

Optical Qualification of the Normal Metal Hot-Electron Microbolometer (NHEB)

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Abstract

We are presenting here the first results of optical responsivity measurements for the Normal Metal Hot-electron Microbolometer (NHEB), a hot-electron direct detector for sub-mm wavelengths. The detector is a metallic microresistor coupled to a planar antenna; superconductor-insulator-normal metal (SIN/NIS) tunnel junctions are employed to monitor the temperature of the electron gas. We aim to achieve with this detector sensitivity around 10^{-17} W/ $\sqrt{\text{Hz}}$ at 0.3 K while the time constant is going to be less than 1 μs . Planar design of the NHEB is favorable for its future expansion into a detector array. Earlier we have measured electrical NEP (noise equivalent power) of 3×10^{-16} W/ $\sqrt{\text{Hz}}$ for an NHEB at 0.3 K. This time we have performed an optical responsivity measurement for another NHEB at 0.5 K using a hot/cold load. We have obtained an optical responsivity value consistent with the electrical responsivity data, and with the estimated efficiency of the quasioptical coupling.

Introduction

Direct detectors can be used in those astrophysical applications where sensitivity is more important than the spectral resolution. Some examples of studies are observation of the extragalactical objects, observation of remote galaxies radiation from which is highly red-shifted, and study of the early phases of the star formation. For these applications the interesting frequency range is between 400 GHz and 1.2 THz [1]. Another kind of study, where bolometers are employed, is the Cosmic Microwave Background (CMB) study. In the CMB experiments astrophysicists try to resolve fine fluctuations of intensity in the relict radiation with equivalent black-body temperature around 2.7K, that is why the interesting frequency range there is 50..300 GHz.

Today's most common type of bolometers is the NTD-Germanium thermistor suspended on a SiN-mesh. The newer type is a superconducting transition-edge sensor (TES), also suspended on thin SiN or Si supports [2][3]. All these bolometers have noise equivalent power (NEP) around 10^{-17} W/Hz^{1/2}, which usually means that their sensitivity is already

limited by noise from fluctuations in the stream of received photons (photon noise). However the time constant is at the level of 1 ms, which means that an experiment requires very long observation time. This problem can be resolved by integrating many bolometers into an array, thus building an imaging camera. Several research groups have proposed different ways how large bolometer arrays could be built, however at present there is still no fully developed solution for a fast, sensitive, and robust bolometer, that could be easily integrated into an array with thousands of pixels.

It would be a great advantage for integrating the detectors if the whole array could be fabricated on a single wafer and processed at the same time instead of assembling it from individual elements as it is usually done nowadays. We are developing a detector which is fully compatible with the planar microtechnology and can be fabricated on a standard silicon wafer without membranes or any suspended structures. This detector, normal-metal hot-electron bolometer (NHEB) is an antenna-coupled device, similar to the widely known hot-electron heterodyne mixers. Its operating temperature is 0.3 K or below, and the sensitivity after optimization can be as good as 10^{-17} W/Hz^{1/2} at 0.3 Kelvin and 10^{-19} W/Hz^{1/2} at 0.1 Kelvin. Furthermore, this bolometer has the time constant as short as 20 μ s at 0.1 K (less than 1 μ s at 0.3 K), thus allowing for high-speed scans. In the following text we review the prospects of this detector and describe its optical qualification that has been done now for the first time.

The Normal-Metal Hot-Electron Bolometer

The normal metal hot-electron bolometer (fig. 1) has been proposed by M. Nahum *et al* [4][5]. It consists of a normal-metal absorber strip with small volume connected as a matched load to a planar antenna, and a pair of Normal metal-Insulator-Superconductor (NIS) tunnel junctions. The electron gas in the absorber strip receives thermal energy from the high-frequency currents induced in the antenna and gives it away to the lattice phonons in the film. At low temperatures the electron-phonon interaction time is much longer than the electron-electron interaction time, so that the electrons arrive at thermal equilibrium at a temperature which is higher than the lattice temperature (hot-electron effect). In order to avoid energy loss through diffusion of the electrons into the antenna the strip is contacted via superconducting electrodes, since the Andreev effect prohibits energy transport from the normal metal to the superconductor at an NS-interface. Variations of the electron temperature in the absorber strip of the NHEB are detected from smearing of IV-curves of the NIS junctions, which have the strip as their N-electrode. In the latest design of our devices the absorber strip is made of copper and has dimensions $5.6\mu\text{m}\times 0.25\mu\text{m}\times 0.03\mu\text{m}$. The superconducting electrodes are made of aluminum. The NIS junctions have normal resistance between 1 and 10 kOhms.

