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ELECTRONICS AND RADIO ENGINEERING

A Wideband Radio-Frequency Amplifier for Investigations at Temperatures from 300 to 0.1 K

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Abstract—A wideband cooled measuring amplifier, which solves a wide class of search problems in the area of cryoelectronics at frequencies of 10–100 MHz, is described. The amplifier differs from the existing prototypes in the reduced power consumption and influence on the source (suppressed back action effect), serviceability in a temperature interval of 0.1–300 K, and high regulated gain (up to 40 dB). The power consumed (dissipated) by the first ultralow-temperature stage, is ~1 μW. The circuitry components are commercially available.

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INTRODUCTION

A highly sensitive measuring amplifier (HSMA) is an indispensable attribute of radio engineering tools, used in electrophysical studies at low temperatures. Often an informational signal from the primary source is very weak, and the source itself, e.g., a quantum system (qubit), is very sensitive to parasitic electromagnetic actions (pick-ups). For these reasons, the HSMA should be placed in immediate proximity to the sources. Owing to this fact it must be operable at low and ultralow temperatures. The primary sources may be different (superconductor–insulator–superconductor mixers, superconducting quantum interferometers (squids), single-electron transistors, etc.), but the basic function of the HSMA is invariable, i.e., the amplification and transmission of a signal from the "cold" source (sensor) to the "room" periphery for processing data.

A variety of electric properties of the sources and problems to be solved force researchers to design specialized HSMAs, as a rule, with extreme performance characteristics [1–4]. The existing devices possess high noise characteristics and low power consumption. At the same time, increasingly complicated physical problems, on the one hand, and swiftly renewed circuitry components of electronics with new capabilities, on the other hand, make the HSMA creation problem urgent.

Complying with the research practice, it is possible to formulate the following requirements for the universal HSMA:

(1) capability of operating in a range of room (adjustment mode) to ultralow (conditionally, 300 K–100 mK) temperatures;

(2) ultralow noise factor ($F = 0.1$–0.01 dB);

(3) minimal back action [5] on the signal source;

(4) regulated gain G that is sufficient for excluding the influence of noise of the subsequent equipment ($G = 20$–40 dB);

(5) wide dynamic range (no less than 60 dB);

(6) commercial availability of the circuitry components and possibility of replication in standard physical laboratory conditions;

(7) power of consumption/dissipation P_c is at least an order of magnitude smaller than the cooling capacity of widespread cryorefrigerators.

It is quite easy to fulfill the latter requirement for "helium" temperatures (1.6–4 K). At temperatures of about 1 K, especially for long-term experiments with liquid-helium cryostats, P_c should not exceed a few milliwatts. It is rather difficult to fulfill this requirement for high-frequency multistage amplifiers. The situation becomes dramatically complicated at ultralow temperatures (1–0.1 K and below), where the capacity of dilution refrigerators can be roughly evaluated by a value of 100 μW at a working temperature of 100 mK. Here, the satisfactory P_c value will vary from 1 to 10 μW. This requirement becomes extremely severe.

Below is a description and characteristics of the HSMA, which, in the authors' opinion, at most meets

