Optical Response of a Cold-Electron Bolometer Array Integrated in a 345-GHz Cross-Slot Antenna

Mikhail A. Tarasov, Leonid S. Kuzmin, Valerian S. Edelman, Sumedh Mahashabde, and Paolo de Bernardis

***Abstract*—Two series/parallel arrays of ten cold-electron bolometers with superconductor–insulator–normal tunnel junctions were integrated in orthogonal ports of a cross-slot antenna. To increase the dynamic range of the receiver, all single bolometers in an array are connected in parallel for the microwave signal by capacitive coupling. To increase the output response, bolometers are connected in series for dc bias. With the measured voltage-to-temperature response of 8.8 μV/mK, absorber volume of 0.08 μm^3, and output noise of about 10 nV/Hz$^{1/2}$, we estimated the dark electrical noise equivalent power (NEP) as NEP $= 6 * 10^{-18}$ W/Hz$^{1/2}$. The optical response down to NEP $= 2 * 10^{-17}$ W/Hz$^{1/2}$ was measured using a hot/cold load as a radiation source and a sample temperature down to 100 mK. The fluctuation sensitivity to the radiation source temperature is $1.3 * 10^{-4}$ K/Hz$^{1/2}$. A dynamic range over 43 dB was measured using a backward-wave oscillator, a variable polarization grid attenuator, and cold filters/attenuators.**

***Index Terms*—Bolometer arrays, cold-electron bolometers (CEBs), cross-slot antennas, superconducting integrated circuits.**

I. Introduction

The COLD-electron bolometer (CEB) array has been proposed for use as the detector for the 345-GHz channel of BOOMERanG [1]. The requirement is to develop a CEB array with a junction field-effect transistor (JFET) readout for 90 channels. The noise equivalent power (NEP) of the CEB should be lower than photon noise for an optical power load of 5 pW, and polarization resolution should be better than 20 dB for observations of cosmic microwave background (CMB) foregrounds. The radiation power in the CEB is absorbed in a thin normal metal film connected to two superconductor–insulator–normal (SIN) metal tunnel junctions. These SIN junctions serve for electron cooling (similarly to the Peltier effect in semiconductors), and the output signal proportional to the absorbed power is measured on them. Electron cooling makes it possible not only to improve the sensitivity but also to expand the dynamic range due to an increase in the saturation power, because the absorbed power is removed from the absorber by a cooling current [2]. Contrary to heating by dc bias in a hot-electron bolometer, in the CEB, dc bias leads to *direct electron cooling*. As a result, the noise properties of this device are considerably improved by decreasing the electron temperature. However, for applications in atmospheric radio astronomy such as the BOOMERanG project, the power of microwave background radiation is usually higher than the saturation power of a single bolometer. Our previous theoretical and experimental studies on single CEBs show quite promising NEP down to $2 * 10^{-18}$ W/Hz$^{1/2}$ [3] for dark measurements. Nevertheless, simulations show that it is impossible to satisfy power load requirements of 5 pW with a JFET readout for a single CEB, for both current- and voltage-biased modes. A novel concept of a series/parallel array of CEBs in a current-biased mode has been proposed to effectively match a JFET amplifier readout [4].

The main advantage of the CEB array in comparison with a single CEB is the distribution of incoming power between N CEBs; summing the output signals results in an increased response from the array. An effective distribution of power is achieved by a parallel RF connection of CEBs, which couple to the RF signal through additional capacitance values. The total response is increased because the voltage response of each CEB improves for lower background power, and this is increased by a factor of N in the array configuration, with a corresponding decrease in absorber overheating and saturation. The voltage responsivity in the current-biased mode is $S_V = (\partial V_{\rm arr}/\partial T_s)/G_{\rm sum} = N((\partial V_{\rm sing}/\partial T_s)/G_{\rm sum})$, where $V_{\rm arr}$ and $V_{\rm sing}$ are voltages across an array and a single bolometer, respectively; T_e is the electron temperature; and $G_{\rm sum}$ is the total heat conductance. The amplifier noise related to the array is also proportionally reduced to array responsivity S_V. The amplifier impact to NEP $\mathrm{NEP}^2_{\rm amp} = (\partial V^2 + (NR\delta I)^2)/S_V^2$, where δV and δI are the voltage and current noise spectral densities, respectively, and T_e is the electron temperature. On the other hand, an increase in N leads to an increase in electron–phonon noise. In our design, we found an optimal number of CEBs, i.e., around ten; in this case, the total noise of the detector becomes less than the photon noise of the incoming signal power load of 5 pW [4].

