Low-noise S-band DC SQUID based Amplifier

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Abstract— **A low-noise rf amplifier based on a dc SQUID (SQA) is tested in the frequency range 3.3 - 4.1 GHz. A new signal launching system for the SQA rf coupling has been developed and successfully implemented. The following parameters have been measured at 3.65 GHz using a band-pass filter at the input of a single-stage SQA: gain (11.0±1.0) dB, 3 dB bandwidth of 300 MHz and noise temperature (4.0±1.0) K. This figure corresponds to a flux noise $S_\Phi^{1/2} \approx 0.6\ \mu\Phi_0/Hz^{1/2}$ and an energy sensitivity $\varepsilon_i \approx 75\ \hbar$. The input saturation power, P_S, (1 dB gain compression) is measured for different bandwidths of the input band-pass filter. A corresponding input signal saturation temperature (normalized for a 1 GHz bandwidth) $T_{SAT}^{1GHZ} = P_{SAT}/k_B$ is estimated to be 11.5 K*GHz at an SQA bias voltage 27 μV (condition for minimum noise temperature). The dependencies of the SQA gain, noise temperature and saturation level on the operation point are studied. A reason of the SQA saturation is discussed.**

Index Terms— **dc SQUID, Josephson junctions, rf amplifier, superconducting device.**

I. Introduction

THE paper presents results of an experimental study of a completely integrated RF amplifier based on a dc SQUID (SQA) [1].

The SQA appears to be a good choice as IF amplifier integrated with a SIS mixer pumped by a flux-flow oscillator (FFO) in an all-superconducting sub-mm receiver [2] which can be used, e.g., for radio astronomy. A semiconductor-based IF amplifier 'integrated' into the fixture of the SIS mixer has demonstrated quite encouraging result [3]. However, the use of such amplifiers create sever problems with heating (20 mW per stage, typically). The SQA has a number of advantages compared to traditional semiconductor amplifiers: ultra-low power consumption, small size and natural compatibility with SIS based structures. The study of the SQA is a logical step for further integration of superconducting rf devices which simultaneously can minimize noise, heat and space problems in future receivers and rf detectors.

The SQA is a promising device for the following applications: i) IF amplifier of a sub-mm spectrometer based on Superconducting Integrated Receiver (SIR) with phase-locked loop (PLL) [4]; ii) IF amplifier for a superconducting Imaging Array receiver [5]; iii) amplifier for satellite communication.

It has been shown by Mück et al. [6] that RF amplifiers based on a niobium dc SQUID with a resonant stripline input can achieve a gain of about 18 dB and a noise temperature as low as (0.5± 0.3) K at 80 MHz and (3.0 ± 0.7) K at 500 MHz. With the SQUID amplifier cooled to (0.4 - 0.5) K in a ^{3}He refrigerator, an intrinsic noise temperature of about 0.1 K has been measured at frequencies up to 500 MHz [7]. Two microstrip SQUID amplifiers with the same resonant frequency have been cascaded to achieve a gain of (33.5 ± 1.0) dB at 386 MHz (4.2 K) [8]. Such amplifiers have shown a gain of about 15 dB at frequencies up to 1.6 GHz. [9].

However for most radio astronomy applications the intermediate frequency bandwidth of at least 4 GHz is required. Our preliminary study of the SQA revealed strong saturation effects for the two-stage configuration [10]. Saturation may occur even in single-stage operation when SQA used in a wide frequency band. Here we report on a detailed study of the dynamic range and saturation effect of the rf amplifier based on a dc SQUID.

II. SQA RF Design

The microwave design of the S-band SQA with resonant input circuit has been described in details elsewhere [1], [10]. To avoid parasitic resonances in the SQUID, the design of the coupling circuit has been developed by using scale modeling to optimize the shape of both the SQUID washer and the input coil. The single-stage SQA consists of a double-washer type SQUID which has two square holes in the ground plane, each of the same size with side length 60 μm. The input coil consists of two identical sections connected in series and positioned inside the corresponding holes in the washer. This configuration yields a small SQUID inductance L_{SQA} = 70 pH as well as a large coupling coefficient ($k^2 \approx 0.6$).

