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Study of a Multi-Channel RF Amplifier Based on DC SQUID for 3-5 GHz Band

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***Abstract*— A low-noise rf amplifier based on a dc SQUID (SQA) is developed and tested within frequency range 3.0 - 4.5 GHz. The 4-channel chips are designed using proven balanced output configuration; they employ special damping filters. Each channel is tested separately demonstrating the following parameters at 3.95 GHz central frequency: gain (9.5±1.0) dB, 3-dB bandwidth 300 MHz and noise temperature (1.0±0.5) K. The 1-dB gain compression estimate is 50 K*GHz for bias voltage 80 μV and characteristic voltage 285 μV.**

***Index Terms*— RF Amplifiers, Josephson effect, SQUIDs.**

I. Introduction

THE SQA appears to be a good choice as rf amplifier for ultra low-noise applications within frequency range of a few GHz. The SQA has a number of advantages compared to traditional semiconductor amplifiers: nearly quantum limited noise, which can be reduced to the mK level via deep cooling [1], ultra-low power consumption, small size and natural integration compatibility with many superconducting detectors and signal processing structures. Our study of multi-channel SQA is a logical step towards integration of superconducting rf devices that simultaneously can minimize noise, heat and packaging problems for future superconducting rf detectors. The SQA is a promising device at least for the following applications: i) IF amplification after a SIS-mixer and especially for imaging array mixers including a Superconducting Integrated Receiver with phase-locked loop [2]; ii) rf pre-amplifier for RSFQ ADC; iii) amplifier for mobile and satellite communications.

In previous papers [3]-[6] we have already presented experimental data on rf SQUID amplifiers. The present paper continues the detailed experimental study of dynamic and noise characteristics of SQA towards practicable rf applications.

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II. Design of 4-channel SQA Chip

A. General Design

Photo of the 4-channel chip is presented in Fig. 1; the chip size is 5 mm x 5 mm. Each SQA channel (marked from 1 to 4) occupies an area 1 mm x 5 mm and can be tested separately. These single-stage SQAs, based on shunted high quality Nb-AlOx-Nb SIS junctions, contain the double-washer gradiometer SQUIDs, which have two square holes in the ground plane, each of the same size 40 μm x 40 μm, as shown in Fig. 2. Two identical double-layer coils connected in series and positioned inside the holes of the 'washer' introduce the input signal flux. Two integrated capacitors, C1 and C2, tune the coil of each SQA to its specific central frequency. The balanced SQA contains two output low-pass filters, as shown in Figs. 1 and 4. The roll-off frequency of the filters is about 50-100 GHz; they prevent the Josephson ac current from leaking and provide also symmetrical biasing of the SQUIDs. To adjust the flux (magnetic bias), the current through the common part of the washer is used. The balanced configuration of the output circuit allows for canceling signal leak from the SQA input to its output and vice versa. The frequency selection (at the input) and the power combining (at the output of the amplifier) have to be realized via special

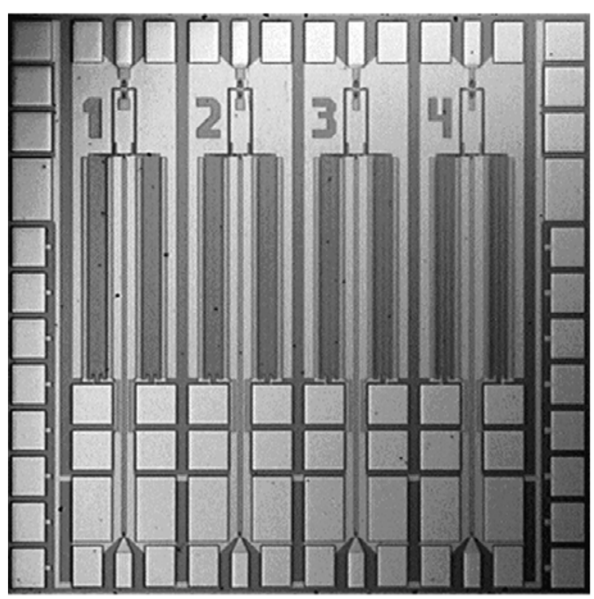

Fig. 1. Photo of 4-channel SQA chip.

