Cold-Electron Bolometer Integrated with a Unilateral Finline

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Abstract— **The Cold-Electron Bolometer (CEB) is a very sensitive millimetre-wave detector which is easy to integrate with planar circuits. CEB detectors have other important features such as high saturation power and very fast response. We have designed, fabricated and tested CEB detectors integrated across the slot of a unilateral finline on silicon substrate. Bolometers were fabricated using e-beam direct-write trilayer technology. The CEB performance was tested in a He^3 sorption cryostat HELIOX-AC-V at a bath temperature of 280 mK. To reduce the background power radiation overheating the optical window in the cryostat was equipped with two low-pass filters with cut-off frequency 33 cm^{-1} and 100 cm^{-1} and 2 neutral density filters with 10 db attenuation each. DC IV curves were measured in a current bias mode, optical response was measured by irradiating samples with a microwave signal from IMPATT diode at 110 GHz modulated at 127 Hz. These tests were conducted by coupling power directly into the finline chip. The signal response was measured using a lock-in amplifier. The bolometer dark electrical noise equivalent power is estimated to be about NEP=$5\cdot 10^{-16}$ W/Hz$^{1/2}$.**

I. Introduction

A new generation of bolometric detectors is needed for advanced telescopes for sub-mm imaging, CMB polarization experiments and far-infrared spectroscopy. One candidate technology is the capacitively coupled Cold-Electron Bolometer (CEB) [1]-[4]. The CEB can be used with both JFET [3] and SQUID readout [1, 2] systems, both of which are now well developed for use in astronomical instruments. JFET readout systems have been used with NTD semiconductor bolometers on ground based, balloon borne and space based instruments. SQUID readout and multiplexing have been developed for TES (Transition-Edge Sensor) bolometers [1] and used in both ground and balloon based instruments. Our goal is to develop CEBs that can be read by a JFET or SQUID, so that the performance of the two systems can be compared. .

The CEB is a planar antenna-coupled superconducting detector with high sensitivity and high dynamic range. A unique feature of this device is electron cooling by SIN tunnel junctions with strong electro-thermal feedback [5]. The CEB devices considered here consist of a normal metal absorber coupled to superconducting electrodes via SIN tunnel junctions at each end of the absorber. RF power from the antenna is capacitively coupled through the SIN tunnel junctions into the absorber. The absorbed power heats electrons above the Fermi level and the hottest electrons eventually tunnel through junction oxide barrier.

The cooling of the device as a result of removing the hot electrons from the absorber increases dynamic range of the system, thus substantially increasing the detector saturation power. This is to be contrasted with the operation of the TES where a biasing constant voltage source heats the device to keep it near the transition temperature. It has already been shown [1-3] that a cold-electron bolometer with strong electrothermal feedback can potentially give state of the art noise performance in presence of a realistic background power load. The time constant of CEB could be considerably reduced by the loop gain of negative electrothermal feedback to the level of 10 ns which is several orders of magnitude shorter than that for TES detectors. The CEB is therefore a very promising device for future space telescopes due to fast response, high sensitivity and low noise.

II. CEB Device Model

The operation of CEB can be described using the heat balance equation [1, 2]:

$$P_{cool}(V,T_e,T_{ph})+\Sigma\Lambda(T_e^5-T_{ph}^5)+\frac{V^2}{R_j}+I^2R_{abs}+C_\Lambda\frac{dT}{dt}=P_0+\delta P(t) \quad (1)$$

The right hand side represents the total power injected into the device.

The first term in the left hand side of the equation (1) $P_{cool}(V,T_e,T_{ph})$ is the cooling power of the SIN tunnel junction, where and T_e and T_{ph} are, respectively, the electron and phonon temperatures of the absorber. The second term $\Sigma\Lambda(T_e^5—T_{ph}^5)$ is the heat flow from the electron to the phonon subsystems in the absorber with Σ being the material constant and Λ is the volume of the absorber; $C_\Lambda = \Lambda\gamma T_e$ is the heat capacity of the absorber; R_j is the subgap resistance of the tunnel junction; R_{abs} the resistance of the absorber; $P(t)$ the incoming RF power.