The dc SQUID consists of two ~1 μm^2 Nb-AlO$_X$-Nb SIS shunted junctions. Two capacitors in the input circuit tune the SQA to the center frequency $f_S \approx 3.7$ GHz. The low-pass filter at the output has a cut-off frequency of about 50 GHz. This filter transmits *dc* bias current and the signal at f_S, but prevents the Josephson current $f_J >> f_S$ from leaking out of the SQUID. To adjust the magnetic bias, the common part of the two-loop washer of the SQUID is used as an integrated control line. The balanced configuration of the output circuit is designed to cancel a possible signal leakage (common mode) from the SQA input. An improved launching system (so called SQA-unit) is a sort of housing that provides dc bias and rf coupling between the input/output coaxial connectors (SMA) and the chip amplifier.

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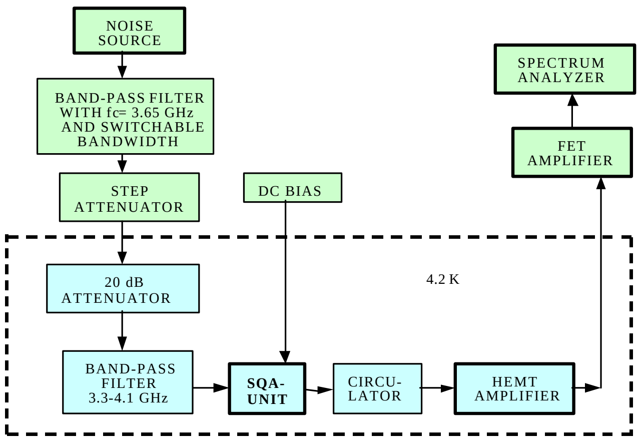

Fig.1. Block-diagram of the SQA measurement set-up.

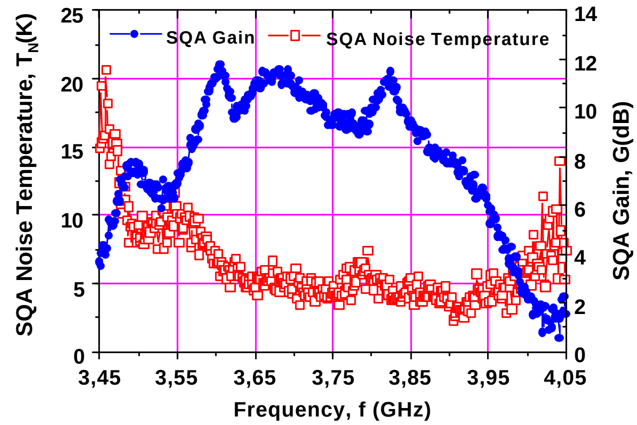

Fig. 3. SQA noise temperature and gain for a wideband input signal $T_{IN}^{HOT} \approx 16.0$ K. The error bars are 1.0 dB and 1.0 K respectively.

III. Measurement Set-up

A block-diagram of the measurement set-up is shown in Fig. 1. The cryostat, with the sample chip placed in the SQA-unit, is shielded by two room-temperature μ-metal cans. A solid state noise source (Noise Com, NC 3208-A, $T_{NS} \approx 2.0 \cdot 10^5$K at 4.0 GHz) was used to supply a calibrated signal to the SQA input. A switchable band-pass filter [11] with fixed center frequency $f_C = 3.65$ GHz has three 3 dB bandwidths of $\Delta f_1 \approx 141$ MHz, $\Delta f_2 \approx 41$ MHz and $\Delta f_3 \approx 15.5$ MHz. A precise step HP attenuator is used to adjust the level of the input signal. A stainless steel cable followed by a 20 dB attenuator was placed at 4.2 K to reduce the 300 K room temperature noise at the input of the SQA-unit. An additional a band-pass filter (3.3 - 4.1) GHz reduces the noise power input to the SQA. A cooled circulator is used after SQA-unit to minimize the noise contribution from the next amplifiers. A cooled HEMT amplifier [11] (G = 30 dB, T_N = 20 K) and a room temperature FET amplifier (G =34 dB, T_N = 120 K) boost the signal to the spectrum analyzer HP-8563A.