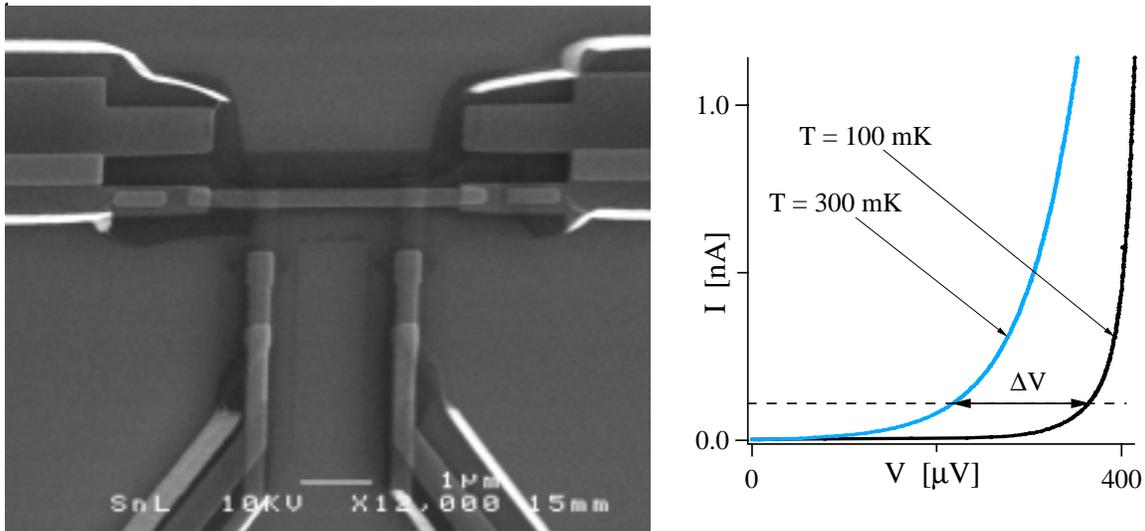


Fig. 1

Left panel – SEM image of the power sensor (tilted view). The structure is fabricated by *e*-beam lithography and shadow metal evaporation from different angles.

Right panel – principle of operation of the NIS thermometer. Two junctions in series are biased with a constant current. Voltage over the junctions is then almost linearly dependent on the electron temperature in the normal electrode.

The following expressions can be used for a simple estimation of speed and sensitivity of the detector at various temperatures:

$$NEP = e_n / S$$

is the Noise Equivalent Power (NEP), which is the common measure of sensitivity for bolometers; e_n is the total voltage noise at the output of the bolometer and S is the bolometer's responsivity (output voltage change per unit of input power change). The output noise is a sum of many contributions: thermal fluctuation noise, shot noise in the tunnel junctions, noise from thermal flow fluctuations in the junctions, amplifier noise, and the photon noise. A detailed analysis of the different noise contributions can be found in [6]. Here we can mention that in all experiments reported by now the output noise has been dominated by the noise of a semiconductor amplifier. In our latest experiment we had $e_n = 15 \text{ nV/Hz}^{1/2}$ at 35 Hz with a room-temperature amplifier, and we estimate that by using a cold amplifier we must be able to reach $e_n = 3 \text{ nV/Hz}^{1/2}$.