The power flowing in and out of the CEB may be separated into two parts; a time independent term,

$$\Sigma\Lambda(T_{e0}^5 - T_{ph}^5) + P_{cool0}(V,T_{e0},T_{ph})=P_0 ,$$

and a time dependent term,

$$(\partial P_{cool}/\partial T + 5\Sigma\Lambda T_e^4 + i\omega C_\Lambda)\ \delta T = \delta P \quad (2)$$

The term $G_{cool} = \partial P_{cool}/\partial T$ is the effective cooling thermal conductance of the SIN junction that gives rise to the negative electrothermal feedback (ETF). When it is large, it reduces the temperature response δT because cooling power, P_{cool}, compensates for the change of signal power in the bolometer. The term $G_{e\text{-}ph} = 5\Sigma\Lambda Te^4$ is the electron-phonon thermal conductance of the absorber. From Eq. (2) we define an effective complex thermal conductance which controls the temperature response of CEB to the incident signal power

$$G_{eff} = G_{cool} + G_{e\text{-}ph} + i\omega C_\Lambda \qquad (3)$$

In contrast with TES, the effective thermal conductance of the CEB is increased by the effect of electron cooling (negative ETF).

In what follows we will assume that the SIN tunnel junction is voltage-biased, and that the current is measured by a SQUID. The sensitivity of the device is then characterized by the current responsivity S_I, which is the ratio of the current change and the change in the power load of the bolometer,

$$S_I = \frac{\partial I_\omega}{\partial P_\omega} = \frac{\partial I/\partial T}{G_{cool} + G_{e\text{-}ph} + i\omega C_\Lambda} = \frac{\partial I/\partial T}{G_{cool}} \frac{L}{(L+1)[1+i\omega\tau]} \qquad (4)$$

where $L = C_{cool}/G_{e\text{-}ph} >> 1$ is ETF gain and

$$\tau = \frac{C_\Lambda}{G_{e-ph}(L+1)} = \frac{\tau_0}{L+1} \qquad (5)$$

is an effective time constant, with $\tau_0 = C_\Lambda/G_{e\text{-}ph}$ (τ_0 ~10 µs at 100 mK).

The strength of the electrothermal feedback is estimated as:

$$L(\omega) = \frac{G_{cool}}{G_{e-ph}(1+i\omega\tau)} = \frac{\partial I/\partial T}{G_{cool} + G_{e-ph} + i\omega C_\Lambda} \qquad (6)$$

The noise properties of the detector are characterized by the *NEP*, which is the sum of three different contributions:

$$NEP^2_{total} = NEP^2_{e\text{-}ph} + NEP^2_{SIN} + \delta I^2/S_I^2 \qquad (7)$$

where $$NEP^2_{e\text{-}ph} = 10k_B\Sigma\Lambda(T_e^6 + T_{ph}^6) \qquad (8)$$

is the noise associated with electron-phonon interaction. NEP^2_{SIN} is the noise of the SIN tunnel junctions, and the last term $\delta I^2/S_I^2$ is the noise of a SQUID (or other) current amplifier with δI expressed in pA/Hz$^{1/2}$.

The noise of the SIN tunnel junctions, NEP_{SIN}, has three components: shot noise $2eI/S^2_I$, the fluctuations of the heat flow through the tunnel junctions, and the anticorrelation term between these two processes [1]:

$$NEP^2_{SIN} = \delta P^2 - 2\frac{\delta P_\omega \delta I_\omega}{S_I} + \frac{\delta I^2_\omega}{S_I^2}. \qquad (9)$$

III. Design of CEB and unilateral finline

The detector reported here uses a CEB with SIN tunnel junctions as a detector of an incoming radiation propagated through a 97 GHz WR-10 waveguide and a finline taper (Figure 1). The integrated circuit comprises a finline with a CEB device deposited across the fins. The CEB chip will be inserted into the E-plane of a rectangular waveguide block designed for 97 GHz frequency and fabricated by the Oxford Physics workshop (Figure 2). The devices are fabricated using the trilayer direct-write technology presented in [6, 7]. This approach is suitable for low-frequency applications as it allows for large size tunnel junctions, which are difficult to fabricate using traditional shadow evaporation technique. The latter is more suitable for higher frequencies (350 GHz and above) as smaller tunnel junctions are required and can be more easily fabricated in that technology. The next step of our work will be fabrication of parallel-series arrays of CEBs to overcome the amplifier noise of a JFET-readout system [8].

