

Two-Stage S-band DC SQUID Amplifier

Georgy V. Prokopenko, Dmitry V. Balashov, Sergey V. Shitov, Valery P. Koshelets
Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Mokhovaya 11, 103907 Moscow, Russia

Jesper Mygind
Department of Physics, Technical University of Denmark, B309, DK-2800 Lyngby, Denmark

Abstract — A 6 mm x 6 mm chip comprising two identical dc SQUID based amplifiers (SQAs) has been designed, fabricated and tested as a two-stage RF amplifier in a frequency range 3.5-4.0 GHz. Each SQA consists of a double washer type dc SQUID with novel integrated input resonant circuit. The reflection coefficient of both input and output of the SQA has been measured in the two-stage configuration. To avoid SQA saturation at the wide band noise tests a tunable 40 MHz band-pass YIG-filter has been used. The following parameters of the two-stage SQA have been measured at the 3.65 GHz: gain of (17.5 ± 1) dB, 3 dB bandwidth of about 250 MHz, and noise temperature (4.0 ± 0.5) K what corresponds to intrinsic flux noise $S_{\Phi}^{1/2} \approx 0.6 \mu\Phi_0 \text{Hz}^{-1/2}$ and energy sensitivity $\epsilon_i \approx 75 \hbar (7.8 \cdot 10^{-33} \text{ J/Hz})$. If the measured RF mismatch between the input/output of SQA and source signal/post-amplifier is taken into account a gain of (20.5 ± 1.5) dB and noise temperature as low as (2.5 ± 1.0) K (intrinsic flux noise $S_{\Phi}^{1/2} \approx 0.4 \mu\Phi_0 \text{Hz}^{-1/2}$, energy sensitivity $\epsilon_i \approx 47 \hbar$) can be estimated.

INTRODUCTION

The dc SQUID based RF amplifier (SQA) is advantageous for integration with a SIS mixer and a flux-flow oscillator (FFO) to complete a fully superconducting submm wave receiver [1]. This is due to its low noise, low power consumption and excellent compatibility with both the SIS mixer and the FFO. It has been shown that RF amplifiers based on dc SQUID can realize power gain up to 20 dB at frequencies of about 100 MHz [2]. Recently the RF amplifiers based on niobium dc SQUIDS with a noise temperature of (3.0 ± 0.7) K at 500 MHz (at an operating temperature of 4.2 K) have been demonstrated; the gain was typically 18 dB [3]. A noise temperature as low as (0.25 ± 0.15) K has been achieved at 1.8 K. This is optimistic result for developing of RF dc SQUID as intermediate frequency amplifier taking into account the linear decreasing of the noise temperature with the bath temperature up to about 0.1 K [4]. We have recently developed an advanced design of SQA for considerably higher frequency of about 4 GHz [5], [6]. This paper presents the recent results for two-stage 4 GHz SQA, which demonstrate its feasibility as an intermediate frequency amplifier for a submm wave integrated receiver [7]. The SQA seems especially attractive for an Imaging Array Receiver.

II. SQA DESIGN AND MAIN PARAMETERS.

The design of the integrated S-band SQA which is based on the lumped element approach has been published elsewhere [5], [6]. It was shown [5], [6] that a single-stage SQA has relatively low gain ~ 10 dB; that is not sufficient to

attain low noise temperature of the system and efficiently reduce the noise influence of a post-stage HEMT-amplifier. To overcome these problem we have used the two-stage configuration. Two identical single-stage SQAs are connected by the quarter-wave 50Ω coplanar line which works as an *rf* impedance transformer between two stages within the frequency band 3.5-4.0 GHz. The design of the interconnecting line allows us to measure SQAs either separately or in the two-stage connection. The equivalent diagram of the two-stage balanced SQA with the novel input resonant circuit is shown in the Fig. 1. The main parameters of the SQA are listed in the Table 1.