The responsivity is given by

$$S = \frac{dV}{dT} \cdot \frac{dT}{dP} = \frac{dV}{dT} \cdot \frac{1}{G}$$

where T is the electron temperature in the absorber strip, dV/dT is the temperature responsivity of the tunnel junctions, and G is the thermal conductance from electrons to

phonons in the absorber strip. dV/dT for aluminum junctions is nearly constant from 0.15 K to 0.45 K with nominal value of 8×10^{-4} V/K per pair. Low thermal conductance is of the key importance for obtaining high responsivity and low NEP, and it is strongly dependent on the operating temperature. For copper films which we use for the absorber strip in the NHEB, the electron-phonon cooling rate is given by

$$P_{ep} = \Sigma \Omega (T^5 - T_0^5)$$

where Ω is the volume of the strip ($0.045 \mu\text{m}^3$), Σ is the material parameter (2.5×10^{-9} W $\mu\text{m}^{-3}\text{K}^{-5}$ for copper), and T_0 is the phonon temperature. Then the thermal conductance will be

$$G = 5\Sigma\Omega T^4.$$

The time constant of the bolometer is equal to the electron-phonon interaction time in the absorber strip. According to the data that can be found in literature [5] this constant for our type of films is

$$\tau_{ep} = 20 / T^3 \text{ ns.}$$

By substituting the typical values into the formulas above we get the following summary of performance parameters expected for the NHEB:

	$T = 0.3 \text{ K}$	$T = 0.1 \text{ K}$
thermal conductance G	$5 \times 10^{-12} \text{ W/K}$	$6 \times 10^{-14} \text{ W/K}$
responsivity S	$1.8 \times 10^8 \text{ V/W}$	$9 \times 10^9 \text{ V/W}$
NEP with $e_n = 15 \text{ nV/Hz}^{1/2}$	$8 \times 10^{-17} \text{ W/Hz}^{1/2}$	$1.7 \times 10^{-18} \text{ W/Hz}^{1/2}$
NEP with $e_n = 3 \text{ nV/Hz}^{1/2}$	$1.7 \times 10^{-17} \text{ W/Hz}^{1/2}$	$3 \times 10^{-19} \text{ W/Hz}^{1/2}$
time constant	$0.7 \mu\text{s}$	$20 \mu\text{s}$

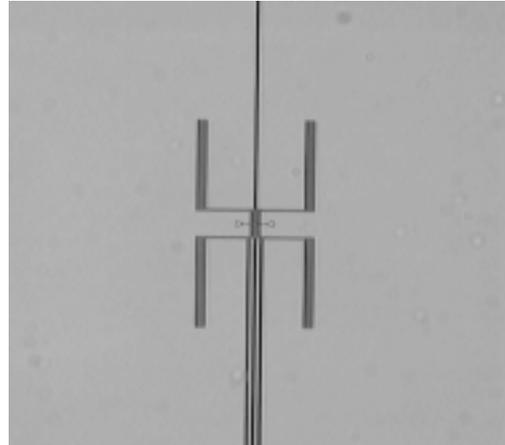
In our earlier experiments we measured the so-called electrical responsivity of a NHEB, that is response at the output per unit power dissipated in the absorber strip by a constant current applied through it. We obtained $S_E = 1 \times 10^8 \text{ V/W}$ at 0.3 K and $S_E = 4 \times 10^9 \text{ V/W}$ at 0.1 K for a bolometer with absorber strip of double the volume used in the calculations above [7]. Thus the experimental values were in a good correspondence with theory.

In order to measure the optical responsivity, which is the response per unit power of an external sub-mm wave signal coupled to the bolometer, we had to incorporate the NHEB power sensor with a suitable planar antenna. We have chosen the twin-slot antenna because of its reasonably narrow pattern and frequency characteristics. The slot dimensions were designed using the calculation procedure developed at Caltech [8]. To simplify the fabrication process coupling between the slots and the power sensor has been

done by two co-planar waveguides (CPW) with characteristic impedance of 30 Ohms, which is equal to the antenna impedance at the resonance frequency (300 GHz) – see figure 2.

Fig. 2

The twin-slot antenna. The bolometer (in the center) is connected to the slots by a CPW transmission lines with characteristic impedance of 30 Ohms, which matches the calculated impedance of the slots at 300 GHz. The ground plane is divided by another narrow slot in order to allow measurements of resistance of the absorber strip and to make space for the bias wiring of the tunnel junctions.



The optical setup

The concept of our optical setup was described in detail in [7]. These are its main elements:

- Helium dewar with an optical window, type HDL-8 from IR-labs; minimum temperature of the cold plate is about 1.5 K achievable by pumping on the helium bath.
- Closed-cycle ³He cryocooler mounted at the cold plate of the dewar and providing cooling of a detector holder to 0.3 K.
- Detector holder containing the detector, a hyperhemispherical silicon lens, and a focusing dielectric lens.
- Filter unit mounted in the dewar window and cooled to the cold plate temperature.