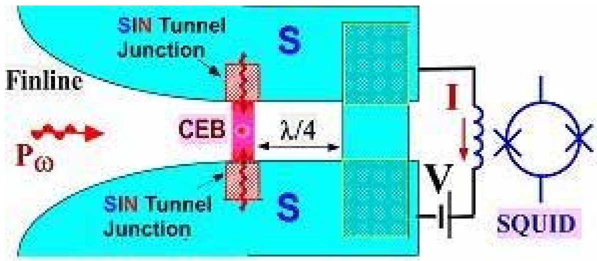


Fig. 1. A Cold-Electron Bolometer (CEB) coupled to a finline with SQUID readout

The SQUID readout can be used the same as for TES bolometers with typical SQUID sensitivity of 1 pA/Hz$^{1/2}$. The relatively moderate dynamic resistance of CEB (~1kOhm) should be matched to the low noise equivalent resistance of SQUID.

An attractive readout option is to use a JFET-readout, which can operate at room temperature. For this type of readout system, a higher dynamic resistance at the CEB output is desirable, which can be readily achieved using a parallel-series array [8]

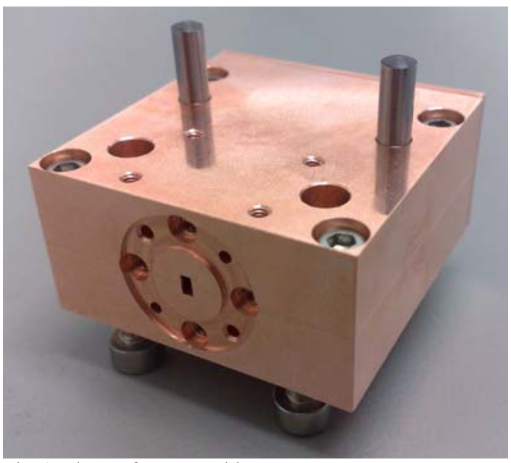


Fig. 2. Photo of a waveguide mount.

The performance of a cold-electron bolometer suitable for above described detector has already been analyzed in [1], at a frequency range centered at 70 GHz.

Assuming the presence of the typical background power load (P_0 = 0.2 pW per polarization component), the results of simulation are presented in Fig. 3.

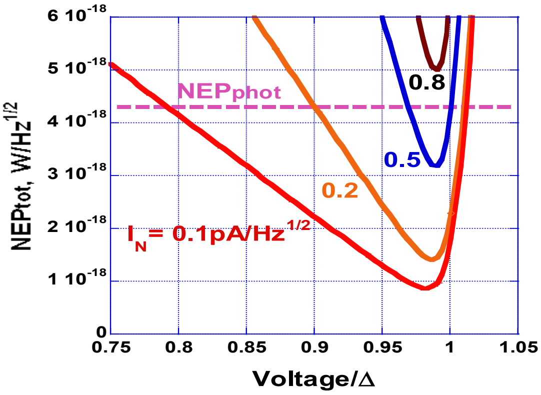


Fig. 3 Total NEP of the CEB with SIN tunnel junction for the 70 GHz channel, with a SQUID noise current from 0.1 pA/Hz$^{1/2}$ and 0.8 pA/Hz$^{1/2}$.
R=0.2 kOhm, S=2μm^2, Vol=0.03μm^3, power load P_0 = 0.2 pW, T=100 mK. The NEP$_{phot}$= 4.3·10^{-18} W/Hz$^{1/2}$ is shown by dashed line [1].

In Fig. 3, the photon shot noise at power load P_0 is given by

$$NEP_{phot} = \sqrt{2P_0 hf} \qquad (10)$$

For a detector centred at 70 GHz, the photon noise at power load P_0 = 0.2 pW is estimated as NEP$_{phot}$= 4.3·10^{-18} W/Hz$^{1/2}$.