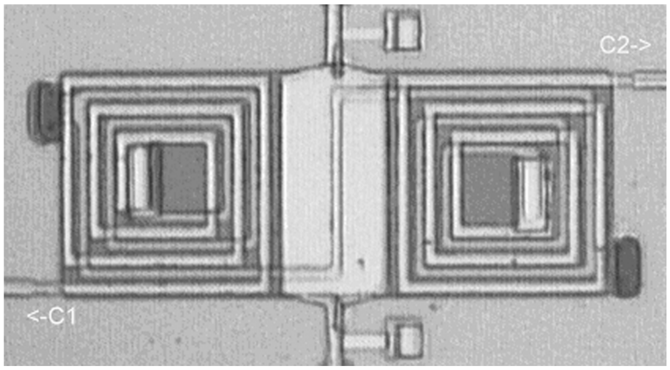

Fig. 2. Photo of two-layer coil.

(optional) circuit, which is an extension to the present chip [7]. The double-layer coil, shown in details in Fig. 2, allows for a tight winding (with gaps between turns less than 1 µm). This coil of increased inductance is placed inside a smaller loop 40 µm x 40 µm, thus, providing quite similar coupling factor, if compared to our previous design [3]-[6]. The SQUID inductance is now decreased down to ≈ 40 pH, and higher critical current for the Josephson junctions is now possible.

B. Output Filters Concept and Practical Design

The RSJ model predicts an IV-curve of the Josephson junction, assuming its current loaded with the purely resistive shunt and the junction's capacitance. However, this model is too simple to be used in practice. Creating an amplifier, we have to establish at least two extra connections between the SQUID and the outer world: input and output circuits. The input connection provides the signal via magnetic coupling, and the output one takes some signal current out of the SQUID system. If we assume a RF-matched amplification system, only half of the output power is remaining within the SQA pre-amplifier, while the other 50% are taken away towards the following buffer amplifier(s). This means that we got risk of strong coupling of the SQUID to the external RF system at Josephson frequency. Note that the bandwidth of the following off-chip amplifier (which is that practicable RF load) is usually limited approximately to about twice the center frequency. The absence of proper damping outside the signal band results usually in the distortion of the IV-curve of SQUID due to the multiple resonances of the Josephson current (up to $2eV_C/h \approx 100$ GHz, where V_C is characteristic voltage, e is unit charge and h is the Plank's constant). The distorted IV-curve

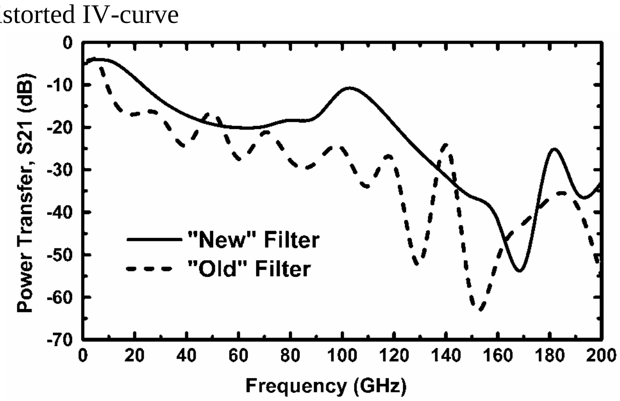

Fig. 3. Calculated transmission of "new" and "old" filters.

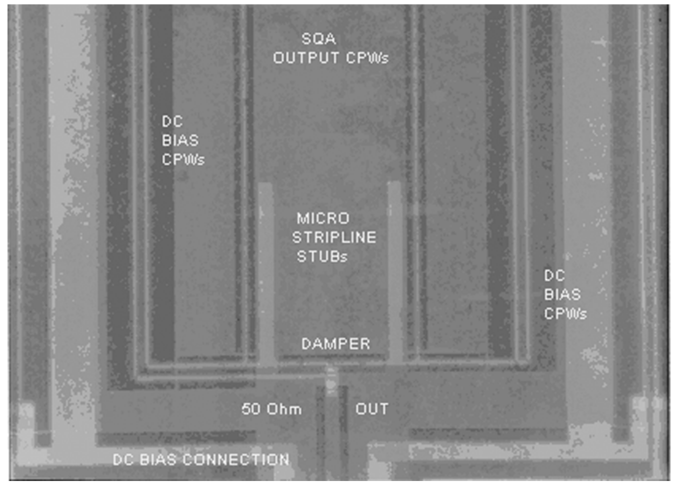

Fig. 4. Photo of main part of output filter.

