Note: Ultra-high frequency ultra-low dc power consumption HEMT amplifier for quantum measurements in millikelvin temperature range

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We have presented theory and experimentally demonstrated an efficient method for drastically reducing the power consumption of the rf/microwave amplifiers based on HEMT in unsaturated dc regime. Conceptual one-stage 10 dB-gain amplifier showed submicrowatt level of the power consumption (0.95 μW at frequency of 0.5 GHz) when cooled down to 300 mK. Proposed technique has a great potential to design the readout amplifiers for ultra-deep-cooled cryoelectronic quantum devices. [doi:10.1063/1.3518974]

Modern cryogenic amplifiers operate at temperature $T \leq 4.2$ K with single electron transistors, superconducting quantum interference devices, qubits and other quantum-limited detectors of electrical charge, magnetic flux, and electromagnetic power.[1–5] In most cases the amplifiers with low noise temperature T_N and low dc power consumption P_C are based on high electron mobility transistors (HEMTs). In recent years, several groups[2,3,6,7] have demonstrated excellent characteristics for cryogenic HEMT amplifiers: $T_N \approx 0.1-1$ K, $P_C \approx 15$ μW at frequencies f up to 100 MHz and $P_C \approx 0.1-1$ mW in the frequency range 0.5−2 GHz. However, the ultra-low dc power dissipation remains the crucial requirement for an amplifier intended for millikelvin temperature range quantum measurements like quantum information processing with superconducting qubits, state preparation, readout, and error correction. For example, it was shown recently[8] that the electromagnetic noise coming from a HEMT amplifier placed at $T = 1.5$ K should be significantly suppressed by a wide-band dissipative powder filter cooled down to 10 mK to ensure effective thermalization of a superconducting qubit-based detector operating at 10 mK. The experiments on the search for dark matter particle[9] with detectors cooled down to a few millikelvins also require minimizing the Planck radiation from elements of the cryogenic amplifier and the transmission line.[10] Therefore, further improvement of millikelvin quantum measurements depends critically on the development of low-noise HEMT amplifiers for 0.5−1 GHz frequency range with P_C at least one order of magnitude less than that which can be achieved with modern cryogenic HEMT amplifiers.[11] In this paper we introduce a concept of the ultra-low dc power consumption HEMT amplifier for fast and sensitive quantum measurements.

The maximum available gain ($G_{a\,\max}$) is about 30 dB for modern HEMTs at $f \approx 1$ GHz. At the same time, the maximum stable gain ≤ 20 dB, i.e., is much smaller. The excessive, by the stability criterion, gain can be used to reduce P_C. To reduce P_C at lower frequencies, $f \leq 100-150$ MHz, it is possible to go into an economic regime of the HEMT drain microcurrents. In this case, P_C falls down to 15 μW per stage due to increasing the load impedance[7] and/or designing HEMTs having high transconductance at low drain currents.[12] Such a device can be placed onto $T \approx 100$ mK level of a dilution refrigerator where cooling capacity is typically about 100 μW.

The implementation of high impedance load at a frequency around $f \sim 1$ GHz is a difficult task. For this frequency range, we suggest using the unsaturated HEMT regime characterized by the Ohmic law for the drain current I_d as a function of the drain-source voltage U_{ds}. In this regime, P_C can be substantially reduced due to decrease in both the I_d and U_{ds}, keeping the output resistance of the transistor and the impedance of the load within reasonable limits, i.e., from tens to hundreds of ohms. This assumption is supported by recent paper.[13] Following,[13,14] we write down $G_{a\,\max}$ for the HEMT amplifier in the form

$$G_{a\,\max} = \left(\frac{f_t}{f}\right)^2 \frac{R_{ds}}{4R_{gs}}, \tag{1}$$

where R_{ds} and R_{gs} are the HEMT channel and the source-gate region resistances, correspondingly. Using the definition of the transconductance G_m through the drain current I_d and the gate-source voltage U_{gs}, we get the transistor cutoff frequency

$$f_t = (dI_d/dU_{gs})/2\pi \cdot C_{gs} = G_m/2\pi \cdot C_{gs}, \tag{2}$$

where C_{gs}, the gate-source capacity, is determined mainly by the HEMT topology and weakly depends on the U_{ds}. Let us assume that $f_t/f \geq 10$ and $G_{a\,\max} > 20$ dB for the chosen HEMT type. This "quality reserve" is sufficient to keep gain $G \approx 10$ dB while proceeding to the unsaturated part of the HEMT output current-voltage curve. In the unsaturated regime, the channel resistance R_{ds} has close-to-Ohmic behavior, i.e., $dR_{ds}/dU_{ds} \approx 0$ and $dR_{ds}/dU_{gs} \approx const$. In this approximation we get for the transistor transconductance

$$G_m = \frac{dI_d}{dU_{gs}} = \frac{d(U_{ds}/R_{ds})}{dU_{gs}} = U_{ds} \cdot \frac{d\left(R_{ds}^{-1}\right)}{dU_{gs}} \approx const \cdot U_{ds}. \tag{3}$$

