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Concept of a pHEMT readout and frequency domain multiplexing for bolometers.

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ABSTRACT

We propose a pHEMT readout and frequency domain multiplexing concept for bolometer arrays. The readout is analyzed using the example of a cold electron bolometers (CEB) and a multiplexing technique working in the radio-frequency range below 100 MHz, where this could be extended in the future up to a frequency of 1 GHz. This concept combines the outstanding sensitivity of the pHEMT technique together with the possibility controling many bolometers with a minimum number of connecting lines between the sensors and amplifier. The energy balance between the bolometer and readout electronics, back-action and the optimum condition for CEB cooling are discussed. The minimum voltage spectral noise density of the amplifier with respect to the input is about 140 pV/sqrt(Hz). The power consumption of the amplifier is in the range of 15–400 μW. The minimum noise equivalent power of ~6 aW/Hz$^{1/2}$ (caused by the total setup noise) was estimated from CEB measurements with a pHEMT readout.

INTRODUCTION

Some of the rapidly developing areas connected with bolometric measurements [1 - 4], characterization of qubit circuits [5 - 8] etc., impose strong requirements on the sensitivity and speed of their respective read-out electronics.

Most pseudomorphic high electron mobility field-effect transistors (pHEMT) have been designed for the microwave frequency range, and because of the high corner frequency of the flicker noise, it was expected that these transistors would be unsuitable for sensitive measurements at frequencies below the GHz range [9 - 11]. This low frequency noise limitation is substantially caused by the pHEMT design, which is optimized to give a maximum 2DEG mobility in the microwave frequency range.

However, there are many applications in the field of condensed-matter physics and cryogenic measurements where an extremely low readout noise temperature in the radio frequency working range is required [1 - 8]. For this purpose we designed and tested two versions of a cryogenic pHEMT amplifier with an optimized noise performance for frequencies below 100MHz [12 - 14].

We have already demonstrated the superior sensitivity of the pHEMT readout and significant progress has been made in the reduction of the flicker noise corner frequency [12 - 14]. A minimum noise temperature of 100 mK was measured at an ambient temperature of about 380 mK for frequencies between 1 and 4 MHz for a source resistance of 10 kOhm. As follows from our estimation, our three-stage pHEMT amplifier achieves a minimum expected value of the energy resolution of ~30±15 h ($T_{N\,MIN}$~6±3 mK) at ~4 MHz [12]. The minimum voltage spectral noise density of the amplifier with respect to the input was about 200 pV/ Hz$^{1/2}$ and the corner frequency of the 1/f noise is close to 300 kHz. Its ultra-low power consumption (100-600 μW) has allowed us to place the amplifier at an ambient temperature of below 400 mK.

We have designed and described several cryogenic multistage pHEMT amplifiers for quantum device readout. They were successfully employed for quantum measurements with flux and charge qubit circuits [5 - 8]. A decoherence time of ~2.5 μs was demonstrated during the continuous monitoring of Rabi-oscillations in a Josephson flux qubit inductively coupled to the tank circuit on the input of the pHEMT amplifier [12 - 14].

For bolometric measurements and multiplexing of bolometric arrays we have already demonstrated a very promising system performance over a considerable frequency range (~ 0.3 - 100 MHz). Therefore, we present a frequency domain readout and multiplexing concept for bolometer arrays which is based on our improved version of the pHEMT amplifier.

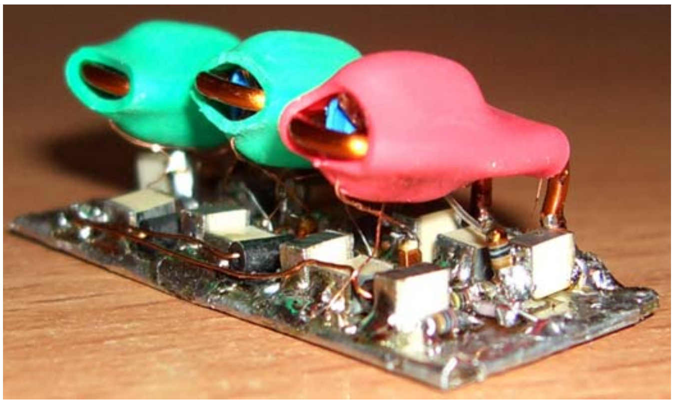


Fig. 1. pHEMT amplifier with an extended frequency range.

