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Optical Response of a Cold-Electron Bolometer Array

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A multielement bolometric receiver system has been developed to measure the power and polarization of radiation at a calculated frequency of 345 GHz. Arrays of ten series–parallel connected cold-electron bolometers have been pairwise integrated into orthogonal ports of a cross-slot antenna. Arrays are connected in parallel in the high-frequency input signal and in series in the output signal, which is measured at a low frequency, and in a dc bias. Such an array makes it possible to increase the output resistance by two orders of magnitude as compared to an individual bolometer under the same conditions of high-frequency matching and to optimize the matching with the JFET amplifier impedance up to dozens of megohms. Parallel connection ensures matching of the input signal to the cross-slot antenna with an impedance of 30 Ω on a massive silicon dielectric lens. At a temperature of 100 mK, a response to the thermal radiation of a thermal radiation source with an emissivity of 0.3, which covers the input aperture of the antenna and is heated to 3 K, is 25 μV/K. Taking into account real noise, the optical fluctuation dc sensitivity is 5 mK, the estimated sensitivity corresponding to the noise of the amplifier is about 10^{-4} K/Hz$^{1/2}$, and the noise-equivalent power is about (1–5) × 10^{-17} W/Hz$^{1/2}$.

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The measurement of the polarization and intensity of the cosmic microwave background radiation, as well as radioastronomical observations of narrowband sources, is important for cosmological experiments. One such experiment is the BOOMERANG-3 ballon project for the 350-GHz range [1]. A cold-electron bolometer [2–4] can be an optimal detector for this problem. Several functions of a superconductor–insulator–normal metal (SIN) tunnel junction are implemented in the cold-electron bolometer: the measurement of the temperature, the high-frequency coupling with an integrated antenna, and the efficient thermal insulation [2–4] and electronic cooling [5]. The response of the cold-electron bolometer is very high due to the small volume of the absorber and low temperature. According to the numerical estimates, the noise-equivalent power of the cold-electron bolometer can reach 10^{-19} W/Hz$^{1/2}$ when using it in space telescopes with a low background radiation power. In an experiment with an effective dc power load of 20 fW at a temperature of 100 mK, a noise-equivalent power of 2 × 10^{-18} W/Hz$^{1/2}$ was obtained under electric heating [6]. Such a sensitivity satisfies the requirements of the B-Pole European Space Telescope [7]. For ballon- and ground-based telescopes, the sensitivity can be better than the photonic noise of the signal at a sufficiently large optical load [8].

At present, there are three competing types of superconducting bolometers for reception of radiation. The first, most developed type is the superconducting transition edge sensor [9]. The second type is the kinetic inductance detector [10] with a high-frequency bias at the resonance frequency. The third promising receiver is the cold-electron bolometer, which is connected to an antenna through tunnel junction capacitances and is manufactured on a planar substrate. Let us list the expected advantages of the cold-electron bolometer as compared to the transition edge sensor:

—efficient electron cooling of the detector by the bias and reading current in contrast to the inevitable overheating of the transition edge sensor by the bias current, i.e., lower electron temperature and smaller noise in the cold-electron bolometer;

—a much higher saturation power due to the possibility of the removal of the incoming power from the absorber by means of electron cooling;

—less stringent requirements on the stability of the temperature, because the cold-electron bolometer measures the voltage with the flowing tunnel current and the contribution from the electron–phonon interaction decreases strongly;

—the possibility of a connection to existing field-effect transistor amplifiers with a noise-optimal resis-