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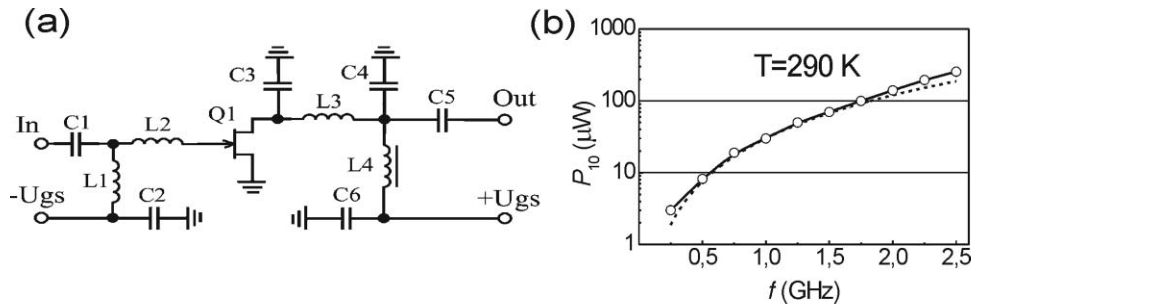

FIG. 1. One-stage amplifier based on PHEMT in unsaturated dc-regime. (a) Schematic circuit. Q1 is Agilent ATF-36077; $U_{gs} = -0.2-0.35$ V, gate current $I_g = 5-7$ nA. The amplifier is absolutely stable at $U_{ds} < 100$ mV, $I_d \leq 1$ mA, and $G \leq 20$ dB. (b) Power consumption P_{10} (for 10 dB gain) at 290 K vs operating frequency f. Dashed line is the theoretical curve [Eq. (5)], K = 30. Experimental data (solid line) are obtained at $U_{ds} = 30-300$ mV and $I_d = 0.1-1$ mA.

Using expressions (1–3) and introducing C_g as a new "quality parameter" of the HEMT, we find $G_{a\,\max}$ in the unsaturated regime

$$G_{a\,\max} \approx C_g (U_{ds}/f)^2. \tag{4}$$

Generally, the gain $G(P_C)$ depends on the transistor consumption $P_C = U_{ds}^2/R_{ds}$. Let P_{10} will denote the dc power consumed by the HEMT when its gain is 10 dB. Then P_{10} and the operating frequency f will be bound together via quadratic law

$$P_{10}(f) = \mathrm{K} \cdot f^2. \tag{5}$$

Fitting factor K for the unsaturated regime can be found experimentally. It follows formally from relation (5) that essential decrease in consumption is possible by lowering the operating frequency, or, in more accurate terms [see Eq. (1)], by increasing (f_t/f) ratio. Practically, reduction of P_{10} is limited by own quality factor of input matching circuit elements and required band characteristics.

The circuit diagram of a stage of the pseudomorphic HEMT (PHEMT) amplifier with ultra-low dc power consumption is shown in Fig. 1(a). The input (C1, L1, L2) and output (L3, C3, C4) matching circuits are tuned to obtain maximum gain with bandwidth of about 10% at input/output standing wave ratio (in 50 ohm transmission line) of less than 1.5/1.2.

The experimental data and the theoretical curve [Eq. (5)] for $P_{10}(f)$ of the amplifier at room temperature are presented in Fig. 1(b). Since K value was determined from measurements at 1 GHz, the calculated and experimental curves coincided near this frequency. A deviation of the measurements from the theory in low-frequency region is due to inadequate (low) quality factor of inductive elements L1, L2 at room temperature. A deviation at high frequencies (where actual $U_{ds} > 150$ mV) is generally due to violation of the "Ohmic approximation." The obtained results imply that no principal limitation is found for reducing the HEMT dc consumption provided if the operation frequency is simultaneously decreased.