PHEMT AMPLIFIER

In comparison with the previous design we considerably (up to the ~1 GHz) increased the working frequency range of our amplifier (see Fig.2). Following this, we improved the power consumption of our three-stage design. The very flexible circuit design gives us the possibility to vary the dynamic and noise parameters of our readout for the power consumption range between 15 μW and 1 mW.

As in our previous design [12 - 14] new amplifier has a three-stage construction and was assembled on a printed board of size 33 mm by 13 mm (see Fig.1).

In Fig.3 we have presented the voltage noise dependence on the common power consumption in the case when the amplifier is adjusted to the minimum noise figure to power consumption ratio. Measurements where conducted at an ambient temperature ~ 3.5 K.

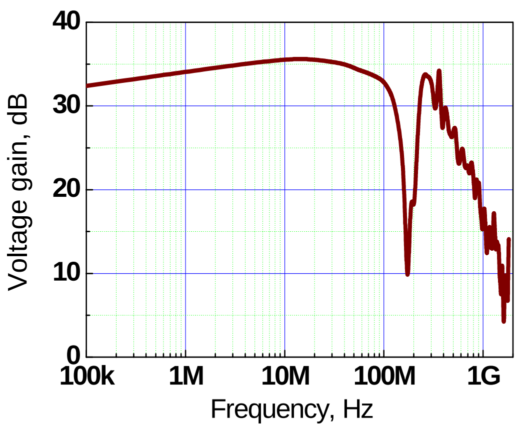


Fig.2. Voltage gain factor of the cryogenic amplifier with a power consumption of about 200 μW at an ambient temperature of ~3.5 K.

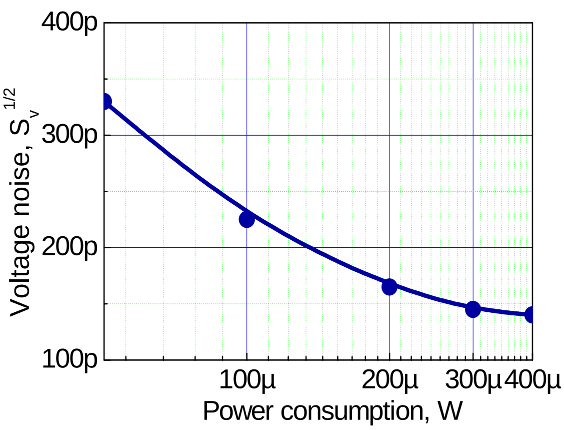


Fig.3. Dependence of the voltage noise of the cryogenic amplifier on the common power consumption for an ambient temperature of ~3.5 K.

CONCEPT OF BOLOMETERS READOUT AND MULTIPLEXING

In this section we will discuss inductively coupled resonant readout on the pattern of cold electron bolometers (CEB) [1 - 4].

This technique provides a galvanic decoupling of the CEB from readout and bias line, which can be especially important for the protection of bolometer from external interferences (see Fig.4). A wide range of bolometer impedances (from ~ 1 Ω to ~1 MΩ) and biasing modes (from voltage- to current-bias) are available with this technique. In addition, a bias-modulation technique, along with a lock-in detector, can be applied to the signal processing. Resonant circuits give us the possibility to reconstruct the real part of the bolometer impedance at the resonant frequency. Furthermore, the resonant circuit provides a good decoupling factor between the channels, which can be used as a natural solution for multiplexing the bolometers. One common line can be used for the biasing and readout of ~10 - 1000 bolometers with an allowable power consumption of ~ 100 nW/bolometer.