The single-stage of SQA is consists of the double washer SQUID which has two square holes of the same size formed by a $30 \mu\text{m}$ wide strip of the top electrode film crossing the washer ($60 \mu\text{m} \times 150 \mu\text{m}$) patterned in the bottom electrode, as shown in Fig. 2. The two parts of the washer are connected in parallel to form a simple gradiometer in order to minimize an external interference. Two shunted micron-size Nb-AlO_x-Nb SIS tunnel junctions are placed at the ends of the $30 \mu\text{m}$ wide strip; this strip is also used as an integrated control line (\pm CL) for the magnetic bias of the SQUID. The input coil

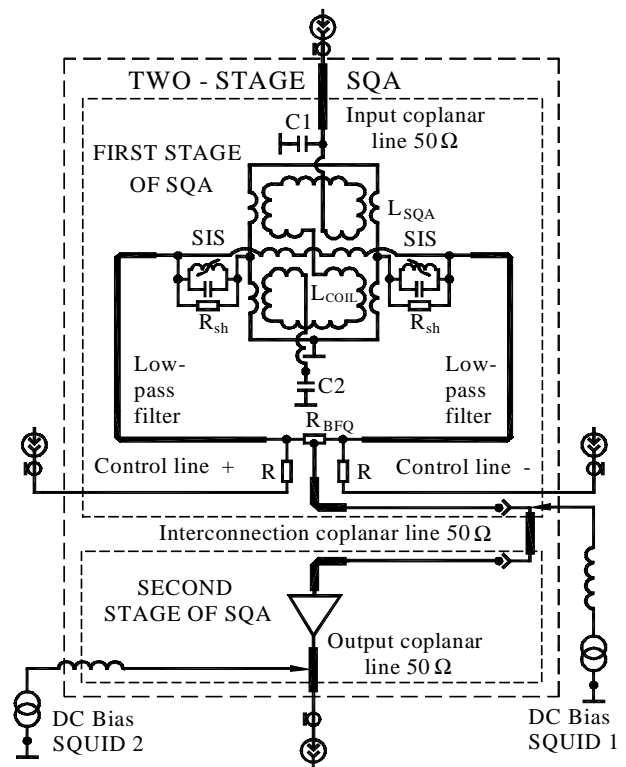


Fig. 1. Equivalent diagram of the two-stage S-band balanced SQA integrated in one chip. It consists of two identical single-stage SQAs connected by quarter-wave length 50Ω coplanar line.

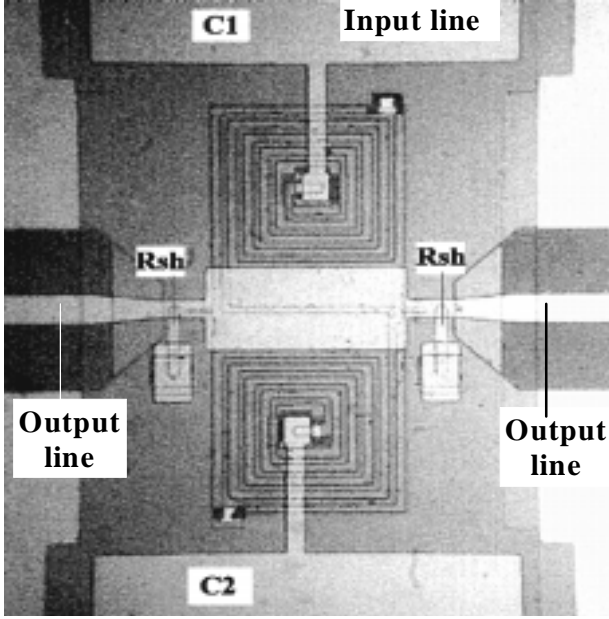


Fig. 2. Photograph of the central part of the single-stage balanced SQA. The resonant input coil consists of two parts connected in series. The tuning capacitors $C1$ and $C2$ (partly seen at the top and the bottom) are connected to the centers of the input coils. The wide wiring film (in the center of the photograph) is connecting the two SQUID loops via the two SIS junctions shunted by Ti strips resistors R_{sh} . The SQA output lines are connected via coplanar lines (low-pass filters, see Fig. 1).

consists of two identical series connected four-turn sections that are positioned inside the corresponding holes in the washer and placed *in-plane* with the washer. This makes the parasitic capacitance much smaller than the junction capacitance. The planar resonant flux transformer provides efficient coupling over a wide bandwidth ($> 5\%$) with low mutual inductance between the coils.