Fig. 3 shows the results of a simulation of a CEB with a single SIN junction, with realistic parameters for the tunnel junction and absorber, and values of SQUID noise from 0.1 pA/Hz$^{1/2}$ to 0.8 pA/Hz$^{1/2}$. It has been shown theoretically [1] that the level of NEP$_{phot}$ can be achieved for SQUID noise lower than 0.5 pA/Hz$^{1/2}$

IV. Analysis of CEB-Finline IC

We have analyzed electromagnetic behaviour of the CEB-finline integrated circuit using Ansoft Designer and HFSS software. An equivalent circuit for the CEB was simulated with an ideal transmission line in Ansoft Designer software (Figure 4). In this model, the incoming signal propagates through a transmission line of electrical length of 360° and the power is fed into the CEB represented here by RLC tank circuit assuming matched terminals. The end of the transmission line is shorted at a distance called here “back short distance”. This value was set first to λ/4 and then optimised in order to achieve the best matching between the characteristic impedance of the transmission line and the input impedance of the RLC circuit over the band of interest.

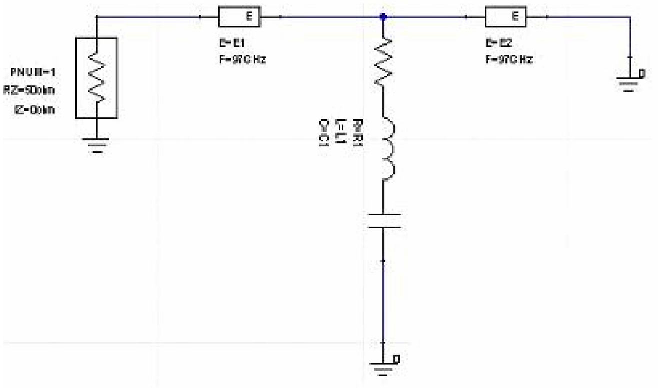
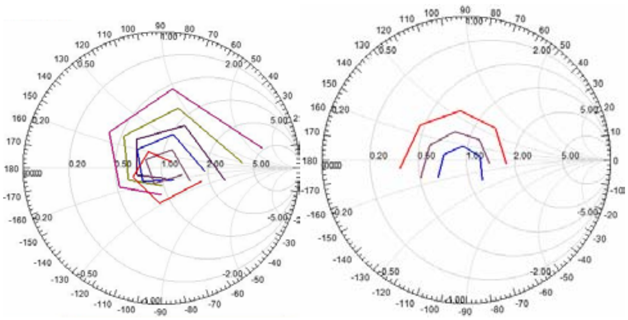


Fig. 4. Equivalent circuit used for simulations in Ansoft Designer.

Next we used HFSS to simulate a finline CEB with finline slot widths between 2 and 10 microns, deposited on silicon or quartz. The CEB itself was represented by an equivalent RLC circuit. The profile of the finline taper was designed using an optimum taper technique, implemented in the *Finsynth* software described in [9].

Simulations performed in Ansoft Designer and HFSS showed that most reliable matching can be achieved using tunnel junctions of 1.5×1.5 to 2×2 microns area, which correspond to capacitance values of 100-200 fF. For Si substrate, the optimum values obtained for the inductance and the resistance are 2.4 pH and 45 Ω respectively. For a quartz substrate, the corresponding values were 2.6 pH and 70 Ω. Simulations also showed that using a back short distance of 225-250 μm and 5 μm slot width a reflection coefficient down to -20 dB can be achieved for Si, while the result is rather insensitive to small variations in absorber resistance and inductance values. S_{11} for Si and quartz are shown in Figure 5a and 5b respectively. Similar values (-18 dB) were obtained for quartz substrate at a backshort distance of 500 μm (Figure 5b). Based on these simulations, we decided to fabricate a CEB-finline structure at 5 μm width on silicon substrate; using quartz substrate is still an option.



