# A low-noise S-band dc SQUID amplifier

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**ABSTRACT:** A completely integrated RF amplifier based on a dc SQUID (SQA) has been designed, fabricated and tested in the frequency range 3.3 - 4.1 GHz. A new launcher system (SQA-unit) has been developed in order to improve RF coupling between coaxial connectors and coplanar lines on the chip. A negative feedback loop has been implemented to increase the dynamic range of the SQA. The following parameters have been measured for the single-stage device at 3.65 GHz in the feedback mode: gain of (11.0±1.0) dB, 3 dB bandwidth of about 210 MHz, and noise temperature (9.0±1.0) K that corresponds to the flux noise $S_\Phi^{1/2} \approx 0.7\mu\Phi_0/\sqrt{Hz}$ and energy sensitivity $\varepsilon_i \approx 160\ \hbar$ ($2.0\cdot10^{-32}$ J/Hz).

## 1. INTRODUCTION

A completely RF amplifier based on a dc SQUID (SQA), proposed by Koshelets et al (1996), looks a good choice for an IF amplifier integrated with a SIS mixer and a flux-flow oscillator (FFO) in a fully superconducting sub-mm receiver which can be used for radio astronomy at sub-mm. A SQA has a number of advantages over traditional coolable semiconductor low noise amplifiers due to its ultra-low power consumption and natural compatibility with both SIS mixer and FFO. Following the concept of a completely integrated superconducting receiver (Koshelets et al (1997)) the study of an integrated SQA is a logical step towards a densely packed imaging array at sub-mm (Shitov et al (1999a)). Recently Muck et al (1998) have shown that RF amplifiers based on a niobium dc SQUID can achieve gain of about 18 dB and a system noise temperature in the ranged from 0.5±0.3 K (at 80 MHz) to 3.0±0.7 K (at 500 MHz). However for a real radio astronomy application the intermediate frequency bandwidth of at least 4 GHz is required. Recently the advanced design of a SQA has been developed by Prokopenko et al (1997, 1999) at about 4 GHz. This paper presents recent results on the study of a single-stage 4 GHz SQA with a negative feedback loop, which demonstrates its feasibility as an intermediate frequency amplifier for the PLL sub-mm integrated receiver (Shitov et al (1999b)).

## 2. DESIGN OF SQA

A microwave design of the 4 GHz SQA with a novel input resonant circuit has been developed and described by Prokopenko et al (1997). Fig. 1 presents a single-stage SQA that consists of the double washer SQUID, which has two square holes of the same size. The input coil consists of two identical connected in series four-turn sections, which are positioned inside the corresponding holes in the washer. The capacitors $C_1$, $C_2$ are chosen to tune a resonance of the input coil ($L_{COIL}$) at the signal frequency $f_S \approx 3.7$ GHz. The low-pass filter, based on the two coplanar lines with a cut-off frequency of about 50 GHz, is used to transmit the *dc* bias and the signal at $f_S$, but prevents the Josephson current $f_J >> f_S$, from leaking out of the SQUID. The strip

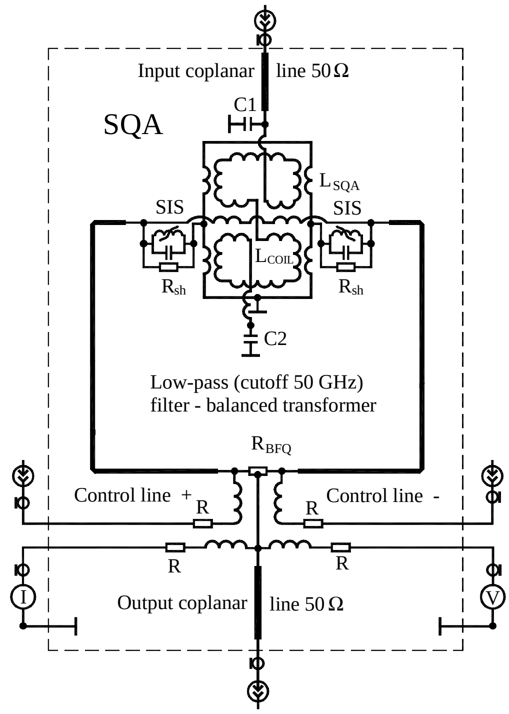


Fig. 1 Equivalent diagram of a single-stage S-band SQA integrated in one chip.

