



Extra-low power consumption amplifier based on HEMT in unsaturated mode for use at subkelvin ambient temperatures



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ABSTRACT

A new approach to deep-cooled amplifier design with microwatt level consumed/dissipated power is presented. The relevant technique is based on exploiting the unsaturated regime of the high electron mobility transistor. The power consumption of several microwatts for 20 dB gain amplifier was obtained at 300 mK ambient temperature. This is at least an order of magnitude better than the figures known up to date for high-frequency (0.1–1 GHz) amplifiers.

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1. Introduction

Readout amplifiers are an inherent part of cryoelectronic receiving equipment used in a variety of physical instruments, from radio telescopes to quantum computers. Primary sources (sensors, detectors, transducers) of the signal may be different: SIS, SET, HEB, QUBIT, etc. The function of the readout amplifier (RA) is to provide communication between the deep-cooled sensor and a room-temperature processing periphery. The noise temperature T_n and dissipated power P_c are the basic characteristics for an RA. Minimization of both T_n and P_c is the main task for a designer of a deep-cooled RA.

Concerning the noise, the figure of $T_n < 1$ K can presently be considered as satisfactory. Obtaining such a low noise temperature, in general, is a technical challenge. The solution, however, greatly simplified by deep cooling and at high frequencies where $1/f$ noise component is almost negligible. Minimizing P_c is a more complex issue since the readout amplifier should be placed as close to the primary sensor as possible, i.e. on the coolest stage of a refrigerator. The cooling capacity of subkelvin dilution refrigerators rarely exceeds 100 μ W at the stage temperature of about 100 mK, and decreases rapidly with further decrease in temperature. At the same time, the modern physical problems require processing signals at ambient temperature T_{amb} of tens of mK. These are, for example, dark matter detectors [1,2], Josephson

qubits [3] and other quantum objects. Thus, there is a need for amplifiers that can function being supplied by a power per 10 dB-gain stage P_{10} less than 1 μ W. SQUID-based amplifiers have excellent noise/power characteristics [1,4] but poor dynamics. So, many researchers have focused on the development of transistor RAs [5–7]. To date, the best transistor amplifiers are characterized by P_{10} of tens microwatts [8,9]. This is too much to be used in promising low temperature physical research instruments.

In this paper a new approach to the design of an amplifier with microwatt-level dissipated power is presented. To the authors' knowledge, it is the topmost result for the HEMT-based radio frequency amplifiers at the moment. The relevant technique is based on exploiting the unsaturated regime of the HEMT.

2. General concept

Deep-cooled transistor devices are most commonly based on field-effect transistors (FETs) with high electron mobility (HEMTs). These devices demonstrate no low-temperature threshold degradation. There are a few specific solutions to minimize consumed/dissipated power of a FET-based amplifier. The drain microcurrent regime is effectively used at frequencies below 100 MHz. But this way is unacceptable for the higher frequencies since supposes high impedance loads to be implemented. In the microwave range ABCS is very promising technology to reduce the drain-source voltage U_{ds} by an order of magnitude [6,7]. Another method is to reduce P_c and involves the development of specialized HEMTs with low saturation voltage and high transconductance g_m at low drain

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currents I_d [5]. The last two methods are suitable for radio frequencies, but are based on a special high-cost semiconductor technology. As for amplifiers made on commercial general-purpose HEMTs, their characteristics are poor enough: $P_{10} > 10 \mu\text{W}$ [8–11].

We have proposed the unsaturated, or ohmic, FET regime to be used, in which the dissipated power was reduced by simultaneous decreasing both I_d and U_{ds} . Correspondingly, output load impedance remains in reasonable limits of tens to hundreds Ohms.

The unsaturated FET regime has been barely studied because of common opinion that there was no amplification in this transistor regime. It is true indeed concerning the voltage gain. Intrinsic voltage gain is $G_u = g_m \cdot R_{ds}$, where R_{ds} is source-to-drain resistance. Really, low g_m ($\approx 1 \text{ mS}$) and R_{ds} (tens to hundreds of Ohms) that are an order of magnitude less than those in the saturated regime can provide $G_u = 1$ at the best. However, the situation alternates for the current gain G_i . This can easily be illustrated by writing the known (see, e.g. [12]) expression for the maximum available power gain G_a :

$$G_a = \left(\frac{f_t}{f}\right)^2 \cdot \frac{R_{ds}}{4R_{gs}} = \frac{1}{4} G_i \cdot G_u = \frac{1}{4} g_m \cdot R_{ds} \frac{g_m}{R_{gs}(2\pi f C_{gs})^2}, \quad (1)$$

where f_t is the transistor cutoff frequency, f is the amplifier operation frequency, C_{gs} is the transistor gate-to-drain capacitance.

The intrinsic current gain $G_i = g_m / [R_{gs}(2\pi f C_{gs})^2]$ in this expression is inversely proportional to the square of the operation frequency and tends to infinity when lowering the frequency. As for the power gain, an ideal FET, from the physical standpoint, is a device with the pure-electrostatic field control of the channel conductance that does not require any power from the input signal at all. In a real amplification device, the gain will be limited by band-pass characteristics of matching circuits and by stability requirements. The excessive (by stability criterion) power gain can be sacrificed specifically to reduce P_c . One of the specific methods to do this is to use the unsaturated regime. The results of a preliminary theoretical consideration and an experimental study of amplification properties of a HEMT in the unsaturated regime can be found in [13].

