# Some phenomena due to SQUID input properties when local feedback is present

**Mikko Kiviranta[1], Leif Grönberg[1], Nikolai Beev[1] and Jan van der Kuur[2]**
[1]VTT, Tietotie 3, 02150 Espoo, Finland
[2]SRON, Sorbonnelaan 2, 3584CA Utrecht, the Netherlands

E-mail: Mikko.Kiviranta@vtt.fi

**Abstract.** We have constructed a two-stage SQUID amplifier, in which series-mixing local feedback has been used to screen the SQUID input inductances and hence to boost the power gain of the amplifier. 2.9 pA/Hz$^{1/2}$ current noise and 2.9 nH input inductance of the lower SQUID stage imply energy resolution of 18 times Planck constant at 4.2 K, which, arguably, can be further improved by input inductance screening. The upper stage consists of a 184-series 4-parallel SQUID array, which, when used alone, shows lower than 0.03 $\mu\Phi_0$/Hz$^{1/2}$ flux noise, but which as a part of the two-stage amplifier is operated at a higher flux noise level to provide robust, EMI-tolerant output signal. The series-mixing feedback also facilitates negative SQUID input impedance, which would allow self-oscillating SQUID-based frequency domain multiplexing.

## 1. Introduction

Signal chains for frequency-domain multiplexed arrays of transition edge sensors (TESes), such as the SPICA / SAFARI [1] and ATHENA+ / X-IFU [2] instruments require SQUID amplifiers with a large power gain. In order such instruments to be detector limited rather than readout limited, the noise equivalent signal power, roughly -160 dBm/Hz at the detector outputs, must be amplified within the cryogenic stage sufficiently to overcome the noise of the subsequent low noise amplifier (LNA). Even more important may be the electromagnetic interference (EMI), which couples to the cable between the deep cryogenic detector stage and the moderate-cryogenic stages capable of housing semiconductor LNAs. In the SPICA spacecraft that cable is estimated to be up to 10 meters in length. Additionally, amplification should be performed with as few cascaded SQUID stages as possible, because each bias and flux setpoint line in the wiring harness adds complexity and heat leakage. We have approached the power gain quest in two ways: (a) two-stage amplification chain using local feedback to boost the gain of individual stages, and (b) three-stage amplification chain where the two upper stages share the bias and flux setpoint lines and hence don't require additional lines in the wiring harness. The bias-reusing chip is a subdivided version of the 184x4 SQUID array chip described later, where a 4x4 intermediate array drives a 180x4 final array. In this paper we concentrate on the local feedback version, however.

The power gain of a single SQUID stage, or rather, its available output power to the (reactive) input power ratio is [3]

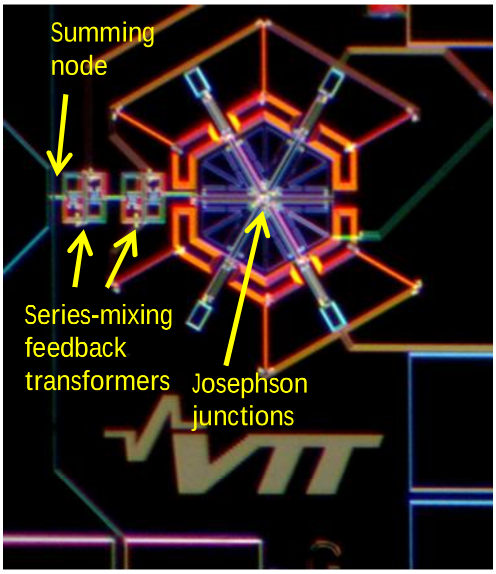


**Figure 1.** Microphotograph of the 6-subloop fractional-turn SQUID

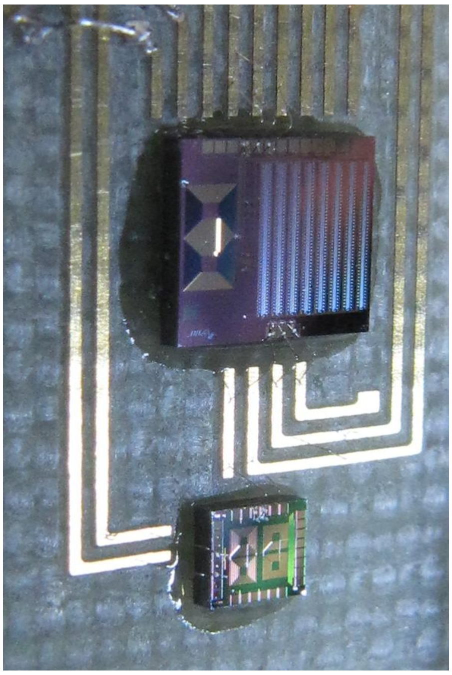

**Figure 2.** Photograph of the 184x4 array with the screening transformer chip.

.
$$\frac{dP_O}{dP_I} = \frac{R_D \left( {dI}/{d\Phi} \times M \right)^2}{\omega_C \, L_{IN}} \qquad (1)$$