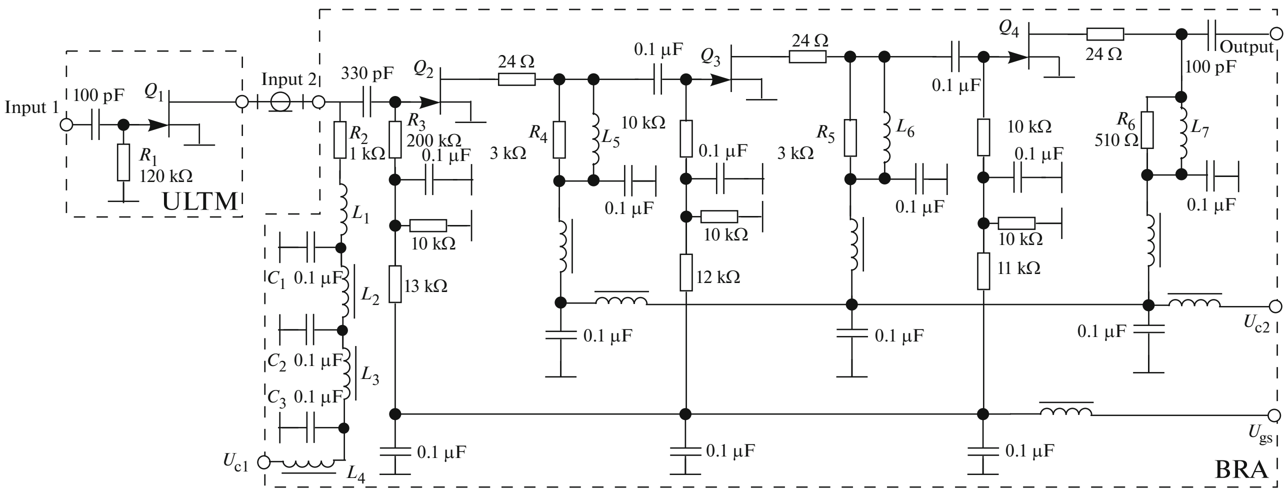

Fig. 1. Schematic diagram of the BRA/ULTM: (Q_1) ATF36077, (Q_2–Q_4) ATF35143; (R_1, R_4–R_6) MLT-0.125 metal-film resistors, and the remaining are SMD 0805; the capacitors are SMD 0805; (L_1, L_5, L_6) 3 µH, (L_7) 2.3 µH, and (remaining SMD 0805 chokes) 1 µH.

the formulated requirements. The device is intended for operation in the radio-frequency (10–100 MHz) band, claimed by the wide practice.

SCHEMATIC CIRCUIT AND FEATURES OF OPERATION

To minimize the noise action of the end measuring equipment, in accordance with the Friis formula [6], it is required to ensure a sufficiently high gain (about 20–40 dB). Hence, the amplifier must be multistage, but this is hardly compatible with the requirement for low power P_c, especially if we are oriented to operation at temperatures below 1 K. Therefore, we went on the way of creating the modular design, consisting of the basic amplifier with the regulated gain (BRA) and the ultralow-temperature module (ULTM), which is connected if necessary.

The schematic diagram of the BRA (Fig. 1) is quite traditional for similar-purpose devices (3 stages on field-effect transistors, connected in the common-source circuit, with the inductive correction of the frequency characteristic (see, e.g., [7])). However, some features of the BRA and ULTM require more detailed comments.

For the measuring amplifier, the important qualitative parameter is the invariability of the shape of the amplitude–frequency characteristic (AFCh) and output impedance Z_{out} at any selected gain value (here, supply voltage). In the considered case, the fixation of Z_{out} by the standard method (using an output attenuator) cannot be admitted as a good solution. The introduction of the additional stage, which is necessary for compensating the attenuation of the attenuator, will cause a growth of the total dissipated power. From the viewpoint of preserving the stable operation, an increase in the number of stages over the minimally required is also undesirable. In our case, Q_4 operates in the unsaturated mode (drain current $I_d \leqslant 3$ mA and drain–source voltage $U_{ds} \leqslant 300$ mV). As a result, the drain–source resistance weakly changes. Thereby, the sufficient stability of $Z_{out} = 150 \pm 40$ Ω is ensured in the active part and no more than $+j50$ Ω in the reactive part, if the common supply voltage U_c varies from 100 to 500 mV. While operating into a 50-Ω load (matched 50- feeder), the output stage does not amplify the voltage and is the active impedance transformer. The best matching conditions and the additional voltage amplification are ensured under loading with a matched 150- feeder. This fact should be taken into account, when the cryosystem is designed. The optimal matching using a 50- feeder is possible, if Q_4 is replaced with a wide-gate ATF33143 transistor and the drain current of Q_4 is increased to 8 mA.

Input 1 (ULTM) is the high-impedance, roughly modeled by parallel-connected resistor R_3, capacitance of the gate–source of transistor Q_2, and capacitance of the input reference point of the board, totally amounting to about 2 pF. The value of resistor R_3 (200 kΩ) is selected so that the input reactance of the amplifier should be exceeded at least by two orders of magnitude in the whole working frequency range. In these conditions, thermal noises of R_3 give an insignificant contribution to the total noises of the amplifier. On the other hand, the increase in the resistance of R_3 over 1 MΩ is also undesirable, since the leakage current of the selected transistors in the selected bias/power supply mode can reach 1 pA. The circuit R_2, C_1–C_3, and L_1–L_4 is used only in operation with the ULTM.