This setup provides coupling of the external radiation to the detector cooled to 0.3 K by a nearly gaussian beam, so that the whole throughput of the antenna is covered by an external load. It also prevents overheating of the bolometer by thermal radiation at high frequencies. For the latter purpose we are using three sequential filters (in order from room to detector):

- metal mesh resonant low-pass filter with sharp edge at 450 GHz
- alkali-halide low-pass filter with edge at 1650 GHz; this filter blocks the resonant leaks of the metal-mesh filter at higher frequencies
- neutral density filter with 1.3% (-18.9 dB) transmission reducing the overall power load on the bolometer from the room-temperature environment.

All the filters are fabricated by QMCI [9]. The schematic diagram of the quasioptical path and a view of the cold work area of the dewar are shown in the figures 3 and 4.

Fig. 3

Ray traces in the quasioptical path (at the -8.7dB relative power level) for frequencies from 180 GHz to 420 GHz. The components on the drawing from left to right are the filter unit aperture, the dielectric lens and the hyperhemispherical lens (shown by a small circle). The traces are calculated in the assumption of the gaussian beam shape.

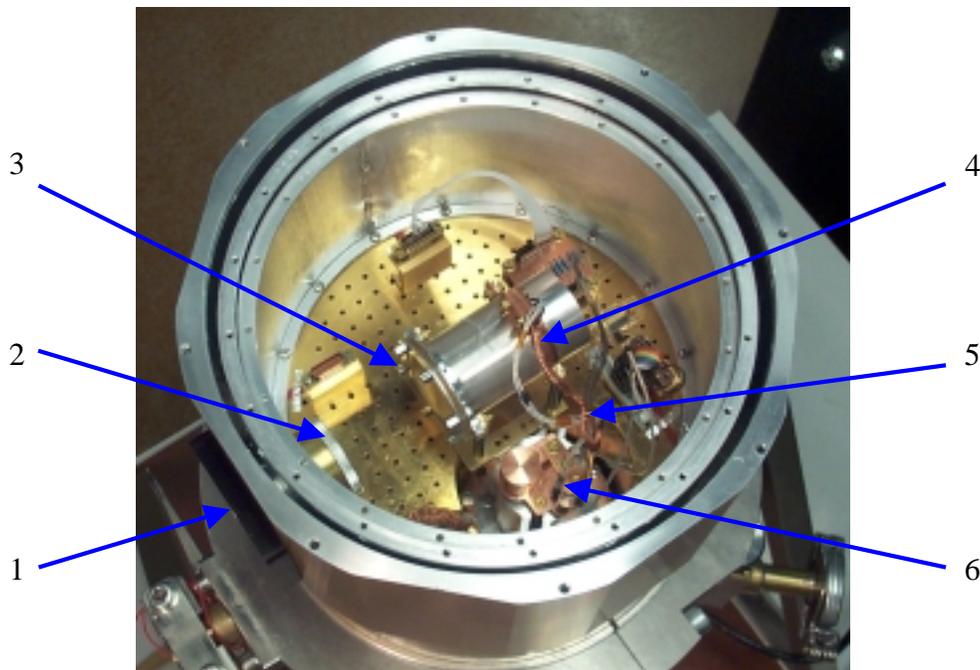
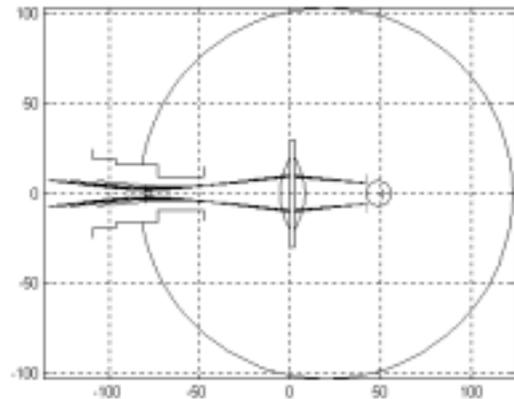