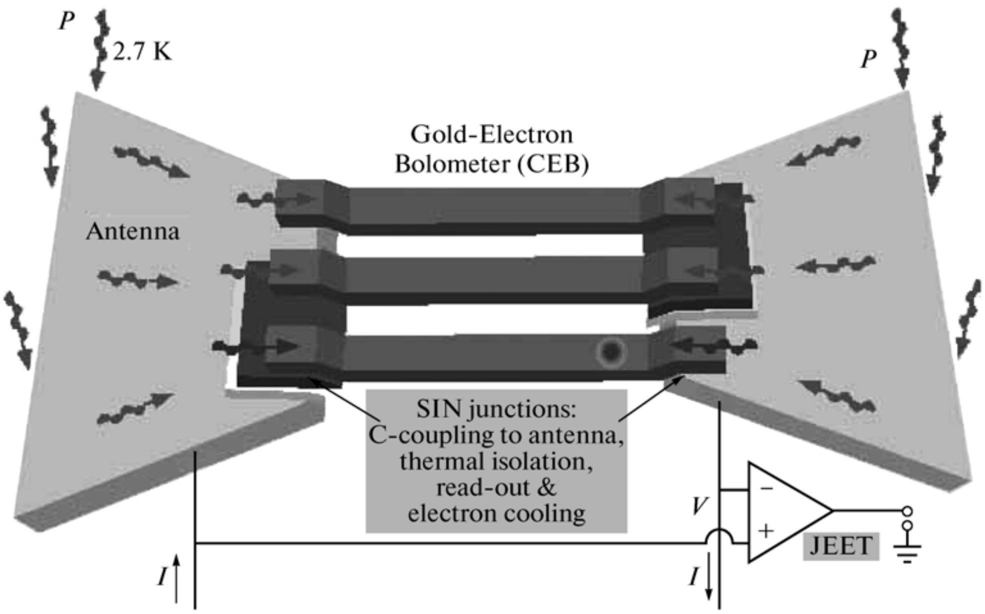

Fig. 1. Layout of the array of three cold-electron bolometers connected in series in direct current and in parallel in the input microwave signal. The parallel high-frequency connection is ensured by an additional capacitor between the superconducting edges of the bolometer and the antenna.

tance of about a megohm, in contrast to the transition edge sensors, where only a complex low-ohmic SQUID is acceptable in the signal readout system.

The difference between the transition edge sensor and the cold-electron bolometer increases in measurements with high optical background power load. In this case, the saturation power of the transition edge sensor should be chosen as no less than the expected maximum signal; this choice leads to additional thermodynamic noise. The cold-electron bolometer allows larger flexibility in the choice of the subsequent electronics, which can be based on JFET transistors, MOSFETs, or SQUIDs. In the first case, the matching is achieved by the series connection of cold-electron bolometers [10], which is described in this work.

In application to the investigations of the cosmic microwave background radiation at a frequency of 350 GHz, the noise of the bolometer at a characteristic optical load of 5 pW [1] should be less than the statistical photon noise of the signal. A numerical simulation indicates that the use of a single bolometer and a field-effect transistor cannot ensure these conditions in either a current bias mode [8] nor in a voltage bias mode [11]. To solve this problem, a novel concept of a series–parallel array of bolometers was proposed [8] (see Fig. 1). The input power in such a array is distributed over N bolometers and the output response is summed. The effective distribution of the power is achieved by the inclusion of the capacitance coupling between each bolometer and the antenna. In this case, the heating of each absorber decreases and the low-frequency response increases. The contribution of the voltage noise of the amplifier decreases proportionally.

At the same time, an increase in the number of bolometers is accompanied by an increase in the total volume of the absorber and by a corresponding increase in electron–phonon noise. The calculation of all the components of the noise-equivalent power of this array indicates that total noise is lower than the photon noise of the incoming signal when the number of bolometers is larger than six. The array of 10 bolometers was taken to create an experimental sample.

Figure 2a shows the photograph of the central part of a chip with a cross-slot antenna developed similar to [12]. Each port of the antenna contains an array of five bolometers, which are in turn connected in series for the horizontal and vertical polarizations, so that the array of 10 bolometers works for each polarization. The dark diagonal slots of the antenna are covered through the insulator by an aluminum film, which forms the capacitance shunting of the slot at the signal frequency. The absorbers of the bolometers are made of a thin aluminum film with a chromium sublayer, ensuring the normal conductivity and the possibility of the formation of a Cr/Al/AlOx/Al tunnel junction as described in [13, 14]. Figure 2b shows the electron microscopy image of the array of five bolometers located at one of the ports of the antenna.

