays is the reference dynamic resistance $R_{D,REF}$, i.e., the shunt resistance times the array aspect ratio. More important in practice is the differential dynamic resistance $R_D$ at the dwell point, where the booster resides waiting for X-ray detection events. The point is typically chosen to provide a large SQUID gain $dV/d\Phi$ and large available dynamic range for the flux swing. We have marked an example dwell point for the O11 in Fig. 3(a) and (b), where we measure the $R_D = 148 \Omega$.

The O11 has moderately large input inductance $L_{IN} = 270$ nH, as measured by tuning the input with a known capacitor. This implies that to provide a large output signal, the O11...
requires a moderately large input drive power from the previous stage. The state of affairs is due to the finite power gain provided by the SQUID cells forming the O11 array, and it cannot be changed by forming a parallel or series array from the cells. Attempts to combine a larger number of series or parallel SQUID cells to generate more output signal power would increase the $L_{IN}$ further. The remedy would be cascading two or more amplifier stages.

The O12 device (Fig. 2(b)) is formed by dividing each 44-series SQUID chain into 4-series 1st stage and 40-series 2nd stage, sampling the voltage of the 1st stage by on-chip resistors, and feeding the resulting signal to input of the 2nd stage. Note that the new 2-stage cascade still requires only one wire pair for bias current and one for flux setpoint.

Flux response\(^2\) of the O12 device is shown in Fig. 4. The output swing of the 1st stage does not fit within monotonous input range of the 2nd stage, but rather folds over where the 2nd stage gain changes sign. The non-dashed part of the trace corresponds to one period of the 1st stage signal, and orange trace corresponds to the monotonous half-period of the 1st stage signal which we would like to use as the operational range. Note further that the input current regions show instability when the O12 resides on falling slope of its 2nd stage flux response, even if the O11-type is stable on both rising and falling slope when our differential-bias differential-readout electronics is used.

Regardless of the above non-idealities, there is a usable input current range, extending $I_{IN} = -0.5 \ldots +1.5 \mu A$ in Fig. 4. We have ascertained stability by measuring flux noise and frequency response there, with typical results shown in Fig. 5. Frequency response indicates the sharp cutoff at $f > 12$ MHz, characteristic of our LNA and wiring setup, and an additional $-3$ dB dip around $\sim 1$ MHz whose cause we are investigating. The $-3$ dB dip does not show in the LT-SPICE behavioural model of the 2-stage booster, hence we speculate the mechanism may be due to interaction of the 2-stage amplifier with the insufficiently isolated bias wiring in our dipstick setup.

The average transresistance $R_{TR}$ over the $-0.5 \ldots +1.5 \mu A$ range is $3 \ 500 \ \mu V/\mu A$ and reaches a higher value at some regions.

\(^2\)Two-stage SQUID response generation examples are shown eg. in [20], Fig. 3.

Fig. 4. Flux response of the O12-type two-stage amplifier at bias current generating roughly maximal modulation depth $\Delta V$.

The O12 has much smaller measured $L_{IN} \approx 29$ nH than the O11, and hence requires less driving power from the preceding amplifier stage.

The X-IFU system level specification for input inductance of the $T = 2$ K booster is $L_{IN} \leq 100$ nH, which would allow much larger 1st stage and 2nd stage arrays, and hence much larger output voltage swing $\Delta V$ while still remaining within the $L_{IN}$ and output $R_D$ constraints. We were not able to fit larger format arrays than the O11/O12 on the $3 \times 3$ mm chip size offered by the fabrication opportunity, however, hampered by the physical dimension of our standard SQUID cell. The X-IFU designated chip size for boosters is $4 \times 4$ mm.

IV. DISCUSSION AND CONCLUSION

Folding of the flux characteristic in Fig. 4 is due to a factor-of-2 calculation error made in the design phase. The interstage resistors, now $20 \ \Omega + 20 \ \Omega$, should more optimally have been $40 \ \Omega + 40 \ \Omega$, in which case 1st stage output response would roughly fit to the 2nd stage monotonous range, and usable input range would be closer to the X-IFU required wide input current range of $\Delta I_{IN} = 7 \ \mu A$. This would also have reduced the observed transresistance $R_{TR}$, but there is no escaping the fact that with the limited output swing $\Delta V \approx 7$ mV and the required input range $\Delta I_{IN} = 7 \ \mu A$, the average transresistance cannot exceed $R_{TR} = 1 \ 000 \ \mu V/\mu A$. More ‘muscular’ 2nd stage SQUID arrays with larger $\Delta V$ would be needed. In the X-IFU case the increase of $\Delta V$ is constrained by the dynamic range ceiling of the LNA in the WFEE box, however.

One design issue not discussed above is that the relative input current of Fig. 4 is not centered at zero $\mu A$ of absolute current, and hence a more clever dimensioning or an added flux shift circuit will be needed for a practical 2-stage amplifier. It is conceivable to share a single such flux-shift circuit between many independent amplifier channels integrated on a single chip, an example shown in Fig. 6.

We note an analogy to semiconductor integrated circuits, where either a number of cascaded transistor stages or a number
A two-stage booster presented in [29] is implemented with constant voltage bus. We are suggesting a separate chip for this work.

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