between two shunted ($R_{sh}$) micron-size Nb-$AlO_x$-Nb SIS tunnel junctions is used as an integrated control line (±) for magnetic bias of the SQUID. The resistors R (about 500 Ω each) designed as a high

Table 1. Main parameters of the SQA

| PARAMETERS: | MEASURED VALUE: |
|---|---|
| 1. SQUID inductance | $L_{SQA} \approx 70$ pH |
| 2. Coupling coefficient | $k^2 \approx 0.6$ |
| 3. Area of SIS junction | $\approx 1.0\ \mu m^2$ |
| 4. Capacitance of SIS junction | $C_{SIS} \approx 0.1$ pF |
| 5. Critical current | $I_C \approx 21\ \mu A$, |
| 6. McCamber parameter | $\beta_C \approx 0.1$ |
| 7. Inductance parameter $\beta_L$ | $\beta_L \approx 1$ |
| 8. Shunt resistance per junction | $R_{sh} \approx 8$ Ohm |
| 9. Time constant of the SQUID | $\tau = L_{SQA}/R_{sh} \approx 10^{-1}$ sec |
| 10. Inductance of input coil | $L_{COIL} \approx 3$ nH |
| 11. Input circuit capacitance | $C_1 = C_2 \approx 1$ pF |
| 12. Size of two-stage SQA chip | $6 \times 6$ mm |
| 13. Central operating frequency | $f_c \approx 3.7$ GHz |
| 14. Dynamical resistance at bias point | $R_D \approx 23$ Ohm, |
| 15. Voltage at the bias point | $V_B \approx 18\ \mu V$, |
| 16. Power gain | $G_1(max) \approx 11.0 \pm 1.0$dB |
| 17. Noise Temperature | $T_N(min) \approx 9.0 \pm 1.0$ K |
| 18. Intrinsic flux noise | $S_\Phi^{1/2}(min) \approx 0.7 \mu\Phi_0 Hz^{-1/2}$ |
| 19. Frequency bandwidth of the SQA | $\Delta f\|_{3dB} \approx 210$ MHz |

impedance coplanar line and used to prevent leak of RF signals. The resistor $R_{BFQ}$ = 0.1-1.0 Ω is used to prevent a flux trapping in the loop of the output circuit. This configuration of the output circuit is designed especially to cancel possible signal leakage (common mode) from the input of the SQA. We call this configuration Balanced Output SQUID Amplifier. The main parameters of the SQA are listed in the Table 1.

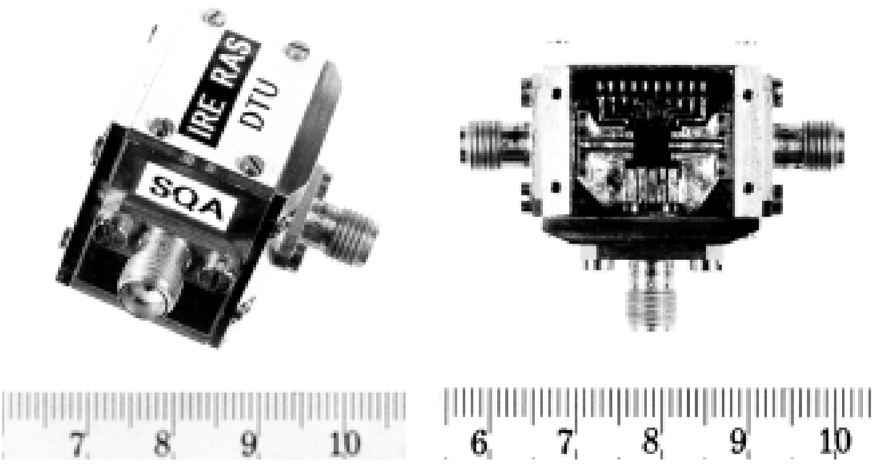


Fig. 2 View on the SQA-unit.