The capacitors C_1 , C_2 are chosen to tune the resonance of the input coil L_{COIL} at the signal frequency $f_s \approx 3.7$ GHz. The inductance of the SQUID washer is presented by L_{SQA} . The Nb-AlO_x-Nb SIS tunnel junctions of the SQUID are shunted by the low inductive resistors, R_{sh} . The resistors, R , (about 500 Ω each) are used to prevent the leak of the *rf* signal. Two coplanar low-pass filters with a cut-off frequency of about 50 GHz are used to transmit the *dc* bias and the signal (f_s), but prevent the Josephson current, $f_J \gg f_s$, from leaking out of the SQUID. These filters are also transforming the relatively low output impedance of the SQUID (see Table 1) into about 50 Ω . The resistor $R_{BFO} = 0.1-1$ Ω is used to prevent the flux trapping in the loop of the output circuit. This specific configuration of the output circuit is designed to cancel the possible signal leakage from the input of the SQA. We call this Balanced Output SQUID Amplifier. The fabrication procedure of the SQA is based on our standard Nb-AlO_x-Nb process currently used for production of integrated circuits with micron-size SIS junctions [7], [8].

III. EXPERIMENTAL SET-UP.

The experiments were performed with the sample placed at a holder inside a liquid ⁴He cryostat shielded by two external μ -metal cans. The typical *dc* I-V curves of SQA are presented in Fig. 3 at the different *dc* magnetic bias.

TABLE 1
MAIN PARAMETERS OF TWO-STAGE SQA #2_4(2)

PARAMETERS:	MEASURED VALUES
1. SQUID inductance L_{SQA}	$L1_{SQA} \approx L2_{SQA} \approx 70$ pH
2. Coupling coefficient k^2	$k^2 \approx 0.6$
3. Area of SIS junction	$0.8 - 1.2$ μm^2
4. Capacitance of SIS junction	$C_{SIS} \approx 0.1$ pF
5. Critical current I_C	$I1_C \approx 24$ μA , $I2_C \approx 26$ μA
6. Mc Cumber parameter β_C	$\beta_C \approx 0.1$
7. Inductance parameter β_L	$\beta_L \approx 1$
8. Shunt resistance R_{sh} per SIS junction	$R_{sh} \approx 8$ Ω
9. Time constant of SQUID	$\tau = L_{SQA}/R_{sh} \approx 10^{-11}$ sec
10. Inductance of input coil L_{COIL}	$L1_{COIL} \approx L2_{COIL} \approx 3$ nH
11. Input capacitance's C_1, \dots, C_4	$C_1=C_2=C_3=C_4 \approx 1$ pF
12. Size of two-stage SQA chip	6 mm \times 6 mm
13. Central operating frequency f_c	$f_c \approx 3.7$ GHz
14. Dynamic resistance R_d (op. point)	$R1_d \approx 23$ Ω , $R2_d \approx 21$ Ω
15. Bias voltage at the operational point	$V1_B \approx 37$ μV , $V2_B \approx 35$ μV
16. Power Gain of single-stage SQA	$G1(\text{max}) \approx 10.5 \pm 1.0$ dB
17. Power Gain of two-stage SQA	$G2(\text{max}) \approx 17.5 \pm 1.0$ dB
18. Noise Temperature of single-stage SQA	$T_N(\text{min}) \approx 12 \pm 0.5$ K
19. Noise Temperature of two-stage SQA	$T_N(\text{min}) \approx 4.0 \pm 0.5$ K
20. Intrinsic flux noise of two-stage SQA	$S_{\Phi}^{1/2}(\text{min}) \approx 0.6 \mu\Phi_0 \text{Hz}^{-1/2}$
21. Intrinsic energy sensitivity of two-stage SQA	$\epsilon_i(\text{min}) \approx 75$ \hbar ($7.8 \cdot 10^{-33}$ J/Hz)
22. Frequency bandwidth of two-stage SQA	$\Delta f_{3dB} \approx 250$ MHz