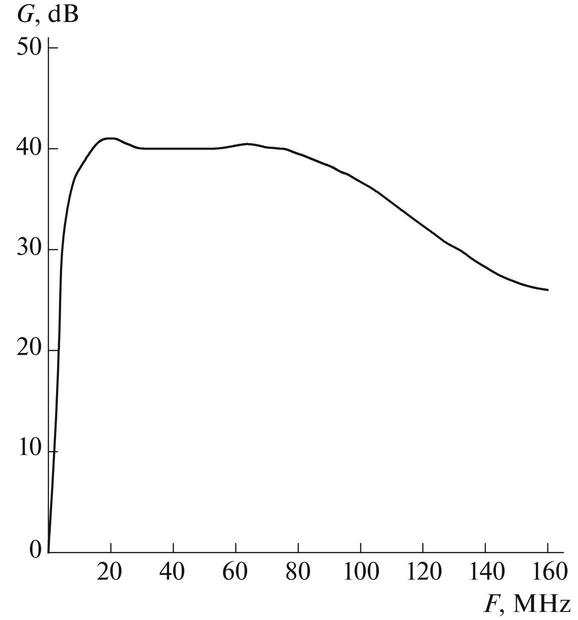

Fig. 2. Dependence of the gain G of the BRA on the frequency F at a preset maximal gain of 40 dB. $T_{\mathrm{amb}} = 4.5$ K.

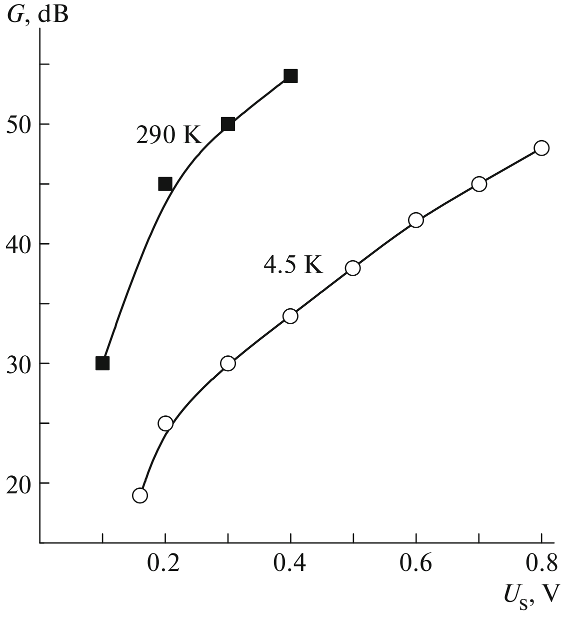

Fig. 3. Dependences of the maximal gain G of the BRA on the supply voltage U_s at a frequency of 50 MHz for two T_{amb}.

Transistors Q_2 and Q_3 operate as voltage amplifiers. Their direct-current modes are close to the unsaturated mode: I_{d2} and I_{d3} are up to 1.5 and 1 mA, and U_{ds2} and U_{ds3} are up to 500 mV, respectively. Such a selection of the modes is the trade-off between the desire to achieve a higher per-cascade amplification and the need in keeping the drain–source resistance of transistors Q_2 and Q_3 within 300–600 Ω to stabilize the shape of the AFCh, when U_c changes, i.e., when the gain is being regulated.

The operating practice showed that there was no need in the individual regulation of the bias voltage at the gate U_{gs} for each transistor, even when transistors were replaced and in the whole ambient temperature range T_{amb}. Therefore, in contrast to the earlier described devices [1], the bias voltage U_{gs} is applied to the transistor gates not separately but through the common wire. This sharply simplified the prompt regulation and reduced the number of lead-ins to the cryostat (possible noise penetration ways). For the same purpose (minimization of the number of inlets), we rejected the bias circuit in the ULTM scheme. The selected type of the transistor (pseudomorphic HEMT AVAGO ATF36077) differs by the fact that on cooling below 80 K, about 10% samples are capable of operating at the zero bias voltage across the gate. The criterion of selection of Q_1 is the drain current that should be no higher than 15 mA at room temperature and zero bias.

The ULTM transistor operating in the unsaturated direct-current mode [7, 8] is powered from a separate source with a voltage of 0.03–0.2 V. The current consumption (for different Q_1) varies from 50 to 300 μA. The minimal power-supply values are required at $T_{\mathrm{amb}} < 100$ mK. The power consumption P_c at the unity voltage gain (ULTM operates in the current amplification mode) is 2 μW. In principle, it is possible to decrease P_c to submicrowatt values but in this case, it is required to apply additional bias voltages (–0.15...–0.25 V) to the gate. For the BRA, the power consumption (totally, in power supply and bias circuits) varies from 0.1 to 10 mW, depending on the preset gain.