Fugure 5. Reflection coefficient for Si substrate(a) and quartz (b)

V. Fabrication

The CEB-finline samples have been fabricated using e-beam lithography in direct-write mode using the trilayer technology principle of fabricating tunnel junctions proposed by L. Kuzmin and described in [6, 7]. First, gold contact pads and wires have been patterned using e-beam exposure and thermal evaporation. Then finlines have been patterned in the same way and finally the Cold-Electron Bolometer structures have been fabricated in the middle of the finline using the trilayer process [6, 7]. As the last step, the Cu-Au layer has been removed by Ion-Beam Etching on the top of the trilayer structure. The photo of the fabricated CEB on finline is shown in Figure 6.

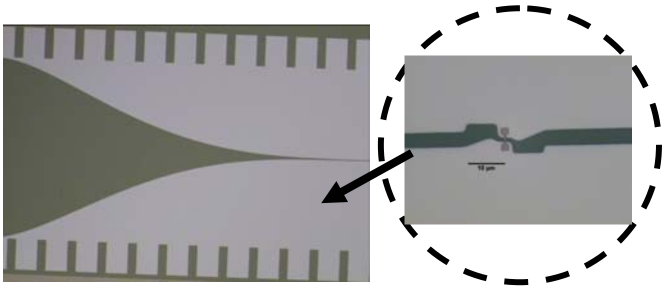


Fig. 6. Photo of finline with CEB across the slot.

VI. Measurement results and analysis

Testing of the CEB-devices was carried out at Chalmers University of Technology using an Oxford Instruments HELIOX-AC-V He^3 sorption cryostat, which can reach a base temperature of 280mK. In order to keep the optical power load on the detectors to acceptable levels, two low-pass filters with cut-off frequencies of 33 cm^{-1} and 100 cm^{-1} and two neutral density filters with 10dB attenuation each were mounted over the windows in the radiation shields inside the cryostat.

DC current-voltage characteristics of the CEB devices were measured in the fixed current bias mode, using a differential bias circuit with room temperature amplifiers and bias resistors. This circuit uses a driver circuit with bias resistance switchable in a range from 100kOhm to 10GOhm, and AD743 BiFET based first stage amplifiers with input voltage noise of around 4nV/√Hz. I-V curves were taken at several bath temperatures between 286mK and 356mK.

The voltage to temperature response, $S_{V/T} = dV/dT$ of CEB is calculated by comparing the I-V curves at different bath temperatures. The IV curve of the fabricated device is shown in Figure 7. Voltage response to the temperature versus bias voltage is shown in Figure 8.

Noise measurements were made using a lock-in amplifier referenced to a signal generator to make a spot measurement of the noise power at the voltage output of the bias system at 127Hz, using a 24dB/oct filter. The measured total voltage noise is shown as a function of bias voltage in fig. 9.

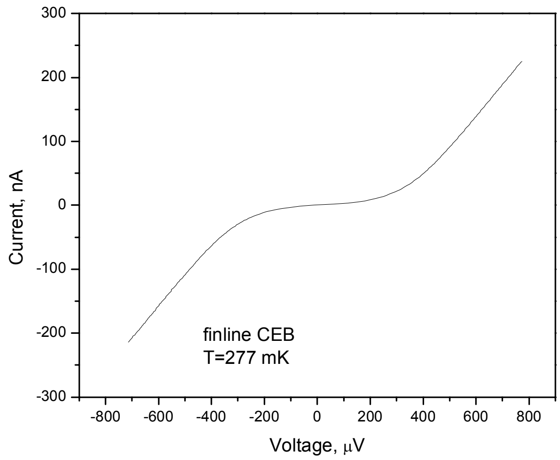


Fig. 7. The IV curve of CEB at temperatures 277 mK.

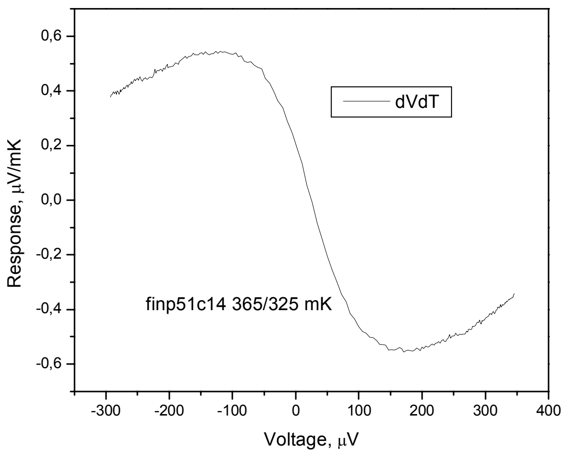


Fig. 8. Voltage response of the CEB with changing temperature versus bias voltage.