The coolable 3 - 6 GHz HEMT amplifier was situated in the liquid He (30 dB, T_n is about 50 K referred to the SQA output, see Fig. 4). The additional room temperature FET amplifier (25 dB) is used in front of the spectrum analyzer HP-8563A. The combination of a solid state noise source ($T_{NS} \approx 2.0 \cdot 10^5$ K at 4.0 GHz [9]) and the precise step attenuator was used to supply the well calibrated signal. It has been found in [5] that effects of saturation and direct detection can change the I-V curve of the SQA. To avoid these effects the tunable 40 MHz band-pass YIG-filter was used. To reduce the influence of the room temperature noise at the input of the SQA, the stainless steel cable was followed by 20 dB attenuator placed at 4.2 K. The losses in the input/output cables were carefully measured by replacing the SQA with an *rf* connection.

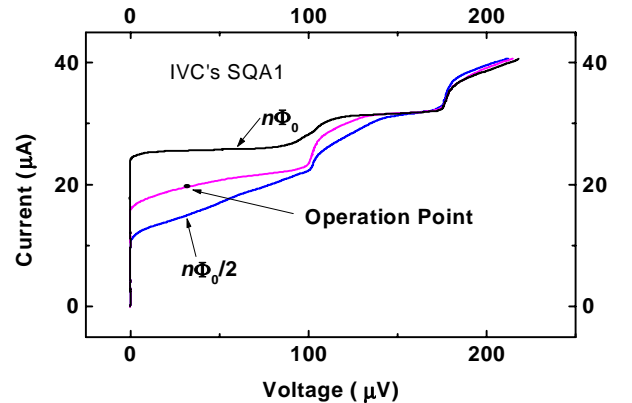


Fig. 3. Typical SQA IVCs at the different *dc* magnetic bias.

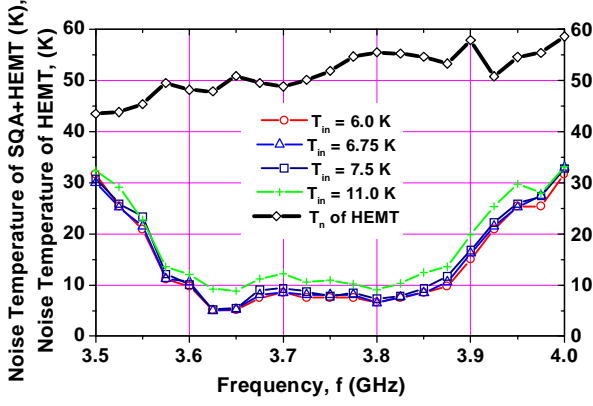


Fig.4. Noise Temperature of the system: two-stage SQA + HEMT amplifier, measured at four different values of the input signal. The noise temperature of the system without the SQA is shown by the solid line.

IV. EXPERIMENTAL RESULTS AND DISCUSSION.

The noise temperature and gain of the system has been evaluated via hot/cold response read by the spectrum analyzer. The value of the background noise applied to the input of SQA (the “cold” signal) was estimated as (5.75 ± 0.25) K for cold attenuator of 20 dB and the step attenuator set at 110 dB. Several different settings of the step attenuator have been used to check the linearity of the two-stage SQA. The set of curves presenting the formally evaluated noise figure of the system is shown in Fig. 4. These curves were measured at four different settings of the step attenuator 30, 26, 24 and 19 dB that corresponds to the “hot” signal level of 6.0, 6.75, 7.5 and 11.0 K (± 0.25 K).