reduces dynamic range of the SQA, as it was discussed in [6]. This means some special measures have to be taken for the wide-band damping of the Josephson current of the SQUID in presence of the strong coupling of the SQA output at the signal frequency. To realize such damping, special attenuators can be used at the output leads of the SQUID [8]. This measurement technique allows for quite accurate measurement of the SQA parameters within a complex experimental setup. However, the resistive damping results in the loss of gain and such amplifiers may be not so attractive for the practicable applications. We have tried to develop special filters, which support the desirable isolation of the SQUID from the output circuit at frequencies much higher than the signal frequency (above approximately 5 GHz in our case). The output filter contains two high-impedance CPW lines, which are connected at the output port with two low-impedance microstrip stubs, as shown in Fig. 4. This combination forms a pair of low-pass sub-filters. The filters support high transmission for the amplified signals, assuming that the damping provided by the load is close to 50 Ohm. At higher frequency the impedance of the filters at the port connected to the SQUID is growing up to 150 Ohm, providing low leak of the Josephson current and, thus, suppressing strong resonance phenomena, which could disturb the IV-curve, up to about 200 µV (see Fig. 5). In other words, in presence of the filters the important portion of the IV-curve (within the range of 10-200 µV) behaves, as the SQUID were completely isolated. Additional high-resistive CPW lines are used for the dc bias, which are also connected near the output port of the circuit.

The additional thin-film damping resistors (just several Ohms) are used for suppressing the specific high frequency resonances of the superconducting filters at high frequencies. The transmission of the "new" and "old" filters is shown in the Fig. 3. The "new" and "old" filters have similar design, except the length of high-impedance CPW, which for "old" filter is about 3 times longer (≈2.5 mm). The length of microstrip stubs is tuned for optimum performances of each filter. One can see from Fig. 3 "new" filter has only one pronounced resonance at about 100 GHz that corresponds to 200 µV of dc bias.

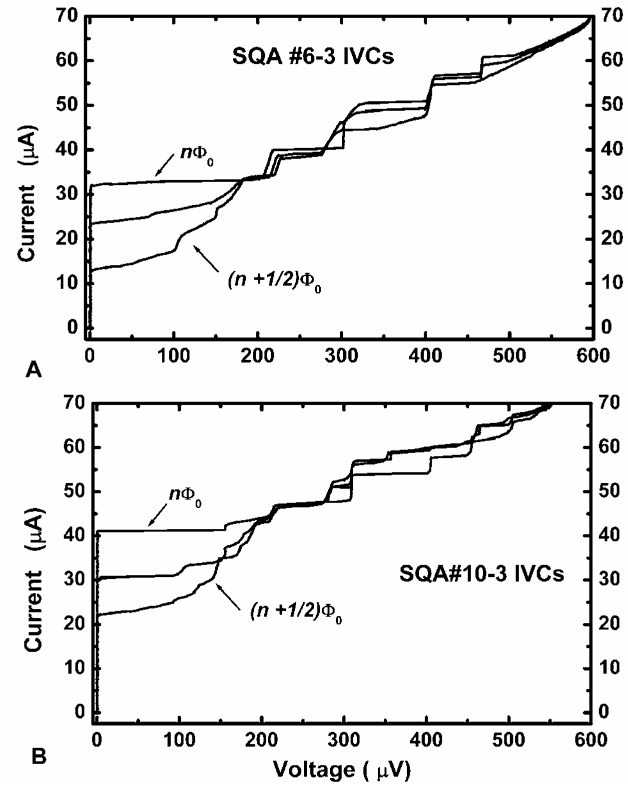

Fig. 5. IV-curves of SQA#6-3 - (A) and #10-3 (B).

The “old” filter has several resonances within frequency region 20-100 GHz that can limit the dynamic range of SQA.

III. Experimental Results and Disccussions

The typical IV-curves of tested SQAs are presented in Fig. 5. One can see multiple steps, which can be associated with resonance phenomena of the distributed output filters at the Josephson frequencies. The “new” output filter of SQA #6-3 suppresses the small resonance steps in the “active” operation region of 10-100 μV. The out-of-band steps are shifted to higher dc voltage – higher than 100 μV.

The “old” filters, which are improved by the additional dumping resistor, also provide quite smooth IV-curves below 100 μV. These mean that amplitude of distributed resonances is sufficiently suppressed by the damper. More experimental data of the filters functioning can be obtained from studying the dynamic characteristics of the SQA.

