Development of TES Bolometers with High-Frequency Readout Circuit (on-line issue)

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***Abstract*—In order to improve the frequency division multiplexing in transition-edge sensor (TES) arrays, it is suggested to replace commonly used SQUID amplifiers with a semiconductor high-frequency cooled amplifier. This would result in a single 10-GHz bandwidth amplifier serving up to and possibly more than 1000 TES detectors of an imaging array. The basic idea is to implement an antenna-coupled TES as a load for high-Q resonator, weakly coupled to an RF throughput line. To verify new concept, prototype TES absorbers made of Ta and Nb films are developed and tested above 4 K. The NEP of about 1.5×10^{-15} is estimated for experimental micron-size prototype devices made of Nb at 4.5 K. The *IV*-curves of the absorber at different temperatures are recovered; presence of negative electrothermal feedback is verified that may qualify the new approach as "TES with GHz readout".**

***Index Terms*—Frequency division multiplexing, FDM, transition edge sensor, TES, bolometer, electrothermal feedback, imaging array, high-Q resonator, terahertz range.**

I. Introduction

THE superconducting bolometers based on transition-edge sensing (TES) are nowadays of active interest, due to their great potential for ultra-low-noise operation with noise equivalent power (NEP) down to 10^{-19} W/Hz$^{0.5}$ and below [1]. Usually TES acts as a thermometric device, which changes its resistance abruptly near the temperature of the superconducting transition, thus detecting the power coupled to the attached absorber. The antenna-coupled TES devices are relatively new; they comprise absorber and thermometer in the same sub-micron-sized film [2]-[4]. In fact, it is a bad thermometer, which is operated with too high probe current. Under such condition a little extra current from the feeding antenna combined with the probe current makes a noticeable effect. In order to read out the imaging array, the frequency division multiplexing method (FDM) [5] is tested successfully with practicable systems for more than 1000 pixels. However, the restricted bandwidth of SQUID-sensor sets a limit for FDM for about 100 channels.

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II. Concept and Approaches

A. General Idea

To improve the capability of the multiplexing circuit, we suggest to go for a higher frequency band [6]. This could result in creating a relatively simple system, containing just single amplifier (connected to room with only one or two coaxial cables), which serves up to 1000 or even more TES detectors of an imaging array integrated with the FDM filter system**.** In fact, it is suggested to replace the low-frequency wires and lumped LC circuits with coaxial cables and RF IC's. TES-loaded Resonant Circuit.

The basic idea is to use the high-Q resonator technology, which is similar to one used for microwave kinetic inductance detection (MKID) [4]. We suggest reading the response caused by variations in resistivity of the tiny antenna-coupled TES absorber inserted in the quarter-wave resonator. The equivalent scheme of such resonator is shown in Fig. 1. When the extra heat is provided from the THz antenna, the resistance of the absorber will grow, and the Q-factor will change, changing the RF throughput signal. Such joint heat effect can be expected

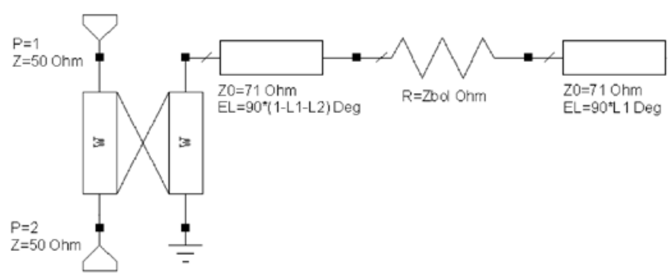

Fig. 1. Equivalent scheme of RF driven TES bolometer. The *open-end* quarter-wave resonator (*Z0* = 71 Ohm) is weakly coupled to the throughput line (ports P1 and P2, Z = 50 Ohm). The resonator is split in two arbitrary parts *L1* and *L2* (*L1* + *L2* ≈ 1) by the inserted antenna-coupled TES absorber (Zbol).

when the bolometer/absorber are slow enough.

The new approach might bring a few advantages over both traditional MKID and TES. i) Better signal coupling, since the TES absorber is a lumped resistor, which is definitely easier to match to the receiving antenna. ii) TES is generally independent of receiving frequency, since only the heat effect is important. iii) In respect to present TES technology, the *open-end* high-Q resonator will provide almost perfect protection of the nanometer-scale absorber from electrical shocks including static discharge, since there is no wire chain connected to the absorbing film and the effective capacitance of the RF "connection" is extremely small.

B. Design Approach and Estimate for Ultimate Sensitivity

To evaluate the new concept, we design a prototype detector circuit operated at temperature 280-300 mK. The TES absorber can be made of thin (20-30 nm) films of Titanium (Ti, T_c about 300 mK), which demonstrated a pronounced effect of electron gas heating at this temperature [7]. The compact THz-range double-slot antenna [8] loaded with TES absorber is placed in the CPW resonator and then positioned in the focus of hyper-hemispherical lens.

We have estimated the sensitivity of the new device using S-parameters of a particular layout and its EM-model. Setting the noise figure for the cooled LNA as $T_N = 3$ K, which surely dominates the noise of the 300-mK device, we get for the whole detector-amplifier chain $NEP = 1.6\ 10^{-19}$ W/Hz$^{1/2}$. This result [6] is encouraging enough to be verified experimentally.

III. Experimental Details and Discussion

A. Fabrication

Since the low-temperature experiments are quite laborious, expensive and time consuming, we decided to verify our EM-model and most basic approaches, at 4-K temperature level. A pilot device was designed and fabricated using thick (200 nm) Nb with $T_c = 8.8$ K for the throughput line and quarter-wave resonator. The films of Nb were sputtered in UNIVEX 450 magnetron sputtering system with deposition rate 0.27 nm/s.