The measured noise temperature of the HEMT-amplifier referred to the output of the SQA is also shown in Fig. 4 by a solid line. To extract the gain of the SQA, we used well-known equation for cascaded amplifiers:

$$G_{SQA} = [(N_2 - N_1)/(T_h - T_c)] / [(N_2' - N_1')/(T_h' - T_c')], \quad (1)$$

where N_1 , N_2 are the power levels at the output of the system SQA+HEMT that correspond to the input signals of T_c , T_h . The second set of values N_1' , N_2' are measured at T_c' , T_h' with the HEMT amplifier only. The gain and the noise temperature of the experimental SQA for $T_{in} = 6.75$ K are shown in Fig. 5 as a function of the frequency. The gain up to 17.5 dB and a noise temperature as low as 4.0 K were realized for a two-stage SQA. The 3 dB gain bandwidth of the SQA was estimated as 250 MHz.

To realize the ultimate (best possible) performance of the SQA, the reflection at input/output ports of the real device is of great interest. The test signal was applied from synthesizer HP 8673A via directional coupler (-16 dB) [10] which was connected directly to the appropriate port of the SQA. The HEMT amplifier was connected to the “reflection” port of the cold directional coupler. This measuring configuration prevents the possible influence of input noise of the HEMT amplifier (≈ 50 K) to the SQUID. The input and output reflection coefficients have been measured for two-stage SQA at three different values of dc bias of the first-stage SQUID and for the same dc bias of the second stage SQUID. The experimental data are shown in Fig. 6.

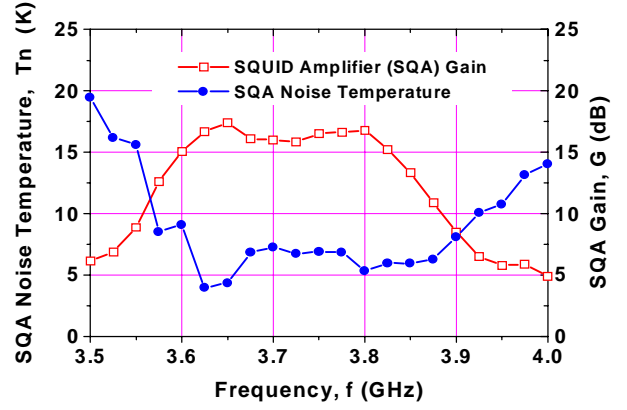


Fig.5. Noise temperature and gain of the two-stage SQA measured for the input signal temperature of 6.75 K. The error bar for the data are 0.5 K and 1.0 dB, correspondingly.

The experimentally measured input reflection of SQA at the best operation point occurs *more* than one. In the reference [11] it has been shown that the current $J(\omega)$ around the SQUID loop induces a voltage $-j\omega M_i J(\omega)$ into the input circuit, where M_i - mutual inductance between input coil and SQUID loop. The part of amplified signal is coupling back into the input circuit, and we may measure the back reaction larger than the signal applied to the input of the SQA.

In order to realize whether our test procedure is correct, the measurements of the input reflection at the different bias voltages, but *with the same* R_d have been performed. Two zero-gain bias voltages of 50 μ V and 80 μ V (closer to the R_N region) have been selected. The input reflection coefficient of such “inactive” point with the same R_d was used for the further estimation of the “real” input reflection of the SQA biased at its “active” point. The correction to the SQA input reflection gives a maximum available gain of 20.5 dB and the noise temperature as low as 2.5 K for the two-stage SQA as it is shown in Fig. 7.

It should be mentioned that the nonlinearity effect is clearly seen even for rather small input signals (Fig. 4). To investigate the nature of the nonlinearity we applied to the input of SQA the signals from two synthesizers with closely spaced frequencies, both within the frequency band of the

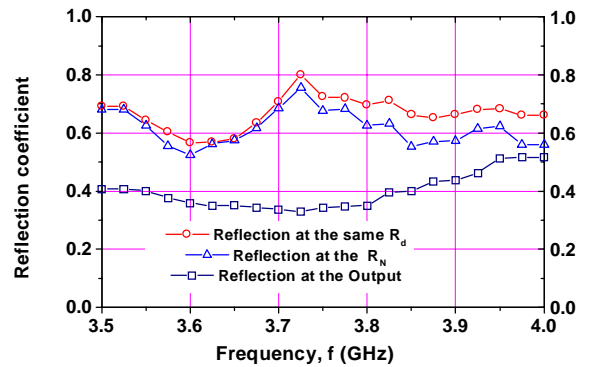


Fig. 6. The reflection coefficients of two-stage of the SQA: reflection at the input in the point with the same R_d as in the operational point, at the input in the region close to R_N ; reflection at the output.