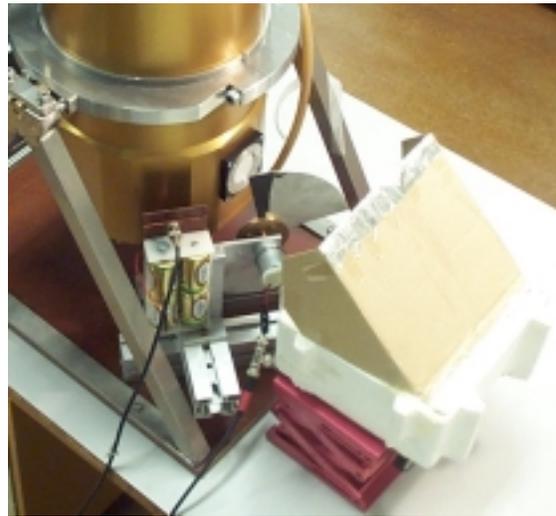
Fig. 4 View of the cold working area in the cryostat: 1 – the optical window; 2 – the filter unit; 3 – the focusing dielectric lens; 4 – the detector holder (position of the Si lens); 5 – the 0.3 K thermal strap; 6 – the ³He cryocooler.

The measurement results

In our optical qualification experiment we have measured how voltage across the tunnel junctions of the NHEB changes in response to switching between the hot (room temperature) and cold (liquid nitrogen) loads placed outside the dewar window. View of the experimental setup is presented in the Fig. 5. The measurements were done with a lock-in amplifier and the chopping frequency was 35 Hz. We have also measured the voltage noise at the output of the amplifier in order to determine the NEP of the bolometer. By modulating an external microwave source irradiating the bolometer we could estimate the post-detection bandwidth of the system, which was limited by the RC-constant of the readout.

Fig. 5

Setup used in the optical responsivity measurement: the chopper disk is tilted 45° from the optical axis; the bolometer sees either the lab environment reflected by a chopper blade (hot load) or an Eccosorb pad floating in liquid nitrogen in the foam box behind the chopper (cold load).



The NHEB used in this experiment had an absorber strip with resistance of 30 Ohms. The detector sample had been tested first electrically in a dilution refrigerator at $T = 0.3$ K.. 0.5 K. We have recorded IV-curves of the junctions at different temperatures, which has allowed us later to measure the electron temperature of the absorber strip in the optical experiment.

The results of the optical responsivity measurements are shown in the Fig. 6. The maximum response was 4 μ V at the optimal bias current of 1.2 nA. By comparison of the junctions' IV-curve with the IV-curves recorded in the dilution refrigerator we could conclude that the electron temperature in the absorber strip was 0.50 K, which also was the minimum electron temperature we could achieve in this experiment, even though the cryocooler's physical temperature was as low as 0.30 K. Presently we suspect that this overheating was due to the rf-interference from outside the cryostat penetrating through the test wiring attached to the antenna plane.

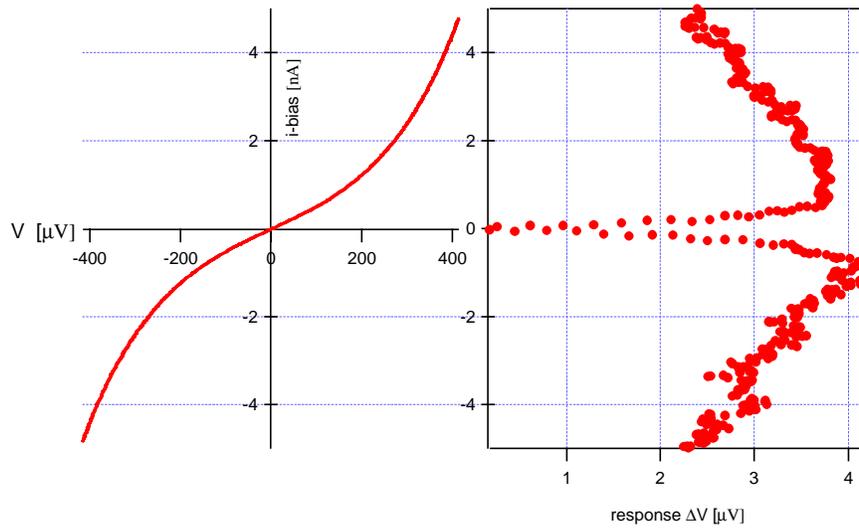


Fig. 6 Left panel: *IV-characteristics of the SINIS tunnel junctions in the optical responsivity measurement; the curve corresponds to the electron temperature of 0.5 K in the N-electrode (absorber strip).* Right panel: *Voltage response corresponding to chopping between cold and hot loads outside the dewar window. The measurement has been done with a lock-in at 35 Hz. The vertical axis is the junctions' bias current (same as in the left panel).*