Preliminary optical tests of the bolometers were performed at 110 GHz with IMPATT diode as a signal source. The optical response was measured using lock-in amplifier. A photo of the experimental setup is presented in Fig. 10. Measurements were performed by mounting the CEB-finline chip on a sample holder not far away from the cryostat window and illuminating it from the outside. In this experiment, a small amount of optical power from a 110GHz

IMPATT diode with a horn was coupled into the finline which when mounted in free space behaves somewhat like a Vivaldi antenna, loaded on one side by the dielectric of the substrate. The output of the IMPATT diode was modulated at 127Hz and the bolometer response detected via a lock-in amplifier, at three levels of signal power. The measured optical response is shown in fig. 11.

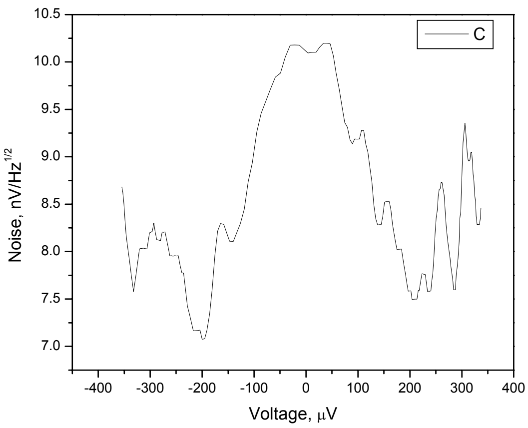


Fig. 9. Noise of CEB at 127 Hz.

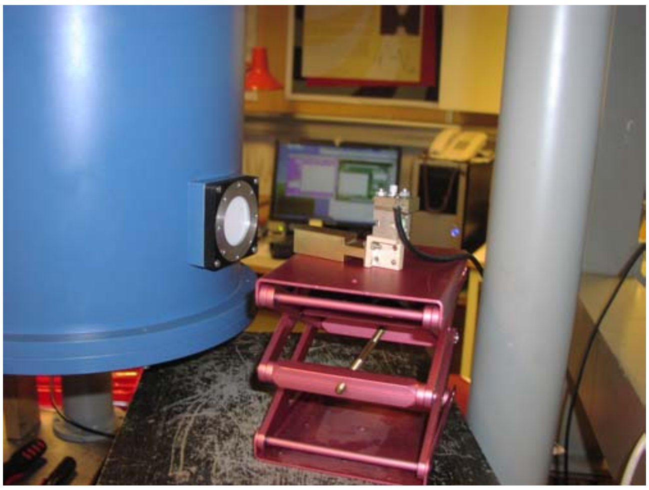


Fig. 10. IMPATT diode source irradiating sample at 110 GHz through optical window

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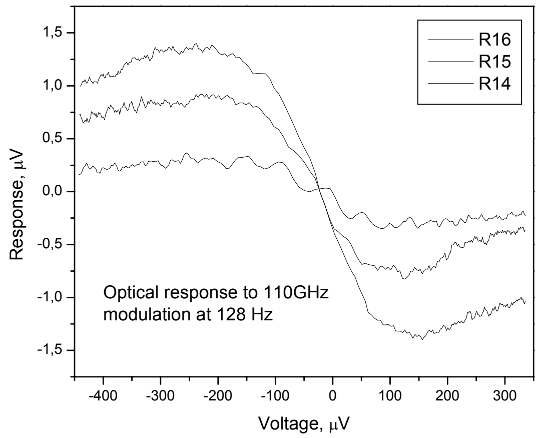

Fig. 11. Voltage response of bolometer to the incoming signal at 110 GHz at three levels of signal power