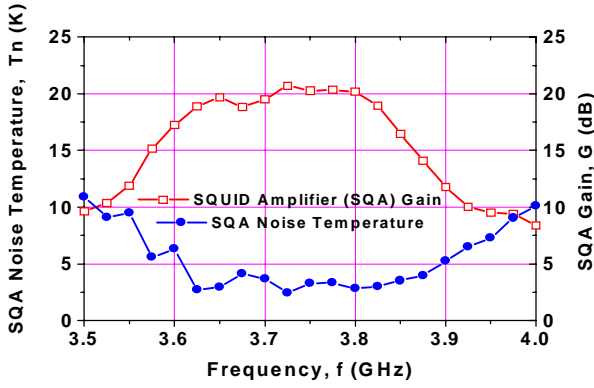


Fig. 7. Noise temperature and gain of the two-stage SQA evaluated for the input signal temperature of 6.75 K with taking into account the mismatch between the input/output of SQA and source signal/post-amplifier. The error bars for the data are 1.0 K and 1.5 dB, correspondingly

SQA. We have observed the linear transfer of the spectrum by SQA within its frequency range as shown in Fig. 8.

One can see the absence of harmonics at difference frequencies $(n \cdot f_{s1} \pm m \cdot f_{s2})$ that point out to linear conversion of spectrum by SQA. The nature of the nonlinearity can be described in terms of the nonlinear flux-to-voltage transfer function similarly to the usual low frequency SQUID used in a magnetometer.

The second stage of the SQA (SQA2) seems decreasing the dynamic range of the whole SQA with factor proportional to its gain G_2 . As it has been shown in reference [2], the dynamic range D of tuned dc SQUID-based rf amplifier can be evaluated as:

$$D \approx \xi^2 Q \Phi_0^2 / L k_B (T + T_N), \quad (2)$$

where $\xi \Phi_0$ is the maximum rms. flux that can be applied to the SQUID without introducing noticeable nonlinearity, ξ is typically of the order of 0.1 for a single-stage amplifier and $10^{-1}/(G1)^{1/2}$ for two-stage amplifier; Q is the quality factor, L is inductance of the SQUID, T is the physical temperature, T_N is the noise temperature. We estimated the dynamic range from this equation for a single-stage SQA is equal about

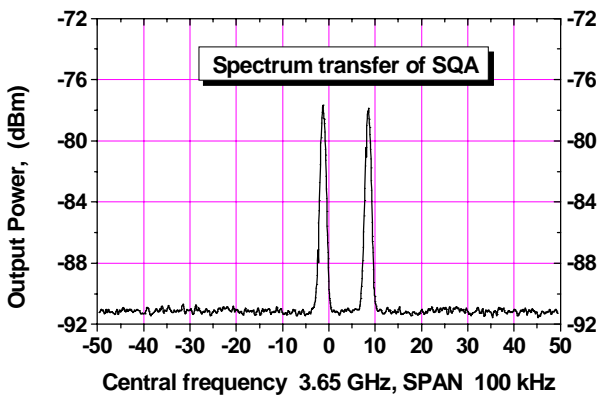


Fig.8. Transfer of the Spectrum by SQA.

16.1 dB and 10.3 dB - for two-stage SQA amplifier. The evaluation of the dynamic range for single- and two-stage SQA is in good quantitative agreement with experimental data.

To increase the dynamic range of rf SQA, it seems reasonable to work-out a technique analogous to the Flux-Locked Loop (FLL) as it has been demonstrated for dc SQUID-magnetometer in [12].