A voltage bias is used for the SQA study because the dc SQUID has a relatively high differential resistance, $R_D \approx 50\ \Omega$ Actually, it is similar to a standard SIS-mixer operation.

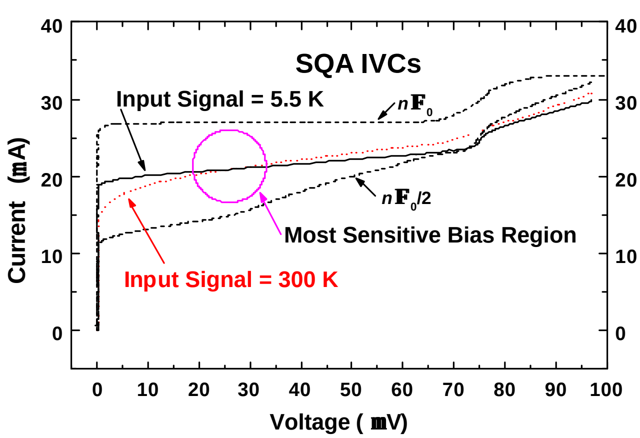

Fig. 2 SQA IVC recorded with an wideband input signal at 5.5 K and 300 K.

The IV-curves at different flux bias of the SQA (equal to $n^*\Phi_0$, $n^*\Phi_0/2$ and $n^*\Phi_0/4$) are shown in Fig. 2. A flux bias equal to $n^*\Phi_0/4$ was found to be the optimum value for SQA operation.

The noise temperature and gain of the SQA were measured by the standard Y-factor technique using “hot” and “cold” input signals. The "cold" signal was estimated to 5.5±0.25 K for a 4.2 K 20 dB attenuator in series with a 110 dB room temperature attenuator. This includes loss in the cables and in the band-pass filters. Incremented settings of the step attenuator (24 dB, 21 dB, 18 dB, 15 dB, 12 dB, 9 dB, and 6 dB) were used to generate the "hot" signal with noise temperatures T_{IN}^{HOT} = 6.5 K, 8.0 K, 11.0 K, 16.0 K, 29.5 K, 50.0 K, and 97.0 K at 3.65 GHz.

IV. Experimental Results and Discussions

The influence of the wideband input noise of about 300 K on the IVC of SQA is clearly seen in Fig. 2 as a smoothing of the IVC near its corners. This effect is described in [12]. It means that the amplitude of the wideband signal (amplified by the SQA) is so large that a self-detection effect is seen (SQA saturates). The input power P_{IN} can be defined as $P_{IN} = k_B \cdot T \cdot \Delta f$, and is of the order of 1.2 pW for thermal noise of T = 300 K and an effective bandwidth Δf = 300 MHz. Here k_B is the Boltzmann's constant. Due to saturation only low input signals were used for SQA tests in wideband mode.

The noise temperature and gain of the SQA-unit for the wideband input signal $T_{IN} \approx 16$ K are shown in Fig. 3. The data are taken with a SQA bias of 27 μV that is close to the condition of minimum noise temperature. The dependencies of the SQA gain and noise temperature are presented in Fig. 4 as a function of the input temperature T_{IN}^{HOT}. In this case the input bandwidth is defined by the effective bandwidth of the SQA, not by the filter. A 3 dB bandwidth $\Delta f\,|_{3dB} \approx 300$ MHz is found from the gain curve (see Fig. 3). From Fig. 4 one can see that the gain decreases with increasing T_{IN}^{HOT}. The 1 dB compression point occurs at an input signal of 34 K for a bandwidth of about 300 MHz.