The chip with the antenna was placed on an extended hyperhemispherical silicon lens with a quarter-wave antireflection coating of a hemisphere 14 mm in diameter. The assembly was mounted on the samples holder, which is connected through a heat guide

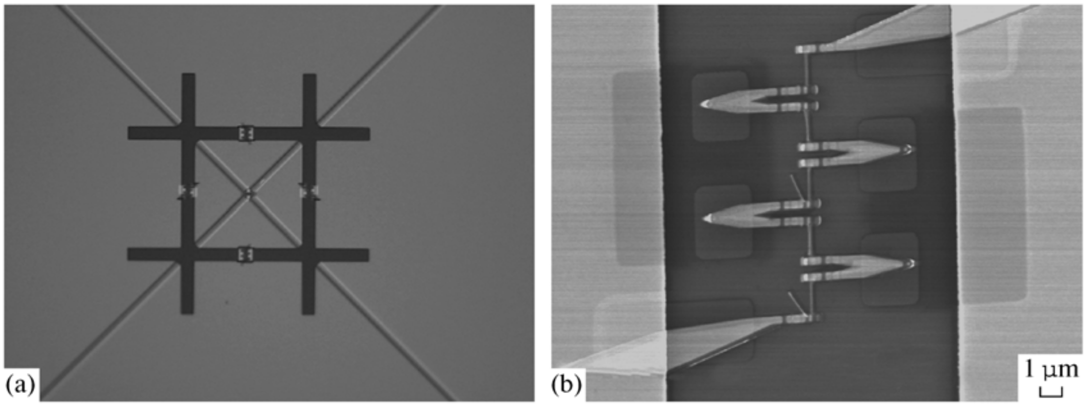

Fig. 2. (a) The optical photograph of the cross-slot antenna with the arrays of bolometers at four nodes (ports) of the antenna. (b) The electron microscopy image of the half of the array consisting of five absorbers and ten SIN junctions.

to the mixing chamber of the dilution microcryostat [15]. Radiation incident on the lens from outside passes through the optical window (or emits by a warm cap) and three narrowband quasioptical filters [16], which are located on thermal shields with the temperatures of 100, 4.2, and 0.4 K. The infrared radiation was attenuated by ZITEX^{tm} and FLUOROGOLD^{tm} filters mounted on the 100- and 4.2-K screens, respectively. The filters attenuate incoming infrared radiation on the sample holder to about 0.1 μW. However, the power of the 350-GHz radiation component at room temperature attenuated only by 5 dB is enough to deeply saturate the bolometer. For this reason, the response of the bolometer to thermal radiation was tested using a 0.4-K shield screening the input radiation flux.

The current–voltage characteristics of the array of 10 cold-electron bolometers exhibit a total energy gap of 20 SIN junctions. In the presence of the 0.4-K screen and cooling of the bolometer below 0.2 K, the ratio of the maximum resistance at zero bias, ~10 MΩ, to the normal asymptotic resistance exceeds 1000. Note that the differential resistance is saturated at the temperature of the holder below 200 mK. Since the chip contains not only the bolometer, but also other elements, it was verified that the temperature of the bolometer, which was estimated from its differential resistance, changed only by several hundredths of a Kelvin under the direct electric heating of the chip by a power of 0.2 μW. Since the picowatt power is supplied to the chip when performing the measurements, the temperature of the bolometer is expected to coincide with the temperature of the holder. Therefore, other causes of saturation should be sought. It is possibly due to parasitic overheating by interference currents (50-Hz interferences, cellular telephony, television, etc.). However, the results obtained under different grounding and shielding conditions, as well as at different laboratories, are almost the same; this behavior implies that there are a set of the causes of visible saturation in the complex multielement system of tunnel junctions that are included in series and connected through the capacitances under electron cooling.