A simple estimation of how the radiation power coupled to the bolometer changes with switching between the cold and the hot loads can be obtained with the following expression, derived from the Plank's formula for blackbody radiation in the limit of high temperatures and low frequencies:

$$\Delta P = \eta \cdot k_B (297K - 77K) \cdot \Delta f .$$

η represents all the optical and coupling losses, and Δf is the detection bandwidth which in our case is determined by the width of the main resonance in the frequency characteristics of the antenna. We have accounted for the following losses:

- Dewar windows (teflon), reflection, -0.4 dB
- Neutral density filter, calibrated by the manufacturer, -18.9 dB
- Focusing dielectric lens (TPX), reflection, -0.2 dB
- Silicon lens, reflection, -1.5 dB

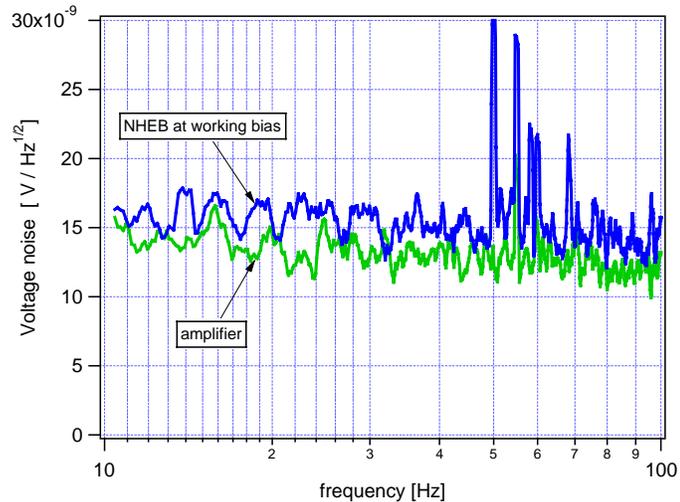
This gives in total -21 dB, or $\eta = 7.9 \times 10^{-3}$. The unaccounted losses can be absorption losses, interference losses, antenna losses, and antenna-to-bolometer matching losses. The bandwidth Δf has been estimated from a measurement done on a 100:1 scale model of the antenna as $0.3f_0$, or 100 GHz (accurate within about $\pm 50\%$). Substituting the

estimations for the losses and for the bandwidth into the expression above we get $\Delta P = 2.4 \times 10^{-12}$ W and maximum responsivity $S = \Delta V / \Delta P = 1.7 \times 10^6$ V/W.

The theoretical responsivity of the NHEB with this volume of the absorber strip would be $S_{\text{theor}} = 1.5 \times 10^7$ V/W at 0.5 K. If we associate the discrepancy solely with the unaccounted losses it would mean that those losses in this experiment were as large as -9.5 dB.

Fig. 7

Voltage noise from the NHEB at the operating conditions and the amplifier's own noise. The optical responsivity has been measured at 35 Hz.