3. Experimental amplifier

At the pre-qualification stage of design, several types of low-power PHEMTs have been tested at $T_{amb} = 80 \text{ K}$, these are ATF-36077 (AGILENT), ATF-35143 (AGILENT), NE3210S01 (NEC), and FHC40LG (Fujitsu). ATF-36077 was selected for its lowest saturated drain-source voltage U_{ds} , negligible gate leakage current and perfect reproducibility of the characteristics after rapid cooling to the liquid nitrogen temperature. According to our measurements, deep-cooled ATF-36077 operates in close-to-unsaturated regime when $U_{ds} < 40 \text{ mV}$ (Fig. 1).

In order to both modeling the transistor and designing an amplifier, the parameters of the equivalent circuit were extracted from standard (AGILENT) S-parameters and from the DC measurements at 300 mK. Since R_{gs} and C_{gs} are weak functions of temperature, their values, 7Ω and 0.35 pF , respectively, were extracted from the room-temperature S-parameters. Alternatively, R_{ds} and g_m were obtained from DC measurements at 300 mK. For example, $R_{ds} = 900 \Omega$ and $g_m = 1.4 \text{ mS}$ are for the measurement point $U_{ds} = 25 \text{ mV}$, $I_{ds} = 38 \mu\text{A}$ (Fig. 1). According to expression (1), maximum available gain can be 17 dB per stage under perfect matching at $f = 0.5 \text{ GHz}$. Looking ahead, we note that the measured gain in the specified operating point is only 12 dB. Such a discrepancy in the data is understandable since R_{ds} and g_m measured at direct current are always greater than their actual values at radio frequencies.

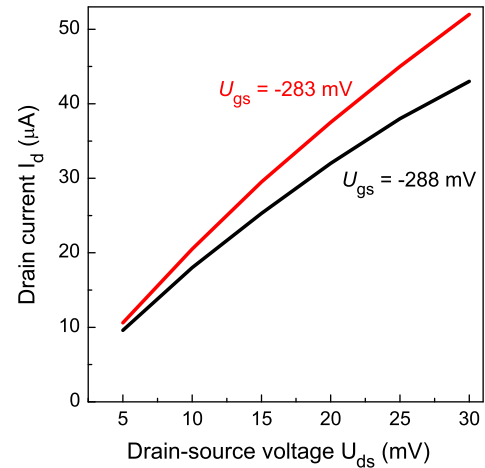


Fig. 1. Static characteristics of AGILENT ATF36077 PHEMT at 300 mK for two different gate-source voltages U_{gs} .

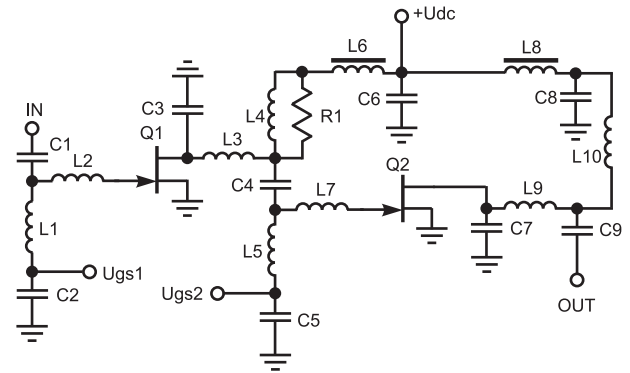


Fig. 2. The amplifier schematic. Q1, Q2 – ATF-36077.

The experimental amplifier consists of two stages. Its schematic (Fig. 2) is basically similar to that of the amplifiers described previously [13]. A distinctive feature of the actual design is the total absence of additional elements used routinely to enhance stability. It should also be noted that a high intrinsic stability of the FET in the unsaturated mode is due to a sharp decrease in the cutoff frequency (f_t is close to f) and low voltage gain (G_u is close to 1). So, the unconditional stability is achieved without the source inductors and resistors in series with the drain. Capacitor C3 and coils L1–L5, L7, L9, and L10 were calculated and tuned by maximum gain matching criterion.

The shunt resistor R1 (500Ω) provides stability at room temperature and $U_{ds} > 0.1 \text{ V}$, that is, during manual adjustment of matching circuits. R1 may not be installed in the final design step when amplifier operates at $U_{ds} < 0.05 \text{ V}$.

Fig. 3 illustrates the amplifier printed circuit board. The amplifier was built using wire-wound inductors, SMD0603 capacitors and chokes (L6, L8). The thermal expansion coefficients of the substrate and the discrete passive components were harmonized. The foiled substrate ($10 \times 20 \times 0.5 \text{ mm}^3$, $\varepsilon \approx 5$) was soldered to copper chassis by pure indium. The HEMT source leads were directly soldered to the chassis through holes in the substrate.

4. Measurement results and discussions

Figs. 4–6 show results of the amplifier measurements. Fig. 4 exhibits the amplifier gain and the output power at 1 dB gain compression (1-dB compression point) P_{1dB} versus supplied/dissipated

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