To measure the optical response, a heated constantan foil covering the input aperture of the lens was mounted inside the radiation screen of the cryostat at a temperature of 0.4 K. The measured coefficient of reflection of the foil at a frequency of 350 GHz is 0.7 ± 0.05; i.e., the emissivity is $\kappa = 0.3 \pm 0.05$. The upper panel of Fig. 3 shows the response to the radiation of the heater at its temperature T, i.e., the difference between the current–voltage characteristic at $T < 1$ K, when the radiation power is negligible, and the current–voltage characteristic corresponding to the current temperature. The same figure shows the response of the bolometer to a change in its temperature. It is seen that the shapes of the curves describing the effect of the irradiation and heating are noticeably different. Thus, the mechanism of the formation of the response to radiation noticeably differs from trivial heating.

The lower panel of Fig. 3 shows the response as a function of the temperature of the sample holder. It is seen that, similar to the differential resistance, the response first increases rapidly and is then saturated at about 0.2 K with the cooling of the bolometer. Note that due to saturation, the receiver is weakly sensitive to small changes in its temperature; this property is useful for applications.

The upper panel of Fig. 4 shows the time dependence of the voltage response at the bias current corresponding to the maximum signal and at the temperature of the radiator; the upper panel of Fig. 4 shows the radiator-temperature dependence of the response. According to this figure, change in the response at $T =$ 3 K is 25 μV/K. Taking into account the emissivity of the radiator and a real rms noise of 0.38 μV, the fluctuation sensitivity in the 0–40-Hz measurement band is 0.005 K. If the spectral density of the noise of the

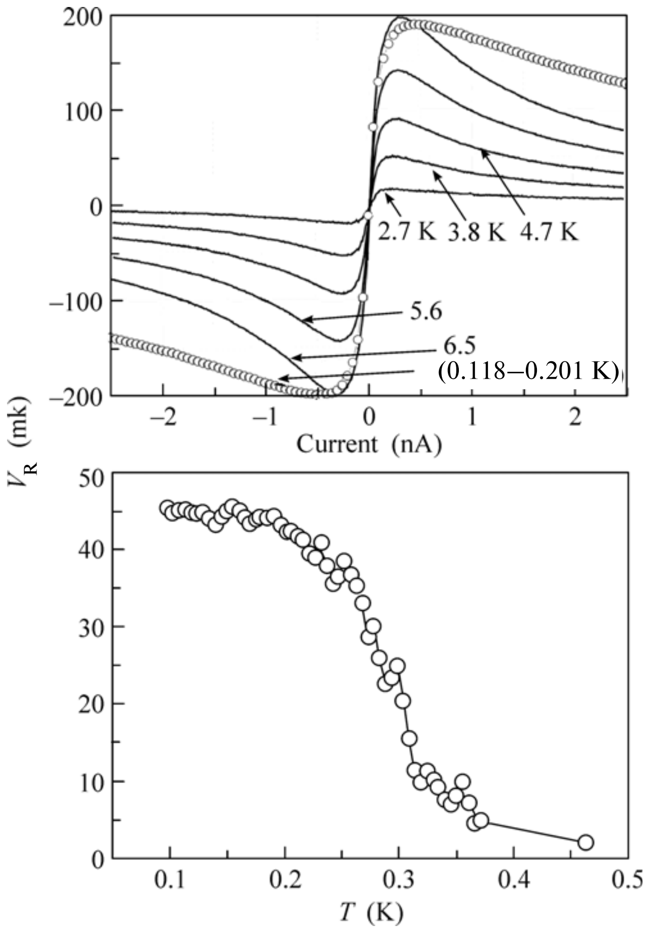

Fig. 3. (Upper panel) Voltage response V_R at a bolometer holder temperature of 0.1 K for various radiator temperatures indicated in the figure and with variation of the bolometer temperature from 0.118 to 0.201 K. (Lower panel) The bolometer temperature dependence of V_R at a fixed emitted power.