We have designed and tested an SQA-unit (see Fig. 2) - the new launcher system with improved RF coupling between input/output coaxial SMA-connectors and coplanar lines of the SQA chip. Although the chip includes two SQA's it is possible to measure each SQA separately. An intermediate (side) SMA-connector of the SQA-unit is intended for the single-stage measurement (see Fig. 2).

## 3. MEASUREMENT SET-UP

A block diagram of the measurement set-up is shown in Fig. 3. The sample was placed in the SQA-unit inside a liquid $^4$He cryostat shielded by two external μ-metal cans. The combination of a solid state noise source (Noise Com, NC 3208-A, $T_{NS} \approx 2.0 \cdot 10^5$K at 4.0 GHz) and precise step attenuator was used to supply a calibrated signal to the input of the SQA. A stainless steel cable followed by a 20-dB attenuator was placed at 4.2 K to reduce influence of the 300 K noise at the input of the SQA. A coolable HEMT amplifier (G = 30 dB, $T_N$ = 20 K) and a room temperature FET amplifier (G = 34 dB, $T_N$ = 120 K) are used in front of the spectrum analyzer HP-8563A.

In previous experiments Prokopenko et al (1999) have used a room temperature narrow

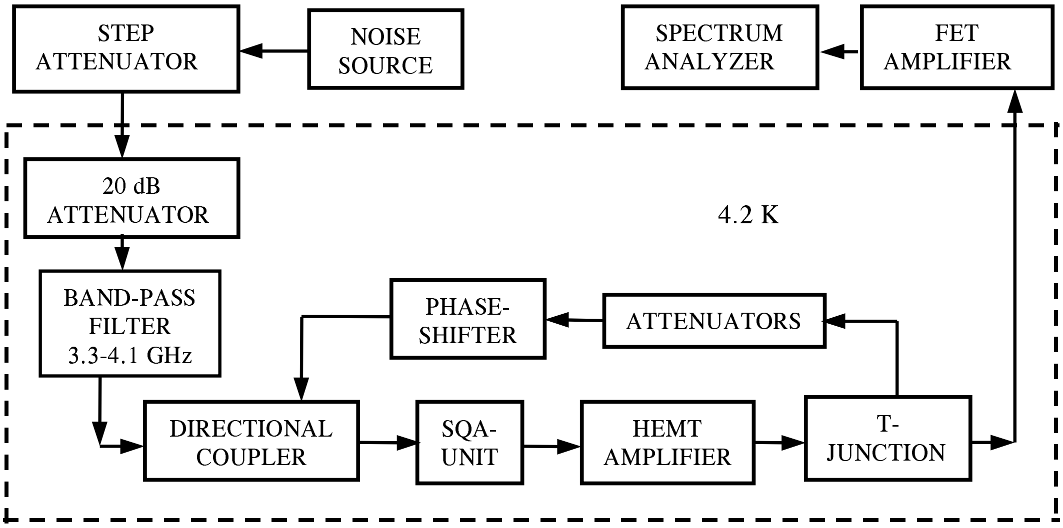


Fig. 3. Block diagram of the measurement set-up for the SQA.

band-pass filter (Δf = 40 MHz) at the input of SQA to avoid saturation that appeared as a noticeable shift of the working point. To increase the dynamic range of a SQA, the negative feedback loop is implemented, and preliminary results are reported in this paper. The loop is formed by a directional coupler (-16 dB) placed at the SQA input, an attenuator, a phase-shifter, and T-junction. To adjust the feedback signal, coolable attenuators in the range of 23 - 26 dB and a tuneable phase-shifter are used. The implementation of this “soft” (-39...-42 dB) feedback loop resulted in locking the operation point of the SQA for input signals up to about 100 K.

## 4. EXPERIMENTAL RESULTS AND DISCUSSIONS

A noise temperature and a gain of the SQA have been evaluated by a standard Y-factor technique using hot/cold response of the system by reading data from the spectrum analyzer. The "cold" signal was estimated as 5.75±0.25 K for the cold input attenuator of 20 dB and the room temperature step attenuator set at 110 dB. Several different settings of the step attenuator (15 dB, 11 dB and 5 dB) have been used that corresponds to the "hot" signal of 23 K, 55 K, and 122 K at the input of the SQA.