The special features of the embodiment of deeply cooled units are described many times [9]. Note that it is desirable to use metal–film (not metal–oxide) resistors, the increase of whose resistance does not exceed 20% even at 50 mK, as compared with its value at room temperature.

The amplifier design assumes that in principle it is possible to expand the working frequency range down to 1–2 MHz, when the inductance of elements L_1, L_5, L_6, L_7 increases proportionally (Fig. 1). In this case, one should pay attention to the natural resonance frequency of these elements, which should be higher than the upper bound of the working range.

TEST RESULTS

Figure 2 shows the AFCh of the BRA, which is obtained with applying the signal to input 2 at a temperature of 80 K and a preset maximum gain of 40 dB. The deviations of the shape of the AFCh with the gain

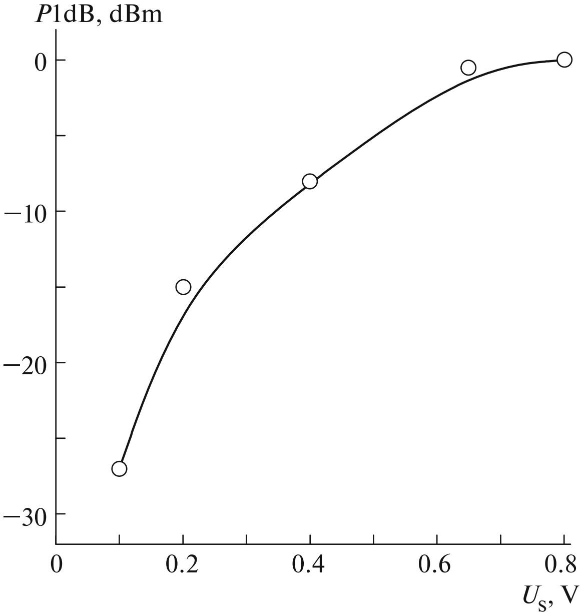

Fig. 4. Dependence of the output power with the signal compression by 1 dB ($P1$dB) on the supply voltage U_s for the mode with a 3-mA consumed current at $U_s = 300$ mV.

regulation within 20–40 dB do not exceed 3 dB for any T_{amb} in an interval of 0.3–300 K.

The through AFCh of the ULTM + BRA strongly depends on the capacitance of the connecting cable. When the cable capacitance is 5 pF, the AFCh has a "roll-off" of 3 dB at the high-frequency edge of the range. It is possible to decrease the "roll-off" of the AFCh by selecting the inductance of L_1. The stable voltage gain of the ULTM varies from 0.5 (current amplification mode, or active impedance transformer; the dissipation power of Q_1 varies from 1 to 2 μW) to 5 (dissipation power of Q_1 is 1 mW).

Figure 3 shows the dependences of the maximal gain G of the BRA at 50 MHz on the supply voltage U_c for two T_{amb}.

The bias voltage was selected to obtain the maximally stable amplification (for operation at a temperature of 290 K) or the minimal power with a 30-dB gain (for operation at the cryogenic temperatures). The above-mentioned characteristics of stability of the AFCh shape and output impedance correspond to the gain regulation range $G = 20$–40 dB.

Figure 4 shows the dependence of the output power of the BRA on the supply voltage, when the signal is compressed by 1 dB ($P1$dB). It is easy to calculate that the dynamic range of the BRA exceeds 80 dB even at the minimal supply voltage and noise temperature $T_n = 300$ K (knowingly overestimated value). This range is perfectly sufficient for solving the overwhelming majority of measuring problems in cryoelectronics. The presence or absence of the ULTM does not influence the parameter $P1$dB.

Figure 5 shows the noise characteristics of the BRA, which were measured by the standard Y-method ("two-temperature" method) with a resistive noise generator R_g. By comparing the characteristics at T_{amb} 290 and 80 K (Figs. 5a and 5b, respectively), it is possible to note that the dependence $T_n(T_{amb})$ is close to a directly proportional one. From here, one can conclude that the nature of noises is predominantly thermal. This conclusion quite agrees with the results of works [7, 8, 10], pointing to the absence of a noticeable contribution of $1/F$ noise to noises of pseudomorphic HEMTs in the microcurrent power-supply mode at radio frequencies. Then, by extrapolating the obtained results to the lower temperature region, it is