Taking into account the above experimental data we can estimate the dark NEP as follows. Voltage response is $S_v=dV/dP=(dV/dT)/G$, thermal conductivity due to electron-phonon interaction $G_{e-ph}=5\Sigma vT^4$. Another component of thermal conductivity is due to thermal flow by electrons:

$$G_i = \frac{dP_i}{dT} = \frac{d}{dT}\left(kT\frac{I}{e}\right) = \frac{kI}{e}$$

For the sample with two SIN tunnel junctions of 1.5×1.5 µm^2, absorber thickness of 50 nm, volume of absorber is $2\cdot10^{-19}$ m^3, material parameter $\Sigma=3\cdot10^9$ Wm^{-3}K^{-5} for copper, at temperature of 280 mK the thermal conductivity due to electron-phonon interaction can be estimated as $G_{e-ph}=1.84\cdot10^{-11}$ W/K. At bias current of 20 nA thermal conductivity due to thermal flow by electrons will be $G_{e-ph}=1.6\cdot10^{-12}$ W/K, which yields the total thermal conductivity of $2\cdot10^{-11}$. Taking the maximum experimental value for bolometer output noise of 10 nV/Hz$^{1/2}$ (including the amplifier noise) and temperature response 0.5 mV/K we can get the rough estimation $NEP_{ibias}=5\cdot10^{-16}$ W/Hz$^{1/2}$.

For reduced volume of absorber and in the voltage bias mode with SQUID readout the dark NEP of CEB can achieve rather promising level. For most of practical cases the NEP will be determined by a background power load that is about P_{bg} = 5 pW and for our signal frequency 100 GHz it corresponds to

$$NEP_{phot} = \sqrt{2P_{bg}E_{quant}} = \sqrt{2P_{bg}hf} = 2.4\cdot10^{-17}\ \text{W/Hz}^{1/2}.$$

We expect improvements in the fabrication and design of this device and its bias circuit to yield improved responsivity [9, 10]. Fig. 12 shows the calculated NEP and current responsivity anticipated for a device with a responsivity a few times better than our estimated value for the measured device. These results are obtained by simulation using advanced CEB models and assuming a SQUID readout.

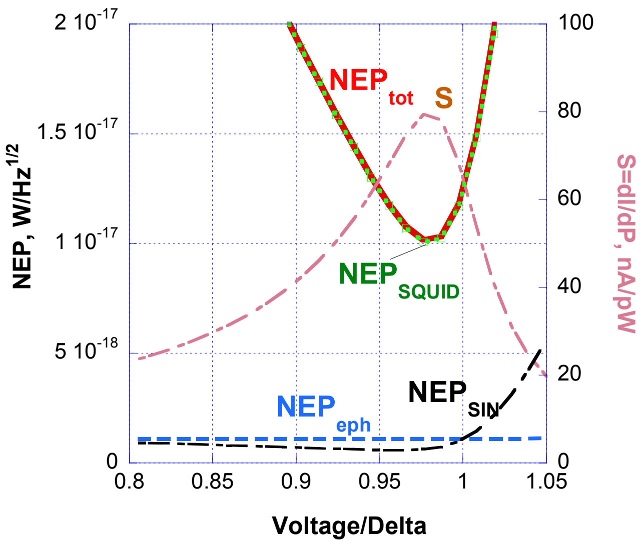

Fig. 12. Simulated NEP components and responsivity S for improved parameters of the CEB, power load of 20 fW, and SQUID noise current of 0.8 $pA/Hz^{1/2}$.

VII. Conclusions

The analysis of a Cold-Electron Bolometer deposited across a unilateral finline on a planar substrate has been presented. The detector can be a potential candidate for the next space cosmology missions and can also be of interest to ground-based experiments as a result of the simplicity of its integration to planar circuit technology, high saturation power and fast response.

We have fabricated finline coupled CEBs using direct-writing of the detector structures. We have estimated the dark noise equivalent power for devices in the current biased mode operating at 300mK and read by room temperature op-amp electronics as NEP=$5\cdot10^{-16}$ $W/Hz^{1/2}$.

We have also measured the detector's optical response to CW signals at 110 GHz, directly coupled to the finline chip.

Acknowledgment

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