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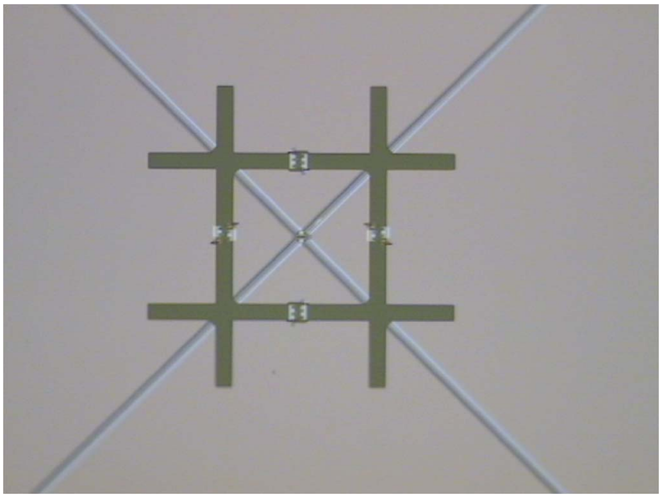

Fig. 1. Optical image of the cross-slot antenna. Arrays of CEBs are connected to four ports of the antenna. Diagonal slots are capacitive shunted by an additional Al layer deposited above a SiO insulator.

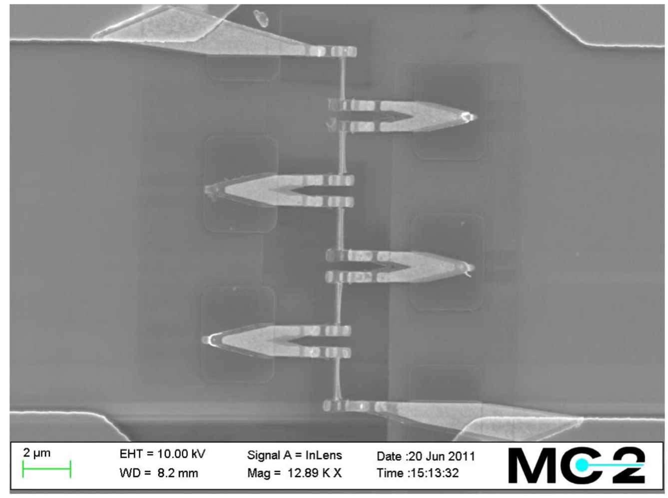

Fig. 2. SEM image of half of an array consisting of five absorbers and ten SIN tunnel junctions. One can see five absorbers of bolometers as narrow strips in the center. SIN tunnel junctions (horizontal, center) are connected to the antenna terminal at its edges through a planar capacitor that provides a parallel connection of bolometers to the antenna port.

II. Experimental Technique

The layout design of a CEB array is optimized for polarization measurements in a 345-GHz frequency band in order to measure the CMB and foreground polarization with balloon-borne experiment BOOMERanG. Bolometers are integrated in a cross-slot antenna that is placed in the center of a 7 mm × 7 mm chip on an oxidized Si substrate. Antenna design is similar to [5]. Each orthogonal array consists of ten CEBs connected in series for dc bias and readout. A photo of the antenna is presented in Fig. 1. Dark narrow slots are covered with an Al oxide capacitive layer. In each port of the antenna, there are placed five CEBs that are connected in series for each polarization, producing an array of ten CEBs for the vertical and ten CEBs for the horizontal components. The SIN tunnel junctions of the CEBs are made of a CrAl/AlOx/Al trilayer with a nonsuperconducting CrAl bilayer as a normal layer. An advanced shadow-evaporation technique was used for fabrication of the CEB. A detailed view of half of an array with five absorbers and ten tunnel junctions is presented by a SEM image shown in Fig. 2.

Such a chip with the antenna is attached by the back side to an extended hyperhemispheric Si lens with an antireflection coating at 345 GHz. For dynamic range measurements, the lens faces the optical window of the cryostat and is protected against overheating by two low-pass filters (LPFs).