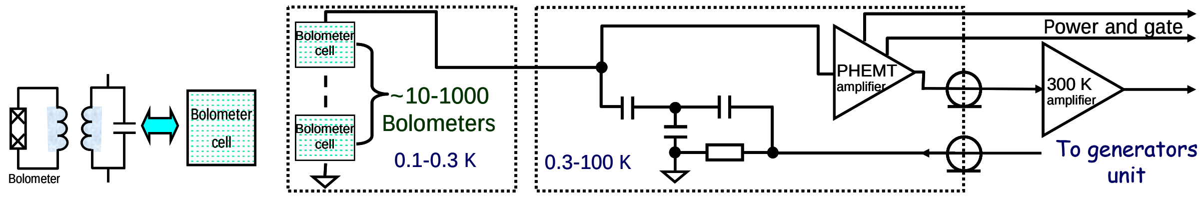


Fig.4. Simplified functional diagram of the resonant frequency domain readout and multiplexing.

In order to prevent the possible bifurcation of the output of the resonant transformer we limited our circuit analysis to a coupling coefficient $k \approx 1$.

MAIN OBJECTIVES AND ENERGY RATIOS

In this section we discuss possible optimizations of the resonant readout for several objectives. The task of providing a minimum back-action from the amplifier and tank circuit to the bolometer should be considered together with a maximum signal/noise ratio at the output of the resonant circuit.

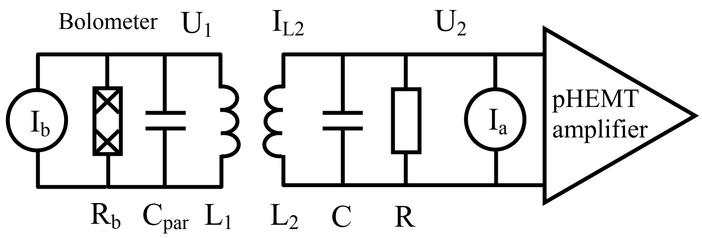


Fig.5. Schematic circuit of the bolometer resonant readout.

By analyzing the circuit in Fig.5 we can estimate the back-action on the bolometer for different resonant circuits and bolometer resistances.

$$\frac{\varepsilon_{\mathrm{ba}}^{\mathrm{phonon+amp}\to\mathrm{bol}}}{\hbar\omega_0} = \frac{\sqrt{S_{\mathrm{Vb}}S_{\mathrm{Ib}}}}{2\hbar\omega_0} \approx \frac{R_{\mathrm{b}}L_1L_2}{2\hbar\omega_0}\left(\frac{R_2}{R_2L_1+R_{\mathrm{b}}L_2}\right)^2\left(\frac{4\mathrm{k}T}{R_2}+S_{\mathrm{Ia}}\right),$$

In Fig. 6 we present the back-action on the bolometer, which is due to the phonon noise originated from energy losses of the inductance and capacitance, and amplifier back-action. For this figure, T ~ 0.3K is the phonon temperature of the common setup, R_2 ~ 100 kΩ is the equivalent resistance of all active energy loss in tank circuit, and $S_{\mathrm{Ia}}^{1/2} \approx 3$ fA/Hz$^{1/2}$ is the amplifier current noise.