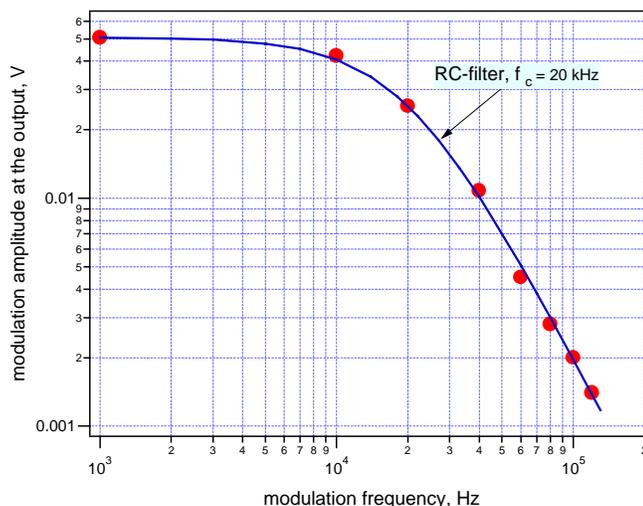
The results of the noise measurements are shown in the Fig. 7. The noise from the amplifier (INA110, differential OpAmp with an FET input) is the dominating contribution ($13 \text{ nV/Hz}^{1/2}$ at 35 Hz). The total bolometer noise at 35 Hz (the frequency used in the optical responsivity measurement) is about $15 \text{ nV/Hz}^{1/2}$ which corresponds to $NEP = e_n/S = 9 \times 10^{-15} \text{ W/Hz}^{1/2}$. For the same bolometer operating at 0.3 K and in the absence of coupling losses this output noise would have corresponded to $NEP = 9 \times 10^{-17} \text{ W/Hz}^{1/2}$.

Finally, we attempted to measure the time constant of the detector or that of the measurement system, whichever would be shorter. We had placed an IMPATT oscillator radiating at 62 GHz in front of the dewar window and modulated it at frequencies up to 200 kHz. To reduce the incident power the window was blocked by a metal bar, leaving a small gap just enough to get a measurable response from the NHEB. We have observed a -6 dB/octave roll-off with characteristic frequency 20 kHz (Fig. 8). Considering the dynamic resistance of the tunnel junctions at the working point (100 kOhms) and capacitance of the wiring connecting the junctions to the amplifier (about 100 pF), this frequency behavior perfectly corresponds to the low-pass filtering action of the readout circuit. The conclusion has been made that the time constant of the bolometer itself is at least below 10 μs . The theoretical value of the NHEB's time constant at 0.5 K is 0.16 μs ($f_{\text{mod}} > 6 \text{ MHz}$).

Fig. 8

Dots: Amplitude of the bolometer's response to radiation from a strong 62 GHz-source modulated at different frequencies.

Curve: theoretical frequency characteristics of an RC lowpass filter with $f_c=20\text{kHz}$. This value corresponds quite well to the R and C of the readout circuit. No rolloff contribution from the bolometer itself could be identified.



Further development

In the near future we are aiming to improve our experiment and achieve better values of sensitivity. The primary issue is to avoid the rf interference by installing additional filters in the cryostat. In this way we hope to reduce the working temperature of the bolometer to the physical temperature of the cryocooler, that is 0.3 K. The next step will be to minimize the output noise by using a cooled amplifier with noise level below $5 \text{ nV/Hz}^{1/2}$ in the vicinity of the detector. These two measures should improve the sensitivity by the factor of 20. At the same time we will need to identify and measure the unknown losses in the optical coupling and measure the true frequency spectrum of the receiver. We plan to do this by using a Fourier Transform Spectrometer.

Later on we would like to improve the performance of the NHEB even more by decreasing the absorber strip volume and by trying out materials other than copper and aluminum. It has been reported that in Hafnium and possibly in some other thin films one could obtain dependence of the τ_{ep} on temperature as T^4 instead of T^3 [10]. This would mean that the electron-phonon thermal conductance might be reduced even more, thus enhancing the bolometer responsivity. And besides the development of the individual detector element we plan to provide eventually also an array solution with a few NHEBs operating simultaneously on the same chip.

Conclusions

We are developing the NHEB - an antenna-coupled hot-electron direct detector particularly suitable for creating rapid bolometer cameras. According to the electrical responsivity measurements this detector can have sensitivity of $\text{NEP} = 10^{-17} \text{ W/Hz}^{1/2}$ and

time constant in the microsecond range at 0.3 K; a greatly better performance is possible at 0.1 K. Functionality of the NHEB has now been demonstrated in an optical qualification experiment with hot/cold load; the detector has been operated at 0.5 K and it has shown the optical NEP = 9×10^{-15} W/Hz^{1/2}. In the near future we aim to improve performance of the NHEB at 0.3 K and obtain the predicted level of sensitivity; later on we will also start to develop an array solution.

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