These multimesh filters are produced by QMC Instruments and provide more than 10-dB attenuation above the cutoff frequency of 3 THz for LPF W97s and above 1 THz for LPF B694. The filters were placed at the windows in the radiation shields, at the 70- and 3-K temperature stages. To improve the thermal performance, we placed neutral density filters (NDFs) with attenuation of about 6 dB in front of each LPF. As a result, IR radiation is suppressed; the temperature of the radiation background is the same as that of the radiation shield, and by this, we are able to avoid any visible overheating of the cold stage or reduction in the hold time for the cryostat.

III. DC Measurement Results

The IV characteristic of an array of ten SINIS CEBs clearly demonstrates the sum gap voltage of 20 SIN junctions. A ratio of dynamic resistance at zero voltage to normal resistance of this array is over 1000, which is close to the theoretical estimation for the operating temperature of 280 mK. We measured the voltage at 0.1 nA bias current as a function of temperature. The maximum measured voltage response to temperature is 8.8 μV/mK. For NEP estimation, we measured the output noise of the array using a MOSFET input instrumentation amplifier (OPA111) as the first amplification stage. For theoretical estimations of the performance of such a bolometer array, we can use the power flow determined by electron–phonon interaction $P = \sum \nu (T^5 - T_0^5)$ so that $G = dP/dT = 5 \sum \nu T^4$. In this case, the responsivity is $S = dV/dP = (dV/dT)/(dT/dP) = (dV/dT)/G$. The volume of the absorber for our array of ten bolometers is $\nu = 10^{-19}$ m^3, and the material parameter for aluminium is $\sum = 1.2 * 10^9$ W $\cdot$ m$^{-3} \cdot$ K^{-5}; the thermal conductivity is thus $G = 3.6 * 10^{-12}$ W/K at 280 mK phonon temperature. Using the measured bolometer output voltage noise ($v_n = 10$ nV/Hz$^{1/2}$ in the white noise region) and the temperature response of $dV/dT = 8.8 * 10^{-3}$ V/K, we can estimate the minimum dark electrical NEP $= v_n/S = 6 * 10^{-18}$ W/Hz$^{1/2}$. For the actual power load of 5 pW at 345 GHz, the photon contribution to the total NEP can be estimated as $\mathrm{NEP_{phot}} = (2P_0 hf)^{1/2} = 4.8 * 10^{-17}$ W/Hz$^{1/2}$. It means that our bolometer will operate in a background phonon noise limit.

IV. Optical Response

We measured the response of this array to the microwave radiation emitted by a cryogenic blackbody radiation source. The radiation source was mounted on the 0.4-K stage; it consists of a constantan foil equipped with a heater and a thermometer. This foil covers the radiation pattern of the antenna and lens. Using

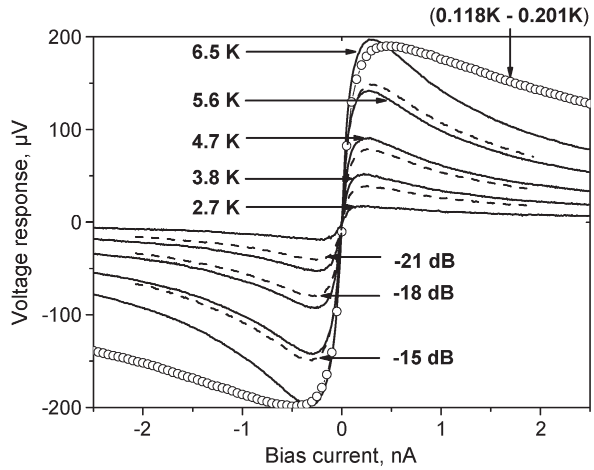

Fig. 3. Voltage response of the bolometer array to (open circles) bath temperature changes 0.118–0.2 K; (solid lines) variations of blackbody source temperature 2.7, 3.8, 4.7, 5.6, and 6.5 K; and (dashed lines) 345-GHz radiation from a BWO with additional attenuation of −21, −18, and −15 dB.