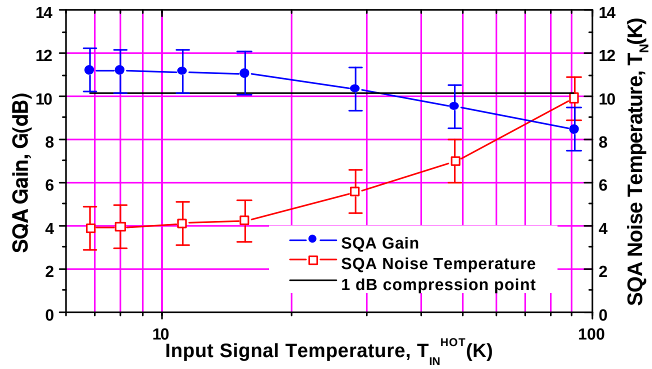

Fig. 4. The SQA gain and noise temperature as a function of input signal for a wideband input signal at the frequency 3.65 GHz.

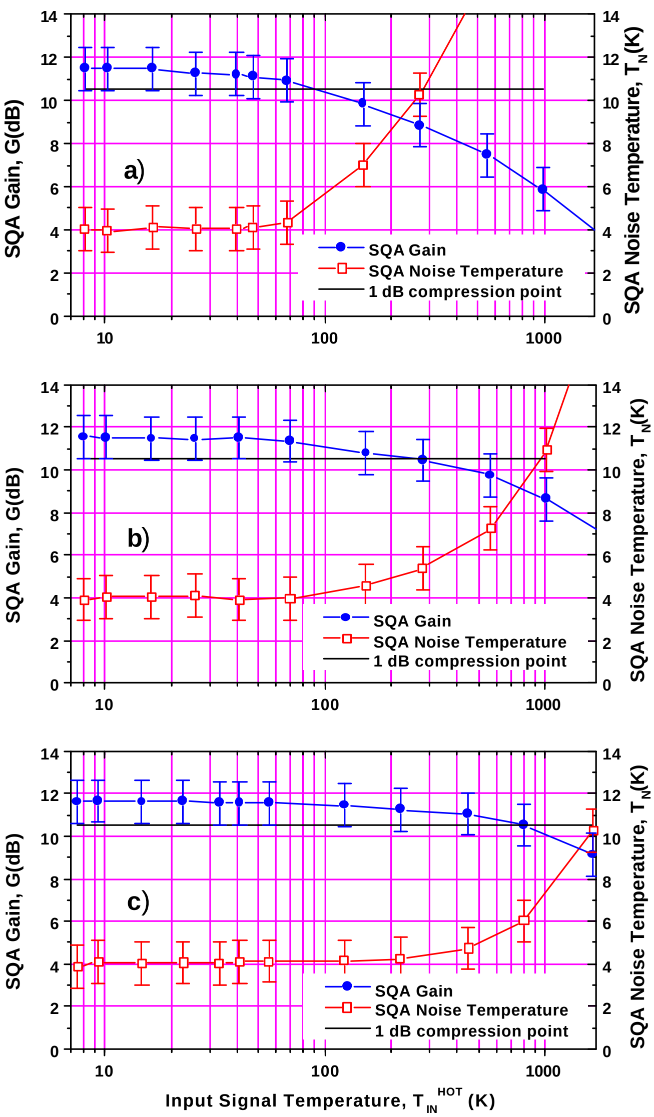

Fig. 5. The SQA gain and noise temperature measured at 3.65 GHz as function of the input signal temperature for different bandwidths of the input signal:. a) 141 MHz; b) 41 MHz; c) 15.5 MHz.