With lowering the ambient temperature of the amplifier its power consumption, P_{10}, falls down (Fig. 2) and comes to saturation $P_{10}(T) \cong 1\ \mu$W below 1 K for the given transistor type. To calculate $G_{a\,\max}$ by Eqs. (1) and (2), we extracted equivalent circuit parameters $R_{gs} = 7$ ohms and $C_{gs} = 0.35$ pF (which are weak functions of temperature, frequency, and dc regime) from Agilent data sheet *S*-parameters (which, in opposite, are principally frequency-dependent) and measured the temperature-dependent $R_{ds} = 910$ ohms, $G_m = 1.4$ mA/V directly at 300 mK for working point $U_{ds} = 25$ mV, $I_d = 38\ \mu$A. The calculated $G_{a\,\max} = 52$ (or 17 dB) while the measured value is 10 dB. The difference is likely due to detuning of matching circuits at low temperature after they were initially tuned at 290 K. Figure 3 shows gain as a function of power consumption at temperatures $T = 290$ K, 80 K, and 4.2 K obtained under the condition of absolute stability. As one can expect, the supply power should be increased to raise the gain G of the PHEMT amplifier in unsaturated regime.

To study macroscopic quantum dynamic of a single superconducting qubit[3,4,8] or a system of coupled qubits[5,15] with minimal measurement-caused decoherence, a prototype of 3-stage amplifier was designed. The amplifier has a gain of 45 dB at frequency $f = 0.5$ GHz. The total power consumption is 5 μW. First stage consuming 1 μW is being intended to be placed at 30 mK-level of a 10 mK dilution refrigerator while the other two at $T \leq 1.5$ K. In this case, the noise temperature of the qubit-to-amplifier transmission line and the spectral density of Planck radiation emitted by elements of the measuring circuit will be determined by the 30 mK level. The amplifier noise temperature measured by

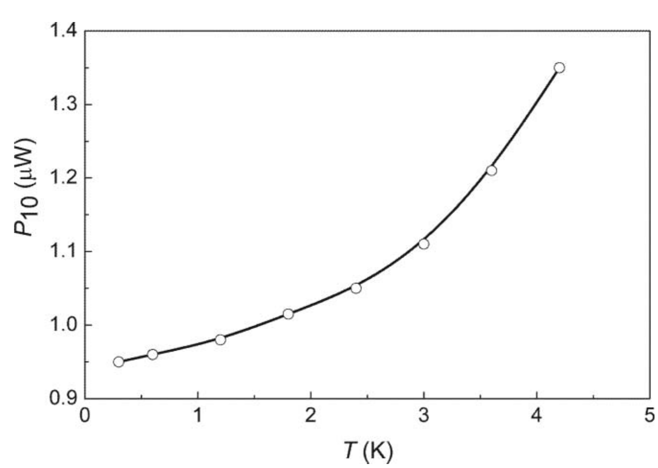

FIG. 2. Power consumption P_{10} vs temperature T at $G = 10$ dB, $f = 0.5 \pm 0.015$ GHz, $U_{ds} = 30$ mV.

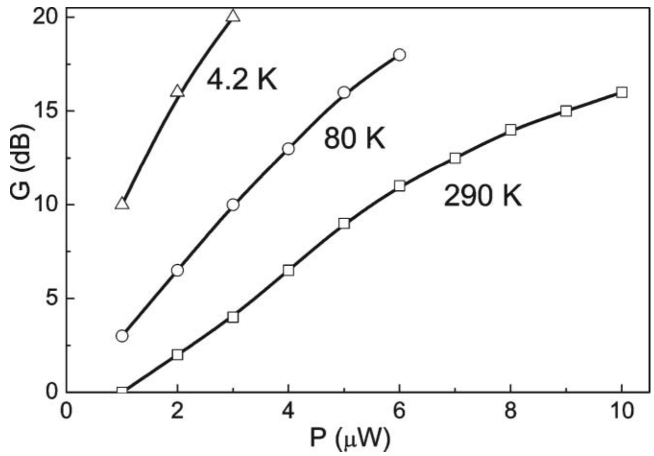

FIG. 3. Stable gain G vs power consumption P at various temperatures. $U_{ds} = 25-85$ mV.

hot/cold load method at ambient temperatures of 80, 20, and 4.2 K equals 20 ± 1, 6 ± 1.5, and 2 ± 2 K, correspondingly. It follows from papers[3,7,12] that $1/f$ noise of a PHEMT in ultra-high frequency (UHF)band at ultra-low I_d and U_{ds} will be much less than thermal one and can be neglected in evaluations. The transistor self-heating at dissipated power of about 1 μW is negligible as well. In this case, the extrapolated noise temperature of the amplifier, at matching parameters kept unchanged, will not exceed 200 mK at temperature of the PHEMT chip of 300 mK.

It follows from the model [Eqs. (1)–(5)] and the experimental results that, within the framework of the proposed conception for design of ultra-deep-cooled cryogenic amplifiers, further reduction in power consumption down to level of 0.1 μW per stage at rf and ultra-high frequencies (0.1 − 1 GHz) can be predicted when using modern HEMTs with higher f_t/f ratio.

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