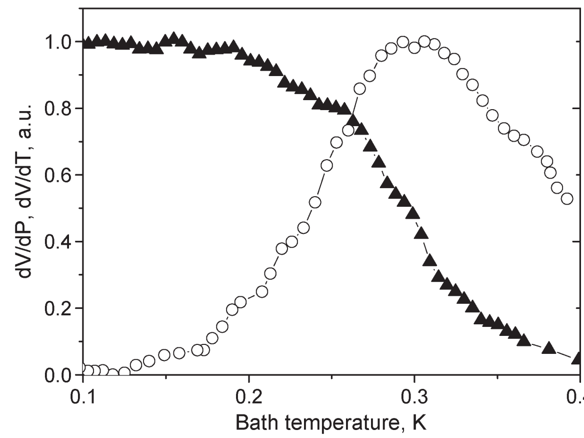

Fig. 4. Voltage response to (triangles) fixed radiation power dV/dP and (open circles) temperature response dV/dT_{ph} versus phonon temperature of the bolometer array.

a backward-wave oscillator (BWO) spectrometer/reflectometer, we measured reflection of the foil $R = 0.70 \pm 0.05$ at 345 GHz. This value is different from the zero reflectivity of a blackbody, and the actual emissivity of such source is $\kappa = 0.30 \pm 0.05$. The response to heating of the emitter is presented in Fig. 3. The measured voltage response to temperature variations of the emitter is 25 μV/K. Taking into account the emissivity of foil and the root-mean-square (rms) voltage noise 0.38 μV in the frequency range 0–40 Hz (mainly determined by external interferences), one can obtain the temperature sensitivity, which is 5 mK rms. Taking the experimentally measured voltage noise spectral density of the amplifier of 10 nV/Hz$^{1/2}$, which dominates in the total noise, we obtain a temperature sensitivity of $1.3 * 10^{-4}$ K/Hz$^{1/2}$. We can also calculate the power emitted by the heated foil using Planck's formula for central frequency $f_0 = 345$ GHz and for bandwidth $\delta f = 100$ GHz of a cross-slot antenna. At a temperature of 3 K, we get

$$\Delta P = \frac{\kappa \cdot hf \cdot \delta f}{\exp(hf/kT) - 1} = 3 * 10^{-14} \text{ W}$$

where $h = 6.626 * 10^{-34}$ J $*$ s is Planck's constant, $k = 1.38 * 10^{-23}$ J/K is Boltzmann's constant, f is the frequency, and κ is the emissivity of the radiation source. The voltage response to incoming power is thus $dV/dP = 8 * 10^8$ V/W. For the experimentally measured noise of 10 nV/Hz$^{1/2}$, this corresponds to an optical NEP $= 2 * 10^{-17}$ W/Hz$^{1/2}$. In Fig. 3, we show that the responses of the detector to variations in the power from a thermal radiation source and from a BWO are very similar, whereas the response to changes in the physical temperature of the sample is clearly very different. This difference can be due to suppression of the energy gap due to thermal heating.

Voltage saturation to phonon temperature $V(T_{\mathrm{ph}})$ below 200 mK with its derivative dV/dT_{ph} approaching zero at low bath temperatures does not lead to a decrease in optical response dV/dP (see Fig. 4). This means that the electron system is still sensitive to the incoming radiation, and this even makes measurements more stable in the region of saturation to phonon temperature.

Such phonon temperature saturation of voltage can be explained as a balance between electron cooling and overheating due to external radiation and Joule heating via the leakage resistance of tunnel junctions. Estimating the cooling power at 0.1 nA and 1 mV gives $P_{\mathrm{cool}} \sim I(V_\Delta - V) \sim 10^{-13}$ W. Joule heating for $V = 1$ mV bias and zero-bias resistance that we assume as leak resistance $R_0 = 10$ MΩ give $P_{\mathrm{heat}} = V^2/R = 10^{-13}$ W. The voltage of saturation for a given current can be obtained from the simple expression $IV_\Delta - IV = V^2/R$: we get $V_s = 0.5IR_0[(1 + 4V_\Delta/IR_0)^{1/2} - 1] = 1.1$ mV, which is close to the observed value.