Fig. 5 shows the SQA gain and noise temperature measured by using the band-pass filter with fixed center frequeny, 3.65 GHz, and different values of the 3-dB bandwidth: 141 MHz, 41 MHz and 15.5 MHz. From Fig. 5 we find that the 1 dB compression takes place: 90 K for 141 MHz bandwidth; 250 K for 41 MHz, and 750 K for 15.5 MHz, correspondingly. The input power at 1 dB compression point, P_{SAT}, was determined for different values of the band-pass filter and was found to be approximately 0.16 pW. A more convenient quantity – the saturation temperature (normalized to 1 GHz bandwidth), $T_{SAT}^{1GHz} = P_{SAT}/k_B$, can be introduced. This gives $T_{SAT}^{1GHz} = (11.5 \pm 1)$ K*GHz for a bias voltage of about 27 μV.

The parameters of the SQA strongly depend on the bias voltage. To avoid saturation effects the characteristics were measured with the narrow 15.5 MHz band-pass filter. The dependences of the SQA gain, noise temperature and the normalized saturation temperature on bias voltage are shown in Fig. 6. One can see from Fig. 6a that the optimum bias voltage for maximum gain (about 15 μV) is different from voltage of minimum noise temperature. This is also usual for semiconductor amplifiers. The saturation temperature increases almost linearly with bias voltage up to 35 μV, this behavior will be discussed later.

The differential resistance R_D defines the important parameter - the output coupling coefficient between the SQA and the load. The differential resistance measured from the IVC as a function of the operation point is presented in Fig. 7a. This figure shows also the SQA coupling coefficient which is used for calculation of maximum available output

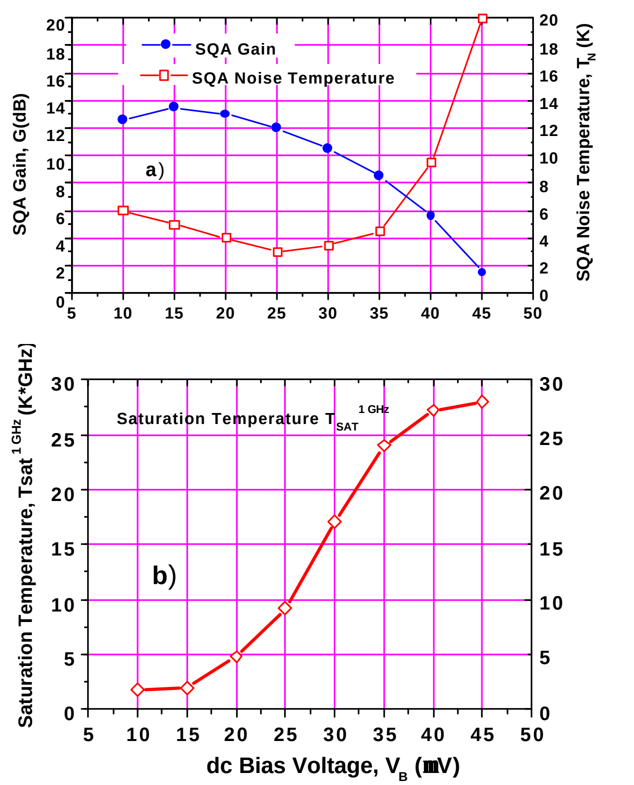

Fig. 6. SQA gain and saturation temperature in dependence on dc bias voltage at the dc flux bias $\Phi_0/4$.