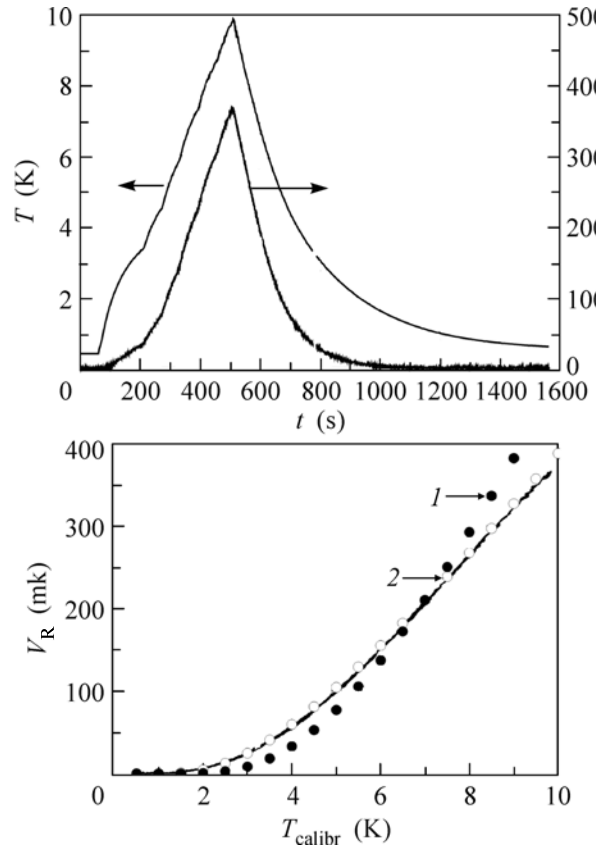

Fig. 4. (Upper panel) Time dependence of the bolometer response V_R at a current of 0.25 nA corresponding to its maximum under change in the radiator temperature T. (Lower panel) The temperature dependence $V_R(T)$; the closed and open circles are the dependences according to the Planck formula at the frequencies of 350 and 210 GHz, respectively; and the temperature of the bolometer is 0.1 K.

amplifier, ~10 nV/Hz$^{1/2}$, is taken for noise, the fluctuation sensitivity is approximately equal to 1.3×10^{-4} K.

Let us estimate the power emitted by the heated foil using the Planck formula, taking into account the passband of the double slot antenna $\delta f = 100$ GHz, taking a calculated value of 350 GHz for the central frequency, and taking into account that the detector operates in the single-mode regime. At a temperature of 3 K, we obtain

$$\Delta P = \kappa \frac{hf}{\exp(hf/kT) - 1}\delta f = 0.3 \times 10^{-13} \text{ W}.$$

The volt/watt sensitivity is $dV/dP = 8 \times 10^8$ V/W, and at noise corresponding to the noise of the amplifier, the optical noise-equivalent power is estimated as 1.2×10^{-17} W/Hz$^{1/2}$. Note that this estimate is rather rough, because the signal intensity varies strongly in the antenna band: according to the Planck formula, its values at the lower and upper edges of this band are three times higher and lower than that at the center of the band, respectively. In addition, the real frequency response of the antenna can differ from the calculated one. This is seen when comparing the response as a function of the temperature of the radiator with the dependence calculated by the Planck formula at various central frequencies of the antenna (see the lower panel of Fig. 4). It is seen that good agreement of the calculation with the experimental data is reached not at a frequency of 350 GHz, but at the noticeably lower frequency of 210 GHz. If this value corresponds to the central frequency of the antenna, the optical noise-equivalent power is estimated as ~6×10^{-17} W/Hz$^{1/2}$. To solve this problem, experiments with tunable narrowband radiation sources are required. We are beginning to prepare such experiments.

In summary, the proposed bolometer cooled below 0.2 K ensures a sensitivity close to the value required for solving cosmological problems. A further advance in this field can be expected if the mechanism of the limitation of the differential resistance and sensitivity at temperatures below 0.2 K could be revealed by comparing the results with the theoretical model.

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