when expressed in terms of SQUID parameters: mutual- and self-inductances $M$ and $L_{IN}$ of the input coil, dynamic resistance $R_D$ and flux-to-current response $dI/d\Phi$. One might consider using local positive feedback [4,5] to boost the $dI/d\Phi$. In the simple-minded approach $R_D$ and $L_{IN}$ degrade, however, leaving the $dP_O/dP_I$ unchanged. We have implemented series-mixing feedback [6] rather than the traditionally used shunt-mixing. The technique can be seen as a virtual negative inductance in series with input, leading to improvement of $L_{IN}$ rather than $dI/d\Phi$ in Eq. 1.

## 2. Devices and experiments

We used a 6-subloop fractional-turn SQUID as the lower stage in the experiments (Fig 1). The counterwound loop construction resembles [7], but the input coil only contains only one turn. We measure input sensitivity $M^{-1}$ = 5.8 μA/$\Phi_0$, and output swing $\Delta I$ = 12 μA. The device is equipped with transformers for series-mixing feedback.

The upper stage is a 184-series 4-parallel array, constructed out of the same cascadeable cells as [3]. The purpose of the large form factor is to reach a large noise-equivalent output power, when driven by the lower SQUID with roughly 1:1 flux ratio between lower and upper stage. Although not taken advantage of here, the array shows routinely 0.06 μ$\Phi_0$/Hz$^{1/2}$ flux noise at 4.2 K when read out with a 20 MHz room-temperature SiGe LNA.We have measured 0.022 μ$\Phi_0$/Hz$^{1/2}$ flux noise at 2.8 K with a cryogenic LNA [8]. Series-mixing feedback for the array was accomplished by wire-bonding a separate thin-film transformer chip (Fig.2), with a choice of 25 nH or 120 nH mutual inductance.

The traditional shunt-mixing feedback [4,5] creates steep and shallow slopes in the flux response of the SQUID (Fig. 4, lower). The series-mixing feedback creates a fast slope where SQUID input inductance is supressed and R/L cutoff frequency is higher; and slow slope where SQUID inductance is enhanced and R/L cutoff is lower. The bandwidth is visible as different RMS noise on different slopes in (Fig. 4, upper).

The natural $L_{IN}$ = 160 nH of the 184x4 array is screened to $L_{IN}$ = 60 nH on one slope and enhanced to $L_{IN}$ = 260 nH on other slope. This is consistent with $M$ = 25 nH of the transformer and roughly 4 μA/μA current gain provided by the SQUID array. When the $M$ = 120 nH winding is used, one slope becomes unstable due to the negative total input impedance. We intend to use this configuration to implement the self-oscillating frequency domain multiplexer [9]. The array exhibits a clean 3 MHz oscillation when coupled to an external LC resonator in this mode.

The two-SQUID amplifier (Fig. 3) has shown the performance summarized in table 1. Input inductances were measured via the R/L cutoff, with a 5 mΩ resistive wire bonded across the input. The bandwidth limitation is roughly consistent with the $R_D/L_{IN}$ cutoff between the first and second stage, including the interstage parasitic inductance, and $R_D$ variation of the first stage as a result of applied feedback. Currently, no precautions against $R_D$ variation has been taken.

Note that our series-mixing balance circuit against the $L_{IN}$ enhancement on the steep slope (Fig. 4, lower) appears to be over-compensating, as the $L_{IN}$ measures *lower* on the steep slope.

Finally note that the energy resolution,

$$. \qquad \varepsilon = \tfrac{1}{2} L_{IN}\, i_N^2 \tag{2}$$

when expressed in terms of input-referred current noise spectral density $i_N$ and the SQUID input inductance $L_{IN}$ appears to improve by the series-mixing feedback. In fact, eq. 2 is not valid for an inductive load, because it lacks the back-action noise terms. As a figure-of merit for resistive loads at low frequencies, such as TES arrays, eq. 2 is convenient, however.