A few channels are tested at 4.2 K, and their main parameters are summarized in Table 1, where I_C is the critical current and R_N - normal resistance of SQUID. The standard hot/cold technique was used. The experimental setup is described in more detail elsewhere [3]-[5]. The wideband noise signal $T_{IN}^{HOT} \approx 30$ K ($T_{IN}^{COLD} \approx 4.8$ K) and dc bias 60 μV are used for all measurements of frequency-dependent noise temperature and power gain are presented in Fig. 6. We would like to emphasize that all measurements of gain and noise are referred to the input connector of the SQA-unit and are not corrected for loss of the input/output filters, which are at least 4 dB (see Fig. 3). Comparing the old and new results, we may conclude that the improvement in the design of filters

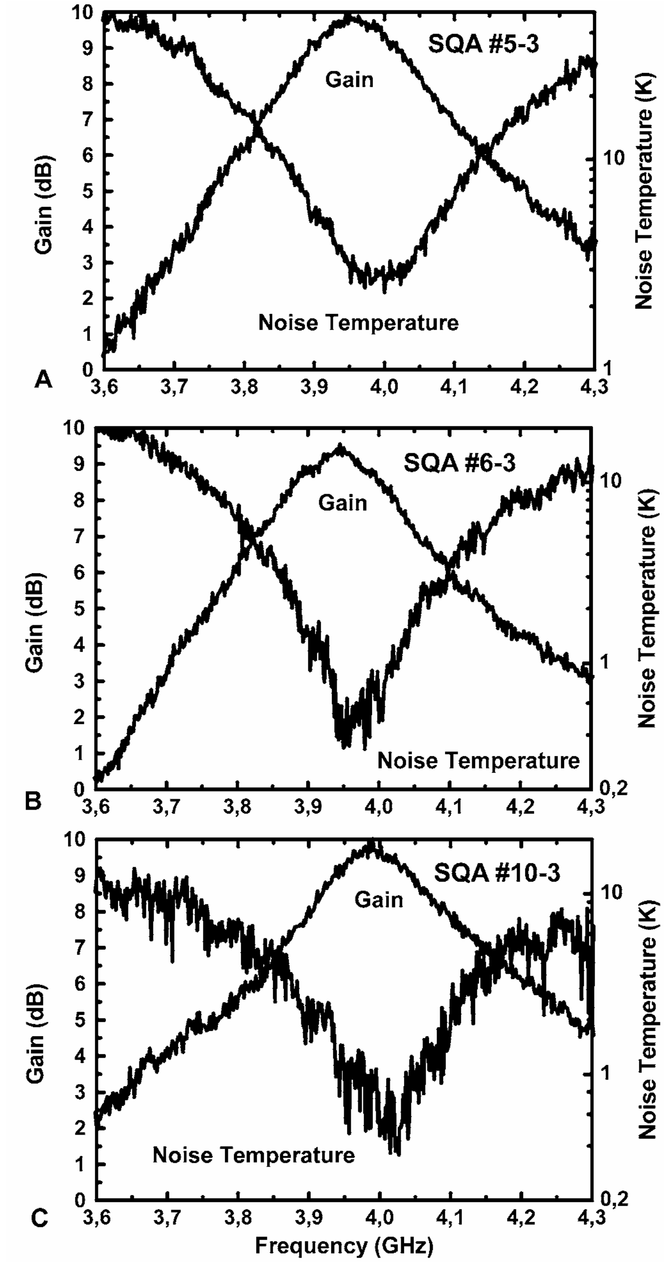

Fig. 6. Noise temperature and power gain vs. frequency of SQA#5-3 (A), #6-3 (B), and #10-3 (C).

TABLE I
SQA Parameters

Sample ID	Channel #	V_C (μV) I_C (μA) R_N (Ω)	Gain (dB)	Noise temperature (K)	BW (MHz)	Central frequency (GHz)
#5-3 “new” filter	3	V_C = 407 I_C = 49 R_N = 8.3	9.8±1	2.5±0.5	300	3.95
#6-3 “new” filter	3	V_C = 285 I_C = 32 R_N = 8.9	9.5±1	0.5+0.5/-0.25	300	3.95
#10-3 “old” filter	3	V_C = 349 I_C = 49 R_N = 8.3	9.7±1	1.0±0.5	250	4.0

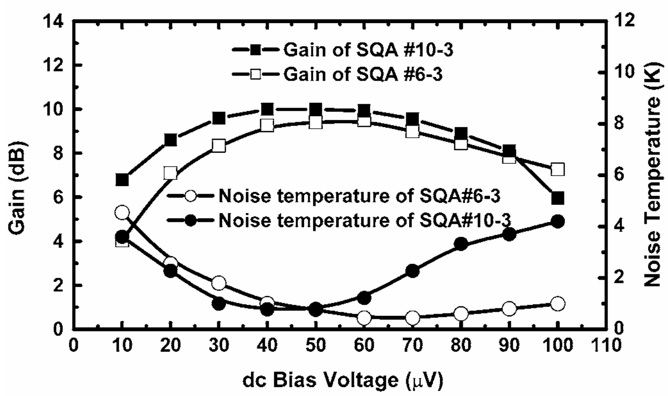

Fig. 7. Gain and noise temperature vs. dc bias voltage of SQA#10-3 and #6-3.