The data set presenting the experimental noise temperature of the system SQA+HEMT, and HEMT alone is shown in Fig. 4. The upper plot is measured for open feedback, the lower plot is for closed one. One can see that the closed feedback mode allows to get the almost linear response up to input signals of about 100 K, while in the open feedback mode the SQA saturates at the input signal as low as ≈55 K. The noise temperature and the gain for these two cases are shown in the Fig. 5. In the case of an open feedback (upper plot): the gain is 8-9 dB, $T_N \approx$ 7-10 K; for a closed feedback (lower plot): the gain is ≈ 9-11 dB, $T_N \approx$ 9-12 K. The increase of $T_N$ for the closed feedback can be explained by extra noise from the following HEMT- and FET-amplifiers ($T_N$ = 20 K and 120 K respectively) introduced to the input of the SQA via the feedback path, while the effective gain can, in principle, be larger due to improvement of match between the SQA and the signal source. One can see that the feedback mode gives also some improvement of a frequency band of the amplifier (see Fig. 5).

## 4. CONCLUSION

The experimental S-band amplifier based on a dc SQUID with negative feedback is designed and tested. The main parameters of SQA referred to the SMA connectors of the amplifier in the feed back mode: gain 11.0±1.0 dB, 3 dB bandwidth 210 MHz, noise temperature 9.0±1.0 K at the center frequency of 3.65 GHz. The dynamic range at the input is increased up to 100 K that makes the feedback SQA applicable as an IF amplifier for a SIS mixer. The SQA of present design is planned for use with a superconducting integrated receiver as a preamplifier of a coolable IF chain.

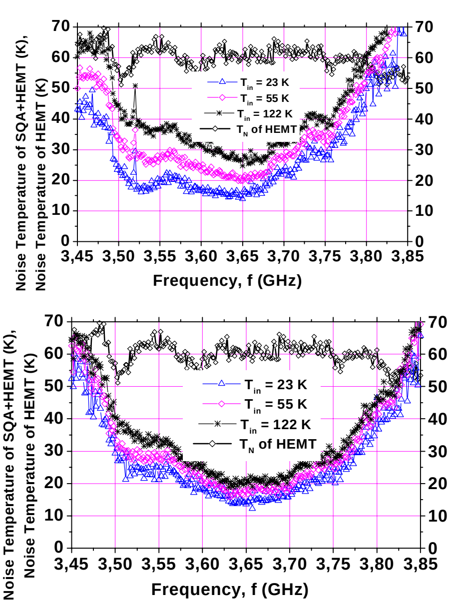


Fig. 4 Noise temperature of the system SQA + HEMT and for HEMT only: open feedback (top), closed one (bottom).

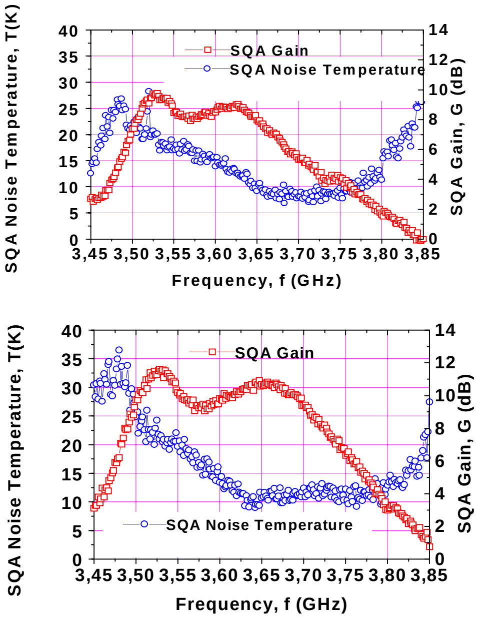


Fig. 5 Noise temperature and gain for $T_{in}$ ≈ 122 K: open feedback (top) and closed one (bottom) The error bar is 1.0 K and 1.0 dB

## 5. ACNOWLEDGEMENTS


The work was supported in parts by the Russian SSP "Superconductivity", INTAS project 97-1712, the Danish Research Academy, and the Danish Natural Science Foundation.


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