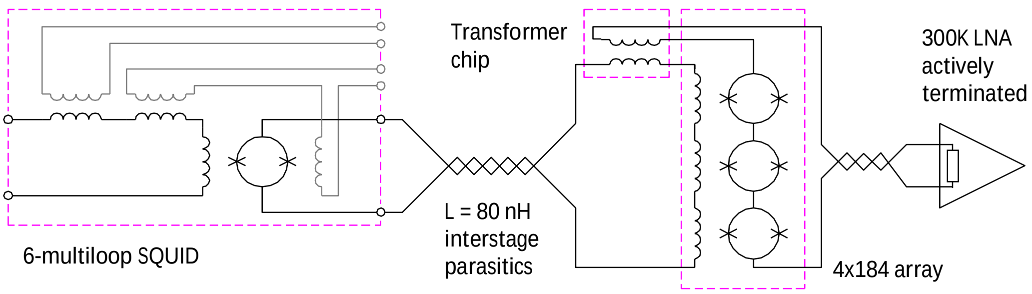


**Figure 3.** The two-stage amplifier schematic. Local feedback is not active in the lower stage, as drawn.

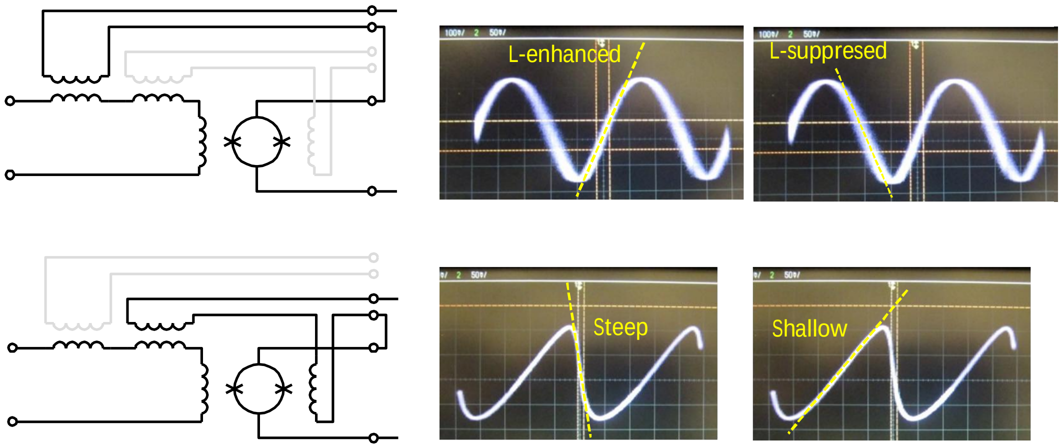


**Figure 4.** Local feedback configurations of the lower stage. (Upper) The plain series-mixing feedback and the associated flux-to-current characteristics. A 5 mΩ noise-providing resistor is connected at the SQUID input. (Lower) Shunt-mixing feedback produces steep and shallow slopes to the flux-to-current characteristics, but its $L_{IN}$-enhancing effect is counteracted by the additional series-mixing feedback.

**Table 1.** Bandwidth, flux noise and input inductance of the two-stage amplifier at various configurations.

| | Lower SQUID configuration ⇒ | Steep slope | Shallow slope | L-enhanced | L-suppressed |
|---|---|---|---|---|---|
| | $L_{IN}$ [ nH] | 1.5 | 3.4 | 4.7 | 1.2 |
| Upper array L-suppressed | Bandwidth [MHz] | 2.1 | 7.1 | 6.8 | |
| | Flux noise [$\mu\Phi_0/\mathrm{Hz}^{1/2}$] | 0.45 | 0.6 | 1.3* | |
| Upper array L-enhanced | Bandwidth [MHz] | 0.9 | 4.9 | 3.0 | |
| | Flux noise [$\mu\Phi_0/\mathrm{Hz}^{1/2}$] | 0.6 | 0.6 | 1.1* | |
| * Symptoms of instability at a few tens of MHz observed | | | | | |

**Acknowledgement.**
Device fabrication was supported from GSTP program of the European Space Agency. Oscillator and feedback development has received support from the grant no. 262947 of the European Communitys seventh framework programme (FP7/2007-2013).

[1] Jackson B D et. al. 2012 *IEEE Tran. THz Sci. Tech.* **2** 12-21. Doi: 10.1109/TTHZ.2011.2177705
[2] Barret D et. al. 2013 *Preprint* astro-ph/1308.6784
[3] Kiviranta M, Grönberg L and Sipola H 2011 *SuST* **24** 045003. Doi: 10.1088/0953-2048/24/4/045003
[4] Drung D, Cantor R, Peters M and Scheer H J 1990 *Appl. Phys. Lett.* **57** 406. Doi: 10.1063/1.103650
[5] Kiviranta M 2008 *SuST* **21** 045009. Doi:10.1088/0953-2048/21/4/045009
[6] Sedra A S and Smith K C 1998 *Microelectronic circuits*, 4th edition, Oxford University Press
[7] Kiviranta M, Grönberg L and Hassel J 2012 *IEEE Tran. Appl. Supercond.* **22** 1600105. Doi: 10.1109/TASC.2012.2190286
[8] Beev N and Kiviranta M 2013 *Cryogenics* **57** 129-33. Doi:10.1016/j.cryogenics.2013.06.004
[9] Van der Kuur J and Kiviranta M 2013 *APL* **102** 023505. Doi: 10.1063/1.4788683