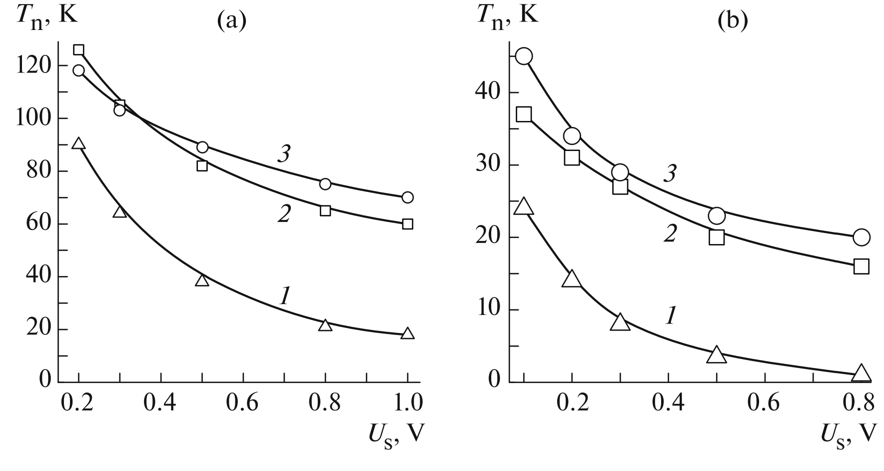

Fig. 5. Dependence of the noise temperature T_n of the BRA on the supply voltage U_s for three resistance values of the noise generator R_g = (*1*) 1 kΩ, (*2*) 100 Ω, and (*3*) 10 kΩ at temperatures T_{amb}: (a) 290 and (b) 80 K. The size of experimental points corresponds to the T_n measurement error value.

possible to expect that $T_n \sim (0.1–0.3)T_{amb}$, depending on the closeness of the signal-source resistance to the optimum.

Concerning the dependence of the noise temperature on the resistance of the resistive noise generator $T_n(R_g)$, it is necessary to explain the following. The unexpectedly sharp growth of T_n at $R_g = 10$ kΩ is the consequence of the shunting influence of the coaxial cable stub with a capacitance of 5 pF by which the resistive noise generators were connected to the input of the amplifier under test. With the used generators, which were cooled to 80 K, the absolute error of measurement of T_n was 2 K. Therefore, for the measured value T_n at temperatures of 4 K and below, we can give only the upper estimate $T_n < 2$ K for $R_g = 0.1–1$ kΩ and $U_c > 200$ mV. The same can be said about the system ULTM + BRA, i.e., $T_n < 2$ K at a calculated (extrapolated) value 0.2 K and less (at $T_{amb} = 1$ K).

The general serviceability of the ULTM was checked down to $T_{amb} = 50$ mK. The gains of the ULTM and BRA are 6 and 30 dB, respectively, in the entire working band of 10–100 MHz. The so-called back action effect was also evaluated for the ULTM. It is known that while operating with sources, processes in which have a substantially quantum pattern, it is necessary to minimize the action of the measuring unit on the measured object. In this case, this means the minimization of the energy, emitted to wards the source and, in addition, in a very wide frequency band that is orders of magnitude wider than the working band (minimization of the radio-brightness temperature). The excess of the effective temperature of electrons of the conducting channel over the lattice temperature by 2 orders of magnitude is characteristic of transistors in whole. It is possible to suppress the radiation of this ensemble (transmitted to the input through the intrinsic drain–gate capacitance of the transistor) by connecting the transistor in the common-drain circuit [7]. Unfortunately, this method creates conditions for the parasitic excitation of the transistor at frequencies of 0.1–10 GHz and can be hardly recommended for the universal amplifier. In the described ULTM, the transistor operates in the common-source circuit (the stability is absolute) but in the unsaturated, or ohmic, mode, whose typical feature is the absence of so-called “hot” electrons in the HEMT channel. By comparing, using the direct radiometry method [11], the effective radio-brightness temperatures of the ULTM output (the input is shorted) and 500-Ω resistor (close to the output impedance of the ULTM in the selected mode), we determined that they are close with an accuracy of up to 5 K. The measurements were performed at $T = 80$ K. The experimental data are insufficient for making final conclusions, but there is already good reason to believe that the back-action effect is substantially suppressed.

CONCLUSIONS

This work describes the broad-band cooled wide-application measuring amplifier. The amplifier has a set of electric and user characteristics, which allow one to solve most search problems in cryoelectronics at frequencies of 10–100 MHz. The amplifier differs from the existing prototypes in the reduced power consumption, serviceability in a temperature interval of 100 mK–300 K, and a high regulated gain. The circuit components are commercially available.

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