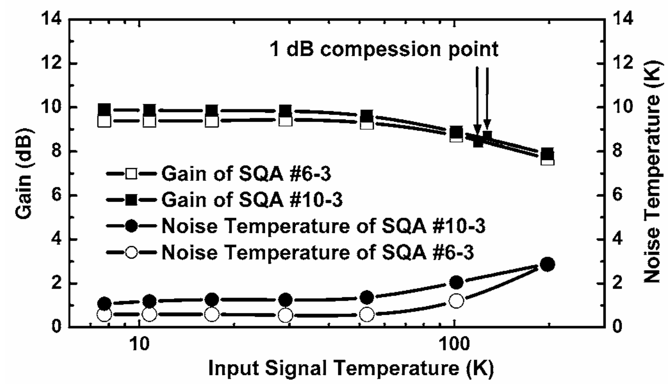

Fig. 8.Gain and noise temperature vs. input signal of SQA#6-3 and #10-3.

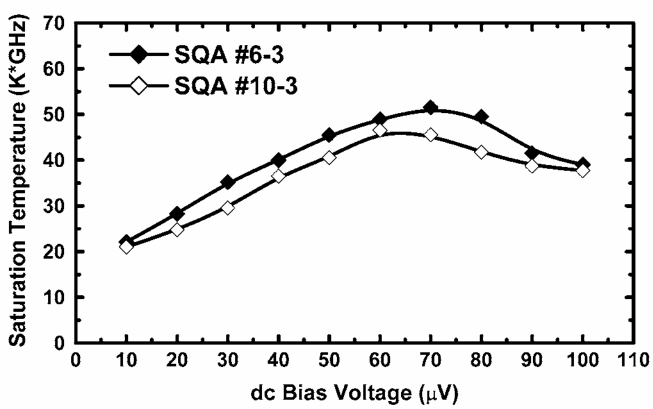

Fig. 9. Saturation temperature vs. dc bias voltage of SQA #6-3 and #10-3.

allows better performance of SQA without significant increasing of V_C [6]. The higher noise of SQA#5-3 can be explained with slightly hysteretic IV-curve of the device that is possibly related to its higher V_C (see Table 1). Fig. 7, Fig. 8 and Fig. 9 present the data for two amplifiers with different output filters as a function of dc bias voltage and input signal temperature. Different dc voltage-dependences of gain and noise temperature between #6-3 and #10-3 is shown in Fig.7. Especially #6-3 shows wider low noise region than #10-3, indicating that "new" filter behaves better than "old" one.

It seems the difference can be explain via rf matching conditions between the Josephson junction and the input impedance of the filters at higher (out of signal band) frequencies. The numerical analysis of the SQA, using for example PSCAN software [9], shows a very complex time-domain behavior and numerous combination frequencies, which termination depends on the design of the damping filter. Thus, operation of different SQAs can depend on the dc bias (on the Josephson process at the bias point).

It is found using Fig. 8 that 1-dB gain compression point corresponds to the input temperature of about 150 K for SQA #6-3 (BW=300 MHz) and about 170 K for SQA #10-3 (BW=250 MHz). The resulting saturation temperature normalized to 1 GHz bandwidth, T_{SAT}^{1GHz}, on dc bias voltage is shown in Fig. 9. The normalized saturation temperature of SQA #6-3 is smoothly increasing with dc voltage up to about 50 K*GHz; it has a clearly expressed maximum at the bias voltage of 75 μV. The saturation level of SQA#10-3 has maximum of about 45 K*GHz at 60 μV. One cannot see significant difference on saturation temperature between #6-3 and #10-3, but #10-3 has higher V_C then #6-3 (see Table 1). These values of saturation are acceptable, if a combination of SQA with a submillimeter SIS mixer is planned.

IV. Conclusion

A 4-channel SQA chip is developed and fabricated; a few channels are preliminary tested. The SQA with double-layer high-density input coil is demonstrated being a promising new design, which fits requirements of the RSFQ technology. Experimental study of the output circuit demonstrated possibility of improvement in the noise temperature of SQA without increase of V_C; two designs of the integrated output filter are tested. The best result is attained with improved filter at 3.95 GHz: noise temperature of (0.5+0.5/-0.25) K, gain of (9.5±1.0) dB and normalized saturation temperature of 50 K*GHz.

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