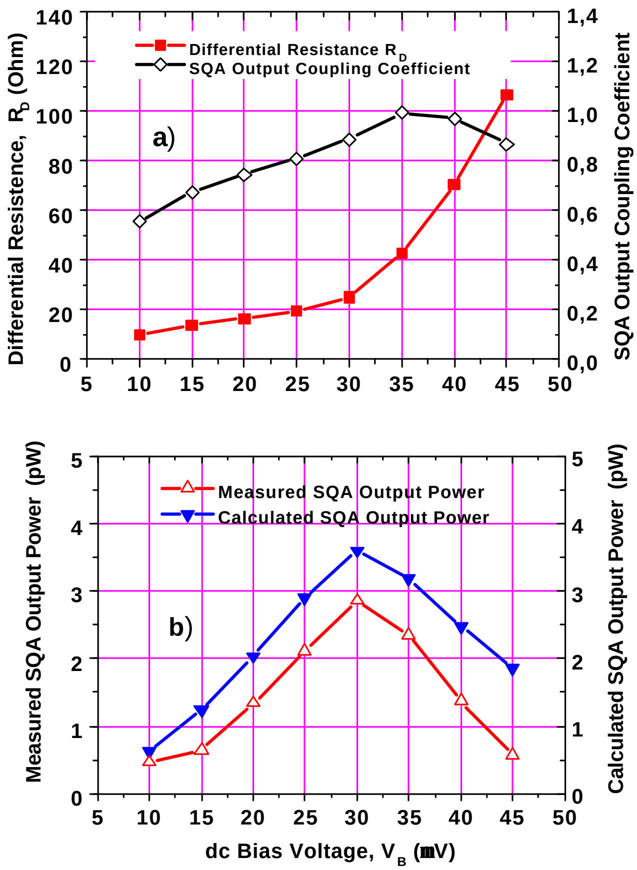

Fig. 7. a) The differential resistance R_D and SQA output coupling coefficient C_{OUT} versus dc bias voltage; b) the output saturation power (measured and calculated) as function of bias voltage.

SQA power. The coupling coefficient is calculated from the standard equation: $C_{OUT} = 4R_DR_{LOAD})/(R_D+R_{LOAD})^2$, where R_{LOAD} is the 50 Ω impedance of the circulator.

The measured SQA output power for a 15.5 MHz input filter and the maximum available output power, calculated from the IVC operation point, are shown in Fig. 7b. The measured SQA output power is defined from the measured figures using $P_{OUT} = k_B(T_N+T_{SAT})\Delta f_{15}G_{1dB}$, where T_N – is the SQA noise temperature, T_{SAT} – the input signal saturation temperature, Δf_{15} – the effective bandwidth of the 15.5 MHz band-pass filter, G_{1dB} – SQA the gain at the 1 dB compression point (see Fig. 6a). The calculated maximum available output power is defined as $P_{OUT}(calculated) = C_{OUT}[(V_{AMP})^2/8R_D]$. The value $C_{OUT}(V_B)$ is the SQA output coupling coefficient (see Fig. 7a), $V_{AMP}(V_B)$ is the maximum rf voltage amplitude of the SQA, that can be realized without limitations by the zero voltage state. The value of $V_{AMP}(V_B)$ is taken equal to V_B for this estimation. One can see from Fig. 7b that there is a good agreement between the experimental and calculated output power.

The saturation temperature of the SQA can be estimated from $T_{SAT} \approx C_{OUT}\cdot V_B^2/(8R_D\cdot kB\cdot\Delta f\cdot G_{SQA}) - T_N$; i.e., T_{SAT} depends strongly on V_B. In turn, the characteristic voltage $V_C = I_CR_N$ defines the highest possible V_B.

IV CONCLUSIONS

The experimental S-band amplifier based on a dc SQUID is designed and studied. The main parameters of the SQA referred to the SMA connectors of amplifier are following: gain (11.0±1.0) dB, 3 dB bandwidth of about 300 MHz and noise temperature (4.0±1.0) K. The dependence of these parameters on bias voltage has been evaluated. The saturation effects have been studied, the value of the input signal saturation temperature (normalized for 1 GHz bandwidth) is estimated as 11.5 K*GHz. In order to increase the dynamic range of the SQUID amplifier one should increase the characteristic voltage V_C and use a parallel array of junctions.

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