V. CONCLUSIONS.

The experimental study of a two-stage S-band amplifier based on dc SQUID have been performed in order to estimate its feasibility for use as an IF amplifier in a low noise SIS receiver. The study has shown encouraging results with the good consistency of design and measured data. The following parameters of the real two-stage SQA have been measured: noise temperature about 4.0 K, gain 17.5 dB and 3 dB bandwidth of about 250 MHz at center frequency of 3.65 GHz. The results of this preliminary study seem quite encouraging for future investigations of the SQA for integration with a SIS mixer and FFO in a fully superconducting sub-mm wave receiver.

REFERENCES.

- [1] V.P. Koshelets, S.V. Shitov, L.V. Filippenko, A.M. Baryshev, A.V. Shchukin, G.V. Prokopenko et al, "Integrated Submillimeter Heterodyne Receivers", *Proc. 30th ESLAB Symp., ESTEC, Noordwijk, The Netherlands*, ESA SP-388, pp. 193-202, 1996.
- [2] C. Hilbert and J. Clarke, "DC SQUIDS as radio frequency amplifiers", *J. Low Temp. Phys.*, vol. 61, pp. 263-280, 1985.
- [3] M. Muck, J. Gail, C. Heiden, M.-O. Andre and J. Clarke, "Low Noise Radio Frequency Amplifiers Based On Niobium dc SQUIDS with Microstrip Input Coupling", *Abstracts of 4th Twente HTS Workshop*, p.11, 6-7 May 1998.
- [4] F.C. Wellstood, C. Urbina and J. Clarke, "Hot-electrons effects in metals", *Phys. Rev.*, B49, pp.5942-5955, 1994.
- [5] G.V. Prokopenko, S.V. Shitov, V.P. Koshelets, D.V. Balashov, J. Mygind, "A dc SQUID based low noise 4 GHz amplifier", *IEEE Trans. on Appl. Supercond.*, vol. 7, pp. 3496-3499, 1997.
- [6] G.V. Prokopenko, V.P. Koshelets, S.V. Shitov, D.V. Balashov, J. Mygind, "Low noise and wide-band 4 GHz amplifier based on dc SQUID", *Inst. Phys. Conf., Ser.No 158*, pp. 731-735, 1997.
- [7] V.P. Koshelets, S.V. Shitov, A.M. Baryshev, I.L. Lapitskaya, L.V. Filippenko, H. van de Stadt, J. Mess, H. Schaeffer, T. de Graauw, "Integrated Sub-MM Wave Receivers", *IEEE Trans. on Appl. Supercond.*, vol. 5, pp. 3057-3060, 1995.
V.P. Koshelets, S.V. Shitov, L.V. Filippenko, A.M. Baryshev, W. Luinge, H. Golstein, H. van de Stadt, J.-R. Gao, T. de Graauw, "An Integrated 500 GHz Receiver with Superconducting Local Oscillator", *IEEE Trans. on Appl. Supercond.*, vol.7, pp. 3589-3592, 1997.
- [8] V.P. Koshelets, S.A. Kovtonyuk, I.L. Serpuchenko, L.V. Filippenko, and A.V. Shchukin, "High Quality Nb-AlOx-Nb Tunnel Junctions for Microwave and SFQ Logic Devices", *IEEE Transactions on Magnetics*, vol. 27, pp. 3141-3144, 1991.
- [9] Noise Com, NC 3208-A, SN1409 8732.
- [10] NARDA, 2-18 GHz MOD 4203-16.
- [11] J.M. Martinis and J. Clarke, "Signal and Noise Theory for a DC SQUID Amplifier", *J. Low Temp. Phys.*, vol. 61, pp. 227-236, 1985.
- [12] D. Drung, R. Cantor, M. Peters, H.J. Scheer, and H. Koch, "Low-noise high speed dc superconducting quantum interference device magnetometer with simplified feedback electronics", *Appl. Phys. Lett.* vol. 57, pp. 406-408, 1990.