The geometry of the device was formed by standard contact photolithography. At the first step thin (15 nm) Nb film was deposited on the whole sapphire substrate. At the second step the throughput line, CPW resonator and planar antenna were patterned from a thick (200 nm) Niobium film by lift-off process. Finally, the TES bridge with sizes of 5×2.5×0.015 μm^3 was formed by etching away the bottom layer with Ar^+ ion gun.

B. DC measurement

Since the small Nb bridge of the TES absorber is completely decoupled at DC, the measurement of its superconducting and thermal properties were done using witness structures of the same size and fabricated on the same wafer as the resonators. The optimized witness bridges had critical temperature $T_c = 6.7$ K and transition width $\Delta T_c = 50$ mK. TES absorber has volume $v = 5$ μm × 2.5 μm × 15 nm. The NEP as low 1.5×10^{-15} W/Hz$^{1/2}$ can be estimated at 4.5 K.

The estimate for time constant gives $\tau = C/G_{th} \approx 0.5$ ns, where C is calculated from material parameters as in [9], is in good agreement with the value in Nb HEBs [10]. Referring to the value of τ, one may suggest experimental study the bias frequency higher than 4 GHz.

C. RF measurements

The frequency response at 4 K is measured with the Agilent PNA-X series network analyzer with incident power ranged from -27 dBm up to +6 dBm. Figure 2 presents the effect of hot-spot response to a high power signal, with current amplitude close to the I_c of the TES absorber. The response did not change below the power range presented in the inset for Fig. 2, since the absorber remains in the superconducting state. The Q-factor of about 7000 can be estimated from the graph, along with both the dip and the resonant frequency close to their design values of -0.8 dB and 5.85 GHz respectively. These data have validated the RF design successfully.

D. Discussion on Regime of Operation

To prepare the optical sensitivity measurements, we have to go for low-power regime. The dynamic model of the system is developed along with procedure for extraction of *IV*-curve at RF. The dynamic model exploits the *S*-parameters of the structure along with physical parameters of the absorber, including $R(T)$ for the particular experimental batch (for its witness device, actually).

We found that for the case of $R / R_{emb} < 1$ the operation is unstable, since the resonator acts as a current source, so we got *positive* electrothermal feedback. This is exactly what we can see in the experiment (see Fig. 2) – fast triggering from very low (nearly zero) resistivity to the normal state – hot-spot nucleation in the middle of the dip. In case of $R / R_{emb} > 1$ the resonator

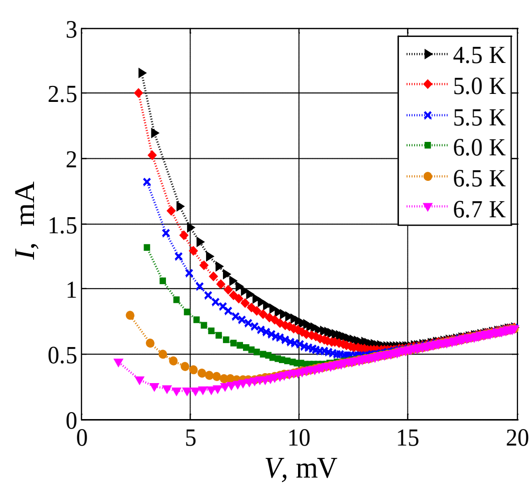

Fig. 3. *IV*-curves of experimental TES absorber calculated using *S*-parameters of EM-model. Each point is a self-consistent solution for the dependence $P(R(T_e(P,T_{bath})))$ for various bath temperature T_{bath} (see inset) and scanning incident power P across the absorber.

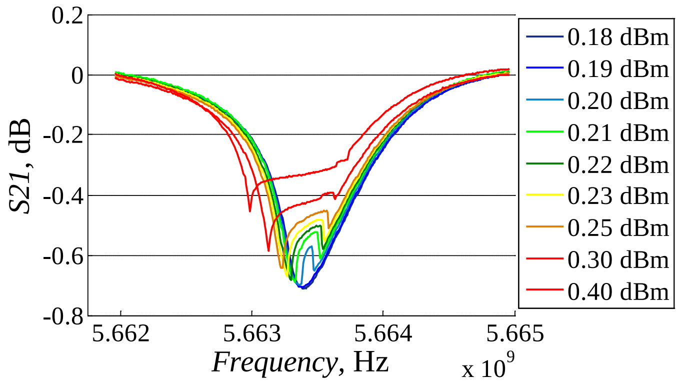

Fig. 2. Frequency dependence transmission of the throughput line of the Nb TES-loaded resonator device at bath temperature about 5 K. The triggering to hot-spot regime occurs at the same RF power. The two lowest dips correspond to superconducting state of the resonator, its Q-factor can be estimated to *Q* = 7000.

acts as a voltage source. Here we got *negative* electrothermal feedback.

To estimate *IV*-curves of our RF-connected devices, we have searched for self-consistent solutions for RF power *P* and resistance *R* across the absorber as $P(R(T_e(P,T)))$. The RF power transfer to TES absorber is calculated using S_{31}-parameter of EM-model. Each point in Fig. 3 is a self-consistent solution for various bath temperatures T_{bath} and scanning incident power P_{in} at the input of the throughput line. These *IV*-curves are very similar to ones reported for HEB mixers and traditional (low-frequency) TES bolometers, which are stabilized with negative electrothermal feedback. From these data one may clearly conclude that the new device is indeed a TES bolometer operated at GHz bias frequency suitable for combination in large imaging arrays served with fewer cooled semiconductor LNA's.

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