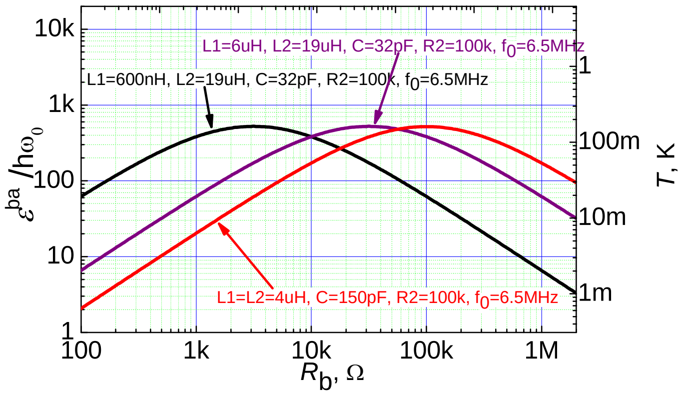
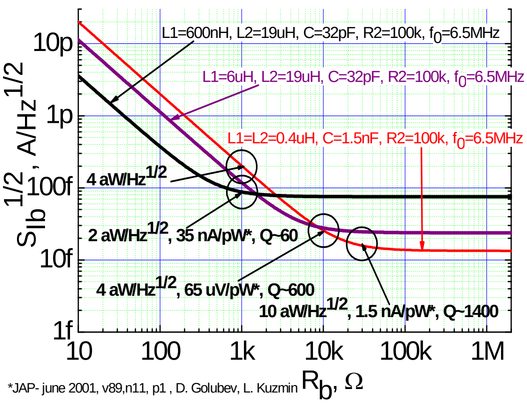


Fig. 6. Back-action energy on the bolometer.

The current sensitivity and noise equivalent power (NEP) for readout with different resonant circuits and bolometers can be estimated using the following equation:

$$\sqrt{S_{\mathrm{Ib}}} \sim \sqrt{\frac{L_2}{L_1}\left(\frac{4kT}{R_2} + S_{\mathrm{Va}}\left(\frac{R_2L_1 + R_\mathrm{b}L_2}{R_2R_\mathrm{b}L_2}\right)^2 + S_{\mathrm{Ia}}\right)}$$

In Fig. 7 we present the readout current sensitivity (bolometer noise is not included) dependence on bolometer resistance at the working point. For this $S_V^{1/2} \approx 140$ pV/Hz$^{1/2}$ is the amplifier voltage noise. In the same figure we have presented the minimum NEP corresponding to this current sensitivity for 1 kΩ, 10 kΩ, and 30 kΩ bolometer resistance [1].



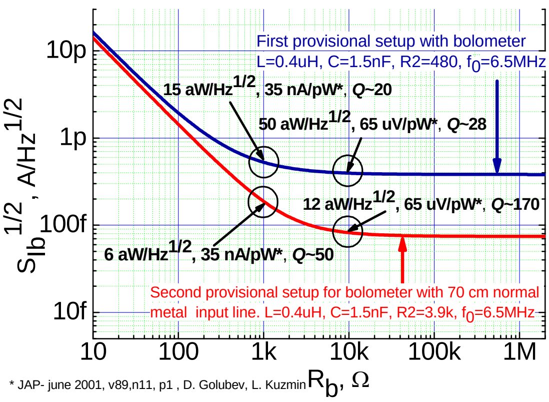


Fig. 7. Estimations of the current sensitivity and corresponding NEP for a pHEMT readout with different resonant circuits dependence on the CEB

Fig. 8. Measurements of the current sensitivity and corresponding NEP dependence on the CEB working point resistance with a pHEMT resonant readout.

In figure 8 we presented the results of the first measurements with a CEB. We could not achieve a maximum Q-factor in our first provisional setups (because of the presence of a high resistive dc-line in parallel with the tank circuit in the first case, and the presence of a 70 cм - length normal metal connecting line between the tank circuit and the amplifier in the second case). Nevertheless, the second setup showed a rather good current noise performance $S_{\mathrm{Ib}}^{1/2} \sim 80$ fA/Hz$^{1/2}$ (NEP ~12 aW/Hz$^{1/2}$) for a CEB with a resistance of ~10 kΩ at the working point. A minimum noise equivalent power (determined by the total setup noise) ~6 aW/Hz$^{1/2}$ ($S_{\mathrm{Ib}}^{1/2} \sim$ 190 fA/Hz$^{1/2}$) for a CEB with the pHEMT readout was estimated in the case where the bolometer resistance is close to 1 kΩ.

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