V. Dynamic Range Measurements

The effectiveness of connecting bolometers in an array and of electron cooling is illustrated by optical measurements of the dynamic range. For this purpose, we used a BWO that operates in the frequency range 250–380 GHz. A calibrated polarization grid attenuator was used for ramping the incident power on the detector. Inside the cryostat, in addition to a cold 20-dB NDF, we also used a cold rotatable stage with a can switch between a 10-dB NDF and an open aperture by an external magnetic field. The measured dependence of the output voltage versus the attenuation of the signal is presented in Fig. 5. Assuming that the weakest detectable signal is determined by amplifier noise $(10$ nV/Hz$^{1/2})$ and that the strongest is determined by the saturation level, as presented in Fig. 5, at 200 μV, we find that the full dynamic range of this bolometer array is over 43 dB. With a better readout amplifier, this value can increase.

VI. Polarization Sensitivity

We also measured the sensitivity to the polarization degree of the incoming signal by rotating the polarized signal source in front of the optical window. In this experiment, we used a 115-GHz impact ionization avalanche transit time (IMPATT) oscillator and frequency tripler. The voltage dependence of response for polarization angle $\varphi = 0°, 15°, 30°, 45°, 60°$ is presented in Fig. 6. The maximum response scales as $\sin\varphi$.

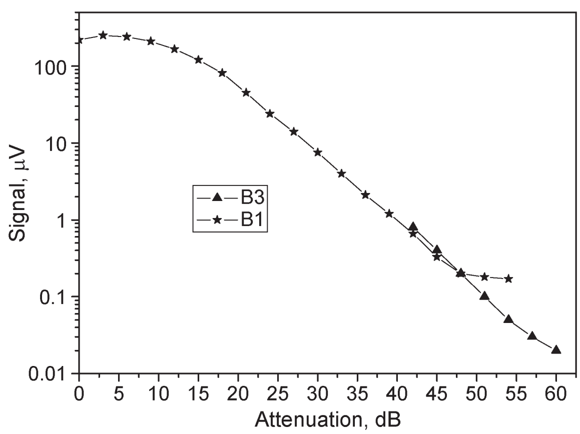

Fig. 5. Dependence of the output voltage on the attenuation of the incoming signal for the 345-GHz radiation from a BWO. Signal attenuation values for curve B1 are directly taken from the calibrated attenuator. Curve B3 is taken from an additional 10-dB cold attenuator.

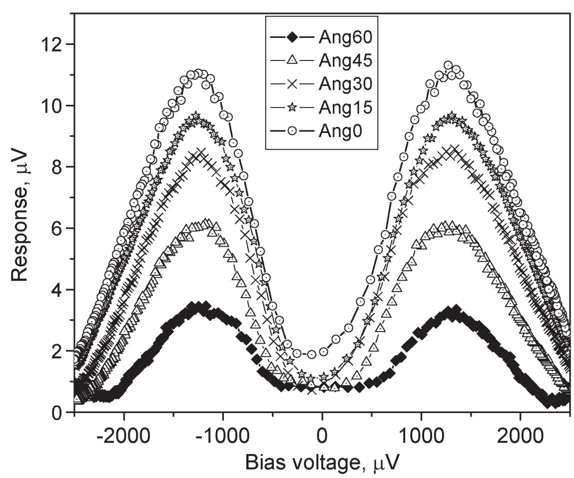

Fig. 6. Output voltage dependence on bias voltage for a rotation of the polarized signal source in steps of 15°.

We were not able to measure the ultimate polarization resolution due to vibrations that make instabilities and reflections dominant when the rotation of polarization reduces the signal by more than 10 dB.

VII. Conclusion

The CEB array integrated in a cross-slot antenna was measured in a dilution refrigerator with an optical window in the temperature range 0.3–0.1 K. The optical response with $\mathrm{NEP} = 2 * 10^{-17}$ W/Hz$^{1/2}$ and fluctuation sensitivity to the radiation source temperature of $1.3 * 10^{-4}$ K/Hz$^{1/2}$ were measured using a cryogenic blackbody radiation source. The dynamic range over 43 dB and the sensitivity to polarization of the incoming 345-GHz radiation were measured through an optical window using a BWO and an IMPATT diode with frequency tripler. Measured characteristics satisfy requirements for balloon-borne experiment BOOMERanG, and CEBs could be considered for future balloon- and ground-based radio telescope experiments.

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